GEOLOGICA BELGICA (2011) 14/3-4: 277-288.

MIDDLE AND LATE HOLOCENE VEGETATION AND LANDSCAPE EVOLUTION OF THE SCHELDT ESTUARY. A PALYNOLOGICAL STUDY OF A PEAT DEPOSIT FROM DOEL (N-BELGIUM).

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(3 figures, 2 tables)

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ABSTRACT. Local and regional environmental conditions for the south-eastern Scheldt estuary during the middle and late Holocene period have been reconstructed based on pollen analysis, loss-on-ignition and radiocarbon dating of a sediment core from Doel (N-Belgium) and the comparison with existing data from other sites from the same region. Postglacial relative sea level rise resulted in the formation of alder carr vegetation in the lower parts of the landscape from *c.* 7640 cal BP onwards. The vegetation succession was weakly influenced by the deposition of tidal clay deposits between *c.* 6550 and 5650 a cal BP and eventually culminated in the development of an oligotrophic bog. Peat accumulation seems to have ceased between *c.* 2030 and 1220 a cal BP, well before it was covered by marine sediments in the late Middle Ages.

KEYWORDS: Palynology, Holocene, Scheldt, Belgium

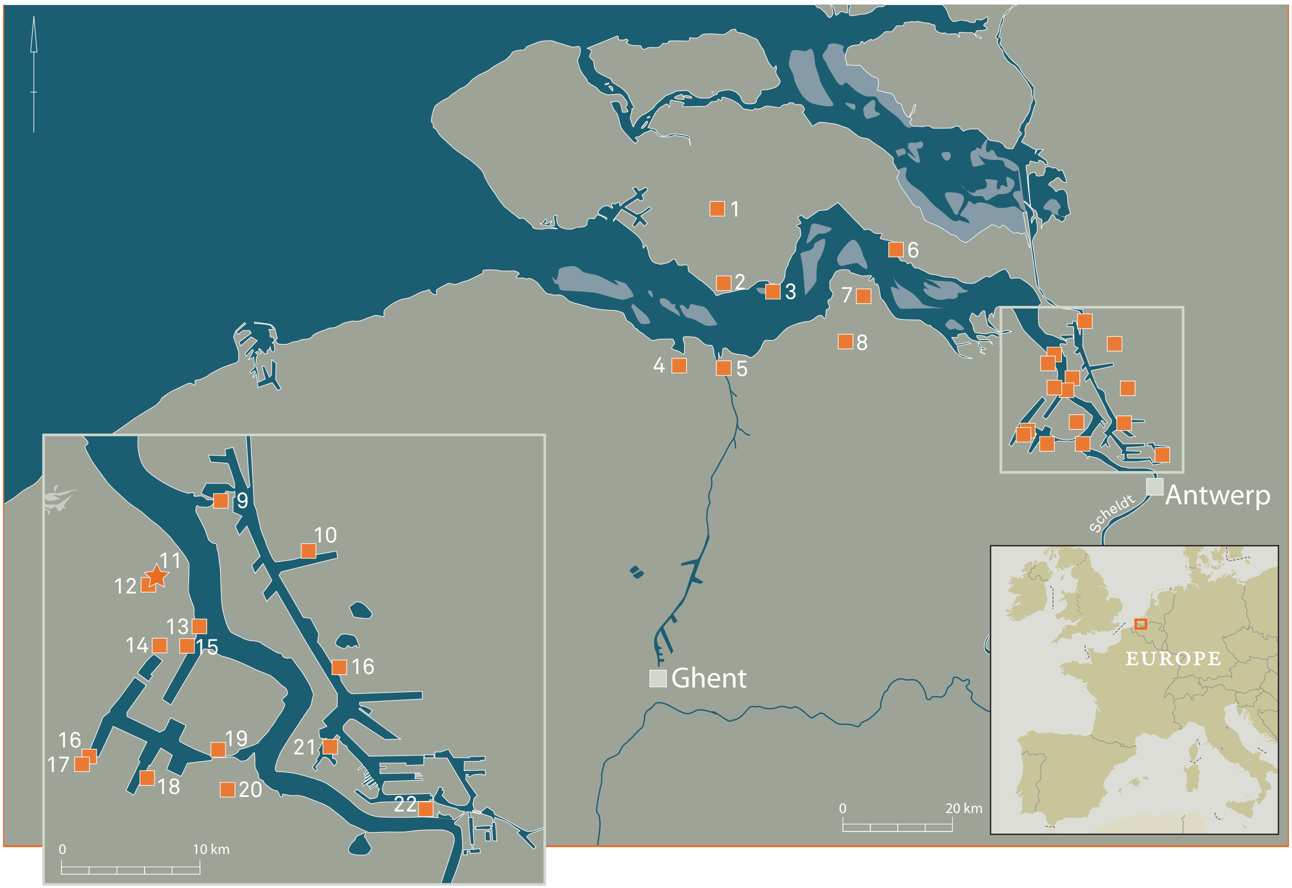

Figure 1. Location of the sampling site (11) and other sites mentioned in the text. (1) Borsele (Van Rijn, 2001); (2) Ellewoutsdijk (Van Rijn, 2003; Van Smeerdijk, 2003); (3) Baarland (De Jong, 1986); (4) Braakman (Munaut, 1969); (5) Terneuzen (Munaut, 1967); (6) Waarde (Jelgersma, 1961); (7) Perkpolder (Vos & Van Heeringen, 1997); (8) Oude Stoof (Vos & Van Heeringen, 1997); (9) Zandvliet (Munaut, 1967); (10) Berendrecht (Mys et al., 1983); (11) Doel – NPP (this publication); (12) Doel 9 & 10 (Denys & Verbruggen 1989); (13) Doel – Deurganckdok A (Gelorini et al., 2006); (14) Doeldok (Minnaert & Verbruggen, 1986); (15) Doel – Deurganckdok B (Deforce et al., 2005); (16) Verrebroek – dok1 (Deforce et al., 2005); (17) Verrebroek – dok 2 (Deforce et al., 2005); (18) Kallo – Vrasenedok (Janssens & Fergusson, 1985); (19) Kallo – zeesluis (Kuijper, 2006); (20) Hof ten Damme (Verbruggen & Denys, 1991); (21) Kruisschans (Vanhoorne, 1951); (22) Oosterweel (Denys & Verbruggen, 1989).

1. Introduction

The Scheldt estuary is one of the most studied areas in Belgium concerning Holocene palaeobotany (Fig. 1). This is due to the combination of (1) the presence of peat in the subsoil and (2) the numerous infrastructural works related the harbour of Antwerp, which create opportunities to sample and study large sections of these peat deposits. This region has been shown to have had a very dynamic geomorphological evolution caused by Lateglacial wind erosion and deposition, Holocene relative sea level (RSL) rise, medieval land reclamation and post medieval strategic inundations.

A large number of archaeological sites, ranging from the late Palaeolithic to the post medieval period, have been excavated in this region, due to the harbour-related infrastructural works. Several of these sites date to the middle Holocene period and some of these are key sites for the understanding of the Meso-Neolithic transition in northern Belgium (Crombé, 2005; Crombé et al., 2000; 2002; 2004). Then palaeoecological studies are important for the interpretation of the archaeological data, but most of them lack a good chronological framework.

An overview of the Holocene evolution of the northern and western parts of the Scheldt estuary, which are situated in the Netherlands, is given by Vos & Van Heeringen (1997) but for the south-eastern part of the estuary, which is situated in Belgium, no such overview exists. This paper presents new palynological and radiocarbon results from the peat deposits near Doel and gives a summary of the middle and late Holocene vegetation and landscape evolution based on both these new and the existing palaeoecological data for this area.

2. Material and methods

A 520 cm long sediment core (Doel-NPP) was taken close to the nucleair power plant of Doel, northern Belgium (51°19'15.60''N, 4°14'43.29''E). The lowermost 270 cm of this core has been sampled for radiocarbon dating, loss-on-ignition (LOI) and pollen analyses. 8 bulk samples have been ^{14}C-AMS dated. The calibration of these dates and of all other dates mentioned in the text was undertaken using OxCal v. 4.1 (Bronk Ramsey, 2009) using atmospheric data from Reimer et al. (2009). The age-depth model is based on linear interpolation of the median values of the calibrated ^{14}C dates.

Samples for LOI and pollen analyses were taken every 10 cm and are referred to by their depth below the modern surface. For the LOI-analysis, 2 cm³ samples were dried at 105°C until their weight was constant and were subsequently heated at 550°C (4hrs) and 950°C (4hrs) to estimate organic matter and carbonate content (Bengtsson & Enell, 1986; Heiri et al., 2001).

Preparation of the samples (1 cm^3) for pollen analysis followed standard procedures (Moore et al., 1991). The identification of the pollen grains is based on Moore et al. (1991), Beug (2004), Punt et al. (1976-1991) and a reference collection of modern pollen and spores. Only pollen grains with very clear characteristics of *Myrica gale* (Punt et al., 2002) have been identified as *Myrica gale* and all others are included in *Corylus avellana* type (Edwards, 1981). The Poaceae grains have been separated into a Poaceae undifferentiated category (wild taxa), Cerealia type (grain size > 37 µm, annulus diameter > 8 µm) and *Secale cereale* which is the only cultivated cereal species which has been separately identified. *Ranunculus acris* type, *Rumex acetosa* type, and *Rumex aquaticus* type are defined according to Beug (2004). Nomenclature of all other identified pollen types follows Moore et al. (1991). The identification of non pollen palynomorphs is based on van Geel (1978) and van Geel et al. (1981; 1986).

The results of the pollen analyses are presented in a percentage pollen diagram. Percentages of trees and shrubs and those of upland herbs are based on the sum of all terrestrial plants (ΣP); other groups like aquatics, spore plants and non pollen palynomorphs (NPP's) are excluded from this sum. Percentages of these other groups are based on ΣP + group sums. The diagram was drawn using TILIA and TGView software (Grimm, 1992). Stratigraphically constrained cluster analysis was used to establish three local pollen assemblage zones (LPAZ) (Grimm, 1987).

3. Results

3.1. Stratigraphy and loss-on-ignition

The studied sequence and overlying deposits (Fig. 3) consist of the following sedimentary units (depths in cm below the modern surface):
80 cm - surface: sandy clay
250 cm - 80 cm: clayey sand
312 cm - 250 cm: moss peat
385 cm - 312 cm: wood peat
400 cm - 385 cm: sedge peat
467 cm - 400 cm: peaty clay
515 cm - 467 cm wood peat
Below 515 cm: sand

The results of the LOI analysis are presented in Fig. 3. They show that the organic content gradually rises towards the top of the lowermost peat layer (515 - 467 cm). The deposition of the peaty clay (467 cm - 400 cm) corresponds with a decrease of organic matter, reaching a minimum at 430 cm. Between 400 cm and 267 cm organic matter remains constantly high (94.0 % - 98.7 %). There is a slight decrease of organic matter of ±8 % between 267 cm and 256 cm, followed by a very sharp decrease at 250 cm.

The LOI analysis also shows a very low carbonate content for the whole core, though slightly higher percentages have been measured between 515 cm and 425 cm and above 250 cm.

3.2. Radiocarbon dates and chronology

Radiocarbon dates are shown in Table 1 with 2σ calibrated age ranges. An age-depth model is given in Fig. 2. The

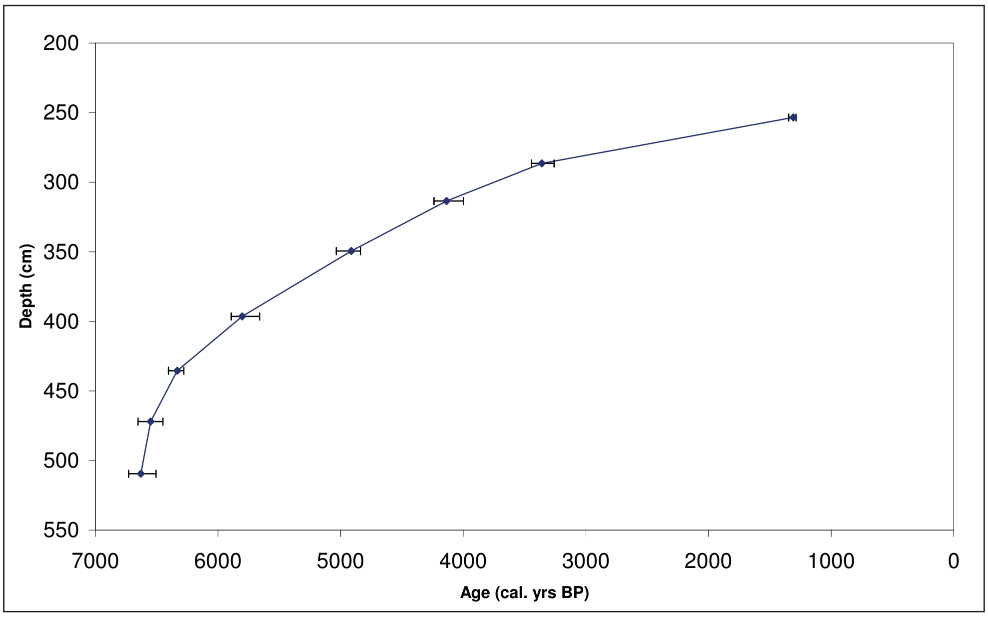

Figure 2. Age-depth model based on linear interpolation of the median values of calibrated ^{14}C ages with 2σ intervals.

Lab code	Depth (cm)	^{14}C-age (yr BP)	Calibrated age range (cal BP) (2σ)	Calibrated age range (cal BC/AD) (2σ)
KIA-33610	253-254	1400 ± 25	1346 - 1286	604 - 665 AD
Beta-261803	286-287	3130 ± 40	3445 - 3260	1496 - 1311 BC
KIA-36911	313-314	3770 ± 30	4239 - 3999	2290 - 2050 BC
Beta-261804	349-350	4340 ± 40	5036 - 4839	3087 - 2890 BC
KIA-36912	396-397	5025 ± 30	5893 - 5661	3944 - 3712 BC
Beta-261805	435-436	5530 ± 40	6405 - 6279	4456 - 4330 BC
Beta-261806	471-473	5750 ± 40	6652 - 6449	4703 - 4500 BC
KIA-36924	509-510	5820 ± 35	6730 - 6505	4781 - 4556 BC

Table 1. Radiocarbon dates from Doel-NPP.

base of the peat deposit has been dated at *c*. 6620 a cal BP and the top of the peat deposit gives *c*. 1310 a cal BP, which demonstrates that the studied sedimentary sequence has accumulated over *c*. 5310 years. The age-depth diagram shows that initial sediment accumulation rates were high (ca. 120 cm/1000 yrs) and that peat accumulation rate strongly decreases towards the top of the studied sequence (ca. 20 cm/1000 yrs).

3.3. Pollen analysis

The percentage pollen diagram is shown in Fig. 3. The first zone is characterised by high percentages of *Alnus*. The second zone shows a decrease of *Alnus* and increases in *Betula*, *Taxus baccata*, Cyperaceae, *Menyanthes trifoliata*, *Utricularia* and Filicales. The uppermost zone of the diagram is characterised by lower AP percentages and high percentages of *Myrica gale*, *Calluna vulgaris* and *Sphagnum*.

4. Local vegetation development

LPAZ-D1 (510 cm - 385 cm):

During this zone, the local vegetation consisted of alder carr at the site investigated, as shown by high pollen values for *Alnus*, shrubs like *Salix, Rhamnus cathartica* and *Humulus* and tall wetland herbs such as *Filipendula*, *Valeriana*, *Lythrum salicaria* type and *Osmunda regalis*. *Solanum dulcamara,* which typically grows in alder carr, was probably also part of the local vegetation, given the high percentages of *Diporotheca rhizophila*, a parasitic fungus on roots of Solanaceae (van Geel et al., 2003), although no pollen of *Solanum dulcamara* was recorded. *S. dulcamara*, which is an entomophilous plant, has only poor pollen production and dispersal capacities however. Moreover, its pollen is very small and thin walled and might have disappeared as a consequence of the poor preservation conditions in this part of the studied core.

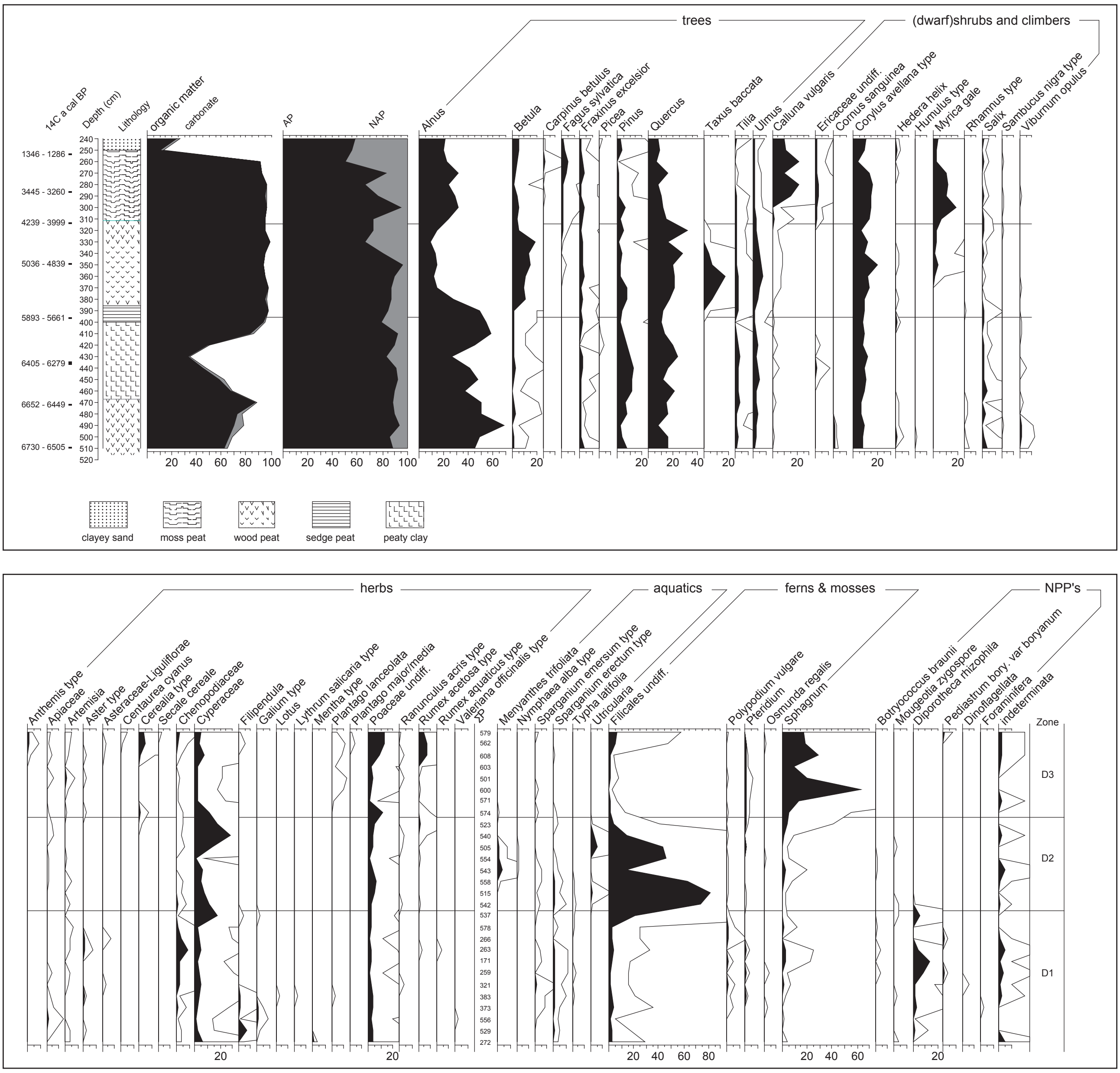

Figure 3. Loss-on-ignition results and percentage pollen diagram of selected taxa (exaggeration x10) from Doel-Nuclear Power Plant (Doel-NPP).

From 467 cm onwards, the alder carr peat is overlain by peaty clay. The increase of Chenopodiaceae and the occurrence of Dinoflagellata indicate a marine influence while the presence of the pelagic colonial green algae *Pediastrum* and *Botryococcus* point to flooding of the site with fresh water. The combination of the two suggests that brackish water flooded the site. The slightly higher percentages of *Pinus* and the occurrence of *Picea* in this part of zone D1 are most probably the result of the marine influence rather than a reflection of changes in the regional vegetation as these conifers are known to be overrepresented in marine deposits due to their high pollen production and floating capacity (Heusser & Balsam, 1977; Turon, 1984).

Alnus shows a first minimum at ca. 460 cm, corresponding with the start of clay deposition, and a more pronounced second one at 430 cm, corresponding with the maximum of Chenopodiaceae. This might be the consequence of repeated flooding of the site as *Alnus* cannot withstand strong water flows (Weeda et al., 1985). At the end of LPAZ-D1, there is an increase of *Typha latifolia*, Cyperaceae and Filicales, which might indicate a shift from eutrophic to slightly more mesotrophic environmental conditions.

The results of the LOI-analysis show that the organic content gradually rises from the base of the peat deposit towards 467 cm, the top of the lowermost peat layer. This must be the consequence of decreasing mineral input from erosion of the sand ridges (see further) as they get covered by the accumulating peat deposits. The deposition of peaty clay, from 467 cm onwards, corresponds with a decrease of organic matter, reaching a minimum at 430 cm. This minimum in the LOI curve corresponds with the maximum in the Chenopodiaceae percentages which suggests a marine origin for the clay.

LPAZ-D2 (385 cm - 313 cm):

The start of this zone is characterised by the replacement of *Alnus* by *Betula* and *Taxus baccata*. *T. baccata* growing on peat might seem questionable given the current natural distribution and ecology of this taxon, but several palaeoecological studies have shown that *T. baccata* was a natural element in carr vegetation in the coastal lowlands of NW Europe during the Sub-Boreal period (e.g. Godwin et al., 1935; Deforce & Bastiaens, 2007).

The occurrence of *Nymphaea alba* type and *Utricularia* in this zone not only indicates slightly higher water but also a further shift towards mesotrophic environmental conditions. Also the start of the *Myrica gale* curve in this part of the pollen diagram and the occurrence of *Menyanthes trifoliata* are indicative of more acidic environmental conditions.

The end of this zone is characterized by a strong decrease of *Betula* and the disappearance of *Taxus baccata* from the pollen diagram. *Fagus sylvatica* occurs sporadically in the diagram from *c*. 4920 a cal BP onwards, which is earlier than *c*. 4480 a cal BP, the date given by Verbruggen et al. (1996) for the first occurrence of *Fagus* in pollen diagrams from Belgium. The end of this zone has been radiocarbon dated to *c*. 4140 a cal BP.

LPAZ-D3 (313 cm - 240 cm):

The lower boundary of this zone corresponds with the start of the in-situ formation of an oligotrophic peat bog, as indicated by increases in *Myrica gale*, *Calluna vulgaris* and *Sphagnum*. *Myrica gale* and *Sphagnum* are likely to have dominated the wet places, *Callluna vulgaris* the drier environments on the bog. The percentages for *Myrica gale* are probably an underestimation as only pollen grains with very clear characteristics have been attributed to this pollen type. Some *Myrica gale* pollen grains might thus be included in *Corylus avellana* type (Edwards, 1981), which is also indicated by the parallel curves of both taxa in LPAZ2 and LPAZ3.

Cerealia type occurs in the diagram from the start of LPAZ3 onwards, which has been dated at *c*. 4140 cal BP. Other possible indicators of human activity like *Rumex acetosa* type and Poaceae already occur in the previous pollen zone but strongly increase in this part of the diagram.

According to the age-depth diagram, the peat accumulation rate for this zone is very low (Fig. 2). The decrease in sediment accumulation rate towards the top can partly be attributed to differential compaction of the peat following the deposition overlying sediments. The upper part of the peat deposit, consisting of moss-peat might be more prone to compaction than the lower wood peat deposits. Also the higher organic content compared to the lower zones, as indicated by the results of the LOI-analysis, could have facilitated compaction. The decrease of the peat accumulation rate towards the top of the deposit is so strong however that it is unlikely that this can be explained by differential compaction alone and probably reflects a real decrease in the peat accumulation rate.

The uppermost part of the pollen diagram corresponds with the deposition of marine sediments on top of the peat deposit. There is no sedimentological or palynological evidence for gradual inundation of the bog vegetation, as in this case, the vegetation succession should include the demise of fresh water communities and the development of transitional reedswamp, followed by saltmarsh communities and subsequent accumulation of intertidal mudflat deposits (Waller et al., 2006). Also the sharp decrease of the LOI-curve also suggests a sudden change of the sedimentary environment. The continuous occurrence of most pollen types in the overlying clayey sand, especially those associated with peat bogs like *Calluna vulgaris* and *Sphagnum*, can be explained by a redeposition of palynomorphs from eroded peat. *Secale cereale* and *Centaurea cyanus* only occur in these uppermost levels and are indicative for a medieval or younger age for these sediments (Verbruggen et al., 1996).

5. Regional vegetation development and landscape evolution

5.1. Start of the peat growth and lower peat deposit

The top of the Pleistocene substrate in the study area consists of periglacial aeolian cover sand ridges with a SW-NE orientation (Vos & Van Heeringen, 1997). Peat accumulation on top of this Pleistocene topography started in the late Atlantic period caused by the postglacial RSL rise, as was the case in most of the coastal areas along the southern North Sea, stretching from northern France to Denmark (Pons, 1992; Behre, 2004). At the investigated site the base of the peat has been dated at *c*. 6620 a cal BP. Earlier dates for the start of peat accumulation from the study area come from Kallo – Vrasene dok: *c*. 7640 a cal BP (Janssens & Ferguson, 1985), Berendrecht: *c*. 7130 cal BP (Mys et al., 1983), Kallo – zeesluis: *c*. 6870 a cal BP (Kuijper, 2006) and Doel-Deurganckdok sector A: *c*. 6710 cal BP (Deforce et al., 2005). According to the map of the Pleistocene substratum for the Scheldt estuary by Kiden (1995), these sites occupied a lower topographical position during the early Holocene as they are situated in the Pleistocene palaeo-valley of the Scheldt, which followed a northwards course in contrast to the modern direction of the river. This explains why these sites were affected earlier by the postglacial sea level rise and peat formation. Sites that are situated more to the west or to the north, like Oude Stoof, Verrebroek and Terneuzen produce dates that are similar or younger compared to Doel-NPP for the start of peat formation (Table 2). Further northwest of Doel the surface of the Pleistocene substratum lowers towards the amphitheatre-like palaeo-valley of Zeeland and here sites like Perkpolder produce older dates for the start of peat accumulation (Vos & van Heeringen, 1997). At all sites in the south-eastern Scheldt estuary (Fig. 1, site 9-22), peat formation started with the development of alder carr vegetation though at sites more to the north and northwest, peat formation is initiated by a *Phragmites* dominated vegetation (Vos & Van Heeringen, 1997).

Site	^{14}C a BP (age ±1σ error)	cal yr BP (2σ range) max (mean) min	Lab. nr.	stratigraphic position	reference
Berendrecht	770 ± 65	562 (715) 901	Lv-898	thin peaty layer in overlaying clay deposit	Mys et al. 1983
Oosterweel	1300 ± 55	1305 (1219) 1080	IRPA-714b	base of the uppermost peat layer	Denys & Verbruggen 1989
Doel - Deurganckdok sector A	1340 ±25	1305 (1272) 1184	KIA-17637	base of the uppermost peat layer	Gelorini *et al*. 2006
Doel-NPP	1400 ± 25	1346 (1312) 1286	KIA-33610	base of the uppermost peat layer	this publication
Waarde	1415 ± 120	1564 (1331) 1062	GRO-346	base of the uppermost peat layer	Jelgersma 1961
Oosterweel	1630 ±55	1692 (1521) 1399	IRPA-652	base of the uppermost peat layer	Denys & Verbruggen 1989
Oosterweel	1840 ± 55	1895 (1772) 1619	IRPA-714a	base of the uppermost peat layer	Denys & Verbruggen 1989
Kallo - Hof ten Damme	1915 ± 40	1948 (1858) 1735	IRPA-950	base of the uppermost peat layer	Verbruggen & Denys 1991
Doel	2050 ± 70	2300 (2028) 1835	IRPA-455	base of the uppermost peat layer	Minnaert & Verbruggen 1986
Ellewoutsdijk	2059 ± 43	2140 (2030) 1925	UtC-12056	base of the uppermost peat layer	Van Smeerdijk 2003
Berendrecht	2200 ± 70	2345 (2204) 2009	Lv-899	base of the uppermost peat layer	Mys et al. 1983
Terneuzen-I	2270 ± 100	2697 (2286) 2000	Lv-117	base of the uppermost peat layer	Munaut 1967a, Gilot 1997
Braakman	2480 ± 85	2740 (2552) 2355	Lv-458	base of the uppermost peat layer	Munaut 1969
Kallo - Vrasene Dok	2810 ± 60	3078 (2927) 2772	IRPA-544	base of the uppermost peat layer	Janssens & Ferguson 1985
Kallo - Hof ten Damme	4300 ± 60	5046 (4885) 4647	IRPA-947	base of the uppermost peat layer	Verbruggen & Denys 1991
Baarland	4440 ± 40	5283 (5082) 4875	GRN-14269	base of the uppermost peat layer	De Jong 1986
Ellemoutsdijk	4460 ± 50	5296 (5114) 4885	UtC-12055	base of the uppermost peat layer	Van Smeerdijk 2003
Terneuzen-III	4560 ± 110	5577 (5218) 4878	Lv-124	base of peat layer	Munaut 1967a, Gilot 1997
Verrebroek – Dok 1	4690 ±30	5577 (5414) 5320	KIA-17992	base of peat layer	Deforce *et al*. 2005
Doel - Deurganckdok - sector A	4955 ± 30	5740 (5680) 5607	KIA-17638	base of uppermost peat layer	Gelorini *et al.* 2006
Doel - Doeldok	4900 ± 60	5856 (5646) 5480	IRPA-454	intercalated clay	Minnaert & Verbruggen 1986
Kallo-Hof ten Damme	5000 ± 40	5893 (5749) 5644	IRPA-946	top of peaty clay	Verbruggen & Denys 1991
Doel - NPP	5025 ± 30	5893 (5790) 5661	KIA-36912	top of intercalated clay	this publication
Kallo-Hof ten Damme	5300 ± 70	6271 (6087) 5928	IRPA-942	base of peaty clay	Verbruggen & Denys 1991
Doel - NPP	5530 ± 40	6405 (6336) 6279	Beta-261805	intercalated clay	this publication
Doel-Deurganckdok - sector A	5740 ± 35	6637 (6541) 6448	KIA-17638	base of intercalated clay	Gelorini et al 2006
Kallo - zeesluis	5750 ± 40	6652 (6552) 6449	GRN-7898	base of gully*	Kuijper 2006
Doel - NPP	5750 ± 40	6652 (6552) 6449	Beta-261806	top of basal peat layer	this publication
Doel -Doeldok	5495 ± 80	6468 (6288) 6021	IPPA-458	base of basal peat layer	Minnaert & Verbruggen 1986
Oude Stoof	5770 ± 100	6793 (6574) 6320	GrN-1042	base of basal peat layer	Vos & Van Heeringen 1997
Doel-NPP	5820 ± 35	6730 (6623) 6505	KIA-36924	base of basal peat layer	this publication
Doel - Deurganckdok sector A	5885 ± 35	6786 6707) 6639	KIA-17640	base of basal peat layer	Gelorini *et al.* 2006
Kallo - Zeesluis	6020 ± 70	7154 (6874) 6673	GRN-7938	base of basal peat layer	Kuijper 2006
Berendrecht	6230 ± 95	7414 (7126) 6891	Lv-900	base of basal peat layer	Mys et al. 1983, Gilot 1997
Perkpolder	6240 ± 70	7306 (7142) 6960	GrN-1045	base of basal peat layer	Vos & Van Heeringen 1997
Kallo - Vrasenedok	6790 ± 80	7820 (7645) 7501	IRPA-546	base of basal peat layer	Janssens & Ferguson 1985

*This gully can stratigaphically be correlated with the intercalated clay deposit.

Table 2. Radiocarbon dates for stratigraphic boundaries from Holocene peat deposits from the southern Scheldt estuary.

The pollen diagram provides little evidence for the vegetation on the higher parts of the coversand ridges, which were not yet affected by the rise of the water table and subsequent peat accumulation. *Quercus*, *Corylus*, *Tilia*, *Ulmus* and *Cornus sanginea* in LPAZ-D1 of Doel-NPP probably reflect the vegetation on these higher places in the landscape. Pollen analysis by Janssens & Fergusson (1985) of a contemporaneous podzol soil profile at Kallo that was situated on the higher part of a coversand ridge and that was only covered by peat at a later date, show high percentages of *Quercus*, *Tilia* and *Corylus* indicating that these taxa were important elements of the vegetation on the drier parts of the landscape.

5.2. (Peri-) marine clay deposits

At Doel-NPP and several other sites in the south-eastern Scheldt estuary, peat formation is interrupted between *c.* 6550 a cal BP and *c.* 5650 a cal BP by the deposition of (peaty) clay (Table 2). At most of these sites, this clay or peaty clay contains indications of a marine influence. At Doel-NPP, Doel-Doeldok (Minnaert & Verbruggen, 1986), Doel-Deurganckdok zone A (Gelorini et al., 2006), and Kallo-Hof ten Damme (Verbruggen & Denys, 1995) this marine influence is demonstrated by an increase in Chenopodiaceae pollen. At Kallo – Hof ten Damme the peaty clay also yielded high percentages of several meso- and polyhaobous diatom taxa indicating brackish water (Verbruggen & Denys, 1995).

At Kallo–Zeesluis, Kuijper (2006) studied molluscs from the sediments from a gully, dated shortly after *c.* 6550 a cal BP, and which can also stratigraphically be correlated with the intercalated clay deposit. All identified mollusc taxa indicate freshwater conditions with one species (*Mercuria confusa*) which is confined to the freshwater tidal environments and which tolerates only very low salinities.

At Zandvliet, Oorderen and Kallo-Vrasene dok no intercalated clay deposit has been reported (Munaut, 1967; Janssens & Ferguson, 1985). At Zandvliet and Kallo-Vrasene dok however, the pollen diagram does show a decrease of *Alnus* and an increase of *Salix*, up to 28% at Kallo, during the corresponding period, which may be the consequence of repeated flooding of the site (Weeda et al., 1985). This decrease of *Alnus* and increase of *Salix*, though less pronounced is also observed at the base of the peaty clay at Doel-NPP.

Archaeobotanical analysis of charcoal and charred seeds from late Mesolithic/early Neolithic sites on top of the Pleistocene coversand ridges at Doel-Deurganckdok, that are dated between *c.* 6490 and *c.* 6060 a cal BP, indicate that the top of these ridges were covered with vegetation dominated by *Quercus*, *Fraxinus excelsior*, *Ulmus* and *Tilia* and shrubs like *Cornus sanguinea* and *Viburnum opulus* (Bastiaens et al. 2005; 2007; Crombé et al. 2009; Boudin et al., 2010). Most burnt fishbone remains from the same sites come from taxa that indicate an estuarine environment for the creeks with a lot of stagnant fresh water, although some taxa are more salt tolerant and probably migrated upstream from (peri-)marine environments (Van Neer et al., 2005).

Similarly the deposits of Doel-Deurganckdok, the fill of the gully at Kallo-Zeesluis, that could be correlated with the intercalated peat deposit and was dated to shortly after *c.* 6550 a cal BP, yielded large amounts of botanical macroremains of *Corylus avellana*, *Cornus sanguinea*, *Prunus spinosa*, *Quercus, Rhamnus frangula and Tilia platyphyllos*, most probably representing the woody vegetation on the higher ridges (Kuijper, 2006).

This clay deposit is referred to as 'Calais' deposit in most publications (e.g. Vos & Van Heeringen, 1997; Gelorini et al., 2006) but the use of this terminology is highly debated (e.g. Weeler & Waller, 1995; Baeteman, 2008 and many others).

5.3. The upper peat deposit

At all sites in the south-eastern Scheldt estuary where the intercalated (peaty) clay deposit occurs, peat accumulation restarted between *c.* 5680 a cal BP and *c.* 4880 a cal BP (see table 2). As for Doel-NPP, peat formation is accompanied by increases in Cyperaceae, *Betula*, Filicales and *Thelyptris palustris* (or *Dryopteris* type) in the corresponding pollen diagrams (e.g. Minnaert & Verbruggen, 1986, Gelorini et al., 2006), changes which are interpreted as indicating higher water levels and a shift from eutrophic to more mesotrophic environmental conditions. A similar shift is recorded at nearby sites were the intercalated clay deposit is missing, e.g. Kallo-Vrasene Dok (Janssens & Ferguson, 1985) and Zandvliet (Munaut, 1967), and were alder carr vegetation is also directly succeeded by a sedge fen and a poor fen stage with *Betula* and *Myrica gale*. This can be seen as a 'normal' autogenic successional pathway of mire vegetations in the coastal lowlands along the southern North Sea (Walker, 1970; Waller et al., 1999). This successional pathway indicates that the deposition of clay had little influence on the vegetation succession near Doel. But it also indicates that the intercalated clay deposit was formed in a freshwater or only slightly brackish environment, as the normal vegetation development on marine/brackish clay would be *Phragmites* swamp, possibly preceded by a salt marsh in case of high salinity levels (Waller et al., 2006). Sites that are situated further the northwest of Doel-NPP, like Baarland (De Jong, 1986) and Ellewoutsdijk (Van Smeerdijk, 2003) do show a *Phragmites*-phase on top of the clay deposit indicating a stronger marine influence.

Taxus baccata appears in the pollen diagram from Doel-NPP from *c.* 5790 a cal BP onwards, which is well before *c.* 5450 a cal BP the previously oldest date for the occurrence of *Taxus* in the region, which was recorded at Oorderen (Munaut, 1967). At Doel-NPP, *Taxus* disappears from the pollen diagram at *c.* 4140 a cal BP, with the transition to an oligotrophic bog, an observation which has been made for most other sites in the Scheldt estuary and the coastal plain (Deforce & Bastiaens, 2007). Between those dates, *Taxus* must have been part of the fen carr vegetation, as is indicated by its seeds and wood that have been found in peat deposits at Kruisschans (Vanhoorne, 1951), Ellewoutsdijk (Van Rijn, 2003) and Borsele (Van Rijn, 2001).

At all sites in the south-eastern Scheldt estuary the final stage of peat development is the formation of an oligotrophic bog vegetation with *Sphagnum*, *Calluna vulgaris* and *Myrica gale* as most important components of the vegetation. At some sites like Doel-Deurganckdok (Gelorini et al., 2006), Baarland (De Jong, 1986) and Kallo-Vrasene dok (Janssens & Ferguson, 1985) there is a strong increase in *Pinus* pollen at the onset of bog formation. At Baarland (De Jong, 1986), Kruiningen (Van Beurden, 2005) and Kallo-Vrasene dok (Janssens & Ferguson, 1985), *Pinus* wood and cones have also been found, demonstrating that *Pinus* was part of the local vegetation. In the upper part of the peat bog deposit *Pinus* percentages drop, indicating that this tree disappeared from the bog vegetation. *Calluna vulgaris* was an important element in the local vegetation at most sites during this (last) stage of peat deposition.

The southern Scheldt estuary, together with much of the Belgian coastal plain, must have formed a vast area of oligotrophic peat bogs by this time, though much of it has disappeared due to medieval peat extraction (Deforce et al., 2007; Augustyn, 1999). According to Waller et al. (1999), this general trend towards acidification in the coastal lowlands of the southern North Sea that occurs from the mid Holocene onwards, can be attributed to the combined effects of a decline in the rate of RSL rise and a shift to a wetter, more oceanic climate.

5.4. The end of the peat growth

Radiocarbon dates from the top of the uppermost peat deposit in the south-eastern Scheldt estuary range between *c*. 2930 a cal BP at Kallo-Vrasene Dok (Janssens & Ferguson, 1985) and *c*. 1220 a cal BP at Oosterweel (Denys & Verbruggen, 1989) (Table 2). The top of the peat deposit may have been eroded by marine transgression, oxidized by drainage of the peat or at some sites truncated by peat cutting. Peat accumulation in the region probably ceased between *c*. 2030 and 1220 a cal BP (or between *c*. 80 BC and *c*. 730 AD) as sites where the topmost part of the peat is clearly intact all produce dates within this range (Denys & Verbruggen, 1989; Gelorini et al, 2006). Most of the overlying clay deposit is however younger than 1300 AD (Denys & Verbruggen, 1989) and in some parts of the region peatlands remained uncovered until they were flooded during storm surges and strategic inundations of the 16th and 17th century (Augustyn, 1999; De Kraker, 2006). This means that during several hundreds of years, there was a sedimentary stand still. This time-gap, between the end of the peat growth and the start of the deposition of marine sediments has been observed before for the Scheldt estuary (Denys & Verbruggen, 1989) and also in other regions bordering the southern North Sea (Waller et al., 2006, Baeteman et al., 2002). The age-depth model for Doel-NPP shows that the accumulation rate decreased dramatically towards the top of the peat deposit. This indicates that peat formation might not have been stopped by the deposition of (peri)marine sediments as has been supposed up to now (Denys & Verbruggen, 1989) but probably had ceased well before that event, which might explain the observed ‘time gap’.

6. Conclusions

Based on pollen analysis, loss-on-ignition and radiocarbon dating of a sediment core from Doel, and comparison with other sites from the Scheldt estuary, a detailed reconstruction of local and regional environmental conditions for the southern Scheldt estuary during the middle and late Holocene has been made. The results show the development of alder carr vegetation between *c*. 7640 a cal BP and *c*. 6290 a cal BP as a result of postglacial RSL rise. Peat formation is interrupted between *c*. 6550 a cal BP and *c*. 5650 a cal BP by the deposition of clay or peaty clay at most sites in the region although at some sites these deposits are missing. During this period, the study area seems to have been situated in the transitional zone between brackish and fresh water environments as some sites in the study area show evidence for a brackish and others for a freshwater (tidal) influence. At all sites, clay deposition had little influence on subsequent vegetation succession. After *c*. 5650 a cal BP, peat accumulation resumed, with the formation of a sedge fen and birch carr and further acidification led to the development of a oligotrophic bog. Peat accumulation in the area seems to have finally stopped during the early Middle Ages.

7. Acknowledgements

I am grateful to Waterways and Sea Canal for financial support, Jan Bastiaens for help during fieldwork , Nele Van Gemert for help with the figures and Freddy Damblon and an anonymous reviewer for useful remarks that helped to improve this publication.

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Manuscript received 14.01.2011, accepted in revised form 21.05.2011, available online 01.06.2011