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## Mid-to Late Holocene landscape reconstruction of the Maye Estuary (Picardy, Northern France) and its implications for human occupation

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# Quaternary International

## Mid- to Late Holocene landscape reconstruction of the Maye Estuary (Picardy, Northern France) and its implications for human occupation --Manuscript Draft--

<b>Manuscript Number:</b>	QUATINT-D-19-00169R1
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<b>Abstract:</b>	<p>The town of Rue was one of the most important coastal harbours of Picardy, Northern France, from the beginning of the 12<sup>th</sup> century to the end of the 15<sup>th</sup> century CE. Document sources and ancient maps confirm the existence of this vibrant harbour. Until now, however, no palaeoenvironmental studies have attempted to reconstruct the configuration of the region's coastline during medieval times. Here we employ a geoarchaeological approach to reconstruct the Mid- to Late Holocene shoreline and landscape changes in the Rue area. Our approach includes a geophysical survey (Electric Resistivity Tomography method) and a series of eight sediment cores that reveal the region's chronostratigraphy. Document sources were also used to shed light on the landscape configuration during the Late Middle Ages (ca. 1300 CE). Our coring results, based on sedimentological analyses, are combined with 2D geophysical profiles down to 21.50 m. This reveals, firstly, that a calm marine environment prevailed at the beginning of the 4<sup>th</sup> millennium BCE, particularly in depressions bordered by Pleistocene coastal spits ( foraines ). Secondly, from ca. 3500 BCE to ca. 1000 BCE, coastal swamps predominated. Then, thirdly, at around 1000–1250 CE, an estuarine depositional environment prevailed, prior to a final period of land reclamation of the former Maye Estuary from the 13<sup>th</sup> century CE onwards. These results agree well with recent work on sea level changes along the Atlantic and English Channel coasts of France, where continuous post-glacial sea level rise has been observed. Our study also proposes a location of the medieval harbour of Rue to the west of the town at the upstream boundary of the upper part of the Maye Estuary, near ' Le Moulin de Saint-Jean' , although archaeological evidence of the exact site of this tidal harbour is still lacking.</p>
<b>Suggested Reviewers:</b>	Alain Trentesaux, Dr Pr, Université de Lille Faculté des Sciences et Technologies alain.trentesaux@univ-lille.fr  Pierre Stephan, Dr Littoral environnement teledetection et geomatique pierre.stephan@univ-brest.fr  Sylvie Coutard, Dr INRAP: Institut national de recherches archéologiques préventives sylvie.coutard@inrap.fr

Response to Reviewers:

15/12/2019

Thijs van Kolfschoten  
Editor in Chief  
Quaternary International

Dear Editor:

I wish to submit a research paper for publication in Quaternary International titled 'Geoarchaeology of the Maye estuary (Picardy, Northern France): Mid- to Late Holocene landscape reconstruction and its implications for human occupation'. The paper was coauthored by Matthieu Ghilardi, Christophe Cloquier, Doriane Delanghe, Yannick Buchot, Daniel Hermitte, Jean-Claude Parisot, and Jean-Marc Hoeblich.

This study reconstructs the geoarchaeology of the Maye estuary in Northern France, combining geophysical and chronostratigraphical investigations with the analysis of historical sources. We provide a detailed description of the palaeoenvironment during the last 5000 years and make inferences about human settlement and land reclamation in the area. We believe that our study makes a significant contribution to the literature because a detailed palaeoenvironmental investigation of the Maye estuary has not been performed before, and our study additionally provides new information about the probable position of the medieval harbour of the town of Rue, the precise location of which was unknown.

We believe that this paper will be of interest to the readership of your journal due to its broad audience of scientists dealing with physical and natural issues in the Quaternary.

Please consider, as potential referees, Pr. Dr. Alain Trentesaux (Faculté des Sciences et Technologies, Université de Lille; [alain.trentesaux@univ-lillefr](mailto:alain.trentesaux@univ-lillefr)) and Dr. Pierre Stéphane (UMR6554 LETG, CNRS; [pierre.stephan@univ-brest.fr](mailto:pierre.stephan@univ-brest.fr)).

This manuscript has not been published or presented elsewhere in part or in entirety and is not under consideration by another journal. We have read and understood your journal's policies, and we believe that neither the manuscript nor the study violates any of these. There are no conflicts of interest to declare.

Thank you for your consideration. I look forward to hearing from you.

Sincerely,  
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1 **Mid- to Late Holocene landscape reconstruction of the Maye Estuary (Picardy, Northern**  
2 **France) and its implications for human occupation**

3  
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17  
18 **Abstract**

19  
20 The town of Rue was one of the most important coastal harbours of Picardy, Northern France,  
21 from the beginning of the 12<sup>th</sup> century to the end of the 15<sup>th</sup> century CE. Document sources  
22 and ancient maps confirm the existence of this vibrant harbour. Until now, however, no  
23 palaeoenvironmental studies have attempted to reconstruct the configuration of the region's  
24 coastline during medieval times. Here we employ a geoarchaeological approach to reconstruct  
25 the Mid- to Late Holocene shoreline and landscape changes in the Rue area. Our approach  
26 includes a geophysical survey (Electric Resistivity Tomography method) and a series of eight  
27 sediment cores that reveal the region's chronostratigraphy. Document sources were also used  
28 to shed light on the landscape configuration during the Late Middle Ages (ca. 1300 CE). Our  
29 coring results, based on sedimentological analyses, are combined with 2D geophysical profiles  
30 down to 21.50 m. This reveals, firstly, that a calm marine environment prevailed at the  
31 beginning of the 4<sup>th</sup> millennium BCE, particularly in depressions bordered by Pleistocene  
32 coastal spits (*foraines*). Secondly, from ca. 3500 BCE to ca. 1000 BCE, coastal swamps  
33 predominated. Then, thirdly, at around 1000–1250 CE, an estuarine depositional environment  
34 prevailed, prior to a final period of land reclamation of the former Maye Estuary from the 13<sup>th</sup>

35 century CE onwards. These results agree well with recent work on sea level changes along the  
36 Atlantic and English Channel coasts of France, where continuous post-glacial sea level rise has  
37 been observed. Our study also proposes a location of the medieval harbour of Rue to the west  
38 of the town at the upstream boundary of the upper part of the Maye Estuary, near '*Le Moulin*  
39 *de Saint-Jean*', although archaeological evidence of the exact site of this tidal harbour is still  
40 lacking.

41

## 42 **Keywords:**

43 Geoarchaeology; Palaeogeography; Sedimentology; Relative sea level rise; Coastal plain;  
44 Holocene

45

## 46 **1. Introduction**

47

48 Over the last decades, particular attention has been paid to the study of palaeoenvironmental  
49 dynamics combined with the human settlement of the French coastal plains of Brittany,  
50 Normandy, and Picardy (Lespez et al., 2004; Gandouin, 2007; Lespez et al., 2010; Pailler et al.,  
51 2011; Stéphan, 2011; Lequint and Fouache, 2012; Daire et al., 2013). However, the Bay of  
52 Somme has been little investigated from a geoarchaeological perspective, despite its long term  
53 history of human activity.

54 The town of Rue is located on the Picardy coastal plain, approximately 7 km from the present-  
55 day coastline (Fig. 1). It was one of the most important coastal harbours of Picardy during  
56 medieval times, from the beginning of the 12th century to the end of the 15th century CE  
57 (Labrecque, 2008). It is generally accepted that this harbour gradually silted up due to a natural  
58 infilling of the estuary with sediment, reinforced by structures (artificial levees in particular)  
59 built for agricultural land reclamation purposes on the coastal plain from the 12th century CE  
60 (e.g., Demangeon, 1905). However, no prior palaeoenvironmental or geomorphological studies  
61 have involved the scrutiny of ancient sketches, maps and plans in the endeavour to reconstruct  
62 shoreline displacements during medieval times.

63 This paper aims to reconstruct the landscape evolution surrounding the medieval town of Rue  
64 and discusses relative sea level change and related morphological impacts on the evolution of  
65 the former Maye Estuary over the last 5000 years.

66

## 67 **2. Physical setting and historical context**

68 2.1. Topographic, geological, and tectonic settings

69

70 The town of Rue is situated in the south of the Picardy coastal plain, which extends between  
71 the Bay of Somme to the south-west and Authie Bay to the north. This flat land is characterized  
72 by an average height of about +4.50 m above mean sea level (a.m.s.l.). It developed to the west  
73 of a relict cliff bordering a plateau composed of Upper Cretaceous chalk with flint (BRGM,  
74 1981) and was built up primarily from wet or drained lowlands (Demangeon, 1905; Munaut  
75 and Gilot, 1977; Le Fournier, 1974, 1980) which surrounded relict Pleistocene coastal spits  
76 composed of rounded pebbles and blocks (called 'Formation de Rue'; Agache et al., 1963; Ters  
77 et al., 1980; BRGM, 1981; Fig. 1). These spits (locally called '*foraines*') tend to form in a  
78 north/south direction and have a maximum elevation of between +9 and +13 m a.m.s.l. The  
79 medieval town of Rue is located at about +7 m a.m.s.l. and is built on the Rue *foraine*, which  
80 was locally incised by small river channels and filled with Holocene marine and continental  
81 sediments (Ters et al., 1980). The coastal plain is bordered to the west by a coastal dune ridge  
82 rising to +36 m NGF which has established over the last 5500 years (Le Fournier, 1974, 1980;  
83 Meurisse, 2005; Meurisse-Fort, 2007).

84 According to BRGM (1981), the relict cliff probably formed through faulting (Fig. 1). In  
85 addition, the coastal plain was likely divided into pieces by a system of faults and flexures  
86 whose movements contributed to the sedimentary filling in of the former undated 'Gulf of Rue'.  
87 BRGM (1981) estimates that these movements have caused the Rue area to uplift by about 5 m  
88 since the 18th century CE. According to Goffé et al. (1998), an active northwest-southeast  
89 strike-slip fault north of the Bay of Somme may have raised the northern compartment,  
90 corresponding to the Rue area. A series of earthquakes occurred during medieval times, for  
91 example in 1467 CE, when such an event damaged the church of Saint-Wulphy (Labrecque,  
92 2008), and in 1580 CE when another earthquake affected the town of Abbeville (Louandre,  
93 1844-1845).

94

95 Conditions along the coastline are megatidal with tidal range varying from 5 m to 8.65 m at  
96 Cayeux-sur-Mer, in the south of the Bay of Somme (SHOM, 2017). The mean high-water  
97 springs (MHWS) are situated at +5.41 m NGF (4.36 m a.m.s.l.) and the level of the highest  
98 astronomical (extreme) tide is +6.13 m NGF (5.09 m a.m.s.l.). Highest sea level can reach  
99 approximately +6.45 m a.m.s.l. with a 100-year return period (SOGREAH, 1995). According  
100 to Goslin (2014), the tidal range has undergone only slight changes since 6000 BCE (a  
101 maximum 0.70 m increase ) in Brittany (western France). The coastal plain is exposed to storm-

102 surge flooding caused by dune breaching. The prevailing wind is in the west-southwest  
103 direction and the longshore drift moves sediments northward (Bastide, 2011; Michel, 2016).  
104 South of the study area, the Bay of Somme is a hyper-tidal (Trenteseaux et al., 2012) and mixed  
105 estuary (Dalrymple et al., 1992;) which has filled in with marine sands (BRGM, 1981, 1985;  
106 Michel, 2016).

107

## 108 *2.2. Holocene sea level changes and coastal evolution in north-western Europe*

109

110 Holocene sea level changes and related coastal evolution are generally considered to be  
111 influenced by the interplay between several factors (e.g. Goslin et al., 2013): (1) eustatism, (2)  
112 isostatic processes (Vink et al., 2007; Shennan et al., 2018), (3) tectonic activity, (4) local  
113 effects controlling the sedimentary record, particularly sediment compaction (the effect of post-  
114 depositional consolidation; Long et al., 2006; Horton and Shennan, 2009; Marion et al., 2009;  
115 Brain et al., 2011) and changes in tidal regime, and (5), other unspecified, random, and hard-  
116 to-quantify factors which influence relative sea level reconstruction, particularly erosion of  
117 sedimentary sequences (Goslin et al., 2013). According to several recent papers, local factors  
118 (4 and 5) play a key role in the effect of sea level change on coastal system morphologies  
119 (Bungenstock and Weerts, 2010; Baeteman et al., 2011). The general geomorphological  
120 evolution of the north-western European coastal plains can be regarded as the cross combination  
121 of natural forcings (such as sea level change, variations in sediment supply and sediment  
122 distribution; e.g., Costa and Suanez, 2013; Pierik et al., 2017) and, for roughly the last 2000  
123 years, a mixture of natural and anthropogenic factors (Pierik et al., 2017).

124

125 Previous research conducted in the southern Picardy coastal plain did not attempt to precisely  
126 reconstruct the geomorphological evolution of the Rue area, despite sediment cores being  
127 drilled in the vicinity of Rue in the 1980s (Lefèvre et al., 1980; Ters et al., 1980; Figs. 1 and 3).  
128 However, the goal of those studies was not the reconstruction of the former shoreline position  
129 west of the town so as to locate its medieval coastal harbour. The published <sup>14</sup>C dating results  
130 were recalibrated by Meurisse-Fort (2007) using the IntCal13 calibration curve (Reimer et al.,  
131 2013). In addition, Meurisse-Fort (2007) considered the influence of sediment  
132 hydrocompaction on her chronostratigraphies to reconstruct the Holocene sea level evolution.  
133 However, the role of sediment hydrocompaction remains difficult to quantify (e.g., Allen, 2000;  
134 Goslin et al., 2013; Brain, 2015; Stéphan and Goslin, 2016; Shennan et al., 2018).

135

136 Along the Atlantic and English Channel coasts of France, some Holocene marine transgressions  
137 and regressions were identified by Ters (1973, 1986). Many papers have since adopted this  
138 description of Holocene transgression-regression cycles. For example, Meurisse-Fort (2007)  
139 reconstructed the coastline evolution of the Picardy coastal plain over the last 6000 years (see  
140 the red curve in Fig. 2):

- 141 • Around 4000 BCE, the sea level maximum was +2 m/+3 m a.m.s.l. with storm surges at  
142 *ca.* +6 m a.m.s.l.. The sea reached the foot of the present relict cliff. According to the  
143 stratigraphies published by Lefèvre et al. (1980) and Ters et al. (1980) and recalibrated by  
144 Meurisse-Fort (2007; date recalibration and consideration of sediment compaction), silts  
145 were deposited at the extreme limit of high waters at *ca.* + 3 m a.m.s.l. in the area of core  
146 Rue 3 (*ca.* 1.5 km west of the present town; Fig. 1).
- 147 • A marine regression occurred between *ca.* 4000 and 3100 BCE, with an increase in rainfall,  
148 peatland growth and development of coastal swamps. According to Meurisse-Fort (2007),  
149 the relative mean sea level was *ca.* -10 m a.m.s.l. at around 3100 BCE.
- 150 • A second marine transgression occurred from *ca.* 3100 BCE to 1400 BCE, during which  
151 shoreline impact varied greatly due to local geomorphological features. At the end of this  
152 phase, mean sea level was *ca.* -2 m/-3 m a.m.s.l.. Finally, around 2500–2000 BCE, the  
153 coastal plain was wider than it is today and consisted of a vast floodplain between bays and  
154 estuaries.
- 155 • From *ca.* 1400 BCE onward, the influence of aeolian dynamics and climate change  
156 exceeded the marine forcings. Mean sea level revealed few deviations from its present-day  
157 height. Storm-surge flooding caused by coastal barrier breaching played a greater role in  
158 landscape evolution, particularly between 450 BCE and 600–700 CE. However, shoreline  
159 stabilisation facilitated multi-stage processes of dune accretion.

160 Around 1000 BCE, a peatland lay southwest of Rue, behind a sandbar (according to a  
161 dating published by Ters et al., 1980 and recalibrated by Meurisse-Fort, 2007). A more  
162 recent (831–1264 CE) freshwater peatland (according to a dating published by Lefèvre et  
163 al. (1980) and recalibrated by Meurisse-Fort (2007)), was identified southeast of Rue in  
164 core M21 (Fig. 1).

165

166 This outline of Holocene transgression-regression cycles is strongly challenged by recent works  
167 which take into account that for the last 10 kyr, there have been only small-scale fluctuations  
168 of global sea level in tectonically stable areas (e.g. Stéphan and Goslin, 2016). Along the

169 Atlantic and English Channel coasts of France, relative sea level is thought to have risen  
170 continuously during the last 8000 years, with a major deceleration of sea level rise around 4000  
171 BCE (e.g. Mrani-Alaoui and Anthony, 2011; Goslin et al., 2013; Goslin, 2014; Stéphan et  
172 Goslin, 2016; Garcia-Artola et al., 2018; Fig. 2). The glacial isostatic component played a major  
173 role in increasing the rate of sea level rise between 4000 and 2000 BCE (Garcia-Artola et al.,  
174 2018). During the last 4000 years, according to the data published by Shennan and Horton  
175 (2002) for south-west England, relative sea level rise due to glacial isostatic adjustment was  
176 around 0.4 mm yr<sup>-1</sup>. Regarding the eustatic component, model ICE-5G (VM2a) published by  
177 Peltier (2004) indicates a relative sea level rise of approximately 1.1 mm yr<sup>-1</sup> over the last 4000  
178 years in our study area (Fig. 1).

179

180 While recent papers agree that relative sea level has continued to increase, they attribute to  
181 climate change the main effect on the geomorphological evolution of the coast of north-western  
182 Europe during the last 3500 years. Increased storminess and pluviometry were recorded at  
183 around 1000 BCE in north-western Europe (Gandouin, 2003; Dark, 2006; Clark and Rendell,  
184 2009; Sorrel et al., 2012; Van Vliet-Lanoë et al., 2014a, 2014b; Pierik et al., 2017). Major  
185 changes in coastal sedimentary systems have been observed for this period along the coasts of  
186 both the English Channel (Long and Hughes, 1995; Lespez et al., 2010; Tessier et al., 2012)  
187 and the Atlantic (Pontee et al., 1998; Tastet and Pontee, 1998; Clave et al., 2001; Moura et al.,  
188 2007).

189 Pouzet et al. (2018) distinguish four main ‘European Atlantic storm events’ (EASEs) over the  
190 last 3500 years: 1300–1600 CE (EASE 1), 200–800 CE (EASE 2), 900–400 BCE (EASE 3)  
191 and 1500–1300 BCE (EASE 4). During these events, marine deposits may have been eroded  
192 by drainage network incision, increased river discharge may have favoured continental  
193 sediment supply, and coastal breaching may have caused river courses to shift (Goslin, 2014).

194

195 For the last 1000 years, the geomorphological evolution of the Picardy coastal plain has been  
196 strongly influenced by human activities and land reclamation for dike construction  
197 (Demangeon, 1905; Dobroniak, 2000). The first dike was likely built in the 12th century CE  
198 between ‘*Le Muret*’ and ‘*La Petite Retz*’ (Briquet, 1930), approximately 7 km north-northwest  
199 of Rue (Fig. 1). Dikes continued to be built until the 1860s (Briquet, 1930) north of the coastal  
200 plain, linked with the shifting of Authie Bay. In the south of the coastal plain, the former mouth  
201 of the Maye (‘*Val de Maye*’; Fig. 1) is protected from coastal flooding by a dike built in 1835.  
202 However, storm-surge flooding still occurred (Meurisse-Fort, 2007), probably linked with

203 episodes of increased storminess which took place in north-western Europe from 100–950 CE  
204 and from 1300–1700 CE (Sorrel et al., 2012; Pierik et al., 2017). Lefèvre et al. (1980) report  
205 marine flooding deposits in the area of core M21 (Fig. 1); these deposits covered the upper peat  
206 layer (Fig. 3) and may have occurred around 1300 CE.

207

### 208 *2.3. Rue: a major harbour in the northwest of France from the beginning of the 12th century* 209 *to the end of the 15th century CE*

210

211 The Rue *foraine*, like all the Pleistocene bars of the Picardy coastal plain (Rougier, 2012), was  
212 favourable for human settlement at least from the Bronze Age (Rougier et al., 2008; Gapenne  
213 et al., 2017). An Early Bronze Age cemetery (Baray, 2001) and a rural peopling dating from  
214 the Iron Age (2nd–1st century BCE; Rougier and Blancquaert, 2001) were discovered together  
215 at the top of a Pleistocene bar, at a location called ‘*Le Chemin des Morts*’, northeast of Rue. A  
216 coin hoard dated to the 3rd century CE (Ben Redjeb and Foucray, 1989) and the archaeological  
217 remains of a Gallo-Roman villa were discovered in the *Bleue foraine* (at ca. +9 m a.m.s.l.) south  
218 of Rue (Notte, 2002). Other remains have been unearthed at the top of Pleistocene bars (the  
219 *Hère foraine*; Rougier, 2012), indicating a human occupation since the Bronze Age, even the  
220 Neolithic (Gapenne et al., 2017).

221

222 Data also lack for the Early Middle Ages. It is generally accepted that the town flourished in  
223 the 12th century CE (Labrecque, 2008). This development can be attributed to a legend claiming  
224 that in 1101, a local villager of Rue discovered a boat washed up on the shore, in which was  
225 found a large wooden cross originating in Jerusalem. The wealth of the city was thereafter built  
226 on pilgrimages and trade (transport of goods by sea). As early as the 13th century, the harbour  
227 of Rue, which is thought to have been located in the Maye Estuary, was as important as those  
228 of the Bay of Somme (Delaporte, 1925). A municipal charter, recognised in 1210 by the Count  
229 of Ponthieu, testifies to the importance and diversity of production and trade (e.g. fishing,  
230 agriculture, farming, textiles; Labrecque, 2008). This suggests that the Count imposed high  
231 taxes on each ship entering the harbour.

232 At the end of the 13th century, a canal project to re-establish access to the sea was proposed to  
233 the inhabitants, which implies that the harbour had silted up. That project was never begun, but  
234 in 1277, a canal was dug to bring the Authie’s flow towards the harbour, probably because of  
235 the increase in siltation (Labrecque, 2008). However, the westward shift of the shoreline seems  
236 to have gradually prevented access to the harbour by heavily laden ships arriving from the

237 Authie. Thus, harbour activity strongly decreased as early as the 14th century CE, even if  
238 commercial maritime activity continued during the 15th century CE (Labrecque, 2008).

239

240 Literary sources indicate that the town of Rue was naturally protected by the Maye to the north  
241 and west, and by marshes to the south and east (Delaporte, 1925). Following the Charter of  
242 1210, fortification works (protecting walls) were built. These essentially took the form of  
243 ditches, on the edges of which stone houses and walls were built. The ramparts were likely  
244 widened in the 15th century before being pierced by five gates, with '*la porte de la grève*' (the  
245 shore gate) to the west (Poiret, 1931). The fortifications were destroyed in 1670, under the reign  
246 of Louis XIV, by order of Jean-Baptiste Colbert, Secretary of State of the Navy. The earliest  
247 map of Rue found in historical archives dates from 1640. A previous excavation near '*le bastion*  
248 *de Saint-Jean*' (Flucher, 2004) identified an embankment under the ravelin. This embankment  
249 diverted the course of the Maye. However, artefacts (mainly ceramics) discovered there provide  
250 only an imprecise chronology of the fortification works.

251

252 Present day landscape configuration does not enable to significantly demonstrate that Rue was  
253 a coastal town. Moreover, archaeological evidence is scarce, and the few historical sources fail  
254 to provide a robust and indisputable reconstruction of landscape evolution surrounding the  
255 medieval town of Rue. In an attempt to do so, we have conducted a palaeoenvironmental study.

256

### 257 **3. Material and methods**

258 Field investigations (geophysical survey and coring) were carried out northwest of Rue,  
259 particularly around '*la porte de la grève*', where the medieval port is thought to have been  
260 located in the upper part of the Maye Estuary. Field investigations were completed by  
261 laboratory analyses (sedimentological analysis and radiocarbon dating of drill core samples)  
262 and by the study of historical sources. All these data, as well as altimetry data '*RGE 1 m*'  
263 provided by the '*Institut Géographique National*', were integrated into a Geographic  
264 Information System database.

265

#### 266 *3.1. Electric resistivity tomography (ERT)*

267

268 To evaluate both the geometry and thickness of surficial deposits and bedrock depth, and to  
269 locate archaeological structures, eight electrical resistivity tomography (ERT) profiles were  
270 established around the town of Rue (Figs. 4, 5a, 5b, and 5c).

271 ERT has been successfully used in various subsurface field studies, especially in  
272 geomorphology (Beauvais et al., 2007; Ghilardi et al., 2017) and archaeology (Siart et al., 2010;  
273 Quesnel et al., 2011; Ghilardi et al., 2015). The 2D subsurface profiles were obtained using the  
274 ABEM Lund Imaging System (Terrameter LS/4 channel) with an array of 64 electrodes with a  
275 Schlumberger-Wenner reciprocal layout protocol. A computer inversion program (Res2Dinv;  
276 Loke, 2003) that includes topography and generates images of the resistivity distribution was  
277 used.

278 To satisfactorily obtain data on the thickness of the surficial deposits and their organisation  
279 (Ritz et al., 1999), ERT profiles were conducted with an electrode distance ranging from 0.60  
280 m (ERT6, with a maximum depth of 5.17 m) to 2.50 m (ERT3, with a maximum depth of 21.50  
281 m).

282 Because different materials can have similar electrical properties, the ERT method does not  
283 allow for unequivocal interpretation. Therefore, two reference profiles were established on sites  
284 where the stratigraphy and/or lithology can be readily seen: ERT7, on an extraction site of  
285 Pleistocene gravels and pebbles, and ERT8, on a chalk plateau near Rue.

286

### 287 *3.2. Sedimentological coring*

288

289 Vibracores with a diameter of 50 mm were drilled to a maximum depth of 8.40 m below the  
290 surface (Fig. 4; Table 1) in May 2012 northwest of Rue using a Cobra TT vibrocorer with  
291 hydraulic extractor (Figs. 6 and 7). The position of the cores was chosen in accordance with the  
292 results obtained from the geophysical survey. Each core was precisely levelled using a  
293 theodolite and local IGN geodetic benchmarks were used as references.

294

### 295 *3.3. Sedimentological analyses*

296

297 The grain-size distribution of the fine fraction (<2 mm) was measured by laser diffraction  
298 granulometry at CEREGE. Preparation of the samples was based on Ghilardi et al. (2014). The  
299 grain-size distribution was then measured using a *Beckman Coulter LS 13 320* laser  
300 granulometer with a range of 0.04 to 2000  $\mu\text{m}$ .

301 Loss-on-ignition (LOI) measurements were made at CEREGE, following Dean (1974), and  
302 Bengtsson and Enell (1986). Sediment samples of approximately 1 g were taken at 5 cm  
303 intervals throughout the core. After drying at 105 °C to a constant weight, the samples were  
304 heated to 550 °C for 7 h to estimate their organic matter content. A second heating phase, to  
305 925 °C for a further 7 h, was undertaken to assess the proportion of carbonates.  
306 Mollusc identification was conducted on all cores, but analyses were limited due to the paucity  
307 of these samples along the cores, and to the small sizes of the materials which were retrieved.

308

#### 309 *3.4. AMS <sup>14</sup>C dating method*

310

311 The chronostratigraphy of the cores was analysed at CEREGE using a series of 14 AMS  
312 radiocarbon determinations derived from charcoal, plant remains, wood samples and peat  
313 samples collected from the cores (Table 2). These analyses were performed at the Poznan  
314 Radiocarbon Dating Laboratory (Poland). Subsequent calibration of <sup>14</sup>C ages was conducted  
315 using the Calib Software Version 7.1 (Stuiver and Reimer, 1993) and the IntCal13 calibration  
316 curve (Reimer et al., 2013).

317

#### 318 *3.5. Examination of historical sources*

319

320 Document sources provide diverse information on coastal landscapes, including physical  
321 environment (e.g. nature of the foreshore), constructions, and various human activities such as  
322 fish species caught, quantities of fish due for rent, goods transported by boats, places of loading  
323 and unloading, peat extraction, and relationships between coastline users and the authorities  
324 exercising rights.

325 For the study area, document sources regarding the medieval coastal landscapes are scarce, but  
326 those available are relatively varied and rich in information. Originally produced by  
327 municipalities or fiefdoms, they are today stored in various collections and series of the  
328 National Archives (Paris), the Departmental Archives of the Somme (Amiens), the National  
329 Library of France (BnF, Paris), and the Abbeville Municipal Library. A large part of the  
330 archives has unfortunately succumbed to the destruction provoked by successive wars. For  
331 example, the documents of the old series of the Abbeville Municipal Archives were lost as  
332 recently as 1940.

333 We implemented a regressive method to study the document sources, beginning with the  
334 analysis of the most recent documents. Unfortunately, for the study area, documentary sources

335 prior to the 13th century are relatively rare and provide no historical maps or figures until the  
336 early 16th century.

337

## 338 **4. Results**

### 339 *4.1. Borehole chronostratigraphy*

340

341 Pleistocene gravels, including rounded flint pebbles and marine shells in a matrix of fine sand  
342 (Ters et al., 1980), were found in the lowermost part of all cores situated west of Rue with a top  
343 bed depth that varied between 2 m and 7 m (Figs. 6, 7 and 8). This reveals the lateral  
344 heterogeneity and extension of these units. These formations were also identified in various  
345 ERT profiles (see § 4.2).

346

347 Above this first layer, four main morphosedimentary units were distinguished in cores R1, R2,  
348 R4, R5, R6, and R7 (Figs. 6, 7 and 8):

349 • Unit A (recorded in R4, R5, R6 and R7) contains medium grey silty sands. It can be divided  
350 into two subunits: from the base layer (-1.15m in R5) to *ca.* +0.70 m a.m.s.l., Subunit A1  
351 comprises medium to fine sand (mean grain-size of *ca.* 210  $\mu\text{m}$  and modal index of *ca.* 230  
352  $\mu\text{m}$ ) and Subunit A2, from *ca.* +0.70 m a.m.s.l., is composed of very fine to silty sand (mean  
353 of *ca.* 70  $\mu\text{m}$ ; modal index of *ca.* 65  $\mu\text{m}$  and *ca.* 60% of particles <62  $\mu\text{m}$ ). This unit has a  
354 low carbonate content (less than 2.5%) and a significant number of macrocharcoals and  
355 plant debris are observed. The thickness (up to 2.50 m in R5) and the surface of this unit  
356 are irregular (between +0.90 m a.m.s.l. in R6 and +2.50 m a.m.s.l. in R2). The uppermost  
357 part of Unit A dates roughly from the beginning of the 4th millennium BCE (4057–3953  
358 cal. BCE in R4, 3824–3695 cal. BCE in R5 (Figs. 6, 7 and 8).

359 Because of the texture, colour, and chronology of the sediments in this unit, we determine  
360 that they were deposited by the sea, in a calm environment, particularly in depressions  
361 bordered by Pleistocene coastal spits (*'foraines'*).

362

363 • Unit B (recorded in R4, R5, R6 and R7) consists of a peat accumulation rich in plant  
364 remains and exhibiting low  $\text{CaCO}_3$  content (less than 5%). Large pieces of charcoal are  
365 visible but molluscs are absent. The height of the base of this formation varies according  
366 to the geometry of the underlying marine deposits, while the top of the unit is almost flat,

367 at about +2.60 to +2.90 m a.m.s.l. Generally, this unit dates from the early 4th to the late  
368 2nd millennium BCE (3824–3695 cal. BCE in R6 and 1134–1004 cal. BCE in R7).

369 The characteristics of Unit B differ from core to core. R4 and R7 are homogeneous and  
370 rich in organic matter (around 60%). Between +1.25 m a.m.s.l. and +1.50 m a.m.s.l., R5  
371 reveals a sandy layer between the peat accumulations. In R6, above +1.90 m a.m.s.l.,  
372 relatively young (834–752 cal. BCE) dark grey peaty silts were identified.

373 The combined sedimentological and geochemical proxies described above lead us to  
374 conclude that this unit provides evidence of coastal swamp environments with sizable peat  
375 accumulation.

376

377 • Unit C, identified in cores R1, R2, R4, R5, R6 and R7, between about +2.60 m a.m.s.l. and  
378 +5.20 m a.m.s.l., from the 11th century to the beginning of the 13th century (989–1052 cal.  
379 CE and 1039–1210 cal. CE in R4), is not homogeneous from core to core.

380 Up to about +4 m a.m.s.l., the unit mainly comprises very fine to silty sands (mean at *ca.*  
381 75  $\mu\text{m}$  and mode at *ca.* 65  $\mu\text{m}$ ) in almost all cores (R1, R2, R4, R5, R6, and R7). However,  
382 the clayey-silty fraction (<63  $\mu\text{m}$ ) was generally higher in the deposits found in R4 - and  
383 to a lesser extent in R7 - than that identified in R5 and R6. This difference indicates that  
384 the deposits occurred in calmer water in the areas from which R4 and R7 were taken.  
385 Between about +2.70 m and +3.20 m a.m.s.l., R5 and R6 show an intercalation of thin  
386 sandy layers with thin clayey beds that correspond to tidal rhythmites (Fig. 9). Such  
387 features were observed by Meurisse-Fort (2007) in the muddy saltmarsh areas of the  
388 Canche Estuary (located north of the Picardy coastal plain).

389 In the uppermost part of Unit C (above +4 m a.m.s.l.), the stratigraphy differs from core to  
390 core:

391 - Up to +5.20 m a.m.s.l., R4 consists of very fine oxidised sands (mean at *ca.* 67  $\mu\text{m}$  and  
392 mode at *ca.* 76  $\mu\text{m}$ ), including marine to brackish bivalve fragments (*Cerastoderma*  
393 *edule*) typical of a sandy or muddy sand area of an estuary and enclosed bay (Bellamy  
394 et al., 2009), and charcoals dated to 989–1210 cal. CE. R1 and R2 contain coarser  
395 sediments (fine to medium sand; mean at *ca.* 250  $\mu\text{m}$  and mode at *ca.* 260  $\mu\text{m}$ ) than that  
396 recorded in R4, R5, R6, and R7. Based on sedimentological and faunal (cockles)  
397 evidence, we surmise that these sediments (Subunit C1) were deposited in a marine  
398 environment.

399 - Subunit C2, identified in R1, R2, R5, R6, and R7, contains fine material (very fine sands  
400 or silty sands; mean at *ca.* 122  $\mu\text{m}$  and mode at *ca.* 75  $\mu\text{m}$ ). It exhibits a relatively higher

401 calcium carbonate content (>35%) in R1, R2, and R7. Between +4.40 m and +4.90 m  
402 a.m.s.l., the very fine sands recorded in R7 contain unidentifiable land snail debris. In  
403 R1, R2, and R5, this fine material is covered by a peat layer containing plant debris,  
404 dated to 380–536 cal. CE (in R5). We surmise that Subunit C2 were deposited in a  
405 riverine or swamp environment.

406 - In R6, we found a layer of fine sands between +4.40 m and +5.10 m a.m.s.l.,  
407 characterised by a multimodal particle size distribution with secondary medium to  
408 coarse sand modes situated at 250  $\mu\text{m}$  and 1000  $\mu\text{m}$ . Even if they contain orange-  
409 coloured archaeological remains; it is difficult to determine which anthropogenic  
410 influence prevailed on these deposits (Subunit C3), and whether they are of marine or  
411 continental origin.

412 Unit C includes coarser sand beds that may correspond to lag deposits, recorded in R4 and  
413 R6 at *ca.* +4.30 m a.m.s.l. In R4, the bed is 0.05 m thick and is characterised by  $D_{90}$  at 805  
414  $\mu\text{m}$ . In R6, this layer is thicker (0.20 m) and is covered by finer marine deposits (Subunit  
415 C1) above a clear contact (erosional surface). These finer deposits are characterised by a  
416  $D_{90}$  ranging from 403 to 660  $\mu\text{m}$ . This bed is covered by fluvial deposits (Subunit C2),  
417 with a bottom layer that is relatively rich in  $\text{CaCO}_3$ .

418 Coastal processes of sedimentation are clearly attested in Unit C (open- to semi-enclosed  
419 marine bay) with local continental influence on the sedimentary processes (rivers or  
420 wetlands).

421

- 422 • Unit D, above +4.90 m to +5.20 m a.m.s.l., contains sandy-silty deposits, highly disturbed  
423 by anthropogenic activities. Deposition began in the 13th century (after 1221 cal. CE in  
424 R6), and these layers contain fragments of marine to lagoonal shells, some pebbles, and  
425 occasionally potsherds. Thin coarse sand beds (main mode around 60  $\mu\text{m}$  with one or more  
426 coarser secondary modes) are recorded in R4 (at +5.40 m a.m.s.l. and +6.10 m a.m.s.l.).

427

428 Units A and B are not recorded in R3, which is located higher in the Rue *foraine*. Nor are they  
429 found in R8, which was drilled into what was likely an embankment at the foot of the medieval  
430 town fortifications of Rue, according to the map dating from 1640 (Fig. 10b).

431

#### 432 4.2. ERT profiles and subsoil resistivity

433

434 No archaeological structures were identified in any of the ERT profiles measured northwest of  
435 Rue. However, the geophysical survey allows to distinguish three main units, described as  
436 follows, from bottom to top (Fig. 5a, 5b, and 5c):

- 437 • The geophysical Unit Ge1, with a top depth that varies from 1 m (in ERT4) to ca. 7 m (in  
438 R5), has highly variable resistivity values, generally greater than 60  $\Omega\text{m}$ . According to the  
439 reference profiles ERT7 and ERT8, Upper Cretaceous chalk and Pleistocene gravels and  
440 pebbles have resistivity values ranging from 40  $\Omega\text{m}$  to more than 180  $\Omega\text{m}$ , depending on  
441 the degree of weathering of the chalk and the presence (or absence) of groundwater.  
442 Comparison of the ERT profiles with the stratigraphy of the cores indicates that the  
443 uppermost part of Ge1 consists of Pleistocene gravels and pebbles. The lowermost part is  
444 probably composed of chalk. The geometry of this unit is irregular, particularly in ERT4,  
445 with a greater depth to the west.
- 446 • Unit Ge2, whose thickness varies from a few centimetres (north-northeast of profile ERT4)  
447 to about 6 m (southeast of profile ERT3), is characterised by low resistivity (<40  $\Omega\text{m}$ )  
448 related to the finest sedimentary particles (very fine sands of marine or fluvial origin, or  
449 organic matter, according to the stratigraphy of R4, R7 and R8). In addition, the  
450 conductivity of this unit may have been enhanced by the presence of shallow groundwater,  
451 as has been observed in similar sedimentary contexts (Ghilardi et al., 2015, 2017). Ge2  
452 probably corresponds to stratigraphic Units A, B and C.
- 453 • Unit Ge3 can be recognized at a depth of ca. 2 m in most of the profiles, especially in  
454 profiles ERT4, ERT5 and ERT6. It is characterisezd by high resistivity values (from 80  $\Omega\text{m}$   
455 to ca. 300  $\Omega\text{m}$ ). In R4, R7 and R8, the sediments corresponding to this unit are sandy-silty  
456 and strongly anthropised (Unit D).

457

## 458 **5. Discussion**

### 459 *5.1. Mid- to Late Holocene landscape reconstruction of the Rue area*

460

461 Palaeogeographical knowledge of the Maye Estuary remains incomplete for the first half of the  
462 Holocene. However, the cross combination of geophysical and sedimentological results derived  
463 from boreholes helps to partly reveal the palaeorelief. Pleistocene deposits composed of  
464 rounded pebbles and blocks (*'Formation de Rue'*; BRGM, 1981) are observed on most of the  
465 geophysical (ERT) profiles. Above this presumed marine formation, fine material accumulated  
466 (Unit A) within a regional context of marine ingressions, related to the rapid post-glacial sea-

467 level rise until around 4000 BCE (Garcia-Artola et al., 2018). Our interpretation is strengthened  
468 through comparison with core Rue 3 (situated southwest of Rue) as analysed by Ters et al.  
469 (1980) (Fig. 1 and 3), who identified and dated foreshore deposits to  $4030 \pm 240$  cal. BCE (after  
470 recalibration by Meurisse-Fort, 2007) in the lowermost part of the sedimentary sequence, below  
471 a peaty layer. According to Gapenne et al. (2017), the coastal plain was covered by an oak grove  
472 around 3000 BCE. These trees slowly disappeared, especially due to the development of bogs.

473

474 • From *ca.* 3500 BCE to *ca.* 1000 BCE

475 Around 3500 BCE, Unit B, defined by the presence of continental peat in several cores, reveals  
476 a major environmental change. Back-barrier marshes extended west of the Rue *foraine*. The  
477 eastern boundary of this area is influenced by the morphology of the Pleistocene gravel and  
478 pebble bar. The ERT profiles performed in the northwest of Rue delineate the upper limit  
479 geometry of the deposit of Pleistocene gravels and pebbles, from its outcropping at the top of  
480 the Rue *foraine* (eastern ends of ERT6 and NNE of ERT4) to the bottom of adjacent valleys  
481 (profile ERT2). Until the beginning of the 3rd millennium BCE, the landscape configuration  
482 combined bogs and woodland (Gapenne et al., 2017).

483

484 The chronology of peat shows a hiatus between the lowermost part, dated to *ca.* 3500 BCE, and  
485 the uppermost part, dated to the late 2nd millennium BCE (Fig. 12a). In addition, the R5 peaty  
486 deposit, whose top was dated to *ca.* 1500 BCE, is disrupted by a sandy layer (between +1.25 m  
487 a.m.s.l. and +1.50 m a.m.s.l.), probably deposited by storm-surge flooding (see § 5.2).

488

489 The upper limit of the peat varies in height, and shows a greater thickness in R4, R5, R6 and  
490 R7 than in cores M21 and Rue3 (Lefèvre et al., 1980; Ters et al., 1980), where it was identified  
491 around 0 m a.m.s.l. (Figs. 1 and 3). Yet, peat thickness in these cores is very close to that of  
492 cores SC1 and SC3, drilled in a small valley south of the Rue *foraine* (Ters et al., 1980). The  
493 cores drilled in 2012 reveal conditions that were more sheltered from the sea than those  
494 evidenced in cores M21 and Rue3. The local geomorphological context of cores SC1 and SC3  
495 is more similar to that of R4, R5, R6 and R7 (Figs. 1 and 4). These differences confirm the role  
496 of the local geomorphological features highlighted by Lefèvre et al. (1980) and Meurisse-Fort  
497 (2007), even if sediment compaction probably strongly disturbed the stratigraphy of core Rue3.  
498 Comparison between R4, R5, R6 and R7 shows a slight variation in the altitude of the upper  
499 limit of the peat. From *ca.* +2.60 m to *ca.* +3 m a.m.s.l., R4 and R7 record the top of Unit B,  
500 with finer sediments, including black patches perhaps indicative of old roots, while R5 and R6

501 show tidal rhythmites similar to those currently observed in the muddy saltmarsh (Smith et al.,  
502 1991). Given these features and their location to the southeast of R5 and R6, the area from  
503 which R4 and R7 were taken would have been submerged only during high tides and was  
504 probably covered by saltmarsh vegetation in *ca.* 1000 BCE (Fig. 12b). In addition, the peat  
505 recorded in R6 laminations (Fig. 9) suggests that the area around the core was at the boundary  
506 of the high marsh (schorre). In addition, the influence of saltwater inputs on the top of the peaty  
507 deposits is proved by a recent analysis of diatoms near the Hère *foraine* (Gapenne et al., 2017).  
508

509 The relatively recent date (834–752 cal. BCE) and the characteristics of the deposits (dark grey  
510 peaty silts) at +1.75 m a.m.s.l. in R6 suggest the influence of human activities on the peatlands  
511 at the beginning of the Iron Age. For comparison, large-scale peatland reclamation in the coastal  
512 plain of Holland began between 600 and 250 BCE, according to Pierik et al. (2017).  
513

514 • Around 1000–1250 CE (Fig. 12c)

515 Human impact (ditches, dikes, fortifications, embankments) on the landscape intensified from  
516 at least the 12th century. The sediments recorded between *ca.* +3.90 m and +5 m a.m.s.l. in R4,  
517 R5, and R6 (Figs. 6 and 7) continued, nevertheless, to be influenced by marine processes. In  
518 these three cores, the sands contain cockle (*Cerastoderma edule*) valves, while the sands in R7  
519 contain land snail fragments that indicate a continental influence of sedimentation. In addition,  
520 the thin beds of coarser sand recorded in R4 and R6 at *ca.* +4.30 m a.m.s.l. (Figs. 6 and 7) can  
521 be defined as storm surge deposits. The erosional surface (clear contact) between the coarser  
522 bed and the underlying marine deposits in R4 testifies to the suddenness of the event  
523 (Chaumillon et al., 2017; Pouzet et al., 2018). Moreover, this kind of massive increase in coarser  
524 grains (30% of sand and a D<sub>90</sub> ranging from *ca.* 400 to *ca.* 800 µm) as compared to underlying  
525 sediments, has occurred in a similar manner in saltmarsh sediments deposited during recent  
526 storm surges (Swindles et al., 2018). The overlying fluvial deposits (Subunit C2) suggest that a  
527 fluvial flooding of the area then followed the storm event, which likely occurred in the 12th/13th  
528 century BCE, according to the sample dated in R6.

529 The fine sands (Subunit C3) in R6 between +4.40 m and +5.10 m a.m.s.l. were mainly  
530 influenced by human activities. At the same height, the sediments recorded in R4 and, in  
531 particular R5, were thinner and even peaty (R5), indicating low energy environments. Mottled  
532 sediments (marked by groups of red, yellow and grey patches), between +4.10 m and +4.50 m  
533 a.m.s.l. in R5 and between +4.30 m and +5.20 m a.m.s.l. in R4, indicate periodic waterlogging.  
534 All these observations suggest that R6 is located near a former river channel that may have been

535 artificially closed after silting-up. About 100 m to the southeast, R4 is likely situated at the  
536 former interface between fresh and saltwater, in the upper part of the muddy flat (slikke) and in  
537 an environmental context favourable to cockles (*Cerastoderma edule*). In the area from which  
538 R1 and R2 was taken, and where fluvial deposits are recorded, freshwater probably flowed into  
539 a natural or artificial channel (ditch).

540 Wetlands and bogs under continental influence were probably located north and northeast of  
541 the former river channel. Freshwater peatlands were identified in sediment cores taken in the  
542 1980s at similar altitudes in other areas to the west, south and southeast of Rue (Lefèvre et al.,  
543 1980; Ters et al., 1980). The peat dating performed in R5 at +4.88 m (380–536 cal. CE) conflicts  
544 with the datings (989–1052 cal. CE and 1039–1210 cal. CE) obtained for R4 between +4.89 m  
545 and +5.12 m a.m.s.l. In addition, the upper peat layer of core M21 analysed by Lefèvre et al.  
546 (1980) was dated to  $1070 \pm 200$  CE (Figs. 1 and 3). These results probably indicate that the peat  
547 dating obtained for R5 is unreliable, whereas the other two results (in R4) were obtained using  
548 charcoal.

549 The fluvial sediments identified in R1 and R2 (Subunit C2) between +4.50 m and +5 m a.m.s.l.  
550 were most likely deposited by the Maye River. The latter, which initially flowed south of the  
551 Rue *foraine* in ‘*le Val de Maye*’ (Lefevre et al., 1980; Ters et al., 1980; Fig. 1), moved  
552 northwards, probably due to sedimentary deposition at the end of the medieval period. This  
553 riverbed change may have been caused by the silting-up of a former pond (called ‘*étang de Rue*’  
554 or ‘*vivier de Rue*’) southeast of Rue, which existed at least from the 13th century CE  
555 (Demangeon, 1905) and which had been maintained by dikes downstream. Its siltation may  
556 have caused the shift of the Maye towards the northwest, to a channel crossing the Rue *foraine*.  
557 In the Late Middle Ages, the channel planform of the Maye was thus similar to today’s. The  
558 tidal harbour of Rue was established in the upper estuary of this river.

559

560 • Since the 13th century CE

561 Continental processes and human activities have played a major role in the aggradation of the  
562 plain since the 13th century. The construction of dikes in the 12th century CE north-northwest  
563 of Rue (Briquet, 1930) assisted this aggradation (Unit D).

564 According to early maps (dating from the late 16th century), the Maye River ended in a closed  
565 gulf and Rue was located inland (Fig. 10a). A map from 1773 shows a lock at the mouth of the  
566 Maye, at a place called ‘*la Haie Pénée*’ approximately 3 km west-southwest of Rue (Fig. 10c),  
567 at the boundary of a probable high marsh (schorre). This map also indicates a destroyed dyke  
568 (‘*digue rompue*’) at the boundary between the saltmarshes and the spring tide line, which

569 probably corresponds to the limit between high marsh and tidal mudflat. The destroyed dyke  
570 also features on the 1758 map by Cassini (Fig. 10d), which confirms the risk of coastal flooding  
571 due to dune or dike breaching at that time. Moreover, the Maye canal has carried water from  
572 the river towards ‘Le Crotoy’ since the 1780s, aiding the drainage of the wetlands around Rue.

573

## 574 5.2. Relative sea level changes in the area of Rue during the last 5000 years

575

576 The basal part of the peat deposit (Unit B) that overlies an incompressible basement, especially  
577 in R5 and R6, can be taken as free basal sea level index points (SLIP), which allow the  
578 estimation of past relative sea levels (Brain, 2015; Hijma et al., 2015). Analyses of the peat  
579 collected in these cores do not allow us to accurately reconstruct the depositional environment  
580 (salinity, in particular) of the peat. Thus, the indicative meaning (the quantitative altitudinal  
581 relationship that connected the SLIP with the reference tidal level at the time of deposition;  
582 Hijma et al., 2015) of the basal peat of R4, R5, and R6 remains difficult to determine. However,  
583 the low concentrations of CaCO<sub>3</sub> (<5%) of the peat and the lack of molluscs suggests a  
584 predominantly continental influence. This assumption is confirmed by a recent analysis of  
585 diatoms collected at the bottom of the peat layer, near the Hère *foraine* (Gapenne et al., 2017).  
586 Indeed, we propose to define these indicators as upper limiting data points (Shennan and  
587 Horton, 2002; Hijma et al., 2015): under normal conditions, the sea does not reach this limit  
588 except, perhaps, during astronomical tides and storm surges. Based on R4, R5, and R6, three  
589 limiting points can be defined: (i) 3824–3695 BCE (at +0.90 m a.m.s.l.), (ii) 3798–3654 BCE  
590 (at +1.50 m a.m.s.l.), and (iii) 3532–3368 BCE (at +2.10 m a.m.s.l.). Given that the present  
591 highest astronomical tide (HAT) is at +6.13 m a.m.s.l. (5.09 m a.m.s.l.), we estimate that:

- 592 • at 3824–3695 BCE, the HAT was at *ca.* 0.14 m below the present mean sea level, and the  
593 mean sea level was likely around 5.23 m below the present mean sea level.
- 594 • at 3798–3654 BCE, the HAT was at *ca.* 0.45 m above the present mean sea level, and the  
595 mean sea level was likely 4.63 m below the present mean sea level.
- 596 • at 3532–3368 BCE, the HAT was at *ca.* 1.05 m above the present mean sea level, and the  
597 mean sea level was likely 4.03 m below the present mean sea level.

598 These three limiting points and the corresponding probable past mean sea level are in good  
599 agreement with the relative sea level evolution over the last 5000 years in Brittany, as  
600 reconstructed by Goslin (2014), even if the HAT indicated by the first limiting data point seems  
601 low compared to the second point. The reconstructed relative sea levels are lower than values  
602 estimated by the Ice-5G model (Peltier, 2004), and higher than values calculated by the models

603 of Bradley et al. (2011) and Kuchar et al. (2012) (Fig. 11). Our results indicate that the role of  
604 tectonic movements in the relative sea level changes over the past 5000 years was insignificant.  
605 The faults of the Rue area seem to be inactive.

606

607 The sandy layer recorded at +1.25 m a.m.s.l. and +1.50 m a.m.s.l. in R5 may be explained by  
608 storm-surge flooding that was likely linked with major climatic changes identified in north-  
609 western Europe (see aforementioned references), particularly ‘European Atlantic storm events’  
610 (as defined by Pouzet et al., 2018). The shorter second phase of peat accumulation at *ca.* 1300  
611 BCE may have been enhanced by the closure of the beach barrier complex. This phase may, in  
612 turn, have been stopped by another ‘European Atlantic storm event’ period that began at *ca.*  
613 1100 BCE (Pouzet et al., 2018), as suggested by the clear contact (erosional surface) identified  
614 between Unit B and Subunit C1 in R5 at +2.50 m a.m.s.l. (Figs. 7 and 8).

615

616 Regarding the present limit between the slikke and the schorre at *ca.* +4 m a.m.s.l. (Michel et  
617 al., 2017), the laminated marine sediments (Subunit C1) situated above the peat sequence in R5  
618 and R6, and deposited close to the limit between slikke and schorre at *ca.* 2.70 m a.m.s.l., are  
619 probably linked to a sea level, at the beginning of the 1st millennium BCE, of *ca.* 1.30 m below  
620 the present one.

621 The coarser sand beds identified in R1, R2, R4, and R6 reflect a greater frequency of marine  
622 incursions since *ca.* 1100 CE. Some of these storm surge deposits can be related to the ‘EASE  
623 1’ period (Pouzet et al., 2018) during the early ‘Little Ice Age’ (in *ca.* 1450 CE), even after land  
624 reclamation (as suggested by Lefèvre et al. (1980)) in the area of core M21.

625

### 626 *5.3. Consequences for human occupation from Neolithic times to the medieval period*

627

628 Our results suggest that the shoreline position was probably located at the foot of the Rue  
629 *foraine* at the end of the Middle Neolithic period (*ca.* 3500 BCE). According to Gapenne et al.  
630 (2017), at the end of the Neolithic, a forest covered the area. From the end of the Neolithic to  
631 the Middle Bronze Age (1600–1350 BCE), much of the lowlands in the area was covered by  
632 peatland. Human settlements were probably preferentially located at the top of the Pleistocene  
633 bars, at least from the Bronze Age (Rougier, 2012; Gapenne et al., 2017). The lowlands were  
634 probably highly exposed to storm surges which, however, did not affect the settlements located  
635 on the Pleistocene bars.

636 From the end of the Bronze Age (*ca.* 1000 BCE) to the Late Middle Ages (987–1492 CE),  
637 sediments deposited in the lowlands in the upper part of an estuary were mainly of marine  
638 origin. Saltmarshes, including muddy flats (*slikke*) and high marshes (*schorre*), developed at  
639 the bottom of the Pleistocene bars. During the Iron Age, peatland reclamation may have begun  
640 (see § 5.1), but human activities in the lowlands were subject to storm surge flooding.  
641 With the aggradation of the plain and the westward migration of the coastline, the drainage  
642 network was shaped.

643

644 Finally, despite the lack of archaeological evidence, our results agree well with different  
645 historical sources and confirm the likelihood of a coastal harbour at Rue during the 12th and  
646 13th centuries CE; this harbour was probably situated northwest of the town, near '*le Moulin  
647 de Saint-Jean*'.

648

## 649 **6. Conclusion**

650

651 Sedimentological analyses derived from boreholes and geophysical investigations conducted in  
652 the Rue area, combined with the scrutiny of historical sources have allowed us to reconstruct  
653 the Mid- to Late Holocene evolution of the Maye Estuary. The geoarchaeological approach we  
654 employ allows to identify: (1) the prevalence of marine environments at the beginning of the  
655 4th millennium BCE, (2) the development of peat accumulation from *ca.* 3500 BCE to the late  
656 2nd millennium BCE, interrupted by a period (between *ca.* 3050 cal. BCE and 1550–1290 cal.  
657 BCE) of marine deposition (probably due to storm surges), (3) an estuarine depositional  
658 environment around 1000–1250 CE, including a foreshore composed of both mudflats (*slikke*)  
659 and high marshes (*schorre*) as well as a river channel (Maye), and (4) land reclamation in the  
660 former Maye Estuary since the 13th century.

661 This palaeoenvironmental reconstruction agrees well with recently published sea level curve  
662 reconstructions for the Holocene. A continuous Mid- to Late Holocene sea level rise does not  
663 conflict with our reconstruction of the Picardy coastal plain evolution.

664

665 Based on our results, in around 1000–1250 CE, the town of Rue was bordered to the west by  
666 the Maye Estuary, thus confirming literary sources and local legends. The inner estuary was  
667 located near '*le Moulin de Saint-Jean*', where a boat carrying a sacred wooden cross from  
668 Jerusalem is reported to have beached during the 12th century. Thus, we suggest that the  
669 harbour of Rue was situated northwest of the town, at the upstream boundary of the Maye

670 Estuary. The creation of an artificial pond southeast of Rue (*'étang de Rue'*) the diversion of  
671 the river towards the medieval town. The discharge of water from the pond to the town was  
672 likely caused by anthropic and natural filling in of the wetland. We suggest that this natural  
673 barrier was dredged to remove sediments from the harbour and/or to maintain the navigability  
674 of the river, as is commonly done today.

675 Further investigation (coring and geophysical surveys) is required to reconstruct the Holocene  
676 evolution of the estuarine landscape to the west and south of Rue. Pollen analyses may also  
677 help reconstruct the landuse of the area, in particular during the period of harbour activity of  
678 the town.

679

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681

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688

689

690

691

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1002

1003

1004 **Figure and table captions**

1005

1006 **Fig. 1: Location and Geological maps of the study area**

1007 1: Spot height (in meters); 2: ‘*Plateau Picard*’: Upper Cretaceous chalk with flints; 3: Flint  
1008 pebble spit; 4: Holocene dunes and sand bars; 5: ‘*Formation du Marquenterre*’: Holocene clay  
1009 and sands; 6: Holocene alluvial deposits; 7: Holocene peat; 8: ‘*Formation de Rue*’: Pleistocene  
1010 pebble spit; 9: Fault; 10: Hidden fault; 11: River; 12: Location of corings undertaken by Lefèvre  
1011 et al. (1980) and Ters et al. (1980) (source: BD ORTHO® IGN, 2017; BRGM)

1012

1013 **Fig. 2: Comparison between the Holocene sea level curves proposed by Meurisse-Fort**  
1014 **(2007) and Mrani-Alaoui and Anthony (2011)**

1015 1: Sea level curves estimated with radiocarbon-dated peat and palaeosol samples (Mrani-Alaoui  
1016 and Anthony, 2011); 2: Sea level curves from Belgium (Mrani-Alaoui and Anthony, 2011); 3:  
1017 High tide level curve proposed by Meurisse-Fort (2007)

1018

1019 **Fig. 3: Comparative sections of five corings, South of Rue (Somme)**

1020 1: Chalk; 2: Chalky loam, with pieces of flint and sand; 3: Pleistocene gravels (rounded flint  
1021 pebbles in a matrix of fine sand; 4: Loam with fine layers of peat; 5: Peat; 6: Clay or loam; 7:  
1022 Loamy silts; 8: Marine sands; 9: Marine sandy silts; 10: Shell debris; 11: Dating – a:  $2910 \pm 90$   
1023 BP according to Ters et al. (1980)/ $1110 \pm 210$  cal. BCE according to Meurisse-Fort (2007); b:  
1024  $4650 \pm 150$  BP/ $3450 \pm 190$  cal. BCE; c:  $5220 \pm 110$  BP/ $4030 \pm 240$  cal. BCE; d:  $980 \pm 100/1070$   
1025  $\pm 200$  cal. BCE; e:  $3060 \pm 110$  BP/ $1270 \pm 270$  cal. BCE; f:  $5080 \pm 140$  BP/ $3940 \pm 300$  cal.  
1026 BCE; g:  $5520 \pm 150$  BP/ $4370 \pm 330$  cal. BCE; h:  $6450 \pm 160$  BP/ $5350 \pm 320$  cal. BCE

1027

1028 **Fig. 4: ERT profiles and drill core locations. Map based on BD ORTHO® (source: IGN,**  
1029 **2017) and RGE ALTI® 1m (source: IGN, 2017)**

1030

1031 **Fig. 5a: ERT2, ERT4, ERT5, and ERT6 profiles (2D view) and identified geoelectric units**  
1032 **(Ge)**

1033 Cores R4, R7 and R8 are reported in the corresponding sections and the reader can refer to the  
1034 description of the sedimentary units.

1035

1036 **Fig. 5b: ERT1, and ERT3 profiles (2D view) and identified geoelectric units (Ge)**

1037 Cores R1, R2 and R7 are reported in the corresponding sections and the reader can refer to the  
1038 description of the sedimentary units.

1039

1040 **Fig. 5c: ERT7, and ERT8 profiles (2D view) and identified geoelectric units (Ge)**

1041

1042 **Fig. 6: Chronostratigraphy of cores R1, R2, R3, and R4**

1043 Organic matter, carbonate content and granulometric indices (mean and mode) are reported for  
1044 each core, plotted as a function of depth below the surface.

1045 1: Heterogeneous sand; 2: Heterogeneous sand with gravels and pebbles; 3: Heterogeneous  
1046 deposit with sand (medium to coarse), pebbles and shell fragments; 4: Coarse sand; 5: Medium  
1047 sand; 6: Very fine to fine sand; 7: Tidal rhythmities; 8: Silty sand; 9: Peaty silt; 10: Peat including  
1048 plant debris; 11: Weathered chalk; 12: Mottled sediments (with red, yellow and grey spots); 13:  
1049 >35 % calcium carbonate content surficial deposits; 14: Potsherds; 15: Cockle fragments  
1050 (*Cerastoderma edule*); 16: Snail fragments; 17: Colluvium; 18: Clear contact; 19: AMS  
1051 radiocarbon dating; 20: Subunit M1; 21: Subunit M2; 22: Unit P; 23: Subunit Ch; 24: Subunit  
1052 Cm; 25: Subunit Cf; 26: Unit H

1053

1054 **Fig. 7: Chronostratigraphy of cores R5, R6, R7, and R8**

1055 Organic matter, carbonate content and granulometric indices (mean and mode) are reported for  
1056 each core, plotted as a function of depth below the surface.

1057 1: Heterogeneous sand; 2: Heterogeneous sand with gravels and pebbles; 3: Heterogeneous  
1058 deposit with sand (medium to coarse), pebbles and shell fragments; 4: Coarse sand; 5: Medium  
1059 sand; 6: Very fine to fine sand; 7: Tidal rhythmities; 8: Silty sand; 9: Peaty silt; 10: Peat including  
1060 plant debris; 11: Weathered chalk; 12: Mottled sediments (with red, yellow and grey spots); 13:  
1061 >35 % calcium carbonate content surficial deposits; 14: Potsherds; 15: Cockle fragments  
1062 (*Cerastoderma edule*); 16: Snail fragments; 17: Colluvium; 18: Clear contact; 19: AMS  
1063 radiocarbon dating; 20: Subunit M1; 21: Subunit M2; 22: Unit P; 23: Subunit Ch; 24: Subunit  
1064 Cm; 25: Subunit Cf; 26: Unit H

1065

1066 **Fig. 8: Chronostratigraphic cross-section based on drilled cores**

1067 1: Heterogeneous sand; 2 : Heterogeneous sand with gravels and pebbles; 3: Heterogeneous  
1068 deposit with sand (medium to coarse), pebbles and shell fragments; 4: Coarse sand; 5: Medium  
1069 sand; 6: Very fine to fine sand; 7: Tidal rhythmities; 8: Silty sand; 9: Peaty silt; 10: Peat including  
1070 plant debris; 11: Mottled sediments (with red, yellow and grey patches); 12: >35 % calcium

1071 carbonate content surficial deposits; 13: Potsherds; 14: Cockle fragments (*Cerastoderma*  
1072 *edule*); 15: Snail fragments; 16: Colluvium; 17: Clear contact; 18: AMS radiocarbon dating  
1073

1074 **Fig. 9: Tidal rhythmites recorded in core R6 (between 2.57 and 2.82 m depth).**

1075

1076 **Fig. 10: Examples of old maps of the Rue area**

1077 9a: Detail of the map drawn in 1579 by J. Surhonio '*Picardiae, Belgicae regionis descriptio,*  
1078 *Joanne Surhonio auctore. Cum Imp. et Reg. privilegio decenn. 1579. Ponthiev, Santerre,*  
1079 *Vermandois, Terrache, Tartenois, Cambresis, Vimevx, Beauvois, Laonnois, Baillage de Hesdin,*  
1080 *Artésia, Champagna, Hannoniae*' (Departmental Archives of the Somme: 1FI956). The town  
1081 of Rue is indicated by a yellow circle.

1082 9b: '*Plan des fortifications de la ville de Rue en 1640*' (Departmental Archives of the Somme:  
1083 1FI285). The brown circles indicate the location of R3 and R8.

1084 9c: Detail of the map drawn in 1773 '*Plan des différents canaux tant de navigation que de*  
1085 *dessèchement projetés dans le terrain situé entre l'embouchure des rivières de Somme, de*  
1086 *Maye et d'Authie*' (National Archives: N III Somme 8-2). The town of Rue is marked with a  
1087 red circle. The lock at 'la Haie Pénée' is indicated by a solid blue circle; the destroyed dyke  
1088 downstream is indicated by a dotted blue circle.

1089 9d: Detail of a map published in 1758 under the direction of César-François Cassini de Thury  
1090 '*Carte générale de la France ; 023. [Dieppe]. N°23. 15e Flle*'  
1091 (<https://www.geoportail.gouv.fr>). The town of Rue is indicated by a red circle.

1092

1093 **Fig. 11: Comparison between the past mean sea level reconstructed in the Rue area, the**  
1094 **sea level index point identified in Brittany (France) by Goslin (2014), and glacial isostatic**  
1095 **adjustment models**

1096 1: Basal peats identified by Goslin (2014); 2: Intercalated sea level index points identified by  
1097 Goslin (2014); 3: Limiting points identified by Goslin (2014); 4: Limiting points defined in our  
1098 study (HAT: reconstructed highest astronomical tide; msl: probable mean sea level); 5: Current  
1099 sea level (HAT: highest astronomical tide; msl: mean sea level); 6: Ice-5G model (Peltier,  
1100 2004); 7: Bradley et al. (2011) model; 8: Kuchar et al. (2012) model.

1101

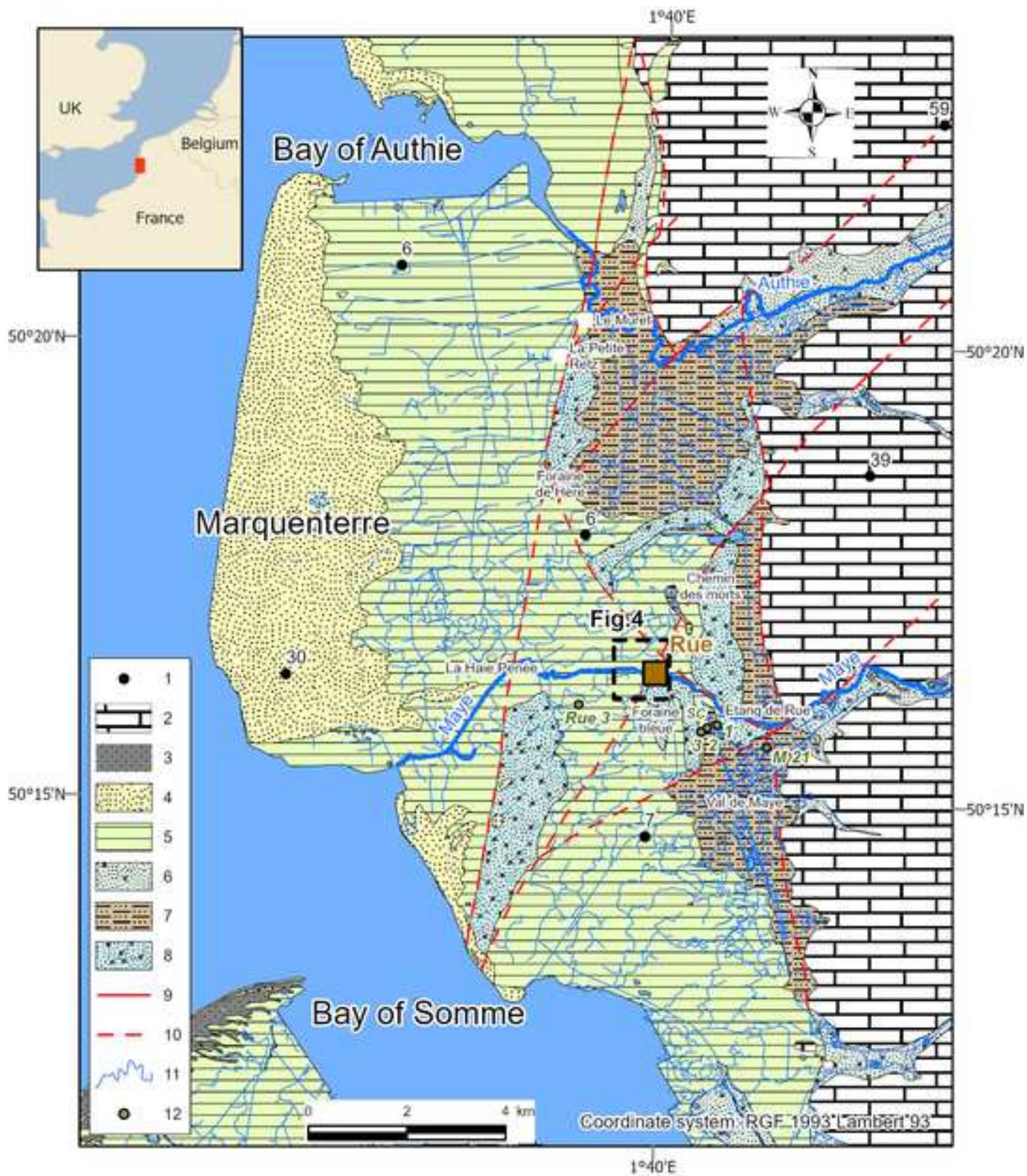
1102 **Fig. 12: Palaeogeographic reconstruction of the northwest of the Rue area from ca. 1300**  
1103 **BCE**

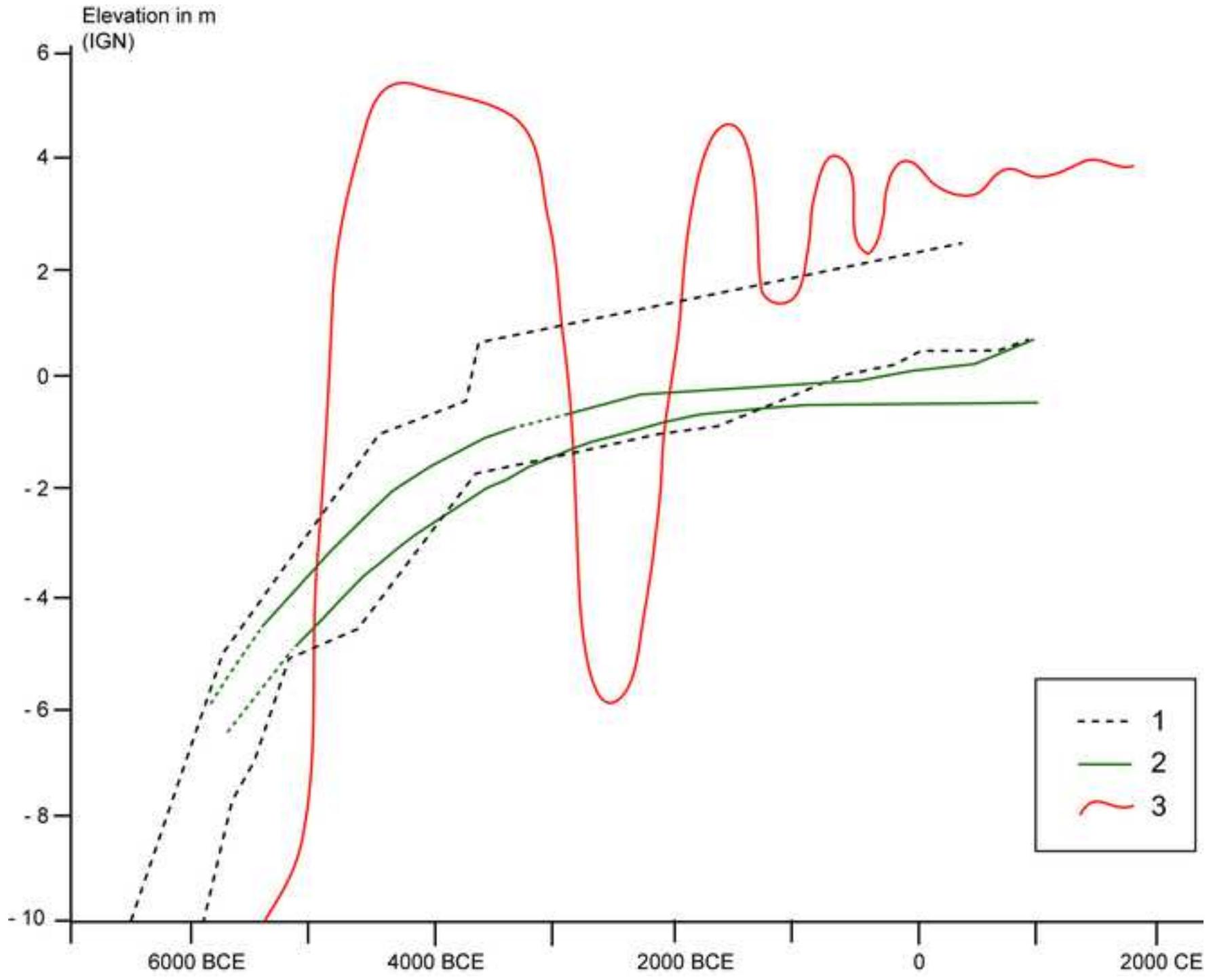
1104 12a—1: Rue *foraine*; 2: Swampy area; 12b—1: Rue *foraine*; 2: High marsh (schorre); 3:  
1105 Mudflat (slikke); 12c—1: Rue *foraine*; 2: Coast; 3: Maye estuary; 4: Limit of the medieval town  
1106 of Rue; 5: Present channel of the Maye; 6: Probable former channel of the Maye

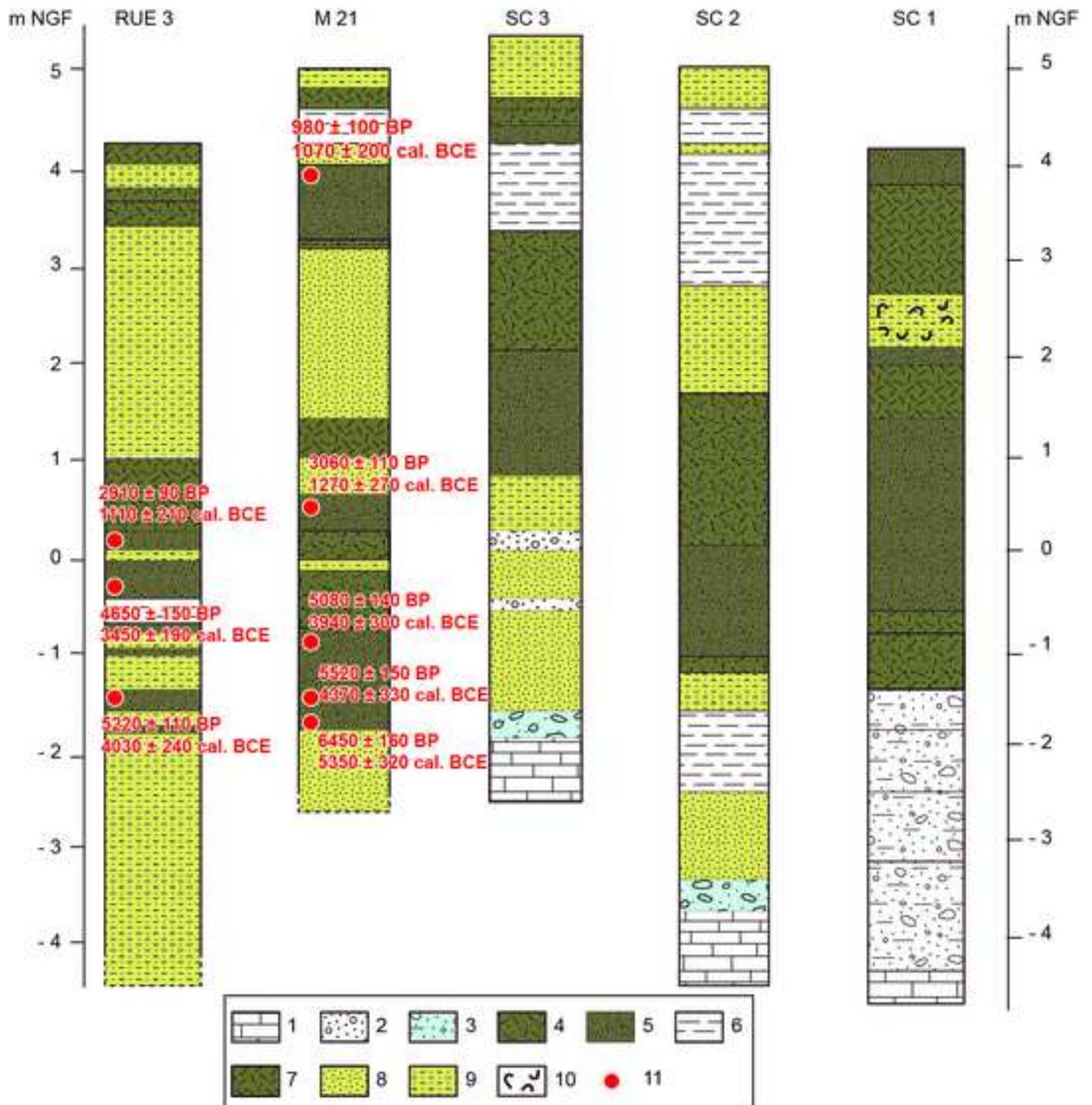
1107

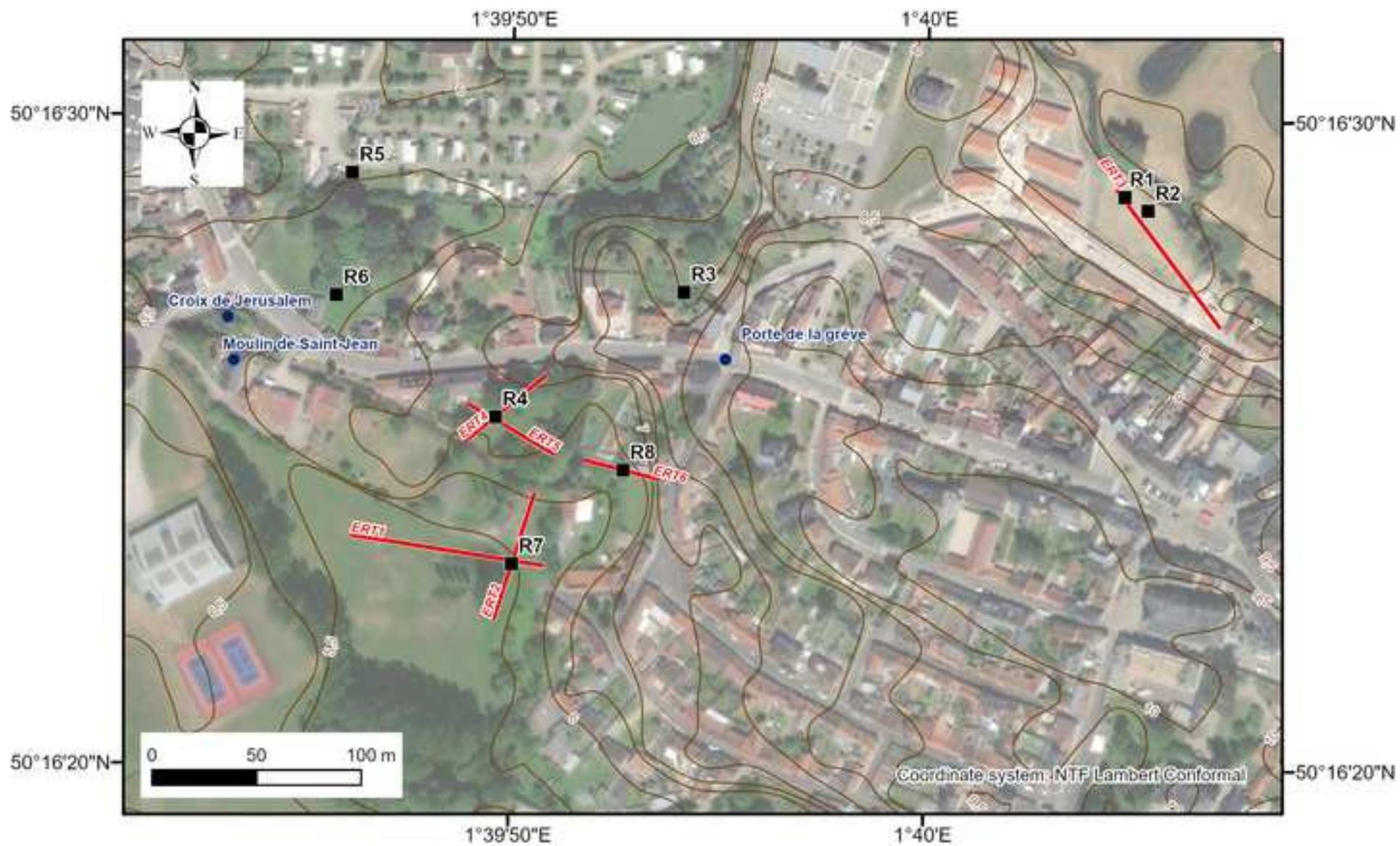
1108 **Table 1: ERT profile locations**

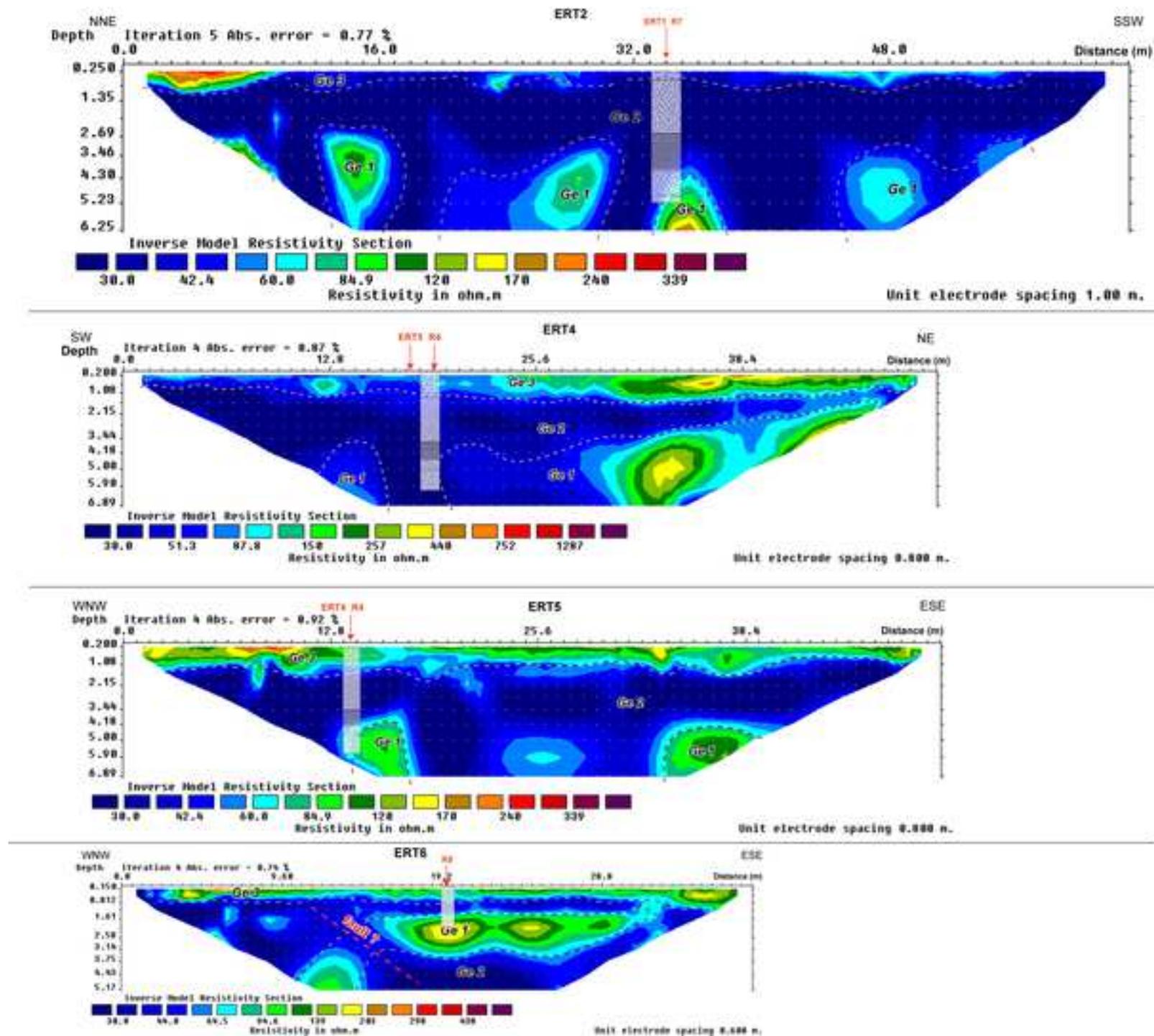
1109 **Table 2: Radiocarbon dating results**

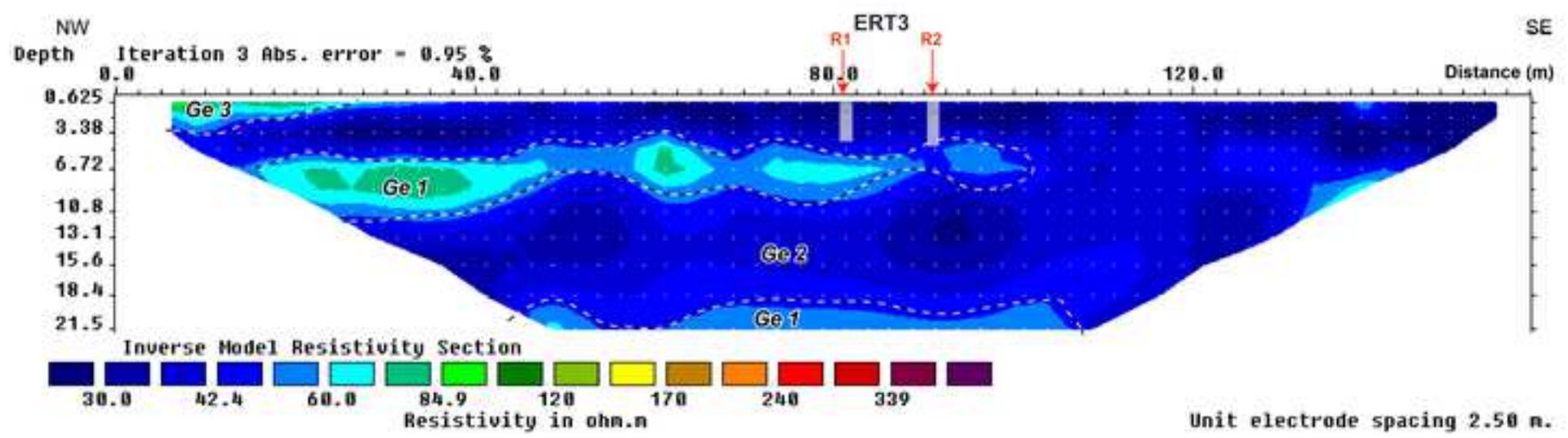
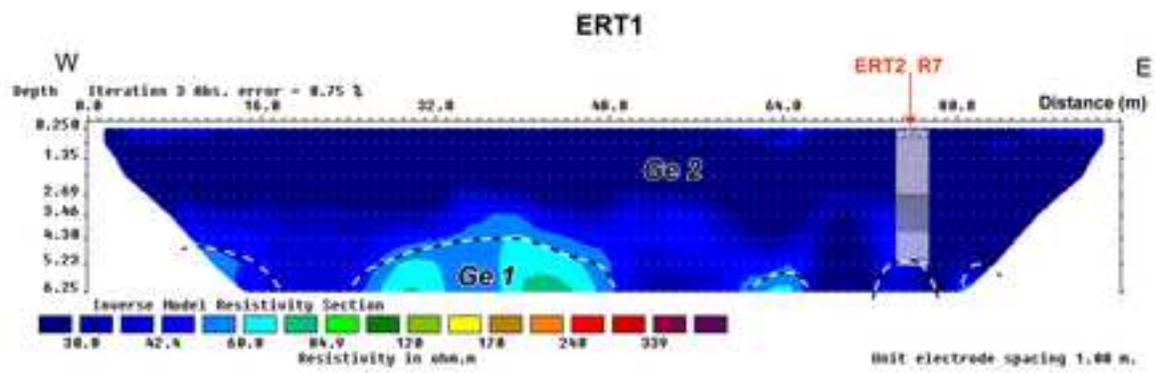


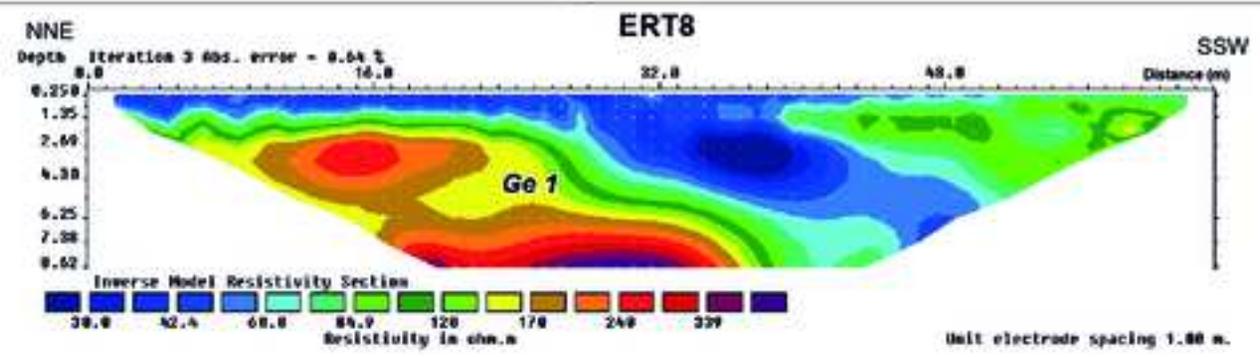
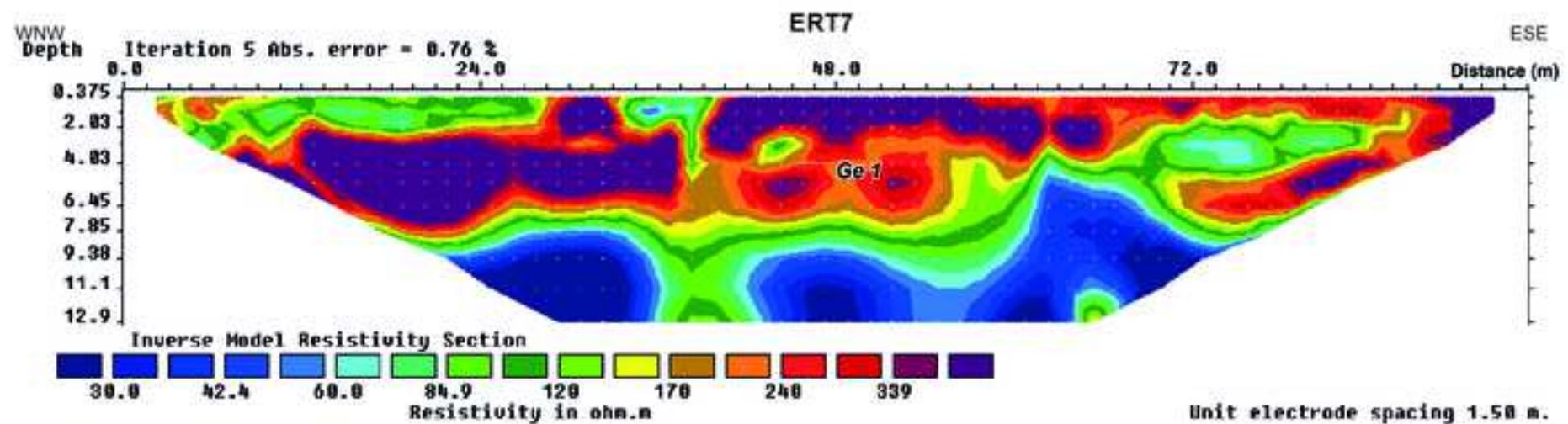


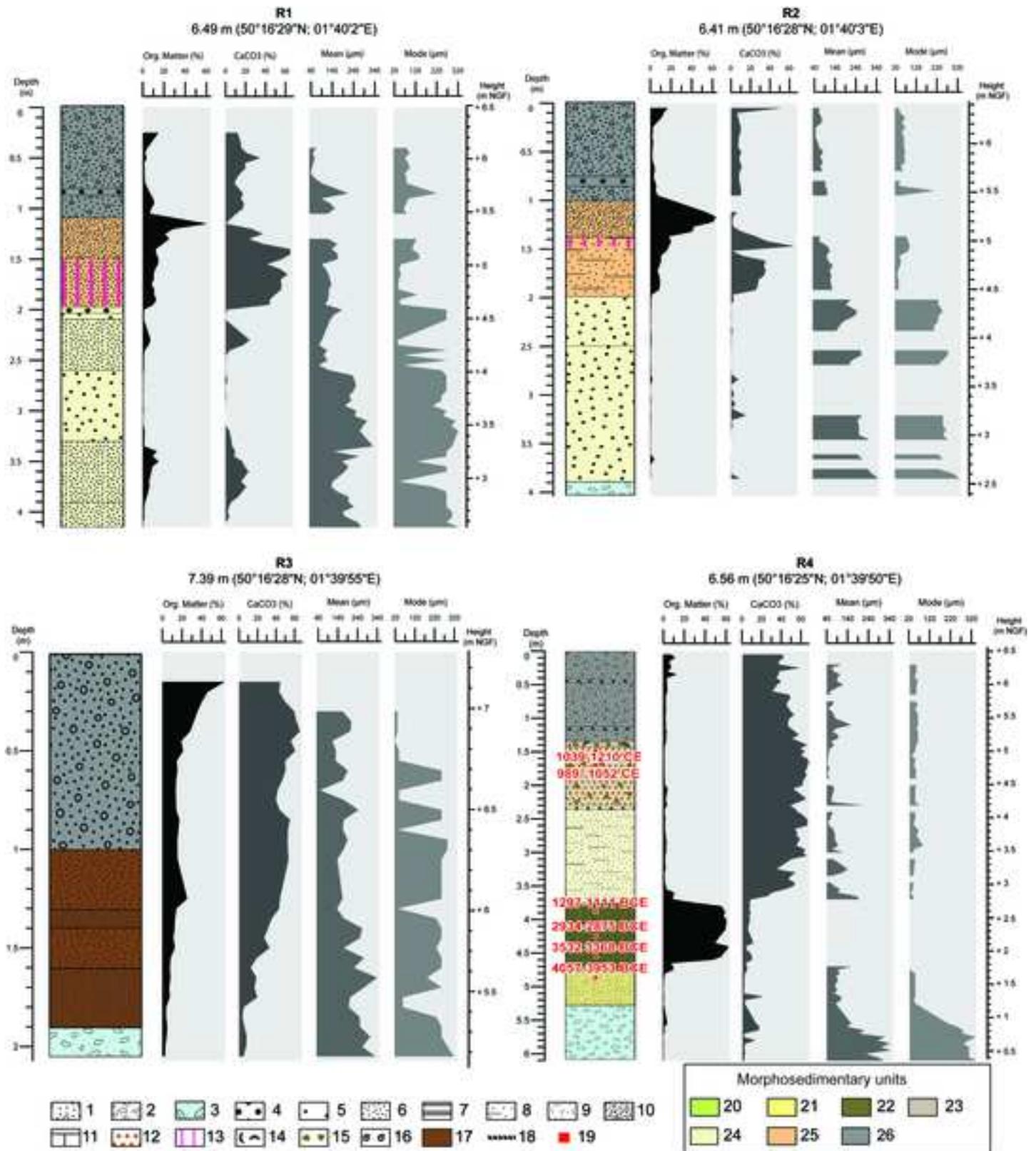


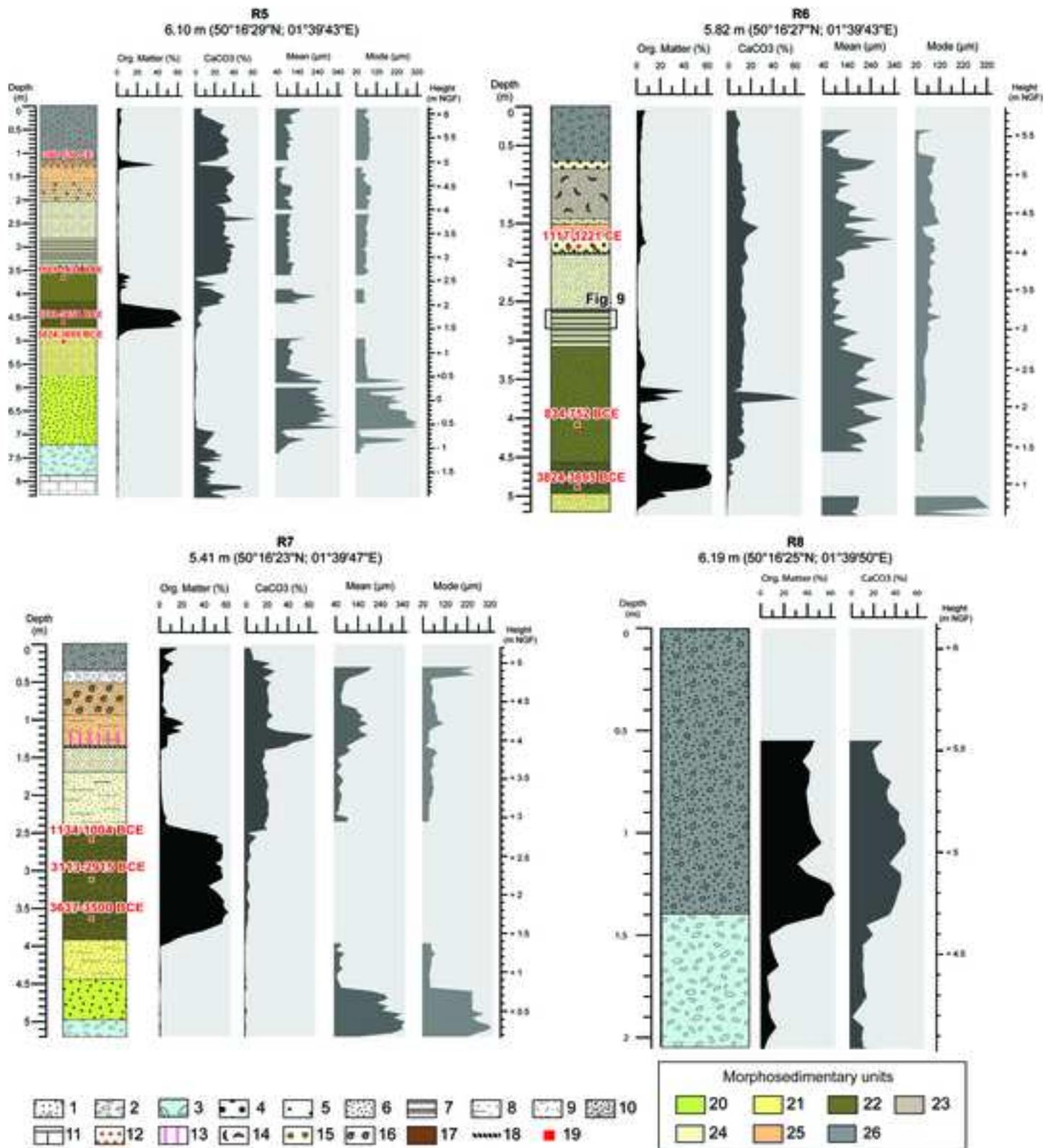


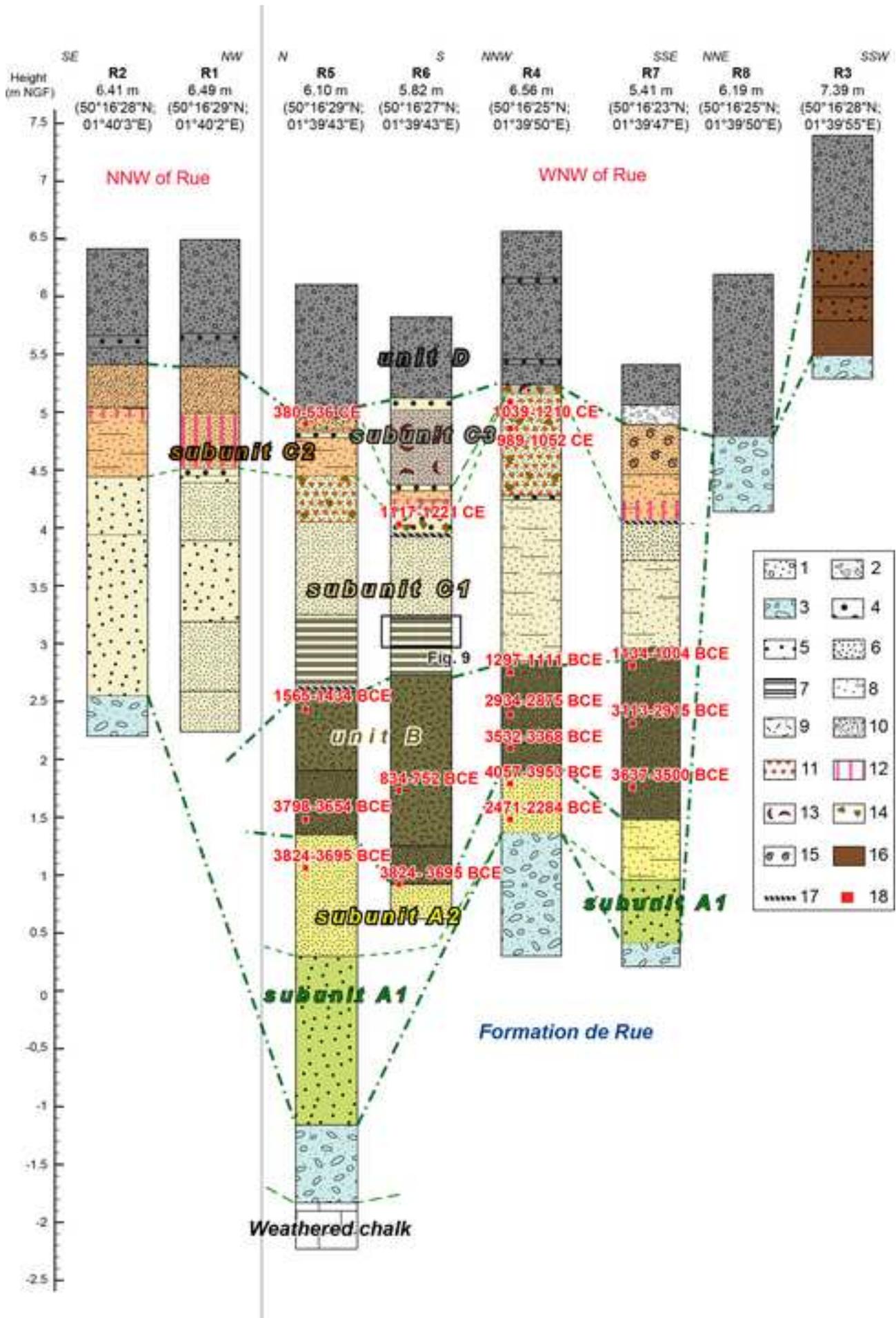


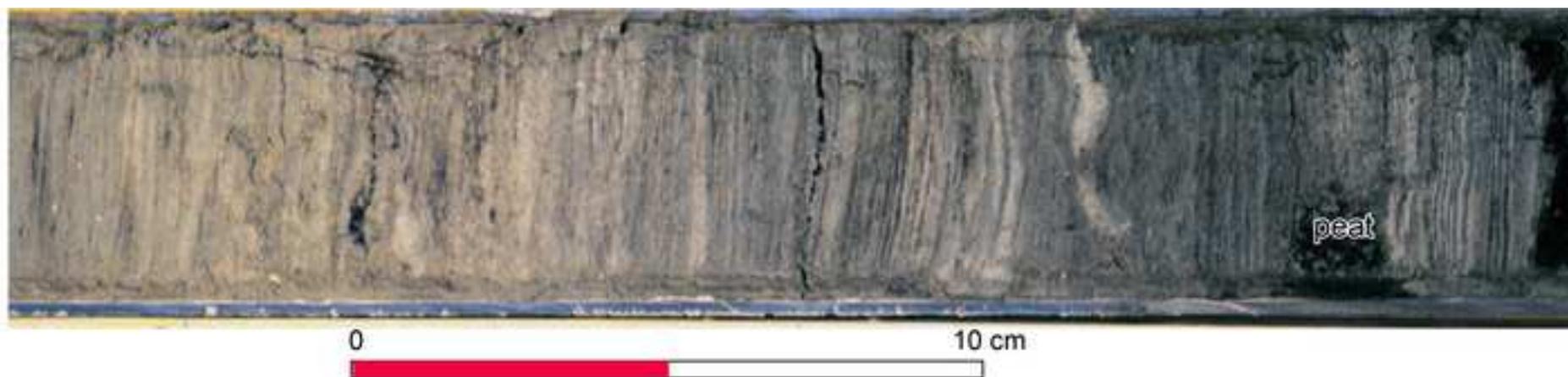


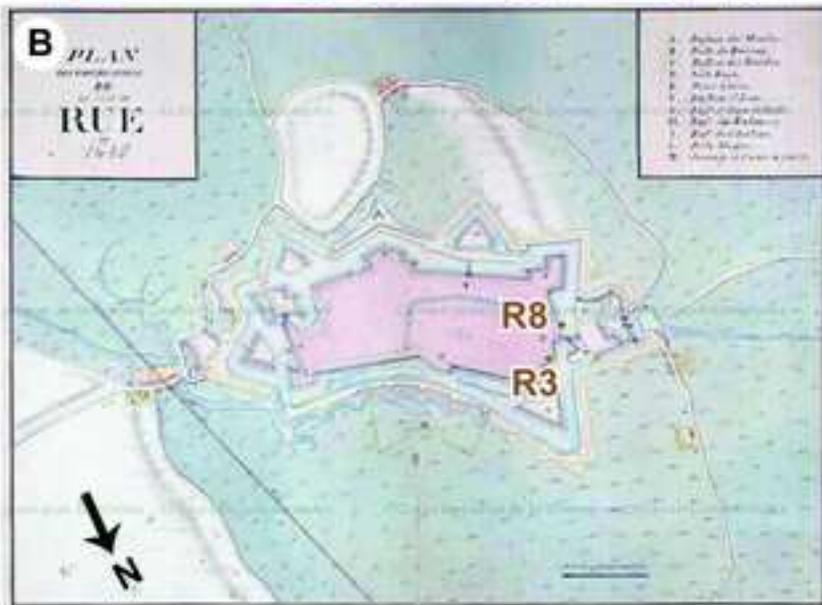


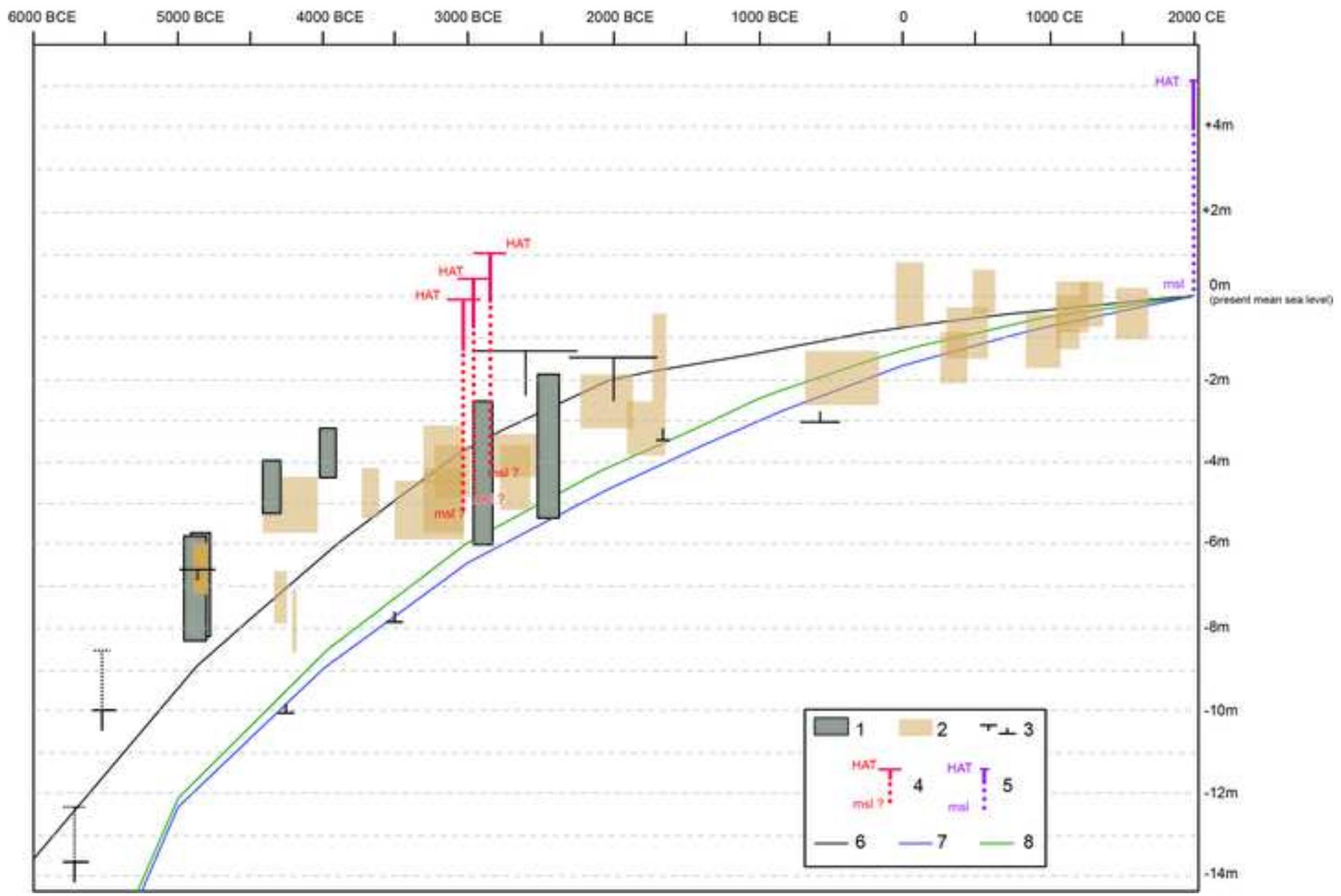


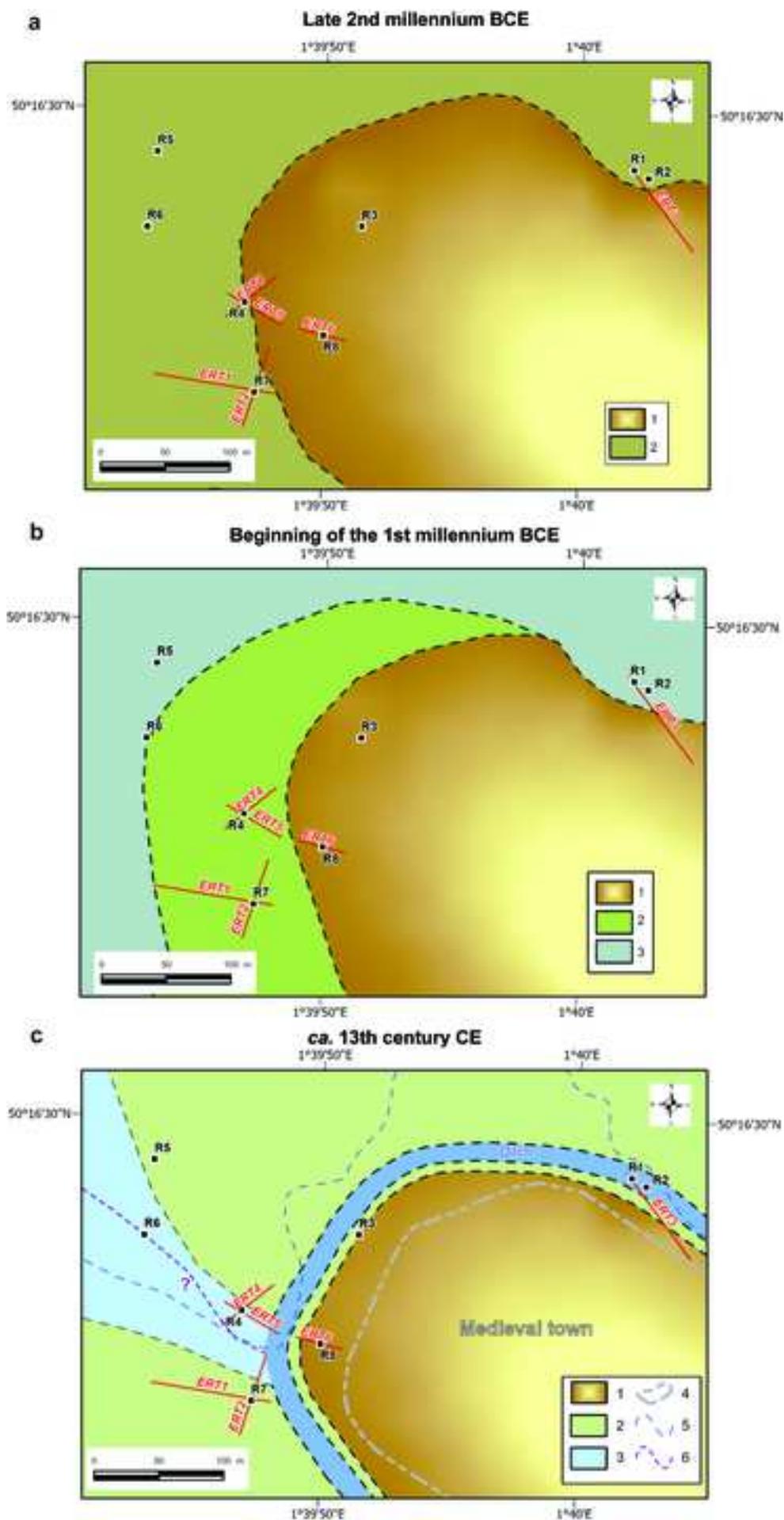












<b>Profile reference</b>	<b>starting point (EPSG 2154)</b>		<b>ending point (EPSG 2154)</b>		<b>length (m)</b>
ERT1	50°16'23"N	1°39'43"E	50°16'23"N	1°39'48"E	96
ERT2	50°16'24"N	1°39'48"E	50°16'22"N	1°39'47"E	64
ERT3	50°16'31"N	1°40'E	50°16'27"N	1°40'40"E	160
ERT4	50°16'25"N	1°39'46"E	50°16'26"N	1°39'48"E	51.2
ERT5	50°16'25"N	1°39'46"E	50°16'25"N	1°39'48"E	51.2
ERT6	50°16'24"N	1°39'49"E	50°16'24"N	1°39'51"E	38.4
ERT7	50°16'54"N	1°40'51"E	50°16'53"N	1°40'56"E	96
ERT8	50°5'28"N	1°25'39"E	50°05'26"N	1°25'36"E	64

Laboratory number	Core	Depth	Material	Conventional radiocarbon age	Calibrated date (2 $\sigma$ )
Poz-54987	R4	144 cm	Charcoal	900 $\pm$ 30 BP	1039-1210 CE
Poz-54988	R4	167 cm	Charcoal	990 $\pm$ 30 BP	989-1052 CE
Poz-54989	R4	380 cm	Peat	2980 $\pm$ 30 BP	1297-1111 BCE
Poz-54991	R4	418 cm	Peat	4285 $\pm$ 30 BP	2934-2875 BCE
Poz-54992	R4	446 cm	Wood	4690 $\pm$ 40 BP	3532-3368 BCE
Poz-54993	R4	477 cm	Charcoal	5200 $\pm$ 35 BP	4057-3953 BCE
Poz-54995	R5	122 cm	Peat	1625 $\pm$ 30 BP	380-536 CE
Poz-54997	R5	367 cm	Peat	3235 $\pm$ 35 BP	1565-1434 BCE
Poz-54998	R5	460 cm	Peat	4960 $\pm$ 35 BP	3798-3654 BCE
Poz-54999	R5	504 cm	Wood	5000 $\pm$ 40 BP	3824-3695 BCE
Poz-55001	R6	179 cm	Plant	880 $\pm$ 30 BP	1117-1221 CE
Poz-55003	R6	408 cm	Peat	2600 $\pm$ 35 BP	834-752 BCE
Poz-55004	R6	490 cm	Peat	5000 $\pm$ 40 BP	3824-3695 BCE
Poz-55005	R7	260 cm	Peat	2900 $\pm$ 30 BP	1134-1004 BCE
Poz-55006	R7	310 cm	Peat	4410 $\pm$ 35 BP	3113-2915 BCE
Poz-55007	R7	365 cm	Peat	4745 $\pm$ 35 BP	3637-3500 BCE