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Mid-Holocene water-level changes in the lower Rhine-Meuse delta (western Netherlands): implications for the reconstruction of relative mean sea-level rise, palaeoriver-gradients and coastal evolution

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Abstract

We present a revised relative mean sea-level (MSL) curve for the Rhine-Meuse delta, western Netherlands, for the period 7900-5300 cal yr BP. The revision is based on a series of new and previously unpublished local groundwater-level index data from buried Late Glacial aeolian dunes in the lower Rhine-Meuse delta, and reinterpretation of existing data.

The new index data consist of (AMS and conventional) radiocarbon dates of samples, collected from the base of peat formed on dune slopes, near Vlaardingen (21 index points), Hillegersberg (one index point), and Hardinxveld-Giessendam (10 index points). The Vlaardingen data represent the coast-nearest Rhine-Meuse delta local water-level record, which therefore is highly indicative for sea-level change. Pollen and macrofossil analysis, and dating of paired samples was carried out to assess the reliability of the groundwater-level index data.

The revision of the MSL curve involves: (1) a significant (0 to >1 m) upward adjustment for the period 7900-7300 cal yr BP; (2) a downward adjustment of ≤0.25 m for the period 6650-5300 cal yr BP. The new data indirectly support the reliability of the part of the curve for the period 7300-6650 cal yr BP. A longitudinally fairly uniform river gradient of 2.5-3.0 cm/km in the lower Rhine-Meuse delta during the period 6650-5600 cal yr BP can be inferred from the data sets. A significant river gradient extended further towards the coastline than previously thought and it may be that also the revised MSL curve reflects river-gradient effects. An increased floodbasin effect (stronger intra-coastal tidal damping) seems to have developed in the lower Rhine-Meuse delta in de period 7500-6600 cal yr BP, and was probably a complex response to a major avulsion of the Rhine.

Keywords: coastal evolution, floodbasin effect, Holocene sea-level rise, Late Glacial aeolian dunes, radiocarbon age determination, river-gradient effect

Introduction

The extensive occurrence, in the lower Rhine-Meuse delta, of Late Glacial aeolian dunes that are largely or completely covered by Holocene fresh- and brackish-water (tidal) deposits has played, and continues to play, a significant role in the study of changes in relative sea level, intra-coastal tidal range, river gradient, palaeoecological and palaeodepositional environments, human occupation, and differential land-level movements (Jelgersma, 1961; Louwe Kooijmans, 1974; Van der Woude, 1983; Van de Plassche, 1980a, 1982, 1984, 1995a, 1995b; Van Dijk et al., 1991; Törnqvist et al., 1998; Cohen, 2003, 2005; Berendsen et al., 2007). Moderate to steeply sloping flanks of peat-covered aeolian dunes offer the possibility of obtaining suites of local water-level index points that are virtually free of compaction effects. Furthermore, the relatively small size of the dunes and dune complexes excludes, along moderate and steeper dune slopes, that the groundwater table rose above the regional water level. Thus, the occurrence of a large number of inland aeolian dunes and dune complexes oriented perpendicular to the coastline facilitates the study of marine, coastal, estuarine, and fluvial factors controlling intra-coastal water-level changes.

Seaward, the dune at Hillegersberg was long held to be the westernmost occurring back-barrier aeolian dune, leaving the stretch of ~30 km to the present-day coastline without a local water-level record (Fig. 1). In 1979, a submerged aeolian dune was discovered in the town of Vlaardingen-Oost (Delft Soil Mechanics Laboratory, 1979), located 9.5 km west of Hillegersberg (Fig. 1). The dune, which reaches to ~4 m below the surface, appeared to be covered by a basal peat over a vertical range of almost 5 m (from ~9 to ~4 m below NAP (= Dutch Ordnance Datum)). In the summers of 1984 and 1985, the first author (OvdP) conducted field research to map the lithostratigraphy of the Holocene deposits that cover the dune's western flank and to collect basal peat samples for the reconstruction of local water-level changes. The lithostratigraphy and chronology of the Holocene sequence, in particular that of the thick basal organic unit, which formed in the period 7350-5350 cal yr BP, was documented and discussed by Van de Plassche (1995a). In the summer of 1997, the third author (WZH) collected a new basal peat sample at the Hillegersberg dune for detailed macrofossil analysis and AMS radiocarbon dating in order to test the accuracy of earlier collected conventionally radiocarbon-dated groundwater-level index points from this location (Van de Plassche, 1982).

Landward, the aeolian dunes in the Rhine-Meuse delta extend well into the fluvial domain proper. In this area the planned construction of the Betuweroute railway led to a large number of archaeological excavations in the late 1990s. The excavation of the Mesolithic sites 'De Bruin' and 'Polderweg' (Fig. 1), each located on a separate buried dune near Hardinxveld-Giessendam, offered a unique opportunity for detailed peat sampling for palaeowater-level research. In 1998, the third author (WZH) took a series of ten peat samples on the excavated and artificially drained dune slopes over a vertical range of almost 6 m (from ~10 to ~4 m below NAP), which is considerably larger than the vertical range of the nearby Wijngaarden data set (Van Dijk et al., 1991; see Fig. 1 for location).

Here, we present twenty-one new water-level index points from the Vlaardingen dune obtained by conventional radiocarbon dating of thin bulk peat samples from the peat-dune sand interface (and one tree-root sample from the top of the dune sand). Together with the new water-level index point from Hillegersberg, and ten new water-level index points from the Hardinxveld-Giessendam excavations, all obtained by AMS dating of selected terrestrial macrofossils from near the peat-dune sand interface, these age-depth data serve to: (1) evaluate the accuracy of the mean-sea level (MSL) curve for the western Netherlands (Van de Plassche, 1982), which heavily relies on lower Rhine-Meuse delta dune data, (2) investigate the westward extension of palaeoriver-gradients in the lower Rhine-Meuse delta, (3) assess mid-Holocene evolution of intra-coastal tidal damping in the lower Rhine-Meuse delta.

Sites and methods

Vlaardingen

Stratigraphic and subsurface topographic mapping was carried out at three sites on the accessible south and west flanks of the Vlaardingen dune by means of manual gouge augers with a diameter of ~3 cm. These narrow cores were logged in the field for colour, lithology, sedimentary structures, consistency, and nature of the bed boundaries. The central part of a cross-section on the south-western flank of the dune (Fig. 2) was selected for detailed stratigraphic and chronologic study as it allowed sampling of the basal organic unit over the largest vertical range (8.8 m to 4.1 m below NAP). Twenty (base-of-)basal peat

V	Vlaardingen (this paper)
H	Hillegersberg (Van de Plassche, 1982; this paper)
BP	De Bruin-Polderweg (this paper)
B	Barendrecht (Jelgersma, 1961; Berendsen et al., 2007)
Bo	Bolnes (Van de Plassche, 1982)
W	Wijngaarden (Van Dijk et al., 1991)

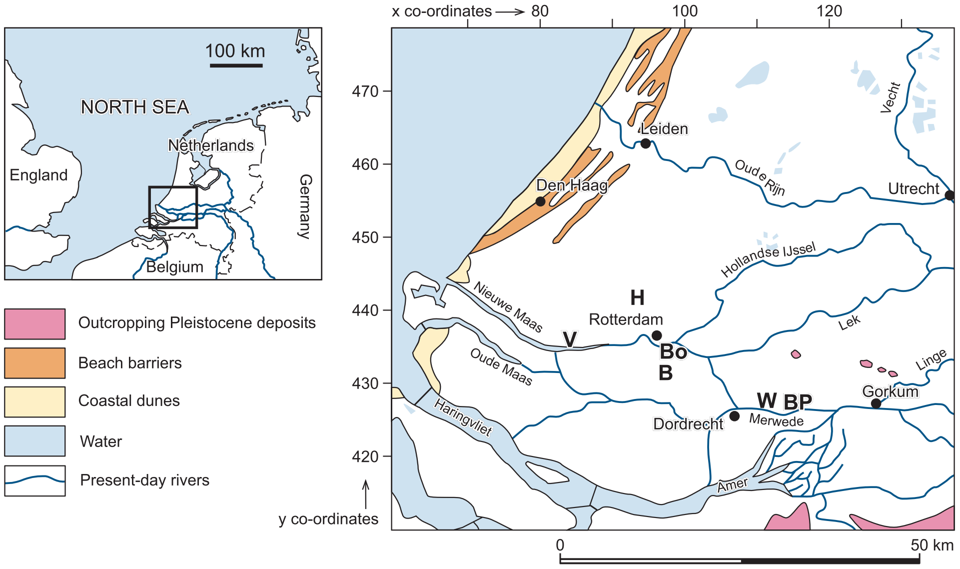

Fig. 1. Locations of the studied sites of Vlaardingen (V), Hillegersberg (H), and De Bruin-Polderweg (BP), and the previously studied sites of Barendrecht (B), Bolnes (Bo), and Wijngaarden (W).

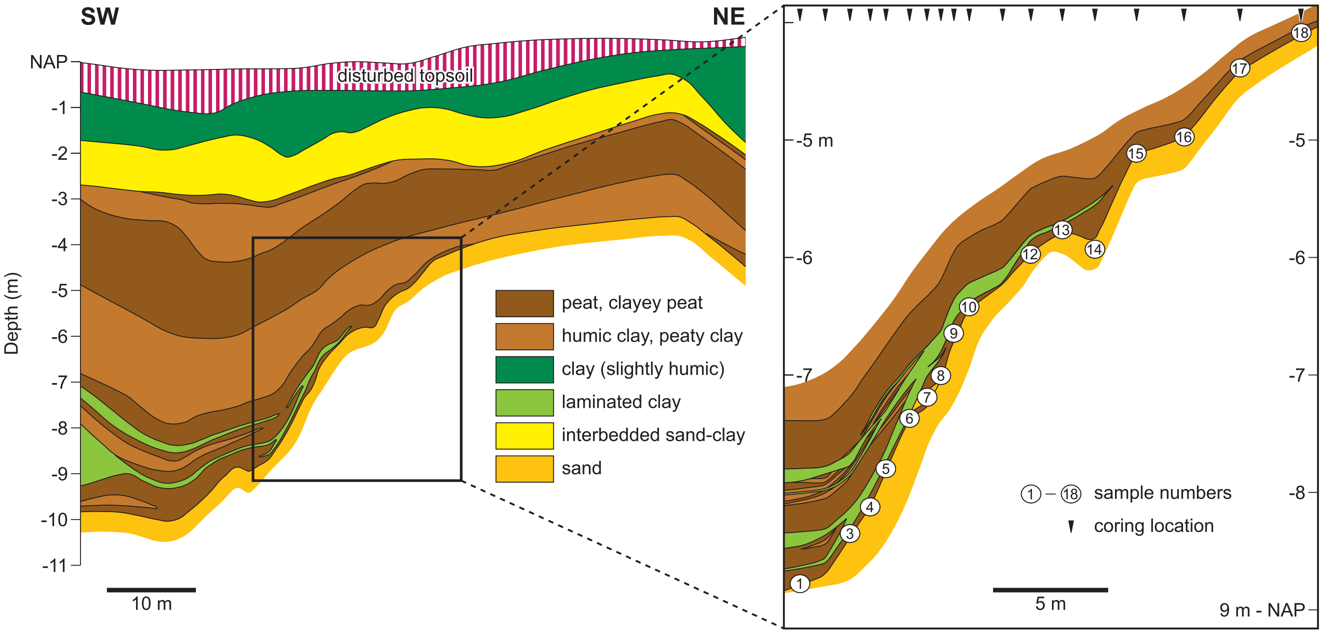

Fig. 2. Cross-section of the Vlaardingen aeolian dune flank, with sample locations. Laminated clay in inset is 'Klappklei' (see text). See also Van de Plassche (1995a, his fig. 5) for a detailed lithostratigraphic picture of the organic units on the dune flank.

samples, including five pairs, and one tree-root sample in the top of the dune sand were obtained from sixteen (out of eighteen) continuous Begemann piston cores (diameter 6.5 cm), collected by the Delft Soil Mechanics Laboratory. Surface elevations of coring and sampling sites were surveyed to a nearby benchmark by means of a conventional levelling instrument.

In each of the Begemann cores, the basal organic unit was carefully logged for (subtle) changes in colour, shine, structure, degree of humification, and presence of clay streaks and sand (Van de Plassche, 1995a). Next, sub-samples for pollen analysis were taken every cm from the lowermost 7-15 cm of the basal peat, including the peat-dune sand transition. Pollen samples were treated according to standard procedures (Faegri & Iversen, 1989), mounted in glycerine jelly, and analysed using 630× magnification. We then cut, from sixteen Begemann cores, 2.5- to 6-cm-thick samples from the very base of the basal organic unit and/or, if sufficiently peaty, from the very top of the dune sand for conventional radiocarbon analysis. The rinds of the peat slices were removed and all (sub-)vertical and horizontal root and rhizome material was carefully removed to reduce the possible effects of root rejuvenation (Van de Plassche, 1979). The composition of these bulk samples immediately above, below or across the peat-dune sand boundary varied from peat or clayey peat to peaty sand (Table 1). In two cores (V7 and V8), in which the transition from dune sand to peat was interrupted by a (thin) sand layer, a sample from immediately above and below this intercalation was submitted for analysis. From three other cores (V9, V15, and V16), sample pairs were taken to examine the effect on age of inclusion or exclusion of the very top of the (strongly peaty) dune sand in the sample.

Our Vlaardingen bulk peat samples were radiocarbon dated conventionally at the Centre for Isotope Research, Groningen, the Netherlands (Table 1), before the advent of the Accelerator Mass Spectrometry (AMS) technique, which enables one to date selected plant macrofossils from the basal part of the basal peat (Törnqvist et al., 1992). These macrofossils can be used to bracket the onset of basal peat growth between the last occurrence of fungi specific to soil formation and the first occurrence of peat-forming species. We used the palynological information for the same purpose and, in combination with lithologic, stratigraphic, and chronologic data, to evaluate the reliability and significance of the water-level index points.

Hillegersberg

We collected a suite of new basal peat samples from the Hillegersberg dune, which has been extensively studied by Van de Plassche (1982), in order to check earlier dates from this location. Only one sample, however, appeared to contain enough terrestrial macrofossils for AMS radiocarbon dating. This sample was taken at the lowest possible position, directly upslope of an onlapping clay layer on the dune flank (see fig. 56 in Van de Plassche (1982) for lithostratigraphy), and its vertical position with respect to NAP was carefully determined by levelling. The sample was taken with a 6-cm-diameter piston corer and was cut into thirty 1-cm-thick slices. Using standard procedures, 11 slices (more or less evenly distributed over the core) were analysed for plant macrofossils and sand content (loss on ignition), and the vertical distribution of macrofossil occurrence and sand content was plotted in a diagram. Terrestrial macrofossils were selected for AMS radiocarbon

Table 1 Radiocarbon age determinations carried out for this study.

Sample	Laboratory code[1]	^{14}C-age (^{14}C years BP)	1σ cal. age range (cal years BP)	2σ cal. age range (cal years BP)	X-Y co-ordinates (km in Dutch co-ordinate system)	Surface elevation (m rel. to NAP)	Depth of sample (cm below NAP)	Vertical error margin (1σ) (cm below NAP)	Vertical error margin (2σ) (cm below NAP)	Material
Vlaardingen										
V1	GrN-15290	6410±45	7360-7272	7400-7224	ca 84.150-435.950	−0.42	877-881	843-879	832-882	Fen peat
V3	GrN-15291	6160±45	7100-6980	7160-6920	ca 84.150-435.950	−0.34	834-837	803-8 37	792-838	Fen peat, sandy/clayey
V4	GrN-15292	6150±50	7100-6960	7160-6900	ca 84.150-435.950	−0.33	809-812	775-810	764-814	Fen peat, sandy/clayey
V5	GrN-15293	6170±45	7100-6980	7160-6920	ca 84.150-435.950	−0.31	778-782	747-782	736-782	Fen peat, sandy
V6	GrN-15294	5980±45	6880-6760	6920-6700	ca 84.150-435.950	−0.31	736-740	706-740	695-740	Fen peat, sandy/clayey
V7.1	GrN-15295	5900±60	6800-6640	6860-6580	ca 84.150-435.950	−0.30	724-727	697-727	685-727	Fen peat, sandy
V7.2	GrN-15296	5840±60	6720-6580	6800-6520	ca 84.150-435.950	−0.30	711-714	651-695	640-706	Fen peat, sandy
V8.1	GrN-15297	5925±50	6808-6688	6868-6636	ca 84.150-435.950	−0.30	701-705	671-705	660-705	Fen peat, sandy
V8.2	GrN-15298	5720±70	6600-6440	6680-6360	ca 84.150-435.950	−0.30	696-700	654-693	642-704	Fen peat, sandy
V9.1	GrN-15299	5830±50	6700-6580	6760-6520	ca 84.150-435.950	−0.17	663-669	628-669	617-669	Fen peat, sandy
V9.2	GrN-15300	5645±40	6484-6396	6524-6352	ca 84.150-435.950	−0.17	659-663	619-658	608-667	Fen peat, clayey
V10	GrN-15301	5650±40	6488-6400	6532-6360	ca 84.150-435.950	−0.29	644-648	614-648	603-648	Fen peat, sandy
V12	GrN-15302	5390±70	6240-6080	6320-6000	ca 84.150-435.950	−0.29	602-607	578-607	567-607	Peaty sand
V13	GrN-15303	5475±40	6304-6216	6348-6176	ca 84.150-435.950	−0.29	582-585	552-585	540-585	Fen peat, clayey
V14	GrN-15304	5605±25	6424-6372	6448-6344	ca 84.150-435.950	−0.28	587-587	576-587	565-587	Tree root
V15.1	GrN-15305	5070±40	5864-5776	5904-5732	ca 84.150-435.950	−0.26	513-519	487-519	476-519	Peaty sand with charcoal
V15.2	GrN-15306	5065±45	5864-5764	5908-5716	ca 84.150-435.950	−0.26	510-513	473-509	462-516	Fen peat, sandy
V16.1	GrN-15307	5005±45	5796-5700	5848-5656	ca 84.150-435.950	−0.13	500-505	476-505	465-505	Peaty sand
V16.2	GrN-15308	4820±60	5620-5480	5700-5420	ca 84.150-435.950	−0.13	497-500	466-500	455-501	Fen peat, sandy
V17	GrN-15288	4760±40	5536-5644	5576-5396	ca 84.150-435.950	−0.04	438-443	401-443	390-444	Fen peat, sandy
V18	GrN-15289	4690±40	5460-5360	5500-5300	ca 84.150-435.950	−0.09	409-414	374-414	362-414	Fen peat
Hillegersberg										
HR4	GrA-12024	6120±50	7060-6900	7160-6840	93.575-441.200	−1.45	780-781	761-783	750-783	Terrestrial macrofossils[2]
De Bruin										
Br1	UtC-9173	5590±50	6420-6328	6472-6288	115.215-427.178	−1.04	548-551	529-551	518-551	Terrestrial macrofossils[3]
Br2	UtC-9136	5120±120	5980-5700	6160-5620	115.207-427.180	−1.04	443-451	394-448	383-454	Terrestrial macrofossils[4]
Br4	UtC-9137	5770±130	6700-6420	6860-6300	115.213-427.169	−1.04	587-593	553-596	542-596	Terrestrial macrofossils[3]
Br5	UtC-9174	6461±43	7416-7340	7448-7300	115.220-427.168	−1.04	840-843	821-843	810-843	Terrestrial macrofossils[3]
Polderweg										
P1	UtC-9138	5700±80	6580-6400	6680-6340	116.121-427.631	−1.33	626-632	600-632	589-632	Terrestrial macrofossils[5]
P2	UtC-9175	6011±49	6900-6780	6960-6720	116.121-427.629	−1.33	667-669	643-672	632-672	Terrestrial macrofossils[3]
P3	UtC-9176	6065±46	6980-6840	7040-6780	116.121-427.628	−1.33	718-720	694-723	683-723	Terrestrial macrofossils[3]
P6	UtC-9177	6679±48	7592-7516	7624-7476	116.121-427.621	−1.33	1023-1024	1009-1024	998-1024	Terrestrial macrofossils[3]
P7	UtC-9178	6220±50	7200-7040	7260-6980	116.121-427.627	−1.33	766-767	742-771	731-771	Terrestrial macrofossils[6]
P10	UtC-9261	6737±48	7632-7560	7668-7524	116.121-427.624	−1.33	966-967	934-967	922-975	Terrestrial macrofossils[3]

1 Laboratory code GrN: Groningen (Centre for Isotope Research) conventional date; laboratory code GrA: Groningen (Centre for Isotope Research) AMS date; laboratory code UtC: Utrecht (R.J. van de Graaff Laboratory) AMS date.

2 *Alnus* bud scales, *Juncus*, *Typha*, *Lythrum* and *Urtica* seeds.

3 *Alnus* bud scales.

4 *Urtica* and *Carex* seeds.

5 *Alnus* bud scales, *Urtica* seeds.

6 *Urtica* seeds.

dating from the level where the amount of dune sand had fallen below 20%, and where fruit bodies of soil fungi were virtually absent. Around and above this level wood and leaf fragments and *Alnus* bud scales as well as remains of wet species, like *Typha* and *Carex*, show an marked upward increase, indicating onset of paludification when the water-level rose above this level. AMS radiocarbon dating of the macrofossil sample was carried out at the Centre for Isotope Research, Groningen, the Netherlands (Table 1).

De Bruin and Polderweg

The samples from the 'De Bruin' and 'Polderweg' dunes, near Hardinxveld-Giessendam were collected in archaeological excavation pits exposing the dune flank. Artificial drainage of the deep pits facilitated sampling far below the present regional groundwater table. The excavation pits, dune morphology, detailed dune flank stratigraphy, and the general lithostratigraphy around the sites were described by Louwe Kooijmans (2001a, b). At both sites the sand-peat transition zone was characterized by soil development in the dune sand and washed-in sandy layers in the peat in which abundant charcoal and archaeological artifacts were found. Samples were not collected in a transect, but at scattered suitable locations within the 16×24 m (De Bruin) and 16×28 m (Polderweg) excavation areas. Samples were collected in 10×10×30 cm metal boxes that were hammered into vertical exposures of the sand-peat transition. The vertical position of the samples was measured with a theodolite relative to the benchmark that was used for the archaeological excavation. From the box cores 12- to 25-cm-thick intervals across the sand-peat interface were cut into 1-cm-thick slices that were analysed for plant macrofossils and sand content (loss on ignition). Following the same procedure as for the Hillegersberg sample, terrestrial macrofossils were selected for AMS radiocarbon dating at the appropriate level. Berendsen et al. (2007) earlier applied the same procedure to their samples from the Barendrecht and Oud-Alblas dunes. AMS radiocarbon dating of the De Bruin and Polderweg macrofossil samples was carried out at the R.J. van de Graaff Laboratory, Utrecht, the Netherlands (Table 1).

Error margins

After radiocarbon age determination (see Table 1 for dating results) the water-level index points were plotted with error margins in age-depth diagrams for comparison with other water-level records. For determining the error margins we followed, as much as possible, the approach described in detail by Berendsen et al. (2007) (see also Van de Plassche (1980b, 1986) and Van de Plassche et al. (2005) for discussions of potential errors and uncertainties involved in water-level reconstruction from local index points), to enable proper comparison with the data sets plotted by them[1]. Following Berendsen et al. (2007), we applied a water depth correction of 10 cm for Vlaardingen samples that consisted of (clayey) fen peat; i.e., the peat was assumed to have formed 10 cm below the local water table. For the other Vlaardingen samples, which consisted of peaty sand (V12, V15.1 and V16.1) and a tree root (V14), no water-level correction was applied. The Hillegersberg, De Bruin and Polderweg samples almost all consisted of wood peat and therefore no water-level correction was applied. An exception is Br2 (clayey fen peat) for which a water-level correction of 10 cm was applied.

Results

Vlaardingen

The detailed lithostratigraphy of the basal organic unit in the Vlaardingen cross-section and the positions of the dated samples are presented in Figure 2. Stratigraphically, the basal unit is composed of three sub-units: two sub-units of alternating clayey peat bands (3-14 cm thick) and layers of less clayey or non-clayey peat (2-5 cm thick), separated by a sub-unit of three humic to peaty clay bands (3-6 cm thick), alternating with cm-thin (slightly) clayey peat bands. These three sub-units are unconformably dissected by laminated clay beds free of any in situ roots and with sharp upper and lower boundaries. These so-called 'Klappklei' layers are thought to have formed during one or more storm surges and/or periods of peak river discharge, when the strongly elevated water level causes the peat to float and rupture sub-horizontally (Behre et al., 1979; Van de Plassche, 1995a). All samples were taken from the continuous, mostly clayey, peat bed covering the flank of the dune.

In order to investigate the influence of in-core sample depth on sample age we dated paired samples from Vlaardingen cores V7, V8, V9, V15 and V16. Vertical space between the samples was 10 and 1 cm for sample pairs V7.1-7.2 and V8.1-8.2, respectively, and 0 cm for the other sample pairs. All deeper samples consisted of sandy peat and peaty sand and may have contained soil carbon predating initial peat formation. The detailed age-depth

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[1] Berendsen et al. (2007) applied compaction correction factors of 2.5 for the base of the dated sample and 3.5 for the top of the dated sample (for instance, a 2-cm-thick sample, taken at 3 cm above the dune surface, was 'decompacted' to 7.5-17.5 cm above the dune surface). However, in the text of their paper they erroneously mention correction factors of 1.5 and 2.5. We applied correction factors of 2.5 and 3.5. Berendsen et al. (2007) used the program CAL25 (Van der Plicht, 1993) which uses the IntCal98 data set (Stuiver & Van der Plicht, 1998) for radiocarbon age calibration. This has been applied here as well, instead of the more recent calibration dataset IntCal09 (Reimer et al., 2009). The main difference between IntCal98 and IntCal09 concerns the extension of radiocarbon age calibration into the (Late) Glacial period. Differences for the Holocene part of the curves are negligible.

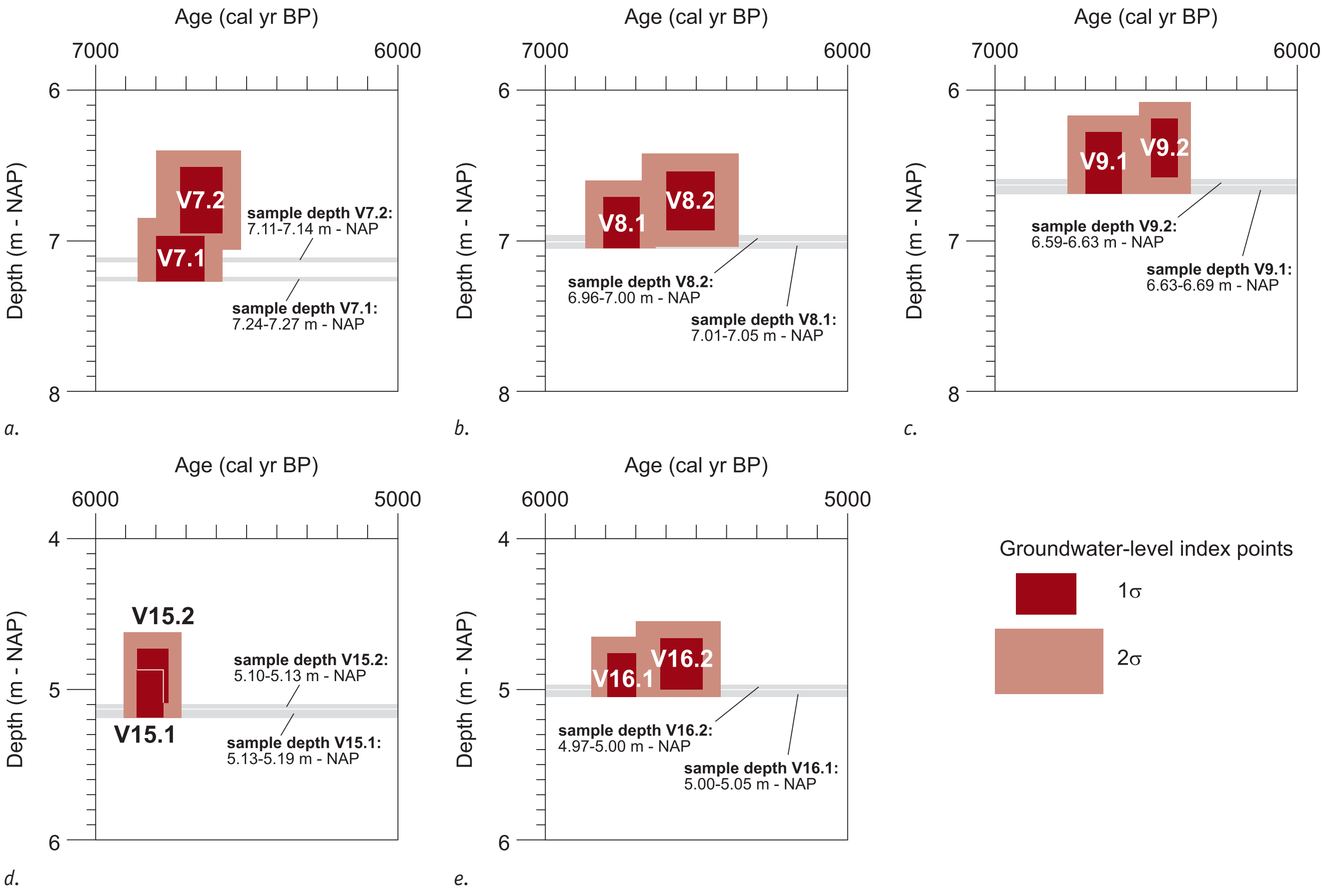


Fig. 3. Age-depth comparison of paired Vlaardingen samples: a. V7.1-7.2; b. V8.1-8.2; c. V9.1-9.2; d. V15.1-15.2; e. V16.1-16.2. Grey horizontal bars indicate sampled depth intervals. For construction of error boxes (1 and 2), including correction for compaction, see text (section 'Error margins').

plots of the sample pairs show significantly older ages (~200 years) for deeper samples in three cases (cores V8, V9 and V16; Fig. 3b, c and e). In these cases the slight differences in depth inadequately explain the age differences: the age-depth offset of the sample pairs does not follow the general age-depth trend of the Vlaardingen index points (Fig. 4). The apparent ageing of samples V8.1, V9.1 and V16.1 could be due to inclusion of old soil carbon, but the alternative option of rejuvenation of the overlying sample by root penetration needs to be considered as well (see below). In two other cases (Fig. 3a and d) age differences are minimal and can be explained by differences in sampling depth.

The available pollen data, including counts of the spores of soil-specific fungi, allow a further assessment of the position of Vlaardingen samples relative to the underlying palaeosol. Cores V6, V7, V8, V10 and V12 were not analysed for pollen composition. Pollen diagrams of cores V1, V3, V17 and V18 indicate that samples from these cores were taken at the appropriate level: directly above the top of the palaeosol as indicated by the marked upward decreasing occurrence of (incidental) degraded pollen grains and the spores of *Gelasinospora* (Van Geel et al., 1989) and *Glomus* (Van Geel, 2001), fungi which indicate soil formation and relatively dry conditions in the peat, respectively. The increase of moist pollen taxa in favour of dry taxa supports the interpretation of an increase in water level. Figure 5a presents an example of this situation, where an upper peak of *Gelasinospora* occurrence seems to be associated with a thin sandy layer between 876 and 877 cm below NAP. In two cases (V4 and V5) pollen diagrams indicate that samples were taken too high above the palaeosol, which does not significantly influence the age-depth analysis because compaction is taken into account. In two other cases (V9 and V15) the pollen analysis yielded insufficient evidence for a proper assessment. Pollen analysis in combination with lithology further suggests a too low position and/or ageing of samples V13 and V16.1-16.2 (Fig. 5b and c). Sample V13, apparently in the right position relative to the top of the sand, contains pollen of wet taxa, but also humic clays and abundant *Glomus* spores. This may indicate the presence of fine reworked old carbon causing an age overestimation of V13. Samples V16.1 and 16.2 are both located below the lithological transition to peat and, therefore, too low, as also indicated by upward increase of *Gelasinospora* and *Glomus* spores and the strong dominance of pollen of dry taxa throughout the profile. If both V16.1 and V16.2 would have contained more or less equal amounts of palaeosol material, the difference in radiocarbon age could be a result of rejuvenation of V16.2 by roots from higher levels (e.g., Streif, 1971, 1972). Fine *Phragmites* rhizomes may not

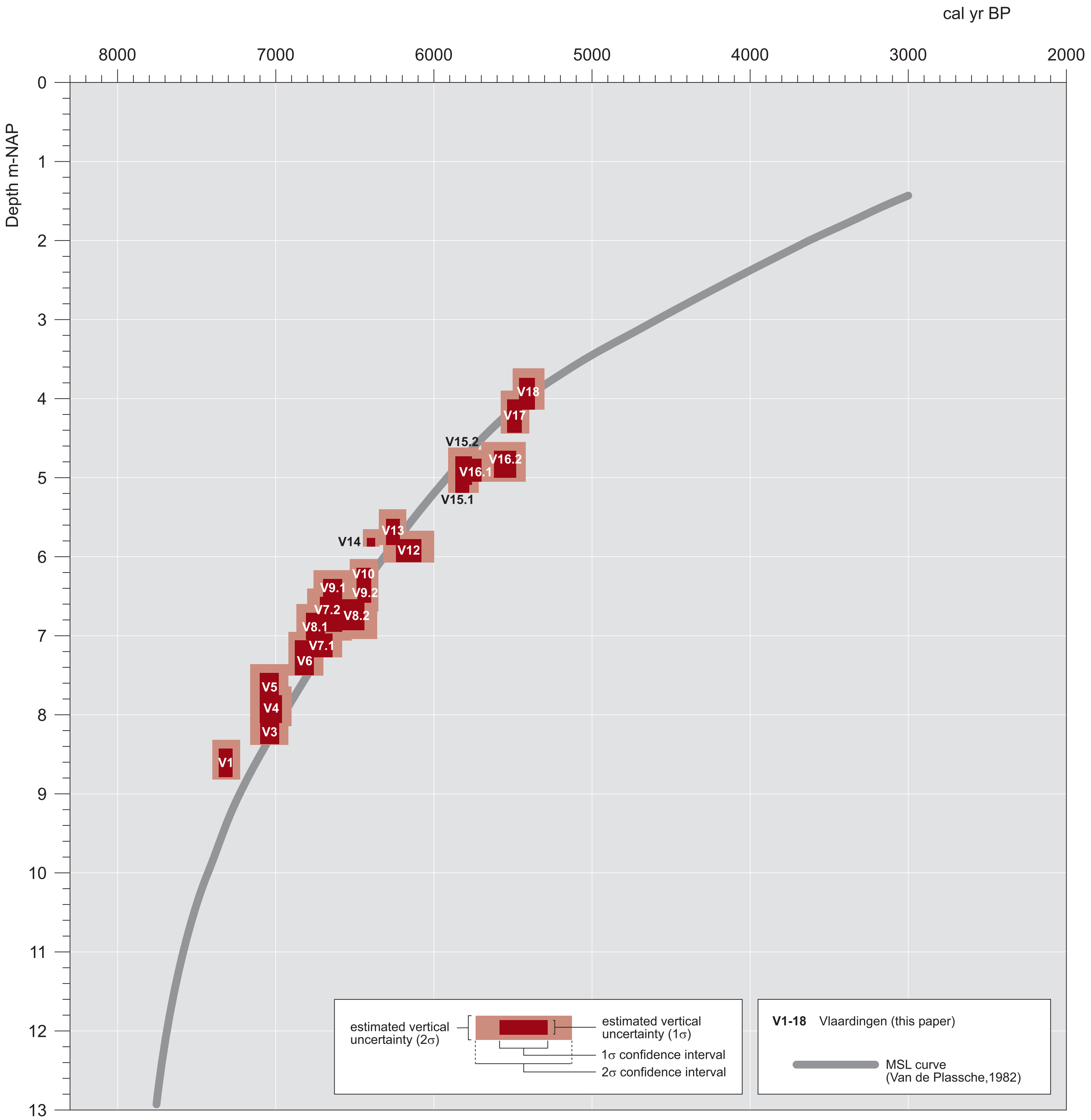
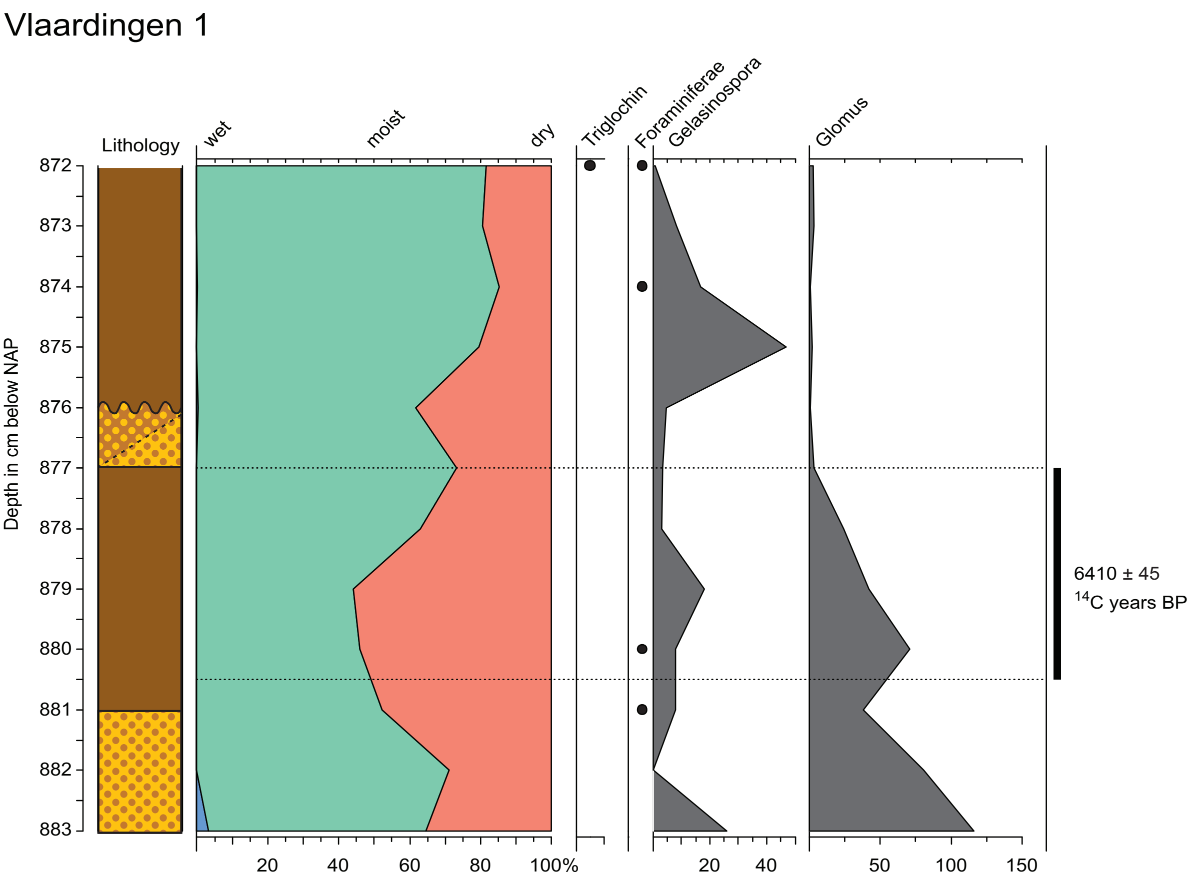
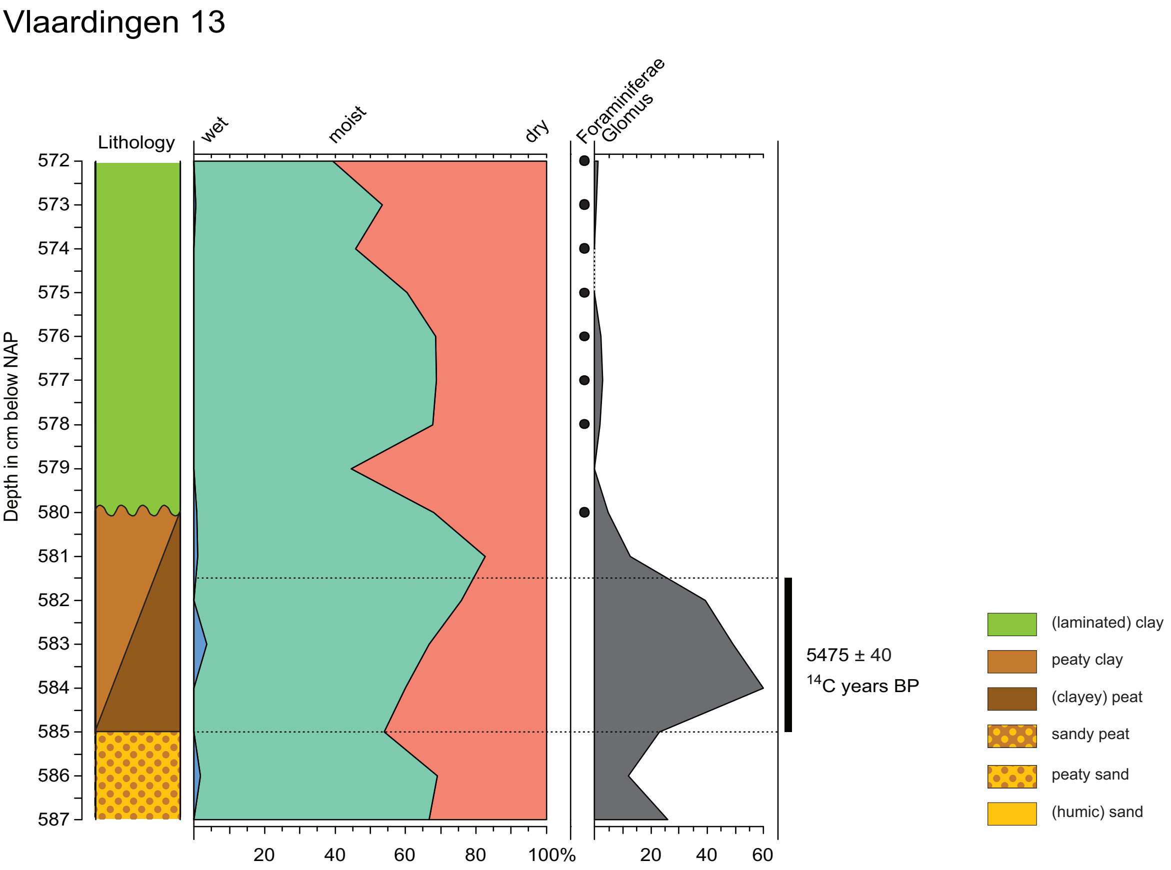


Fig. 4. Vlaardingen groundwater-level index points (brown) compared with the MSL curve (Van de Plassche, 1982).

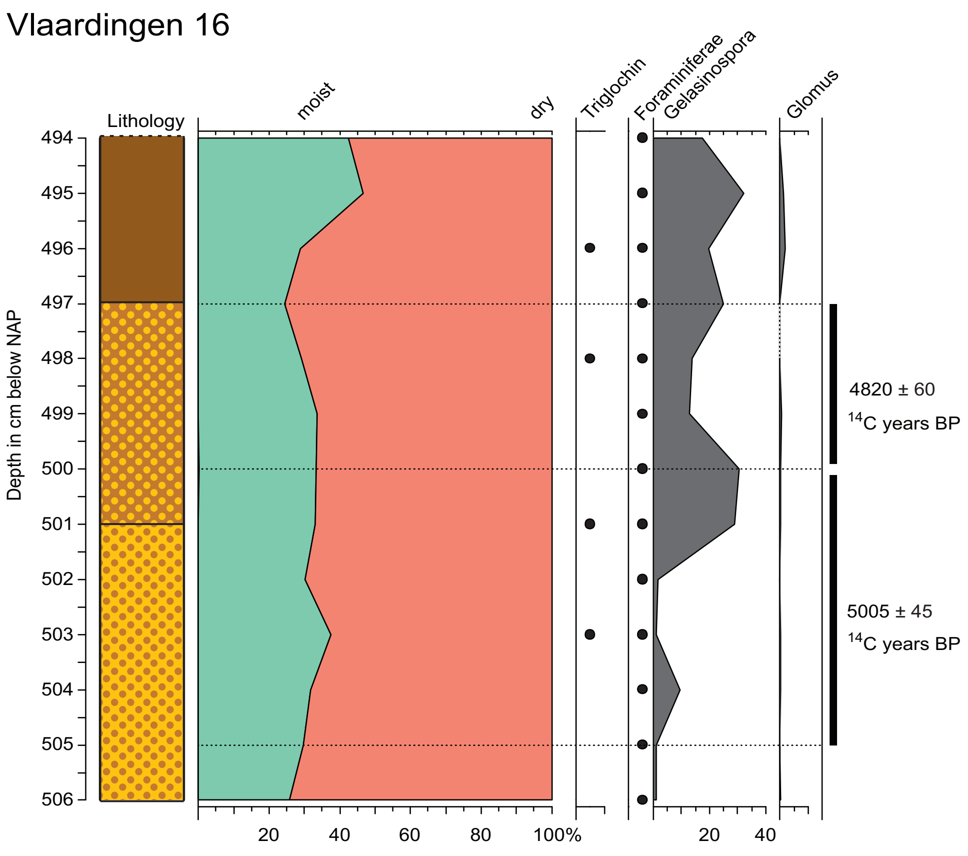
have been recognized in the sample, during pre-treatment for radiocarbon dating (Van de Plassche, 1979). A similar effect could also explain the apparent age difference of V8.1 and V8.2 (Fig. 3b) for which pollen information is lacking, but which both consist of sandy peat that potentially contained roughly equal amounts of palaeosol material. Given the lithologic differences between V9.1 (sandy peat) and V9.2 (clayey peat), the apparent age difference (Fig. 3c) is most likely fully caused by inclusion of palaeosol material in V9.1. In two of the diagrams, V9 and V17, pollen of the typical salt-tolerant *Limonium* (sea lavender) has been encountered, while *Triglochin* (arrowgrass) and foraminifera have also been found in some of the diagrams (Fig 5a, b and c). Especially *Limonium* indicates the nearby presence of saltwater conditions. However, pollen grains can be transported from other locations through the air or by water flow (rivers or tides) and cannot be regarded as explicit indicator of salt conditions at the site. Foraminifera generally indicate salt conditions, but some freshwater species exist, and species have not been determined in this study.


Vlaardingen 1
Lithology
wet
moist
dry
Triglochin
Foraminiferae
Gelasinospora
Glomus
Depth in cm below NAP
872
873
874
875
876
877
878
879
880
881
882
883
20
40
60
80
100%
20
40
50
100
150
6410 ± 45
14C years BP

a.


Vlaardingen 13
Lithology
wet
moist
dry
Foraminiferae
Glomus
Depth in cm below NAP
572
573
574
575
576
577
578
579
580
581
582
583
584
585
586
587
20
40
60
80
100%
20
40
60
5475 ± 40
14C years BP
(laminated) clay
peaty clay
(clayey) peat
sandy peat
peaty sand
(humic) sand

b.



c.

Fig. 5. Pollen diagrams with selected taxa of Vlaardingen core intervals across the sand-peat interface around: a. sample V1; b. sample V13; c. sample V16. The top of the soil is typically located at the transition from (peaty) sand to (sandy) peat (see Fig. 5a for lithological legend). Vertical bars to the right indicate positions of dated samples.

In Fig. 4 the new Vlaardingen age-depth data set is plotted together with the MSL curve for the western Netherlands (Van de Plassche, 1982). The trend of the Vlaardingen age-depth data roughly follows the MSL curve, with some data points plotting on the young side (e.g., V12 and V16.2) and some plotting on the old side (e.g., V1, V9.1 and V14). Based on the above evaluation we selected the most reliable data for the construction of a local groundwater-level curve. In Fig. 6 this selection and the local groundwater-level trend curve (VL) is shown. For lack of index points near 5.5-6.0 m below NAP we included V12, V13 and V14, although there is no positive evidence for their reliability. The pollen analysis suggested that V13 could be too old. In that case V14 must also be too old. V14 represents a tree root from below the dune surface, which was believed to have been preserved because of drowning of the dune surface. If V13 indeed is ~100-200 yrs too old due to inclusion of old carbon, V12 could be correct.

Our Vlaardingen groundwater-level trend curve can be divided into two trajectories: (1) a lower part for the period 7300-6650 cal yr BP running up to 0.5 m above the MSL curve, and (2) an upper part for the period 6650-5300 cal yr BP running down to 0.25 m below the MSL curve. The lower part relies on the relatively high positions of V1 and the cluster V3-V5, which consists of three points of equal indicative value following from our palaeoecological and lithostratigraphical evaluation. Therefore, we drew our trend curve through the middle of this cluster. The upper part of the trend curve relies on the relatively low positions of, mainly, V15.1 and V16.1, and, to a lesser extent, V12 and V17.

Hillegersberg

In Fig. 7 the new AMS-dated index point from Hillegersberg (HR4) is plotted together with the existing Hillegersberg and Bolnes index points. The Bolnes site is located 5 km upstream from the Hillegersberg site (Fig. 1), and the Bolnes index data cover depth ranges not covered by the existing Hillegersberg data: the ranges 7.5-9.5 and <2.5 m below NAP. Because of the river gradient between Hillegersberg and Bolnes (≤5 cm/km; Berendsen et al., 2007), however, Bolnes index points would plot higher than Hillegersberg index points of similar age. Like the neighbouring Hillegersberg index point H17, HR4 plots 0.3 to 0.4 m above the MSL trend curve. Neighbouring Bolnes index points (Bo8, Bo14 and Bo15) plot higher: 0.8 to 1.2 m above the MSL curve. This could be a result of the river gradient between Bolnes and Hillegersberg and slight ageing effects in the Bolnes data (see also Berendsen et al., 2007, p. 348). The existing Bolness and Hillegersberg data sets are based on conventionally dated bulk samples, which were selected following the same procedure as the Vlaardingen samples. The single AMS date on terrestrial macrofossils (HR4) concurs with the earlier conventional dates from Hillegersberg, which gives reasons to believe that an ageing effect in these dates is unlikely.

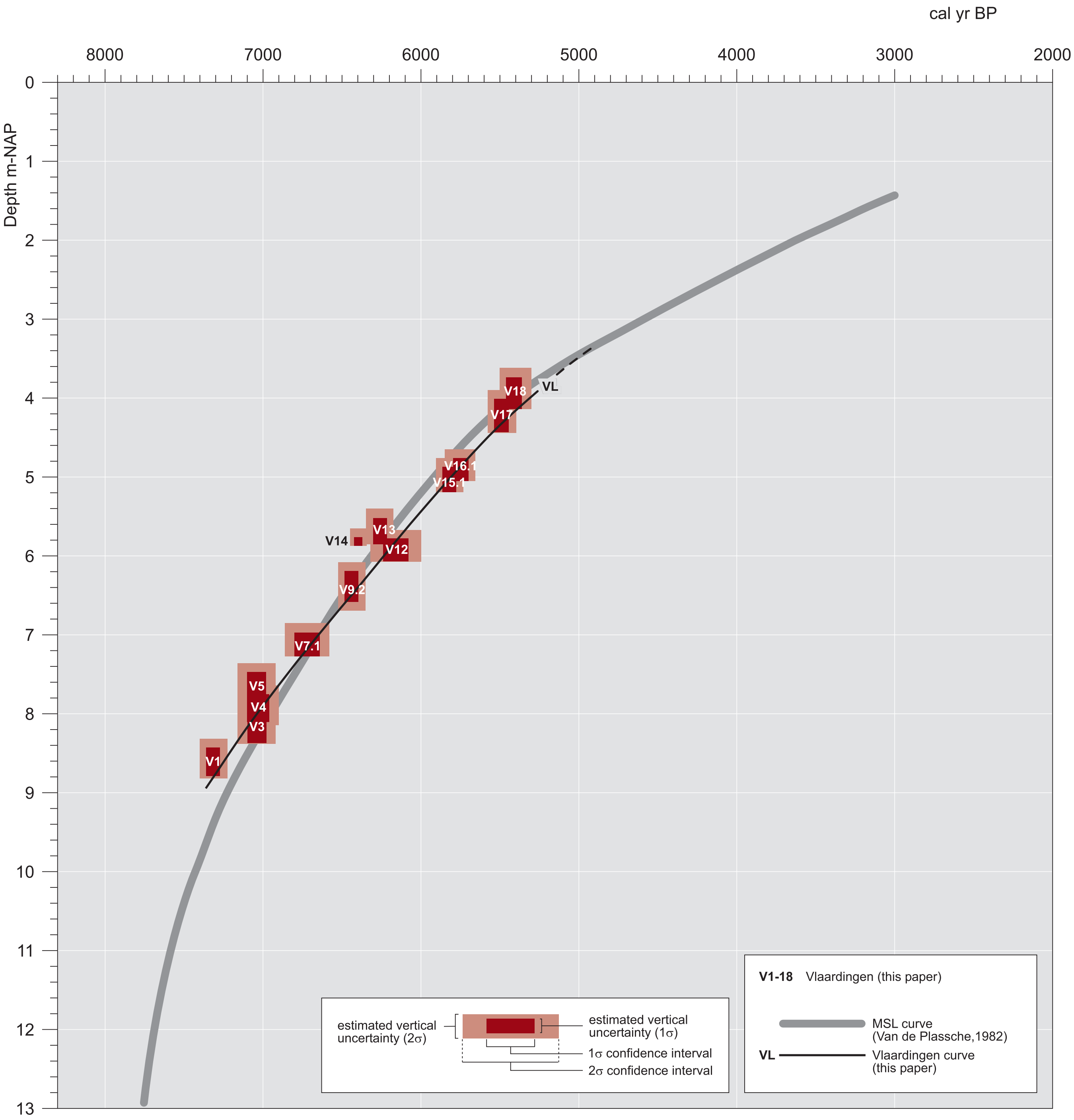


Fig. 6. Selected (see text) Vlaardingen groundwater-level index points (brown) and the local Vlaardingen groundwater-level curve (VL). The MSL curve (Van de Plassche, 1982) is also shown.

De Bruin and Polderweg

The De Bruin and Polderweg index points generally plot significantly higher/older than the Vlaardingen index points (Fig. 8). The deep index points P6 and P10 fall outside the range covered by the Vlaardingen data. The younger part (6650-5600 cal yr BP) of a trend curve (BP) through the majority of the De Bruin and Polderweg index points runs ~0.9 m above the Vlaardingen curve (VL), whereas the older part (7700-6650 cal yr BP) converges with the Vlaardingen curve backward in time. A higher position of the De Bruin and Polderweg index points is a logical consequence of the E-W river gradient in the lower Rhine-Meuse delta, with the De Bruin and Polderweg sites located 31 to 32 km more upstream. The 0.9 m elevation difference between both data sets would result in a river gradient of ~3 cm/km, which is in line with gradients reported for this period by Van Dijk et al. (1991) and Berendsen et al. (2007). Index points P1, P3 and P6 plot

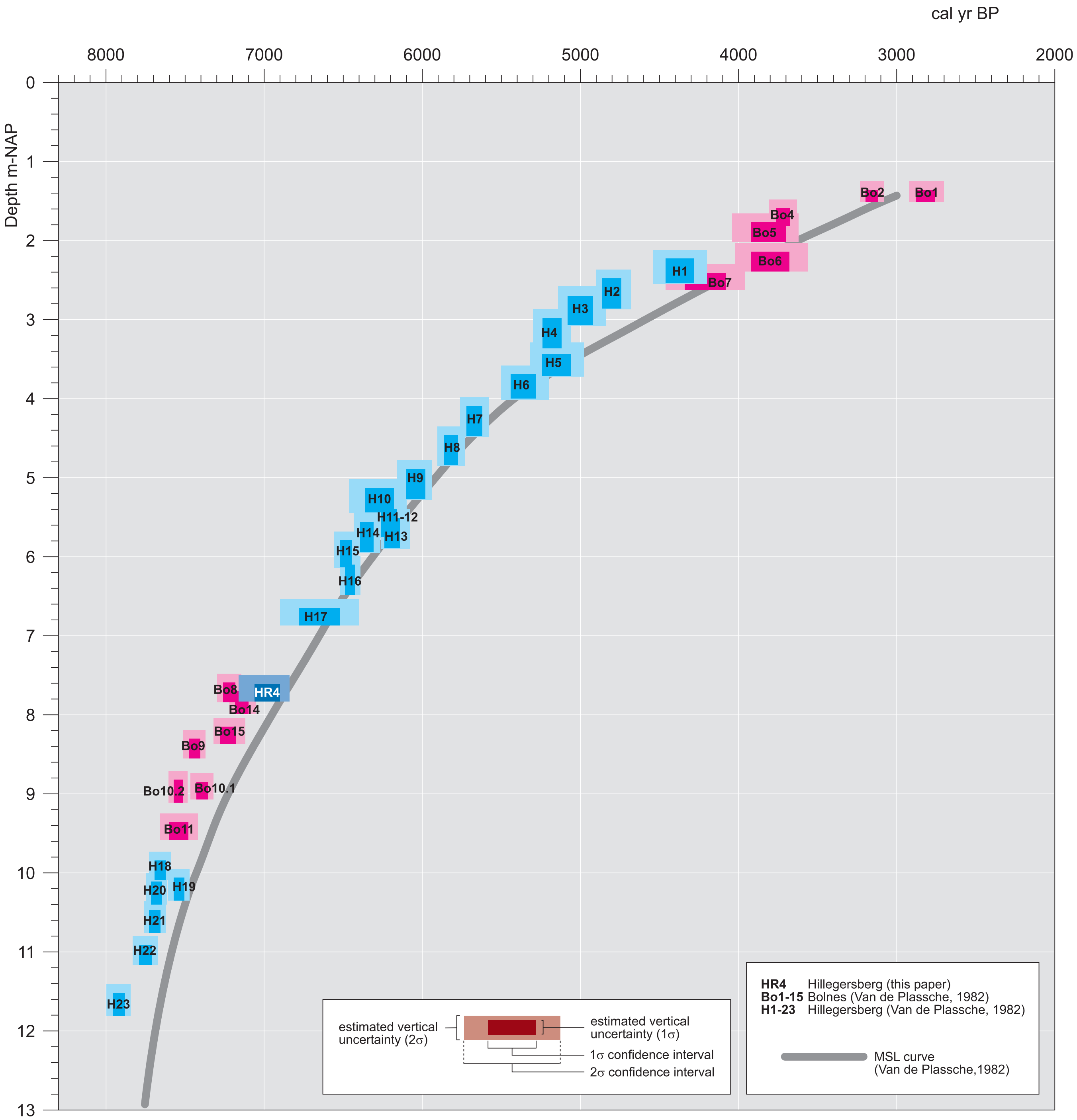


Fig. 7. The new Hillegersberg groundwater-level index point (HR4; dark blue) compared with the Hillegersberg (light blue) and Bolnes (pink) groundwater-level index points as plotted by Berendsen et al. (2007). The MSL curve (Van de Plassche, 1982) is also shown.

low/young relative to the trend indicated by the other De Bruin and Polderweg index points. P1 and P6 plot near the MSL curve which, if the curve is accepted as reliable (discussed below), suggests a minimal river gradient between De Bruin and Polderweg and the sea, which is very unlikely. Moreover, if we would use P6 for our trend curve this would imply a strongly decreasing river gradient backward in time, which is the opposite of the trend described by Van de Plassche (1982) and Van Dijk et al. (1991). Based on these considerations we suspect that P1 and P6 (and to some extent P3) are too young. Because the dated Polderweg samples consisted of selected terrestrial macrofossils, rejuvenation of the samples cannot be a result of root penetration. Given the fact that the Polderweg site has been intensively occupied by prehistoric man who exploited the surrounding wetlands (Louwe Kooijmans, 2001a), an age rejuvenation of a few hundred years could easily result from human activities locally disturbing the top of the former peat surface near the dune. Interesting in this context is

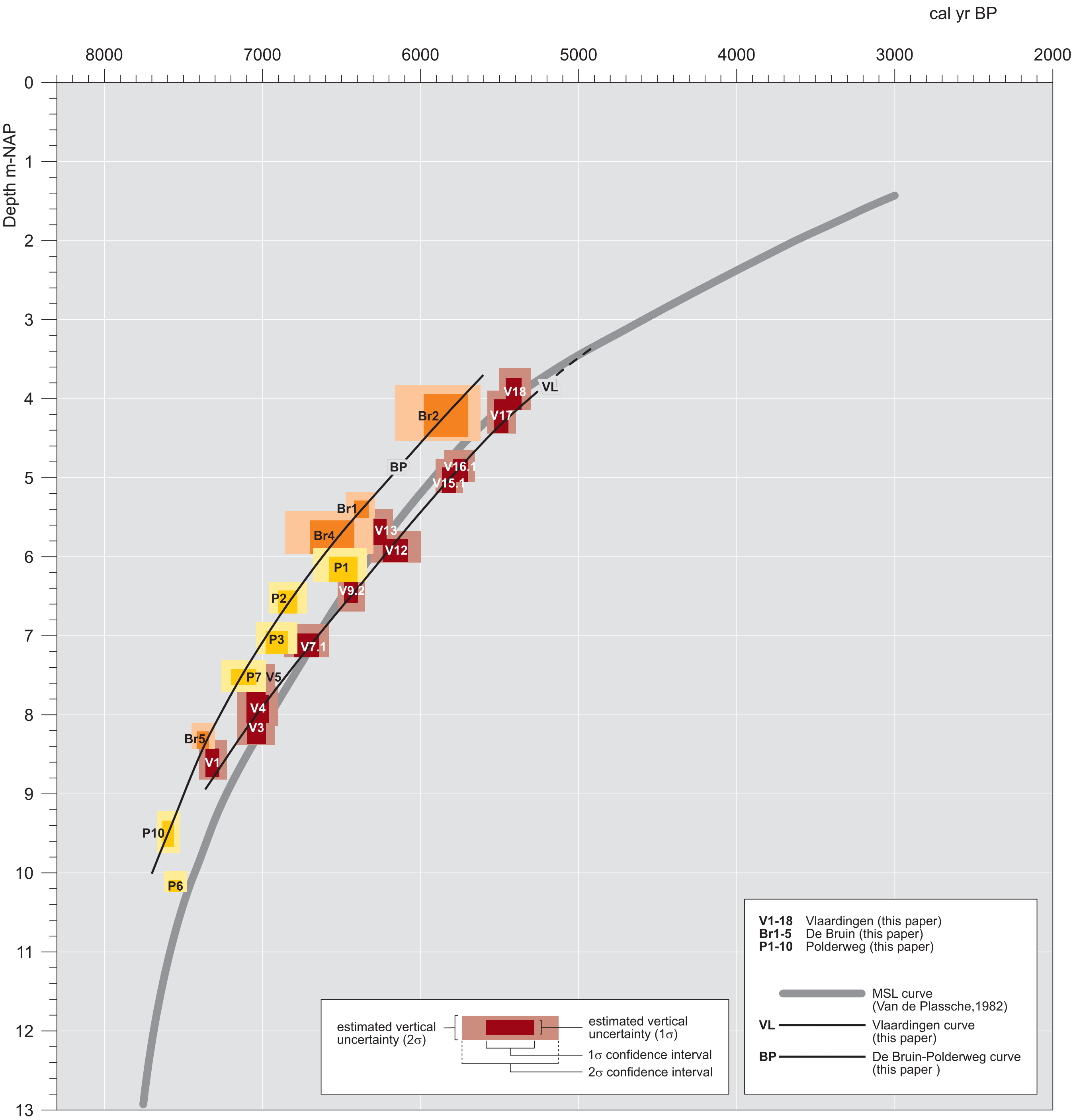


Fig. 8. De Bruin (orange) and Polderweg (yellow) groundwater-level index points and the local De Bruin-Polderweg groundwater-level curve (BP). Selected (see text) Vlaardingen groundwater-level index points (brown), the local Vlaardingen groundwater-level curve (VL), and the MSL curve (Van de Plassche, 1982) are also shown.

that especially the dated sample P1 contained seeds of *Urtica* (Table 1), a species that is often strongly associated with human habitation.

Evaluation and discussion

Because the new Vlaardingen age-depth data represent the most downstream intra-coastal water-level record in the Rhine-Meuse delta, they can be considered highly indicative for MSL change; i.e., they are least influenced by river-gradient effects (Van de Plassche, 1982). On the other hand, the location near the coastline may have resulted in significant tidal effects in this water-level record, because in back-barrier lagoons peat formation occurs near local mean high water (MHW) level, rather than near MSL (Van de Plassche, 1982; personal observations in modern environments first author). It is known that in large tidal basins the tidal amplitude decreases away from the tidal inlet due to friction and lateral storage of the tidal prism (the water volume entering the tidal basin upon passage of the tidal wave). The magnitude of this 'floodbasin effect' (Van Veen, 1950; Van de Plassche, 1982, 1995b) largely depends on the relative sizes of the tidal inlet and the back-barrier storage basin, variables that may change in time with coastal evolution. Interpretation of water-level records from a delta-plain, like the ones presented in this paper, importantly involves unravelling floodbasin and river-gradient effects.

For the period 6650-5300 cal yr BP, the new Vlaardingen curve (Fig. 6) runs below the MSL-curve for the western Netherlands, which for this period is largely based on the data from the Hillegersberg dune, located 9.5 km upstream. The Vlaardingen curve runs on average ~0.25 m below the Hillegerberg index points for this period, which would imply a palaeoriver-gradient of ~2.5 cm/km between Hillegersberg and Vlaardingen. This gradient is in line with the 3.0 cm/km gradient inferred above for the reach between De Bruin-Polderweg and Vlaardingen. The roughly constant vertical offset (0.9 m) between the Vlaardingen and De Bruin-Polderweg curves suggest that tidal effects, if present, have not changed significantly over the period 6650-5600 cal yr BP. Because the new Vlaardingen data presented here show that the river gradient seaward of Hillegersberg has been underestimated in MSL reconstruction by Van de Plassche (1982), we feel that the MSL curve for the western Netherlands needs a slight downward adjustment based on the Vlaardingen curve. In absence of conclusive data for the period after 5300 cal yr BP, we leave this part of the MSL curve unchanged, although it may reflect a comparable river-gradient effect as well. It also should be mentioned that, with Vlaardingen located 20 to 25 km from the former coastline and significant palaeoriver-gradients potentially having extended further seaward, our revision may still insufficiently eliminate the river-gradient effect from the MSL curve. A lower MSL curve for the western Netherlands bridges (at least partly) the gap with the MSL curve for the central Netherlands (period 6000-3500 cal yr BP; Van de Plassche et al., 2005), which runs 0.15 to 0.6 m below the unrevised MSL curve for the western Netherlands. This lower position was previously fully attributed to differential subsidence (Berendsen et al., 2007).

For the period 7300-6650 cal yr BP, the Vlaardingen curve runs above and diverges from the MSL curve backward in time, while gradually approaching the De Bruin-Polderweg curve (minimal vertical elevation difference 0.6 m; Fig. 8). We conjecture that this configuration reflects a gradual change in intra-coastal tidal amplitude at Vlaardingen and will explore this option below using independent data on coastal and delta evolution.

A reconstruction of the evolution of the coast of Holland (Beets et al., 1992) shows gradual closure of tidal inlets after ~6300 cal yr BP, which must have strongly influenced the back-barrier tidal amplitude. However, already well before 6300 cal yr BP, the tidal amplitude in the lower Rhine-Meuse delta probably was affected by the interaction of fluvial and coastal processes. Palaeogeographic reconstructions of the Rotterdam area by Hijma (2009, p. 118) show important developments in the period 7500-6800 cal yr BP, when a northward avulsion of the main Rhine branch in the central delta plain at ~7300 cal yr BP caused abandonment of the large estuary near Rotterdam. Erosion of the coastal Rhine-Meuse promontory provided sediments that were (partly) transported inland by tidal currents. This caused narrowing of the tidal inlet and infilling of the tidal basin, leading to reduced tidal inlet capacity and increased frictional loss (dissipation) of tidal wave energy, which in turn caused a gradual reduction of the intra-coastal tidal amplitude. This process was indirectly recorded at the Vlaardingen dune.

Van de Plassche (1995a) described periodic clay deposition between 7350 and 5350 cal yr BP in the peat swamps surrounding the dune. After a phase of predominantly clastic deposition, at ~7350 cal yr BP fen peat formation started, with periodic clay influx in the peat swamp causing a banded peat-clayey peat unit. This phase of peat formation was followed by a phase of, also periodic, clay deposition, after which peat formation resumed at ~6200 cal yr BP. Although the cause of the depositional cycles remains unknown, the banded units at Vlaardingen can be recognized as products of the palaeogeographic developments, with a change to peat formation upon abandonment of the estuary by the Rhine, followed by transgressive fluvial-tidal deposition causing infilling of the tidal basin. Around the more landward dunes of Hillegersberg and Barendrecht the phase of upper estuarine humic clay deposition was much shorter and peat formation started again around 6800 cal yr BP (Van de Plassche, 1982; Berendsen et al., 2007). Hijma et al. (2009) described the banded and laminated clays with abundant woody debris in the Rhine-Meuse estuary from this period, as predominantly freshwater fluvial-tidal floodbasin deposits, which were included by them in the fluvial Echteld Formation as the newly introduced Terbregge Member.

A substantial intra-coastal tidal amplitude in the seaward part of the Rhine estuary, which was in the process of being abandoned, could explain the rapid initial filling of the tidal basin in the period 7500-6800 cal yr BP. The position of index point V1 at about 0.75 m above the MSL curve (Fig. 6) suggests a reduced, but nevertheless significant, tidal amplitude at Vlaardingen by 7300 cal yr BP. However, the part of the MSL curve older than 6500 cal yr BP is poorly constrained by independent MSL indicators (e.g. Van de Plassche & Roep, 1989). Recently, new deep (>13 m below NAP) index points from the Rotterdam area have become available (Hijma & Cohen, 2010) that allow an evaluation of this part of the MSL curve. Based on these new points (not shown in Fig. 9) and a reinterpretation of the deeper Hillegersberg data, Hijma & Cohen (2010) proposed a substantial upward adjustment of the MSL curve for the period before 7300 cal yr BP (MSL-R1; Fig. 9). Hijma & Cohen (2010) assumed an intra-coastal tidal amplitude of 0.25 m near Hillegersberg around 8000 BP and therefore

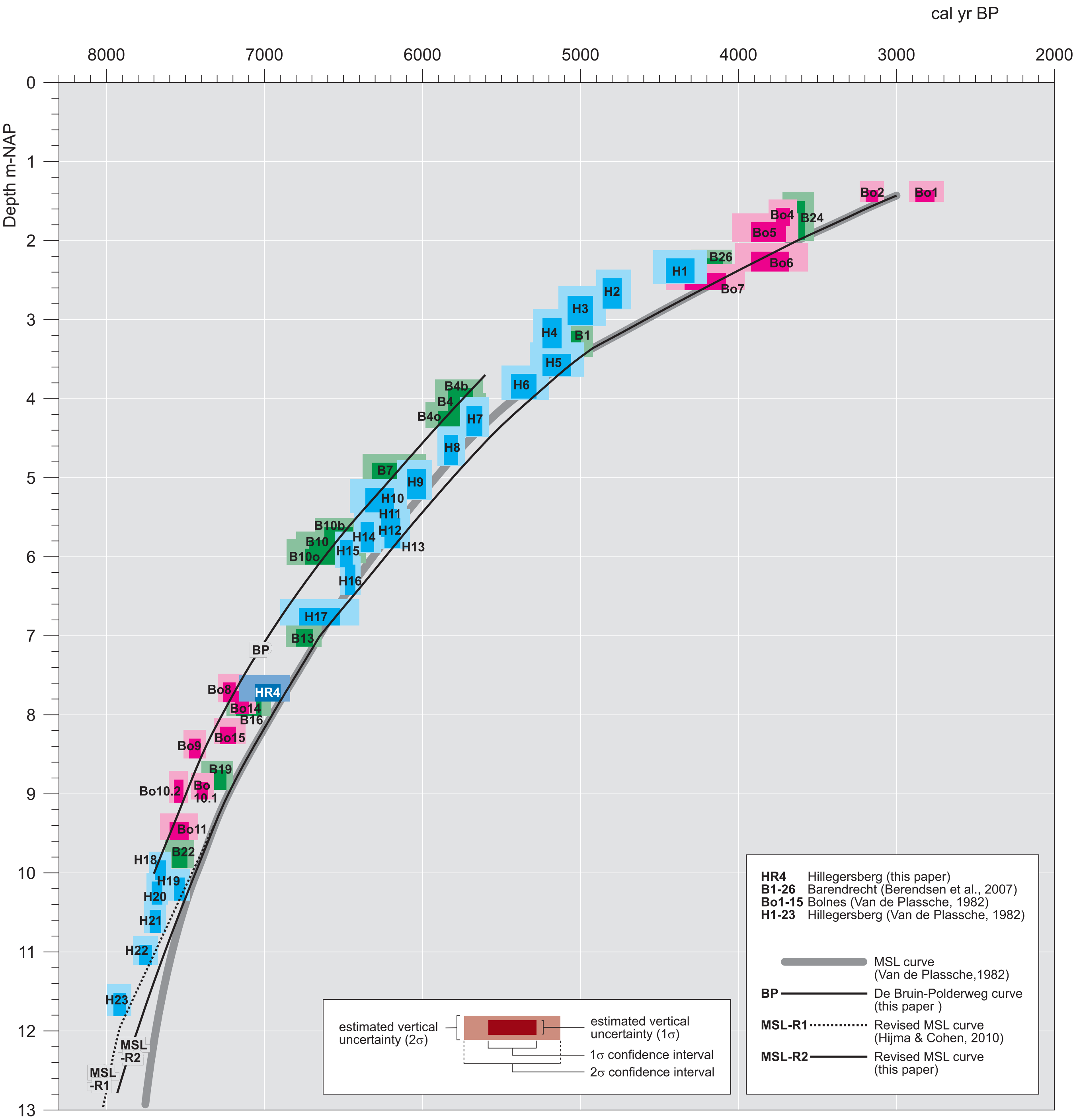


Fig. 9. The revised MSL curve proposed by Hijma & Cohen (2010) (MSL-R1) and the revised MSL curve proposed in this study (MSL-R2). The MSL curve of Van de Plassche (1982) and the local De Bruin-Polderweg groundwater-level curve (BP) are also shown, as well as the new Hillegersberg groundwater-level index point (HR4; dark blue) from this study and the existing Hillegersberg (light blue), Bolnes (pink), and (AMS-dated) Barendrecht (green) groundwater-level index points as plotted by Berendsen et al. (2007).

drew their adjusted MSL curve 0.25 m below index point H23 to connect it through a straight line with the existing MSL curve (Van de Plassche, 1982) at 9.4 m below NAP. In contrast, Van de Plassche (1982), when constructing his MSL curve, assumed a coastal tidal amplitude of ~0.9 m and very limited intra-coastal tidal damping before 7600 cal yr BP, whereas he considered index point H23 somewhat too old.

In the light of the new MSL indicators available (Hijma & Cohen, 2010), the older part (>7300 cal BP) of the 1982-MSL curve is certainly too steep/low, but we feel that the MSL reconstruction by Hijma & Cohen (2010) for the period 8000-7300 cal yr BP (MSL-R1; Fig. 9) insufficiently takes into account: (1) the potential intra-coastal tidal amplitude, (2) the river gradient between Hillegersberg and the coastline, and (3) the option that H23 (based on a conventional bulk peat date) is somewhat (~100 yr) too old. The extensive, sand-dominated intertidal flat deposits in the western Rotterdam area representing the period 8000-6500 cal yr BP (Naaldwijk Formation, Wormer Member; Hijma et al., 2009, their Fig. 17), suggest substantial tidal energy for the major part of this period. The intra-coastal tidal amplitude of 0.25 m supposed by Hijma & Cohen (2010) seems rather conservative, also given the results of numerical modelling by Van der Molen & De Swart (2001, their fig. 6) yielding coastal tidal ranges of ~1.9 m for 7800 cal yr BP and ~2.25 m for 6800 cal yr BP (present-day range 1.7 m at Hoek van Holland). We propose a revised MSL curve (MSL-R2; Fig. 9) running below the curve of Hijma & Cohen (2010) based on an arbitrary, but substantial, ~50% tidal damping near Hillegersberg and a river-gradient effect of 0.25 m. The latter is considered a minimum estimate and is based on the average elevation difference between the Vlaardingen and Hillegersberg index points for the period after 6650-5300 cal yr BP, thereby ignoring a potential seaward extension of the river gradient beyond Vlaardingen and the option of steeper river gradients in the period before 6650 cal yr BP (cf. Fig. 10). Because there is evidence for significant mid-Holocene differential isostatic land-level movements within the Netherlands (Kiden et al., 2002; Vink et al., 2007), we stress that the revised MSL curve is valid for the Rhine-Meuse delta region only.

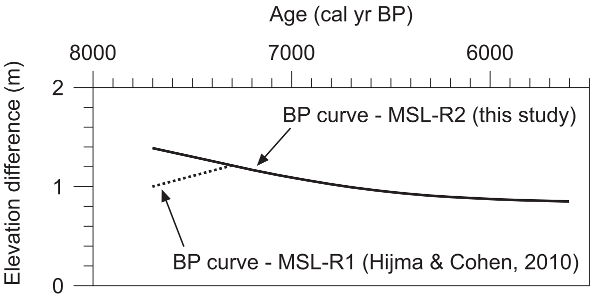


Fig. 10. Elevation difference between the De Bruin-Polderweg (BP) curve and the revised MSL curve proposed in this study (MSL-R2). Elevation difference between the De Bruin-Polderweg (BP) curve and the revised MSL curve proposed by Hijma & Cohen (2010) (MSL-R1) is also shown (stippled line).

If the revised MSL curve (MSL-R2; Fig. 9) is accepted, then gradual lowering of intra-coastal MHW relative to MSL in the Rotterdam area can be inferred to have taken place between 7500 and 6600 cal yr BP. The Vlaardingen (V1, V3-5, V7.1), Hillegersberg (H18-21, HR4, H17) and Barendrecht (B22, B19, B16, B13) index points for this period all gradually converge with the MSL-R2 curve forward in time. The timing of this development from an intermediate (~50% tidal damping) to a full (100% tidal damping) floodbasin effect is relatively early in the coastal evolution: gradual closure of tidal inlets along the coast of Holland did not set in before 6300 cal yr BP (Beets et al., 1992). As shown above, deviating intra-coastal water-level evolution in the lower Rhine-Meuse delta can be explained as a complex response to the abandonment of the tidal basin by the Rhine at ~7300 cal yr BP.

Of course, this interpretation strongly depends on the robustness of the revised MSL curve proposed in this paper, and especially the part representing the period 7300-6650 cal yr BP, which was left unchanged in this study, but which might in theory be too high because of river-gradient effects. An indirect test of the validity of the revised MSL curve can be carried out using the De Bruin-Polderweg curve, provided that this trend curve is free of significant tidal effects and of local/sub-regional effects, such as accelerations and decelerations of groundwater-level rise related to avulsions (Berendsen et al., 2007). The far inland location of the sampling locations and the shape of the trend curve suggest that these conditions are fulfilled, in which case the elevation difference between this curve and the revised MSL curve reflects the river-gradient effect, which generally decreases with time (Van de Plassche, 1982; Van Dijk et al., 1991). In Fig. 10 the elevation difference between both curves is plotted, yielding a so-called gradient-effect reduction curve (Van de Plassche, 1982, his fig. 33). The revised MSL curve (MSL-R2) neatly satisfies the theoretical criterion of a steadily decreasing river-gradient effect with time. Significant adjustments of the MSL-R2 curve for the period 7300-6650 cal yr BP only, either upward or downward, would disturb this trend, which more or less confirms the validity of this part of the MSL-R2 curve. For the period before 7300 cal yr BP, Fig. 10 suggests a too high position of the MSL-R1 curve (Hijma & Cohen, 2010) for this period, because it indicates a decreasing river gradient backward in time. Some caution must be used in making this interpretation because the overlap in time between the De Bruin-Polderweg curve and the MSL-R1 curve is limited (400 years) with the De Bruin-Polderweg curve being entirely based on index point P10 in this time interval.

The MSL-R1 curve was constructed as a part of investigations of a sea-level jump, a short period of accelerated sea-level rise, around 8400 cal yr BP (Hijma & Cohen, 2010). The present research, indicating a significant palaeoriver-gradient between Hillegersberg and Vlaardingen that potentially extended further seaward, may have implications for magnitude assessment of the inferred 8400 cal yr BP sea-level jump, because index points marking the end of the event are from a ~32 km more inland location then those marking the start, with a zero-gradient situation supposed (Hijma & Cohen, 2010). Our data show that a river gradient of ~2.5 cm/km existed in the area in the period 6650-5300 cal yr BP. Because the river gradient probably was steeper around 8400 cal yr BP (cf. Fig. 10), it may account for a considerable part of the inferred sea-level jump of 2.11 ± 0.89 m. However, the data set presented in this paper is too shallow/young to provide conclusive evidence on this issue.

In addition to the 8400 cal yr BP sea-level jump, other, somewhat later, early-Holocene accelerations and decelerations in relative sea-level rise have been recognized worldwide, and have been linked to the ablation history of northern hemisphere ice sheets. One of these events is an abrupt sea-level rise at 7600 cal yr BP (Yu et al., 2007) and a marked deceleration after 7000 cal yr BP (Flemming et al., 1998). The lower Rhine-Meuse delta sea-level record shows no compelling evidence for both events, which may result from local/regional effects (e.g. tides) and errors and uncertainties, but may also be due to strong glacio-isostatic adjustments (Kiden et al., 2002; Vink et al., 2007) leading to high rates of relative sea-level rise overshadowing smaller fluctuations. Both the magnitude assessment of glacio-isostatic adjustments and the potential identification of eustatic sea-level signals, warrant further relative sea-level research in the lower Rhine-Meuse delta, especially in the Early and early-Middle Holocene timeframe.

Conclusions

The new data presented in this paper, and some recently published data from the lower Rhine-Meuse delta, necessitate a partly revision of the mean sea level (MSL) curve for the western Netherlands (Van de Plassche, 1982). For the time interval 7900-7300 cal yr BP, we propose a substantial upward adjustment (>1 m around 7750 cal yr BP) of the MSL curve based on recently published MSL index points and a reinterpretation of the lower Hillegersberg index points. For the time interval 7300-6650 cal yr BP, the validity of the existing MSL curve is confirmed directly by new Vlaardingen and Hillegersberg index points and indirectly (through river-gradient effect considerations) by the new index points from De Bruin and Polderweg. For the time interval 6650-5300 cal yr BP a downward adjustment of ≤0.25 m is proposed based on the low position of multiple new Vlaardingen index points.

Comparison of the Vlaardingen and De Bruin-Polderweg data sets indicate a river gradient of 2.5-3.0 cm/km in the lower Rhine-Meuse delta during the period 6650-5600 cal yr BP. A systematic ~0.25 m elevation difference between the Hillegersberg and Vlaardingen index points (sites ~9.5 km apart in the alongstream direction) over the same time interval suggest a longitudinally fairly uniform river gradient in the lower Rhine-Meuse delta. Given this and the fact that Vlaardingen is located 20 to 25 km from the former coastline, the possibility exists that the river-gradient effect is still insufficiently taken into account in the construction of our revised MSL curve. For the period after 5300 cal yr BP, not covered by our data, the present MSL curve may also be slightly too high due to an underestimated river-gradient effect. Because a lower MSL curve for the lower Rhine-Meuse delta has important implications for the assessment of interregional differential (tectonic or isostatic) subsidence and the magnitude of early-Holocene sea-level jumps (e.g. Hijma & Cohen, 2010), the issue of potentially remaining river-gradient effects in the revised lower Rhine-Meuse delta MSL curve deserves further research.

An increased floodbasin effect seems to have developed in the lower Rhine-Meuse delta in de period 7500-6600 cal yr BP, as indicated by the gradual convergence of Vlaardingen, Hillegersberg and Barendrecht index points with the revised MSL curve. The onset of increased tidal damping in the Rotterdam area seems indirectly determined by a major avulsion of the Rhine causing partial abandonment of the estuary, coastal erosion and tidal import of sediments into the estuary mouth area. These events significantly preceded gradual closure of tidal inlets of the coast of Holland, which started ~6300 cal yr BP.

Acknowledgements

This paper was in preparation when the first author passed away and was finished by the second and third authors. Orson dedicated his life to sea-level research and would undoubtedly have made a better fist of this, if he would have had the time. Nevertheless, we are happy to present this long-awaited data set, in the hope that it will energize further sea-level studies. We thank Roel van Elsas for pollen analysis, Mark van Ree for selection of macrofossils, and Klaas van der Borg for AMS radiocarbon age determinations (UtC-numbers). The thoughtful comments of the journal reviewers Torbjörn Törnqvist, Patrick Kiden and Kim Cohen are very much appreciated.

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