Improving Methodology for High-Resolution Reconstruction of Sea-Level Rise and Neotectonics by Paleoecological Analysis and AMS ^{14}C Dating of Basal Peats

Torbjörn E. Törnqvist and Mark H. M. van Ree

The Netherlands Centre for Geo-ecological Research (ICG), Faculty of Geographical Sciences, Utrecht University,
P.O. Box 80115, NL-3508 TC Utrecht, The Netherlands

and

Ron van 't Veer and Bas van Geel

The Netherlands Centre for Geo-ecological Research (ICG), Hugo de Vries Laboratory, University of Amsterdam,
Kruislaan 318, NL-1098 SM Amsterdam, The Netherlands

Sea-level research in several submerging coastal regions has traditionally been based on ^{14}C dating of basal peats that overlie a compaction-free substratum and can be related to paleo-(ground)-water levels. Provided that an unequivocal relationship between (ground)water level and sea level can be assumed, this approach contains two sources of uncertainty: (1) the paleoenvironmental interpretation of samples is usually based on inherently inaccurate macroscopic descriptions in the field, and (2) ^{14}C ages of bulk peat samples may be erroneous as a result of contamination. Due to the uncertainties in both the altitude and the age—the two crucial sources of evidence necessary to arrive at accurate sea-level curves—sea-level index points are therefore represented by considerable, but typically not quantified, error boxes. Accelerator mass spectrometry (AMS) opens new perspectives for this type of sea-level research, as illustrated by a paleoecological and AMS ^{14}C study of basal peats from a small study area in the Rhine–Meuse Delta (The Netherlands), where previous (conventional) work revealed highly problematic results. A detailed macrofossil analysis has two purposes: (1) an inferred paleoecological succession indicates a relatively accurate level of paludification of the site, and hence rise of the (ground)water level; (2) suitable macrofossils from that specific level are then selected for AMS ^{14}C dating. In spite of very small sample sizes, our results are consistent and indicate that this approach can constitute a step forward in high-resolution reconstruction of sea-level rise. The new results further enable a revision of Holocene (ground)water gradient lines for the Rhine–Meuse Delta. A knickpoint in these gradient lines can be related to the effect of faulting. This approach therefore also has considerable potential to unravel and quantify neotectonic activity in submerging coastal settings.   © 1998 University of Washington.

INTRODUCTION

Reconstruction of the rise of Holocene relative sea level (RSL) in submerging coastal areas is usually carried out by radiocarbon dating basal-peat samples (e.g., Jelgersma, 1961; Bloom and Stuiver, 1963; Belknap and Kraft, 1977; Van de Plassche, 1982a, 1995; Van de Plassche *et al.,* 1989; Gehrels and Belknap, 1993; Denys and Baeteman, 1995; Kiden, 1995; Gehrels *et al.,* 1996; Kearney, 1996). Such samples directly overlie a relatively consolidated substratum which is assumed to be essentially compaction-free, and the sample itself is related to a (ground)water level (GWL) which corresponds directly or indirectly to contemporaneous sea level (SL). Many studies of this nature have been carried out in the Rhine–Meuse Delta, central Netherlands (Fig. 1), where several hundred basal-peat samples have been ^{14}C dated (e.g., Jelgersma, 1961; Van de Plassche, 1982a; Berendsen, 1982; Van Dijk *et al.,* 1991; Törnqvist, 1993). Many of these studies concern the dating of basal peats that overlie the steep slopes of Younger Dryas-age eolian sand dunes which rest on a Pleistocene substratum and were subsequently buried due to Holocene fluviodeltaic aggradation. In an important paper, Van Dijk *et al.* (1991) combined new evidence from four such dunes with previous data, enabling them to reconstruct (ground)water (GW) gradient lines covering a major part of the Holocene (Fig. 2). Their main conclusion was that the westernmost (downstream) parts of these GW-gradient lines exhibit very small (~2.5 cm km^{-1}) gradients, and hence define an up-to-50-km wide coastal zone, where a close GWL–SL relationship (cf. Van de Plassche, 1986) exists. Upstream of a marked knickpoint (Fig. 2), a river-gradient effect (Van de Plassche, 1980a; Van Dijk *et al.,* 1991) blurs this relationship.

The basal-peat approach contains two potential sources of error. First, the GWL-relationship, and hence the SL-relationship of such samples, is not always straightforward. For instance, frequently used *Phragmites* peat may
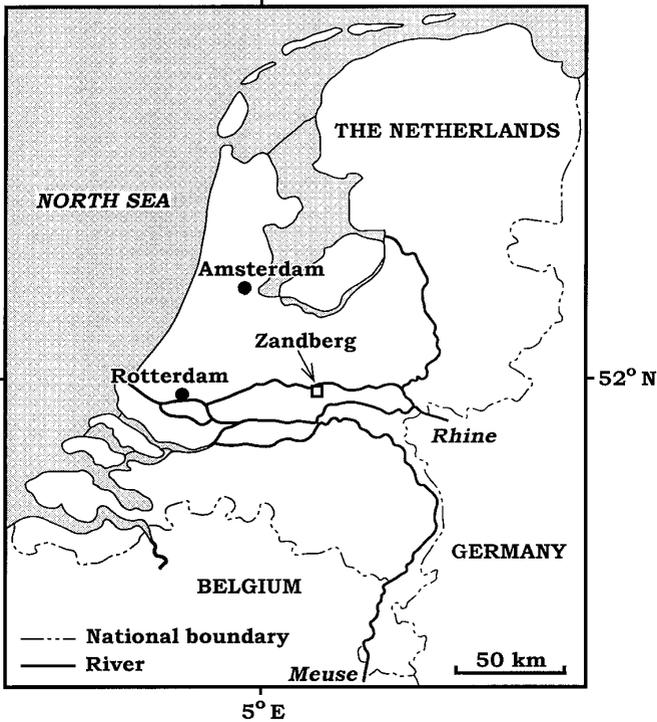
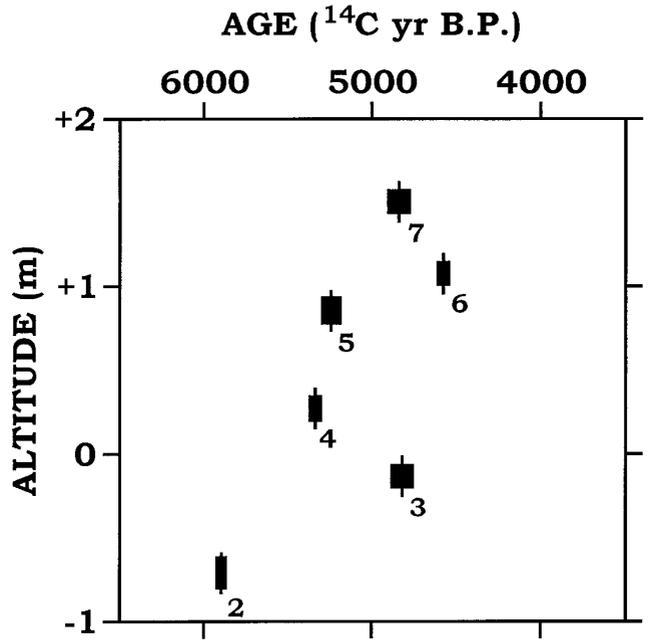**FIG. 1.** Map of The Netherlands showing location of the study area.

FIG. 3. Age–altitude data for the Zandberg dune according to Van Dijk *et al.* (1991), plotted versus ^{14}C yr B.P. 0 = Dutch Ordnance Datum. Indicated are the central values (vertical bars), and the 1σ-confidence interval (black boxes). For sample numbers see Table 2.

represent GWLs well above the land surface (Kidson, 1982; Van de Plassche, 1982a). Second, recent SL research in The Netherlands (Gotjé, 1993; Van de Plassche, 1995) has cast doubt on the reliability of ^{14}C ages of bulk basal-peat samples, mainly because they may be contaminated with older carbon from underlying paleosols. A good example of problematic dating results, possibly due to this type of contamination, was provided by one of the sites of Van Dijk *et al.* (1991). The inconsistent time series from the eolian dune known as the Zandberg (Figs. 1 and 3) was partly attributed to difficulties in establishing a good GWL-relationship for their samples.
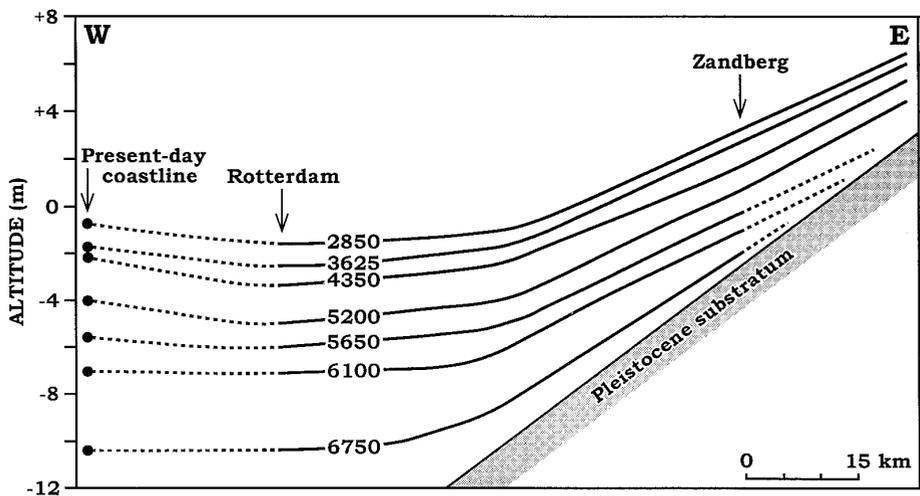

FIG. 2. Holocene (ground)water (GW) gradient lines for the Rhine–Meuse Delta (Van Dijk *et al.,* 1991, slightly modified after Van de Plassche, 1995), based on approximately 100 basal-peat ^{14}C ages. 0 = Dutch Ordnance Datum. Ages are in ^{14}C yr B.P. Black circles represent coastal MHW (mean high water) (Van de Plassche, 1982, 1995).

Radiocarbon dating of carefully selected botanical or zoological macrofossils by means of accelerator mass spectrometry (AMS) yields considerably more accurate results than conventional bulk peat ages (Törnqvist *et al.,* 1992). The present study aims at an improved methodology for dating local rise of GWL by AMS ^{14}C dating of botanical macrofossils. This approach not only brings significant advantages in improved age accuracy, as recently demonstrated for basal peats by Gehrels and Belknap (1993) and Gehrels *et al.* (1996), but also allows a better-defined GWL-relationship (altitude), and hence a reduction of the vertical indicative range (Van de Plassche, 1986; Behre, 1986). We have carried out paleoecological reconstructions (macrofossil analysis) of basal-peat sections representing the paludification of the sampling sites in order to pinpoint the level of paludification more accurately. A comparable paleoecological approach was followed by Gotjé (1993). However, because he used conventional ^{14}C dating of bulk material, uncertainties in the age determination remained. Our detailed paleoecological approach is also comparable to the large number of recent RSL studies based on high-resolution pollen, diatom, foraminiferal, and other microfossil records (e.g., Fletcher *et al.,* 1993; Nelson *et al.,* 1996; Shennan *et al.,* 1996), although those studies have typically not been applied to compaction-free basal peats.

We selected the Zandberg dune previously studied by Van Dijk *et al.* (1991) to apply the new approach in a setting where conventional methods failed (Fig. 3). It should be kept in mind that the results from that area merely have an indirect SL-relationship due to a river-gradient effect resulting from the relatively upstream location of the study area. Nevertheless, the methodological implications are equally significant for areas closer to the coast, where the GWL–SL relationship is more direct (Fig. 2).

METHODS

We hand-drilled approximately 20 new boreholes on the relatively steep northern flank of the Zandberg dune (Figs. 1 and 4). Our cross section is located in the same line of section where Van Dijk *et al.* (1991) collected their data, but it provides considerably more detail. We sampled the transition from dune sand to organic deposits (peat or humic clay), thereby avoiding depressions in the dune morphology to circumvent local, SL-independent early peat growth (cf. Jelgersma, 1961; Van de Plassche, 1982a). We collected six 15-cm-long samples using a 6-cm-diameter gouge (Oele *et al.,* 1983). The sampling sites were leveled using two benchmarks. We estimate our altitudinal error during leveling and gouging at ±2 cm. The altitudinal error during sampling of the data set presented by Van Dijk *et al.* (1991) is likely to be higher (H. J. A. Berendsen, personal communication, 1996), and is estimated here to be ±5 cm.

Each of the six samples were cut into 1-cm-thick slices. Part of the material was used for loss on ignition (LOI) measurement and pollen analysis; the remainder (∼28 ml per sample) was treated with 5% KOH overnight at room temperature prior to sieving over a 150-μm screen, and subsequently subjected to macrofossil analysis. Two sections (Zandberg III and VI) were screened for key pollen taxa to validate the vegetation reconstruction based on the macrofossil diagrams. After interpretation of the macrofossil diagrams (Figs. 5A–5F) in terms of vegetational succession and paludification (see below), ^{14}C samples were selected and submitted for dating at the Robert J. Van de Graaff Laboratory, Utrecht University (Van der Borg *et al.,* 1987).

RESULTS

Stratigraphy

Our cross section (Fig. 4) shows a sloping dune surface with some minor undulations. The top of the dune sand is admixed with clay, presumably deposited during extreme floods prior to the rise of the GWL (cf. Van de Plassche, 1980b; Van Dijk *et al.,* 1991). The Holocene cover consists of a thin (<1 m) clastic bed without admixed sand (predominantly humic clay), overlain by ∼1 m of peat and up to 3 m of clastic sediment. Plant remains that could be identified in the field indicate that the peat covering the dune sand was primarily formed in an *Alnus* swamp, which was later replaced by a *Phragmites*-dominated fen in the northwestern part of the cross section. The basal part of the overlying clastic bed is a flood-basin deposit that contains two well-developed vegetation horizons (paleosols), and a thin bed of amorphous peat or humic clay. The latter tapers out southeastward where it approaches the eolian sand body. The upper part of the clastic bed consists primarily of natural-levee deposits of two Late Holocene Rhine distributaries (the Ravenswaay and Nederrijn-Lek systems; Berendsen, 1982; Verbraeck, 1984). We collected samples at topographic highs, vertically separated by ∼40 cm (Fig. 4).

Paleoecology

The botanical composition of the peats and underlying humic clays, as determined in the field, suggests a transition from eolian deposits to a wood-dominated environment (*Alnus*) at most sampling sites, with the exception of section Zandberg V, where primarily herbaceous remains (*Phragmites*) cover the Pleistocene substratum. The transition from dune sand to organic deposits (Figs. 5A–5F) shows a gradual decrease of sand content over vertical intervals of 6–10 cm. There are several possible causes for this phenomenon:
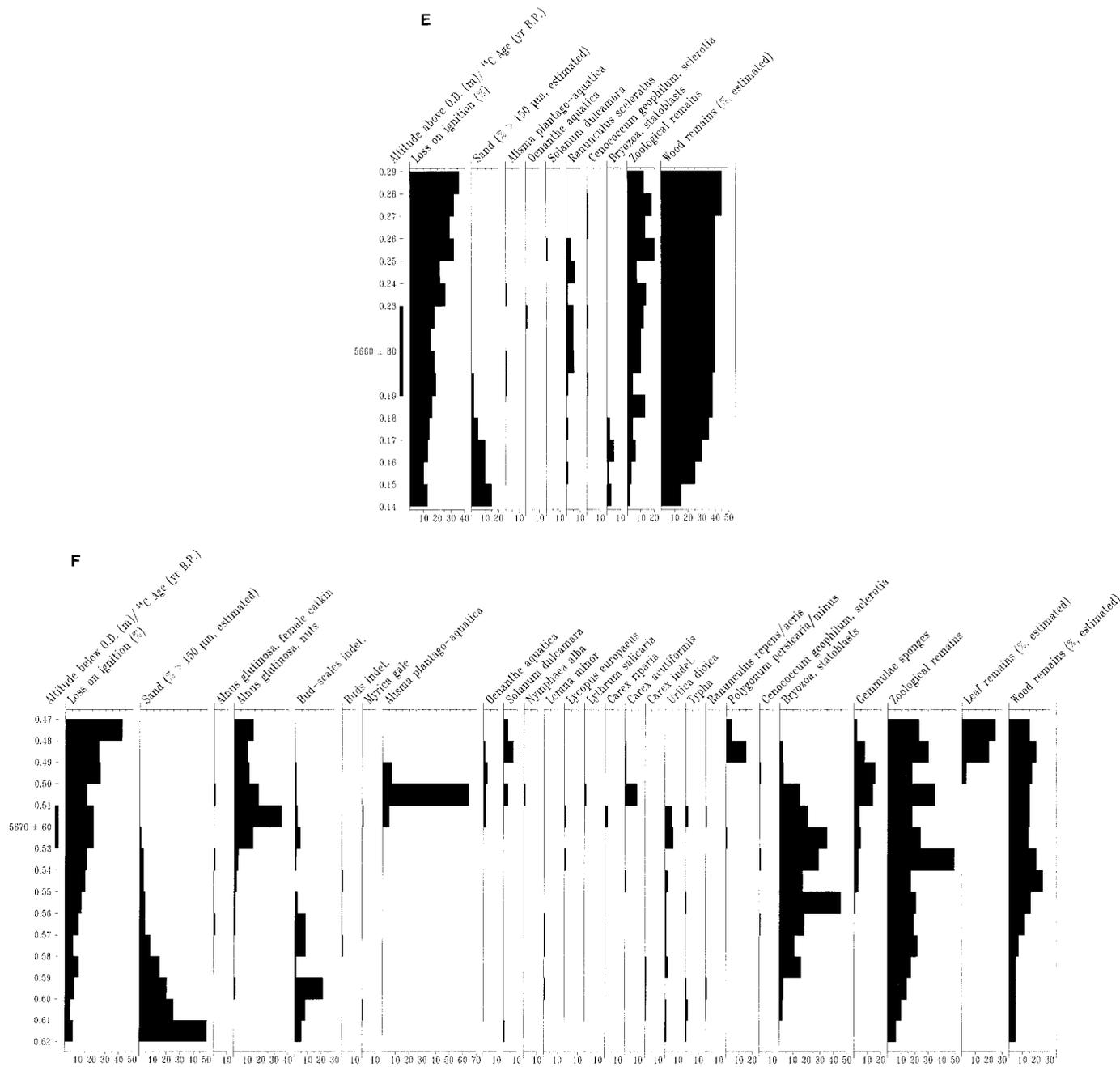
FIG. 4. Cross section over the northern flank of the Zandberg dune, and location of samples for macrofossil analysis and ^{14}C dating. 0 = Dutch Ordnance Datum textural nomenclature after Nederlandse Normalisatie-instituut (1989); lithostratigraphy after Berendsen (1984) and Törnqvist *et al.* (1994).

1. Roots have penetrated from higher levels into the sandy subsoil. This must have started prior to paludification of the sites, but particularly after the rise of the GWL rootlets and woody root material were preserved.

2. Bioturbation also played a role. Prior to paludification, soil formation resulted in an A-horizon of dune sand with admixed clay and decomposed organic material. The process of bioturbation most likely continued during the initial stage of paludification.

3. Some sand may have been washed downslope after paludification, particularly on the relatively steep parts of the dune.

The ecological requirements of most of the recorded taxa (Oberdorfer, 1983; Weeda *et al.,* 1985, 1987, 1994; Table 1) point to wet eutrophic conditions, as expected in an area that is strongly influenced by nutrient-rich river water. Various plant communities (descriptions based on Westhoff and Den Held, 1969; Moore, 1984) can potentially develop during the initial, dynamic phase of regular flooding and associated fluctuating GWLs, including *Bidentetalia* (annual herb communities), *Phragmitetea* (reed-dominated fens), *Filipendulion* (tall, perennial herb communities), and *Salicion albae* (willow swamps). A subsequent succession to *Salicion cinereae* or *Alno-Padion* (alder-willow swamps) represents the

FIG. 5. Macrofossil diagrams Zandberg I–VI (A–F), showing numbers per sample or estimated volume percentages. LOI-values have not been corrected for interlayer water losses; the uncertainty due to this is <4%.

establishment of more stable conditions. Alder-willow swamps are usually somewhat less nutrient-rich due to accumulation of rain water during the wet season. Species like *Myrica gale, Carex rostrata,* and *Ranunculus flammula,* typical of mesotrophic conditions, may be present in shallow pools in such environments. Previous paleoecological work in the Rhine–Meuse Delta has demonstrated the abundance of extensive *Alnus*-dominated swamps at some distance from

coeval distributaries (Van der Woude, 1985). Because observations in modern analogs (Clerkx *et al.,* 1994) indicate that the land surface in such environments occurs in a narrow range (<20–30 cm) above average low GWL, whereas annual GWL-fluctuations are <20–40 cm, we consider this environment the best proxy for paludification (Table 1).

Screening of the pollen indicated high numbers of *Salix* pollen throughout the sections Zandberg III and VI. *Salix* is

FIG. 5—*Continued*

known to produce very few identifiable macrofossils, even when pollen data demonstrate its local presence (Pals *et al.,* 1980; Van Geel *et al.,* 1983). We therefore assume an important role of *Salix* swamps during the dynamic phase prior to permanent paludification relative to the three other communities indicative of such environmental conditions, which probably only occurred as small patches. A general vegetational succession which is a response to initial occasional flooding of the sites, followed by a more permanent

and stable paludification, can be inferred from many of the diagrams and will be described in more detail below. Taxa representing drier habitats that must have existed prior to the rise of the GWL have hardly been preserved. The following short description and interpretation of the macrofossil diagrams is given for the six sites (also see Table 1).

Zandberg I (Fig. 5A). Sand-rich samples representing the prepaludification phase are characterized by the presence of sclerotia of the soil fungus *Cenococcum geophilum.*

FIG. 5—*Continued*

Alisma plantago-aquatica, Typha, as well as gemmulae of freshwater sponges and various zoological remains are the main indicators of eutrophic wet conditions after the rise of GWL. The gemmulae and zoological remains possibly indicate the presence of shallow pools in a stable, paludified environment, but the limited number of preserved plant macrofossils renders this diagram difficult to interpret in terms of plant communities. Fruits of *Alisma plantago-aquatica* were selected for ^{14}C dating.

Zandberg II (Fig. 5B). Also at this site samples from the sandy subsoil contained sclerotia of *Cenococcum geophilum.* Numerous finds of bud scales indicate a local vegetation, which in the lower part of the section may have been dominated by *Salix,* suggesting dynamic conditions with frequent floods. The sudden increase of the LOI values at 1.26 m indicates a rising GWL; however, only above the 1.30 m level are clear indications found for the establishment of a mixed *Alnus–Salix* swamp. The occurrence of gemmulae

TABLE 1
Potential Natural Plant Communities and ''Key Taxa''
in Fluvial Environments

Key taxon[a]	Plant community				
	1	2	3	4	5
Ranunculus sceleratus	++	−	−	−	−
Typha latifolia	++	+	−	−	−
Oenanthe aquatica	+	++	−	−	−
Typha angustifolia	−	++	−	−	−
Carex acutiformis	−	++	+	−	−
Carex pseudocyperus	−	++	+	−	−
Carex riparia	−	++	+	−	−
Galium palustre	−	++	+	−	−
Lycopus europaeus	−	++	+	+	+
Mentha aquatica	−	++	+	+	+
Alisma plantago-aquatica	−	++	+	+	+
Phragmites australis	−	++	+	+	+
Lythrum salicaria	−	+	++	+	+
Lemna minor	−	+	−	+	+
Dryopteris spp.	−	−	+	+	+
Urtica dioica	−	−	+	+	+
Solanum dulcamara	−	−	++	++	+
Filipendula ulmaria	−	−	++	+	−
Salix spp.	−	−	−	++	−
Salix cinerea	−	−	−	+	++
Alnus glutinosa	−	−	−	−	++
Frangula alnus	−	−	−	−	++

++ very characteristic
+ characteristic
− mostly not present

1. Annual, nitrophilous herb communities (*Bidentetalia*). Annual pioneer communities at nitrophilous sites with a fluctuating GWL. Inundated during fall, winter, and spring; at clayey, silt-rich soils.

2. Reed-fen communities (*Phragmitetea*). Waterlogged, sometimes semi-floating, pioneer communities of mostly eutrophic sites. Succeeding into *Salicion cinereae;* at more exposed sites succeeding into *Filipendulion* or *Salicion albae.*

3. Tall, perennial herb communities (*Filipendulion*). Wet, 2–2.5 m high communities in eutrophic environments, with a GWL slightly below the land surface. At exposed, frequently inundated sites a rather stable stage; at sheltered sites succeeding into *Salicion cinereae.*

4. Willow swamp (*Salicion albae*). Eutrophic willow swamp. Moderately species rich communities which are frequently flooded. Succeeding into *Salicion cinereae* or *Alno-Padion.*

5. Mixed alder–willow swamp (*Salicion cinereae/Alno-Padion*). Swamp communities at sheltered places, distant from river activity. Rarely flooded by rivers, but inundated during the wet season by groundwater and rainwater.

[a] Only taxa recorded in the macrofossil diagrams (Figs. 5A–5F) or discussed in the text are indicated.

(sponges), *Alisma plantago-aquatica, Ranunculus flammula,* and *Lemna minor* indicates the presence of small, temporary, shallow pools during the wet season. *Carex* nuts from 1.29–1.31 m were used for dating.

Zandberg III (Fig. 5C). The interval 0.83–0.85 m represents the transition from relatively dry conditions to the es-

tablishment of an *Alnus–Salix* swamp. The local environment of the early peat-forming stage was characterized by the presence of *Alnus glutinosa, Salix* spp., *Lythrum salicaria, Mentha aquatica,* and *Lemna minor.* The occurrence of seeds of *Carex rostrata* and *Myrica gale* is remarkable since these taxa are generally assumed to represent mesotrophic environments. However, *Carex rostrata* is also known from shallow, meso-eutrophic pools (Weeda *et al.,* 1994), whereas *Myrica gale* has been recorded from peaty sand soils with *Alnus glutinosa, Salix aurita,* and *Frangula alnus* (Hegi, 1957). Both species could be present in permanently water-logged depressions where during the wet season the groundwater is mixed with rain water. The almost sand-free material at 0.85–0.86 m was interpreted to represent the paludification, and *Carex* nuts and a *Solanum dulcamara* seed were used for dating.

Zandberg IV (Fig. 5D). *Urtica dioica* dominates the macrofossil diagram of this site, including the lower, sandy part of the core. In view of the wide range of habitats occupied by *Urtica,* we consider this species ecologically indeterminate for our purposes. Because true wetland taxa are almost absent from this diagram, we do not exclude the possibility that the paludification level may be located above the sampled section and that this sequence might represent a *Salix*-dominated vegetation. There is only slight evidence for a permanently high GWL above 0.65 m, where low numbers of *Urtica,* and the increase of bud scales and gemmulae, might be related to the establishment of an *Alnus–Salix* swamp. However, we consider the paleoecological evidence too weak to obtain a meaningful ^{14}C age from this section.

Zandberg V (Fig. 5E). Seeds of *Ranunculus sceleratus* with some other taxa (*Alisma plantago-aquatica, Oenanthe aquatica*) that indicate wet, eutrophic pioneer conditions and a fluctuating GWL (Weeda *et al.,* 1985), dominate the levels above the sandy part of the section. No transition from this relatively dynamic environment to the stable *Alnus–Salix* swamp can be observed, consistent with the fact that at this site no *Alnus* peat covers the dune sand (Fig. 4). Therefore, the most suitable plant community for dating does not occur, just as in section Zandberg IV. However, in order to avoid a large vertical gap in our sequence of samples, we have used fruits of *Ranunculus sceleratus* for ^{14}C dating at the level where sand disappears (0.19–0.23 m). Their presence points to GWLs above the land surface at least part of the year, contrary to the ecologically indeterminate *Urtica dioica* that dominates section Zandberg IV.

Zandberg VI (Fig. 5F). The samples above 0.53 m below O.D. (transition to sand-free samples) clearly indicate the presence of an *Alnus*-dominated swamp with, among other species, *Alisma plantago-aquatica, Oenanthe aquatica, Solanum dulcamara, Carex riparia, Urtica dioica,* and

freshwater sponges (gemmulae). Pollen screening indicates the local presence of *Salix* in the swamp vegetation. There is no clear evidence for the presence of the pioneer communities recognized in the other sections. *Alnus glutinosa* nuts were selected for dating at the level where sand disappeared (0.51–0.53 m below O.D.).

A characteristic usually found in the six diagrams is the presence of a dynamic phase resulting from regular floods, particularly well-developed in the sections Zandberg IV and V. This is related to the frequent occurrence of admixed clay in the uppermost eolian deposits, which is likely due to river flooding prior to a permanent rise of the GWL (cf. Van Dijk *et al.,* 1991). This clay layer (just as the overlying humic clay) was deposited by the Maurik system, a distributary at only 1 km distance from the study area (Verbraeck, 1984) which was active prior to ~5300 yr B.P. (Berendsen, 1982; Hofstede *et al.,* 1989; Van Dijk *et al.,* 1991). We propose that fluctuating GWLs associated with this Rhine-distributary controlled the development of plant communities in its direct vicinity. The transition to an *Alnus*-dominated swamp indicates less dynamic conditions, more suitable for inferring GWL-relationships, so this environment was our target for obtaining ^{14}C ages.

^{14}C Ages

We attempted, as far as possible, to select macrofossils for ^{14}C dating that constitute the most obvious proxy for paludification with minimal GWL fluctuations, i.e., the onset of development of an *Alnus–Salix* swamp. Our dated samples most likely represent an altitude slightly below mean GWL, because preservation of organic matter is unlikely when the land surface is above GWL more than half the year. Observations in modern *Alnus* swamps (Clerkx *et al.,* 1994), as discussed above, provide evidence of a consistent position of the land surface relative to GWL. We consider a vertical indicative range of 20 cm to be a reasonable estimate for this ecosystem, and have therefore incorporated a vertical uncertainty of ±10 cm in our error boxes (Fig. 6A).

By dating macrofossils we avoided contamination by roots or organic substances from the underlying soil. Previous work in the Rhine–Meuse Delta has shown that the potential risk of dating redeposited macrofossils is very small (Törnqvist *et al.,* 1992). We selected ^{14}C samples from all sites, with the exception of section Zandberg IV, where no clear succession due to paludification could be inferred. The ^{14}C ages (Table 2) were obtained for very small samples ranging in size from 28 to 540 µg. As a result, the standard deviation of the smallest sample (Zandberg I-1) is very large. Despite this, the ^{14}C measurements have resulted in a stratigraphic order consistent with sample altitudes (Fig. 6A); thus, our results constitute a significant improvement over those obtained by Van Dijk *et al.* (1991). A curve representing the rise of local GWL was calculated by an exponential function
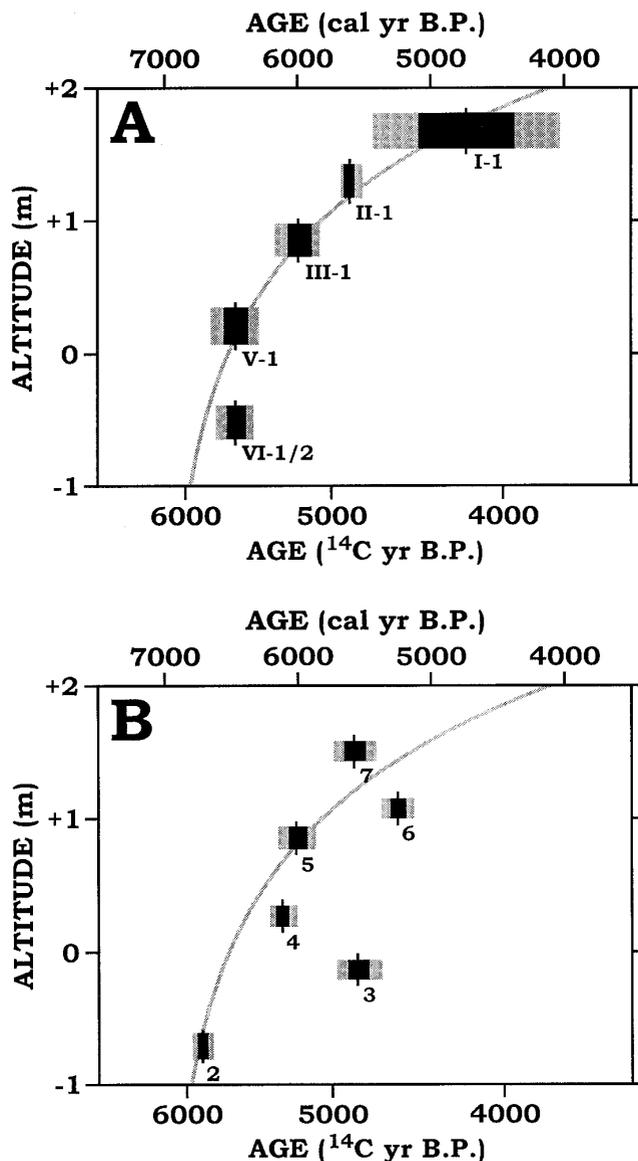

FIG. 6. GWL rise at the Zandberg dune according to (A) the present study, and (B) Van Dijk *et al.* (1991). 0 = Dutch Ordnance Datum. Each sample was calibrated to calendar years according to Van der Plicht (1993) and Törnqvist and Bierkens (1994). Indicated are the median of the probability distributions (vertical bars), the 1σ-confidence interval (black boxes), and the 2σ-confidence interval (gray boxes). The thickness of each sample is also indicated: a ±12 cm error has been added in (A) (±2 cm for errors during sampling, ±10 cm for the vertical indicative range), and a ±5 cm error in (B) (only representing errors during sampling; a vertical indicative range could not be established due to the uncertain indicative meaning of the material). For sample numbers see Table 2.

through the data points (Fig. 6A) and shows a gradual decrease in the rate of GWL rise, similar to what can be observed in RSL curves for the southern North Sea Basin. Our regression analysis yielded a correlation coefficient of 0.98, considerably better than the value obtained previously (0.66; Van Dijk *et al.,* 1991).

TABLE 2
List of [14]C Ages

Laboratory number[a]	[14]C age (yr B.P.)[b]	Weight (mg C)	Coordinates and surface elevation relative to Dutch Ordnance Datum (m)	Depth below surface (cm)	Sample altitude relative to Dutch Ordnance Datum (m)	Sample name	Material[c]
GrN-11470	4840 ± 70		152.394/440.288/+3.88	235–240	+1.48–+1.53	Zandberg 7	Slightly clayey peat
GrN-11471	4575 ± 40		152.385/440.290/+3.85	275–280	+1.05–+1.10	Zandberg 6	Peat
GrN-11472	5240 ± 60		152.378/440.307/+3.82	293–300	+0.82–+0.89	Zandberg 5	Peat
GrN-11473	5335 ± 40		152.351/440.339/+3.79	349–355	+0.24–+0.30	Zandberg 4	Peat
GrN-11474	4820 ± 70		152.318/440.373/+3.94	405–410	−0.11–−0.16	Zandberg 3	Strongly clayey peat
GrN-11475	5895 ± 35		152.308/440.387/+3.99	465–475	−0.66–−0.76	Zandberg 2	Strongly clayey peat
UtC-3944	4200 ± 260	0.028	152.387/440.281/+3.63	194–197	+1.66–+1.69	Zandberg I-1	5 *Alisma plantago-aquatica* fruits
UtC-3945	4850 ± 40	0.54	152.383/440.285/+3.57	226–228	+1.29–+1.31	Zandberg II-1	2 *Carex* sp. nuts
UtC-3946	5220 ± 70	0.23	152.370/440.300/+3.57	271–272	+0.85–+0.86	Zandberg III-1	1 *Carex rostrata* nut, 1 *Carex* sp. nut, 1 *Solanum dulcamara* seed
UtC-3947	5660 ± 80	0.23	152.326/440.354/+3.62	339–343	+0.19–+0.23	Zandberg V-1	17 *Ranunculus scleratus* fruits
UtC-3948	5880 ± 260[d]	0.12	152.287/440.400/+3.84	436–437	−0.52–−0.53	Zandberg VI-1	14 *Alnus glutinosa* nuts
UtC-4164	5660 ± 60[d]	0.32	152.287/440.400/+3.84	435–436	−0.51–−0.52	Zandberg VI-2	35 *Alnus glutinosa* nuts

[a] GrN-samples: Van Dijk *et al.* (1991); UtC-samples: this paper.

[b] Assumed δ^{13}C for all UtC-samples: −27.5‰ (cf. Törnqvist *et al.,* 1992).

[c] The lithology as determined by Van Dijk *et al.* (1991) is sometimes inconsistent with the present study.

[d] Weighted mean of UtC-3948 and UtC-4164: 5670 ± 60.

DISCUSSION

Implications for Sea-Level Research

We believe that uncertainties concerning age accuracy and GWL-relationship that are inherent in the conventional basal-peat dating strategy can be reduced with this new approach. AMS ^{14}C dating of macrofossils is significantly more accurate than dating of bulk peat samples (Törnqvist *et al.,* 1992), and thus reduces the horizontal error in age–altitude plots. The vertical error is reduced because paleoecological analysis permits an improved GWL-relationship (cf. Van de Plassche, 1986) and a relatively precise sampling of the paludification surface; hence, the combination of the two approaches can reduce the size of error boxes of SL-index points. It is our impression that these uncertainties have been considerably underestimated in the past, resulting in unrealistically small error boxes. Since our GWL-error boxes incorporate essentially all uncertainty, we suggest that their size is more realistic. In addition, our approach is not just limited to peats, but also permits the establishment of realistic age–altitude data for humic clays.

When our new GWL curve (Fig. 6A) is compared with the evidence of Van Dijk *et al.* (1991), there is a tendency for their data points to be too young, with the exception of sample Zandberg 7 which is too old (Fig. 6B). As a result, the suggestion that systematic contamination (aging) by admixed soil material (Gotjé, 1993; Van de Plassche, 1995)

would occur in such data sets is not supported by the new Zandberg evidence. Three samples (Zandberg 3, 4, and 6) are up to 1000 cal yr younger than our GWL curve. Gehrels and Belknap (1993) reported AMS basal-peat ages of botanical macrofossils up to 1000 ^{14}C yr older than ages for bulk material, which was explained by percolation of humic acids and/or contamination by vertically penetrating roots. However, age differences of that magnitude between bulk peats and macrofossils have never been observed in the Rhine–Meuse Delta (Törnqvist *et al.,* 1992), particularly not in rapidly (>5 cm/century) accumulating peats. Anomalously young basal-peat ages have been noted before in the Rhine–Meuse Delta (Van de Plassche, 1982b; Törnqvist, 1993), but could not be adequately explained.

We do not exclude the possibility that the anomalous results of Van Dijk *et al.* (1991) might be a result of disturbances during the sampling process itself. On several occasions, we have noticed problems with the Dachnowsky sampler (Oele *et al.,* 1983), which was used during that study at the Zandberg (H. J. A. Berendsen, personal communication, 1994). Relatively consolidated sediment, like the organic deposits overlying the Zandberg dune, encounter considerable friction in the ~5-cm-diameter metal barrel of the Dachnowsky sampler. The possibility should therefore be considered that only the upper part of the intended section was sampled, and the lower part of the peat (the true basal peat) was pushed aside during drilling. Erroneous sampling of
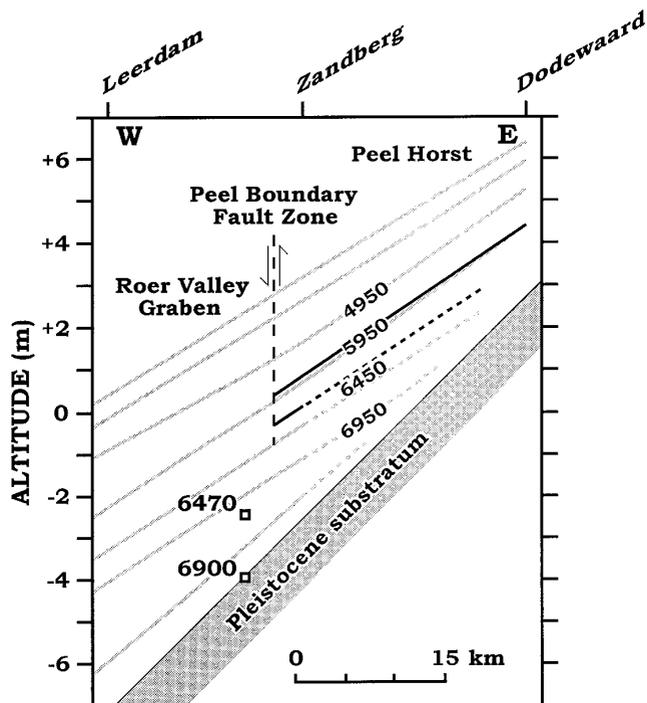
FIG. 7. Revised GW-gradient lines for the area surrounding the Zandberg dune. 0 = Dutch Ordnance Datum. Ages are in calendar years B.P. Pleistocene substratum (generalized) and original GW-gradient lines (in gray) after Van Dijk *et al.* (1991), who did not take into account tectonic deformation. Revisions based on the new Zandberg data are in black. Also plotted are calibrated basal-peat ages from Weerts and Berendsen (1995), which have been projected to the central axis of the Rhine−Meuse Delta. Note that the exact location of the Peel Boundary Fault Zone is unknown.

peat well above the organic−clastic transition might explain part of the age differences. The implication is that a comparison between our AMS data and the older conventional ages in terms of contamination by soil material is completely overruled by this effect. New work focusing on such a comparison (cf. Gehrels and Belknap, 1993) is now in progress.

Neotectonics

Recent work has shown the considerable potential of RSL data to allow inferences to be made of Holocene neotectonism, particularly along the Pacific coast of North America (Nelson *et al.,* 1996). As will be shown, SL-controlled GWLs can be used in a similar way. We have used the new GWL curve for the Zandberg to reevaluate the Holocene GW-gradient lines for the eastern Rhine−Meuse Delta of Van Dijk *et al.* (1991). Our GWL curve covers three of their gradient lines (6450, 5950, and 4950 cal yr B.P.). When the new altitudes of GWL are plotted (Fig. 7), assuming that the data of Van Dijk *et al.* (1991) for the neighboring sites at Dodewaard and Leerdam are correct (see below), the 6450-line must be displaced upwards by 45 cm and the 5950-

line by 15 cm, whereas the 4950-line remains more or less unchanged. The revised GW-gradient lines exhibit a knickpoint, downstream of the Zandberg, which is more pronounced with increasing age. We therefore believe that differential crustal movement is the most likely explanation for this phenomenon. As mentioned, this depends on the reliability of the Leerdam and Dodewaard data sets (for locations, see Fig. 8). Most bulk basal peats that have been dated in areas west of the Zandberg consist of *Alnus* peat, in view of the dominance of *Alnus* swamps in these areas (Van der Woude, 1985). Although the GWL-relationship established by those studies is less accurate than ours, major errors due to a large vertical indicative range are unlikely. The GWL curve for Leerdam is based on a consistent sequence of ages (*r* = 0.99; Van Dijk *et al.,* 1991), and there is no reason to question its validity. The Dodewaard data consist of compaction-free depositional levels of flood-basin clays (Steenbeek, 1990), which are assumed to represent a slightly higher level than average GWL (Van Dijk *et al.,* 1991). This lends support to the inferences made above, since if the true GWL at Dodewaard is located below the presently assumed lines, this would only amplify the offset of the GW-gradient lines downstream from the Zandberg.

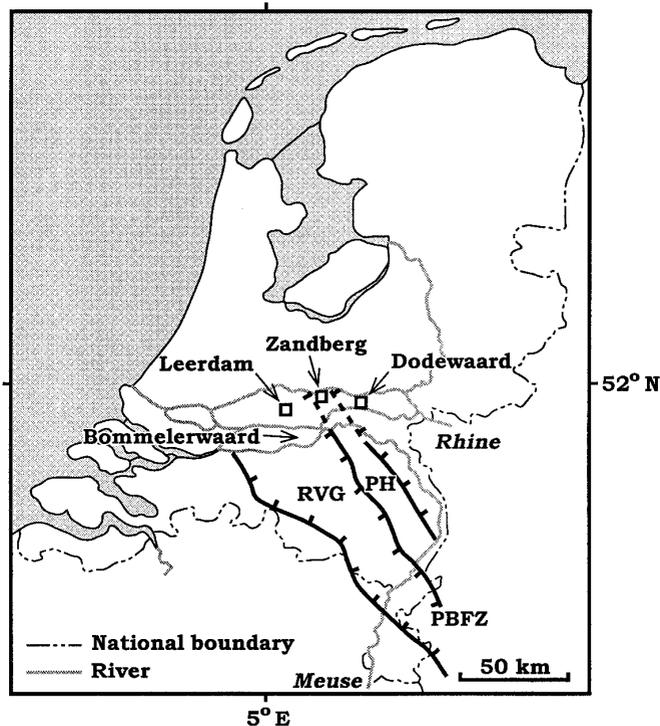The Peel Boundary Fault (Fig. 8), which has been active

FIG. 8. Main tectonic features in the southeastern Netherlands, and assumed continuations of principal displacement zones into the Rhine−Meuse Delta (Geluk *et al.,* 1994; Verbraeck, 1984), modified according to the new data. PBFZ = Peel Boundary Fault Zone; RVG = Roer Valley Graben; PH = Peel Horst.

since the Late Oligocene (Geluk *et al.,* 1994), is a conspicuous tectonic feature in The Netherlands. Normal dip–slip movement along this fault caused the Roermond earthquake of 1992, one of the most severe earthquakes in northwestern Europe in historical time (Van Eck and Davenport, 1994). Tectonic maps of Van Montfrans (1975) and Verbraeck (1984) suggest that the northwestern continuation of the Peel Boundary Fault is represented by a number of downstepping *en echelon* faults, the Zandberg being located in the Roer Valley Graben. Our evidence suggests that the principal displacement zone of the Peel Boundary Fault (cf. Van den Berg *et al.,* 1994) is located west of the Zandberg. Gradual relative uplift of the Peel Horst throughout the Holocene is compatible with the observed increased offset of GW-gradient lines with increasing age.

Whereas the revisions of GW-gradient lines based on the new Zandberg evidence are rather subtle, other, more compelling evidence suggesting differential crustal movements in the Rhine–Meuse Delta during the Holocene has recently become available. Weerts and Berendsen (1995) published two basal-peat ages from the Bommelerwaard in the southern part of the Rhine–Meuse Delta (Fig. 8). These plot up to 2 m below the GW-gradient lines of Van Dijk *et al.* (1991) (Fig. 7) and therefore indicate significant subsidence compared to the central axis of the delta. Since the basal-peat samples from the Bommelerwaard are from relatively thin peat beds (Weerts and Berendsen, 1995; H. J. T. Weerts, personal communication, 1996), potential technical problems during sampling such as those described above can only have had limited effects.

Recent analysis of high-resolution leveling data indicates that parts of the southern Rhine–Meuse Delta have subsided at a relatively rapid rate during the last century (Lorenz *et al.,* 1991; Van den Berg *et al.,* 1994; R. E. Molendijk, personal communication, 1996). Lorenz *et al.* (1991) indicate differential crustal movement of ~6 cm/century between the Zandberg region and the Bommelerwaard, which is primarily released along the Peel Boundary Fault Zone. This supports our observations compared to those of Weerts and Berendsen (1995). Based on the limited new data now available, we estimate that the mean rate of differential crustal movement over the time period studied has probably not exceeded ~3 cm/century. Comparison of the measured rates of differential movement over the last century with our data for the Holocene suggests significant variation in time. The driving force causing this phenomenon remains to be established.

CONCLUSIONS

1. Macrofossil analysis of basal-peat sections permits a more accurate identification of the paludification surface caused by rising GWL. Subsequent AMS ^{14}C measurement of macrofossils from that particular level yields consistent

dating results, and thus provides a more realistic assessment of error boxes of GWL (and, hence, SL) index points. This method is not limited to peats, but can also be successfully applied to humic clays. This approach therefore opens new perspectives for high-resolution reconstruction of SL rise, including the detection of subtle SL fluctuations, and intracoastal GW gradients caused by local differences in tidal range (cf. Van de Plassche, 1982a, 1995).

2. The new GWL curve for the Zandberg requires a revision of the GW-gradient lines of Van Dijk *et al.* (1991), indicating a position of the Peel Boundary Fault Zone west of the study area. GW-gradient lines need increasing adjustment with age, and thus reflect neotectonic activity during the Holocene. High-resolution reconstruction of the rise of GWL can thus contribute to a more detailed understanding of neotectonics, and is a potentially powerful technique for the mapping of faults and estimating rates of fault displacement in areas where other techniques are less easily applied (cf. Van den Berg *et al.,* 1994). A similar approach is feasible for the identification of larger scale crustal movements like differential isostatic responses, including forebulge displacements (cf. Gehrels and Belknap, 1993; Denys and Baeteman, 1995; Kiden, 1995).

REFERENCES

Behre, K.-E. (1986). Analysis of botanical macro-remains. *In* ''Sea-Level Research: A Manual for the Collection and Evaluation of Data'' (O. van de Plassche, Ed.), pp. 413–433. Geo Books, Norwich.

Belknap, D. F., and Kraft, J. C. (1977). Holocene relative sea-level changes and coastal stratigraphic units on the northwest flank of the Baltimore Canyon trough geosyncline. *Journal of Sedimentary Petrology* **47,** 610–629.

Berendsen, H. J. A. (1982). De genese van het landschap in het zuiden van de provincie Utrecht, een fysisch-geografische studie. *Utrechtse Geografische Studies* **25,** 1–255.

Berendsen, H. J. A. (1984). Problems of lithostratigraphic classification of Holocene deposits in the perimarine area of the Netherlands. *Geologie en Mijnbouw* **63,** 351–354.

Bloom, A. L., and Stuiver, M. (1963). Submergence of the Connecticut coast. *Science* **139,** 332–334.

Clerkx, A. P. P. M., Van Dort, K. W., Hommel, P. W. F. M., Stortelder, A. H. F., Vrielink, J. G., De Waal, R. W., and Wolf, R. J. A. M. (1994). ''Broekbossen van Nederland.'' IBN-rapport 096, Instituut voor Bos- en Natuuronderzoek/Staring Centrum, Wageningen.

Denys, L., and Baeteman, C. (1995). Holocene evolution of relative sea level and local mean high water spring tides in Belgium—A first assessment. *Marine Geology* **124,** 1–19.

Fletcher III, C. H., Van Pelt, J. E., Brush, G. S., and Sherman, J. (1993). Tidal wetland record of Holocene sea-level movements and climate history. *Palaeogeography, Palaeoclimatology, Palaeoecology* **102,** 177–213.

Gehrels, W. R., and Belknap, D. F. (1993). Neotectonic history of eastern Maine evaluated from historic sea-level data and ^{14}C dates on salt-marsh peats. *Geology* **21,** 615–618.

Gehrels, W. R., Belknap, D. F., and Kelley, J. T. (1996). Integrated high-precision analyses of Holocene relative sea-level changes: Lessons from the coast of Maine. *Geological Society of America Bulletin* **108,** 1073–1088.

Geluk, M. C., Duin, E. J. Th., Dusar, M., Rijkers, R. H. B., Van den Berg, M. W., and Van Rooijen, P. (1994). Stratigraphy and tectonics of the Roer Valley Graben. *Geologie en Mijnbouw* **73,** 129–141.

Gotjé, W. (1993). ''De Holocene Laagveenontwikkeling in de Randzone van de Nederlandse Kustvlakte (Noordoostpolder).'' Unpublished Ph.D. dissertation, Vrije Universiteit, Amsterdam.

Hegi, G. (1957). ''Illustrierte Flora von Mittel-Europa. Band III/1. Teil.'' Carl Hanser, München.

Hofstede, J. L. A., Berendsen, H. J. A., and Janssen, C. R. (1989). Holocene palaeogeography and palaeoecology of the fluvial area near Maurik (Neder-Betuwe, The Netherlands). *Geologie en Mijnbouw* **68,** 409–419.

Jelgersma, S. (1961). Holocene sea level changes in the Netherlands. *Mededelingen van de Geologische Stichting, Serie C* **6**(7), 1–100.

Kearney, M. S. (1996). Sea-level change during the last thousand years in Chesapeake Bay. *Journal of Coastal Research* **12,** 977–983.

Kiden, P. (1995). Holocene relative sea-level change and crustal movement in the southwestern Netherlands. *Marine Geology* **124,** 21–41.

Kidson, C. (1982). Sea level changes in the Holocene. *Quaternary Science Reviews* **1,** 121–151.

Lorenz, G. K., Groenewoud, W., Schokking, F., Van den Berg, M. W., Wiersma, J., Brouwer, F. J. J., and Jelgersma, S. (1991). ''Heden en Verleden. Nederland naar Beneden??? Interim-Rapport over het Onderzoek naar Bodembeweging in Nederland.'' Rijkswaterstaat/Rijks Geologische Dienst, Delft/Haarlem/Rijswijk.

Moore, P. D., Ed. (1984). ''European Mires.'' Academic Press, London.

Nederlands Normalisatie-instituut (1989). ''NEN 5104 Geotechniek. Classificatie van Onverharde Grondmonsters.'' Nederlands Normalisatie-instituut, Delft.

Nelson, A. R., Shennan, I., and Long, A. J. (1996). Identifying coseismic subsidence in tidal-wetland stratigraphic sequences at the Cascadia subduction zone of western North America. *Journal of Geophysical Research* **101,** 6115–6135.

Oberdorfer, E. (1983). ''Pflanzensoziologische Excursionsflora.'' Eugen Ulmer, Stuttgart.

Oele, E., Apon, W., Fischer, M. M., Hoogendoorn, R., Mesdag, C. S., De Mulder, E. F. J., Overzee, B., Sesören, A., and Westerhoff, W. E. (1983). Surveying The Netherlands: Sampling techniques, maps and their applications. *In* ''Special Issue in the Honour of J. D. de Jong'' (M. W. van den Berg and R. Felix, Eds.), *Geologie en Mijnbouw* **62,** 355–372.

Pals, J. P., Van Geel, B., and Delfos, A. (1980). Paleoecological studies in the Klokkeweel bog near Hoogkarspel (prov. of Noord-Holland). *Review of Palaeobotany and Palynology* **30,** 371–418.

Shennan, I., Long, A. J., Rutherford, M. M., Green, F. M., Innes, J. B., Lloyd, J. M., Zong, Y., and Walker, K. J. (1996). Tidal marsh stratigraphy, sea-level change and large earthquakes, I: A 5000 year record in Washington, U.S.A. *Quaternary Science Reviews* **15,** 1023–1059.

Steenbeek, R. (1990). ''On the Balance between Wet and Dry. Vegetation Horizon Development and Prehistoric Occupation; a Palaeoecological-Micromorphological Study in the Dutch River Area.'' Unpublished Ph.D. dissertation, Vrije Universiteit, Amsterdam.

Törnqvist, T. E. (1993). Fluvial sedimentary geology and chronology of the Holocene Rhine–Meuse delta, The Netherlands. *Nederlandse Geografische Studies* **166,** 1–169.

Törnqvist, T. E., and Bierkens, M. F. P. (1994). How smooth should curves be for calibrating radiocarbon ages? *Radiocarbon* **36,** 11–26.

Törnqvist, T. E., De Jong, A. F. M., Oosterbaan, W. A., and Van der Borg, K. (1992). Accurate dating of organic deposits by AMS ^{14}C measurement of macrofossils. *Radiocarbon* **34,** 566–577.

Törnqvist, T. E., Weerts, H. J. T., and Berendsen, H. J. A. (1994). Definition of two new members in the upper Kreftenheye and Twente Formations (Quaternary, the Netherlands): A final solution to persistent confusion? *Geologie en Mijnbouw* **72,** 251–264.

Van den Berg, M. W., Groenewoud, W., Lorenz, G. K., Lubbers, P. J., Brus, D. J., and Kroonenberg, S. B. (1994). Patterns and velocities of recent crustal movements in the Dutch part of the Roer Valley rift system. *Geologie en Mijnbouw* **73,** 157–168.

Van de Plassche, O. (1980a). Holocene water-level changes in the Rhine–Meuse delta as a function of changes in relative sea level, local tidal range, and river gradient. *Geologie en Mijnbouw* **59,** 343–351.

Van de Plassche, O. (1980b). Compaction and other sources of error in obtaining sea-level data: Some results and consequences. *Eiszeitalter und Gegenwart* **30,** 171–181.

Van de Plassche, O. (1982a). Sea-level change and water-level movements in the Netherlands during the Holocene. *Mededelingen Rijks Geologische Dienst* **36,** 1–93.

Van de Plassche, O. (1982b). Significance of a new basal peat date for the trend of Holocene mean sea level rise in The Netherlands. *Geologie en Mijnbouw* **61,** 397–399.

Van de Plassche, O. (1986). Introduction. *In* ''Sea-Level Research: A Manual for the Collection and Evaluation of Data'' (O. van de Plassche, Ed.), pp. 1–26. Geo Books, Norwich.

Van de Plassche, O. (1995). Evolution of the intra-coastal tidal range in the Rhine–Meuse delta and Flevo Lagoon, 5700–3000 yrs cal B.C. *Marine Geology* **124,** 113–128.

Van de Plassche, O., Mook, W. G., and Bloom, A. L. (1989). Submergence of coastal Connecticut 6000–3000 (^{14}C) years B.P. *Marine Geology* **86,** 349–354.

Van der Borg, K., Alderliesten, C., Houston, C. M., De Jong, A. F. M., and Van Zwol, N. A. (1987). Accelerator mass spectrometry with ^{14}C and [10]Be in Utrecht. *Nuclear Instruments and Methods in Physics Research* **B29,** 143–145.

Van der Plicht, J. (1993). The Groningen radiocarbon calibration program. *Radiocarbon* **35,** 231–237.

Van der Woude, J. D. (1985). Two mid-Holocene millenia of swamp forest in the Rhine/Meuse deltaic plain. *Boreas* **14,** 267–272.

Van Dijk, G. J., Berendsen, H. J. A., and Roeleveld, W. (1991). Holocene water level development in The Netherlands' river area; implications for sea-level reconstruction. *Geologie en Mijnbouw* **70,** 311–326.

Van Eck, T., and Davenport, C. A., Eds. (1994). Seismotectonics and seismic hazard in the Roer Valley Graben; with emphasis on the Roermond earthquake of April 13, 1992. *Geologie en Mijnbouw* **73,** 91–438.

Van Geel, B., Hallewas, D. P., and Pals, J. P. (1983). A Late Holocene deposit under the Westfriese Zeedijk near Enkhuizen (Prov. of Noord-Holland, The Netherlands): Palaeoecological and archaeological aspects. *Review of Palaeobotany and Palynology* **38,** 269–335.

Van Montfrans, H. M. (1975). Toelichting bij de ondiepe breukenkaart

met diepteligging van de Formatie van Maassluis. *In* ''Toelichting bij Geologische Overzichtskaarten van Nederland'' (W. H. Zagwijn and C. J. van Staalduinen, Eds.), pp. 103–108. Rijks Geologische Dienst, Haarlem.

Verbraeck, A. (1984). ''Toelichtingen bij de Geologische Kaart van Nederland 1:50.000. Blad Tiel West (39 W) en Blad Tiel Oost (39 O).'' Rijks Geologische Dienst, Haarlem.

Weeda, E. J., Westra, R., Westra, Ch., and Westra, T. (1985). ''Nederlandse Oecologische Flora. Wilde Planten en hun Relaties 1.'' IVN, Amsterdam.

Weeda, E. J., Westra, R., Westra, Ch., and Westra, T. (1987). ''Nederlandse Oecologische Flora. Wilde Planten en hun Relaties 2.'' IVN, Amsterdam.

Weeda, E. J., Westra, R., Westra, Ch., and Westra, T. (1994). ''Nederlandse Oecologische Flora. Wilde Planten en hun Relaties 5.'' IVN, Amsterdam.

Weerts, H. J. T., and Berendsen, H. J. A. (1995). Late Weichselian and Holocene fluvial palaeogeography of the southern Rhine–Meuse delta (the Netherlands). *Geologie en Mijnbouw* **74,** 199–212.

Westhoff, V., and Den Held, A. J. (1969). ''Plantengemeenschappen in Nederland.'' Thieme, Zutphen.