Holocene evolution of relative sea level and local mean high water spring tides in Belgium-a first assessment

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Abstract

Holocene age-depth data from the Belgian coastal plain, basal peat data particularly, are assessed in terms of local water and tide levels. Basal peat formation was generally induced by sea-level rise; effects of local seepage were limited and significant river-gradient effects were absent. No relation was found between the timing of basal peat inception and substrate permeability. In genera!, edaphic (moisture) conditions were unfavourable for organic accumulation prior to sea-level related rise of the groundwater table. Error envelopes for the minimum level of local mean high water spring tides and for upper and extreme lower relative mean sea-level limits during the last 9400 solar years (8400 yrs B.P.) are presented. These indicate that the rate of relative sea-level rise showed marked retardations at ca. 7500-7000 yrs cal B.P. (± 6650-6100 yrs B.P.) and ca. 5500-5000 yrs cal B.P. (4400 yrs B.P.). A eustatic explanation appears to be plausible, particularly for the former. Prior to ca. 4000 yrs cal B.P. (ca. 3600 yrs B.P.), the relative sea-level rise in Belgium differs noticeably from that established for the western Netherlands, with both diverging progressively back in time. This implies that considerable differential crustal movement occurred between the two areas in the early Holocene.

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1. Introduction

The age--depth reconstruction of the Holocene relative sea-level (RSL) rise in Belgium has only recently drawn attention (Baeteman, 1981; Mostaert, 1985; Köhn, 1989; Mostaert and De Moor, 1989), and no studies have specifically been aimed at obtaining precise SL data from the coastal area. Consequently, the present database comprises only a limited number of reliable ^{14}C-dated index points. An assessment of the available radiocarbon dates of relevance to RSL reconstruction is also lacking.

The intermediate position of the Belgian coastal plain between the southem North Sea and the Atlantic Ocean renders considerable value to a reliable RSL curve for this area. Moreover, preliminary comparisons with the detailed RSL models for the Netherlands, as presented by Jelgersma (1979) and Van de Plassche (1982), reveal that index points from basal peats in Belgium consistently indicate a higher RSL position. Baeteman (1981, 1991) and Mostaert (1985) suggested that this difference might possibly result from Holocene crustal movements in the southem North Sea and Channel area.

In this paper the Belgian RSL trend and its divergence from that of neighbouring areas are explored by considering the ^{14}C-dated RSL evidence collected during the geological mapping of the coastal plain, as well as data obtained in the framework of more local studies. The Belgian part of the Schelde Estuary is not included here as it receives specific attention by Kiden (this volume).

On the basis of all the data presently available, an error envelope is estimated for the minimum height attained by the highest local mean high water spring tides (1-MHWS's) in the coastal area during the last 9400 solar years. Using basal peat data mainly, a similar envelope is also derived for the lowest observed local mean high waters (l-MHW's), hence providing an upper limit for the relative mean sea level (MSL). A tentative error envelope is constructed for an extreme lower limit of relative MSL's. The pattern of relative MSL rise suggested by these envelopes is discussed and a comparison is made with the relative sea-level trend established for the Netherlands.

2. Study area

The Belgian coastal plain (Fig. 1) is a ca. 15 km wide polder area, situated along the macro-tidal southern North Sea coastline (tidal ranges 3.8 ± 0.05 m, and 4.4 ± 0.05 m for semidiurnal and spring tides, respectively). The area is crossed by only one small river with a very low discharge, the IJzer, along which the plain extends inland for some 10 km. Surface elevations on the plain range from + 2 to + 5 m T.A.W. The Belgian T.A.W. ordnance datum refers to mean lowest low water spring at Oostende. Datums for the Netherlands (N.A.P.) and France (N.G.F.) are 2.33 m and 2.29 m higher respectively.

The plain evolved during the Holocene in a wave/tide-dominated transgressive setting. Deposits reach a thickness of ca. 30 m in the seaward area and thin on the emerging Pleistocene sandy to loamy subsoil near the inland border. In a large part of the area the Holocene sequence consists of siliciclastic deposits alternating with one or several peat layers; adjacent to the shoreline and at the inland margin the sequence is entirely siliciclastic. A basal peat occurs nearly everywhere, except in well-delimited areas where tidal scouring has occurred, or where the subsoil exceeds +2.5 m (Fig. 2). Fluviatile sediments are not generally

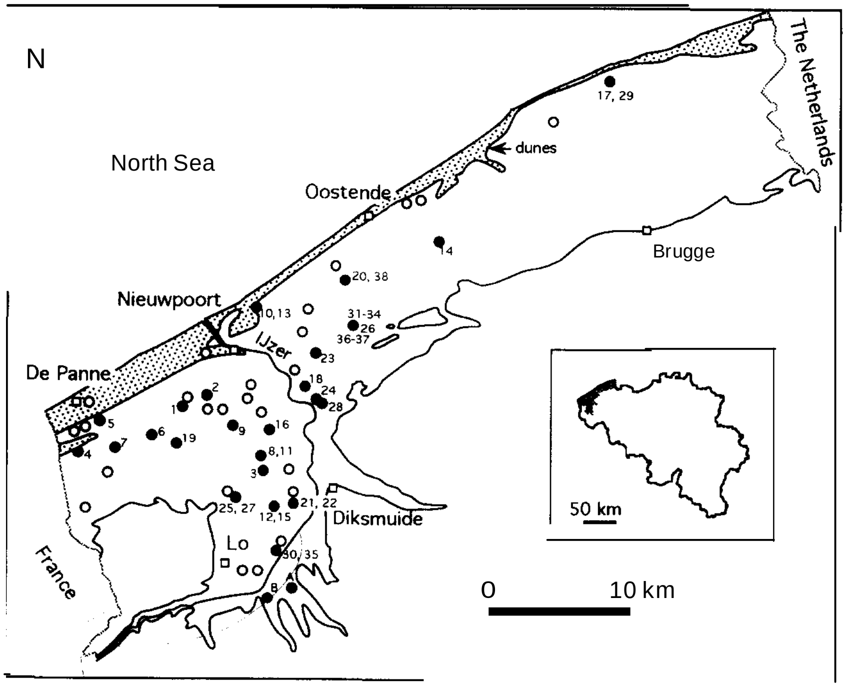

Fig. 1. Map of the Belgian coastal plain, with location of ^{14}C sites (dots: intercalated and/or basal peat dates, circles: intercalated peat dates only; numbers refers to index points listed in Table 1).

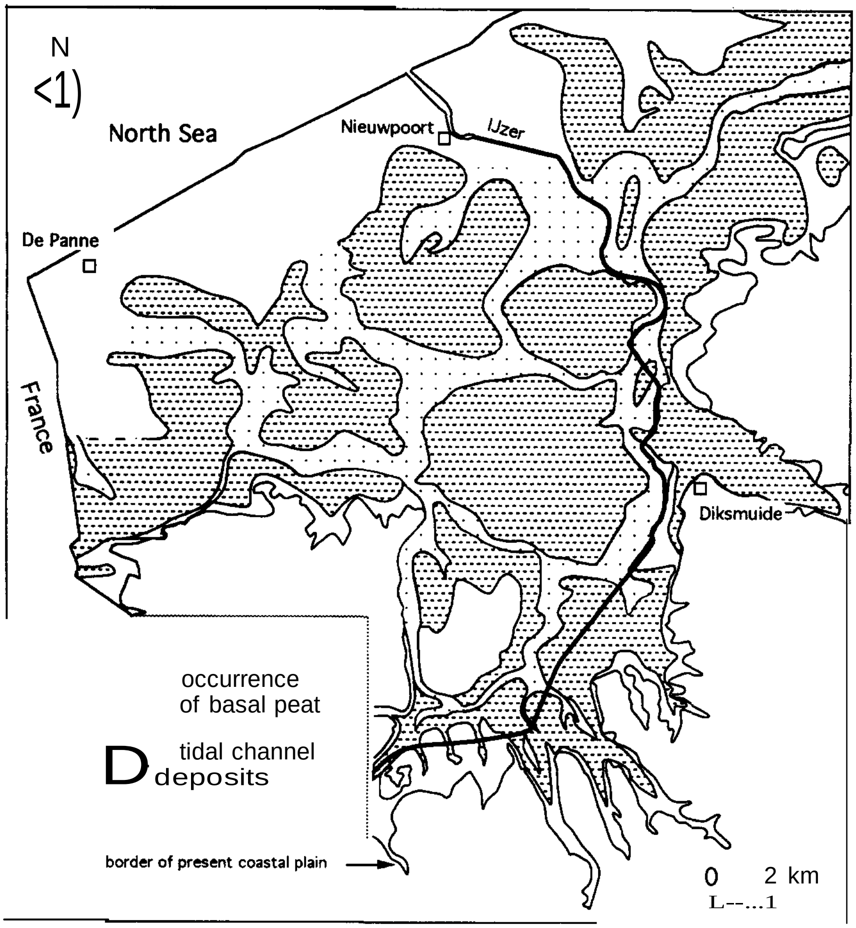

Fig. 2. Occurrence of basal peat in the western part of the coastal plain (after Baeteman, 1993).

encountered, except very locally at the base of some small paleovalleys in the extreme south of the plain (Baeteman and Van Strijdonck, 1989; Baeteman, 1991; Denys, 1993).

The deeper subsoil comprises Tertiary strata. In the western part these consist of stiff Eocene clays. In most places the Tertiary subsurface is overlain by Pleistocene deposits.

Adjacent to the coastline, the Pleistocene subsoil dips fairly rapidly towards the northeast. In the western half of the plain its morphology has a distinct NW-SE alignment (Fig. 3). Here a deep, narrow valley extends inland, turning south-southeast and branching into three tributaries. Outside these valleys the Pleistocene relief is rather flat in the most inland part. This is also the case in the landward part of the eastern coastal plain (Fig. 4); here the elevated nature of the subsurface restricted marine sedimentation prior to the Subatlantic.

The lithology of the Pleistocene deposits in the western part of the plain is variable. In a limited seaward part of the area, marine Pleistocene (Eemian) crag deposits occur together with fine sands, clays and peats (Fig. 5A). Middle Pleistocene sediments of a coastal/estuarine embayment also occur in the more landward part. Fine-grained fluvial channel fill sediments, of probable Weichselian age, are found in a N-S orientated belt (Fig. 5B) and further to the east, thick beds of Weichselian fluvio-periglacial and niveo-eolian cover sand occur. Thinner beds of these

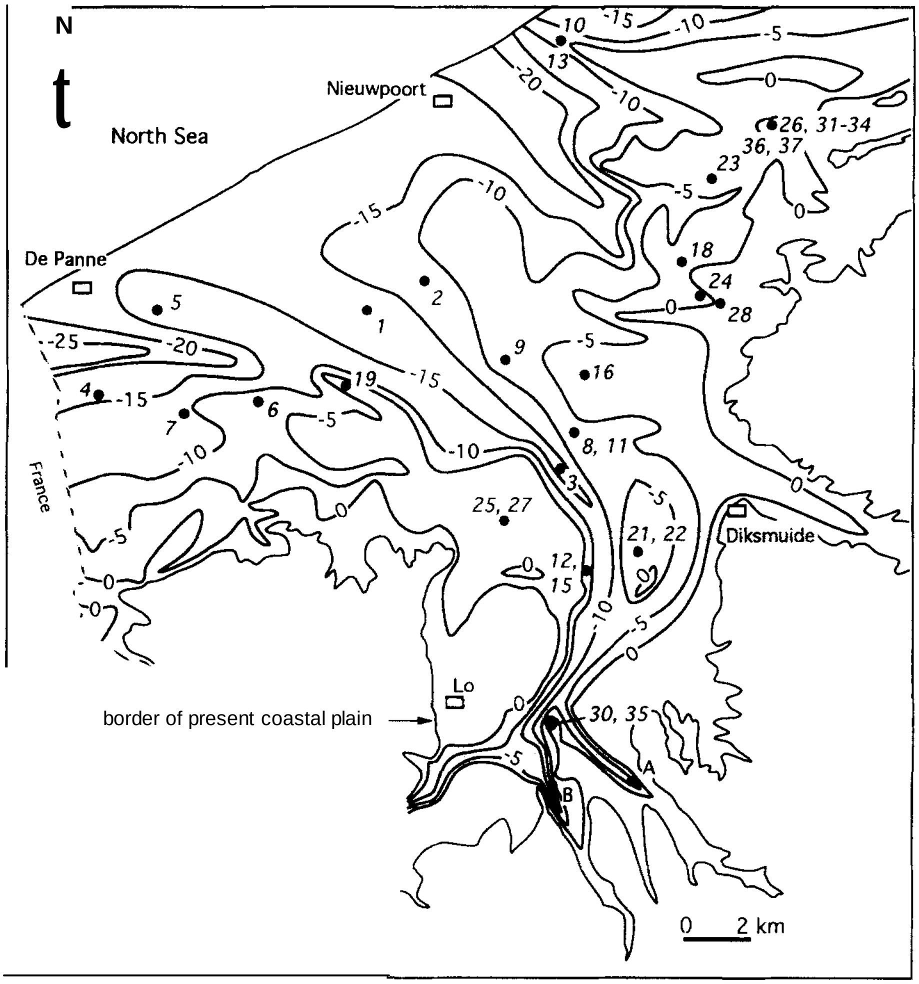

Fig. 3. Morphology of the Pleistocene surface in the western part of the coastal plain. Contours in meters (after Baeteman, 1993). Solid circles and numbers refer to index points listed in Table J.

sands and deposits consisting largely of reworked Eocene clay are found in the most western area. In the eastern part of the plain, Weichselian cover sands overlie Eemian tidal flat deposits (De Moor and Mostaert, 1993).

3. Database and methods

3.1. Data

Most of the radiocarbon dates from the Belgian coastal plain are derived from mechanica! corings (10 cm diameter) which penetrated the underlying Eocene deposits, Other data are from temporary pits or trenches and hand-augered gouge drillings. Their location is given in Fig, 1. Very few data have been collected in the eastern part of the coastal plain, Dates on peaty deposits, as well as on soils and wood were included in the study. If present, *Phragmites* rhizomes or smaller roots were removed only occasionally from the bulk samples submitted for dating. The top of a peat layer was sampled only if there were no visible signs of erosion. The error on the altitude of the sample includes those associated with levelling and sampling.

In most cases conventional dating techniques

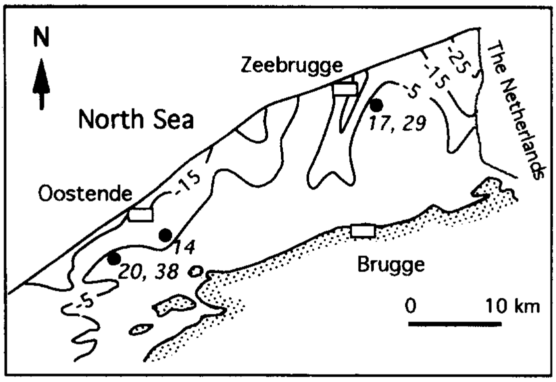

Fig. 4. Morphology of the Pleistocene surface in the eastem part of the coastal plain. Contours in meters (after Houthuys et al., 1992, slightly altered). Dots and numbering refer to index points listed in Table 1.

were employed. Dates were calibrated with CALIB 3.0.3 (Stuiver and Reimer, 1993). The *2u* intercepts with the bidecadal curve (method A) were used in constructing the error envelopes.

The database includes 38 basal peat dates (base, top, or whole layer) and 88 dates on intercalated peat beds (transgressive or regressive overlaps, or whole layer). Data from archaeological studies and ^{14}C dates on dune peats and soils were also considered. Most of the ^{14}C data used in this study are listed by Baeteman and Van Strijdonck (1989) and Denys (1993). The relevant information on all basal peat index points, and some intercalated peat data of specific interest, is given in Table 1.

3.2. Minimal level of highest 1-MHWS's

An error envelope for the minimum level reached by the highest 1-MHWS's was determined in two steps: a first approximation was based on basal peat data only; next additional data were considered.

The top of a basal peat may be used to indicate a minimum 1-MHWS level if it can be shown that it did not form subaquatically and if erosion can be excluded. A gradual transition of the peat to the overlying marine sediments confirms a genuine transgressive overlap. However, given the nature of core work, erosion may be overlooked in some cases. Diatom analysis provides a reliable means of excluding this possibility and also gives information on the environmental succession. This is illustrated by an example from the core Orthodoxe Kerk (Fig. 6; Denys, 1993), which yielded index points 8 (IRPA 533, base of the peat) and 11 (IRPA 534, top). Here the lowermost part of the basal peat contained no diatom remains, probably as a result of insufficient moisture, which would have prevented preservation. The lowermost assemblage, with *Navicula contenta* and some *Diploneis interrupta,* is characteristic of a rather

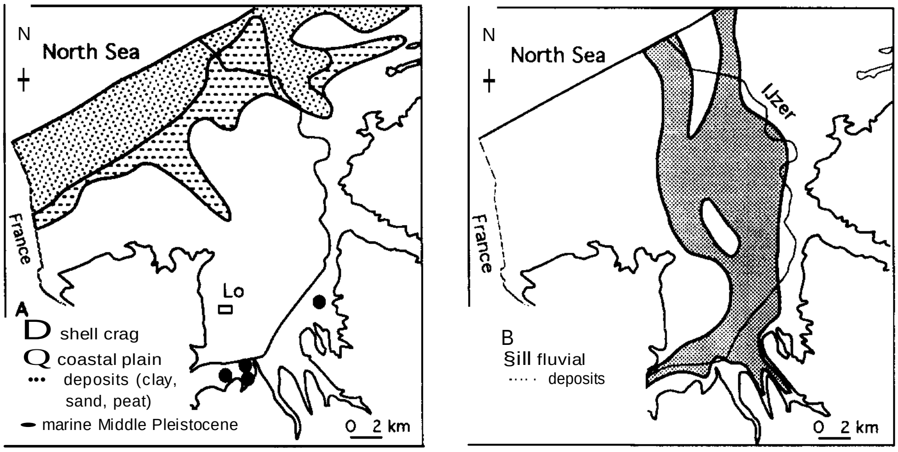

Fig. 5. Facies of Pleistocene deposits, other than coversands or reworked Eocene, in the western part of the coastal plain. (A) Marine deposits, (B) fluvial deposits (after Baeteman, 1993).

Table 1
Index points from the Belgian coastal plain. To obtain the vertical errors shown in Fig. 7, add 0.1 m plus half the sample thickness to the error on altitude

No.	Site (sampling method)	Geographical coordinates lat. N, long. E.	Laboratory number	Age (yrs B.P.)	Calibrated age (yrs cal B.P.)	Sample altitude (T.A.W., m)	Error on altitude (m)	Stratigr. position	Dated material (thickness of whole layer, m)	Substrate texture	Botanica! analyses *excluding erosion (reference)
Basal peat data											
1	Schoudervliet (!)	51°05'30", 2°42'15"	IRPA 681	8440 ± 130	9781-9041	-16.67/ -16.64	0.10	top	reed peat (0.33)	clay with sand laminae	pollen, diatoms*
2	Allaertshoeve (1)	51°06'05", 2°43'40"	IRPA 566	8250 ± 95	9442-8964	-11.34; -11.27	0.10	top	peaty soil in sand (0.17)	clayey fine sand	diatoms*
3	Oostkerke (1)	51°02'40". 2°43'30"	IRPA 734	8170 ±90	9379-8733	-15.63/ -15.59	0.10	base	amorphous peat	sandy clay	diatoms (1)
4	Woestijne (1)	51°03'40". 2°43'50"	IRPA 616	8120 ± 100	9370-8652	-15.25·-15.17	0.10	top	peaty, clayey sand (0.27)	medium sand. small gravels	pollen diatoms*
5	Noord Gasthuis (1)	51°05'00". 2°36'25"	IRPA 678	7620 ± 90	8548 - 8170	-13.75;-13.73	0.10	base	peaty soil in sand	slightly clayey fine sand	
6	Veurne (1)	51°04'00". 2°39'20"	Utc 2625	7490 ± 130	8492-7967	-9.64/ -9.62	0.10	top	clayey peat (0.05)	clayey fine sand	
7	Moerhof (1)	51°03'57". 2°38'05"	Utc 2626	7420 ± 190	8546 7820	– *11.061* – 11.02	0.10	mean	peat (0.07)	medium sand. small gravels	
8	Orthodoxe Kerk (1)	51°03'20". 2°47'32"	IRPA 533	7230 ± 85	8131-7847	-5.23 -5.20	0.07	base	amorphous peat	fine sand	diatoms (1)
9	B 363, Avekapelle (1)	51°04'40", 2°45'25"	Hv 8797	7170 ± 275	8426-7472	-7.05.· -6.95	0.10	top	sandy amorphous peat (0.38)	silty fine sand	pollen (2)
10	Westende 4 (1)	51°09'53", 2°46'47"	IRPA 614	7160 ± 85	8121-7766	-5.08/ -5.03	0.10	top	sandy peat (0.16)	sandy organic clay	
11	Orthodoxe Kerk (1)	51°03'20", 2°47'32"	IRPA 534	7110 ± 90	8070-7690	-5.17/ -5.13	0.07	top	amorphous peat (0.09)	fine sand	diatoms* (1)
12	Dijk (!)	51°01'11". 2°48'10"	IRPA 542	6870 ± 70	7881-7536	-5.1/ -5.07	0.10	base	peaty clay	clayey fine sand	
13	Westende 4 (1)	51°09'53", 2°46'47"	IRPA 615	6780 ± 80	7706-7472	-5.19/ -5.14	0.10	base	sandy peat	sandy organic clay	
14	Zandvoorde (2)	51°12'30", 2°58'30"	ANTW zvll	6750 ± 125	7790-7385	-6.8/ -6.70	0.10	base	peat	silty sand	
15	Dijk (!)	51°01'11", 2°48'10"	IRPA 541	6680 ± 80	7631-7388	-4.93/ -4.90	0.10	top	peaty clay (0.20)	clayey fine sand	
16	Spoorweg 1 (1)	51°04'25". 2°48'00"	IRPA 927	6665 ± 60	7575-7392	-3.72/ -3.67	0.10	top	clayey peat (0.13)	clayey fine sand	diatoms* (1)
17	Zeebrugge (2)	51°19'12". 3°12'44"	Lv 856	6320 ± 70	7377-7026	-0.90/ -0.85	0.20	base	peaty soil in sand	medium sand	macroremains (3)

18	B 742, Schore (1)	51°06'30", 2°50'35"	IRPA 725	5970±120	7161-6494	-2.25/-2.10	0.10	base	sandy peat and reed peat	dayey fine sand	
19	B 407, Steenkerke (!)	51°04'12", 2°41'34"	ANTW 136	5830±115	6892-6357	-2.25/-1.75	0.10	mean	peat (0.10)	silty fine sand	
20	Noordhoek (1)	51°11'05", 2°53'20"	IRPA 729	5770±100	6845-6316	-2.37/-2.30	0.10	base	peat	silty very fine sand	
21	Jacobs (1)	51°01'30", 2°49'45"	IRPA 618	5720± 70	6715-6319	-2.64/-2.59	0.10	top	wood (0.78)	dayey very fine sand	
22	Jacobs (1)	51°01'30", 2°49'45"	IRPA 617	5710± 70	6706-6316	-2.71/-2.67	0.10	top	wood peat (0.78)	dayey very fine sand	
23	Spermalie 2 (1)	51°07'50", 2°51'15"	IRPA 519	5650± 70	6632-6298	-1.09/-1.04	0.10	top	dayey reed peat (0.22)	silty fine sand	diatoms* (4)
24	B 746, Schoorbakke (1)	51°05'58", 2°50'45"	IRPA 722	5490±100	6471-5998	-0.56/-0.46	0.10	base	sandy peat	dayey fine sand	
25	B 71, Lampernisse (1)	51°01'52", 2°45'50"	ANTW 251	5310±190	6470-5652	-1.25/-1.15	0.10	base	peat	sandy and dayey silt	
26	Leffinge 2 (2)	51°08'40", 2°52'13"	ANTW 105	5190±140	6287-5645	0.97/1.03	0.10	base	wood (oak)	fine sand	pollen (5)
27	B 71, Lampernisse (1)	51°01'52", 2°45'50"	ANTW 250	5100± 140	6188-5586	-0.95/-0.85	0.10	top	peat (0.30)	sandy and dayey silt	
28	B 747, Leke (1)	51°05'40", 2°51'00"	IRPA 723	4990± 70	5908-5594	0.89/0.99	0.10	base	fen peat, some wood	fine sand	
29	Zeebrugge (2)	51°19'02", 3°12'44"	Lv 855	4880±65	5738-5474	-0.85/-0.75	0.20	base	wood (alder)	medium sand	macroremains (3)
30	B 990, Lo-Reninge (3)	50°58'30", 2°47"05"	Utc 2636	4720±100	5649-5073	0.14/0.17	0.30	base	peat	silty day	
31	Leffinge 2 (2)	51°08'40", 2°52'13"	ANTW 102	4630±140	5645-4869	1.17/1.23	0.10	base	wood (alder)	fine sand	pollen (5)
32	Leffinge 2 (2)	51°08'40", 2°52'13"	IRPA 282	4465± 220	5644-4448	1.77/1.83	0.10	base	wood peat	fine sand	pollen (5)
33	Leffinge 2 (2)	51°08'40", 2°52'13"	IRPA 337	3340± 185	4079-3089	2.17/2.23	0.10	top	fen peat (0.40)	fine sand	pollen (5)
34	Leffinge 2 (2)	51°08'40", 2°52'13"	IRPA 338	3225±160	3833-2999	2.17/2.23	0.10	top	wood (0.40)	fine sand	pollen (5)
35	B 990, Lo-Reninge (3)	50°58'30", 2°47'05"	Utc 2280	3150±50	3465-3218	1.85/1.87	0.30	top	peat (1.73)	silty day	
36	Leffinge 2 (2)	51°08'40", 2°52'13"	IRPA 283	3140±165	3699-2877	2.17/2.23	0.10	top	fen peat (0.40)	fine sand	pollen (5)

(*continued*)

№	Site (sampling method)	Geographical coordinates lat. N, long. E.	Laboratory number	Age (yrs B.P.	Calibrated age (yrs cal B.P.)	Sample altitude (T.A.W., m)	Error on altitude (m)		Dated material (thickness of whole layer, m)	Substrate texture	Botanical analyses *excluding erosion (reference)
	Leffinge 2 Z	51°08'40' 2°52'13"	[illegible]	[illegible] 0±50	2952	2.17/2.23	ei. 0	2 P..	fen peat (0.40	fine sand	pollen (5
[illegible]	[illegible]	51°11'05' 2°53'20"	IRPA 730	[illegible]	[illegible]	[illegible]	ei. 0	2 P..	peat (2.58)	silty very fine sand	
Intercalated peat data											
A	Drie Grachten (1)	50.57'40' 2.49'30"	[illegible]	[illegible]	7947–7646	[illegible]	0		clayey peat	silty clay	
B	Waterhoek (1)	50.57'15' 2.47'38"	IRPA 872		1612–1353	2.28/2.33	0		[illegible]		diatoms*

Sampling method: 1 = mechanical coring, 2 = excavation, 3 = hand auger (gouge).
References: 1 = Denys (1993), 2 = Baeteman (1981), 3 = Allemeersch (1977), 4 = Denys 985), 5 = Baeteman et a

dry subaerial environment, with only a limited tidal influence. It approximately indicates 1-MHWS. It is succeeded by a more brackish salt-marsh assemblage *(Navicula peregrina, N. elegans, Diploneis ovalis)* which reflects the approaching 1-MHW. Increasingly wetter conditions are indicated by an improved representation of *Fragilaria construens* var. *subsalina.* At the interface with the more clastic sediments, mud-flat species *(Nitschia navicularis, N. granulata, Diploneis didyma)* and polyhaline tychoplankton *(Delphineis surirella, Para/ia sulcata, Rhaphoneis amphiceros)* indicate regular tidal inundation, implying that the 1-MHW was reached. The diatom record shows that the mean water depth did not exceed a few centimeters before the onset of tidal sedimentation. The level corresponding to the 1-MHWS in the core occurs immediately above index point 8, and below index point 11. The Jatter corresponds closely to the 1-MHW and can be used to estimate a minimal 1-MHWS.

Table 1 indicates where it was possible to exclude erosion of the top of the basal peat by diatom analysis. To infer a minimum level for 1-MHWS's from such index points, an indicative value of ±0.1 m was used. The highest/oldest dates from the top of the basal peat give an envelope for the minimum level of the highest 1-MHWS's.

A problem which cannot be accurately accounted for when using peat tops is compaction. This will depend on several factors, including initial water content, composition of the peat, its age and nature of the overburden. To obtain an indication of the effect of compaction on the uppermost limit, a mean compaction of 50% of the original thickness was assumed. This value may be an underestimation in a number of cases, although in the case of fen-wood peats it may be an overestimation (cf. Menke, 1988).

The envelope derived from the top of the basal peat was then compared with the age-depth position of transgressive and regressive overlaps, or mean dates, of intercalated peat layers and with dated habitation levels from within or just outside the coastal plain. It was also compared with dates from the lowest dune soils and peats. Overlaps from intercalated peats have an indicative meaning similar to the top of the basal peat (about 1-MHWS

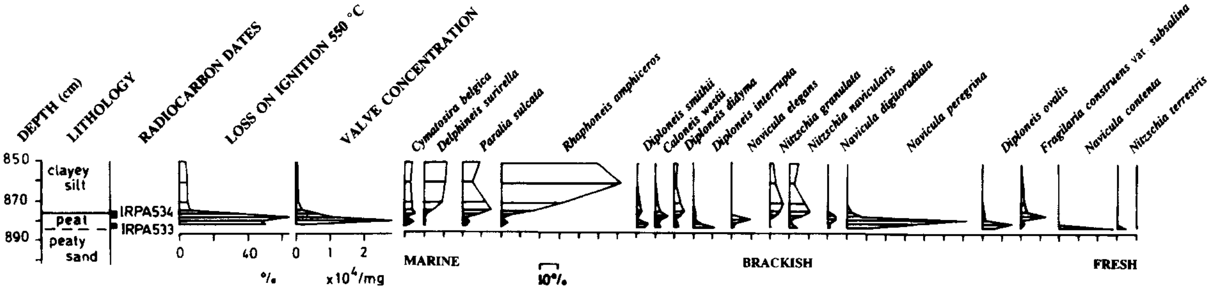

Fig. 6. Diatom diagram (most abundant taxa only) from the transgressive overlap of the basal peat in the core Orthodoxe Kerk, showing the development from rather dry semi-terrestrial conditions to an intertidal environment.

to 1-MHW), but compaction effects may be much larger. Since an envelope for the minimal level of highest 1-MHWS's is envisaged, no attempts were made to account for this. Dune soils and peats were considered not to have formed below the 1-MHWS, and neither were the habitation levels. Of the latter, those overlying Holocene deposits may have been affected by compaction.

3.3. *Upper MSL limit*

In a tidally influenced area, telmatic basal peat growth (= the peat surface remaining subaerial) will begin at around or above the 1-MHW (concerning the relations between basal peat formation and water or tide levels cf. Jelgersma, 1961; Roeleveld, 1974; Tooley, 1978; Behre and Streif, 1980; Van de Plassche, 1982; Van de Plassche and Roep, 1989). Hence, the lowest levels of 1-MHW's represented by the database are the youngest/ lowest dates from the base of the basal peat. The position of these index points will converge to MSL, due to extinction of the tidal wave, but may still lie above this level. An envelope based on these index points therefore represents an upper MSL-limit (Van de Plassche and Roep, 1989).

For dates from the base of the basal peat bed, lowering by compaction is negligible. Vertical errors are limited here to those associated with depth measuring and levelling (as above) and the indicative meaning. The latter corresponds to the mean water depth, and will be within ±0.1 m for a semi-terrestrial peat. Occasionally, the cumulative vertical error for levelling, sampling and indicative meaning may be constrained to a lower value by an overlying top sample.

3.4. *Extreme lower limit for MSL*

A tentative extreme lower limit for MSL was derived from the envelope for the minimal height of the highest 1-MHWS's, uncorrected for compaction of the basal peat, by subtracting the present-day difference between coastal mean tide level (MTL) and MHWS at Nieuwpoort (2.45 m; this difference decreases along the coast towards the east). The assumption made here that the highest l'MHWS's will not have been lowered relative to contemporaneous coastal MHWS as a result of flood-basin and friction effects is quite unlikely. The assumed absence of compaction will also contribute to an extreme lower estimate of MSL. Field evidence on former tidal ranges is almost completely lacking from the area (see however Mostaert, 1985). Nevertheless, a somewhat larger range than present at certain times in the past cannot be entirely dismissed (cf. Roep and Beets, 1988). It is significant to note, however, that results obtained by tidal modelling (Post, 1976; Franken, 1987; Austin, 1991) point to a smaller tidal range at a lower MSL position than present.

3.5. *Basal peat*

In view of the importance of basal peats for the interpretation of former local water and tide levels, its characteristics and growth conditions will be considered further here.

The facies of the basal peat in the Belgian coastal plain vary considerably, and range from a thin structureless peat, to a well-developed layer up to several meters thick with well-preserved plant remains. In the latter case, fen, fen-wood, reed, and more oligotrophic peats are encountered. In some areas full peat growth was inhibited and only a humic to peaty soil developed on the Pleistocene subsurface.

In general the peat becomes more amorphous with increasing age-depth. Pollen preservation is generally poor and concentrations are low in the late Boreal soils and humified reed/sedge peats from the western part of the study area, reflecting oxidation. Pollen may be more abundant and better preserved near the top, due to the moister conditions which precede tidal sedimentation. Tree remains may be important constituents in younger peats. At all the sites studied in detail so far, the basal peat appears to have been formed under minerogenic, rather eutrophic and subaerial conditions. The only exception applies to the very thick beds, where autogenic oligotrophication may have occurred (Baeteman et al., 1981; Allemeersch, 1984; Denys, 1993).

The distribution of the Boreal and early Atlantic basal peat data on the Pleistocene surface (Baeteman and Denys, unpubl. data) clearly reflects the generally transgressive growth of this peat, which formed rapidly as a narrow belt in front of the tidal area. Local peat growth was short-lived in this period, and depended strongly on the RSL rise ('basis peat' sensu Lange and Menke, 1967). Peat growth remained confined to the steeper parts of the Pleistocene subsurface until the late Atlantic and early Subboreal, when it extended over the higher, flatter areas, including most of the eastern coastal plain. Subsequently thicker beds of fen-peat developed, with a more complex vegetational succession.

Basal peat development can also occur in flat or gently sloping areas, where drainage is hampered or where seepage occurs. In such cases the peat may form independently of RSL. On steeply inclined surfaces and on ridges, peat formation is not likely to begin before the local groundwater table approaches the surface as the result of SL rise. So far, the deep position of the peat has prevented a more detailed reconnaissance of the small-scale morphology of the Pleistocene surface, and only occasionally has it been possible to dismiss the possibility of peat growth in closed, water-holding depressions by mapping. However, from the large-scale morphology of the Pleistocene surface (Fig. 3) it would appear that local watertable fluctuations, independent of SL are unlikely in the case of index points 8, 10, 12, 13, 19, 26, 30, 31 and 32. For index points from the valley floors (i.e. No. 3), a relatively large fresh-water supply might be expected. Here botanical analyses have also shown that local conditions were rather dry during peat formation (Denys, 1993), even though tidal influence occurred at about the same time and altitude elsewhere (cf. index points 1 and 4).

In most of the places where its base was dated, the basal peat rests on sediments with a rather fine, or even clayey texture (Pleistocene fluviatile or marine sediments), and not on more permeable sandy deposits (only Nos. 7, 18, 19, 24, 26, 28, 31 and 32). This may again be a reason to consider the possibility of basal peat inception that was unrelated to SL.

4. Results

4.1. Minimal level of highest 1-MHWS's

The time-depth data from Table 1 are plotted as error boxes in Fig. 7. The oldest dates for the base of the basal peat are all from the westernmost part of the area (index points 1, 2, 4 and 6). A discrepancy occurs between the age-depth position of the most seaward index point 2 and that of Nos. 1 and 4, which are of comparable age. Whereas the latter two points both lie below -15 m, point 2 is situated several meters higher. Diatom analyses show that there was no erosion of the peat in all three cases. The upper parts of the peat contain salt-marsh diatom taphocoenoses which grade into mud-flat assemblages at the upper limit of the ^{14}C samples. At present, it seems more appropriate to accept only index points 1 and 4 to infer a minimal level, particularly as their position agrees well with that of index point 3, where a

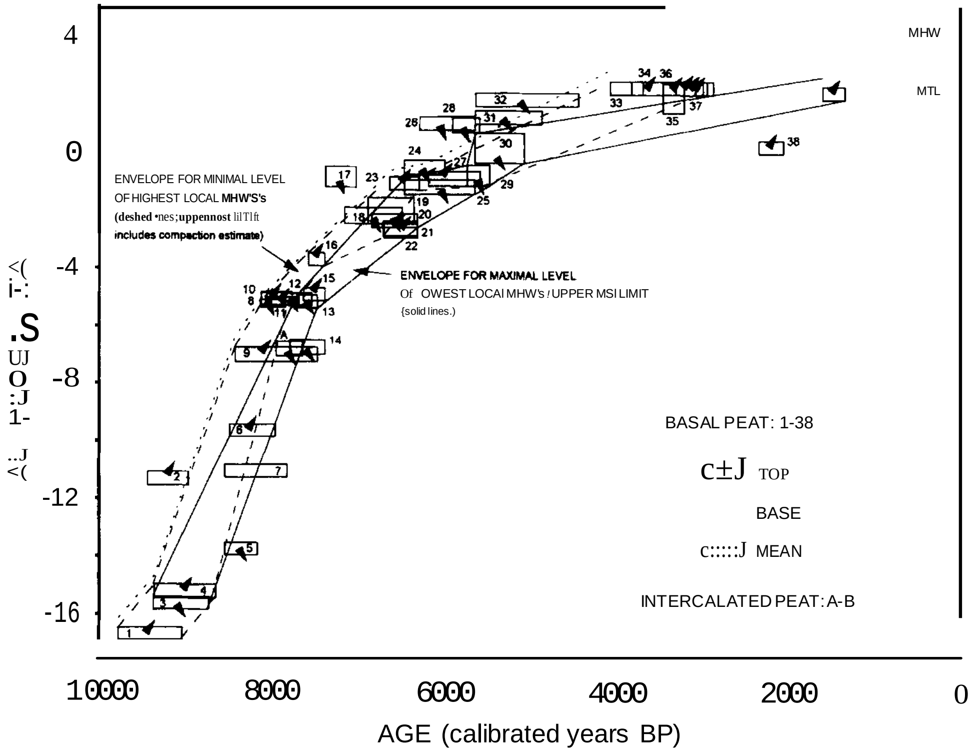

Fig. 7. Time-depth distribution of the index points listed in Table l, with inferred envelopes for the minimum level attained by the highest 1-MHWS's, and for an upper limit of MSL. Present-day MTL, MHW and MHWS from tide-gauge data at Nieuwpoort.

mud-flat diatom assemblage occurs in the clayey peat immediately above the dated, diatom-barren part of the peat (Denys, 1993). Possible explanations for the aberrant position of index point 2 may be that the top of the peat contained redeposited older organic material, or simply that the sample was contaminated by older soil material from the site itself. In view of the rather low organic content of the dated material (peaty soil), even small amounts of older carbon could have influenced the dating result considerably (cf. Olsson, 1991).

At about 8000 yrs cal B.P., index points 9, 10 and 11 are available. However, the dates for the top and the base of the sandy peat at Westende 4 (index points 10 and 13 respectively) are reversed. This is somewhat surprising, since one would rather expect an apparent age that is too old, instead of too young for the base of a basal peat. Index point 10 is therefore not included as contamination appears possible. Index point 11, from almost the same depth, is unsuspect, however, and only slightly younger.

Between ca. 7500 and 5500 yrs cal B.P. index points 16, 19, 23 and 27 were used. Only for the latter can an age comparison with the base of the peat (index point 25) be made, but none of them appear conspicuously old.

The youngest dates for the top of the basal peat comprise a series of rather diverging results from a 40 cm thick bed at Leffinge 2, all levelled at ca. + 2.2 m (index points 33-34, 36-37), and two dates from very thick peat beds (index points 35 and 38). The extremely low position of index point 38 (obviously due to compaction) disqualifies it for further use.

In Fig. 8 the data from intercalated peats, habitation levels and dune peats or soils are plotted. The intercalated peats allow the envelope to be narrowed considerably between ca. 7000 and 4000 yrs cal B.P. and also suggest a higher upper limit at about 7500 and between ca. 6500 and 3500 yrs

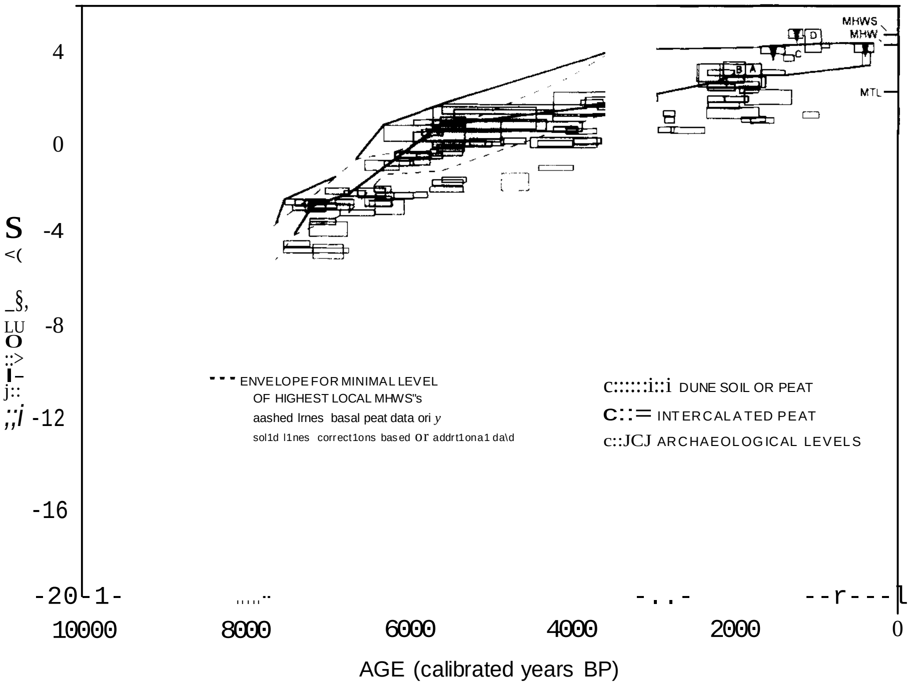

Fig. 8. Improvement of the envelope for the minimum height of highest 1-MHWS's, based on basal peat, by comparison with additional age-depth data. (A) Iron Age to Roman settlements on Pleistocene sands at Fort Lapin, Brugge (Thoen, 1978), (B) Iron Age saltings within the coastal plain at Veurne (De Ceunynck and Termote, 1987), (C) Medieval habitation levels in the coastal area (Mostaert, 1985), (D) 11th century habitation on the Pleistocene mound ('donk') of Kasteel Ten Berge, north of Brugge (Mostaert, 1985), (E) reed peat at archaeological site of Damme (Mostaert. 1985). Present-day tide levels as in Fig. 7.

cal B.P. than the basal peat data. Moreover, the envelope can be extended to ca. 500 yrs cal B.P. The position of Iron Age, Roman and Medieval habitation levels (A, B and C) within the envelope can be attributed to compaction effects and/or local reduction of the tidal amplitude. Even in the youngest part of the envelope, the uppermost limit does not entirely reach the present-day coastal MHWS level. It is apparent from Fig. 7 that, with the possible exception of the interval between 8000-7000 yrs cal B.P" the position of this limit may be influenced significantly by compaction phenomena.

4.2. *Upper MSL limit*

Prior to ca. 7500 yrs cal B.P" where index points 3, 5, 7, 14 and 13 are available as lowest/youngest dates for the base of the basal peat, the construction of the envelope is not straightforward (Fig. 7). This is because there are good reasons to suspect that the dating results are too young for several index points. No problem arises for the oldest index point 3 (see above). However, if the position of No. 5 is compared to that of No. 6, or if that of point 7 is compared to No. 9 or even 11, and that of No. 14 to index points 15 and 16, one has to accept either inadequate dating, or differences in local tidal amplitudes in excess of several meters between the respective sites. The latter option is not realistic. Index point 6 is situated 4 km more inland than No. 5; the basal peat cannot have been flooded at a level of at least -9.6 m, if at the same time peat growth began in the more seaward area at -13.75 m. The same applies to index point 7 versus 9. To explain the difference between index point 14, and the end of peat growth in the NW-SE directed valley (represented by Nos. 11, 15 and 16) a strong river-gradient effect might be inferred {cf. e.g. Van de Plassche, 1982). However, this must be considered quite unlikely because: (1) fluviatile sediments are absent in this part of the depression; (2) elaborate diatom analyses show that there was very little freshwater influence (Denys, 1993); (3) the age-depth position of the index points within this valley does not indicate a gradient effect, but rather a lowering of tide levels with increasing distance from the sea (compare, for example, index points 15 with 16, and 21-22 with 23). The question remains which index points should be considered reliable: the lowermost bases, Nos. 5, 7 and 14, or the tops, Nos. 6, 9, and especially 11, 15 and 16? The dates for index points 11 and 15 are consistent with the results obtained for the base of the peat at these sites (Nos. 8 and 12). An additional indication is given by index point A, from the southernmost part of the area. This is a date from the base of a fen peat, situated on 2.5 m of early Holocene, clayey fluviatile sediments, which are mottled and somewhat crumbly at the top (Baeteman and Van Strijdonck, 1989; Denys, 1993). Within this freshwater peat, diatom remains are first recorded above the middle of the ^{14}C sample, and at this level include small amounts of marine valves. Although it is not a basal peat in a stratigraphic sense, the peat apparently developed in response to a renewed rise of the groundwater table after deposition of the fluviatile sequence. The marine diatoms indicate that the 1-MHWS cannot have been much lower at this time. Local tidal amplitudes were probably minimal this far inland. Given that the height of the peat may have been affected by compaction, the lowest level attained by 1-MHW's at this time should not lie much below point A. Such a limit can be obtained by connecting index points 3 and 13, but not by including the Nos. 5, 7 and 14. If the age probability distributions of the latter are considered, the likelihood that these rejected index points are still situated within this construction amounts respectively to ca. 0.11, 0.56 and 0.27. For index point 5, a peaty soil, this probability would increase markedly if some lowering due to compaction was taken into account. This may be the case as it rests upon a few centimeters of non-marine sand and is underlain by a 22 cm thick bed of humic to peaty sand with wood remains at the top, dated at 9190 ± 185 yrs B.P. (Baeteman and Van Strijdonck, 1989). Moreover, it is covered by 1 m of clay, penetrated by roots and eroded by a gully. Hence, rejuvenation by younger plant material may have occurred. The available data do not warrant a further evaluation of index point 13. The somewhat older age of index point 8 might suggest that seepage influenced peat inception at this site.

Up to ca. 5000 yrs cal B.P" there are four index points (Nos. 20, 25, 29 and 30), which either present a rather large *2a* range, or were not levelled very precisely. The slightly higher age of index point 18 relative to No. 20 may again reflect a local groundwater effect. Two other index points from the same area, Nos. 24 and 28, also show a conspicuously high position, indicating that this region may be particularly susceptible to seepage phenomena. A marked difference also appears between index points 17 and 29, both from Zeebrugge; a result of early soil development induced by local seepage or contamination. The date for No. 17 was obtained on humic acids extracted from the peaty soil (Dauchot-Dehon et al., 1986). The result for No. 29, dated on alder wood, must be considered more reliable, but a slightly higher original position cannot be excluded. The high position of index points 26, 31 and 32, relative to No. 30 are probably not due to a groundwater effect; these are from the slope of a Pleistocene mound ('donk'), upon which growth of fen-wood peat would have began as the 1-MHW levels rose (cf. Baeteman et al., 1981). Situated relatively far seaward, and next to an important gully, local tide levels will have been higher here than at the more landward, sheltered site of index point 30.

There are no dates from the base of the basal peat younger than 5000 yrs cal B.P. Therefore, index point B, the top of a thick bed of intercalated fen and fen-wood peat near the inland margin of marine sedimentation, was used to extend the envelope. For a thick bed of fen-wood peat it may be argued that most of the compaction will already have occurred during its growth (Menke, 1988). The acceptance of this index point as a fairly reliable indicator is based on the observation that at a site 3 km to the east, 1.5 km southeast of index point A, diatom and pollen analyses of the valley fill showed that the 1-MHWS level <lid not exceed + 2.97 ± O.l m since late-Medieval times (Denys, 1993). At index point B, the surface of the mud-flat sediments (l-MHW) lies at + 2.5 ± 0.l m, and must be younger than the 4th-5th century. From this comparison, an estimated lowering of index point B with no more than ca. 0.3 m appears realistic. It may be noted that Mostaert (1985) also inferred that 1-MHW's <lid not exceed + 2.5 m at the inner fringe of the coastal plain from the thinning out of all peat on the Pleistocene surface.

4.3. Extreme lower limit/or MSL

Fig. 9 shows both of the envelopes derived above, together with the tentative envelope for an extreme lower MSL limit, based on the minimum height of the highest l'MHWS's. The most likely age--depth positions of the lowest/youngest dates from the base of the basal peat, as well as of the rejected basal peat dates, are also indicated.

The large and overlapping *2u* age ranges of the oldest index points cause substantial coincidence of both bands prior to 7500 yrs cal B.P. If their most probable position is considered, the rejected index points from the base of the basal peat are still within the extreme lower MSL envelope.

For the last 7500 years a reasonable match is observed between the lowermost limit of the envelope for the upper MSL limit and the uppermost limit for the extreme lower MSL band. The difference is maximal, ca. 0.9 m, at about 6500 yrs cal B.P.; elsewhere it does not exceed ca. 0.65 m. A perfect match cannot be expected, as this would imply that: 1. the lowermost limit of the upper MSL band corresponded with coastal MTL; 2. the observed highest 1-MHWS's reached the same height as coastal MHWS's and no compaction occurred; 3. the value taken as the difference between coastal MHWS and MTL would be valid for almost the entire coast, and would have remained unchanged throughout. It will nevertheless be clear that if no major changes in tidal amplitude occurred, it is more likely for MSL to lie in the vicinity of these two approaching limits (especially between them), rather than near the

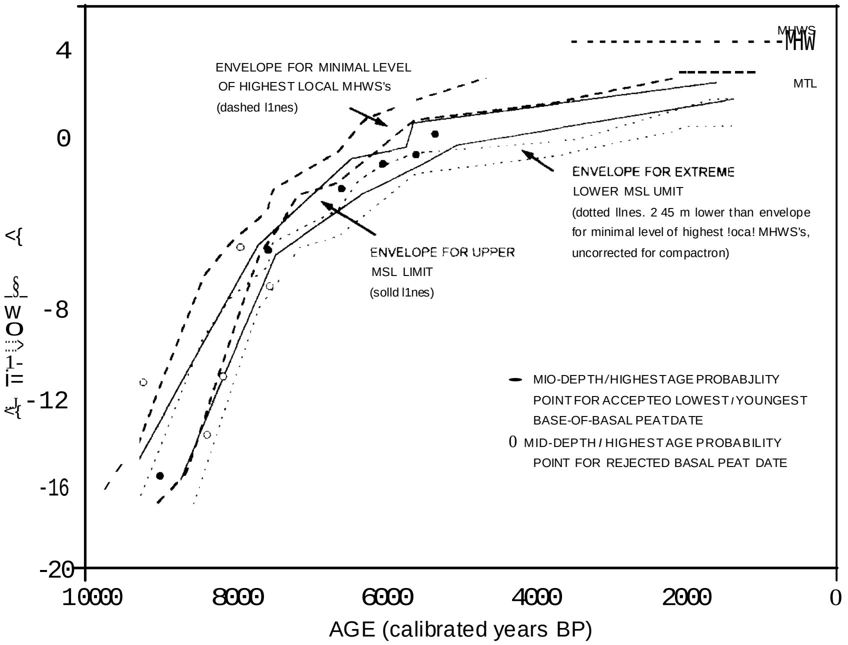

Fig. 9. Envelope for a tentative extreme lower MSL limit, based on the minimum height of highest 1-MHWS's, compared to the error band for an upper MSL limit. Most probable position of accepted Jowest/youngest base-of-basal peat index points, and rejected basal peat data indicated. Present-day tide levels as in Fig. 7.

outer limits of the envelopes. This also suggests that contemporaneous MSL was not far below the lowest/youngest index points from the base of the basal peat during this interval.

4.3. *Influence of substrate texture on basal peat inception*

It is generally accepted that substrate permeability can strongly influence basal peat inception. Inspection of Table 1 and Fig. 7 shows, however, that several of the lowest/youngest dates for its base are from peat which developed on a clayey subsoil (Nos. 3, 13, 25 and 30). Although the number of observations remains limited, this indicates that even where the subsoil was sufficiently impermeable to sustain a local watertable, and allow the establishment of marsh vegetations, this did not occur until the regional groundwater table rose sufficiently in response to the SL rise. It should also be noted, that seepage will occur much less readily on a clayey substrate than on a sandy one (cf. Nos. 18, 24 and 28).

4.4. *Comparison with the RMSL trend for the Netherlands*

In Fig. 10, the error bands for the upper and tentative extreme lower limits of the RMSL in Belgium are compared with a calibrated, smoothed (no oscillations) version of the RMSL trend curve for the western Netherlands (Van de Plassche, 1982, p. 85, fig. 68).

A very good agreement is found between the Dutch RMSL trend and the lowermost limit of the envelope for the Belgian upper RMSL limit for the last 4000 years. Further back in time the trend curve for the Netherlands dips below the Belgian upper MSL envelope. By 5300 yrs cal B.P. it even sinks beneath the lowermost limit of the extreme lower RMSL estimate for Belgium. Prior to 6700 yrs cal B.P., the difference with this extreme lower limit increases progressively with age, exceeding 3 m by 8000 yrs cal B.P. At this time the RMSL trend curve for the Netherlands already lies well over 4 m below the lower limit of the Belgian upper RMSL band (this difference would still remain more than 2 m with inclusion of index point 5 in the envelope).

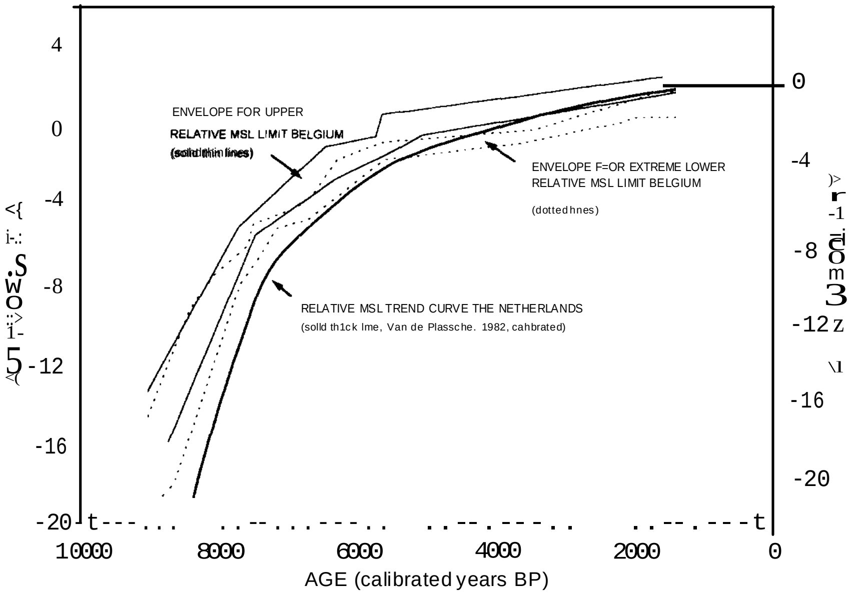

Fig. 10. Comparison of the Belgian error bands for an upper and an extreme lower RMSL limit with the calibrated RMSL trend curve for the western Netherlands.

Even when a considerable error margin is taken into account for the oldest part of the calibrated RMSL trend curve for the Netherlands, a significant difference between the RMSL's of both areas prior to ca. 7000 yrs cal B.P. must be acknowledged. Gradually diminishing, this difference possibly continues up to 4000 yrs cal B.P. If the possibility of lower tidal amplitudes during the earlier Holocene is considered (see above), the extent of this phenomenon becomes even more important.

5. Discussion

5.1. Basal peat as a SL indicator in the Belgian coastal plain

In contrast to the generally accepted notion that peat on free-draining sandy substrates is preferable for SL studies, there appears to be no relation between the permeability of the Pleistocene subsoil and the time/depth position of basal peat index points in the Belgian coastal plain. Apparently local SL-independent groundwater tables were too low to allow substantial peat growth even in the deeper parts of the major pre-Holocene valleys. Conditions favourable to basal peat inception only developed here in direct response to the SL rise. After peat inception, semi-terrestrial conditions prevailed until the rapid establishment of a tidal regime. Although the main pre-Holocene valley in the western coastal plain served as an active drainage channel in the earliest Holocene (Baeteman and Van Strijdonck, 1989; Denys, 1993), the freshwater here probably also remained confined to one or several narrow, or perhaps intermittent streams. The groundwater sloped steeply towards the well-drained valley floor. It should be noted that the densely vegetated hinterland provided relatively little run-off to the valleys at that time (Verbruggen, 1971; Cleveringa et al., 1988). Edaphic dryness explains why basal peat is quite a reliable SL indicator in the area during the early Holocene. Only after ca. 7000 yrs cal B.P. did seepage effects become noticeable in the more gently sloping sandy regions. As the freshwater influence remained minimal elsewhere, basal peat can still be used as a SL indicator in other regions, especially further inland, where local tidal amplitudes were strongly reduced.

5.2. The RSL trend

The limited number, and the low dating accuracy associated with some of the Belgian index points prevent the establishment of a detailed RMSL trend curve. Nevertheless, the envelopes do allow a general assessment of this trend, although actual RMSL positions can rarely be estimated with a precision exceeding ± 1 m.

It appears that the general rise of tide levels and RMSL did not follow a very smoothly declining rate. On the contrary, two rather distinct retardations appear to be present: a more marked one at about 7500-7000 yrs cal B.P., and a second one centring near 5500-5000 yrs cal B.P. Prior to 7500 yrs cal B.P. the mean rate of rise can be estimated to about 7 m/kyr, whereas from this time to 5000 yrs cal B.P. this rate decreases to an average of only ca. 2.5 m/kyr. After 5000 yrs cal B.P. the pace of the RSL rise slows down to ca. 0.7 m per millennium, which is close to the estimated 0.01 m/decade derived from tide-gauge measurements at Oostende during the last two centuries (Baeteman et al., 1992)

Quite similar retardations are also obvious in the calibrated MSL curve for the northern and western Netherlands, where they appear as inflections (Fig. 10; Van de Plassche, 1991). A tentative eustatic explanation was given to the 5000 yrs cal B.P. inflection by Van de Plassche (1991). Because it apparently occurred within a century in the Netherlands, and is matched by several RSL records across the North Atlantic (Delaware, Virginia, Connecticut, Nova Scotia), it was considered a potential meltwater signal. Such an assumption is not convincingly supported by existing models for ice cap melting (Nakada and Lambeck, 1988; Fairbanks, 1989). It also seems that the exact timing and duration of the event are insufficiently known at present to rule out alternative explanations. For instance, Newman and Baeteman (1987) suggest that palaeogeoidal warping decreased strongly in the northwest European region after ca. 5700 yrs cal B.P. (5000 yrs B.P.).

Another possibility, which is suggested by comparative work in the same area by Shennan (1987, 1989), may be that crustal movements decreased appreciably on a large scale at about this time. Also, the possible influence of isostatic phenomena, which could result in similar RSL trends, should not be ignored.

A eustatic origin is, however, quite likely for the 7500-7000 yrs cal B.P. retardations in the Dutch and Belgian RSL records-which remain almost fully obscured in a ^{14}C yrs B.P. time scale. Both model predicted RSL changes, equivalent to melt water input, and far-field RSL records (Nakada and Lambeck, 1988) show a marked retardation at about 6900 yrs cal B.P. (6000 yrs B.P.).

In view of the greater crustal stability of the Belgian coastal region- situated on the margin of the Brabant-London Massif-relative to the Netherlands, this area might be more suited for future investigations regarding eustatic phenomena, as these should become more prominent in less rapidly subsiding areas.

5.3. Higher RSL in Belgium than in the Netherlands

The present analysis confirms the higher position of older Belgian RSL indicators compared to the RSL data from the Netherlands. During the early Holocene the Belgian RSL was several meters higher than the Dutch RSL. This difference decreased progressively with time, disappearing completely at least 4000 years ago. On the other hand, there is good agreement between the Belgian RSL and the altitude at which marine influence is recorded in late Boreal to early Atlantic times at Watten, in nearby northem France (Sommé et al., 1992). The magnitude and behaviour of the difference in RSL between Belgium and the Netherlands indicate that important differential crustal movements, probably of isostatic origin, occurred between the two areas. This will be discussed in detail by Kiden and Denys (unpubl. data).

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