10,000 years of vegetation history of the Aa palaeoestuary, St-Omer Basin, northern France

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a b s t r a c t

The analysis of sediments and pollen from three sedimentary profiles in the St-Omer basin (Pas-de-Calais, France) has allowed the reconstruction of local and regional vegetation history from the late Preboreal to the Subatlantic. Hydrological changes induced vegetation changes, with freshwater marshy vegetation dominating during fluvial episodes, and halophilous grasslands, typical of shore areas, dominating during episodes of salt water input (five marine episodes, so-called St-Omer I to St-Omer V). Pollen markers indicative of human presence and agricultural activities, along with contemporaneous signals of forest disturbance, are recorded from *ca* 4000 cal BP onwards.

1. Introduction

Influence of past climate changes, sea level fluctuations and human disturbances on vegetation organisation are recorded in estuarine sedimentary archives, as shown from the analyses of Holocene deposits in France (e.g., Morzadec-Kerfourn, 1985), Britain (e.g., Waller, 1994; Long et al., 1998; Wimble et al., 2000), Belgium (e.g., Munaut and Paulissen, 1973), Germany (e.g., Freund et al., 2004), the Netherlands (e.g., Bohncke and Vandenberghe, 1991; Törnqvist et al., 2000) and outside Europe (e.g., Angulo et al., 1999; Ybert et al., 2003; Pederson et al., 2005; Yi et al., 2006).

In the North Sea area, reconstructions of sea level and coastline changes from the last glacial maximum have been carried out by Scourse and Austin (1995) and Shennan and Andrews (2000). However, the coastal regions of northern France remain relatively poorly known from a palaeoecological point of view (Ters et al., 1980; Vinchon et al., 2000), despite their key position (near the Pas-de-Calais strait) for the understanding of the marine transgressions that took place in the English Channel and North Sea regions during the Holocene.

During the last 10, 000 years, coastal areas of northwest France were regularly subjected to alternating transgressions/regressions of the English Channel/North Sea Complex (Dubois, 1924; Sommé, 1977).

Such changes are well recorded in the pollen sequences of St-Momelin/Clairmarais and Watten, analyzed respectively by Van der Woude and Roeleveld (1985), and Sommé et al. (1994). These sequences yielded two discontinuous pollen records, starting from the Lower Weichselian, and provided evidence for two main Holocene transgressions, “Calais” and “Dunkerque”. These marine transgres-sions have subsequently been subdivided, so as to include more marine episodes within the North Sea basin: Calais I to Calais IV and Dunkerque I to Dunkerque III. The chronological position of each marine episode differs from one region to another according to complex glacio-hydro-eustatic readjustments and neotectonic pro-cesses (Denys and Baeteman, 1995; Lambeck, 1997; Waller and Long, 2003). A chronology for the Flemish–German plain is provided by Behre (2004), but remains undocumented for the St-Omer region until now.

A multidisciplinary programme aimed at reconstructing regional eustatic variations, climatic and environmental changes in the St-Omer basin during the Holocene was launched in 2000. Twenty new sedimentary profiles were sampled for multidisciplinary analyses of sediments, including pollen, moll u s c s a n d i n s e c t s (C o l e o p t e r a , Trichoptera, and Diptera Chironomidae) (Gandouin, 2003; Gandouin et al., 2005, 2006, 2007a; Ponel et al., 2007). This paper presents a palaeoenvironmental reconstruction of vegetation and landscape successions during the last 10,000 years derived from pollen assemblages from St-Momelin and Watten (Pas-de-Calais).

2. Study site

The St-Omer basin (40 km^2) is located in northern France, close to the North Sea, downstream of the Aa river (Fig. 1). The 560 km^2 river catchment is predominantly located in a zone of subsidence (Mansy et al., 2003) on a chalk substratum which extends into Eocene clay in its lower part at the St-Omer basin (from Arques to Watten). A single narrow outlet (about 1 km wide near Watten) connects the large catchment basin and the maritime plain. The gradient of the river along the basin is gentle, only amounting to about 0.1 m/km. Due to its very low elevation (2 m a.s.l.), the basin served as an estuary during the major episodes of postglacial sea level rise.

Today, the tempered oceanic climate of the St-Omer region is marked by annual rainfall of *ca* 800 mm/yr; the mean temperatures of the warmest and coldest months are about 18 °C and 3 °C respectively, and the mean annual temperature is close to 10.5 °C (Gehu, 1970). The modern landscape is a mosaic of cultivated and built up areas. The marsh was artificially drained during the Medieval period but remnants of peat bogs still persist along the Aa and its tributaries, together with scattered woodlands of willows (*Salix cinerea*, *S. alba*, *S. fragilis* and *S. triandra*), alder (*Alnus glutinosa*), poplars (*Populus alba* and *P. tremula*), deciduous oaks (e.g., *Quercus robur* and *Q. petraea*) and beech (*Fagus sylvatica*).

3. Material and methods

3.1. Field and laboratory methods

Profiles S1 (23 m long) and S2 (18 m long) were extracted with an hydraulic piston corer taking core sections of 1 m long and 10 cm wide. Profile P12 was extracted with an auger taking core sections of 1.5 m long and 15 cm wide. Sandy sediments from profile S2 were not recovered; these were located at depth comprised between 3 and 6 m.

Pollen extraction was carried out according to Faegri et al. (1989) and Nakagawa (1998). Minerogenic samples were subjected to heavy liquid pollen flotation ($d = 1.9$). A minimum of 300 pollen grains per sample were counted. Pollen frequencies are expressed as a percentage of the total pollen sum of all trees and herbs; helophytic and hydrophytic plants, Pteridophyta and Cyperaceae were excluded from the pollen sum. *Alnus* pollen was also excluded since it is usually over-represented in sediments from alluvial plains.

A total of 299 samples are presented in the simplified pollen diagrams (Figs. 2–4). "Local Pollen Assemblages Zones" (LPAZ) are identified using percentage changes of at least two significant pollen taxa. "Regional Pollen Assemblage Zones" (RPAZ) are identified using the LPAZ from all three profiles; these allow the main features of regional vegetational change to be depicted (Fig. 5).

3.2. Radiocarbon dating

Eighteen sediment samples or wood fragments were dated using the conventional radiocarbon method (Table 1). Some of the dates, previously published by Gandouin et al. (2005, 2006, 2007a) and Ponel et al. (2007), were calibrated following the INTCAL98 calibration procedure, and using the intercept method (Stuiver et al., 1998). In this paper, calibration has been updated with the INTCAL04 data set (Reimer et al., 2004) using the Calib Rev 5.0 program (Stuiver et al., 2005).

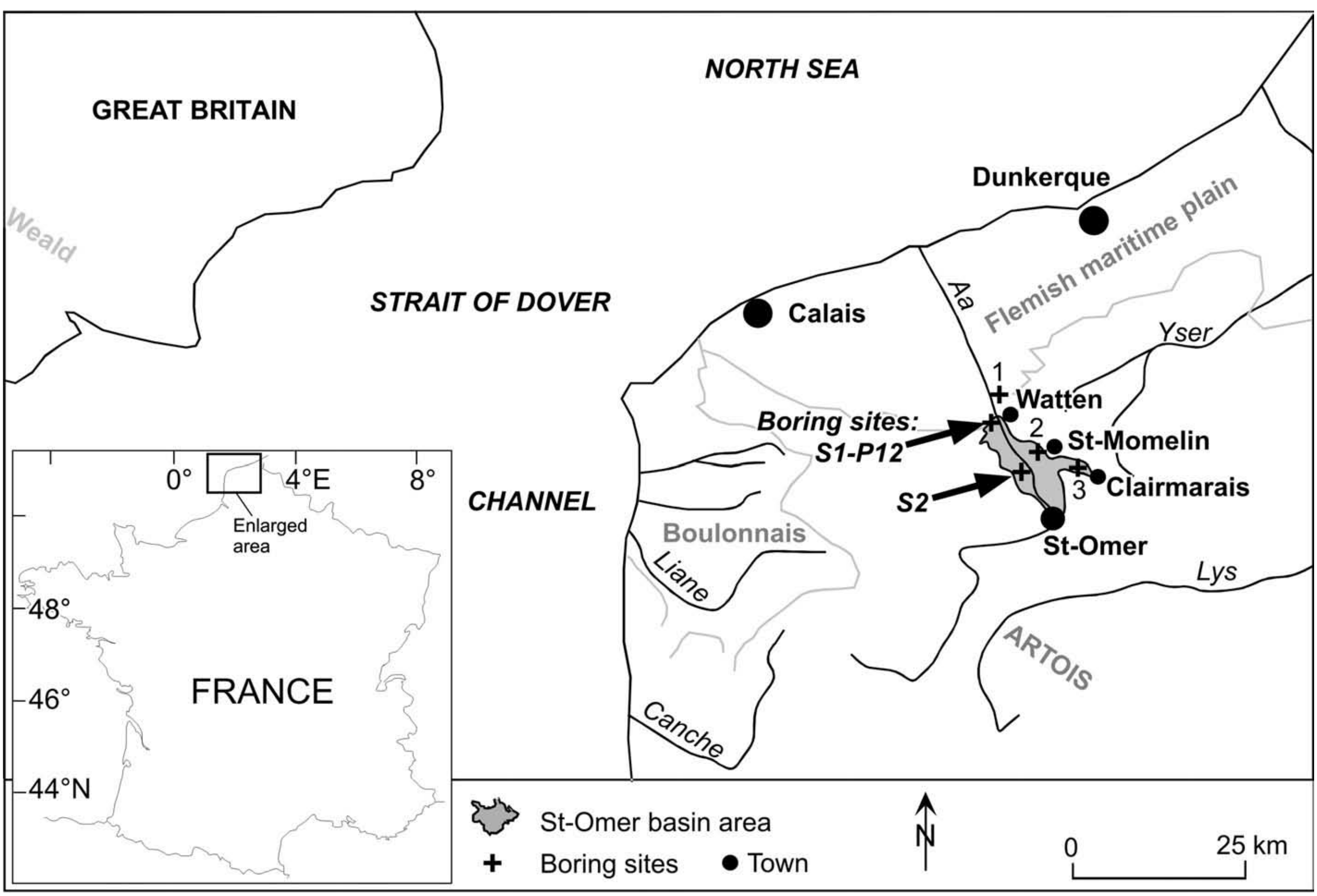

Fig. 1. Geographical location of the St-Omer basin, showing the position of the Watten (P12, S1) and St-Momelin (S2) boreholes. 1: Watten boring studied by Sommé et al. (1994); 2 and 3: St-Momelin and Clairmarais borings studied by Van der Woude and Roeleveld (1985).

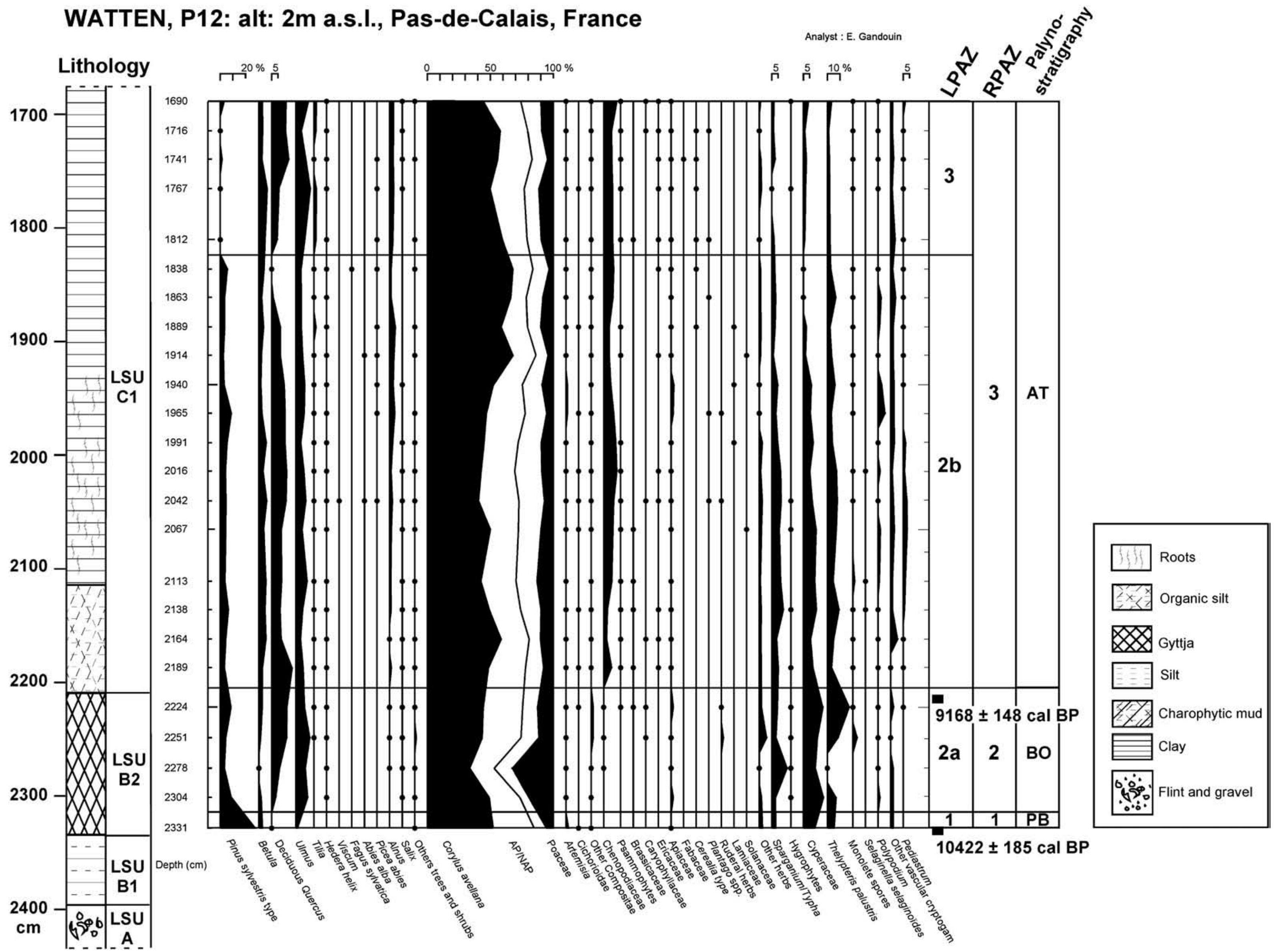

Fig. 2. Pollen diagram (simplified) from borehole P12 at Watten. Radiocarbon dates are (2σ) calibrated years BP (Before Present). RPAZ: Regional Pollen Assemblage Zone; LPAZ: Local Pollen Assemblage Zone; LSU: LithoStratigraphic Units. PB: Preboreal; BO: Boreal; AT: Atlantic.

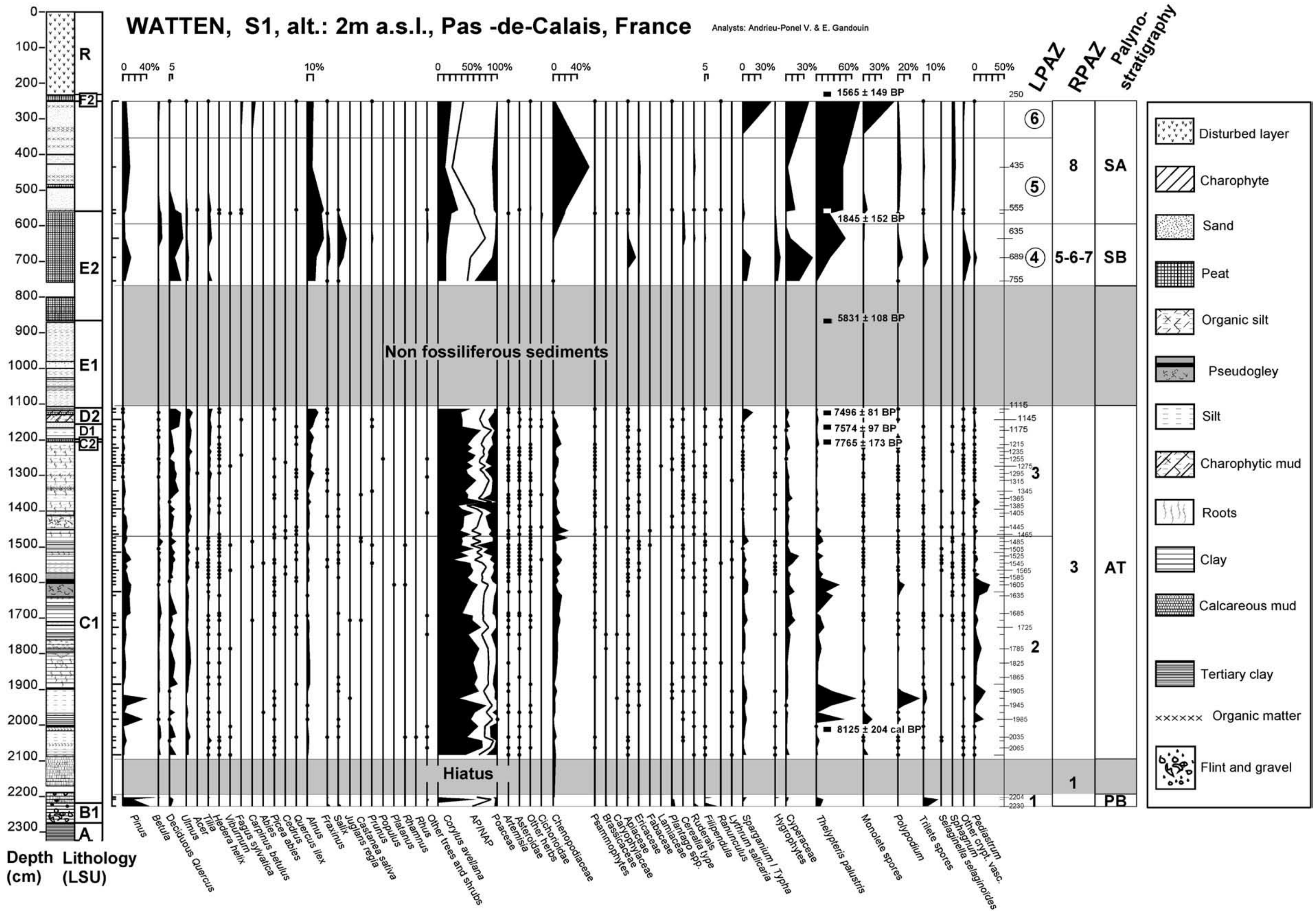

Fig. 3. Pollen diagram (simplified) from borehole S1 at Watten. Radiocarbon dates are (2σ) calibrated years BP (Before Present). RPAZ: Regional Pollen Assemblage Zone; LPAZ: Local Pollen Assemblage Zone; LSU: LithoStratigraphic Units. Distorted zones due to high *Thelypteris* pollen concentration are indicated by black circles in the LPAZ column. Shaded area: sediment lost during coring or non fossiliferous sediment. PB: Preboreal; AT: Atlantic; SB: Subboreal; SA: Subatlantic.

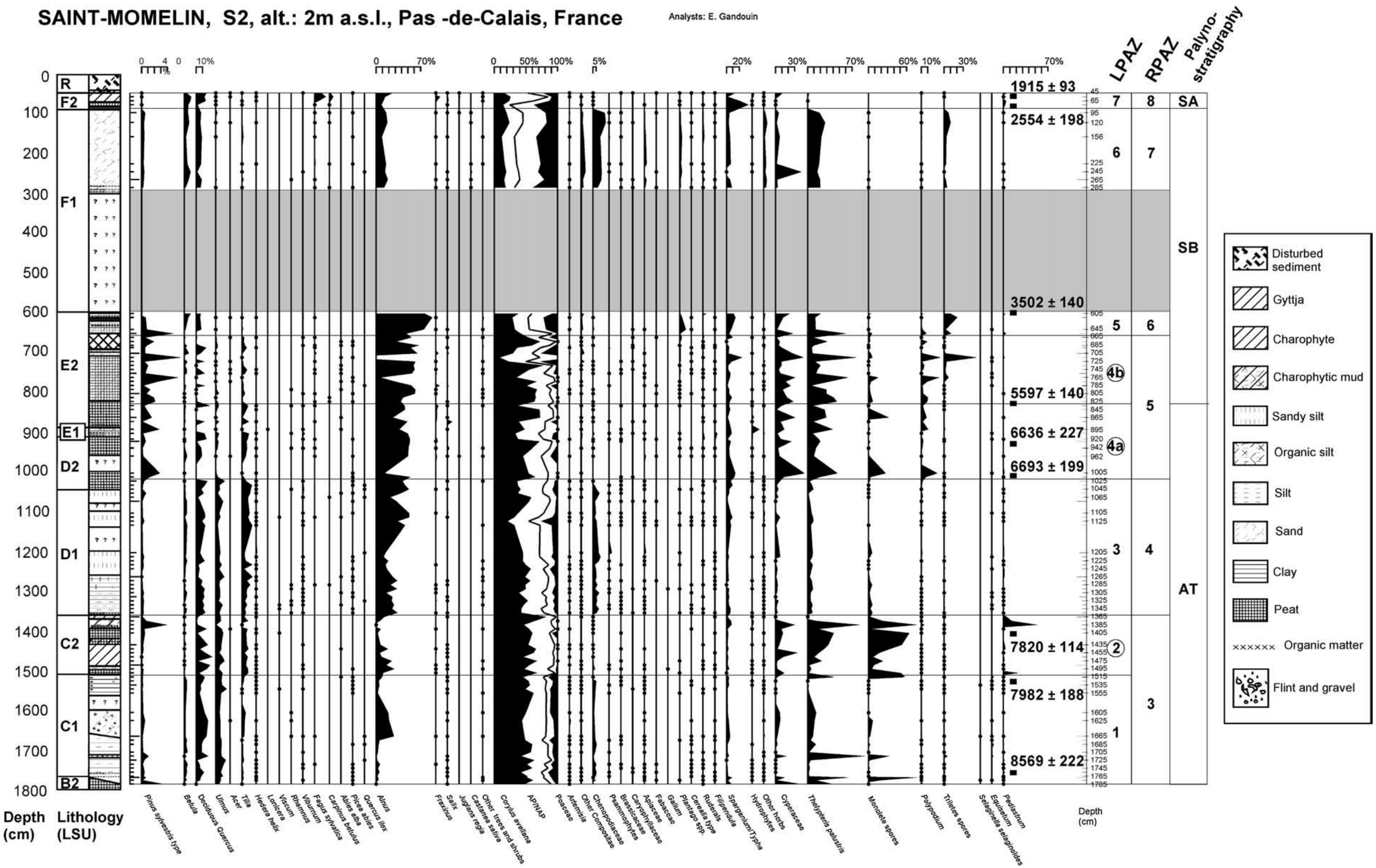

Fig. 4. Pollen diagram (simplified) from borehole S2 at St-Momelin. Radiocarbon dates are (2σ) calibrated years BP (Before Present). RPAZ: Regional Pollen Assemblage Zone; LPAZ: Local Pollen Assemblage Zone; LSU: LithoStratigraphic Units. Distorted zones due to high *Thelypteris* pollen concentration are indicated by black circles in the LPAZ column. Shaded area: sediment lost during coring or non fossiliferous sediment. AT: Atlantic; SB: Subboreal; SA: Subatlantic.

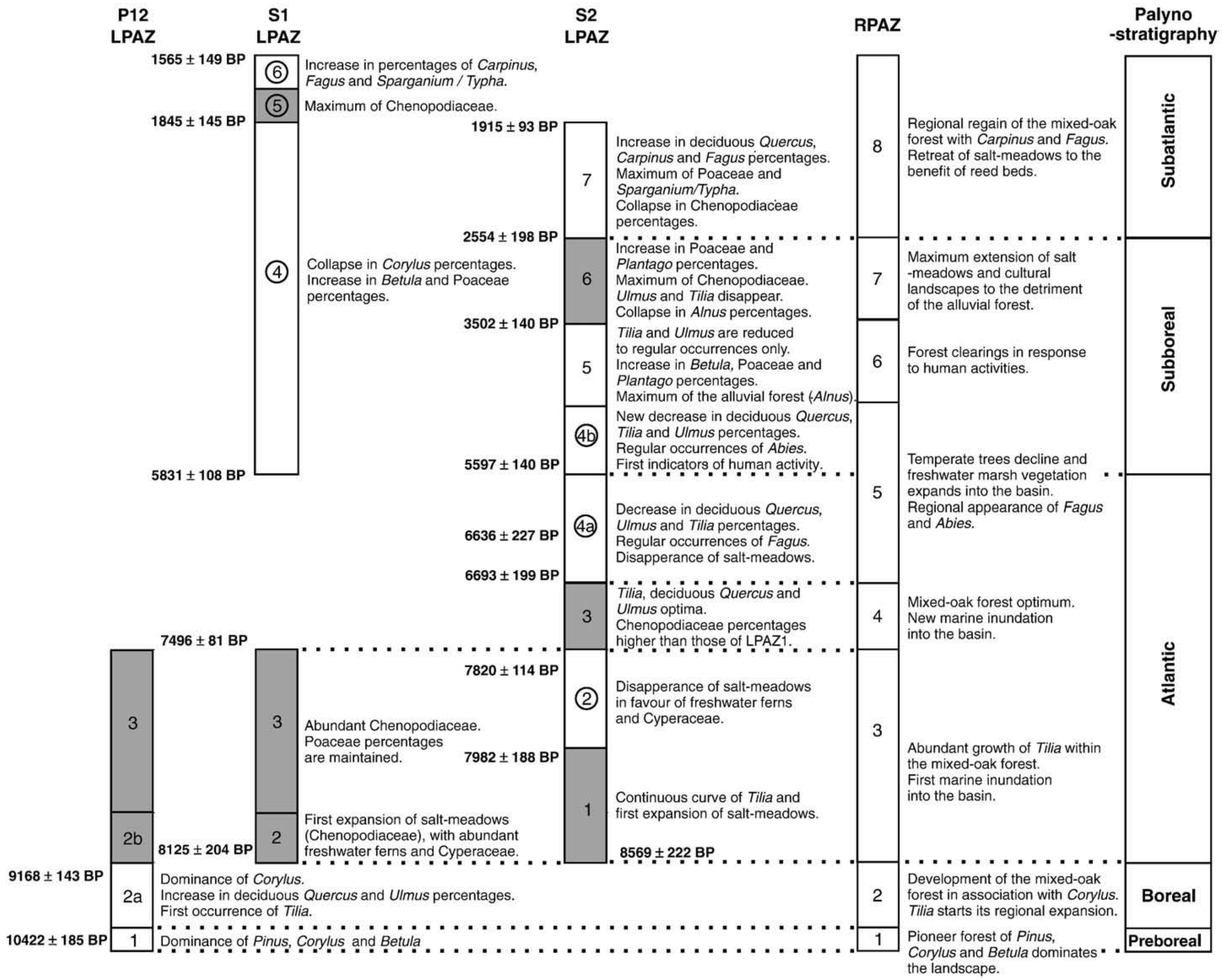

Fig. 5. Summary of the pollen analysis from boreholes P12, S1 and S2, and correlation between Local Pollen Assemblage Zones (LPAZ) and Regional Pollen Assemblage Zones (RPAZ). Distorted zones due to high *Thelypteris* pollen concentration are indicated by black circles. Shaded area: marine inundation episodes marked by salt-meadow expansion (distinguished by Chenopodiaceae, Poaceae and Apiaceae pollen). Radiocarbon dates are (2σ) calibrated years BP (Before Present).

3.3. Lithology and grain-size analysis

Sedimentological data may provide additional information about environmental changes in the catchment area. Thus, continental and marine sediment from profiles P12, S1 and S2 were described in laboratory following the lithofacies descriptions of Allen (2003), Van der Woude and Roeleveld (1985), Sommé et al. (1994) and Berendsen and Stouthamer (2000). In order to provide information about past hydrodynamic processes (finer deposits may characterize standing water depositional environments whereas coarser deposits may correspond to running water environments), a total of 258 samples (each 1 cm thick) were taken throughout the three sedimentary profiles for grain-size analysis. This was performed with a laser particle analyser (MALVERN Mastersizer 2000 Ver. 5.00). Sediments were classified into three grain-size categories according to Chamley (2000): clay particles have a diameter of less than 2 µm; silt particles have a diameter comprised between 2 and 63 µm; and sand particles have a diameter greater than 63 µm. Clay from lithostratigraphical units A (LSU A) in profiles S1 and P12, and peat from LSU D2-E2 in profiles S1 and S2 were not analysed. A detailed grain-size analysis is given by Gandouin (2003).

4. Results and palaeoenvironmental interpretations

Based on sediment analyses, P12, S1 and S2 profiles were subdivided into twelve LSU (Table 2). Fig. 6 shows radiocarbon dates, RPAZ, LPAZ and LSU, and correlations between the P12, S1 and S2 profiles.

Occurrences (less than 1% of the pollen sum) of corroded pollen of *Picea*, *Abies*, *Cedrus*, *Carpinus*, and Pre-Quaternary palynomorphs were identified, these mainly occurred in minerogenic sediments of fluvial or estuarine origin. These should be attributed to sediment reworking during erosive phases (Waller, 1993). *Thelypteris palustris* is over-represented at Watten (S1) in pollen-poor sediments (S1: LAPZ 4 to 6) probably for taphonomic reasons. In profile S2, samples with a high content of *Thelypteris* and "monolete spores" are also rich in *Pinus* pollen. This has already been observed in other pollen records (Jalut et al., 1988; Reille and Andrieu, 1995) and may be interpreted as a distorted record due to pollen concentration induced by dense populations of *Thelypteris*. Pollen zones affected by this bias do not bear any ecological significance at a regional scale.

In northern Europe, the Chenopodiaceae family consists mainly of both halophilous and ruderal species. This mixture blurs the interpretation of

Table 1

Radiocarbon dates from profiles P12, S1 and S2 The calibrated age ranges (2σ interval) were based on the INTCAL98 (Stuiver et al., 1998) and INTCAL04 (Reimer et al., 2004) calibration procedures, using the intercept method and the Calib Rev 5.0 program (Stuiver et al., 2005). All measurements were performed on bulk sediment with a conventional radiocarbon dating procedure. The radiocarbon dating was carried out by Beta Analytic (Miami) and the GAA-institut (Hannover).

Lab No.	Depth (cm)	$\delta^{13}C$ ‰ PDB	Samples	Conventional yrs BP	Datings			
					Intcal98		Intcal04	
					Cal. BP	Cal. BC	Cal. BP	Cal. BC
S1: Beta-166495	241	− 30.1	Organic sediment	1680±60	1570±150	380±150 Cal. AD	1565±149	1221±128
S1: Beta-166494	558	− 28.8	Peat	1900±70	1845±145	145±105 Cal. AD	1845±152	1450±157
S2: Hv-24816	50–54	− 29.3	Peat	1975±45	1915±45	75±25 Cal. AD	1915±93	1533±130
S2: Hv-24815	76–79	− 31.9	Peat	2510±90	2552±193	615±200	2554±198	2140±218
S2: Hv-24814	600–604	− 29.7	Peat	3265±70	3475±90	1627±108	3502±140	3100±201
S2: Beta-161064	830	− 29.0	Peat	4850±70	5590±130	3640±130	5597±140	5114±202
S1: Beta-166493	860	− 28.4	Peat	5100±50	5830±100	3880±100	5831±108	5441±119
S2: Beta-161063	935	− 30.0	Peat	5830±100	6640±230	4690±230	6636±227	6220±230
S2: Hv-24813	1025–1030	− 30.0	Peat	5880±80	6737±103	4850±80	6693±199	6300±176
S1: Beta-166490	1126–1134	− 26.3	Peat	6570±60	7495±85	5540±80	7496±81	7085±149
S1: Beta-166491	1165	− 27.7	Organic sediment	6710±60	7570±100	5620±100	7574±97	7258±134
S1: Beta-166492	1206	− 31.0	Peat	6920±100	7765±185	5820±180	7765±173	7420±176
S2: Beta-161062	1400	− 28.5	Peat	6990±50	7820±120	5865±125	7820±114	7490±83
S2: Hv-24812	1530	− 30.5	Organic sediment	7150±90	7910±80	6065±95	7982±188	7634±175
S1: Hv-24811	2000–2015	− 26.2	Organic sediment	7250±110	8022±103	6080±100	8125±204	7727±206
S2: Beta-161061	1723	28.3	Peat	7740±110	8655±305	6705±305	8569±222	8186±217
P12: Beta-166498	2220	− 28.2	Organic sediment	8220±50	9210±190	7265±185	9168±143	8760±176
P12: Beta-166499	2350	− 26.9	Organic sediment	9250±90	10 445±225	8495±225	10422±185	9999±258

the signal that could be interpreted either as marine or anthropogenic. This problem is especially true over the last 5000 years. However, previous palaeoecological studies (Van der Woude and Roeleveld, 1985; Sommé et al., 1994) carried out on the St-Omer basin had already shown that Chenopodiaceae can be used as an efficient marine palynological signal, if associated to other markers like sedimentological and malacological evidences. In the present study, the malacofauna of the sediment contemporaneous with substantial percentages of Chenopodiaceae reveals the presence of molluscs such as *Hydrobia ventrosa* and *H. ulvae*. These species are characteristic of the middle reaches of estuaries with salt levels of 12–15‰ and of 20–30‰ respectively (Keen, unpublished data). Hence, in the littoral context of the St-Omer basin, Chenopodiaceae may be considered as signal of marine transgression. In addition, Ponel et al. (2007) showed that no extensive human activities occurred at St-Omer before 4180±45 ^{14}C BP (4708±133 cal BP).

4.1. Tertiary and Pleistocene (LSU A and B1)

LSU B1 (Figs. 2 and 3), overlaying the Tertiary clay from LSU A, consists of highly calcareous alluvial deposits characteristic of late Glacial cold periods (Antoine et al., 2000). Over much of NW Europe, where valleys cut through the chalk, calcareous muds were produced at this time by substrate gelifraction that accumulated in the valley bottoms (Ponel et al., 2005). At St-Omer, Ponel et al. (2007) ascribed LSU B1 to the Younger Dryas period based on cold adapted coleopteran assemblages and similarity with lithostatigraphic evidence from Britain (Coope, 1998), Belgium (Munaut and Paulissen, 1973) and the Netherlands (Berendsen and Stouthamer, 2000). The fine sandy silt deposits of this unit (silt 80%, sand 15%, clay 5%) indicate a moderate flow of the river. Unfortunately the sediments from LSU B1 are devoid of pollen.

4.2. The end of the Preboreal and the Boreal (LSU B2 and RPAZ 1–2)

LSU B2 (Fig. 2) is situated above the Younger Dryas sediments and is characteristic of the peat infilling of a late Glacial palaeochannel from the English Channel and North Sea regions and may have been induced by a rise in the groundwater level in response to the progressive rise in sea level (Baeteman and De Gans, 1993; Berendsen and Stouthamer, 2000). This peat infilling began next to the river incision that took place at the transition between the Younger Dryas and the early Holocene (Starkel, 1991; Huisink, 2000; Antoine et al., 2003), in response to the dynamic adjustment of the river in wetter climatic conditions. The timing of this incision differs from one region to another. At St-Omer, the basal part of the peat from the P12 profile is dated to 10 422±185 cal BP (9250±90 ^{14}C BP). During this period, the St-Omer hydrographic system consisted of a river meandering through a vast marshy region, as observed in most of the alluvial plains from northern France (Antoine et al., 2000).

Pollen data from the St-Omer basin show that during the Preboreal, pioneer forests of *Pinus*, *Corylus* and *Betula* dominated the landscape, as observed in the Somme basin (Antoine et al., 2000), the

Table 2

Lithostratigraphical units (LSU).

Lithofacies	Descriptions	Depositional environments
LSU R	Sediment disturbed by agricultural activities	
LSU F2	Blackish-brown peat and charophyte-mud	Freshwater swamp or salt marsh
LSU F1	Sand	Tidal channel (higher hydrodynamism)
LSU E2	Blackish-brown peat and organic rich muds, associated with plant debris and laminated with fine sand layers	Freshwater swamp or salt marsh
LSU E1	Silty sands	Tidal channel
LSU D2	Blackish-brown peat and charophyte-mud	Freshwater swamp or salt marsh
LSU D1	Sandy silts	Tidal channel
LSU C2	Blackish-brown peat, charophyte or organic muds associated with plant debris	Freshwater swamp or salt marsh
LSU C1	Clayey silts millimetric laminated and occasionally bioturbated by roots and shells	Intertidal mudflats
LSU B2	Blackish-brown peat associated with plant debris (leaves, twigs and tree trunks)	Freshwater swamp (infilling side-arm or oxbow lake)
LSU B1	Calcareous alluvial sandy silts with pebbles and flints	Braided river channel
LSU A	Light grey tertiary clay	–

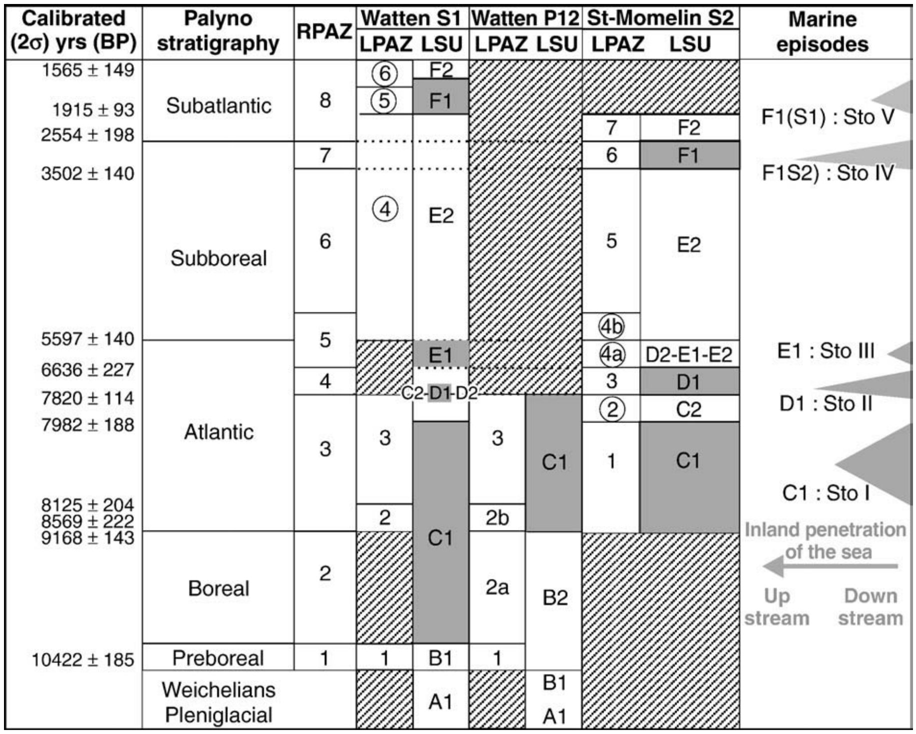

Fig. 6. Correlation scheme between pollen zones from profiles S1, S2 and P12. RPAZ: Regional Pollen Assemblage Zone; LPAZ: Local Pollen Assemblage Zone; LSU: LithoStratigraphic Units. Distorted zones due to high *Thelypteris* pollen concentration are indicated by black circles. Shaded area: marine episode marked by both sediment and pollen evidences; Hatched area: hiatus. The extensions of the marine inundations are based on the progressive increase of salt-meadow pollen percentage from St-Omer I (Sto I) to St-Omer V. The St-Omer III and V are only recorded downstream of the basin in profile S1.

Paris basin (Van Zeist and Van der Spoel-Walvius, 1980; Bakels, 1995; Pastre et al., 2000), the Scarpe Valley (Munaut et al., 1995). Percentages of "deciduous *Quercus*" increased during the Boreal but this taxon was already present at the end of the Preboreal (RPAZ 1). The abundance of *Corylus* (more than 50% of the pollen sum) in association with the mixed-oak forest (deciduous *Quercus*, *Ulmus*, and *Hedera*) and the first occurrences of *Tilia* mark the Boreal chronozone (Sommé et al., 1994).

4.3. The beginning of the Atlantic (LSU C1, C2, D1, and RPAZ 3–4)

The laminated clayey silts of LSU C1 (silt 80%, sand 15%, clay 5%) can accumulate in a wide range of depositional conditions, including subtidal, tidal and minerogenic saltmarsh environments. However, the presence of halophilous herb pollen such as Chenopodiaceae (LPAZ-2 in S1— Fig. 3 and LPAZ-2b in P12 — Fig. 2) indicates salt water input into the basin and progressive increase in regional marine influence, at the onset of the Calais transgression. High values in clay and silt particles into downstream profiles (P12 and S1), characteristic of low hydrodynamism, as well as abundances of Cyperaceae and freshwater ferns such as *Thelypteris palustris* (LPAZ 2 (S1) and LPAZ 2b (P12)) indicate that the marine influence was low and that the sea was probably still far away from the basin.

The salt-meadow expansion that occurred in the coastal plain downstream of Watten (Sommé et al., 1994) induced the opening of the landscape and favoured the establishment of *Betula*, as recorded in P14 and P12 assemblages. At that time, the mixed-oak forest probably grew on drained slopes of the watershed. *Tilia* appeared locally in the mixed-oak forest just before 7982 ± 188 cal BP (7150 ± 90 ^{14}C BP; S2 profile) and expanded to its maximum (RPAZ 4) around 6693 ± 199 cal BP (5880 ± 80 BP); this is in agreement with the date of 5690 ± 80 ^{14}C (6483 ± 171 cal BP) at Watten (Sommé et al., 1994), with the date of 5300 ± 70 ^{14}C (6071 ± 144 cal BP) at Bazoches in Vesle valleys (Bakels, 1995) and other pollen data from Great Britain (Jones and Keen, 1993).

The peaty and organic sediments of LSU C2 (Fig. 4) above the marine deposits of LSU C1 correspond to the organic infilling of a palaeochannel. This short event could have occurred during a pause, or a slight regression, in the sea level rise in response to glacio-hydro-eustatic readjustments, sediment compaction and neotectonic processes (Denys and Baeteman, 1995; Lambeck, 1997; Waller and Long, 2003). At that time, a Cyperaceae marsh with abundant freshwater plants such as *Thelypteris palustris* dominated the vegetation basin upstream.

The coarser LSU D1 deposits in profile S2 (sand 50%, silt 50%, clayb1%) associated with higher percentages of Chenopodiaceae denote an increase of marine influence throughout the basin, with higher hydrodynamism. The basin was flooded by the sea, allowing salt-marshes and salt-meadows to extend (RPAZ 4). This marine inundation occurred between 7820 ± 114 and 6693 ± 199 cal BP (6990 ± 50 and 5880 ± 80 ^{14}C BP).

4.4. The end of the Atlantic (LSU D2, E1 and RPAZ 5 basis: LPAZ 4a (S2))

At the end of the Atlantic period, a vast marshy area occupied the basin and favoured the deposition of peat (LSU D2-E2/Fig. 4) within the river and tidal paleaochannels. Such an event is often observed along the marine plains of the North Sea and the English Channel (Sommé et al., 1994; Berendsen and Stouthamer, 2000). The St-Momelin sequence provides a detailed record of vegetation dynamics that corresponds to the end of the mid-Holocene climate optimum (circa 6700 cal BP/5880 ^{14}C BP, at the base of LPAZ 4a). This moderate deterioration of the climate led to a decline of temperate trees (*Ulmus*, *Tilia*, deciduous *Quercus*) and to the first occurrences of *Fagus* pollen (in LPAZ 4a). As thermal requirements of *Fagus* are less constraining than those of other temperate trees, this cooler period did not prevent it from continuing its regional extension. The extension of *Fagus* to the detriment of other trees could also be attributed to the effect of light competition, since *Fagus* grows easily below a dense canopy.

At St-Momelin (Fig. 4), the decrease in marine influence is shown by a decline in the percentage of halophilous pollen- for example Chenopodiaceae values fall to less than 1% of the pollen sum- and high values of freshwater and hygrophilous plants. At Watten (Fig. 3), it seems that the marine influence persisted, as suggested by the high energy of the deposit (LSU E1: sand 60%, silt 40%, clay b 1%). Unfortunately, the absence of pollen in the sediment, probably for taphonomic reasons, cannot strengthen this interpretation.

4.5. The Subboreal (LSU E2, F1, RPAZ 5 top to RPAZ 7)

The Subboreal is characterized by the disappearance of the marine influence all over the St-Omer basin, as suggested by thick peaty deposits (LSU E2), abundance of freshwater fern spores in profiles S1 and S2 (Figs. 3 and 4), and the forest development on the alluvial plain which is dominated by *Alnus* (pollen percentages of *Alnus* exceed 50% of the pollen sum on average, reaching more than 70% in LPAZ5 in profile S2).

The climatic cooling that began at the end of the Atlantic is still recorded during the Subboreal, as suggested by the appearance of regular occurrences of *Abies*, and a decrease in *Tilia* (LPAZ4b, profile S2). This event, along with the decline of *Ulmus* recorded in LPAZ 4a and b (Fig. 4), occurs after 5597 ± 140 cal BP (4850 ± 70 ^{14}C BP). In Europe the elm decline is dated to the end of the Atlantic and to the Subboreal, and should probably be attributed to several factors such as disease, human impact (Peglar, 1993) and interspecific competition, especially with *Fagus* (Van der Woude and Roeleveld, 1985; Sommé et al., 1994).

The first indicators of human activity are also recorded during the Subboreal (decrease in arboreal pollen and high percentages of *Plantago* in LPAZ 5 of S2 profile, Fig. 4). In LPAZ 6 (S2), *Alnus* percentages collapse (70% in LPAZ 5 (S2) to 10% in LPAZ 6 (S2)). The strong increase of Chenopodiaceae suggests that the retraction of the *Alnus* forest was to the benefit of halophytic vegetation and should be attributed to a rise in brackish groundwater. This vegetation change could be related to a marine transgression episode dated to circa 2554 ± 198 cal BP/ 2510 ± 90 ^{14}C BP (top of LPAZ 6, profileS2), and correlates with the known marine transgression of Dunkerque. During this marine episode the coarse sediments of LSU F1 (85% of sand) suggest an important hydrodynamism.

Sustained percentages of *Plantago* in LPAZ 6 (S2) show that the decline in the forest cover (arboreal pollen below 40% of the total pollen sum) was likely to have been of human origin, and was probably associated with the expansion of grazed grasslands.

4.6. The Subatlantic (LSU F1, F2 and RPAZ 8)

The regional vegetation is clearly recorded in profile S2 only (Fig. 4), as profile S1 is dominated by freshwater ferns (such as *Thelypteris*) introducing distortion in the pollen assemblage (see the onset of the § 4). At St-Momelin, as well as in Subatlantic pollen sequences from northern France and Belgium (Munaut, 1967; Heyvaert, 1980), *Fagus* and *Carpinus* grew within groves of deciduous *Quercus* in areas not strongly disturbed by agro-pastoral activities.

The marine influence fluctuated throughout the Subatlantic. A continental period dated from 2554 ± 198 to 1915 ± 93 cal BP/2510 to 1975 ^{14C} BP (LSU F2) is recorded in profile S2. In LPAZ 7, the pollen data illustrate that this peaty sedimentation was contemporaneous with a freshwater marsh densely inhabited by hygrophytic and hydrophytic plants (e.g., *Sparganium*/*Typha*, *Rumex aquaticus* and *Nymphaea alba*). A marine episode is recorded in profile S1 (LSU F1) between 1845 ± 152 and 1565 ± 149 cal BP (1900 ± 70 and 1680 ± 60 ^{14}C BP) at Watten. This episode is contemporaneous with a strong increase in Chenopodiaceae percentages (LPAZ 5, profile S1) and a high hydrodynamism of palaeochannels (sand percentage close to 90%). At the top of profile S1 (LPAZ 6, Fig. 3), the decrease in marine influence is marked by a fall in Chenopodiaceae percentages associated with an increase in freshwater ferns (*Thelypteris palustris*). This probable sea retreat favoured the peat deposition observed in LSU F2 (profile S1).

5. Discussion

Lithology and pollen data show that the St-Omer basin was strongly subjected to marine influence at several periods of the Holocene. For each marine episode, the sediment is always characterized by a pollen content dominated by high percentages of halophilous taxa (especially Chenopodiaceae). Such change in the vegetation indicates that salt-meadows became established nearby (Morzadec-Kerfourn, 1974; Heyvaert, 1980), maybe induced by a transgressive marine pulse (Metcalfe et al., 2000; Shennan et al., 2000).

At St-Omer, Chenopodiaceae values are increasingly represented in the pollen spectra of the successive estuarine deposits. This could suggest that marine pulses were gradually more extensive. Sedimentological data are also in agreement with this progressive increase in marine influence, because of a change in the sedimentation from a dominant silty regime to a dominant sandy regime, as seen in consecutive palaeochannel complexes (C1, D1, E1 and F1) of P12, S1 and S2 profiles (Figs. 2–4). This has been confirmed by Gandouin (2003) and Gandouin et al. (2007b) in a sedimentological synthesis of 22 boreholes throughout the basin. Nevertheless, as mentioned above, Chenopodiaceae are also ruderal plants often associated to agricultural activities. Hence, this signal must be taken with care in the younger part of the sequence (Neolithic period) because Chenopodiaceae could be overestimated with the cumulative effect of both anthropogenic and marine factors. Moreover, coleopteran data from Ponel et al. (2007) do not contain any taxa associated with cultivated fields until 4708 ± 133 cal BP (4180 ± 45 ^{14}C BP); on the contrary several beetle species typical of pristine, undisturbed primeval forests were identified, for example *Mycetina cruciata*, *Dromaeolus barnabita* and *Dirrhagus lepidus*. The occurrence of *Mycetina cruciata* is especially significant since this saproxylophagous beetle is associated with old forests not affected by human action ("urwald" forests), where it is found in wet rotten wood attacked by fungi. Pollen data are in agreement with this interpretation because of the increase of classical anthopogenic indicator plants, such as cereals and *Plantago*, after *ca* 4000 ^{14}C BP only (Fig. 4: LPAZ5 in S2 profile). After this date, evidence for human impact can be seen in the sudden decrease in the Arboreal/Non Arboreal Pollen curve (AP/NAP ratio), characteristic of major forest clearance.

Sea retreat phases induced the contraction of the estuary and the infilling of the basin with freshwater from the water table, the river Aa and its tributaries; this enabled peat to be deposited in the palaeochannels (Berendsen and Stouthamer, 2000). Thus, fresh water conditions prevailed and favoured the predominance of alluvial forests and swamps (dominated by *Alnus*, *Thelypteris*, and Cyperaceae). The mixed-oak forest was restricted to drained slopes and hills bordering the Aa river catchment, as observed by Van der Woude and Roeleveld (1985) at Clairmarais and St-Momelin. The successive variations in the extent of marine conditions have also an indirect impact on estuarine and floodplain vegetation; this is due to the fact that marine pulses undoubtedly disturbed the vegetation dynamics throughout the Holocene by maintaining a semi-open landscape, with a recurrent grow of pioneering taxa such as *Betula* and *Corylus*.

At St-Omer, as observed by Van der Woude and Roeleveld (1985) and Sommé et al. (1994) it is assumed that the Holocene sea level rises led to the deposit of two main marine sedimentary layers attributed to the Calais and Dunkerque transgressions. These layers are intercalated within the late Atlantic/Subboreal peat. However this marine transgressive scheme has now been dropped by most of the research groups working on the North Sea coasts (e.g., Behre et al., 2004), because it perpetuates an unjustified assumption according which all the coastal areas along the southern North Sea responded in the same way and at the same time. Thus, the present study allowed the description of several subdivisions within the Calais–Dunkerque scheme and the development of an independent and locally-based scheme where: Calais marine sediments were deposited during the salt water input episodes of St-Omer I, II and III; and Dunkerque marine sediments were deposited during the salt water input of St-Omer IV and V.

At the beginning of the flandrian transgression, during St-Omer I, the marine influence was weak as suggested by both low hydrodynamism (presence of laminated clay-silty sediments) and low percentages of halophilous taxa (Fig. 4.), maybe localised downstream of the basin and washed-up from more littoral areas during storm events. The beginning of St-Omer I is dated to 9168 ± 143 cal BP at Watten (− 20 m N.G.F., "Nivellement Général de la France") and to 8569 ± 222 cal BP at St-Momelin (− 14 m N.G.F.). This is in agreement with Sommé et al. (1994) who date the beginning of the flandrian transgression on the maritime plain of Watten to the onset of the Boreal (− 21.5 m N.G.F.).

On the coast of Picardie between Berck and Merlimont (− 21 m N.G.F.), the onset of the flandrian transgression is dated to circa 7400 ^{14}C BP (Vinchon et al., 2000), around 8200 cal BP with the Intcal04 data set (Reimer et al., 2004). The difference in the timing of the transgression at Watten (P12 profile) and on the coast of Picardie could be explained by two hypotheses that are not mutually exclusive. First, an early incision of the Aa channel, during the Pleniglacial and at the late Glacial/Holocene transition, as in most European river systems (Huisink, 2000; Ménot et al., 2006), would have facilitated the marine inundation of the basin. A second hypothesis is a penetration of the sea from the North Sea, contrary to the classic transgression outline given by Jelgersma (1979) who assumed that the Calais transgression reached the present coast of Zeeland (− 17 m) through the Lobourg palaeovalley (− 50 m) at around 8300 ^{14}C BP (Jelgersma, 1979), 9300 cal BP with the Intcal04 data set (Reimer et al., 2004). This also could have been induced by strong subsidence in the St-Omer basin area (Mansy et al., 2003).

St-Omer II (Fig. 6) is dated to between 7820 ± 114 cal BP (6990 ± 50 ^{14}C BP) and 7496 ± 81 cal BP (6570 ± 80 ^{14}C BP). This is a transgressive phase which followed a short phase of stability (documented by a peaty layer dated to 7982 ± 188 cal BP (7150 ± 90 ^{14}C BP) – 7820 ± 114 cal BP (6990 ± 50 ^{14}C BP); see LSU C2 on S2 profile). The sea penetrated landward beyond the maximal extension previously reached during the St-Omer I episode, and subsequently induced an expansion of halophilous grasslands.

At Watten, St-Omer III is dated prior to 5831 ± 108 cal BP (5100 ± 50 ^{14}C BP, Fig. 3). The age of this low amplitude event is close to the estimate of 5100–4400 ^{14}C BP attributed by Behre (2004) to Calais III in Lower Saxony (northern Germany). In northern France this episode has never been identified as a transgression *sensu strictu* (Van Vliet-Lanoë et al., 2004) and it is probably generated by stormy events (Meurisse-Fort, 2008). This could explain the absence of halophilous vegetation in pollen assemblages from St-Momelin at that time.

At the Atlantic/Subboreal transition the Calais deposits are overlain by peats which can be correlated with organic layers observed in the coastal plains along the North Sea (Sommé, 1977; Van der Woude and Roeleveld, 1985; Waller, 1994). Peat was deposited landward of the coastal sand barriers, in swampy areas, during periods marked by a decrease or a pause in the rate of sea level rise (Berendsen and Stouthamer, 2000). Subsequently, the Subboreal peats were eroded at St-Momelin before 2554 ± 198 cal BP (2510 ± 90 ^{14}C BP) during the St-Omer IV transgressive episode. This episode could correspond with the regional Dunkerque I, poorly documented in the regional marine sequences (Sommé, 1977; Van Vliet-Lanoë et al., 2004). However, high values of Chenopodiaceae (Fig. 4.) confirm that the St-Omer basin was subjected to marine influence at that time.

At a regional scale, Dunkerque II is assumed to be the main marine inundation (Sommé et al., 1994). Surprisingly, it seems to be only recorded at Watten (Figs. 3 and 6), within the St-Omer basin, during the St-Omer V inundation. As for St-Omer III, this low amplitude event could therefore be explained by a marine inundation following a strong storm event, as suggested also by Meurisse et al. (2005) from the study of littoral sequences from Picardie.

6. Conclusion

(i) The Holocene vegetation of the St-Omer basin has mainly been shaped by an alternation of estuarine and fluvial processes, inducing successive phases of expansion or retraction of salt-meadows, fresh-water marshy vegetation and alluvial alder forest. However, regional vegetation dynamics are also recorded in the St-Omer pollen sequence. Comparison with other continental sequences from northern France, Belgium and south-eastern Britain shows that the climatic trends described during the Holocene, such as the early Holocene climate improvement or the late Atlantic cooling, have also been recorded elsewhere, and suggests that the St-Omer pollen sequence contains a reliable record of Holocene climate changes. This point will allow a further comparison with Chironomids (Gandouin et al., 2007a) and Coleopteran (Ponel et al., 2007) data that have clearly shown an important role of the climate on Holocene faunal assemblage succession from St-Omer. Hence, it will be possible to infer a regional climatic signal from biological assemblages in a region for which climatic data are rare, due to the lack of lacustrine records unaffected by flooding.

(ii) The cross-comparison of sediment, pollen and radiocarbon data analyses allowed us to evidence the five main marine inundations that affected the St-Omer basin. St-Omer I, which started earlier at Watten in the lower part of the basin, is dated to 9168 ± 143 cal BP (8220 ± 50 ^{14}C BP) and reached St-Momelin at 8569 ± 222 cal BP (7740 ± 110 ^{14}C BP). St-Omer II is dated to between 7820 ± 114 cal BP (6990 ± 50 ^{14}C BP) and 7496 ± 81 cal BP (6570 ± 60 ^{14}C BP) and penetrated landward into the basin. St-Omer III is only observed at Watten, prior to 5831 ± 108 cal BP (5100 ± 50 ^{14}C BP). This low amplitude marine inundation was probably generated by a storm event. St-Omer IV reached St-Momelin in the upper part of the basin and is dated to between 3502 ± 140 cal BP (3265 ± 70 ^{14}C BP) and 2554 ± 198 cal BP (2510 ± 90 ^{14}C BP). On the contrary, St-Omer V (dated to between 1845 ± 152 cal BP (1900 ± 70 ^{14}C BP) and 1565 ± 149 cal BP (1680 ± 60 ^{14}C BP)) is recorded only at Watten and may result from a storm event.

(iii) Pollen data confirm that human populations were installed close to the St-Omer basin during the Subboreal, their activity induced a strong opening of the landscape and massive deforestation. The impact of human activities on the environment began from about 4500 cal BP and increase until *ca* 2500 cal BP. After this date, pollen data have shown a return of woodlands, probably in response to a decrease in human pressure in the area and/or to a change in land use.

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