

# Water-level changes in the Flevo area, central Netherlands (5300–1500 BC): implications for relative mean sea-level rise in the Western Netherlands

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## Abstract

The younger (post 4000 cal BC) part of the water-level curve for the eastern Flevo area, central Netherlands runs below the relative mean sea-level (MSL) curve for the western and northern Netherlands (Mededelingen Rijks Geologische Dienst 36(1) (1982) 93pp). We investigated if this difference can be attributed to (i) root rejuvenation of the bulk-dated basal peat samples on which the curve for the eastern Flevo area is based and/or (ii) underestimation of the water depth in which the dated peat accumulated. It appears that these potential sources of error did not influence significantly the results obtained by Roeleveld and Gotjé (De Holocene laagveenontwikkeling in de randzone van de Nederlandse kustvlakte (Noordoostpolder), unpublished Ph.D. Thesis, Vrije Universiteit Amsterdam, 1993, pp. 76–86). On the basis of new and recently published water-level data from the eastern and southwestern Flevo area we confirm, refine, and tentatively extend the water-level rise reconstruction by Roeleveld and Gotjé and establish a relative MSL-trend curve for the central Netherlands. The systematic age differences of our radiocarbon dates on various fractions of four new basal peat samples from the eastern Flevo area support the interpretation by Roeleveld and Gotjé that the younger part of the 1982-MSL curve may be based on basal peat samples (all from the Rotterdam area), that have been dated 100–200 yr too old. If this interpretation is correct, the fact that the relative MSL curve for the central Netherlands lies below the 1982-MSL curve cannot be interpreted to indicate less crustal subsidence for the Rhine-Meuse delta, as predicted by geophysical modeling (J. Quat. Sci. 17 (2002) 535).

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## 1. Introduction

Accurate relative mean sea-level (MSL) curves are relevant for questions of differential land-level change, paleo-tidal range, sediment transport, accommodation space, ecology, and pre-history. It was, therefore, a significant result when Roeleveld and Gotjé (1993; henceforth RG93) arrived at a relative water-level rise curve for the area of Schokland in the eastern part of the Flevo area, central Netherlands (Fig. 1), which follows a

trend, from ca. 4200 cal BC onwards, below the water-level curve held to approximate the relative MSL rise for the western and northern Netherlands (Van de Plassche, 1982) (Fig. 2). This 1982 MSL curve is based on 15 basal peat dates from river dunes near Rotterdam, three from the northern Netherlands, one from the central Netherlands and five MSL estimates (not based on basal peat data) from the western, central and northern coastal areas. RG93 argued that the difference between the two curves cannot be attributed to differential land movements. They put forward that the two results can be reconciled if, first, the 1982-MSL curve is replaced by Van de Plassche's 1982 water-level rise curve for the Rotterdam area (the "river-dune curve"), and second, if

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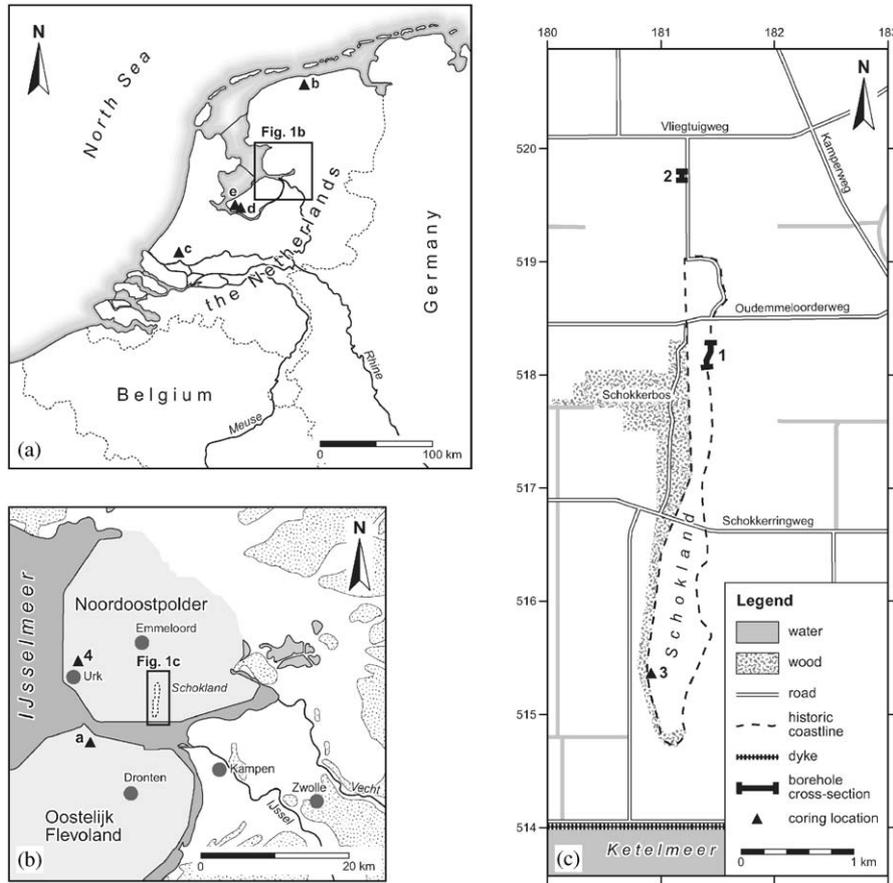


Fig. 1. Location maps of study areas and sampling sites mentioned in the text. (a) Areas outside of the main study area (Fig. 1b) where water-level index data were collected, b: Engwierumer polder (Griede, 1978), c: near Rotterdam (Van de Plassche, 1982), d: and e: near Almere (Makaske et al., 2003); (b) eastern Flevo area, 4: Urk (Roeleveld and Gotjé, 1993), a: Swifterbant (Ente et al., 1986); and (c) former island of Schokland with main study sites (1, 2 and 3) of Roeleveld and Gotjé (1993). For the present paper we revisited site 1.

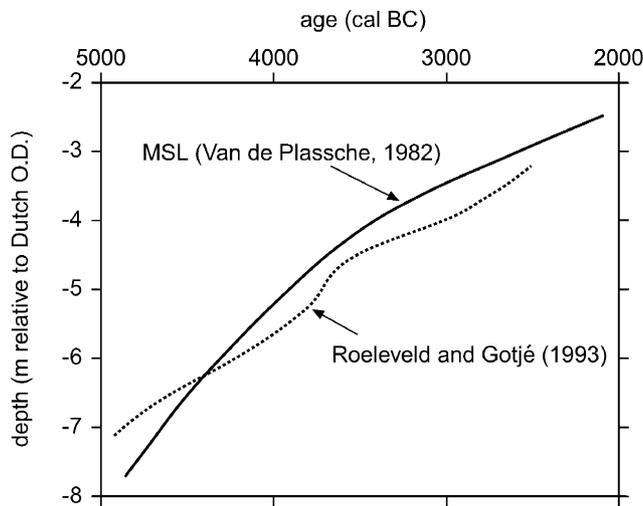


Fig. 2. Comparison of the relative water-level rise curve for the eastern Flevo area (Roeleveld and Gotjé, 1993) with the MSL curve for the western and northern Netherlands (Van de Plassche, 1982).

the MSL curve thus revised is then shifted 100–200 years to younger ages allowing for inferred ageing of many of the basal peat age-depth data due to inclusion of older

(soil) carbon. Van de Plassche (1995) presented data and arguments against the first step suggested by RG93, but accepted the possibility that many of the very sandy peat to peaty sand samples collected from the slopes of river dunes near Rotterdam were dated too old due to the presence of older carbon. Thus, Van de Plassche (1995) left the 1982-MSL curve unchanged, but with the note that the post-4000 cal BC part of the curve may be up to ca. 150 yr too old if the relevant samples have indeed been contaminated by soil carbon. On the other hand, RG93 dated 2–3 cm-thick bulk peat samples without rigorously removing the potentially rejuvenating root fraction (Streif, 1971; Van de Plassche, 1982). Moreover, many of their samples were collected slightly above the substrate surface and might represent peat growth in somewhat greater water depth. In this paper we investigate if the differences between the Schokland and the 1982-MSL curves can or cannot be attributed to the reliability and interpretation of the age-depth data from Schokland. Our objective is to test the hypothesis that the younger part of the Schokland curve runs below the 1982-MSL curve because (1) the radiocarbon ages of the bulk-dated peat samples obtained by RG93 are too

young, and/or (2) the water depth in which the peat of the dated samples accumulated was underestimated.

## 2. Approach

First, we summarise how RG93 selected the (near-) basal peat samples for radiocarbon dating, evaluate how they determined the vertical error margins for their water-level index points, and define the discrepancies between the re-evaluated Schokland age-depth data and the 1982-MSL curve. We then test the first part of our hypothesis by radiocarbon dating, using accelerator mass spectrometry (AMS), three fractions (organics <200 µm, botanical macroremains, and roots) of four new basal peat samples from one of the two main study sites of RG93, and the second part of our hypothesis by assessing the published and new evidence for water depth during initial or early peat accumulation on the dune slopes.

## 3. Re-evaluation of published water-level data from Schokland

RG93 reconstructed the mid-Holocene water-level rise in the area of Schokland using two suites of radiocarbon-dated (near-)basal peat samples from the slopes of two buried Younger Dryas river dunes located ca. 1500 m apart (site 1 in parcel P13 and site 2 in parcel J118; Fig. 1c). In addition, their age-depth database included isolated basal peat dates from three sites located within a radius of 2 to 12 km from their two main study sites (sites 3, 4, and a; Figs. 1b and c. Table 1 (after Appendix B in Gotjé, 1993) summarises their dating results and other relevant sample information.

### 3.1. Sample selection

In many of the 15 6-cm-wide cores collected by RG93 from sites 1 and 2 it proved difficult, due to gradual sand–peat transitions and very dark coloring of the dune sand, to establish visually the depth of initial peat accumulation on the dune surface. RG93 applied different criteria for the selection of samples representing the onset of peat growth within the cores from sites 1 and 2. At the latter site, sample intervals for radiocarbon analysis were selected as the deepest 2–3 cm interval with a minor quantity of soil fungi, an abundance of peat forming taxa, and a very small percentage of sand >240 µm. Effectively, the samples from site 2 were collected above the sand–peat interface. At site 1, they selected 2–3 cm-thick samples for radiocarbon dating immediately above the depth where pollen concentration decreased strongly, arguing that concentration values should be relatively high in the

dune paleo-soil. On the basis of the rather high sand content RG93 concluded that many of the samples from site 1 seem to have been taken from the very top of the dune sand, but after evaluation of the dating results they interpreted only three samples (index points 7, 9 and 11; Table 1) to have contained old soil carbon. They also point out that the high (20–30%) volume of (clean white) sand in sample P13-6 (index point 8; Table 1) must have been blown or washed in. The interpretation that this sample represents peat growth above the dune surface is supported by very low abundance of soil fungi and high abundance of peat forming taxa.

### 3.2. Vertical error margins: sample depth, compaction, and water depth

The vertical error margins of water-level index points such as collected in the Schokland area include errors for measuring the sample depth relative to NAP (Nieuw Amsterdams Peil; national geodetic Datum, about mean sea level), correcting the measured sample depth for compaction, and for estimating how much the dated peat sample was formed above or below the local average water level. RG93 did not add to their sample depth an error margin associated with measuring the in-core depth below the surface and the elevation of the surface relative to Datum. Here, we assume a range of  $\pm 4$  cm for all samples.

Many of the samples were collected slightly (1–6 cm; in one case 14 cm) above the surface of the dune sand (see above). To account for compaction of a peat sample and of the peat between a sample and the dune surface, RG93 applied a minimum and a maximum correction factor of 0 and 3, respectively. We consider the possibility of zero compaction unlikely and use a minimum and maximum correction factor of 1.5 and 2.5, respectively. The maximum factor of 2.5 (rather than 3) is based on an analysis of age-depth data from the Schokland area (Gotjé, 1993) which indicates a compaction factor of slightly more than 2.

The composition of the radiocarbon-dated samples from the area of Schokland varied considerably, ranging from carr peat to (coarse) detritus (Table 1). Given that the majority of their samples consisted of carr peat, fen-carr peat, and sedge peat with birch remains, RG93 argued that the age-depth data older than 2500 cal BC need no or very little correction for water depth during initial peat growth. Here, we quantify their paleohydrological assessment as a vertical uncertainty of  $\pm 10$  cm for each sample except for samples 3B and 1B. For these two youngest samples, RG93 left open the possibility that the peat, which consisted of sedge and reed–sedge remains, respectively, was formed below the average water level. We assume that peat growth in these cases occurred in an average water depth of 10 cm (Table 1).

Table 1  
Age-depth data collected or used for water-level reconstruction in the Schokland area by Roeleveld and Gotjé (1993)

Site <sup>a</sup>	Ind. pt. <sup>b</sup>	Peat dated <sup>c</sup>	Lab. Nr. GrN-	<sup>14</sup> C-age (yr BP)	Calibrated age (cal BC) <sup>d</sup>		Sample depth (m below NAP)	Vertical error margin in Fig. 3 (m below NAP) <sup>e</sup>
					±1σ	±2σ		
a	1	Carr	5067	5610 ± 60	4530–4390	4590–4330	6.15–6.16	5.97–6.29
1	3	Reed-sedge	16381	3350 ± 140	1830–1470	2010–1310	2.39–2.42	2.18–2.44
1	5	Sedge	16382	3740 ± 160	2370–1930	2590–1730	3.22–3.24	3.02–3.25
1	6	Detritus	15128	4330 ± 70	3070–2870	3170–2770	3.98–4.00	3.74–4.07
1	7	Very sandy	15129	4420 ± 100	3230–2950	3370–2810	4.12–4.14	3.95–4.28
1	8	<i>Juncus</i>	15130	4720 ± 90	3590–3370	3690–3250	4.66–4.68	4.47–4.80
1	9	Wet sedge-carr	15131	5310 ± 50	4190–4070	4250–4010	5.39–5.41	5.20–5.53
1	10	Sedge-carr	15132	5400 ± 50	4290–4170	4350–4110	5.98–6.00	5.79–6.12
1	11	Sedge-carr	15133	5950 ± 80	4930–4730	5030–4650	6.53–6.55	6.35–6.68
2	12	Sedge w. birch	16367	4320 ± 60	3030–2850	3130–2790	3.97–4.00	3.75–4.11
2	13	Dry sedge w. birch	16373	4350 ± 45	3050–2910	3110–2850	4.10–4.13	3.92–4.27
2	14	Dry sedge w. birch	16366	4790 ± 70	3650–3490	3730–3410	4.39–4.42	4.19–4.55
2	15	Sedge w. birch	16370	4880 ± 60	3730–3590	3790–3530	4.78–4.81	4.54–4.90
2	16	Sedge	16369	4920 ± 60	3790–3650	3850–3590	4.91–4.93	4.72–5.05
2	17	Sedge	16368	4990 ± 60	3850–3710	3910–3650	5.16–5.19	4.96–5.32
2	18	Very wet sedge	16372	5000 ± 60	3870–3730	3930–3670	5.35–5.38	5.16–5.52
2	19	Sedge w. birch	16371	5160 ± 40	4010–3910	4050–3870	5.70–5.73	5.49–5.85
3	20	Wet sedge-carr	16251	5820 ± 60	4750–4610	4830–4550	6.74–6.76	6.56–6.89
4	21	Carr	16258	5970 ± 60	4930–4770	5010–4710	7.15–7.20	6.93–7.33

<sup>a</sup>See Figs. 1b and c; index point a from Ente et al. (1986).

<sup>b</sup>As used in this study.

<sup>c</sup>Bulk-dated samples from which rhizomes were removed; for more details, see Appendix B in Gotjé (1993).

<sup>d</sup>Obtained using the Groningen calibration program (Van der Plicht, 1993) version CAL25 with a 200-yr-smoothed calibration curve.

<sup>e</sup>Vertical error includes: sample thickness, compaction correction (see text), errors in measurement of altitude of coring location and in-core depth (±4 cm) and a standard error of ±10 cm for uncertainty in the relationship between water level and peat growth (except for index points 3 and 5, see text).

### 3.3. Age

Streif (1971, 1972) demonstrated the rejuvenating effect of reed rhizomes on the radiocarbon age of *Phragmites* peat samples, coined the “Streif effect” by Roeleveld (1974). RG93 submitted 2–3 cm-thick bulk peat samples for conventional radiocarbon dating. From these samples they removed only the coarser, potentially age-rejuvenating fragments such as rhizomes. Consequently, it is still possible that samples were dated too young due to the presence of fine rootlets and medium-sized younger plant elements which remained in the sample. RG93 pointed out that while none of the samples from site 1 were described as composed of organic detritus, it cannot be excluded entirely that samples from site 1 with a depth >–3.4 m NAP contained some (slightly) older detrital material. Index point 6, however, consisted, in accordance with stratigraphic evidence (Fig. 4.1. in Gotjé, 1993), entirely of coarse organic detrital material deposited in (very) shallow pools within a carr or in shallow open water conditions in the immediate vicinity of carr. Even if the stratigraphic and paleo-geographical context of the sample suggests that the sampled material originated

locally (i.e., its age might well be depth-representative), we reject index point 6 as unsuitable for water-level reconstruction on the ground that the reliability of its age cannot be known independently. We also reject index point 7 on the ground that the sample contained >50% sand and very many fruit bodies of soil fungi (*Cenococcum*). With RG93 we agree that this sample may have been contaminated by soil carbon, although this is not evident from its age-depth position. Perhaps, roots and sub-surface stem parts of younger plants present in this very sandy sample may have compensated for possible ageing effects. The sample of index point 9 was taken in the very top of the dune sand and also contained a large number of soil fungi. We concur with RG93 that index point 9 is possibly too old due to contamination with older (soil) carbon. The fact that the age of index point 9 is reversed with respect to that of the slightly deeper index point 19, the sample of which was collected 4 cm above the sand surface and contained only few fruit bodies of *Cenococcum*, supports this evaluation. RG93 attribute the excentric age-depth position of index point 11 to contamination by older soil carbon and/or older detrital material. The ages of the bulk peat samples were obtained by recalibrating

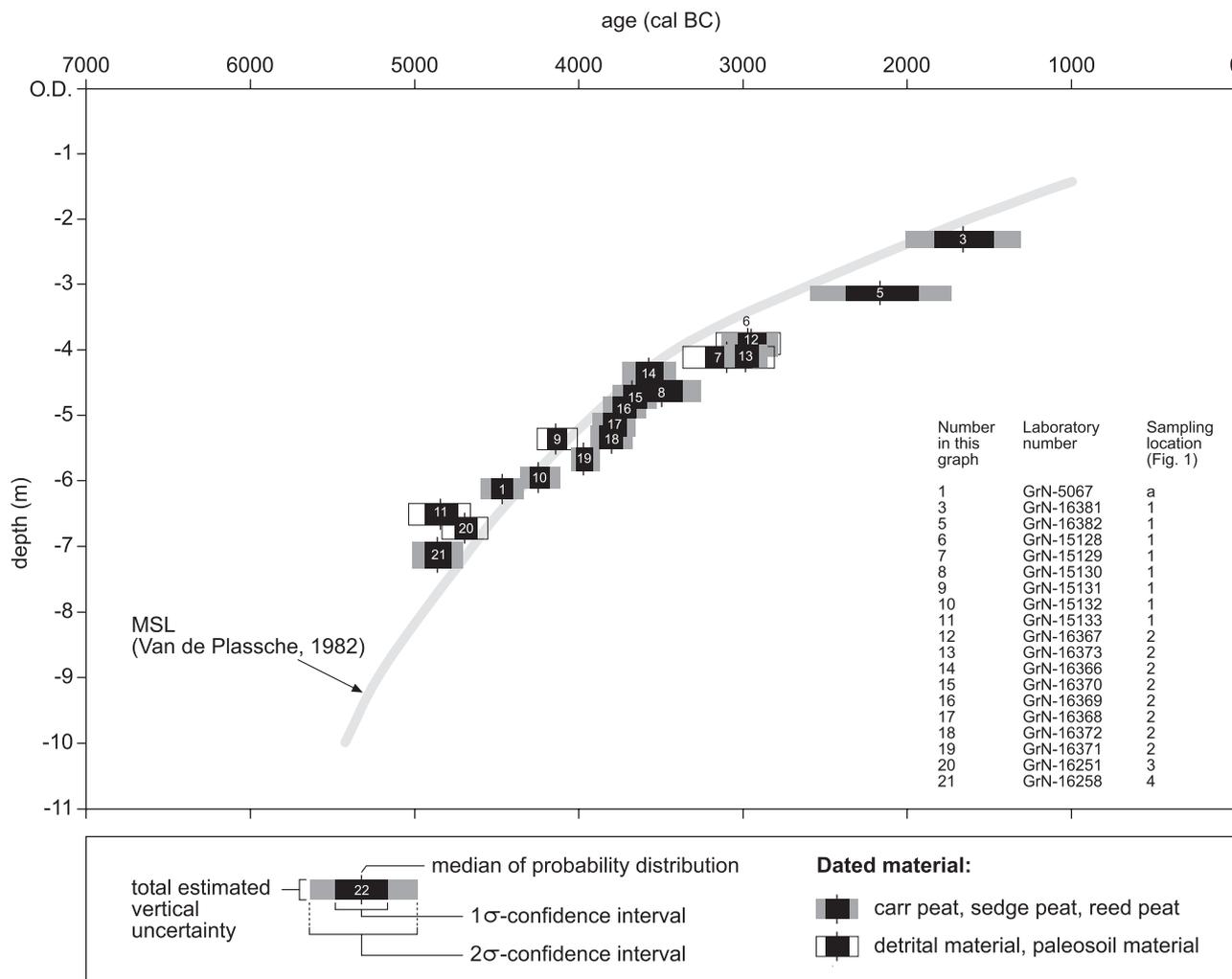


Fig. 3. Age-depth plot of re-evaluated and recalibrated water-level index data from Schokland and surroundings; original data in Roeleveld and Gotjé (1993) and Ente et al. (1986).

their radiocarbon ages using a 200-yr smoothed calibration curve (Van der Plicht, 1993; Stuiver and Van der Plicht, 1998).

### 3.4. Comparison with the 1982-MSL curve

An age-depth plot of the water-level index data from Schokland and surroundings, using the modified vertical error margins and recalibrated ages (Table 1), is shown in Fig. 3. Comparison of the re-evaluated RG93 water-level data with the relative MSL curve for the western and northern Netherlands shows that the remaining water-level error boxes older than 4000 cal BC plot above or on the MSL curve, while all but one (index point 14) of the error boxes younger than 4000 cal BC plot, as found by RG93, partly or entirely below the 1982-MSL curve. In the following sections we investigate if the Schokland water-level data which plot (largely) below the MSL curve do so due to rejuvenation of the (bulk-dated) peat samples by younger rootlets

and/or due to underestimation of water depth during peat growth.

## 4. Age rejuvenation

### 4.1. Approach and methods

RG93 submitted 2–3-cm-thick bulk peat samples for conventional radiocarbon dating. From these samples they first removed the coarser, potentially age-rejuvenating fragments (such as rhizomes). To test the first part of our hypothesis, i.e. to determine if finer rootlets and other younger elements remaining in the samples have (had) a significant rejuvenating effect, we collected four basal peat samples from study site 1 of RG93 and dated for each sample the (largely) allochthonous root fraction and two autochthonous organic fractions, i.e. the organic fraction <200 μm and the fraction of botanical macrofossils. The wide error margins that

characterise their youngest index points (5 and 3, Fig. 3) motivated us to focus on the younger part of the RG93 data set.

First we mapped the sub-surface topography of the north slope of the dune and the overlying peat stratigraphy at the study site, and collected four short peat cores with peat–dune sand interfaces at depths between ca.  $-4.75$  and ca.  $-2$  m NAP (in order of decreasing depth: D1, C4, A3, and B2). The four cores were cut into 1 cm-thick slices, which were treated with KOH and washed over a  $200\ \mu\text{m}$  sieve. The organic fraction  $<200\ \mu\text{m}$  (henceforth the residue fraction) was caught, left to settle and dry out into a thin crust, while the fraction  $>200\ \mu\text{m}$  was analysed for botanical macroremains. On the basis of first appearance or strong increase of peat forming vegetation, (near-)absence of soil fungi, and estimates of sand content (10% or less) we selected from each of the four cores the 1–2 cm interval best representing the onset of in situ peat growth on the dune slope (see below). The macrophytes from this interval were then split into a fraction of botanical macroremains such as seeds, fruits, bud scales, leaf fragments, and small twigs (the sample from core A2 did not yield a suitable sample) and the root fraction (mainly rhizomes, roots, rootlets, and sub-surface stem parts) from which we removed, like RG93, the larger components. Per sample, the macrofossils (if available) and a random sub-sample from each of the other two fractions were AMS dated. Fruit bodies of *Cenococcum* (small firm spheres  $>200\ \mu\text{m}$ ) present in the washed organic fraction  $>200\ \mu\text{m}$  were not included in either of the two sub-fractions  $>200\ \mu\text{m}$ .

#### 4.2. Stratigraphy

The peat stratigraphy in our cores from the north slope of the buried river dune at study site 1 closely resembles that on the south slope as described by Gotjé (1993) (Fig. 4). Apparently, our coring and sampling locations on the north slope differed sufficiently from those of Gotjé (1993) on the north slope that we missed the detritus deposit (although carr peat and coarse detritus can be hard to distinguish). In our two deepest cores (D1 and C4), the ca. 30 cm-thick bed of *Phragmites* peat contained a thin (4–5 cm) layer of humic clay which correlates with the 10-cm-thick lenses of clay found by Gotjé (1993) in the same peat bed at greater distances from the dune.

#### 4.3. Sample selection

The results of the botanical macroremains analysis are summarised in four diagrams (Fig. 5). In Core D1 (Fig. 5a), composed of compacted sedge–carr peat, we selected the interval of 401–400 cm below the surface for radiocarbon analysis. Here, with respect to the deeper

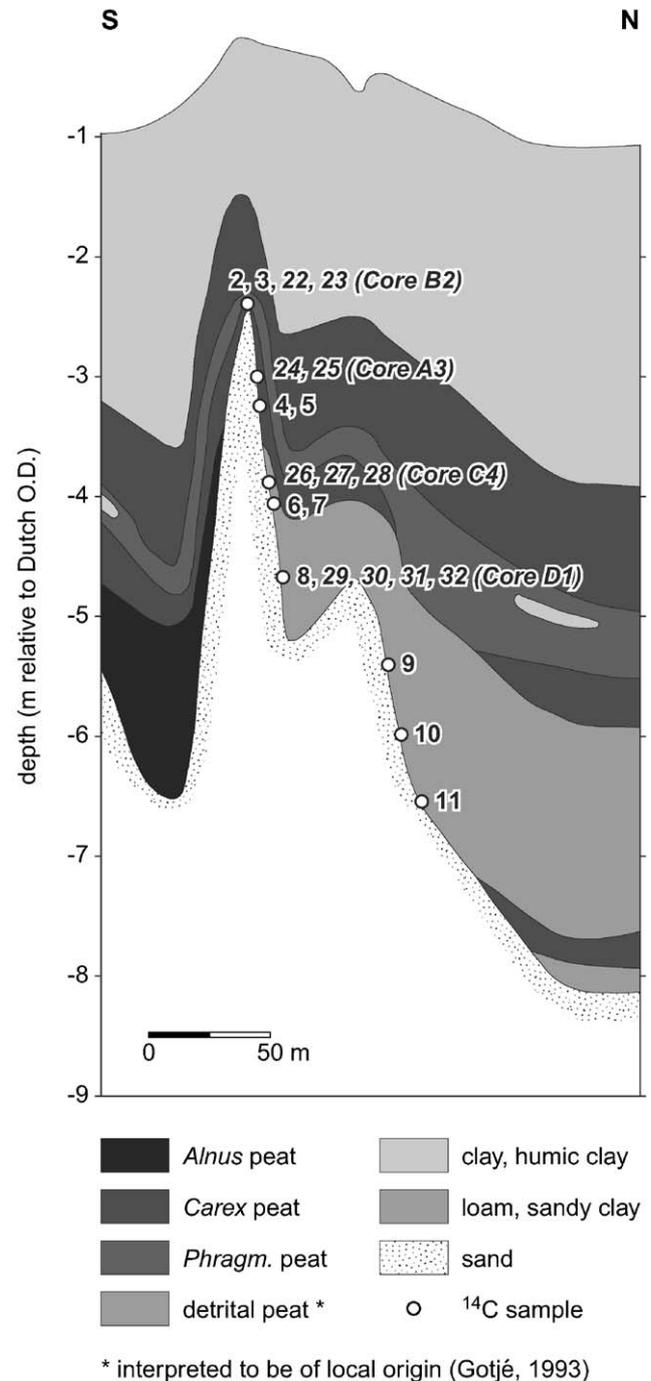


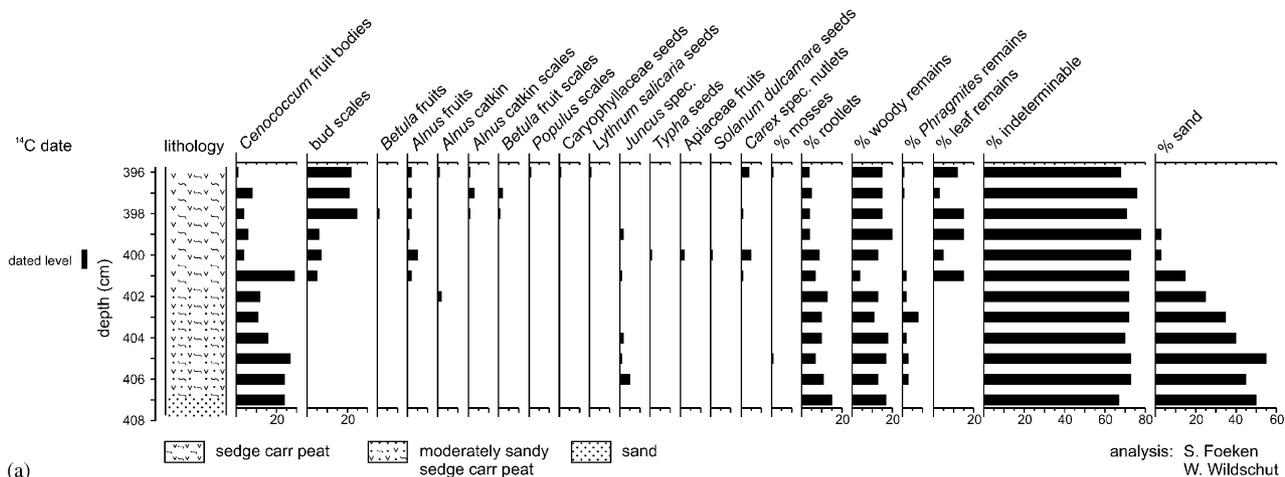
Fig. 4. Peat stratigraphy at the Schokland study site 1 and position of basal peat samples on the north slope of the buried river dune (after Gotjé, 1993). Upright numbers refer to samples collected by Roeleveld and Gotjé (1993); numbers in italics denote samples collected for this study from cores D1, C4, A3 and B2.

levels, the estimated sand content has dropped to less than 10%, *Typha* sp. appears, *Carex*, *Alnus*, and bud scales increase, while *Cenococcum* fruit bodies decrease. The presence of leaf fragments suggests that conditions were wet enough for initial basal peat growth. On the basis of first appearance of leaf fragments, *Carex*,

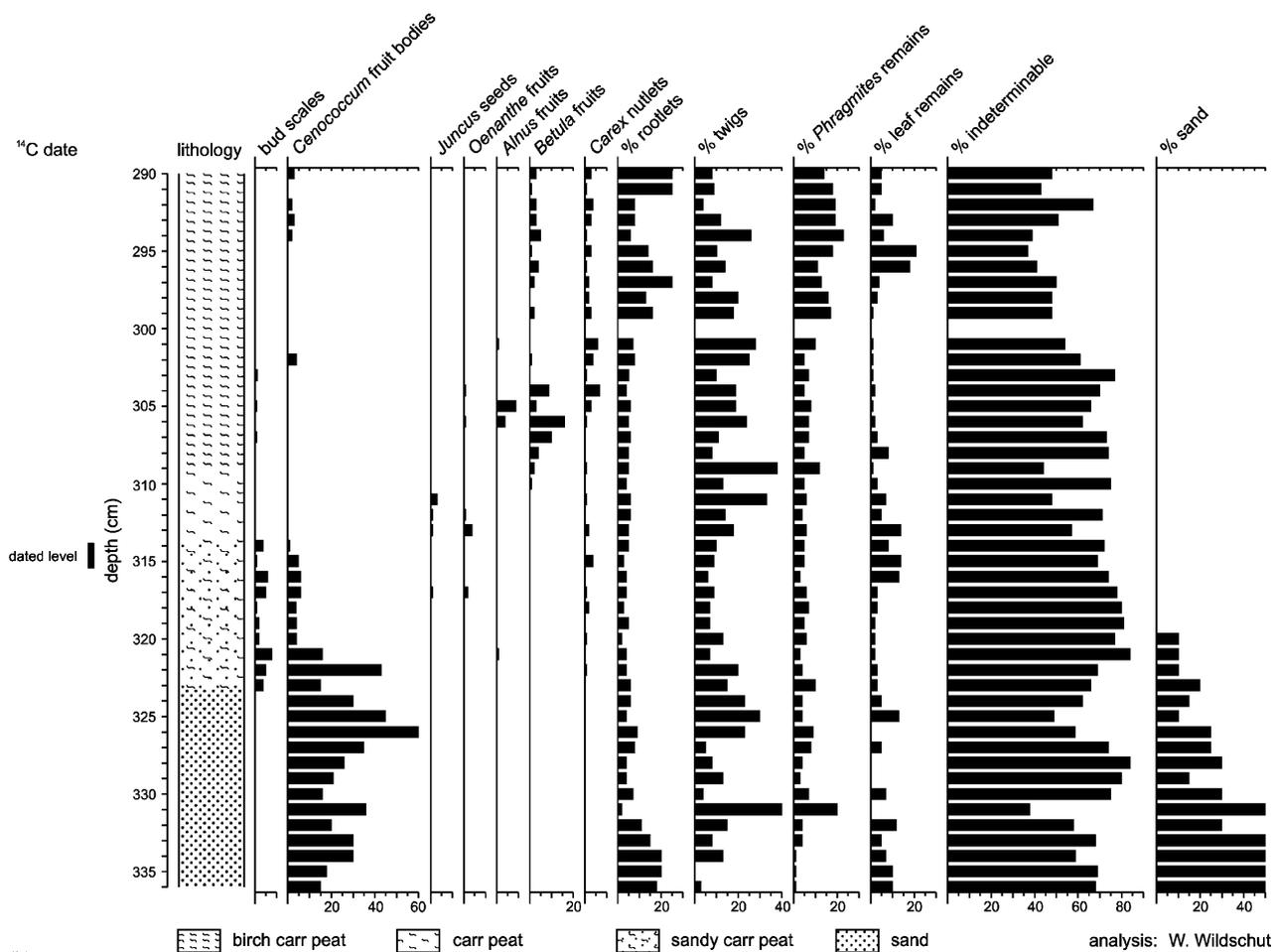
*Alnus*, and bud scales, we could also have selected the sample from 402 to 401 cm below the surface for AMS dating.

In core C4 (Fig. 5b), composed of (sedge-)carr and birch-carr peat, the selection of a sample for radio-carbon dating was complicated by the fact that (1) the

estimated sand content decreases irregularly, (2) the percentages of *Cenococcum* fruit bodies vary strongly and they are present well into the base of the peat, and (3) branches (or woody rootlets?) and leaf fragments were found throughout the sandy substrate. These data probably indicate disturbance of the top of the dune

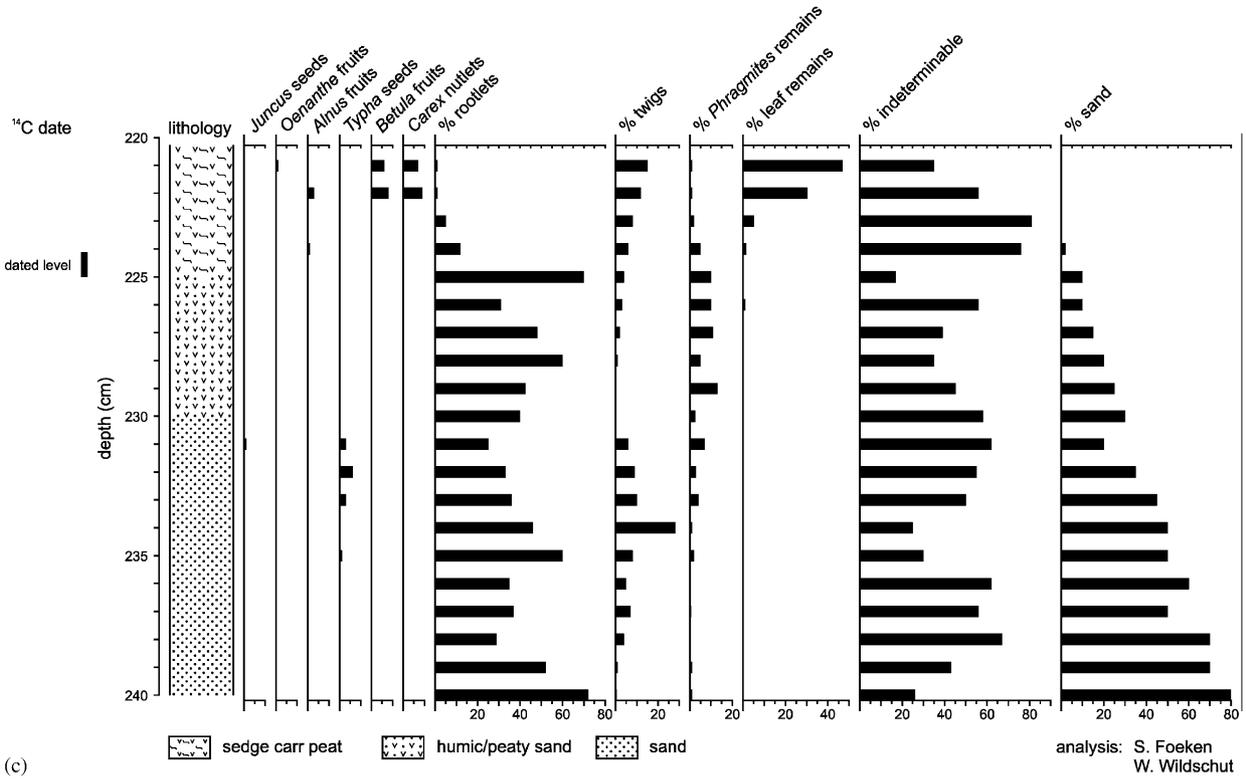


(a)

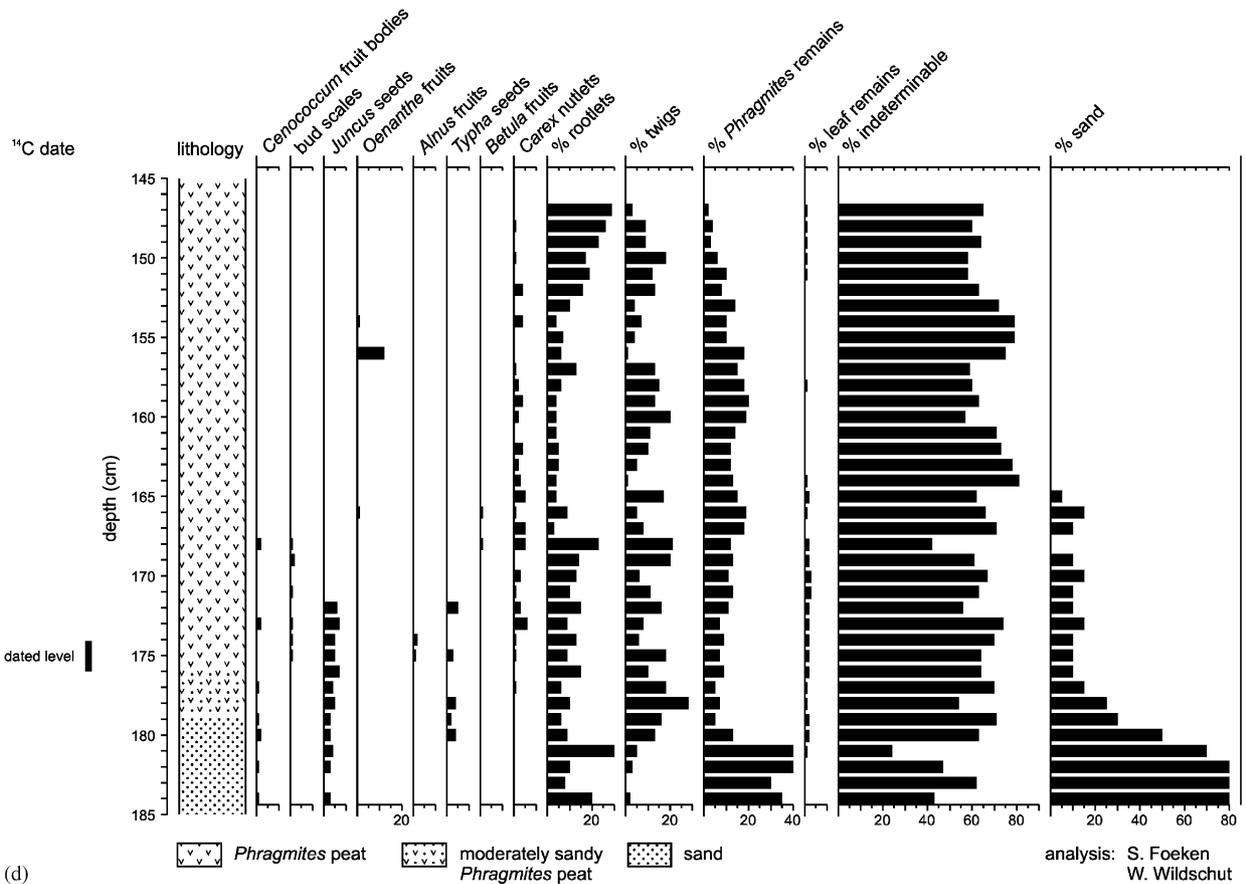


(b)

Fig. 5. Results of the botanical macroremains analysis of the four cores collected for this study: (a) core D1, (b) core C4, (c) core A3, and (d) core B2.



(c)



(d)

Fig. 5. (Continued)

sand. Eventually, we selected the interval 323–321 cm below the surface for radiocarbon analysis for the reason that bud scales appear and in significant quantities, and the sand content has dropped to 10%. Again, the preservation of leaf fragments, present in variable quantities throughout the core, suggests more or less wet conditions.

In core A3 (Fig. 5c), composed of sedge–carr peat, we selected interval 225–224 cm below the surface for  $^{14}\text{C}$ -dating. In the absence of *Cenococcum* fruit bodies and macroremains of peat forming vegetation, we decided on this interval on the basis of, relative to deeper levels, very low sand content (<5%), first *Alnus* fruits, sharp decrease in rootlets, and the start of consistent increase in leaf fragments.

Finally, in core B2 (Fig. 5d), composed of *Phragmites* peat, we selected the interval 176–174 cm below the surface for dating. On the basis of estimated sand content (10%) we could have selected the sample interval 1 cm deeper, but bud scales, *Typha* seeds and *Carex* nutlets appear together for the first time at a depth of 176–175 cm. The continued presence of 10–15% sand within the peat up to a depth of 164 cm below the surface suggests some disturbance of the dune slope surface. As in the three deeper cores, the presence

of leaf fragments points to relatively wet conditions (note, however, that the absence of leaf fragments does not necessarily imply that peat forming conditions were relatively dry). The fraction of macroremains from the sample was lost during preparation for dating.

The radiocarbon ages of the dated fractions were calibrated using a 200 yr smoothing for the residue and root fractions, and a 60 yr smoothing for the botanical macroremains.

#### 4.4. Dating results

The dating results are summarised in Table 2. The relative age differences within each set of fractions are shown in Fig. 6. In all four cases, the residue fraction (<200  $\mu\text{m}$  fraction) gives the oldest age and, not surprisingly, the root fraction (rest fraction >200  $\mu\text{m}$ ) the youngest. The age differences between the residue and root fractions from cores D1, C4, and B2 are significant at  $1\sigma$ , and the residue and root fractions from core A3 at  $2\sigma$  (index points 24 and 25). The ages of the residue fractions overlap at the  $1\sigma$  and  $2\sigma$  levels with those of the botanical macrofossils, except in the case of index point 31. This index point is rejected as too young because the macroremains dated younger than the root

Table 2  
Age-depth data from study site 1 at Schokland obtained for this study

Core	Index point <sup>a</sup>	Material dated <sup>b</sup>	Lab. Nr. GrA-	$^{14}\text{C}$ -age (yr BP) <sup>c</sup>	Calibrated age (cal BC) <sup>d</sup>		Sample depth (m below NAP)	Vertical error margin in Fig. 7 (m below NAP) <sup>e</sup>
					$\pm 1\sigma$	$\pm 2\sigma$		
B2	22	Organic residue <200 $\mu\text{m}$	16219	$3440 \pm 50$	1830–1690	1890–1630	2.35–2.37	
	23	Root fraction	16225	$3290 \pm 50$	1630–1510	1690–1450	2.35–2.37	
	<b>22/23</b>	Bulk (reconstructed)		$3365 \pm 40$ av.	1710–1610	1770–1570	2.35–2.37	2.15–2.40
A3	24	Organic residue <200 $\mu\text{m}$	16216	$3810 \pm 60$	2330–2150	2410–2070	2.85–2.86	
	25	Root fraction	16217	$3500 \pm 50$	1890–1750	1950–1690	2.85–2.86	
	<b>24/25</b>	Bulk (reconstructed)		$3655 \pm 40$ av.	2090–1970	2150–1910	2.85–2.86	2.64–2.88
C4	26	Organic residue <200 $\mu\text{m}$	17064	$4400 \pm 45$	3130–2990	3190–2930	3.87–3.89	
	27	Root fraction	16221	$4210 \pm 60$	2890–2710	2970–2630	3.87–3.89	
	<b>28</b>	Botanical macroremains	12714	$4340 \pm 50$	3010–2910	3090–2870	3.87–3.89	3.66–3.92
	26/27/28	Bulk (reconstructed)		$4340 \pm 30$ av.	3014–2930	3054–2890	3.87–3.89	
D1	29	Organic residue <200 $\mu\text{m}$	16224	$4670 \pm 60$	3510–3350	3590–3270	4.67–4.68	
	30	Root fraction	16220	$4540 \pm 50$	3330–3170	3410–3110	4.67–4.68	
	31	Botanical macroremains	12716	$4350 \pm 70$	3070–2890	3270–2830	4.67–4.68	
	<b>32</b>	Botanical macroremains	12718	$4570 \pm 50$	3410–3230	3450–3090	4.67–4.68	4.49–4.71
	29/30/32	Bulk (reconstructed)		$4585 \pm 45$ av.	3390–3250	3450–3190	4.67–4.68	

<sup>a</sup>Index points 32 and 28 are true water-level index points; index points 24/25 and 22/23 are, for lack of a date on botanical macroremains, surrogate index points obtained by averaging the ages of index points 24 and 25, and 22 and 23, respectively.

<sup>b</sup>Sample index point 28: some leaf fragments, 4 bud scales, 1 *Mentha* seed, 2 thin twigs; sample index point 31: 2 leaf fragments, 3 *Alnus* seeds, 5 *Alnus* seed scales, 1 *Solanum* seed, 2 *Umbelliferae* seeds; sample index point 32: many leaf fragments, 1 bud, 3 bud scales.

<sup>c</sup>The age of index point 31 is rejected as too young.

<sup>d</sup>The  $^{14}\text{C}$  ages of residue and root fractions were obtained using a 200-yr-smoothed calibration curve; for ages of botanical macroremains a 60-yr-smoothed curve was used. The Groningen calibration program (Van der Plicht, 1993) version CAL25 was used for calibration.

<sup>e</sup>Vertical error includes: sample thickness, compaction correction (see text), errors in measurement of altitude of coring location and in-core depth ( $\pm 4$  cm) and an upward range of 10 cm to account for 0–10 cm water depth (see text).

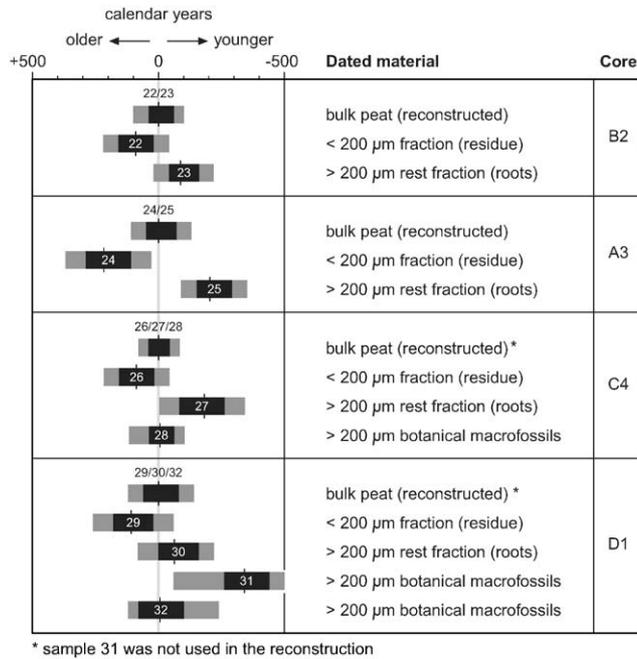


Fig. 6. Relative age differences of dated fractions per sample from cores D1, C4, A3, and B2, each centered on the median of the probability distribution of the average age of the dated fractions per sample. This average age approximates the age which would have been obtained had the sample been bulk dated.

fraction, suggesting an allochthonous origin or a spurious date.

Table 2 and Fig. 6 also present the average ages for the two or three fractions per sample weighted on the basis of the  $1\sigma$  errors. The average ages for the samples from cores D1 and C4 compare closely to the ages of the associated macroremains (index points 32 and 28, respectively). Assuming equal mass for each of the dated fractions within the original sample, these averages approximate the ages which would have been obtained if the original samples (minus large roots and rhizomes) had been conventionally (bulk) dated. This assumption is probably incorrect for most samples, but for lack of reliable estimates of the mass of each fraction per sample we refrain from guessing their relative proportions.

Before we can fully analyse and discuss the implications of these dating results with respect to the first part of our hypothesis, we first need to determine the relationship of the four residue fractions and of the two macrofossil fractions to the contemporaneous average water level.

#### 4.5. Indicative meaning of the dated fractions

The peat at the base of core D1 is composed of sedge–carr peat (Fig. 5a). The presence of leaf remains within the dated interval (401–400 cm below the surface) indicates that the average water table was above the

surface for most of the year. The presence, between 399 and 396 cm, of bud scales indicates an intermingling of carr elements, most likely alder or birch. Where birch or alder carr is mixed with a sedge and reed/mace community, the average water table is assumed to have risen to at least 10 cm above the surface. We conclude that initial peat growth occurred at a water depth of 0–10 cm.

The peat at the base of core C4 is composed of carr peat with sedge and perhaps some reed. For the dated interval (323–321 cm below the surface; Fig. 5b), the presence of bud scales together with leaf remains and nutlets of *Carex*, indicates that an alder carr with an understory of sedges was established on the site, and we infer an average water table between 0 and 10 cm above the surface for most of the year. From 317 cm onward *Juncus* and *Oenanthe* were established on the site indicating more permanent wet conditions, i.e., the average water table was above the surface for most of the year, probably some 15–20 cm.

The peat at the base of core A3 is composed of sedge–carr peat. The abrupt and drastic increase in percentage of leaf fragments, *Betula* fruits and *Carex* nutlets just 2 cm above the dated interval (225–224 cm below the surface; Fig. 5c) indicates permanently wet conditions. Again, we arrive at an estimate for initial peat growth of 0–10 cm below the average water level.

Finally, the peat at the base of core B2 is composed of *Phragmites* peat. The presence in the dated interval (176–174 cm below the surface; Fig. 5d) of leaf remains, *Typha* seeds, *Alnus* fruits, *Juncus* seeds, and bud scales point to peat growth at an average water depth of 0–10 cm. Subsequently, a denser alder carr must have shaded out *Typha*, but some *Phragmites* may have persisted. No major changes follow in the sequence, except for the presence of *Oenanthe* fruits at 157–156 cm, which probably indicates a temporary increase in water depth at that time. Overall, it seems that peat accumulation kept pace with the water-table rise.

#### 4.6. Discussion

In spite of the marked differences in peat composition (sedge–carr peat, *Phragmites* peat), the botanical macrofossils do not indicate significant differences in water depth during initial peat growth. If our interpretations are correct, this result confirms that initial peat accumulation (i.e. including organics in the residue and macrophyte fractions) on the slope of a gradually submerging river dune occurs most likely 0–10 cm below the local mean (high) water level (Van de Plassche, 1982; Roeleveld and Gotjé, 1993). If, however, the dated residue and macrofossil fractions (obtained from the same 1- or 2-cm-thick sample slice) accumulated synchronously in a water depth of 0–10 cm, why then is there a systematic (albeit statistically non-significant)

age difference between the residue and macrofossil fractions of cores C4 and D1? The age difference could imply a difference in indicative meaning.

Barring some unknown fractionation process associated with the partial degradation of organic matter, the simplest explanation for this systematic age difference is that the residue fraction contains organic carbon particles stemming from the period between last terrestrial soil formation and the earliest stages of full aquatic peat accumulation. As the local average (high) water level rises and a given point P on the dune slope comes increasingly within reach of the higher ranges of the tidally and/or seasonally fluctuating water level, the conditions for partial preservation (or incomplete degradation) of (soil) organic material at that point gradually improve until the average (high) water level reaches the level of point P and conditions for (basal) peat accumulation proper set in. From this time onward the preservation potential of botanical macrofossils increases sharply too.

The implication of this model of early preservation of strongly degraded (soil) organic particles leading over into peat growth proper is that the residue fraction of samples collected at or immediately above the dune surface contains carbon produced over a span of time

and over a vertical range of ca. 20 cm above to several cm below the average (high) water level. If correct, this blurred relationship between age and depth reduces the value of the residue fraction as a water-level indicator. Consequently, of the three dated fractions the botanical macroremains (cores D1 and C4) yield the most reliable water-level index points, although the excentric position of index point 31 is a reminder that such macrofossils need not always be in situ (Törnqvist et al., 1992, 1998). Unfortunately, cores A3 and B2 yielded no dates on macrofossils. Given that the average ages for cores D1 and C4 compare well with those of the respective macroremains, we use the average ages of the samples from cores A3 and B2 to obtain two surrogate water-level index points of reasonable reliability (index points 22/23 and 24/25).

#### 4.7. Testing the hypothesis of age rejuvenation

Each of our four new water-level index points (32, 28, 24/25, and 22/23) plot below the 1982-MSL curve (Fig. 7). Consequently, we reject the first part of our hypothesis, and conclude that, while some index points appear to be too young (5 and 13), the age-depth position of almost all of RG93's water-level data

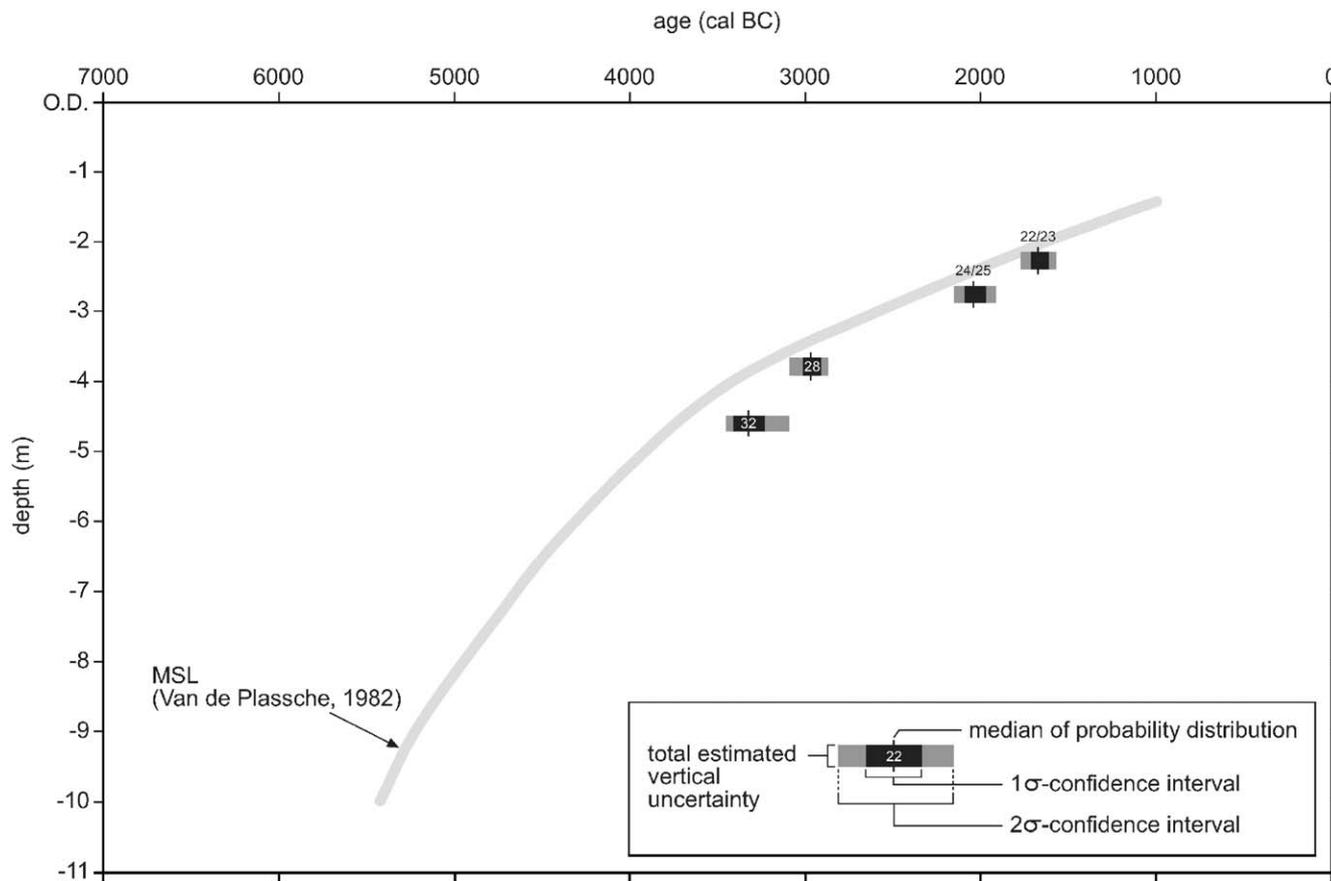


Fig. 7. Age-depth plot of four new water-level index points from Schokland (32, 28, 24/25, and 22/23) relative to the MSL curve for the western and northern Netherlands. The youngest two age-depth error boxes are surrogate index points (see text for explanation).

younger than 4000 cal BC below the 1982-MSL curve (Fig. 3) cannot be attributed to root rejuvenation. Given the young ages of the root fractions of our samples, we speculate that the effects of root rejuvenation in most of the samples of RG93 was (more than) compensated for by one or more ageing effects.

**5. Underestimation of water depth during initial peat growth**

As pointed out by RG93, the composition of the dated peat samples from Schokland varied from “carr peat” and “dry sedge peat with birch” to “very wet

Table 3  
Peat type and range of water depth

Composition of basal peat samples collected in the Schokland area (Gotjé, 1993), arranged from dryer to wetter conditions	Range of water depth (in cm) relative to the local average water level for initial peat accumulation
<i>Juncus</i> peat	+ 10 to -10
Carr peat	+ 10 to -10
Dry sedge peat with birch	+ 10 to -10
Sedge-carr peat with birch	+ 10 to -10
Sedge peat with birch	+ 10 to -10
Sedge peat	+ 10 to -20
Wet sedge-carr peat	0 to -10
Wet sedge peat with various open water taxa	-5 to -30
Very wet sedge peat	-5 to -30
Reed-sedge peat with very many <i>Juncus</i> and <i>Typha</i>	-10 to -40
Very sand-rich peat with very many <i>Juncus</i> fruits and very many soil fungi (washed down soil?)	+ 10 to 0

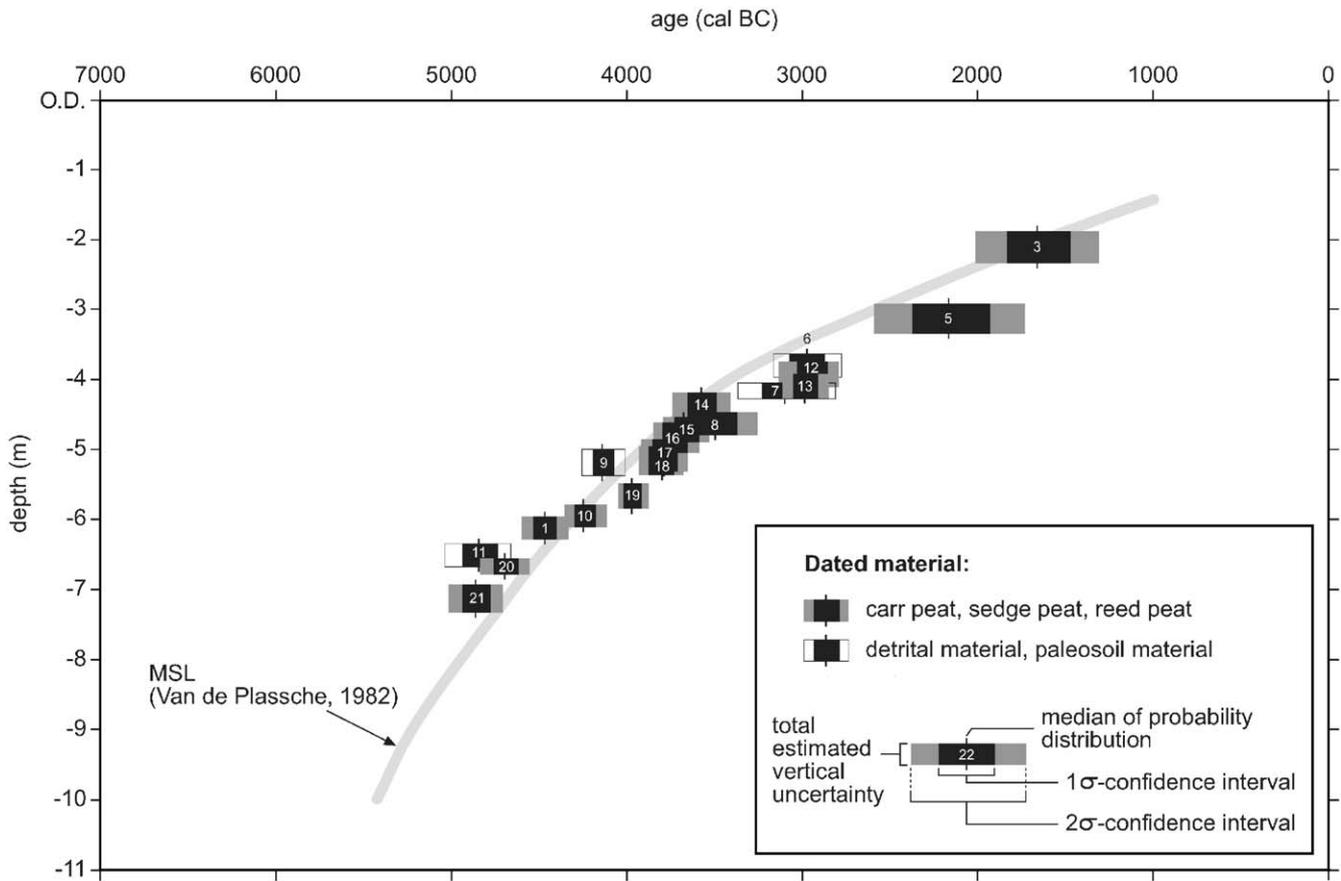


Fig. 8. Plot of the age-depth data from Schokland (Roeleveld and Gotjé, 1993) assuming differentiated minimum and maximum water depths during first basal peat accumulation.

sedge peat” and “inundated reed–sedge peat with very much *Juncus* and *Typha*”. These marked differences in sample composition imply the possibility that the peat of the dated samples may have originated in a range of water depths, and not in all cases, as RG93 argued, under more or less similar hydrological conditions. For instance, index point 18 (very wet sedge peat) plots well below the 1982-MSL curve, while index point 14 (dry sedge peat with birch remains) plots largely on the MSL curve. Perhaps, therefore, underestimation of water depth during (first) peat growth on the dune slopes might explain, in part or in whole, the low position of some of the post-4000 cal BC age-depth data from Schokland.

Our interpretation of the four botanical macrofossil diagrams (see above) supports initial peat growth at or just below the local average water level. We test the second part of our hypothesis by arranging the categories of the dated peat samples along a gradient from dry to wet, and assigning each a maximum vertical range of peat growth relative to the average water level (Table 3; see also Den Held et al. (1992) for hydrological conditions of peat forming vegetation). A re-plot of

the age-depth data with these differentiated indicative ranges (Fig. 8) shows a significantly better fit with the 1982-MSL curve for index point 3, but just marginally improved agreement for index points 18–15 for initial peat growth in maximum water depth, while index points 19, 8, and 12 continue to plot well below the 1982-MSL curve (index points 13 and 5 are ignored as the ages of these points are considered too young, see above). We reject, therefore, also the second part of our hypothesis, that the water depth in which the peat of the dated samples accumulated was underestimated.

6. Discussion

The rejection of our hypothesis implies that the paleowater-level data obtained by RG93 from the area of Schokland are, overall, sufficiently reliable to demonstrate conclusively that the relative average water-level curve for the eastern Flevo area runs, at least between 4200 and 1500 cal BC, ca. 15–60 cm below the 1982-MSL curve. To determine accurately that

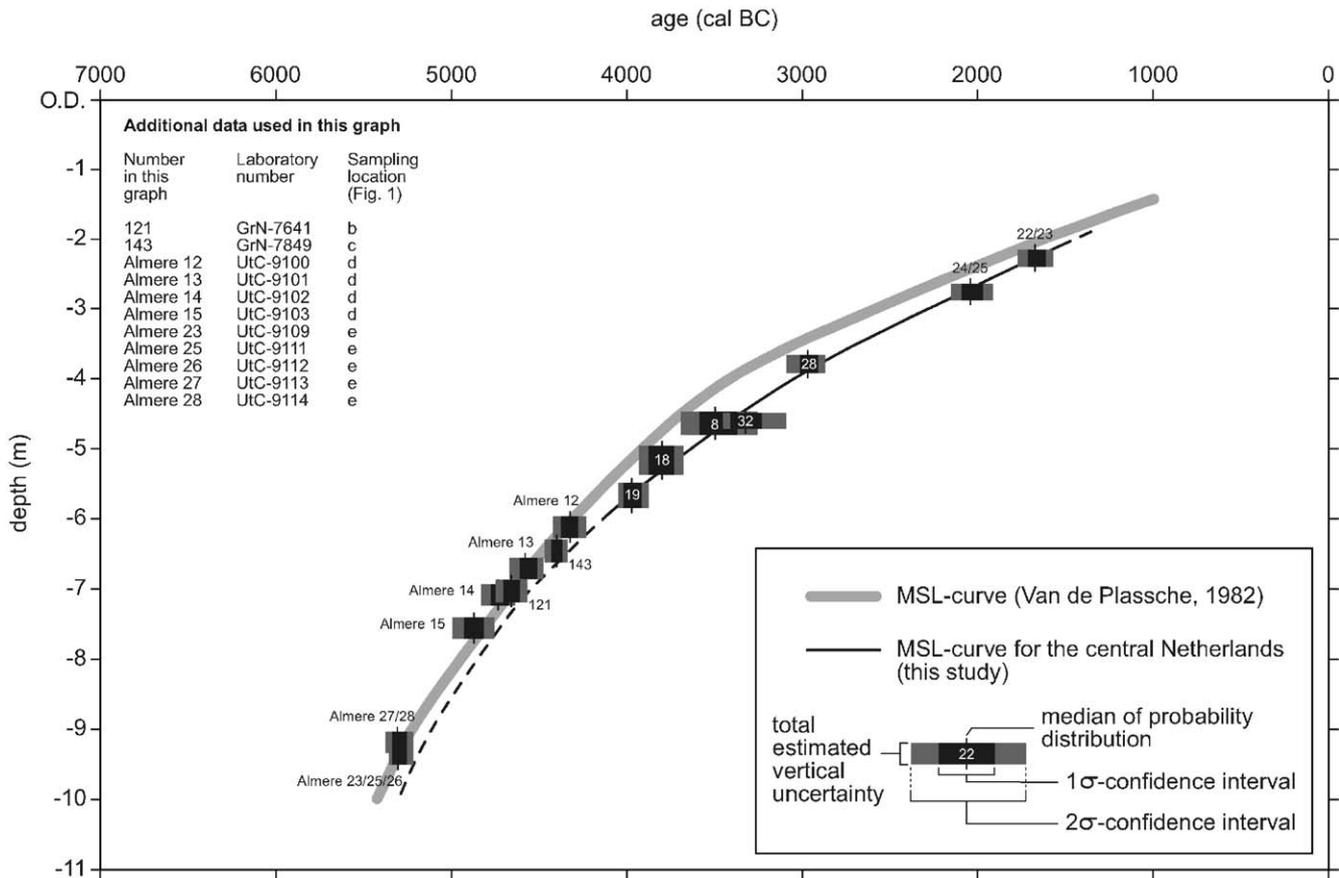


Fig. 9. Trend curve of relative MSL rise (upper limit) for the central Netherlands. The fact that basal peat index point 121 (northern Netherlands) and basal peat index point 143 (Rotterdam area) plot very near this relative MSL curve does not prove that the MSL trend curve for the central Netherlands is representative also for the north of the country and the Rhine-Meuse delta. The reliability, hence the geographical representativity of the 1982-MSL curve is uncertain.

relative average water-level curve (error envelope) it is necessary to collect a new suite of basal peat samples and AMS date selected botanical macrofossils. For lack of such a high-quality data set we use the deepest/youngest index points available (19, 18, 8, 32, 28 (overlaps 12), 24/25, and 22/23 (overlaps 3)) to define, for the period 4100–1500 cal BC, a smooth water-level rise curve which approximates the trend of relative average water-level rise in the eastern central Netherlands (Fig. 9). Because local average water levels are a function of MSL, water-gradient effect, and local tidal range, the trend curve represents an upper limit for MSL rise (Van de Plassche and Roep, 1989; Roeleveld and Gotjé, 1993).

From recently published paleowater-level data we infer that relative average water level in the Flevo area was below the 1982-MSL curve at least as far back as 5300 cal BC. Makaske et al. (2002, 2003) found that the age-depth position of five new, reliable basal peat samples collected ca. 50 km southwest of Schokland (near the town of Almere; sites d and e in Fig. 1a) plot squarely on the 5300–4250 cal BC part of the 1982-MSL curve (index points Almere 23/25/26, Almere 27/28 and Almere 12–15 in Fig. 9; Table 4). As pointed out by Makaske et al. (2003), this result, which would imply very little or no local tidal amplitude, contradicts available paleogeographic data for the Holland Tidal Basin (which evolved into the Flevo lagoon). According to Beets et al. (1992, 2003) and Beets and Van der Spek (2000), this Basin was, prior to 4250 cal BC, still

sufficiently connected to the North Sea to render advanced or complete tidal damping highly unlikely (cf. Van de Plassche, 1995). As such, these index points from near Almere, based predominantly on AMS-dated bulk samples of strongly decomposed basal peat, support a relative MSL-trend curve for the central Netherlands below the 1982-MSL curve at least as far back as 5300 cal BC (tentatively indicated as the dashed part of the MSL-trend curve in Fig. 9).

Index points Almere 23/25/26, 27/28, and Almere 12–15 from the southwestern Flevo area (Fig. 8 in Makaske et al., 2003) tend to plot slightly lower than index points 21, 20, and 1 (Ente et al., 1986) from the eastern part (cf. Figs. 3 and 9), suggesting the possibility of differential land-level change. Two deep glacial tongue basins (of Saalien age), filled with glaciolacustrine deposits (and Eemian marine clays), occur in the deeper sub-surface of the southwestern Flevo area (De Mulder et al., 2003). Hence, compaction of those clays could potentially explain the age-depth difference between the southwestern and eastern Flevo areas. The sampling locations near Almere are, however, all situated over the upper part of the eastern flank of a wide sub-surface ridge composed of ice-pushed fluvial sands and gravels separating the two glacial basins. Thus, compaction, if applicable at all, did probably not significantly affect the altitude of the Almere age-depth data. The comparability of the age-depth data from the southwestern and eastern Flevo areas is, at this stage, insufficient to warrant a meaningful attempt at explain-

Table 4  
Age-depth data from outside of the eastern Flevo area used in this study

Site <sup>a</sup>	Index point <sup>b</sup>	Material dated <sup>c</sup>	Lab. nr.	<sup>14</sup> C-age (yr BP) <sup>d</sup>	Calibrated age (cal BC)		Sample depth (m below NAP)	Vertical error margin in Fig. 9 (m below NAP) <sup>e</sup>
					±1σ	±2σ		
b	121	Fen peat	GrN-7641	5800±40	4702–4610	4746–4566	7.01–7.05	6.87–7.19
c	143	Fen peat	GrN-7849	5560±30	4430–4366	4466–4338	6.44–6.48	6.30–6.62
d	Alm 12	Peat, strongly decompos.	UtC-9100	5400±45	4374–4278	4422–4230	6.09	5.94–6.24
d	Alm 13	Peat, strongly decompos.	UtC-9101	5719±43	4610–4510	4670–4470	6.72	6.57–6.87
d	Alm 14	Peat, strongly decompos.	UtC-9102	5861±43	4770–4670	4830–4630	7.08	6.93–7.23
d	Alm 15	Peat, strongly decompos.	UtC-9103	5980±46	4930–4810	4990–4750	7.56	7.41–7.71
e	Alm 23	Wood	UtC-9109	6299±48	5330–5230	5370–5130	9.34	
e	Alm 25	Botanical macroremains	UtC-9111	6320±48	5350–5230	5390–5170	9.34	
e	Alm 26	Peat, strongly decompos.	UtC-9112	6410±60	5430–5310	5470–5230	9.34	
e	23/25/26			6334±30	5330–5250	5350–5210	9.34	9.19–9.49
e	Alm 27	Peat, strongly decompos.	UtC-9113	6410±50	5410–5310	5450–5250	9.19	
e	Alm 28	Wood	UtC-9114	6254±49	5290–5150	5330–5070	9.19	
e	27/28			6330±35	5330–5250	5370–5210	9.19	9.04–9.34

<sup>a</sup>For location, see Figs. 1b and 1c.

<sup>b</sup>121 (Griede, 1978); 143 (Van de Plassche, 1982); Almere data (Makaske et al., 2003).

<sup>c</sup>Almere 25: *Phragmites australis* epidermis.

<sup>d</sup>Ages of index points 23/25/26 and 27/28 are based on weighted means.

<sup>e</sup>Vertical error for index points 121 and 143 includes: sample thickness, errors in measurement of altitude of coring location and in-core depth (±4 cm) and a standard error of ±10 cm for uncertainty in the relationship between water level and peat growth. Vertical error for Almere data includes: errors in measurement of altitude of coring location and in-core depth (±5 cm) and a standard error of ±10 cm for uncertainty in the relationship between water level and peat growth (sample thickness of Almere samples is 1 cm).

ing the noted age-depth differences in terms of local (ground)water gradients and/or local tidal range, let alone slight differential crustal movements of tectonic and/or isostatic origin.

Results of geophysical modelling of Holocene glacio- and hydro-isostatic land-level changes in the Dutch North Sea sector and in the Belgian-Netherlands coastal plain (Kiden et al., 2002) (see also Kiden, 1995; Denys and Baeteman, 1995) show that the accumulated isostatic lowering of the crust increases substantially from the southwest to the northeast. They show, for instance, that for the time since 4500 cal BC a site in the northern Netherlands has experienced almost 2 m more isostatic subsidence than a site in the west-central Netherlands. Index point 121 (Griede, 1978), the youngest/deepest available basal peat index point from the northern Netherlands (site b in Fig. 1a), plots above the tentatively extended relative MSL-trend curve for the central Netherlands (Fig. 9, Table 4), suggesting that the model over-estimates isostatic crustal lowering. On the other hand, index point 121 represents no more than an upper limit for MSL and the dated basal peat may have formed well above the contemporaneous MSL. We agree with Kiden et al. (2002) that new suites of data, preferably older than 6000 cal BC and based on radiocarbon-dated botanical macrofossils, should be collected in the northern part of the country to test the model prediction of stronger isostatic subsidence.

According to the isostatic model, the Rhine-Meuse delta has experienced less isostatic crustal lowering than the Flevo area. The position of the 1982-MSL curve, the post-4000 cal BC part of which is based largely on basal peat age-depth data from river dunes in the vicinity of Rotterdam (c in Fig. 1a), above the (tentative) MSL curve for the central Netherlands, seems to confirm this prediction. The problem here, however, is that many of those basal peat samples may have been dated too old by 100–200 years (Roeleveld and Gotjé, 1993; Van de Plassche, 1995). In order to date the earliest peat growth and minimise compaction, Van de Plassche (1982) selected the very base of the basal peat in each core (very peaty sand to sandy peat) and, in order to avoid root rejuvenation, he rigorously removed all potentially allochthonous elements from the sample using a binocular microscope. RG93 attributed the discrepancy between their Schokland water-level data and the 1982-MSL curve to this deep sampling strategy, suggesting that it caused the ages to be 100–200 yr too old due to inclusion of older carbon. Van de Plassche (1995) accepted this explanation as reasonable but left the post-4000 cal BC part of the 1982-MSL curve unchanged until evidence for an ageing effect in the post-4000 cal BC river-dune data from the Rotterdam area would become available. If our interpretation of the origin of the carbon in the residue fraction of our Schokland samples is correct (see above), then the fact

that our index points 24 and 22 (residue fractions) plot on the 1982-MSL curve (not shown) supports the interpretation that those younger (post-4000 cal BC) Rotterdam water-level data have been dated somewhat too old. In addition to the deep sampling strategy, the rigorous sample preparation applied by Van de Plassche (1982) is likely to have caused a relative increase of that older carbon component in the deep basal peat samples. It is reasonable to expect, therefore, that if the basal peat samples from the river dunes near Rotterdam had been selected slightly (1–3 cm) higher in the cores (or if macroremains had been selected for dating), their ages would have been younger, and discrepancies between the post-4000 cal BC part of the 1982-MSL curve and the water-level data from Schokland would have been (much) smaller. Again, carefully produced sets of high-quality paleowater-level data are needed to detect, barring masking effects of local tidal range and water gradient, presence or absence of small differential land-level movements. The need for such high-quality data sets is underscored by the fact that index point 143, the deepest/youngest basal peat index point from the Rotterdam area (c in Fig. 1a) and arbitrarily rejected as too young by Van de Plassche (1982, 1995), plots just above the tentative MSL-trend curve for the central Netherlands (Fig. 9; Table 4). Finally, the hypothetical explanation for the origin of the older carbon in the residue fractions needs to be tested by careful microscopic, chemical, and AMS radiocarbon analysis of several suites of samples that cover the transition from humic or peaty dune sand to pure peat well above the substrate.

## 7. Concluding remarks

Whilst the number of new water-level index data from Schokland is very limited (4) and additional high-quality data are needed for confirmation, the internal consistency of the dates on the various organic fractions from each of the four samples supports the overall reliability of the RG93 water-level curve for the eastern Flevo area. The age differences between the (older) residue and (younger) root fraction of our four samples (ca. 175–400 sidereal yr, median values) suggests that this overall reliability may be due to a more or less balancing out of rejuvenating and ageing effects in most of their bulk-dated basal peat samples. These age differences may also explain, at least in part, why many of the rigorously cleaned samples of peaty sand or (very) sandy peat (removal of sub-surface stems, rhizomes, roots, rootlets, bits of wood) collected from the very base of basal peat that formed on river dunes near Rotterdam, and which defined the post 4200 cal BC part of the 1982-MSL curve, dated significantly older (up to 325 <sup>14</sup>C yr, median values) than most of the depth-comparable

basal peat samples from the Schokland area. To determine if, and to what extent, the Rotterdam data are too old is crucially important for correctly interpreting differences between the water-level rise records from the Rotterdam and Flevo areas in terms of differences in local tidal range, water-level gradients and/or crustal movements. As shown by Kiden et al. (2002) and the present study, comparably produced high-quality sets of water-level index data from the western, central and northern Netherlands and from the southern North Sea are needed to further study relative sea-level change along the southern North Sea coast. Meanwhile, the (tentative) water-level rise curve for the central Netherlands (Fig. 9), based primarily on data from Roeleveld and Gotjé (1993), Makaske et al., (2003) and this study, represents the currently most reliable approximation (for the upper limit) of relative MSL rise for the central Netherlands. The reliability and geographical representativity of the 1982-MSL curve is unclear and awaits testing.

It is beyond the scope of this paper to discuss the full implications of a 15–60 cm lower relative MSL curve, but one important aspect is that of changes in (intra-) coastal tidal range and/or water-level gradient (Van de Plassche, 1995). A lower relative MSL implies the possibility of a larger local and coastal tidal amplitude. Since the tidal range is an important environmental factor, and a small increase in range can have a significant influence on, for instance, sediment transport and salinity, the lowering of an existing MSL curve, even by just a few to several decimeters, represents a non-negligible modification. Another important aspect of a lower relative MSL curve concerns the impact of paleowater-levels on prehistoric human occupation. Rich Stone Age sites have, for instance, been discovered in the Flevo lagoon area on top of the Pleistocene substrate (Hogestijn and Peeters, 2001). Rising local water levels driven by relative MSL rise obviously forced prehistoric man to retreat to ever higher grounds. The new lower relative MSL curve for the central Netherlands suggests that parts of the back-barrier landscape became uninhabitable significantly later than could be inferred from the 1982-MSL curve. In view of potentially significant regional differences in isostatic subsidence, this result is of considerable interest for assessing the archaeological potential of the Netherlands coastal plain (e.g., Peeters et al., 2002).

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