Netherlands Journal of Geosciences — Geologie en Mijnbouw | 86 - 4 | 333 - 354 | 2007

New groundwater-level rise data from the Rhine-Meuse delta – implications for the reconstruction of Holocene relative mean sea-level rise and differential land-level movements

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Manuscript received: March 2007; accepted: December 2007

Abstract

We present new local groundwater-level rise data from two Late Glacial aeolian dunes, located near Barendrecht and Oud-Alblas in the western Rhine-Meuse delta. These data are based on AMS radiocarbon dating of terrestrial macrofossils, collected from the base of peat formed on the slopes of these dunes. This method avoids contamination of bulk peat samples by old soil carbon or younger rootlets and rhizomes, as well as the hardwater effect. The new data are used to assess the reliability of previously published groundwater-level index data based on conventional radiocarbon dating of bulk basal peat samples from the slopes of the Late Glacial aeolian dunes at Barendrecht, Hillegersberg, Bolnes and Wijngaarden, all located in the western Rhine-Meuse delta.

Comparison of the new and published groundwater-level data shows no significant systematic difference between conventionally dated bulk peat samples and AMS-dated samples of terrestrial macrofossils. The new data from the dune at Barendrecht confirm the reliability of the younger than 6600 cal yr BP age-depth data from the dunes at Hillegersberg and near Bolnes. This result supports the validity of this part of the mean sea-level (MSL) curve for the western Netherlands. Consequently, the position of the groundwater-level curve for Flevoland (central Netherlands) below this MSL curve can most likely be attributed to differential land-level movement.

The available data show that the groundwater-gradient effect in the western Rhine-Meuse delta became less than 5 cm/km after 6600 cal yr BP. Finally, temporal correlation between temporary increases in local groundwater-level rise with known shifts of river courses in the delta plain suggests, that avulsions can explain sudden local deviations from the trend in groundwater-level rise. A general conclusion of this study is that a complex relationship exists between sea level and local delta-plain water levels.

Keywords: AMS dating, avulsions, Holocene sea-level rise, Late Glacial aeolian dunes, river-gradient effect

Introduction

Reconstructions of Holocene relative sea-level and groundwater-level rise are crucial for understanding the palaeogeographical and geological evolution of coastal plains, while also serving studies of differential land-level change, palaeoecology, and archaeology. At present, the quest for higher accuracy in sea-level reconstruction and for better understanding of differences between local groundwater-level curves is still ongoing.

Studies of Holocene relative (ground)water change and sea-level change in the Netherlands are based primarily on radiocarbon-dated samples from the base of peats which accumulated on pre-Holocene substrates (e.g., Jelgersma, 1961, 1979, 1980; Van de Plassche, 1982, 1995; Van Dijk et al., 1991; Roeleveld & Gotjé, 1993; Kiden, 1995; Cohen, 2003; Makaske et al., 2003; Van de Plassche et al., 2005). In many cases, basal peats from the slopes of Late Weichselian aeolian dunes were used to reconstruct local curves of groundwater-level rise. The approach of using peat as a sea-level or groundwater-level indicator has been validated by independent research methods (e.g., Roep & Beets, 1988). Groundwater-level changes in coastal areas are a function of mean sea-level (MSL) rise, superimposed changes in regional and local tidal range and changes in regional and local river or groundwater gradient. The question is: how should spatial and temporal differences within and between groundwater-level curves be interpreted, given the accuracy and reliability of such curves?

Sea-level curves from roughly before 1990 are based on conventionally radiocarbon-dated bulk samples from (basal) peat layers. A potential drawback of such samples is that they may contain rootlets and reed rhizomes that penetrated the sample from higher stratigraphic levels, resulting in an apparent younger age (e.g., Streif, 1971). Another drawback of dating bulk peat samples is that they may yield apparent older ages due to the so-called hardwater effect (e.g., Törnqvist et al., 1992) or due to inclusion of old soil carbon (Van de Plassche, 1982). The hardwater effect originates from plants that assimilate CO_2 from the water containing CO_2 from dissolved old $CaCO_3$, instead of from the atmosphere. Moreover, conventional ^{14}C dating of bulk peat samples generally requires >10 g organic material from a 5 - 10 cm thick core interval, which may cover a considerable time span. This may affect the accuracy of the age the date is supposed to represent (Törnqvist et al., 1992). To avoid all of these potential problems, accelerator mass spectrometry (AMS) dating is now generally applied. This technique allows analysis of much smaller samples (<20 mg) that generally cover only ~1 cm thick core intervals and presumably results in more representative dates. Errors such as caused by the hardwater effect, the inclusion of old soil carbon or younger roots can be avoided by selecting terrestrial macrofossils instead of bulk peat.

Hitherto, only one study has been carried out in which a (ground)water-level curve based on conventional radiocarbon dating of bulk samples was tested against new AMS-dated samples of terrestrial macrofossils from the same site (Van de Plassche et al., 2005). This study was carried out in Flevoland (central Netherlands, Fig. 1) and yielded water-level index points below the mean sea-level (MSL) curve for the western Netherlands (Van de Plassche, 1982). It confirmed results reached by Roeleveld & Gotjé (1993), which were based on conventionally dated bulk peat samples, and led to a MSL curve for Flevoland running below Van de Plassche's (1982) MSL curve, at least for the part between 6000 and 3500 cal yr BP. Because this part of the 1982 MSL curve was based on conventionally dated bulk peat samples from the western Rhine-Meuse delta, a methodological cause (AMS macrofossil dates vs. conventional bulk dates) of the difference between the two curves was suggested, but alternative causes such as differences in tidal effects and/or land-level movements could not be excluded (Van de Plassche et al., 2005). In this paper we address the question whether previously published dates of bulk peat samples are too old due to the hardwater effect or to the inclusion of old carbon as suggested by Roeleveld and Gotjé (1993).

The aims of this paper are: (1) to evaluate and explain differences in groundwater-level rise data in the western Netherlands in terms of methodological effects, and spatial and temporal effects related to palaeogeography and evolution of the coastal plain; (2) to evaluate the cause of the difference between the curve from Flevoland (Van de Plassche et al., 2005) and the curves from the western Netherlands.

We collected two new local groundwater-level data sets on the flanks of aeolian dunes in the western part of the Rhine-Meuse delta. These new data sets represent AMS-dated samples of terrestrial macrofossils. We compare these new high-quality data with previously published data sets from this area, which are based on conventionally dated bulk peat samples (Jelgersma, 1961; Van de Plassche, 1982; Van Dijk et al., 1991).

Approach and methods

Site characteristics and fieldwork

Based on the geological map of the Netherlands, scale 1 : 50,000 (Verbraeck, 1974; Bosch & Kok, 1994), we selected two buried Late Weichselian aeolian dunes in the western part of the Rhine-Meuse delta. Both dunes are (almost) completely covered by Holocene deposits: only at one of the sites (Oud-Alblas) the very top of the dune is exposed at the surface. We constructed a local groundwater-level rise curve using AMS-dated terrestrial macrofossils from the base of peat, flanking the dunes. The dunes are located near the towns of Barendrecht and Oud-Alblas (Fig. 1). They were selected for accessibility and presence of basal peat on their slopes over a large vertical range. Fieldwork for this study was carried out in 1995, and collected samples were subsequently analysed and dated in 1996 and 1997. Soon after the collection of samples, the Barendrecht site became inaccessible as a result of development by the city of Barendrecht. At both locations, the general topography of the dune was mapped using an Edelman-auger and a 3 cm wide gouge (Berendsen & Stouthamer, 2001).

The dune at Barendrecht (Fig. 2) is ~14.4 m high, with the top of the dune sand at 0.6 m below the surface (outside cross-section in Fig. 2) and the top of the underlying Kreftenheye Formation (fluvial Weichselian deposits) at a depth of ~15 m below the surface. At Oud-Alblas (Fig. 3), the top of the dune is at 1.3 m below the surface in our cross-section. The base of the dune was not reached, but is at more than 10 m below the surface. Based on the maps, detailed cross-sections were

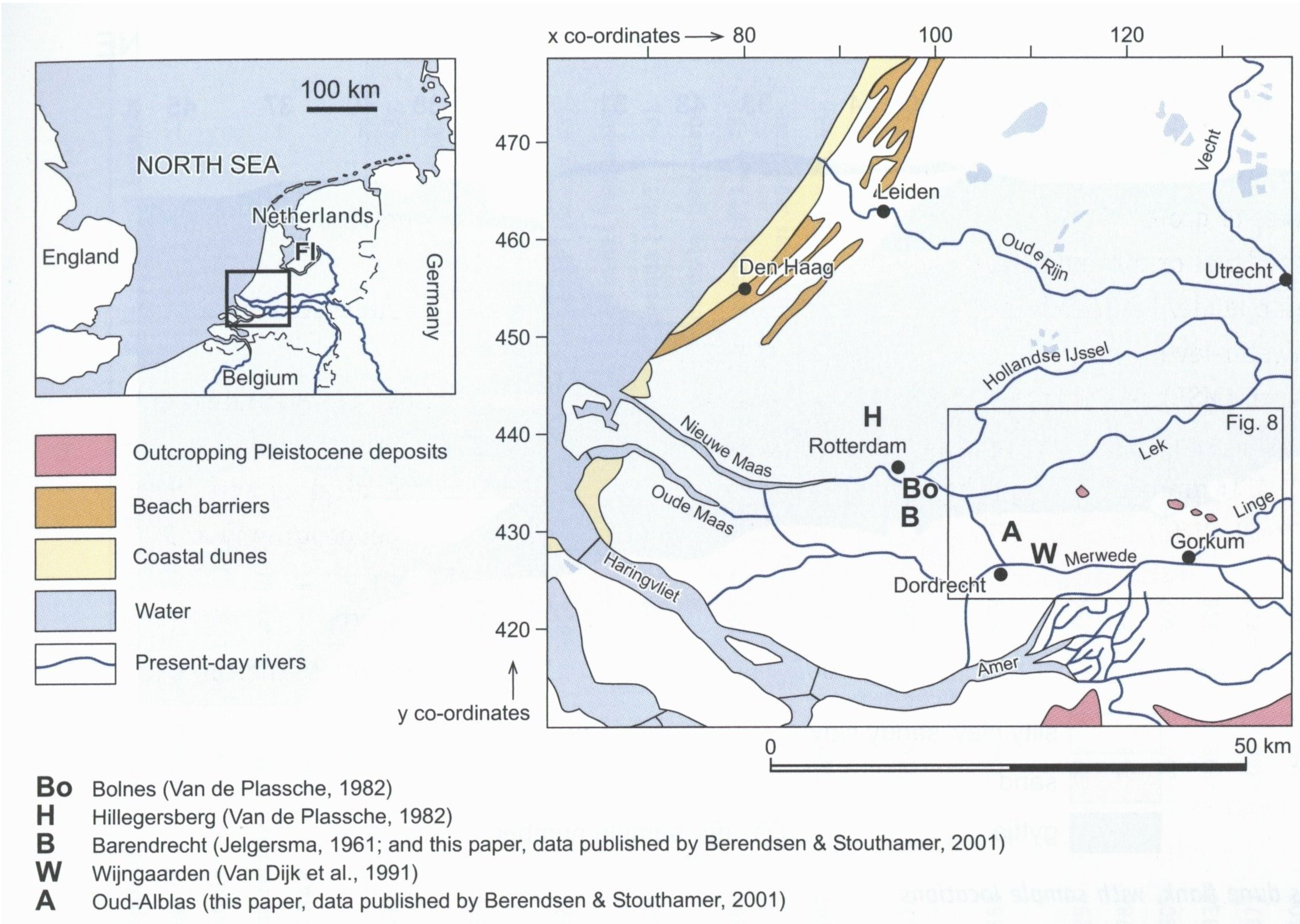

Fig. 1. Locations of the studied aeolian dunes, and the previously studied sites of Wijngaarden, Bolnes and Hillegersberg. Locations of Fig. 8 and Flevoland (indicated by 'Fl' in map of the Netherlands) are also shown.

produced at each dune, using an Edelman-auger and a gouge. The cross-sections are oriented in the direction of maximum slope; coring sites are ~5 m apart. From these cross-sections, approximately 50 cm long undisturbed cores were collected at more or less regular vertical intervals (Figs 2 and 3), using a Dachnowski-sampler and a 7 cm wide gouge. Depressions in the dune surface were avoided as much as possible, because peat formation may have started earlier in depressions relative to better drained slopes (Van de Plassche, 1982). The cores were sub-sampled for AMS dating.

In addition to the newly collected data, the database for this paper contains published groundwater-level index data

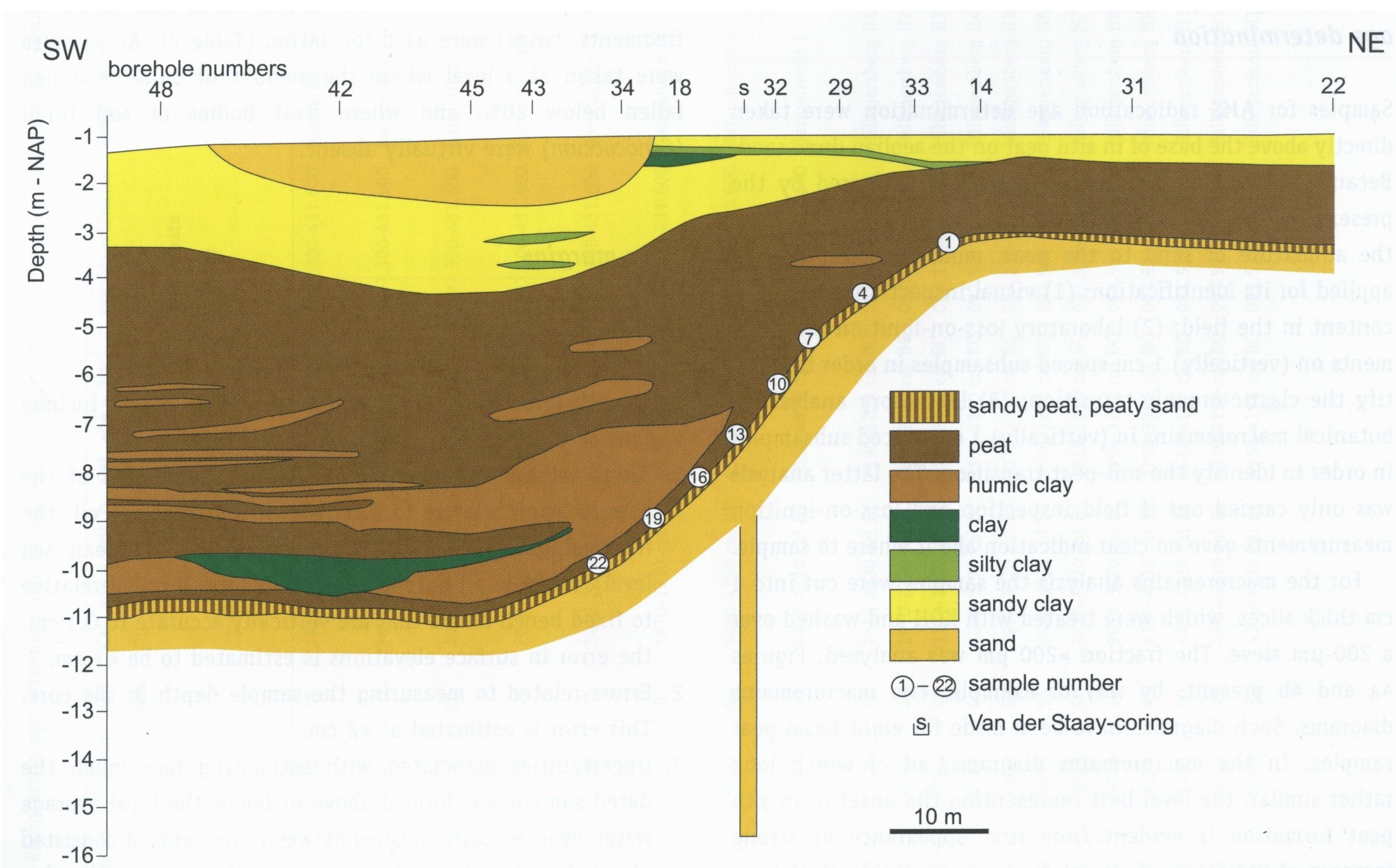

Fig. 2. Cross-section of the Barendrecht dune flank, with sample locations. Samples Barendrecht 23, 24, 26 and 27 were not collected in this cross-section.

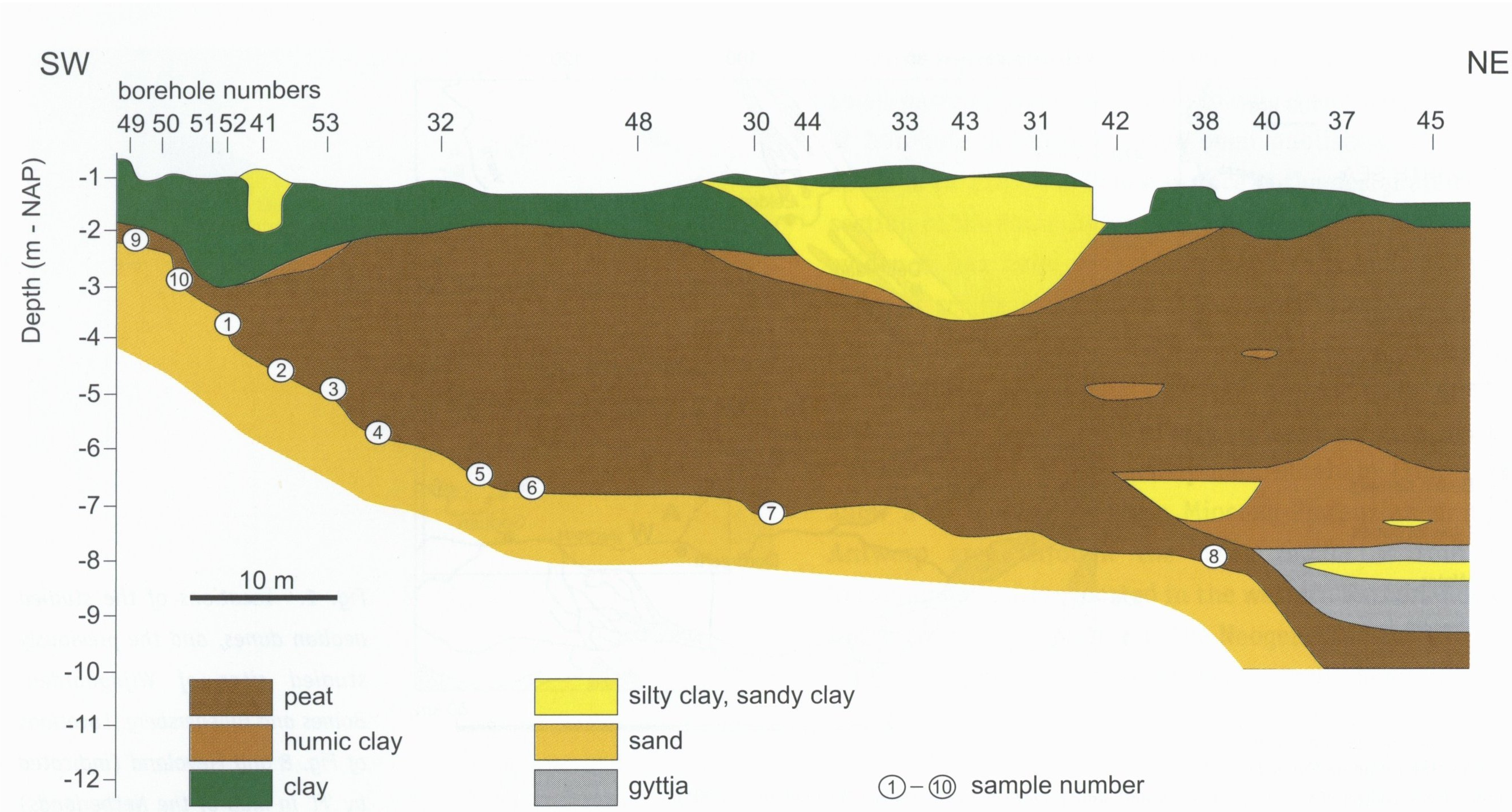

Fig. 3. Cross-section of the Oud-Alblas dune flank, with sample locations.

(conventional radiocarbon age determinations of bulk basal peat samples) for aeolian dunes at Barendrecht (Jelgersma, 1961), Bolnes and Hillegersberg (Van de Plassche, 1982), and Wijngaarden (Van Dijk et al., 1991), see Table 1, and Fig. 1 for locations.

Selection of samples for AMS radiocarbon age determination

Samples for AMS radiocarbon age determination were taken directly above the base of in situ peat on the aeolian dune sand. Because this sand-peat transition usually is blurred by the presence of a palaeosoil in the top of the aeolian sand and by the admixture of sand to the peat, multiple methods were applied for its identification: (1) visual inspection of the core content in the field; (2) laboratory loss-on-ignition measurements on (vertically) 1 cm spaced subsamples in order to identify the clastic-organic transition; (3) laboratory analysis of botanical macroremains in (vertically) 1 cm spaced subsamples in order to identify the soil-peat transition. The latter analysis was only carried out if field inspection and loss-on-ignition measurements gave no clear indication about where to sample.

For the macroremains analysis the samples were cut into 1 cm thick slices, which were treated with KOH and washed over a 200-μm sieve. The fraction >200 μm was analysed. Figures 4a and 4b present, by way of example, two macroremains diagrams. Such diagrams have been made for eight basal peat samples. In the macroremains diagrams, all of which look rather similar, the level best representing the onset of in situ peat formation is evident from first appearance or strong increase of indicators of a peat-forming vegetation (leaf fragments, bud scales, *Typha*, *Carex*, *Alnus* remains), together with the (near-)absence of soil fungi (*Cenococcum* fruit bodies) and a low (<10%) sand content.

After identification of the optimal sampling level, we cut a 1 cm thick slice from the core to extract dateable macroremains. If a particular slice did not yield enough material, the next higher 1 cm thick slice was added to the sample, and so on, if necessary. Terrestrial macrofossils (seeds, fruits, bud scales, leaf fragments, twigs) were used for dating (Table 2). All samples were taken at a level where the amount of dune sand had fallen below 20%, and where fruit bodies of soil fungi (*Cenococcum*) were virtually absent.

Error margins

Depth-error margins

The depth-error margins of water-level index points include various categories of errors and uncertainties.

1. Errors related to measuring the surface elevation of the core location relative to NAP: Nieuw Amsterdams Peil; the national geodetic datum, approximately MSL (mean sea level). Because all borehole locations were levelled relative to fixed bench marks that are vertically accurate to 0.1 cm, the error in surface elevations is estimated to be ≤1 cm.
2. Errors related to measuring the sample depth in the core. This error is estimated at ≤2 cm.
3. Uncertainties associated with estimating how much the dated sample was formed above or below the local average water level. We distinguished between samples that consisted of wood peat and samples composed of reed or reed-sedge peat.

Table 1. Radiocarbon age determinations carried out for this study and previously published radiocarbon data used in this study.

Laboratory nr.	^{14}C age	Std. dev.	Cal. age ± $1\sigma^1$	Cal. age ± $2\sigma^1$	x-y Co-ordinates (Dutch co-ordinate system)	Sample name	Surface elevation (cm relative to NAP)	Depth of top of sample (cm relative to NAP)	Depth of base of sample (cm relative to NAP)	Top of vertical error (1σ) margin (cm relative to NAP)	Base of vertical error (1σ) margin (cm rel. to NAP)	Material	Reference and remarks
GrN-01140	5030	70	3910-3750 cal BC	3990-3670 cal BC	±097.300-431.600	Barendrecht VI	-86	-428	-430	-389	-424	Fen-wood peat	Jelgersma (1961, p. 43); co-ordinates inaccurate
GrN-01144	4640	70	3490-3290 cal BC	3570-3190 cal BC	±097.300-431.600	Barendrecht VIII	-86	-340	-345	-294	-339	Fen-wood peat	Jelgersma (1961, p. 43); co-ordinates inaccurate
GrN-01145	5970	80	4950-4750 cal BC	5050-4650 cal BC	±097.300-431.600	Barendrecht IV	-86	-616	-621	-570	-615	Fen-wood peat	Jelgersma (1961, p. 43); co-ordinates inaccurate
GrN-01146	4270	55	2970-2810 cal BC	3030-2730 cal BC	±097.300-431.600	Barendrecht VII	-86	-319	-324	-273	-318	Fen-wood peat	Jelgersma (1961, p. 43); co-ordinates inaccurate
GrN-01147	3900	70	2470-2270 cal BC	2570-2170 cal BC	±097.300-431.600	Barendrecht X	-86	-263	-267	-219	-261	Fen-wood peat	Jelgersma (1961, p. 43); co-ordinates inaccurate
GrN-01148	3480	50	1870-1730 cal BC	1930-1670 cal BC	±097.300-431.600	Barendrecht XII	-86	-192	-197	-146	-191	Fen-wood peat	Jelgersma (1961, p. 43); co-ordinates inaccurate
GrN-01151	5580	60	4490-4350 cal BC	4550-4290 cal BC	±097.300-431.600	Barendrecht V	-86	-565	-572	-514	-566	Fen-wood peat	Jelgersma (1961, p. 43); co-ordinates inaccurate
GrN-01160	5945	90	4930-4710 cal BC	5050-4610 cal BC	±097.300-431.600	Barendrecht I	-86	-580	-585	-534	-579	Fen-wood peat	Jelgersma (1961, p. 43); co-ordinates inaccurate
GrN-07830	3930	60	2510-2330 cal BC	2590-2250 cal BC	093.535-441.250	Hillegersberg H1	-54	-252	-254	-223	-254	Fen peat	Van de Plassche (1982, p. 71)[2,3]
GrN-07831	4245	40	2910-2790 cal BC	2950-2730 cal BC	093.535-441.250	Hillegersberg H2	-54	-282	-286	-248	-286	Fen peat	Van de Plassche (1982, p. 71)[2]
GrN-07832	4390	50	3130-2970 cal BC	3190-2890 cal BC	093.535-441.250	Hillegersberg H3	-54	-303	-307	-269	-307	Fen peat	Van de Plassche (1982, p. 71)[2,3]
GrN-07833	4525	40	3290-3170 cal BC	3350-3110 cal BC	093.535-441.250	Hillegersberg H4	-62	-332	-336	-298	-336	Fen peat	Van de Plassche (1982, p. 71)[2]
GrN-07834	4500	60	3290-3110 cal BC	3370-3030 cal BC	093.535-441.250	Hillegersberg H5	-68	-369	-371	-340	-371	Fen peat	Van de Plassche (1982, p. 71)[2]
GrN-07835	4655	55	3490-3330 cal BC	3550-3250 cal BC	093.535-441.250	Hillegersberg H6	-78	-398	-400	-369	-400	Fen peat	Van de Plassche (1982, p. 71)[2]
GrN-07838	4925	40	3770-3670 cal BC	3810-3630 cal BC	093.535-441.250	Hillegersberg H7	-84	-443	-447	-409	-447	Fen peat	Van de Plassche (1982, p. 71)[2]
GrN-07840	5070	40	3914-3826 cal BC	3954-3782 cal BC	093.535-441.250	Hillegersberg H8	-89	-480	-484	-446	-484	Fen peat	Van de Plassche (1982, p. 71)[2]
GrN-07841	5275	45	4150-4030 cal BC	4210-3990 cal BC	093.535-441.250	Hillegersberg H9	-95	-523	-527	-489	-527	Fen peat	Van de Plassche (1982, p. 71)[2]
GrN-07842	5490	80	4410-4230 cal BC	4510-4150 cal BC	093.535-441.250	Hillegersberg H10	-100	-542	-544	-513	-544	Fen peat	Van de Plassche (1982, p. 71)[2]
GrN-07843	5420	45	4310-4210 cal BC	4340-4150 cal BC	093.535-441.250	Hillegersberg H11	-104	-569	-571	-540	-571	Fen peat	Van de Plassche (1982, p. 71)[2]
GrN-07844	5440	35	4310-4234 cal BC	4350-4198 cal BC	093.535-441.250	Hillegersberg H12	-104	-571	-575	-537	-575	Fen peat	Van de Plassche (1982, p. 71)[2]

Table 1. Continued.

Laboratory nr.	^{14}C age	Std. dev.	Cal. age ± 1σ[1]	Cal. age ± 2σ[1]	x-y Co-ordinates (Dutch co-ordinate system)	Sample name	Surface elevation (cm relative to NAP)	Depth of top of sample (cm relative to NAP)	Depth of base of sample (cm relative to NAP)	Top of vertical error (1σ) margin (cm relative to NAP)	Base of vertical error (1σ) margin (cm rel. to NAP)	Material	Reference and remarks
GrN-07845	5400	40	4290-4190 cal BC	4310-4130 cal BC	093.535-441.250	Hillegersberg H13	-109	-585	-589	-551	-589	Fen peat	Van de Plassche (1982, p. 71)[2]
GrN-07846	5560	40	4442-4358 cal BC	4482-4314 cal BC	093.535-441.250	Hillegersberg H14	-109	-590	-594	-556	-594	Fen peat	Van de Plassche (1982, p. 71)[2]
GrN-07848	5685	35	4570-4494 cal BC	4606-4454 cal BC	093.535-441.250	Hillegersberg H15	-115	-610	-613	-579	-613	Fen peat	Van de Plassche (1982, p. 71)[2]
GrN-07849	5560	30	4538-4474 cal BC	4570-4442 cal BC	093.535-441.250	Hillegersberg H16	-121	-644	-648	-610	-648	Fen peat	Van de Plassche (1982, p. 71)[2]
GrN-07850	5830	110	4830-4570 cal BC	4950-4450 cal BC	093.535-441.250	Hillegersberg H17	-126	-684	-686	-665	-696	Wood peat	Van de Plassche (1982, p. 71)[2]
GrN-07852	6810	40	5742-5674 cal BC	5778-5642 cal BC	093.535-441.250	Hillegersberg H18	-226	-1005	-1008	-984	-1018	Wood peat	Van de Plassche (1982, p. 71)[2]
GrN-07853	6665	40	5622-5554 cal BC	5658-5522 cal BC	093.535-441.250	Hillegersberg H19	-228	-1030	-1034	-1006	-1044	Wood peat	Van de Plassche (1982, p. 71)[2]
GrN-07855	6835	40	5766-5698 cal BC	5798-5662 cal BC	093.535-441.250	Hillegersberg H20	-228	-1035	-1039	-1011	-1049	Wood peat	Van de Plassche (1982, p. 71)[2]
GrN-07856	6850	40	5778-5705 cal BC	5810-5674 cal BC	093.535-441.250	Hillegersberg H21	-228	-1071	-1075	-1047	-1085	Wood peat	Van de Plassche (1982, p. 71)[2]
GrN-07857	6920	45	5842-5762 cal BC	5882-5726 cal BC	093.535-441.250	Hillegersberg H22	-226	-1112	-1115	-1091	-1125	Wood peat	Van de Plassche (1982, p. 71)[2]
GrN-07859	7105	40	6006-5930 cal BC	6046-5894 cal BC	093.535-441.250	Hillegersberg H23	-228	-1176	-1180	-1152	-1190	Wood peat	Van de Plassche (1982, p. 71)[2]
GrN-08431	3455	35	1814-1726 cal BC	1858-1682 cal BC	098.475-433.775	Bolnes 4	-96	-178	-180	-159	-190	Wood peat	Van de Plassche (1982, p. 71)[2]
GrN-08432	3530	80	1970-1750 cal BC	2090-1670 cal BC	098.475-433.775	Bolnes 5	-100	-198	-201	-177	-211	Wood peat	Van de Plassche (1982, p. 71)[2]
GrN-08433	3510	90	1970-1730 cal BC	2070-1610 cal BC	098.475-433.775	Bolnes 6	-104	-235	-238	-214	-248	Wood peat	Van de Plassche (1982, p. 71)[2]
GrN-08434	3820	90	2390-2130 cal BC	2510-2010 cal BC	098.475-433.775	Bolnes 7	-106	-260	-262	-241	-272	Wood peat	Van de Plassche (1982, p. 71)[2]
GrN-08798	2700	45	930-810 cal BC	970-750 cal BC	098.475-433.775	Bolnes 1	-65	-150	-150	-136	-160	Alder roots	Van de Plassche (1982, p. 71)[2]
GrN-08799	2985	30	1246-1166 cal BC	1282-1130 cal BC	098.475-433.775	Bolnes 2	-65	-150	-150	-136	-160	Oak roots	Van de Plassche (1982, p. 71)[2]
GrN-08916	6245	35	5234-5150 cal BC	5270-5106 cal BC	098.450-433.300	Bolnes 14	-154	-794	-798	-770	-808	Wood peat	Van de Plassche (1982, p. 71)[2]
GrN-08917	6325	45	5330-5230 cal BC	5370-5170 cal BC	098.450-433.300	Bolnes 15	-154	-834	-836	-815	-846	Peat	Berendsen & Stouthamer (2001)
GrN-08927	6670	70	5650-5530 cal BC	5710-5470 cal BC	098.450-433.450	Bolnes 11	-170	-955	-957	-936	-967	Wood peat	Van de Plassche (1982, p. 71)[2]
GrN-08928	6670	35	5622-5562 cal BC	5654-5534 cal BC	098.450-433.450	Bolnes 10.2	-164	-906	-910	-882	-920	Wood peat	Van de Plassche (1982, p. 71)[2]
GrN-08929	6495	40	5478-5406 cal BC	5514-5370 cal BC	098.450-433.450	Bolnes 10.1	-164	-904	-906	-885	-916	Wood peat	Van de Plassche (1982, p. 71)[2]
GrN-08930	6550	40	5526-5454 cal BC	5562-5422 cal BC	098.450-433.450	Bolnes 9	-156	-851	-854	-830	-864	Wood peat	Van de Plassche (1982, p. 71)[2]
GrN-08931	6320	35	5310-5234 cal BC	5346-5194 cal BC	098.450-433.450	Bolnes 8	-170	-780	-783	-759	-793	Wood peat	Van de Plassche (1982, p. 71)[2]
GrN-09558	4150	60	2810-2630 cal BC	2890-2550 cal BC	110.962-426.939	Wijngaarden 2	-139	-246	-250	-202	-244	Peat, sandy	Van Dijk et al. (1991)
GrN-09559	4480	70	3290-3070 cal BC	3370-2970 cal BC	110.961-426.940	Wijngaarden 3	-143	-288	-292	-244	-286	Peat, sandy	Van Dijk et al. (1991)
GrN-09560	4670	70	3530-3350 cal BC	3590-3230 cal BC	110.979-426.941	Wijngaarden 4	-148	-325	-330	-279	-324	Peat, sandy	Van Dijk et al. (1991)
GrN-09561	4990	70	3870-3710 cal BC	3930-3630 cal BC	110.971-426.940	Wijngaarden 5	-146	-366	-370	-322	-364	Peat, sandy	Van Dijk et al. (1991)
GrN-09562	5140	100	4050-3830 cal BC	4170-3730 cal BC	110.976-426.944	Wijngaarden 6	-160	-415	-420	-369	-414	Peat, sandy	Van Dijk et al. (1991)
GrN-09563	5340	80	4250-4070 cal BC	4350-3990 cal BC	110.969-426.950	Wijngaarden 7	-160	-450	-455	-404	-449	Peat, sandy	Van Dijk et al. (1991)

GrN-09564	3400	70	1790-1610 cal BC	1870-1530 cal BC	110.963-426.937	Wijngaarden 1	-114	-171	-175	-127	-169	Amorphous slightly clayey peat on humic clay	Van Dijk et al. (1991)
GrN-10096	5320	80	4230-4050 cal BC	4330-3970 cal BC	110.950-426.962	Wijngaarden 8	-161	-505	-510	-459	-504	Peat, sandy	Van Dijk et al. (1991)
GrA-04181	5000	80	3890-3710 cal BC	3970-3650 cal BC	097.379-431.472	Barendrecht 4	-103	-428	-430	-405	-437	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001); elevation corrected
GrA-04182	5430	90	4370-4150 cal BC	4430-4030 cal BC	097.373-431.468	Barendrecht 7	-105	-520	-521	-481	-517	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001); elevation corrected
GrA-04183	5810	90	4770-4550 cal BC	4850-4450 cal BC	097.368-431.466	Barendrecht 10	-104	-603	-604	-579	-609	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001); elevation corrected
GrA-04308	4470	60	3290-3050 cal BC	3350-2970 cal BC	097.387-431.476	Barendrecht 1	-98	-341	-345	-315	-353	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001); elevation corrected
GrA-04315	1290	50	682-782 cal AD	650-846 cal AD	097.312-431.620	Barendrecht 23	-80	-160	-163	-134	-170	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001); elevation corrected
GrA-05207	5930	50	4850-4742 cal BC	4914-4690 cal BC	097.367-431.465	Barendrecht 13	-106	-711	-712	-692	-720	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001); elevation corrected
GrA-05208	6660	60	5634-5538 cal BC	5678-5494 cal BC	097.356-431.458	Barendrecht 22	-107	-990	-991	-969	-998	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001); elevation corrected
GrA-05215	6360	50	5390-5290 cal BC	5450-5250 cal BC	097.361-431.461	Barendrecht 19	-112	-891	-892	-870	-899	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001); elevation corrected
GrA-05237	6200	50	5230-5070 cal BC	5290-5010 cal BC	097.365-431.463	Barendrecht 16	-109	-797	-800	-776	-810	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001); elevation corrected
GrA-05326	5550	60	4450-4330 cal BC	4510-4290 cal BC	097.305-431.623	Barendrecht 27	-79	-290	-293	-269	-303	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001); elevation corrected
GrA-06511	5300	60	4210-4050 cal BC	4270-3990 cal BC	108.214-430.565	Oud Alblas 3	-116	-518	-520	-499	-530	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001)

Table 1. Continued.

Laboratory nr.	^{14}C age	Std. dev.	Cal. age ± 1σ[1]	Cal. age ± 2σ[1]	x-y Co-ordinates (Dutch co-ordinate system)	Sample name	Surface elevation (cm relative to NAP)	Depth of top of sample (cm relative to NAP)	Depth of base of sample (cm relative to NAP)	Top of vertical error (1σ) margin (cm relative to NAP)	Base of vertical error (1σ) margin (cm rel. to NAP)	Material	Reference and remarks
GrA-06512	5920	60	4850-4710 cal BC	4930-4650 cal BC	108.222-430.573	Oud Alblas 5	−138	−634	−635	−618	−645	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001)
GrA-06513	6280	60	5330-5170 cal BC	5370-5070 cal BC	108.264-430.605	Oud Alblas 8	−156	−812	−813	−796	−823	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001); elevation corrected
GrA-06514	6090	60	5070-4890 cal BC	5190-4830 cal BC	108.227-430.578	Oud Alblas 6	−130	−677	−679	−656	−687	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001)
GrA-07113	5770	70	4710-4530 cal BC	4770-4450 cal BC	108.218-430.569	Oud Alblas 4	−121	−576	−578	−552	−585	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001)
GrA-07114	5730	70	4670-4490 cal BC	4730-4410 cal BC	097.368-431.466	Barendrecht 10/B	−104	−598	−599	−562	−597	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001); elevation corrected
GrA-07122	3490	310	2220-1440 cal BC	2600-1100 cal BC	108.211-430.561	Oud Alblas 1	−112	−379	−382	−358	−392	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001)
GrA-07123	5090	90	3970-3770 cal BC	4070-3690 cal BC	108.212-430.561	Oud Alblas 2	−114	−454	−459	−428	−469	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001)
GrA-07124	3720	70	2230-2010 cal BC	2330-1910 cal BC	108.204-430.555	Oud Alblas 9	−87	−205	−208	−161	−204	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001); elevation corrected
GrA-07125	4500	80	3330-3070 cal BC	3410-2950 cal BC	108.206-430.559	Oud Alblas 10	−98	−291	−294	−270	−304	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001)
GrA-07126	5830	100	4790-4550 cal BC	4910-4450 cal BC	097.368-431.466	Barendrecht 10/O	−104	−607	−609	−588	−619	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001); elevation corrected

GrA-07128	6120	80	5170-4930 cal BC	5250-4830 cal BC	108.237-430.588	Oud Alblas 7	-118	-733	-735	-707	-740	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001)
GrA-07129	5010	70	3890-3730 cal BC	3970-3670 cal BC	097.379-431.472	Barendrecht 4/B	-103	-423	-425	-387	-425	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001); elevation corrected
GrA-07134	5050	90	3950-3750 cal BC	4030-3670 cal BC	097.379-431.472	Barendrecht 4/0	-103	-434	-436	-416	-446	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001); elevation corrected
GrA-13683	3380	40	1730-1630 cal BC	1770-1570 cal BC	097.311-431.620	Barendrecht 24	-79	-189	-195	-150	-199	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001)
GrA-13685	3790	40	2290-2150 cal BC	2350-2090 cal BC	097.306-431.622	Barendrecht 26	-79	-252	-258	-223	-268	Terrestrial botanical macrofossils	Berendsen & Stouthamer (2001)

1 GrN dates: 200-yr moving average smoothing; GrA dates: 60-yr moving average smoothing.
2 Location co-ordinates and surface elevation given by Berendsen & Stouthamer (2001).
3 Sample depth based on Berendsen & Stouthamer (2001) and slightly different from depth as given by Van de Plassche (1982, p. 71).

a) Wood peat: Törnqvist et al. (1998) and Van de Plassche et al. (2005) proposed, rather optimistically, that wood peat is formed within a vertical range of ±10 cm relative to the local average groundwater level. Here, we use a vertical uncertainty of ±20 cm. All new AMS-dated samples consisted of wood peat.

b) Reed peat or reed-sedge peat: this kind of peat forms below the average water level. However, the environment in which the samples were formed (transgressive peats on the flanks of aeolian dunes) excludes significant water depths. Hence we accept an average water depth of 10 cm for reed peat and reed-sedge peat samples and add the same uncertainty margin of ±20 cm as for samples of wood peat.

4. Uncertainties related to compaction. Compaction (Van de Plassche, 1980) depends mainly on depth, overburden and kind of peat. Even if all samples were collected at or only slightly above the compaction-free surface of dune sand, some compaction needs to be taken into account. We applied the same correction factors as Van de Plassche et al. (2005), i.e., a minimum correction factor of 1.5 (for the base of the dated sample) and a maximum correction factor of 2.5 (for the top of the dated sample). For instance, a 5 cm thick sample, taken at 10 cm above the dune surface, is 'decompacted' to 15 - 37.5 cm above the dune surface.
5. Because the correction factors mentioned under point 4 are averages from a wider range of possible correction factors, we added an uncertainty margin for compaction of ±10 cm.

Instead of summing vertical errors and uncertainties to obtain a maximum vertical range, as has been done in previous palaeowater-level studies (e.g., Törnqvist et al., 1998; Makaske et al., 2003; Van de Plassche et al., 2005), we calculated a total vertical standard deviation based on the various vertical errors and uncertainties mentioned above (except the 'one-way upward corrections' 3b and 4) that are considered as estimates of the 2σ error range (Table 1; a table containing the details of the calculations can be downloaded from: *http://www.geo.uu.nl/fg/palaeogeography*). Although this total vertical standard deviation necessarily is based on estimates, this statistical approach is more consistent with the way age-error margins (see below) are represented. In plotting the samples in time-depth graphs, we took the top of the dune sand as the lower limit of the vertical error range, because errors relating to its depth are negligible.

Age-error margins

Age-error margins are determined by the standard deviation in the dated radiocarbon samples, as given by the laboratory. All radiocarbon ages were calibrated using CAL25 (Stuiver & Van der Plicht, 1998). AMS-dated samples were calibrated using a 60-year moving average curve. Conventionally dated bulk peat

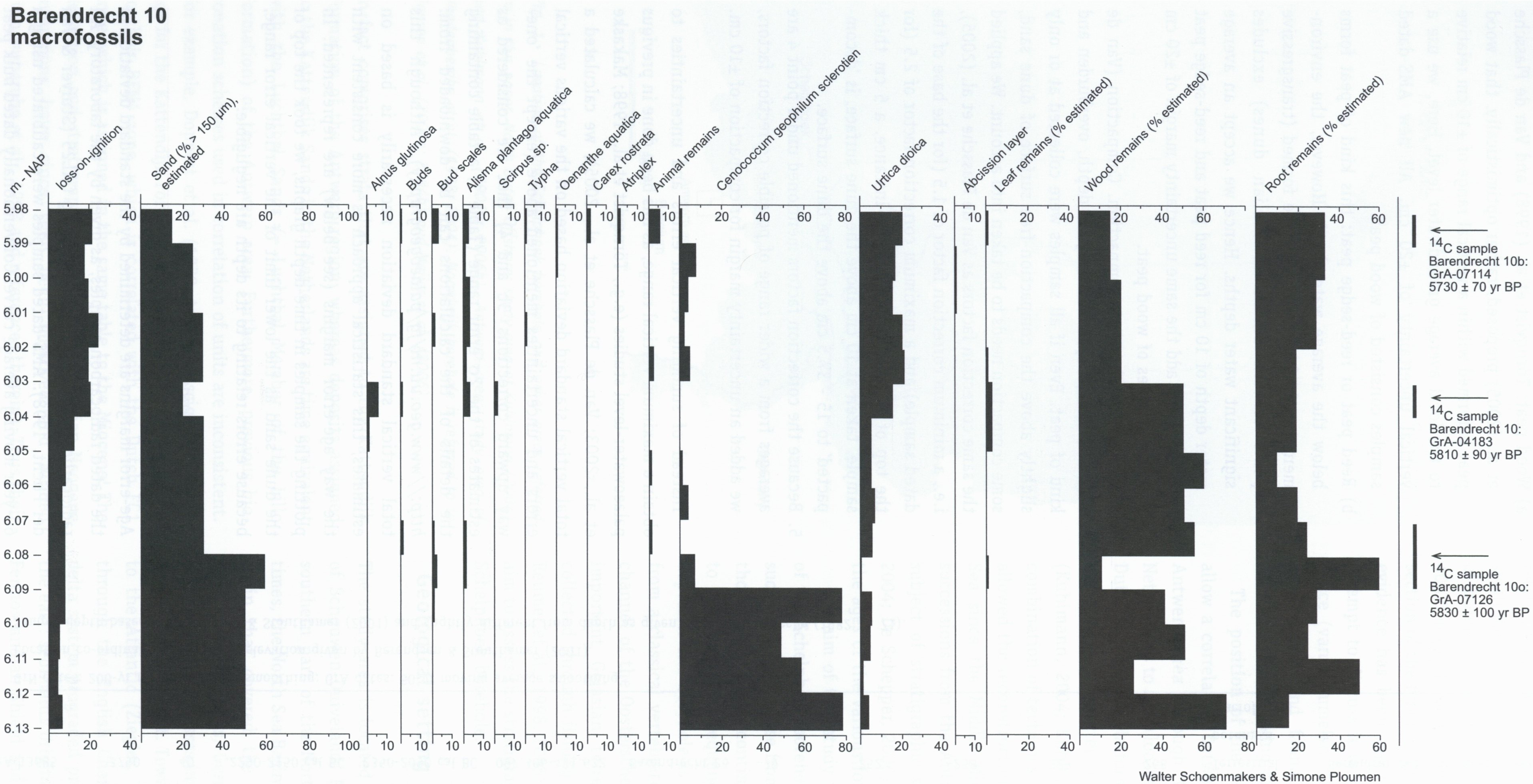

Fig. 4a. Macroremains analysis diagram of sample Barendrecht 10.

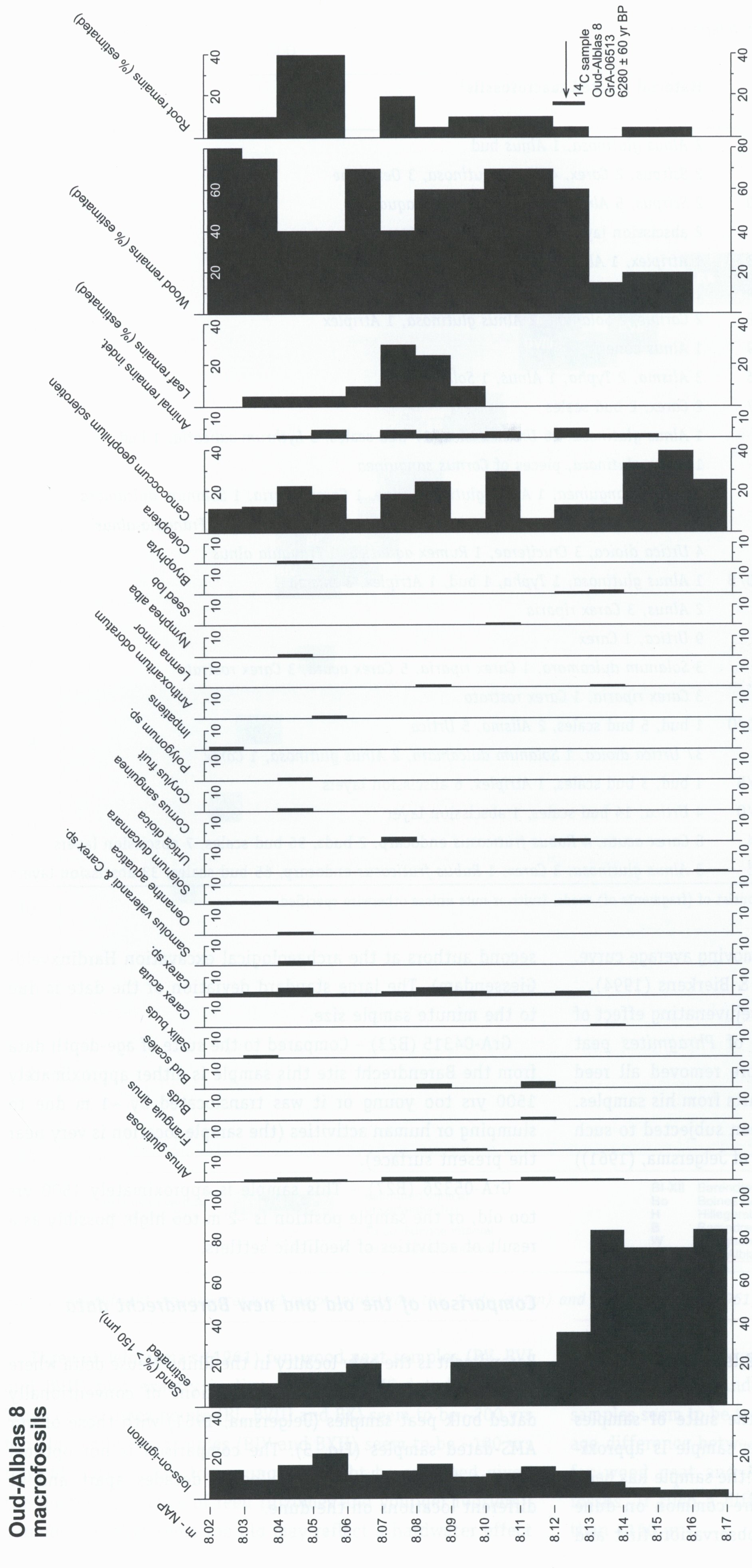

Fig. 4b. Macroremains analysis diagram of sample Oud-Alblas 8.

Table 2. Macroremains used for radiocarbon age determination.

Laboratory number	^{14}C age (yr BP)	Sample name	Material / dated macrofossils[1]
GrA-04181	5000 ± 80	Barendrecht 4	2 *Alnus glutinosa*, 1 *Alnus* bud
GrA-04182	5430 ± 90	Barendrecht 7	2 *Scirpus*, 2 *Carex*, 4 *Alnus glutinosa*, 3 *Oenanthe*
GrA-04183	5810 ± 90	Barendrecht 10	2 *Scirpus*, 5 *Alnus*, 3 *Alisma plantago aquatica*
GrA-04308	4470 ± 60	Barendrecht 1	2 abscission layers, 2 Urtica, 1 Coleoptera fragment
GrA-04315	1290 ± 50	Barendrecht 23	1 *Atriplex*, 1 *Alisma*, 1 *Alnus glutinosa*, 3 *Polygonum*
GrA-05207	5930 ± 50	Barendrecht 13	1 *Cornus sanguinea*
GrA-05208	6660 ± 60	Barendrecht 22	2 *Cornus*, 2 *Solanum*, 2 *Alnus glutinosa*, 1 *Atriplex*
GrA-05215	6360 ± 50	Barendrecht 19	1 *Alnus* cone
GrA-05237	6200 ± 50	Barendrecht 16	3 *Alisma*, 2 *Typha*, 1 *Alnus*, 1 *Solanum*
GrA-05326	5550 ± 60	Barendrecht 27	2 *Carex*, 2 bud scales
GrA-06511	5300 ± 60	Oud Alblas 3	1 *Alnus glutinosa*, 26 *Urtica dioica*, 17 bud scales, 3 *Lythrum salicaria*, 1 bud
GrA-06512	5920 ± 60	Oud Alblas 5	1 *Alnus glutinosa*, pieces of *Cornus sanguinea*
GrA-06513	6280 ± 60	Oud Alblas 8	1 *Cornus sanguinea*, 1 *Alnus glutinosa* cone, 1 *Carex riparia*, 1 *Solanum dulcamara*
GrA-06514	6090 ± 60	Oud Alblas 6	1 *Alisma plantago aquatica*, 1 abscission layer, 12 *Carex acuta*, 4 *Frangula alnus*
GrA-07113	5770 ± 70	Oud Alblas 4	4 *Urtica dioica*, 3 *Cruciferae*, 1 *Rumex aquatica*, 1 *Frangula alnus*
GrA-07114	5730 ± 70	Barendrecht 10/B	1 *Alnus glutinosa*, 1 *Typha*, 1 bud, 1 *Atriplex*, 3 *Alisma*
GrA-07122	3490 ± 310	Oud Alblas 1	2 *Alnus*, 3 *Carex riparia*
GrA-07123	5090 ± 90	Oud Alblas 2	9 *Urtica*, 1 *Carex*
GrA-07124	3720 ± 70	Oud Alblas 9	3 *Solanum dulcamara*, 1 *Carex riparia*, 5 *Carex acuta*, 3 *Carex rostrata*
GrA-07125	4500 ± 80	Oud Alblas 10	3 *Carex riparia*, 1 *Carex rostrata*
GrA-07126	5830 ± 100	Barendrecht 10/0	1 bud, 5 bud scales, 2 *Alisma*, 5 *Urtica*
GrA-07128	6120 ± 80	Oud Alblas 7	37 *Urtica dioica*, 1 *Solanum dulcamara*, 2 *Alnus glutinosa*, 1 *Carex*
GrA-07129	5010 ± 70	Barendrecht 4/B	1 bud, 3 bud scales, 1 *Atriplex*, 6 abscission layers
GrA-07134	5050 ± 90	Barendrecht 4/0	4 *Urtica*, 14 bud scales, 1 abscission layer
GrA-13683	3380 ± 40	Barendrecht 24	8 *Carex acuta*, 4 *Rubus fruticosus* endocarp, 2 buds, 96 bud scales, 7 abscission layers
GrA-13685	3790 ± 40	Barendrecht 26	3 *Alnus glutinosa*, 3 *Carex*, 1 *Rubus fruticosus* endocarp, 65 bud scales, 33 abscission layers

1 Dated macrofossils indicated by species names consist of (fragments of) seeds, fruits or nuts unless otherwise specified.

samples were calibrated using a 200-year moving average curve, following recommendations by Törnqvist & Bierkens (1994).

Streif (1971, 1972) demonstrated the rejuvenating effect of reed rhizomes on the radiocarbon age of *Phragmites* peat samples. Van de Plassche (1982) therefore removed all reed rhizomes, rootlets and subsurface stem parts from his samples. Theoretically, samples which have not been subjected to such preparation (e.g., the Barendrecht samples of Jelgersma, (1961)) may have ages that are too young.

Results

Rejected data

The dating results are summarised in Table 1. The following index points were rejected:

GrA-07122 (A1) – Given the age of the suite of samples from the Oud-Alblas site, the age of this sample is approximately 1300 yrs too young. Alternatively, the sample has been translocated ~2 m by a slump. Slumps are common on dune slopes that drowned quickly (personal observation first and second authors at the archaeological excavation Hardinxveld-Giessendam). The large standard deviation of the date is due to the minute sample size.

GrA-04315 (B23) – Compared to the suite of age-depth data from the Barendrecht site this sample is either approximately 1500 yrs too young or it was translocated by ~1 m due to slumping or human activities (the sample location is very near the present surface).

GrA-05326 (B27) – This sample is approximately 1500 yrs too old, or the sample position is ~2 m too high, possibly as a result of activities of Neolithic settlers.

Comparison of the old and new Barendrecht data

Barendrecht is the only locality in the Rhine-Meuse delta where we can compare the age-depth positions of conventionally dated bulk peat samples (Jelgersma, 1961) with those of our AMS-dated samples (Fig. 5). The comparison is not optimal because the samples were collected decades apart and at different locations on the dune.

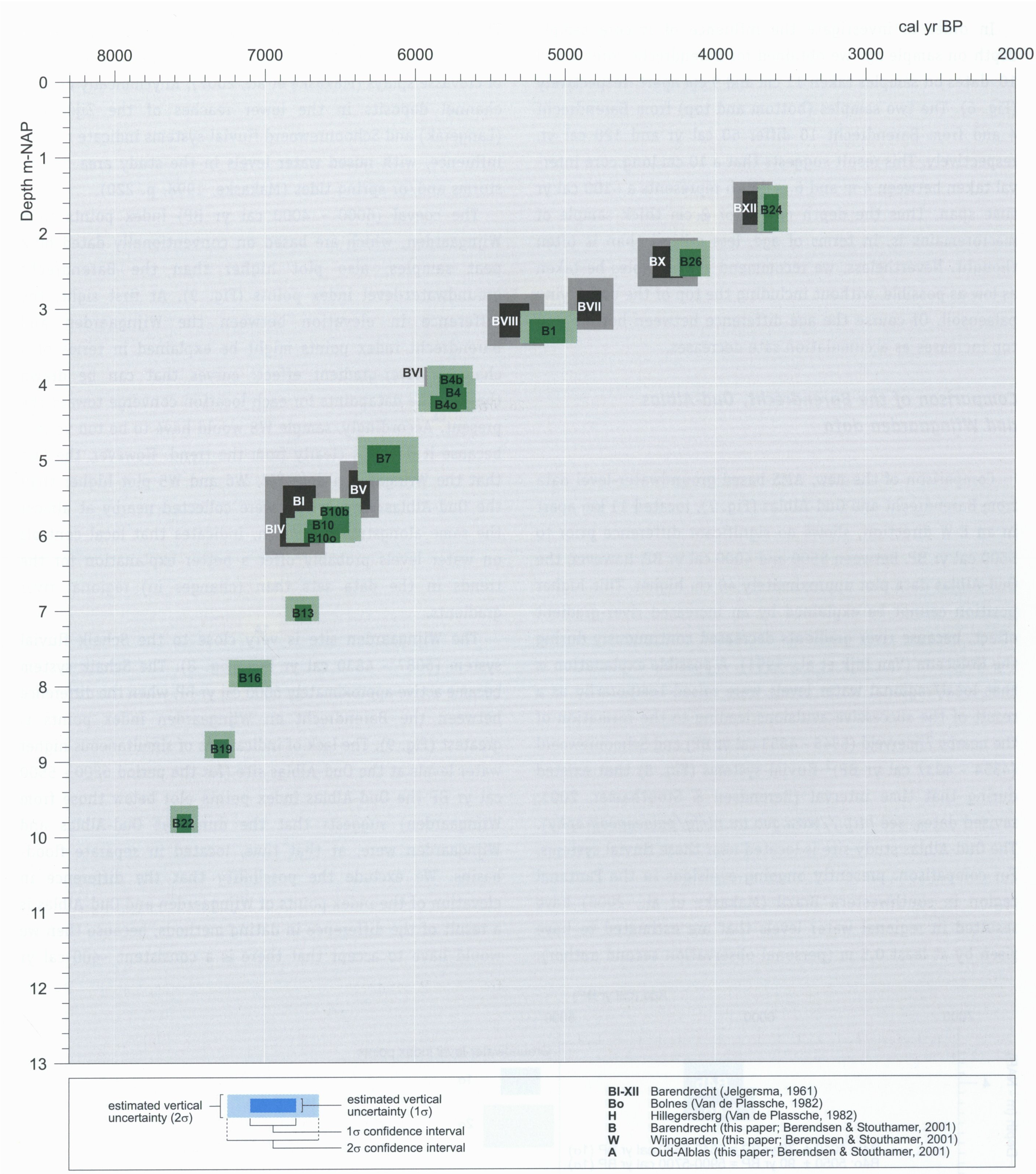

Fig. 5. Barendrecht groundwater-level index points from this study (green) and from Jelgersma (1961) (black).

Three of Jelgersma's (1961) fen-wood peat samples (BV, BVI and BVII) plot exactly in line with the AMS-dated samples. Three of her index points (BI, BVIII and BX) seem to be ~200 yrs too old, while two samples (BIV and BXII) seem to be ~100 yrs too old (rather than too young, as might be expected given the possible presence of reed rhizomes and younger rootlets). Sample ages that seem too old may reflect a hardwater effect or inclusion in the sample of 'old' organic carbon from the humic top of the underlying soil. Although five of Jelgersma's samples seem to be too old, we see no evidence for a systematic age difference between conventionally dated bulk samples of fen-wood peat and AMS-dated samples of terrestrial macro-fossils. If such a difference exists, it is, on average, smaller than ~150 yr.

In order to investigate the influence of in-core sample depth on sample age we obtained for Barendrecht cores 4 and 10, dates on samples taken 11 cm and 9 cm apart, respectively (Fig. 6). The two samples (bottom and top) from Barendrecht 4 and from Barendrecht 10 differ 60 cal yr and 120 cal yr, respectively. This result suggests that a 10 cm long core interval taken between 4 m and 6 m depth represents a ~100 cal yr time span. Thus the depth of a 1 or 2 cm thick sample of macroremains is, in terms of age, less critical than is often thought. Nevertheless, we recommend that samples be taken as low as possible, without including the top of the underlying palaeosoil. Of course the age difference between bottom and top increases as accumulation rate decreases.

Comparison of the Barendrecht, Oud-Alblas and Wijngaarden data

Comparison of the new, AMS-based groundwater-level data from Barendrecht and Oud-Alblas (Fig. 7), located 11 km apart in an E-W direction, shows no significant difference prior to 5500 cal yr BP. Between 5500 and 4000 cal yr BP, however, the Oud-Alblas data plot approximately 40 cm higher. This higher position cannot be explained by an increased river-gradient effect, because river gradients decreased continuously during the Holocene (Van Dijk et al., 1991). A possible explanation is that local/regional water levels were raised temporarily as a result of the successive avulsions leading to the formation of the nearby Zijderveld (5345 - 4653 cal yr BP) and Schoonrewoerd (4354 - 4037 cal yr BP)[1] fluvial systems (Fig. 8) that existed during that time interval (Berendsen & Stouthamer, 2001; revised dates, see *http://www.geo.uu.nl/fg/palaeogeography*). The Oud-Alblas study site is located near these fluvial systems. For comparison: presently ongoing avulsions in the Pantanal region in southwestern Brazil (Makaske et al., 2006) have resulted in regional water levels that are estimated to have risen by at least 0.5 m (personal observation second author). The Schoonrewoerd avulsion in particular is interpreted to have been a similar catastrophic event with extensive formation of crevasse splays (Makaske et al., 2007). Rhythmically bedded channel deposits in the lower reaches of the Zijderveld (Langerak) and Schoonrewoerd fluvial systems indicate marine influence, with raised water levels in the study area due to storms and/or spring tides (Makaske, 1998, p. 220).

The coeval (6000 - 4000 cal yr BP) index points from Wijngaarden, which are based on conventionally dated bulk peat samples, also plot higher than the Barendrecht groundwater-level index points (Fig. 9). At first sight, the difference in elevation between the Wijngaarden and Barendrecht index points might be explained in terms of a changing river-gradient effect: curves that can be drawn through the datapoints for each location converge toward the present. Accordingly, sample W8 would have to be too young, because it deviates clearly from the trend. However, the fact that the Wijngaarden data W7, W6 and W5 plot higher than the Oud-Alblas data, which were collected nearby at almost the same alongstream position, indicates that local controls on water levels probably offer a better explanation for the trends in the data sets than (changes in) regional river gradients.

The Wijngaarden site is very close to the Schaik fluvial system (6087 - 4830 cal yr BP) (Fig. 8). The Schaik system became active approximately 6000 cal yr BP, when the difference between the Barendrecht en Wijngaarden index points is greatest (Fig. 9). The lack of indications of simultaneous higher water levels at the Oud-Alblas site (for the period 6200 - 5500 cal yr BP the Oud-Alblas index points plot below those from Wijngaarden) suggests that the dunes at Oud-Alblas and Wijngaarden were, at that time, located in separate flood-basins. We exclude the possibility that the difference in elevation of the index points of Wijngaarden and Oud-Alblas is a result of the difference in dating methods, because then we would have to accept that there is a consistent ~400 cal yr

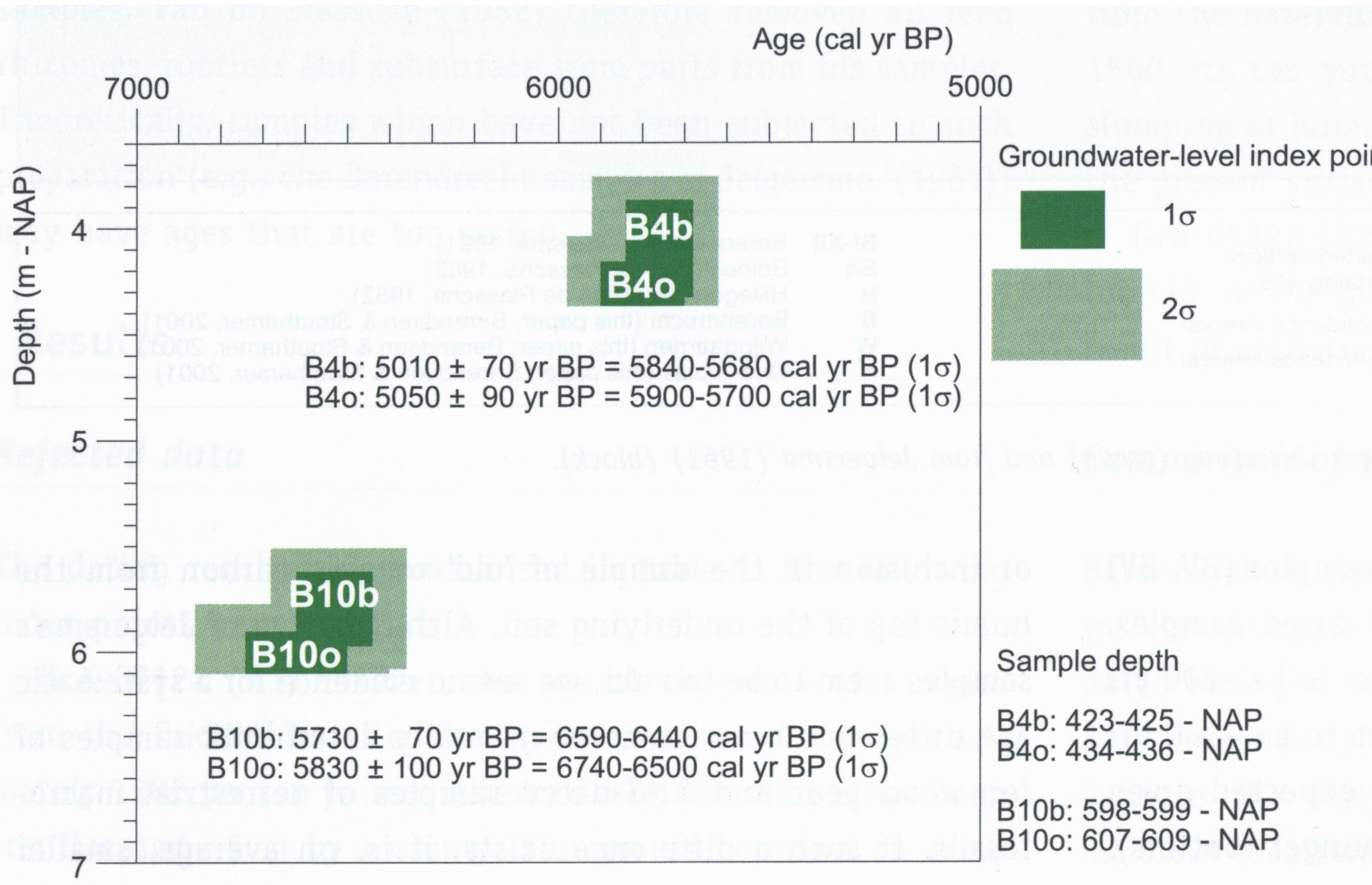

Fig. 6. Comparison of sample ages and depths of closely spaced Barendrecht samples. The diagram suggests that depth of samples is less critical than previously thought, as long as the top of the underlying palaeosoil is avoided.

1 Makaske et al. (2007) proposed a shorter period of activity for the Schoonrewoerd system: 3900-3800 yr BP (~4350 - 4200 cal yr BP).

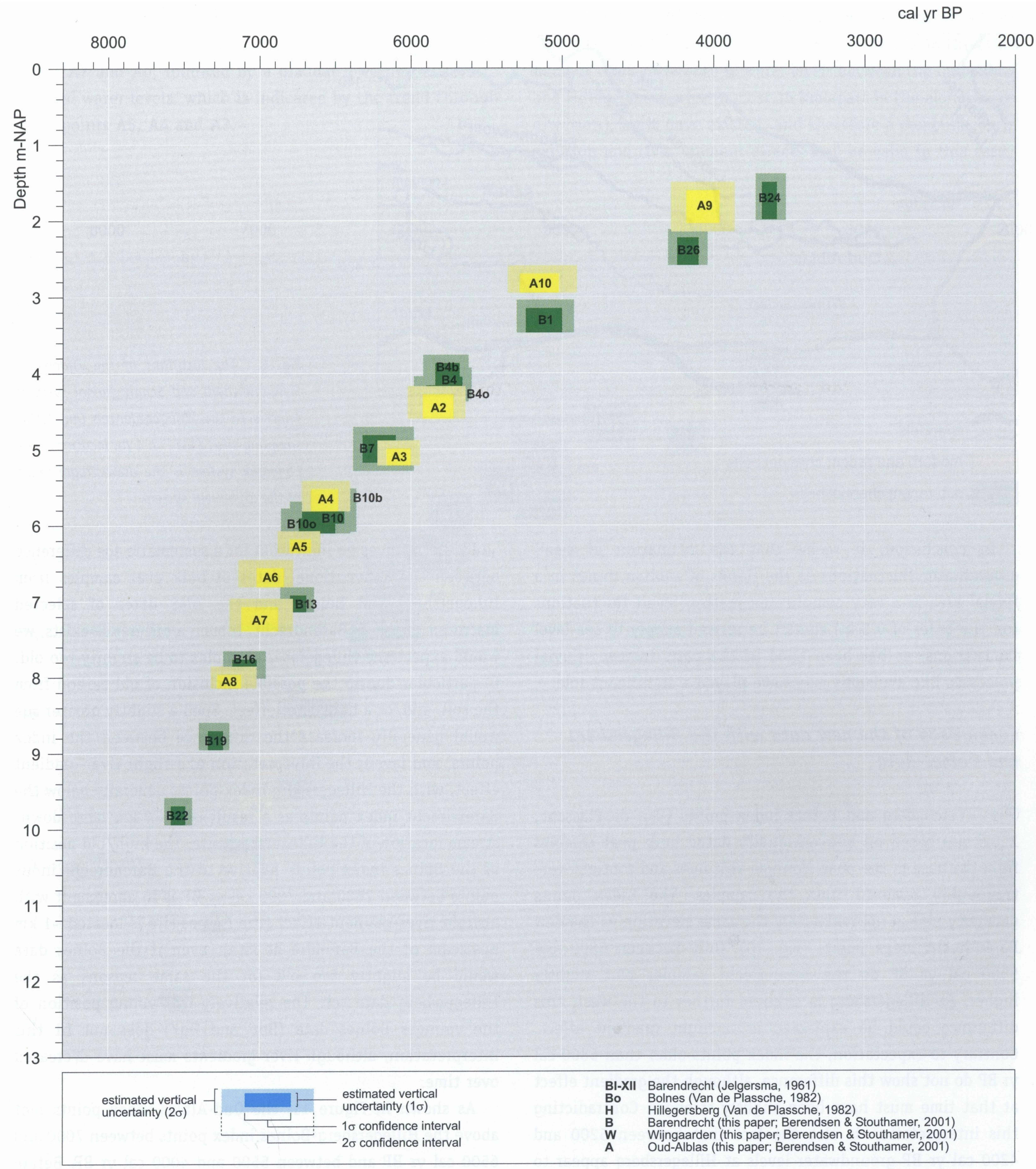

Fig. 7. Barendrecht groundwater-level index points (green) compared with Oud-Alblas groundwater-level index points (yellow).

difference between AMS (Oud-Alblas) and conventional dates (Wijngaarden), which is not evident from the Barendrecht data (Fig. 5). Moreover, after 5500 cal yr BP no age difference is observed between the Wijngaarden en Oud-Alblas data sets.

In any case, the data suggest varying floodbasin-water levels over short distances, possibly related to the avulsion that led to the formation of the Schaik channel belt. If fluctuating floodbasin-water levels in the Rhine-Meuse delta are indeed caused by avulsions, such fluctuations may be related to the average period of existence (~1100 cal yr) of channel belts (Berendsen & Stouthamer, 2001), or to the duration (~500 - 600 cal yr) of avulsion sequences (Stouthamer & Berendsen, 2007). This gives a maximum order of magnitude of the duration of locally raised floodbasin-water levels due to avulsions.

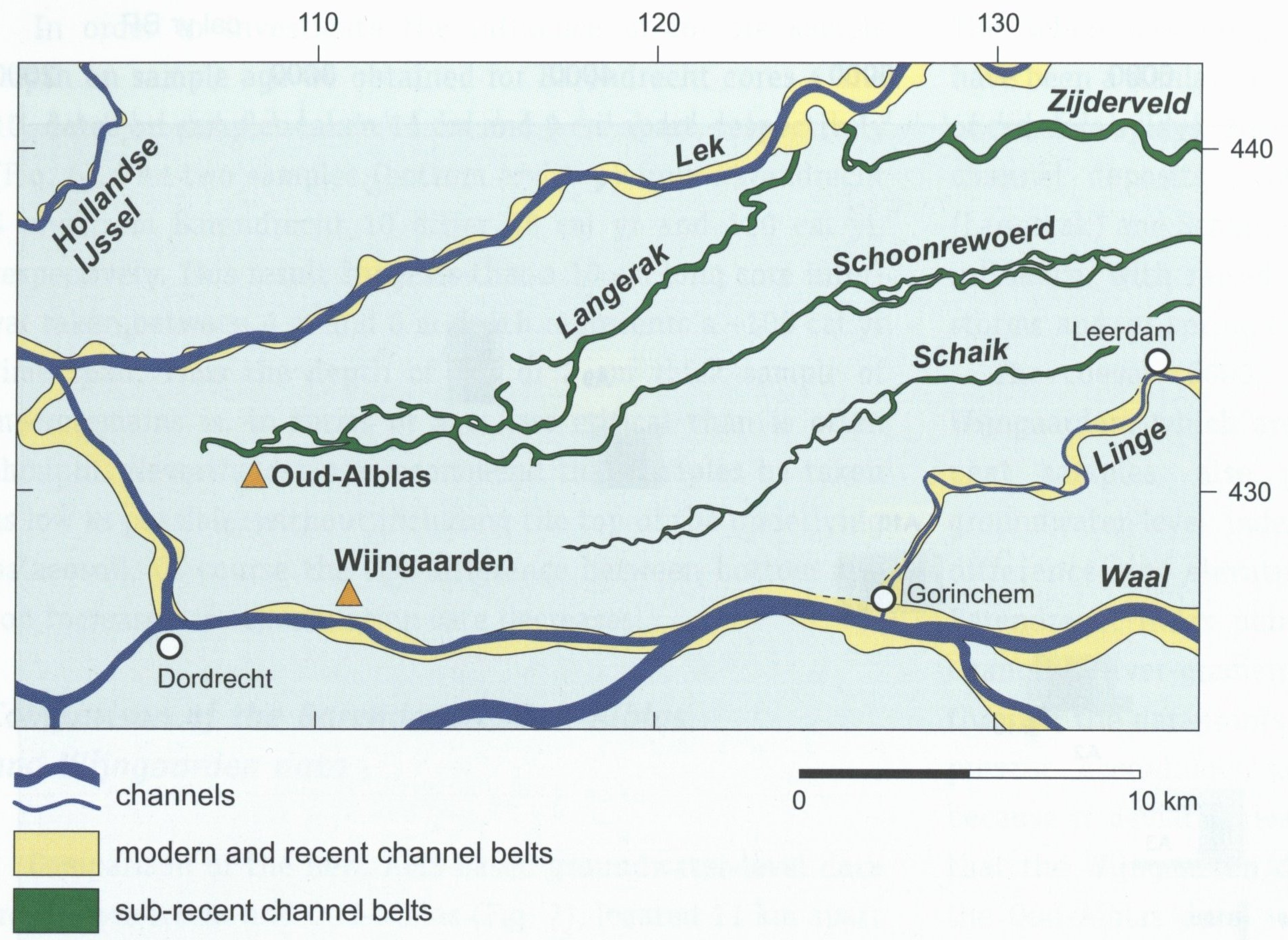

Fig. 8. The locations of the Zijderveld, Schoonrewoerd and Schaik fluvial systems relative to the Wijngaarden en Oud-Alblas sampling sites (see Fig. 1 for location). The Langerak system is the downstream reach of the Zijderveld system.

In conclusion, it seems that the evaluation of small groundwater fluctuations at the flanks of aeolian dunes in a fluvial area is a very complicated matter. Small fluctuations (on the order of 0.5 m) cannot be related simply to sea-level fluctuations, as has been tried in the past. Instead, fluvial processes like avulsions may have played a significant role.

Comparison of the new data with the Hillegersberg and Bolnes data

The Hillegersberg and Bolnes index points (Van de Plassche, 1982) are based on conventionally dated bulk peat samples from the base of the peat. Younger rhizomes and rootlets were thoroughly removed from the samples. The index points generally plot at approximately the same elevation as the new Barendrecht index points (Fig. 10). Only between 6800 and 5500 cal yr BP do the Barendrecht samples plot slightly higher. As Hillegersberg is situated further to the west, this difference could be explained as a slight gradient effect. Contrary to expectation, the index points older than 6800 cal yr BP do not show this difference, although the gradient effect at that time must have been slightly stronger. Contradicting this interpretation is also the fact that between 5200 and 4200 cal yr BP groundwater levels at Hillegersberg appear to be higher than at Barendrecht.

The new Barendrecht index points in Figure 10 suggest an abrupt rise at ~6700 cal yr BP followed by a gradual convergence with the Hillegersberg index points forward in time. This difference in elevation of the Barendrecht and Hillegersberg index points between 6800 and 5500 cal yr BP may also be related to an avulsion, but at present no detailed data are available for this area and that time interval.

Figure 10 gives no indication for a systematic age difference between the conventional dates of bulk peat samples from Hillegersberg and Bolnes and the AMS dates of selected macroremains from Barendrecht. If such a difference exists, we would expect the Hillegersberg samples to be slightly too old, in particular due to the possible inclusion of old carbon from the soil, and/or a hardwater effect. Such a slightly greater age would generally increase the difference between the index points, and favour the interpretation of a slight river-gradient effect, with the Hillegersberg index points generally below the Barendrecht index points as a result of a ~4 km more downstream location of the Hillegersberg site. The high/old position of the Bolnes index points relative to the Barendrecht index points between 7600 and 7000 cal yr BP is in agreement with a slight river-gradient effect (the Bolnes site is located ~1 km upstream of the Barendrecht site), even if the Bolnes data would be slightly too old for the same reasons as the Hillegersberg data set. The relatively low/young position of the younger Bolnes data (Bo6 and Bo7) does not fit this interpretation, although river gradients must have decreased over time.

As shown in Figure 11, the Oud-Alblas index points plot above the Hillegersberg-Bolnes index points between 7000 and 6500 cal yr BP and between 5500 and 4000 cal yr BP. Before 7000 cal yr BP and between 6200 and 5500 cal yr BP they are at the same elevation. If we attribute the relatively high position of the Oud-Alblas index points between 5500 and 4000 cal yr BP to the avulsions of the Zijderveld and Schoonrewoerd fluvial systems (as argued above), the distribution of the index points before 5500 cal yr BP can be taken to represent either (1) a river-gradient effect, with the general divergence backward in time of the Oud-Alblas and Hillegersberg index points indicating an increasing gradient, or (2) an earlier, undocumented avulsion that caused a steep rise in water levels at approximately 7000 cal yr BP, indicated by the index points A7 and A6, followed by a gradual lowering relative to regional water levels, which is indicated by the trend through index points A5, A4 and A3.

The relatively low/young position of the index points A7 and A8 contradicts the 'river-gradient' interpretation. On the other hand, a slight difference in water levels between the Oud-Alblas and Hillegersberg sites (almost 15 km apart in the alongstream direction), must have existed, and therefore a combination of avulsion and river gradient effects may be valid in this case.

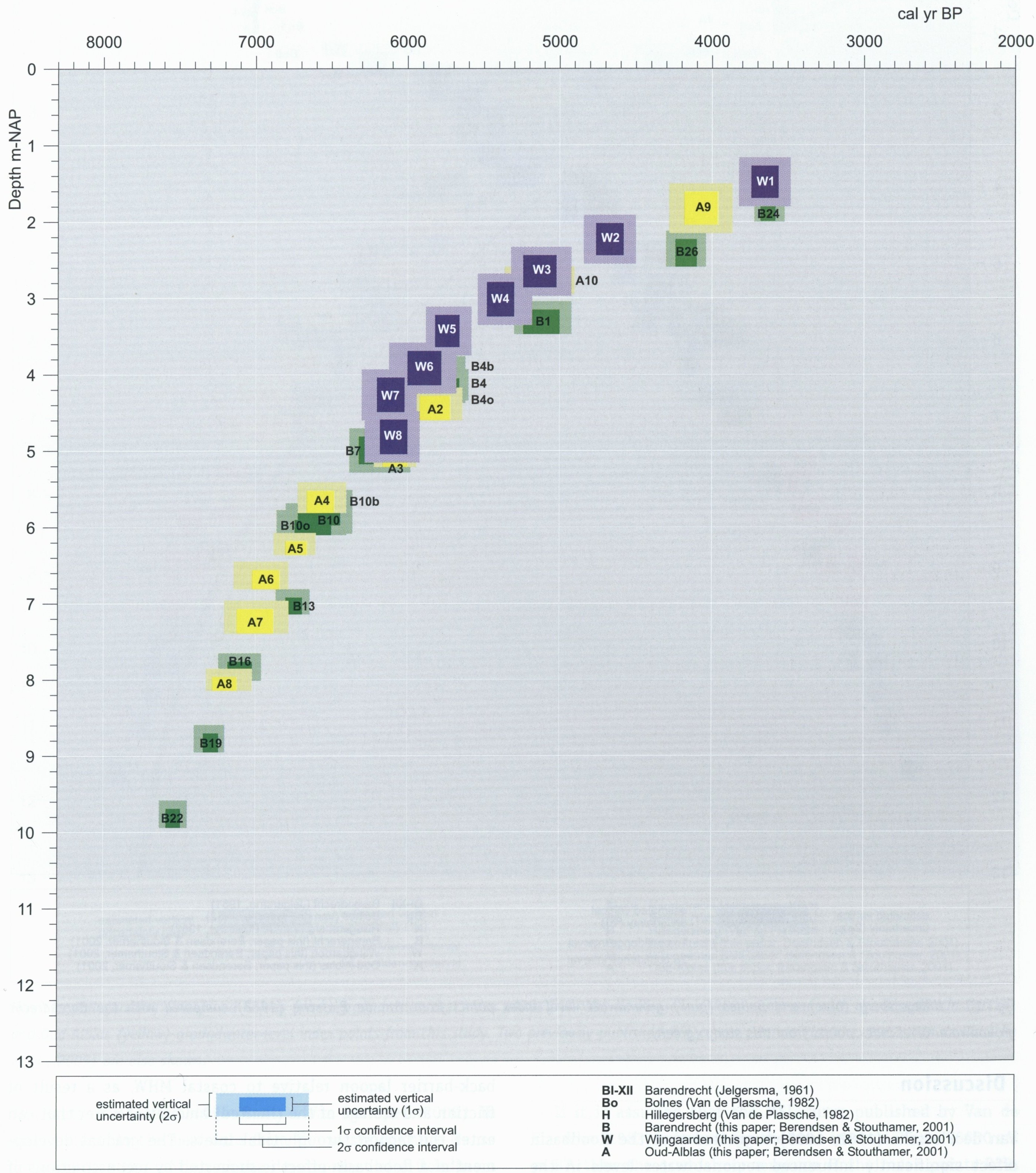

Fig. 9. Barendrecht (green) and Oud-Alblas (yellow) groundwater-level index points from this study, and Wijngaarden (purple) groundwater-level index points from Van Dijk et al. (1991).

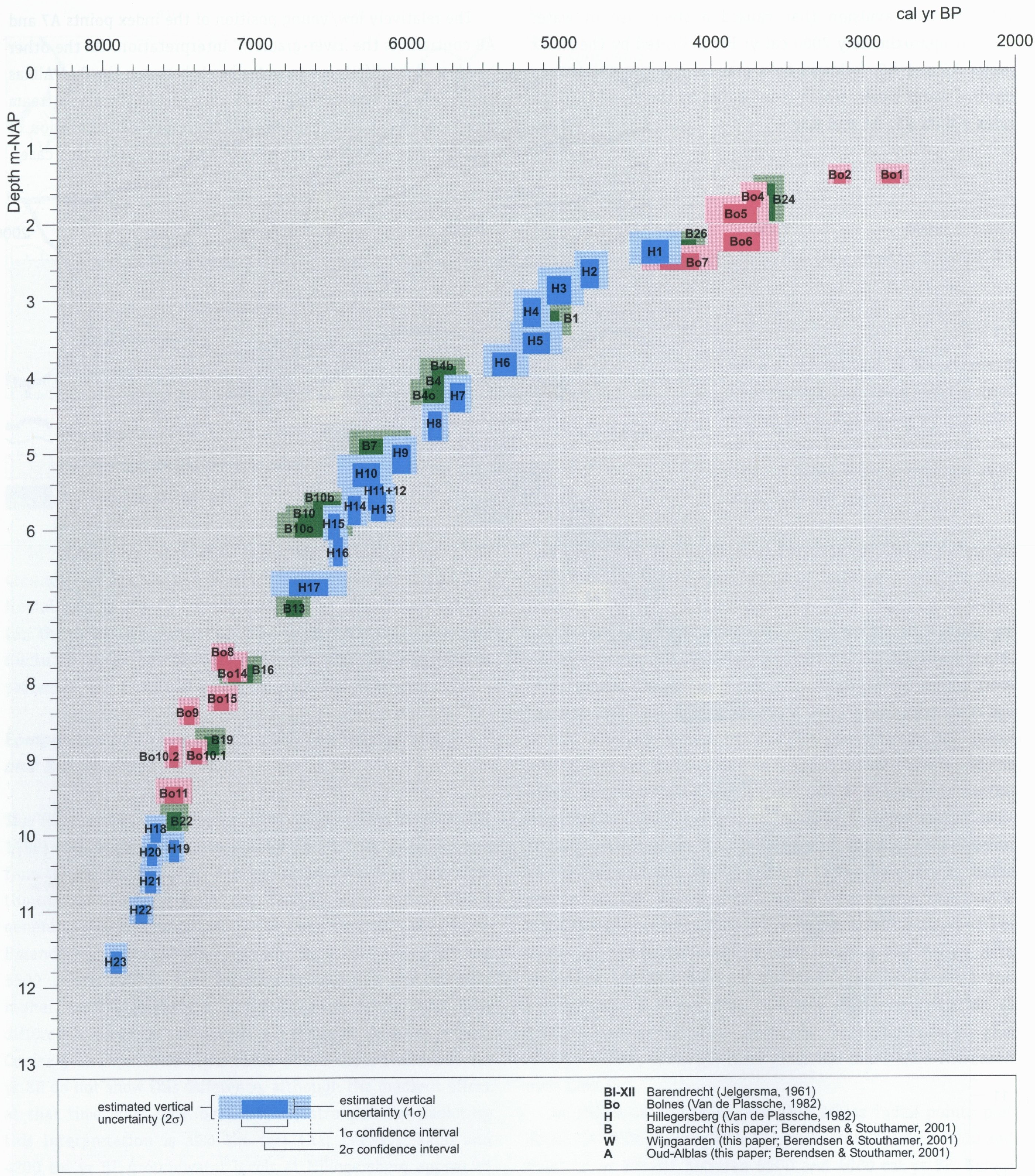

Fig. 10. Hillegersberg (blue) and Bolnes (pink) groundwater-level index points from Van de Plassche (1982) compared with the Barendrecht groundwater-level index points from this study (green).

Discussion

Van de Plassche (1982, 1995) suggested that the floodbasin effect significantly influenced regional water levels in the western Rhine-Meuse delta since ~7500 cal yr BP. The floodbasin effect involves lowering of mean high water (MHW) in a back-barrier lagoon relative to coastal MHW, as a result of friction and storage of the (limited) amount of water that can enter the lagoon through tidal inlets. The gradual development of a floodbasin effect is suggested by reconstructions of Holocene coastal evolution showing narrowing/closure of tidal inlets in the coast of Holland between 6500 and 5500 cal yr

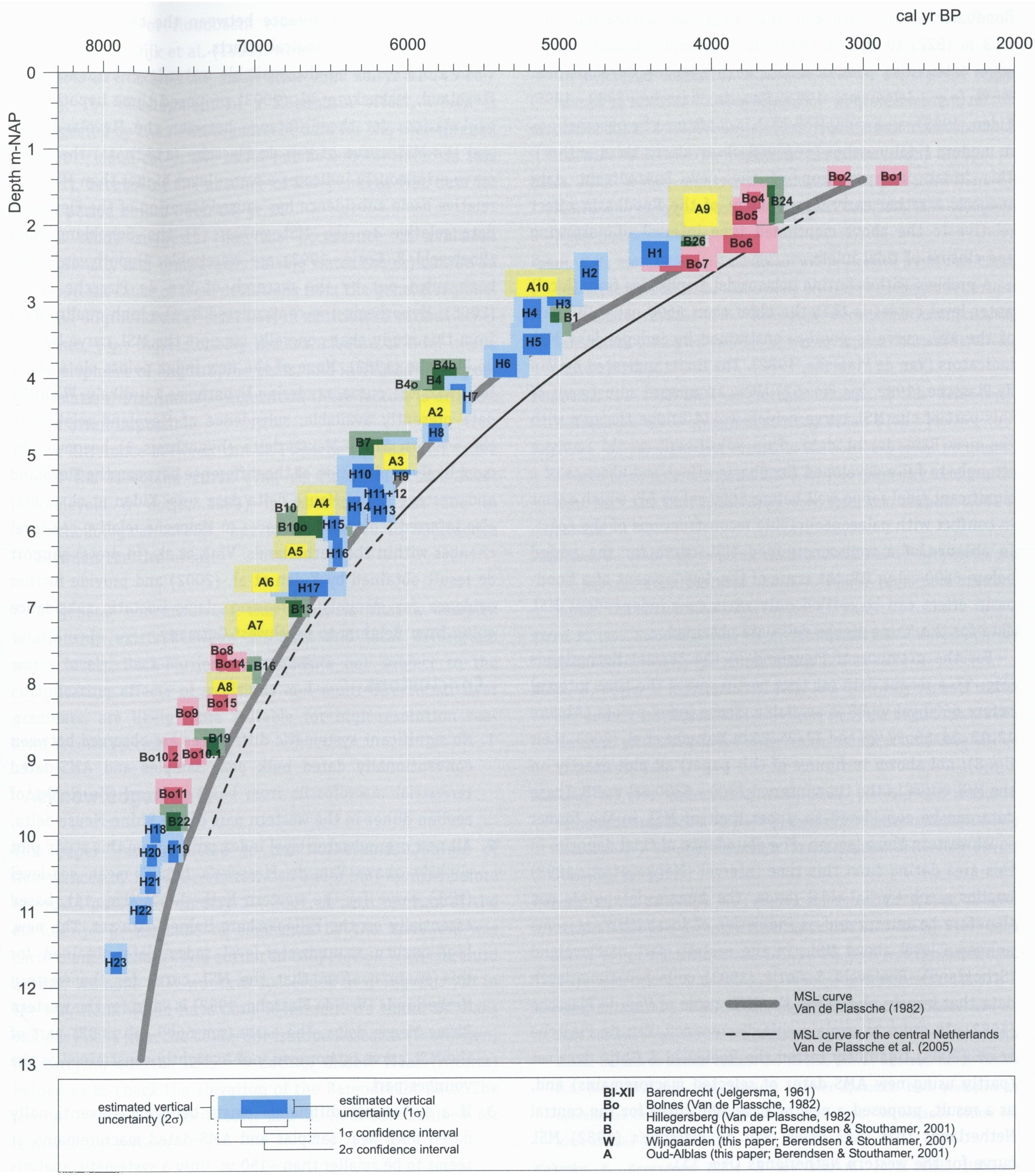

Fig. 11. Hillegersberg (blue) and Bolnes (pink) groundwater-level index points from Van de Plassche (1982) compared with the Barendrecht (green) and Oud-Alblas (yellow) groundwater-level index points from this study. Two previously published MSL curves (Van de Plassche, 1982; Van de Plassche et al., 2005) are also shown.

BP (Beets et al., 1992, 1994; Beets & Van der Spek, 2000). To what extent do the new data from the western Rhine-Meuse delta support this notion of the development of a floodbasin effect since ~7500 cal yr BP?

If it is assumed that the MSL curve published by Van de Plassche (1982) is correct for the time interval 7500 - 6600 cal yr BP, then the gradual convergence of the index points B22, B19, B16 and B13 (representing MHW) with the MSL curve (Fig. 11) could be taken to represent the development of a floodbasin effect, with the tidal amplitude decreasing from ~0.8 m (B22) to ~0.2 m (B13). It is generally assumed that, when tides exist, peat in a back-barrier lagoon develops near MHW (e.g., Jelgersma, 1961; Van de Plassche, 1982, 1995; Kiden, 1995), an assumption that is confirmed by observations in modern tidal marshes (personal observations third author). This 'tidal' interpretation of the new Barendrecht data suggests a rather early development of the floodbasin effect relative to the above-mentioned time interval of narrowing and closure of tidal inlets.

A problem with inferring palaeotidal amplitudes from (local) water-level curves is that the older than 6600 cal yr BP part of the MSL curve is poorly constrained by independent MSL indicators (Van de Plassche, 1982). The limits indicated by Van de Plassche (1982, his Fig. 52) allow an upward adjustment of this part of the MSL curve, which would bridge the gap with the new Barendrecht data. This adjustment would imply a strongly to fully developed floodbasin effect and absence of a significant tidal range well before 6600 cal yr BP, which seems in conflict with palaeogeographic reconstructions of the coast. In absence of a well-constrained MSL curve for the period before 6600 cal yr BP, the issue of the development of a floodbasin effect can be settled only when new independent MSL data for the Rhine-Meuse delta are obtained.

For the province of Flevoland in the central Netherlands (Fig. 1), a recent data set that partly covers the time interval before 6600 cal yr BP is available. These index points (Almere 12, 13, 14, 15, 27/28 and 23/25/26 in Makaske et al. (2003, their fig. 8); not shown in figures of this paper) all plot exactly on the MSL curve in the time interval 7300 - 6300 cal yr BP. These data can be considered an upper limit of MSL in the former southwestern Flevo lagoon. The abundance of tidal deposits in this area dating from this time interval (Menke et al., 1998) implies a substantial tidal range. The Almere datapoints can therefore be interpreted as indicative of local MHW, at some unknown level above MSL. In the eastern part of Flevoland (Schokland), Roeleveld & Gotjé (1993) collected time-depth data that largely plot below the MSL curve of Van de Plassche (1982). In order to explain this discrepancy, Van de Plassche et al. (2005) rigorously tested the Roeleveld & Gotjé data set (partly using new AMS dates of selected macroremains) and, as a result, proposed a new relative MSL curve for the central Netherlands that runs below Van de Plassche's (1982) MSL curve for the western Netherlands (Fig. 11).

Van de Plassche et al. (2005) left open the possibility that the difference between the two MSL curves is due to methodological effects (i.e., the difference between AMS-dated macroremains and conventionally dated bulk samples). At that time, high-quality (AMS) index points were not available for the western Netherlands. This study provides new AMS index points from aeolian dunes in the western Rhine-Meuse delta, that also plot higher than AMS-dated index points from Flevoland (Van de Plassche et al., 2005). This indicates that the difference between the curves cannot be explained by methodological effects.

In a discussion of the available water-level evidence from Flevoland, Makaske et al. (2003) proposed three hypothetical explanations for the difference between the Flevoland data and the MSL curve of Van de Plassche (1982): (1) the latter curve erroneously indicates a water level higher than MSL, (2) relative basin subsidence has caused lowering of the Flevoland data relative to the MSL curve, (3) the Schokland data (Roeleveld & Gotjé, 1993) are unreliable. Hypothesis 3 has been ruled out by the research of Van de Plassche et al. (2005). Hypothesis 1 is contradicted by the high-quality data from this study that generally support the MSL curve by Van de Plassche (1982). None of the new index points plots below the 1982-MSL curve, rendering hypothesis 1 unlikely. With the data presently available, subsidence of Flevoland relative to the western Rhine-Meuse delta (hypothesis 3) becomes the most likely explanation of the difference between the Flevoland and western Rhine-Meuse delta data sets. Kiden et al. (2002) also inferred regional differences in Holocene relative sea-level changes within the Netherlands. Vink et al. (in press) support de result obtained by Kiden et al. (2002) and provide further evidence for strongly increasing glacio-isostatic subsidence going from Belgium to northwest Germany.

Conclusions

1. No significant systematic differences are observed between conventionally dated bulk peat samples and AMS-dated terrestrial macrofossils from basal peat on the flanks of aeolian dunes in the western part of the Rhine-Meuse delta.
2. All new groundwater-level index points from this study plot slightly above Van de Plassche's (1982) mean sea-level (MSL) curve for the western Netherlands (Fig. 11), based essentially on the Hillegersberg-Bolnes data set. The new, high-quality groundwater-level index data obtained for this study confirm that the MSL curve for the western Netherlands (Van de Plassche, 1982) is valid for the western Rhine-Meuse delta. The early (pre-6600 cal yr BP) part of the MSL curve is, however, not as tightly constrained as the younger part.
3. If a systematic difference exists between conventionally dated bulk peat samples and AMS-dated macroremains, it seems to be smaller than ~150 yr. Only a systematic analysis of conventional bulk dating and AMS dating on subsamples from the same sample can provide more information on this.
4. Depth selection of basal peat samples is less critical than previously thought, as long as the top of the palaeosoil in the underlying deposits is not included, and macroremains are selected from levels with indications for wet conditions (peat formation).
5. Differences between groundwater-level rise trends at individual aeolian dunes may be caused by differences in

gradient and/or floodbasin effects. Results confirm the study of Van Dijk et al. (1991), which suggests that gradient effects in this area are small after 6600 cal yr BP (≤5 cm/km). The development of a floodbasin effect, which is suggested by the new Barendrecht data for the time interval 7500 - 6600 cal yr BP, could not be substantiated in this study, because of the absence of independent MSL data for the period before 6600 cal yr BP.

6. This study suggests that the occurrence of avulsions (regionally and temporarily raising water tables) can be an important cause of local deviations from the general regional trend of groundwater-level rise, in addition to various other causes, e.g.: ingressions by the sea, closure of tidal inlets, development of oligotrophic peats, and increased wood peat formation. Discrimination between these factors is difficult and often impossible.
7. The difference between Van de Plassche's (1982) MSL curve and the Flevoland curve (Van de Plassche et al., 2005; Roeleveld & Gotjé, 1993) is most likely not due to methodological effects, but to differences in subsidence between the two areas.

A general conclusion of this study is that a complex relationship exists between sea-level and local delta-plain water levels. Back-barrier environments not subject to the complicating effects of avulsions and multi-directional river gradients, are likely more suitable for high-resolution sea-level reconstruction.

Acknowledgements

This paper was submitted to the Netherlands Journal of Geosciences by Henk Berendsen two and a half months before he would pass away on May 14, 2007. A final revision of the manuscript in response to comments by the reviewers was carried out by the second author in cooperation with the third author. We hope that we have succeeded in doing this job in the way Henk would have done it himself. We thank Dr. Hans van der Plicht from the Center for Isotope Research (Groningen) for carrying out the AMS ^{14}C dating. Gilbert Maas (Alterra) helped us to check the elevation of the Barendrecht data. The journal referees T.N. Olsthoorn and H. Kooi are thanked for constructive reviews.

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