Netherlands Journal of Geosciences / Geologie en Mijnbouw 81 (3-4): 389-405 (2002)

Fluvial deposits as a record for Late Quaternary neotectonic activity in the Rhine-Meuse delta, The Netherlands

K. M. Cohen[1], E. Stouthamer[1] & H.J.A. Berendsen[1]

[1] Dept. of Physical Geography, Utrecht University, Faculty of Geographical Sciences,
Heidelberglaan 2, 3508 TC Utrecht, the Netherlands; e-mail: k.cohen@geog.uu.nl

Manuscript received: July 2001; accepted: February 2002

Abstract

Neotectonic movements have caused differential subsidence in the Lower Rhine Embayment during the Quaternary. The Late Weichselian and Holocene Rhine-Meuse fluvial archive in the central Netherlands was used to quantify neotectonic movements in a setting that was primarily controlled by sea-level rise and climate change. Evidence for neotectonic activity in the central Netherlands is reviewed. Sedimentary evidence shows that fluvial deposits of Late Weichselian and Holocene Rhine and Meuse (Maas) distributaries are vertically displaced along the northern shoulder of the Roer Valley Graben system. Elevation differences in the longitudinal profiles of Late Weichselian terrace deposits were used to quantify tectonic displacements. New results for the southeastern Rhine-Meuse delta (Maaskant area) show that displacements in the top of the Pleniglacial terrace along the Peel Boundary Fault are up to 1.4 m. The maximum displacement between the Peel Horst and the Roer Valley Graben is 2.3 m. This is equivalent to relative tectonic movement rates of 0.09-0.15 mm/yr, averaged over the last 15,000 years.

Keywords: Neotectonics, Fluvial geomorphology, River terraces, Rhine-Meuse delta, Sea-level rise, the Netherlands

Introduction

The Rhine-Meuse delta (Fig. 1) in the Netherlands provides a well-preserved and well-documented fluvial archive. The evolution of the delta during the Late Weichselian (= Weichselian Lateglacial, cf. Mangerud et al., 1974) and Holocene has been extensively studied over the past decades (Berendsen, 1982; Törnqvist, 1993a; Makaske, 1998; Weerts & Berendsen, 1995; Berendsen & Stouthamer, 2000, 2001). These studies mainly focused on two controlling factors in the delta evolution: relative sea-level rise, which controlled base level and provided accommodation space for Holocene aggradation (Törnqvist, 1993b), and climate change, which controlled discharge and sediment supply (Berendsen et al., 1995). Temporal and spatial variation within the deltaic wedge (coastal prism cf. Posamentier et al., 1992; Talling, 1998), such as varying channel width/thickness ratios and fluvial styles, were attributed to these controlling factors and to autogenic controls within the fluvial system, such as heterogeneity in lithology and periodic avulsion of individual distributaries.

The upper Rhine-Meuse delta is located near the tectonic hinge zone (Törnqvist, 1995, 1998; Veldkamp & Tebbens, 2001) along the southeastern margin of the North Sea Basin. In the subsurface the complex Roer Valley Graben (RVG) system (Geluk et al., 1994) is present (Fig. 1). The epicenters of numerous modern and historic, light to moderate earthquakes (e.g. the 1992 Roermond earthquake, local Richter magnitude 5.8), are located along the faults of this Graben system (Camelbeeck & Meghraoui, 1998). Recent results from palaeoseismic studies along faults bordering the RVG indicate that recent activity is not exceptional. Faults in this region have been active during the entire Quaternary, albeit with different movement rates over time.

The Peel Boundary Faultzone (PBF) separates the RVG and the Peel Horst, and is the central zone of displacement in the RVG-system. The PBF is well expressed in the surface topography of the area south of the Rhine-Meuse delta, and is traced in the deposits underlying the delta (Verbraeck, 1984; Zagwijn, 1989). The PBF system has been active in the Late Weichselian and Holocene, and seems to have influenced the evolution of the Rhine-Meuse delta (Berendsen & Stouthamer, 2000; Stouthamer & Berendsen, 2000). The aim of this paper is to review the evidence for neotectonic influence on the fluvial systems in the central Netherlands and to regionally explore the recording potential for neotectonics in the youngest (Late Weichselian-Holocene) fluvial deposits. The structural framework, the Late Quaternary deposits and neotectonics in the Holocene Rhine-Meuse delta are reviewed in the first sections of this paper. In addition, we present new results on the Maaskant area (Fig. 1) in the southeast of the delta: a reconstruction of the Late Weichselian terraces in this area (Fig. 4) and a quantitative analysis of neotectonic deformations in longitudinal profiles across the terraces (Fig. 5).

Neotectonic influence on the fluvial systems in the central Netherlands: a review

Structural framework of the Rhine-Meuse delta

The Roer Valley Graben (RVG) is represented by a 2-km thick sequence of Cenozoic sediments, overlying a fractured Mesozoic and Palaeozoic basement. The structural framework of the system has been described in detail by Geluk et al. (1994). Seismic data suggest that the fault-structure of the RVG originally formed during the Late Carboniferous, and reactiva-

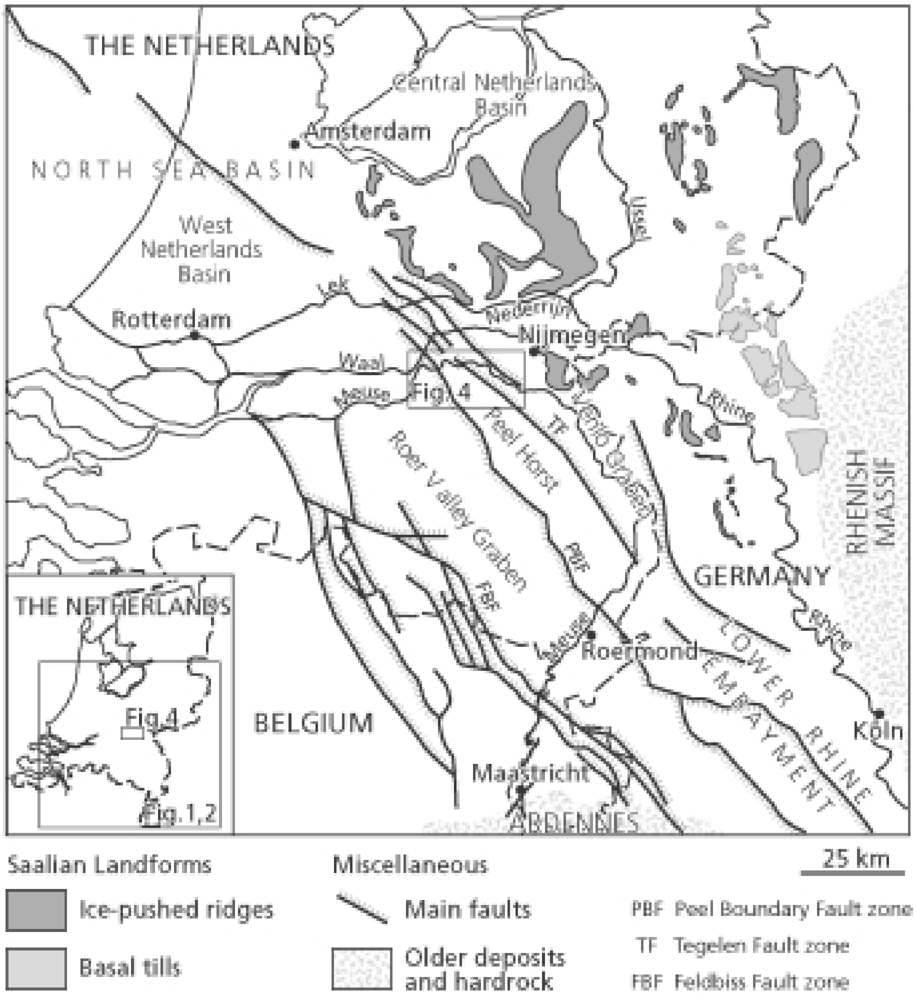


Fig. 1. Structural framework of the central Netherlands (after Zagwijn (1989) and Geluk et al. (1994)). The relatively elevated Peel Horst, and the subsiding Roer Valley Graben and Venlo Graben are part of the Lower Rhine Embayment. To the northwest the Lower Rhine Embayment fades into the North Sea Basin. The Maaskant area is shown in Fig. 4.

tion of these faults occurred during the Mesozoic. In the Cenozoic the RVG-system is part of the Lower Rhine Embayment, the youngest and northwesternmost extension of the continent-scale West and Central European rift system (Ziegler, 1994). Since the Oligocene, tectonics in the RVG-system (and other subsystems of the West and Central European rift system) is related to the redistribution of intra-continental stress (Kooi et al., 1989). This redistribution is part of the changing intra-continental stress regime, caused by the Africa-Europe continental collision that formed the Alps in southern Europe (Dirkzwager et al., 2000).

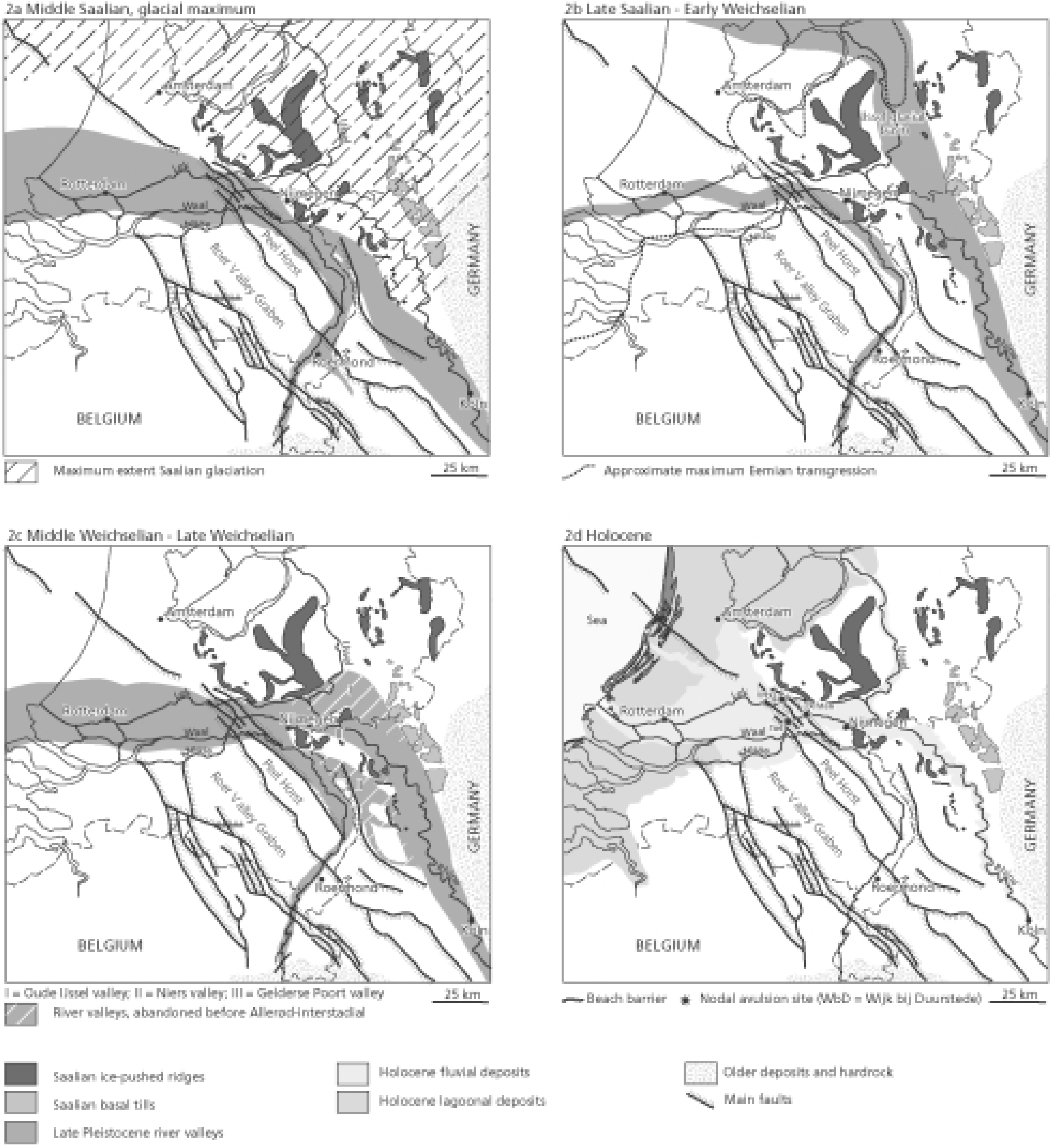
The RVG system consists of several fault blocks, generally separated by faults with a SE-NW strike (Fig. 1). Secondary faults within the blocks have a more E-W strike. Results from seismographic (Van den Berg et al., 1994), backstripping and subsidence analysis (Houtgast & Van Balen, 2000), historic (Alexandre, 1994) and palaeo-seismologic studies (trench-analysis; Camelbeeck & Meghraoui, 1998; Vanneste et al., 1999) indicate that the major faults of the RVG system have been active during the Late Quaternary, and still are active today. Strong differential subsidence within the RVG system started in the Late Oligocene. Since then approximately 1350 m of sediments accumulated in the center of the RVG system and about 200 m on blocks on the shoulders of the Roer Valley Graben (Zagwijn, 1989). The largest Quaternary displacements occurred along the Feldbiss Fault zone (cf. Houtgast & Van Balen, 2000) on the southern shoulder of the RVG and along the Peel Boundary Fault zone (PBF) on the northern shoulder (Van den Berg, 1994; Camelbeeck & Meghraoui, 1998). Houtgast & Van Balen (2000) analyzed the Quaternary stratigraphic record of the RVG and its shoulders. They found minimum displacement rates along the PBF are 50 mm/kyr for the Middle Quaternary (~1.8 to ~0.5 Myr BP) and 80 mm/kyr for the Late Quaternary (since ~0.5 Myr BP).

The structural blocks (Peel Horst, Venlo Graben) on the northern shoulder of the RVG are most important for this study. The PBF is present in the subsurface of the Rhine-Meuse delta, but is not well mapped in the Late Quaternary sediments, because the faults have not been recognized in these sediments. Directly south of the Rhine-Meuse delta, the PBF that separates the relatively elevated Peel Horst and the strongly subsiding RVG (Fig. 1) forms a pronounced scarp in the landscape. To the east, the Venlo Graben is slowly subsiding relative to the Peel Horst. This transition is less sharp expressed in the topography, but is still visible on elevation maps.

The southeastern margin of the North Sea Basin is a tectonic hinge zone, associated with the uplifting Ardennes and Rhenish Massif. The subsequent transgressions and regressions recognized in Miocene, Pliocene and Early Quaternary marine and fluvial sediments in the RVG (Zagwijn, 1989) illustrate the sensitive response to base-level variations of river systems in the tectonic hinge zone on the longer time scale (10^5-10^6 yr). The Ardennes and Rhenish Massif are important sources of sediments filling the deposition centers of the southeastern North Sea Basin. During the Pliocene and Early Quaternary, the West Netherlands Basin and Central Netherlands Basin (Fig. 1) were deposition centers, filled with marine and deltaic fluvial sediments. In these basins, the Rhine and Meuse supplied sediments to the huge delta of the mega river system draining the Baltic area, Fennoscandia and NW Europe into the North Sea Basin (Bijlsma, 1981). During the Quaternary, subsequent glaciation cycles changed the drainage pattern dramatically, and the Baltic river system ceased to exist. Both the Rhine and the Meuse enlarged their drainage basins considerably headwards. They reached their present sizes during the Middle Pleistocene (Quitzow, 1974; Berendsen, 1998).

Since the Early Quaternary, the Roer Valley Graben and Lower Rhine Embayment have been areas of mainly fluvial deposition. In the southeastern part of the Lower Rhine Embayment a flight of 31 Meuse terrace levels spanning the last 4 Myr (Veldkamp & Van den Berg, 1993; Van den Berg, 1996) and a similar flight of Rhine terraces (Klostermann, 1992) have been preserved due to continuous uplift. The terraces formed during the colder periods of the Pliocene and Quaternary. Van den Berg (1994, 1996) used the Meuse terrace flight as a proxy for regional uplift. For the area near Maastricht (Fig. 1), this approach yielded an average uplift rate of 60 mm/kyr over the last 3 Myr, with fluctuations in uplift rates during the Quaternary.

To the northwest, the Lower Rhine Embayment fades into the North Sea basin. The RVG widens into the West Netherlands Basin (Geluk et al., 1994). In this region, the main fault direction shifts about 30° to ESE-WNW. Northeast of the RVG the Late Tertiary Central Netherlands Basin is connected to the Lower Rhine Embayment. Deep glacial scouring and the formation of ice-pushed ridges during the Saalian make detailed analysis of the Quaternary subsidence in the Central Netherlands Basin difficult. The repetitive glaciations of northern Europe, resulted in glacio-isostatic adjustments and is expected to have enhanced tectonics during the Late Quaternary (Stewart et al., 2000; Thorson, 2000; Maddy & Bridgland, 2000).


2a Middle Saalian, glacial maximum

2b Late Saalian - Early Weichselian

2c Middle Weichselian - Late Weichselian

2d Holocene

Fig. 2. Late Quaternary courses of the rivers Rhine and Meuse (essentially after Zagwijn, 1974).

a) Middle Saalian (oxygen isotope stage 6), glacial maximum. During the maximum glaciation, the Rhine followed a course to the west and drained towards the Strait of Dover. Saalian ice reworked the Early and Middle Quaternary deposits of the Central Netherlands Basin.

b) Late Saalian – Early Weichselian. During the Saalian deglaciation the Rhine entered the IJssel glacial basin and drained to the NW. The Meuse presumably continued to drain westward. This situation persisted during the Eemian interglacial (oxygen isotope stage 5e) and Early Weichselian (oxygen isotope stages 5d-4).

c) Middle – Late Weichselian (oxygen isotope stages 3-2). In the Middle Weichselian, the Rhine retook its Saalian imposed course and joined the Meuse downstream of Nijmegen. In the Late Weichselian, the Oude IJssel (I) and Niers (II) valleys were abandoned in favor of the course through the Gelderse Poort (III).

d) Holocene. The Holocene rivers cross the Peel Boundary Fault in the central Netherlands. During the Holocene the Rhine and Meuse distributaries progressively backfilled the Late Weichselian valleys. West of the PBF in the Roer Valley Graben / West Netherlands Basin, a coastal wedge formed on top of the backfilled sequence.

Rhine and Meuse courses during the Late Quaternary

In the Late Quaternary, the Rhine and Meuse rivers crossed the Peel Horst west of Nijmegen (Figs. 1, 2). The depositional record of the RVG system shows that this situation is exceptional: Early and Middle Quaternary fluvial deposits reach their greatest thickness in the Roer Valley Graben (Zagwijn, 1989), indicating that this is the main deposition center. During earlier parts of the Quaternary the Rhine periodically entered the RVG in the southeast of the Netherlands, but during most of the time the Rhine did not enter the RVG at all, following a course more to the east through the Lower Rhine Embayment and the Central Netherlands Basin. The Meuse alternately flowed through the RVG and the Venlo Graben. Van den Berg (1994) suggested that the Quaternary Rhine periodically shifted its course during phases of increased tectonic activity in the Lower Rhine Embayment. During such periods the interplay between foreland compression from the Ardennes and the regional SW-NE tension in the RVG-system would have forced structural blocks to rise and tilt and the Rhine to shift its course.

Eventually, Late Quaternary glaciations have caused the Late Weichselian and Holocene Rhine and Meuse to cross the Peel Horst and enter the RVG almost perpendicular to the tectonic structures, creating the exceptional setting. In the Late Quaternary local deposits filled the RVG and neither the Rhine nor the Meuse flowed through it (Fig. 2). During the Saalian glaciation, the Scandinavian ice-sheets reached the Rhine valley. During its maximum extent, the Saalian ice sheet formed a series of ice-pushed ridges and deep glacial-basins, reworking the Early to Middle Quaternary fluvial sediments (Fig. 2a). During maximum glaciation the Rhine and Meuse were forced to flow westward, directly south of the ice-pushed ridges. During and after the Saalian deglaciation the Rhine entered and partly filled up the IJssel glacial basin (Fig. 2b), but in the Middle Weichselian this course was abandoned (Van de Meene & Zagwijn, 1978). An Eemian-Early Weichselian hiatus in the Late Quaternary Rhine depositional record in the West Netherlands Basin was inferred by Törnqvist et al. (2000) using O.S.L. dating. In the Early-Middle Weichselian, the Rhine reoccupied its western course, eroded the ice-pushed ridges near Nijmegen and joined the Meuse downstream (Fig. 2c). It is unclear what mechanism triggered this Weichselian shift of the Rhine back to its Saalian, glacially imposed, course. A possible mechanism is deflection of the Rhine to the southwest, by an updoming fore bulge created by the load of the Weichselian ice cap. During the Weichselian Glacial Maximum, the nearest ice was located ca. 250 km to the NE (Elbe valley, Germany) and ca. 250 km to the NW (Norfolk, England). During the Holocene, the main Rhine-Meuse channels flowed westward (Fig. 2d), and only in the Late Holocene one distributary reentered the IJssel valley.

The Rhine-Meuse delta in the Late Weichselian and the Holocene

The location of the present Holocene Rhine-Meuse delta (Fig. 2d) is largely inherited from the positions of the Late Weichselian Rhine and Meuse valleys (Berendsen & Stouthamer, 2000). Holocene deltaic fluvial deposits are preserved behind a beach barrier coast. These deposits cover the Weichselian Lateglacial valley of the Rhine and Meuse in the subsurface. They reach a thickness of 20 m near the coast, and about 2 m near the German border (Fig. 3). In the western parts of the delta marine erosion of the older fluvial deposits has occurred. In the lower Rhine-Meuse delta, floodbasin fills consist largely of fresh water peat. Directly behind the barriers brackish clay deposits of (tidal) lagoonal environments occur. In the upper Rhine-Meuse delta, floodbasin fills mainly consist of fluvial clay. Sandy channels cross cut the floodbasin deposits. The Holocene evolution of the delta has been described extensively by Berendsen & Stouthamer (2000, 2001).

During the Late Pleniglacial – Early Holocene rivers formed a series of terraces, as a result of climatic changes (24–9 kyr BP, calendar years are used in this paper, unless indicated differently). The Meuse fluvial pattern changed from braided during the Late Pleniglacial to meandering in the Bølling-Allerød interstadial, to braided during the Younger Dryas stadial, and back again to meandering in the Early Holocene (Huisink, 1997; Tebbens et al., 1999). Similar changes are reported for the Rhine Valley and are inferred from deposits in the subsurface of the Rhine-Meuse delta, although the fluvial style of Lateglacial rivers in the western part of the delta has never been established with certainty.

The difference in elevation between the Late Pleniglacial and Younger Dryas terraces reaches a maximum of 2 meters in the subsurface of the central Rhine-Meuse delta (Berendsen et al., 1995). The terraces converge downstream (Törnqvist, 1998; Berendsen & Stouthamer, 2001). The Lateglacial rivers followed a course through the southern North Sea and the English Channel (Bridgland & D'Olier, 1995). During the formation of the terraces, sea level was >50 m lower, and the coastline was located downstream of the Strait of Dover (Gibbard, 1995). In the Late Weichselian, hard rock in the Strait of Dover (at 40-50 meters below present sea level) probably controlled base level of the Rhine and the Meuse in the Netherlands. In that case it seems reasonable to assume that sea-level rise did not influence the formation of the Lateglacial terraces, because they are located 200-300 km upstream from Dover and are at a 60 m higher elevation. Vandenberghe (1995) and Berendsen et al. (1995) attribute the formation of the terraces to the Lateglacial climatic amelioration, which resulted in changes in sediment load and discharge. In contrast to the terrace flight in the southern part of the Lower Rhine Embayment, elevation differences between these climate-controlled terraces are not necessarily directly related to tectonic uplift of the area.

During the first half of the Holocene, the Southern North Sea Basin was rapidly flooded (Jelgersma, 1979; Zagwijn, 1986). Rising sea level provided accommodation space for the deltaic deposits. An open barrier coast in front of the Holocene delta transgressed and progressively truncated the Rhine-Meuse valley. After ~5.5 kyr BP, sea-level rise slowed down, the barrier coast closed and coastal progradation set in (Zagwijn, 1986; Van der Valk, 1992; Cleveringa, 2000). Offshore of the present coast, Early Holocene deposits in the backfilled Late Weichselian valleys have been eroded by waves and tidal currents in the shallow sea during the marine transgression (Jelgersma, 1979; Beets & Van der Spek, 2000). In the deltaic wedge behind the barrier coast, preservation potential was high, and only locally estuarine and fluvial erosion has occurred (Berendsen & Stouthamer, 2000).

The fluvial style of the Holocene distributaries varies in time and space (Törnqvist, 1993a,b; Makaske, 1998). Sandy channel deposits in the delta have a decreasing width/thickness ratio and decreasing gradient towards the coast (Berendsen & Stouthamer, 2001). The channels frequently avulsed during the period 7.8-0.9 kyr BP (Törnqvist, 1994; Stouthamer & Berendsen, 2000). The combination of rapid base-level rise, extensive peat formation and frequent avulsion makes dating of individual channel belts well possible. Over 1200 ^{14}C samples have been collected and dated by various authors, and are summarized by Berendsen & Stouthamer (2001). ^{14}C-dates of basal peat covering the steep flanks of isolated Younger Dryas aeolian dunes can be used to reconstruct the regional rise of groundwater. The buried aeolian dunes provide a compaction-free subsurface where the basal peat occurrence is directly related to the floodbasin groundwater level. Near the present coast, peat started to form approximately 9.0 kyr BP. Further eastward, on the sloping Late Weichselian subsurface, peat formation started later, and the groundwater level in the central delta was fluvially controlled (Fig. 3). Because basal peat forms when the average groundwater level is just above the surface, and groundwater level rise in the delta is directly related to base-level rise, the derived groundwater gradients also represent longitudinal gradients of fluvial deltaic sediments in floodbasins (Van Dijk et al., 1991).

Neotectonics in the Holocene delta

Evidence for neotectonic influences in the Holocene delta and its Late Weichselian subsurface has accumulated in recent years. Indications for neotectonics are:

- *Deformation of longitudinal profiles of fluvial deposits.* Deformations can be quantified by reconstructing gradient lines of the top of sandy channel deposits (GTS-lines, cf. Stouthamer & Berendsen, 2000) and by comparing them for deposits of different ages. Verbraeck (1990) constructed a gradient line of a 30-cm thick fluvially deposited pumice layer of the Laacher See eruption 13.1 kyr BP (11,063 ± 12 ^{14}C yr BP, Friedrich et al., 1999) within the deposits of the Allerød-Rhine (Fig. 3). This gradient line shows a deformation where the river crossed the Peel Horst. Deformed longitudinal profiles of Lateglacial terraces (Fig. 3) and Holocene channel belts in the central part of the delta show non-linear displacements of 1-2 m over the last 15 kyr (Stouthamer & Berendsen, 2000). The Weichselian Meuse valley in the southern Netherlands, upstream of the Rhine-Meuse delta (Fig. 2d), is comparable to the Late Weichselian subsurface in the central Netherlands. Van den Broek & Maarleveld (1963) mapped the upstream Meuse valley and constructed longitudinal profiles that show a vertical displacement of 1.5 m in the Late Saalian and Middle Weichselian terraces, this is attributed to post-depositional deformation along the PBF.
- *Differential rates of shifting of the terrace intersection of the Pleniglacial terrace and the Holocene deposits*. During the Holocene, delta deposits back-filled the Lateglacial valley. Dates of basal peat directly overlying the Late Weichselian terrace in the subsurface mark the onset of aggrading floodbasin conditions and are used to trace the shifting terrace intersection (Stouthamer & Berendsen, 2000). Near Tiel in the central delta basal peat formation starts ~6.8 kyr BP (Fig. 3). South of Tiel, basal peat formed earlier compared to the north. This implies that the Holocene terrace intersection was stalled in the

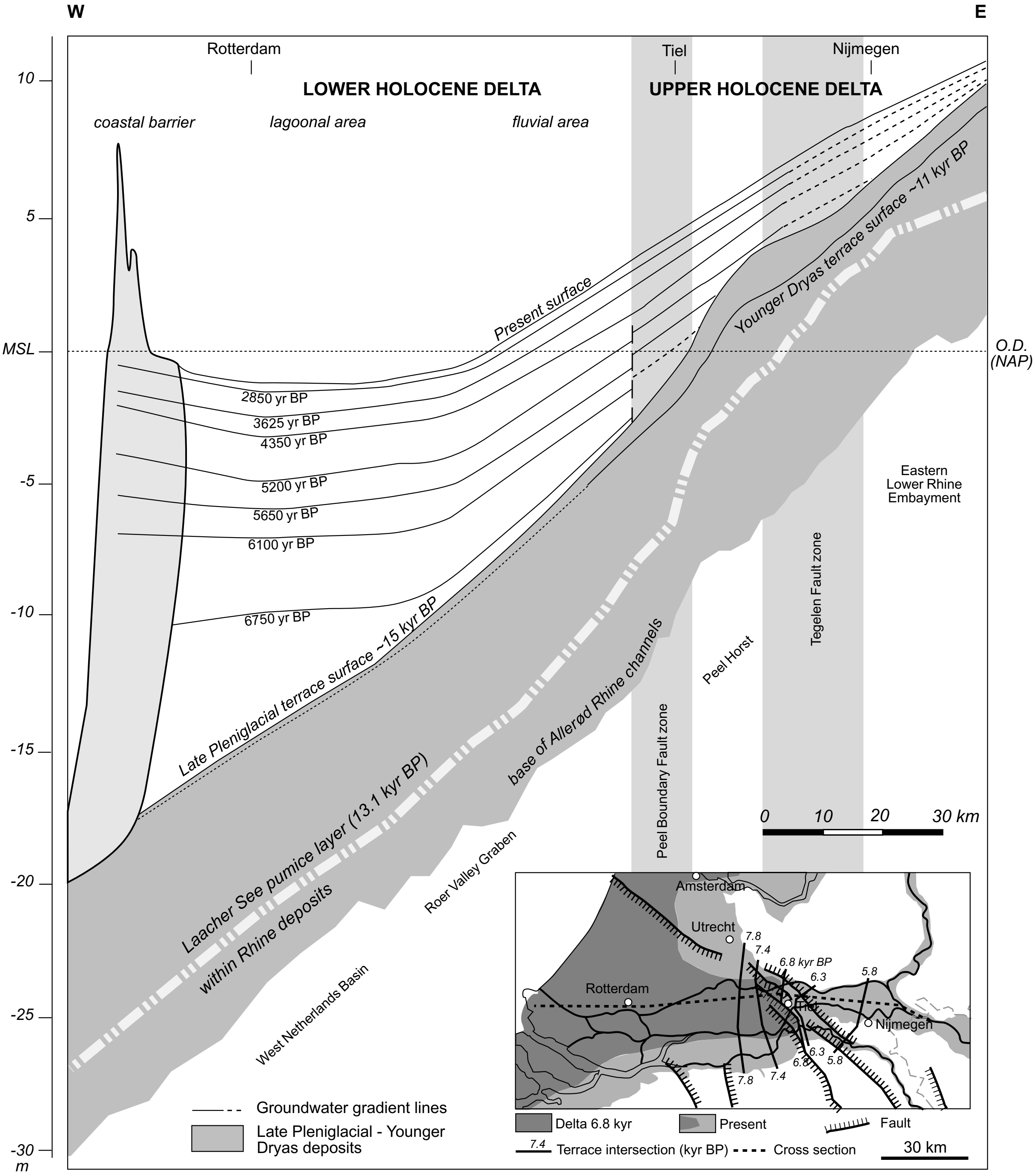


Fig. 3. Neotectonic deformations in gradient lines of Late Weichselian fluvial sediments and Holocene floodbasin groundwater levels in the Rhine-Meuse delta. Late Pleniglacial and Younger Dryas buried terraces – the highest elevations of sand-gravel bars that form the terrace surface are plotted – after Stouthamer & Berendsen (2000). Depth of Laacher See pumice-layer and base of Allerød channels – as preserved in the subsurface of the Younger Dryas terrace – after Verbraeck (1990). Palaeo groundwater levels, after Van Dijk et al. (1991). Groundwater levels in the PBF zone modified after Törnqvist et al. (1998). Location of terrace intersection after Berendsen & Stouthamer (2000, 2001). All ages in calendar years. Dutch Ordnance datum (N.A.P.) ~ MSL.

Middle Atlantic: Holocene channels no longer intersected the Lateglacial valley as a front parallel to the coast or tangential to palaeoflow direction. Stouthamer & Berendsen (2000) conclude that the SE-NW oriented topographic barrier of the Peel Horst temporarily decelerated the upstream shift of the terrace intersection, which at ~6.8 kyr BP became aligned to this tectonic structural element (Fig. 3).

- *Differential aggradation rates.* Reconstruction of the floodbasin aggradation rates using basal-peat age/depth relations indicates neotectonic displacements within the Holocene floodbasin deposits in the central part of the delta (Törnqvist et al., 1998; Fig. 3).

Peat is abundant in the floodbasins in the western delta, but rapidly thins eastwards. This can be explained partly by the eastward narrowing of the delta, resulting in smaller floodbasins with more clastic deposits, but it is also due to subtle differences in floodbasin aggradation rates of the Roer Valley Graben and the Peel Horst areas (Berendsen & Stouthamer, 2001).

- *Distribution of avulsion sites.* Avulsion is the abandonment (or partial abandonment) of a channel belt in favor of a new course (Allen, 1965; Stouthamer, 2001). Avulsion occurs randomly along a channel, when in-channel sedimentation has outrun floodbasin sedimentation, and the gradient of a new course through the floodbasin is in favor of the old downstream gradient. Reconstruction of the different generations of aggrading channel belts in the Holocene delta has revealed the distribution of avulsion locations within the last 7.8 kyr. In the period 5.6-1.6 kyr BP, 83% of the avulsion locations are located in the PBF and Tegelen fault zones (Stouthamer & Berendsen, 2000). At some of these locations channel belts avulsed more than twice during the Holocene: random avulsions are clustered at the nodal sites Tiel, Wijk bij Duurstede and Ochten (Fig. 2d). These nodal sites mark the transition of the upper Rhine-Meuse delta to the lower Rhine-Meuse delta and coincide with the PBF and Tegelen Fault zones (Stouthamer & Berendsen, 2000). The concentration of avulsions in the central delta is explained by the stalled backfilling and differential aggradation rates mentioned above: The neotectonic component in relative subsidence is larger in the lower delta than in the upper delta. This increases floodbasin gradients in the upper-lower delta transition zone, making it the most favorable avulsion location.

New results from longitudinal profiles in the Maaskant area

Field data

The Maaskant is the part of the Rhine-Meuse delta that directly borders the Peel Horst (Fig. 4). Longitudinal profiles of Late Weichselian terraces in the Maaskant were created to trace and quantify neotectonic deformations in the youngest sediments. The source data for this study is a subset of >4000 hand corings selected from the database of the Department of Physical Geography, Utrecht University (Berendsen & Stouthamer, 2001), containing over 200.000 lithological borehole descriptions. Cores were described in the field at 10-cm intervals with regard to texture, grain size, gravel content, organic matter content, color, Fe-oxide content, $CaCO_3$ content, groundwater levels, (palaeo-) soils, stratigraphy and other characteristics. The standard error in combined surface elevation and depth within a borehole description is 0.15 m. Prior to constructing the longitudinal profiles, the palaeogeography of this area was reconstructed in detail.

The Maaskant area (ca. 135 km^2) is bordered by the embanked floodplain of the River Meuse in the north, west and east. The Meuse channel is highly sinuous, but during the 20th century many meanders have been cut off for water management and navigation reasons. In the Maaskant, the Late Weichselian fluvial terraces are partly covered by Lateglacial aeolian dunes and coversands. Holocene Meuse channels locally eroded Late Weichselian sediments and Holocene floodbasin peat and clays partly cover the Late Weichselian subsurface.

Reconstruction of Late Weichselian palaeogeography

In the western part of the study area, Holocene floodbasin sediments are up to 6 m thick and the Pleistocene subsurface occurs at 1-2 m below Dutch Ordnance datum (~ mean sea level). In the east of the study area the Holocene floodbasin deposits are 2-3 m thick and the top of Pleistocene deposits is at 4-5 m above O.D. In the southern part of the Maaskant, the Holocene deposits wedge out to zero thickness, and coversands occur at the surface (Fig. 4).

Four Late Weichselian terrace levels were recognized (Fig. 4). Residual channel fills in the terraces are abundant in the area, some contain datable organic deposits, but few have been dated in this region. Therefore our age control for the four recognized terrace levels is based on stratigraphic correlation. Upstream in the Meuse valley a very similar series of four terraces is found (Huisink, 1997, 1999a; Tebbens et al., 1999) and well dated. Our age estimates are based on the very similar lithostratigraphy of the terraces in that region. The four terrace levels are dated there as Middle Pleniglacial, Late Pleniglacial, Bølling/Allerød and Younger Dryas respectively, although the exact dates (± 0.6 kyr) of the formation, abandonment and style transitions within the latter two terrace levels has been debated (Tebbens et al., 2000). For reasons of convenience, in this paper we will use the chrono-stratigraphy to name the terraces.

In the study area, the four terraces were discriminated on the basis of elevation, terrace-surface morphology (channel scars), stratigraphy and lithology of the terrace fragments. The Middle Pleniglacial terrace

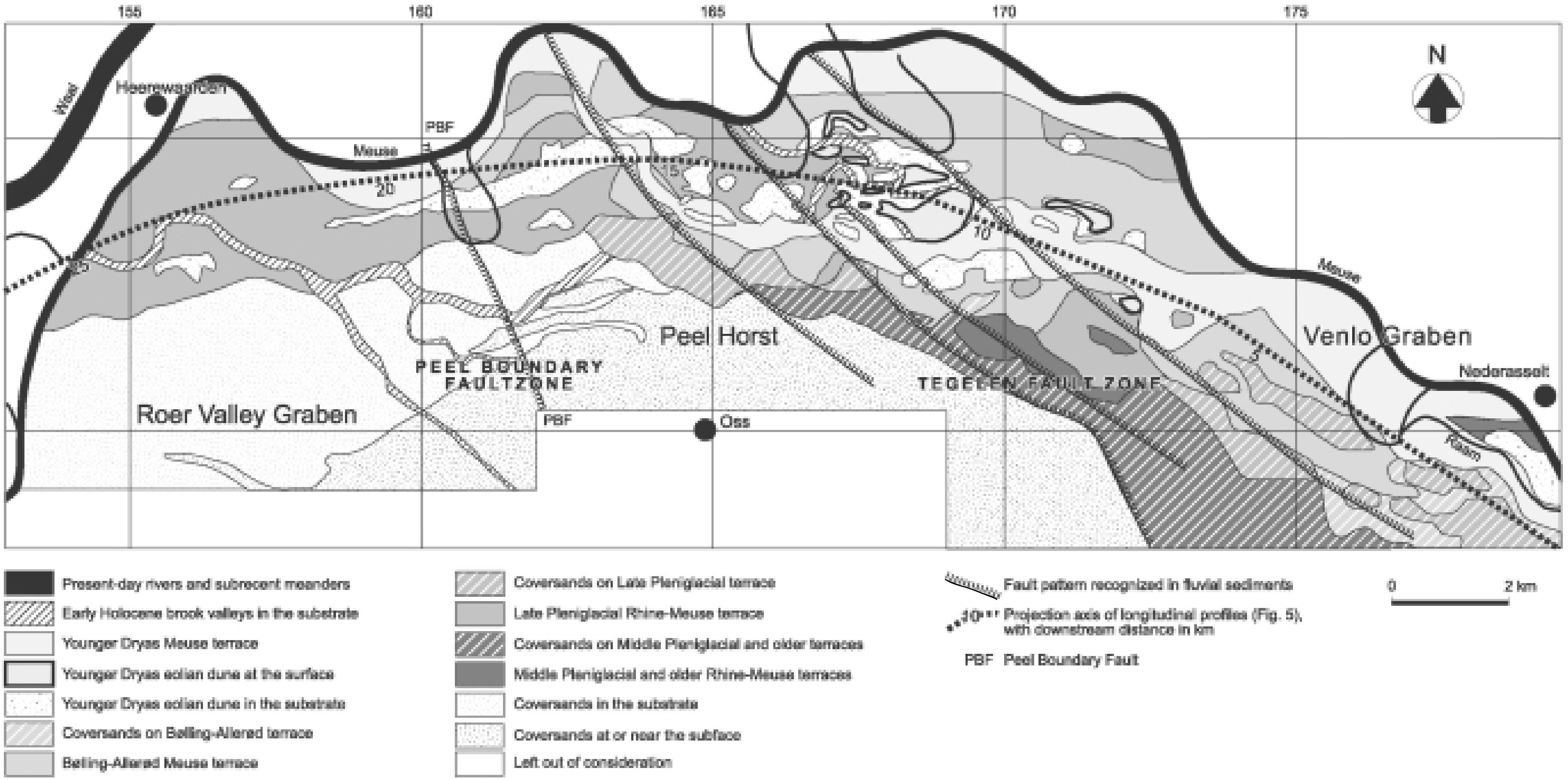


Fig. 4. Geological-geomorphological map of the Maaskant area. At least four buried terrace levels can be recognized, that are correlated to terraces in the north (Berendsen et al., 1995) and east (Huisink, 1997). Coversands overlie the older terraces. Holocene fluvial deposits overly the younger terraces. Younger Dryas inland dunes occur mainly to the NE of Younger Dryas channels. The Bølling/Allerød and Younger Dryas river courses were deflected around the upthrown Peel Horst. Neotectonic fault-activity as expressed in Weichselian and Holocene sediments, occurred along a single fault in the Peel Boundary Fault zone and along a series of faults in the Tegelen Fault zone.

is the highest elevated terrace and is generally overlain by coversands. In the borehole descriptions the Middle Pleniglacial terrace is not clearly recognized because its fining upward surface grades into overlying coversands. Still, in many boreholes in the east of the study area, we found a sharp transition of fine coversands to much coarser fluvial sand and gravel, plotting above the lower terrace levels, that are easier recognized because they are covered with loam (see below). It is uncertain how many Middle Pleniglacial and older levels are present in the data. In the eastern part of the Maaskant, the level can be followed upstream to Pleniglacial and older levels found in the Meuse Valley (Huisink, 1999b; Tebbens et al., 1999). Downstream in the central Maaskant area, pre-Weichselian fluvial deposits locally form the higher terrace level. Because of the large discontinuity and lacking age control, we did not construct longitudinal profiles for the highest level.

The lower three terraces (Late Pleniglacial, Bølling/Allerød, Younger Dryas) are covered by a 0.2-0.8 m thick silty clay and loam layer. This loam layer is a Late Weichselian – Early Holocene floodplain deposit, described as the Wijchen Member of the Kreftenheye Formation (cf. Törnqvist et al., 1994). It is widespread in the entire Rhine-Meuse delta. The Wijchen Member formed during the Late Weichselian and Early Holocene as an overbank deposit on abandoned terraces during floods from incised younger rivers and forms a diachronic marker. During the Bølling/Allerød interstadial fluvial style changed from braided to meandering. The Bølling/Allerød level is discriminated from the Late Pleniglacial braided terrace by its lower elevation and the presence of curved, meandering channel scars.

Inland dunes have developed during the second half of the Younger Dryas (Berendsen et al., 1995; Kasse, 1995). Usually a thin Wijchen Member loam is found underlying the dunes. Younger Dryas channels were the source area for these dunes – Younger Dryas dunes rarely cover Younger Dryas terraces, they generally cover the older terraces (Fig. 4). When a Wychen Member loam is intercalated between dune and terrace deposits, it indicates a Late Pleniglacial-Allerød age of the terrace. The Younger Dryas terrace level is found at the lowest level. Locally Wijchen member deposits can be absent in the Younger Dryas valleys, because Early Holocene channels flowed through the valley and laterally reworked the deposits. In the Maaskant area, a narrow Younger Dryas valley (0.5-0.8 km wide) was traced in the eastern and central parts (Fig. 4). The narrow Younger Dryas valley was either formed by the Younger Dryas River Raam (cf. Pons, 1957) or as a secondary channel of the Meuse. During the Early-Middle Holocene the small River Raam flowed through this valley. The main Younger Dryas Meuse valley was located in the northeast, outside the study area (Berendsen et al., 1995). In this main Younger Dryas valley deep Early Holocene Meuse incisions occur (Berendsen et al., 1995), but there is no indication for deep Early Holocene incision by the Meuse in the study area. The southern edge of a ~1.5 km wide Younger Dryas valley roughly coincides with the location of the present Meuse channel along the north of the Maaskant (Fig. 4).

Construction of the longitudinal profiles

Longitudinal profiles of Late Weichselian terraces were made to test the hypothesis of the influence of neotectonics on fluvial sedimentation in the Rhine-Meuse delta. To account for the irregular terrace topography, and to reduce variance in the data set, we selected the local maxima of the tops of sandy channel deposits to construct the longitudinal profiles (GTS lines, cf. Berendsen & Stouthamer, 2000). These points are presumed to represent the upper levels of sand-gravel bars in the rivers that formed the terraces. The reconstructed gradient lines can be related to the river gradient at bankfull discharge (Berendsen & Stouthamer, 2000). We projected the selected points on a curved central axis for each terrace, and then collapsed the four profiles to one mean axis through the study area (Fig. 4). We manually selected reaches of 4-10 km length that showed different trends, and calculated the gradients by linear regression. For each selected reach, cross-sections perpendicular to the projection axis were used to verify litho-stratigraphic evidence for the different terrace levels, thus excluding propagated effects of errors in the palaeogeographic reconstruction. In the eastern part of the Maaskant, fragments of the Late Pleniglacial, Bølling/Allerød and Younger Dryas terrace levels are preserved. In the western part only the Late Pleniglacial level is widely preserved: the downstream continuations of the younger terraces are located to the north, outside the study area. Longitudinal profiles and gradients for the terrace levels and the Late Holocene Meuse are shown in Fig. 5.

Deformations of longitudinal profiles

The longitudinal profiles (Fig. 5) show deformations that can be attributed to neotectonic movements during and after the formation of the terrace levels. Neotectonics seem to have influenced the profiles in three ways:

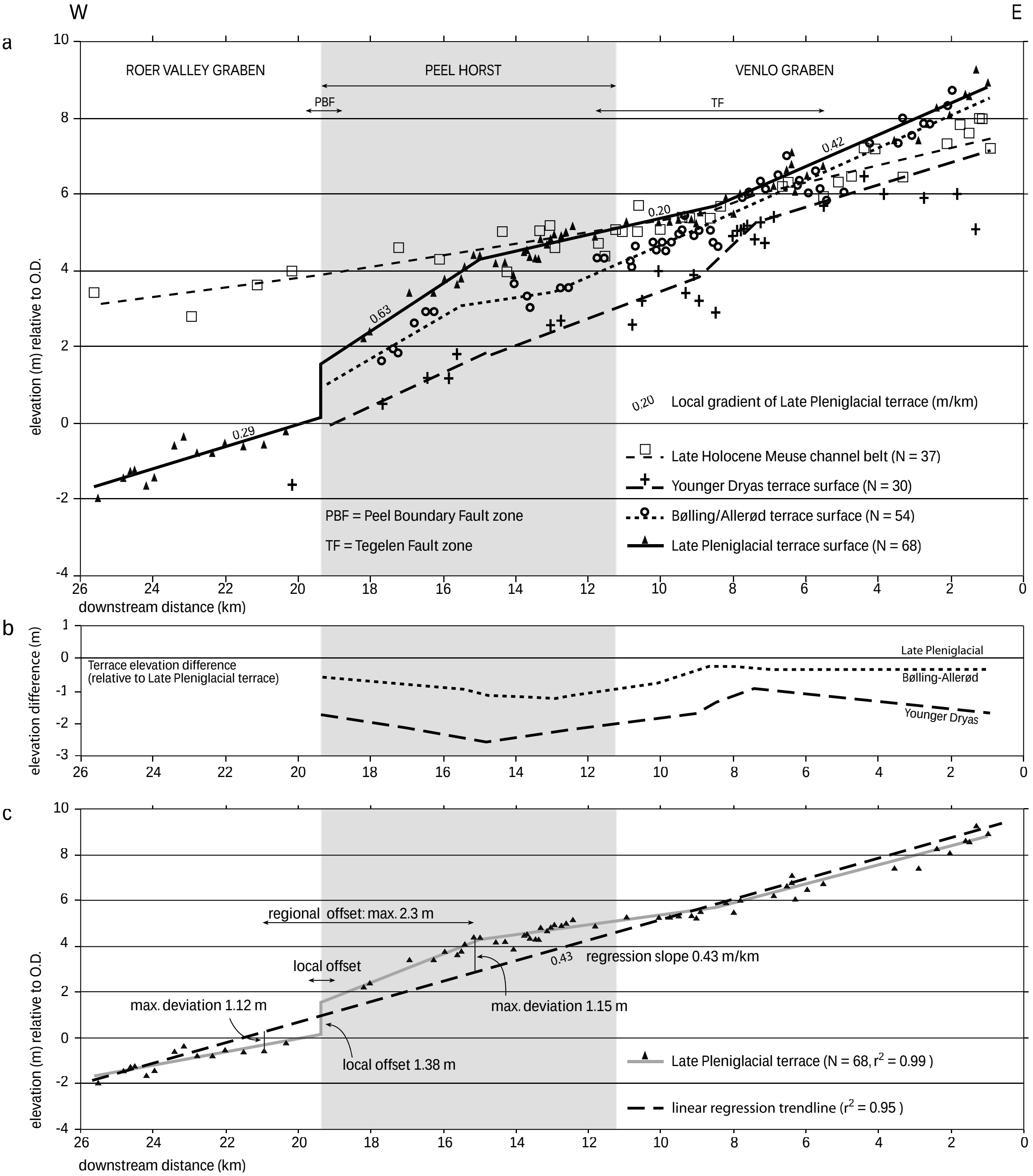


Fig. 5. Longitudinal profiles of Lateglacial terrace surfaces in the Maaskant. The highest elevations of sand-gravel bars are plotted. The profiles are deformed as they cross the Peel Horst.

a) Deformed gradient lines of the Late Pleniglacial, Bølling/Allerød and Younger Dryas terraces compared to the Late Holocene profile of the river Meuse.

b) Relative difference in elevation of the Lateglacial terrace surfaces

c) Quantified local and regional displacements in the Late Pleniglacial terrace. The local displacement is the offset at the main fault. The regional displacement was estimated from the largest deviations from a linear trend.

(1) The Weichselian Lateglacial longitudinal profiles (Fig. 5a) show deformations both as an abrupt step (at x=20) and as a bulge (east of x=20). The profile of the Late Holocene Meuse does not show any deformation. This leads us to believe that the irregularities are mainly caused by post-depositional neotectonic deformation. The sharp displacement at x=20 is interpreted as the PBF,

and indicates that the main displacements between the RVG and the Peel Horst in this region occurred along one single fault (or a very narrow fault zone). The irregularities in the eastern parts of the profiles are interpreted to be caused by neotectonic movements in the Tegelen Fault zone. Displacements are smaller than along the PBF, and probably occurred along more than one fault (Fig 5). Due to the oblique crossing of the terraces through this fault zone, the transition between the Peel Horst and Venlo Graben is less abrupt.

(2) Differences in relative elevations of the three Weichselian Lateglacial terraces (Fig. 5b) reach a maximum in the central part of the study area. This reflects the differences in relative movement rates between the Peel Horst and the Venlo Graben in the period between the Late Pleniglacial and the onset of the Holocene.

(3) Local gradients of the Late Pleniglacial terrace (Fig. 5a) generally are highest in the central area (0.63 m/km), and lowest in the west (0.29 m/km). In the east, gradients are intermediate and show more variation (0.20-0.51 m/km). The Bølling/Allerød and Younger Dryas terraces show similar variations. In contrast, the Late Holocene Meuse is decreasing from 0.23 m/km in the east to 0.11 m/km in the west: a normal concave-up longitudinal profile controlled by sea level, without indication of tectonic deformation in the active river gradient. The absence of deformation in the present river, compared to the convex-up trend in the Weichselian Lateglacial terraces leads us to believe that the steeper gradients in the central part are mainly caused by post-depositional neotectonic deformation.

Additional neotectonic indications

Additional indications for neotectonic influence on fluvial sedimentation have to be taken into account to localize the position of faults and quantify the deformations in the longitudinal profiles. From the palaeogeographic reconstruction a number of additional indications was deduced:

(1) *Deflected Meuse valleys.* During the Pleniglacial, the Rhine and Meuse joined their courses upstream of the Maaskant area (Fig. 2c). The general orientation of the Weichselian Meuse was SE-NW, aligned to the Venlo Graben (Fig. 4). The Pleniglacial Rhine had an E-W flow direction through the Niers valley, but abandoned this course before the end of the Allerød (Van de Meene & Zagwijn, 1978; Berendsen et al., 1995), and took a new course through the Gelderse Poort (Fig. 2c). Since that time the Rhine joined the Meuse near Tiel (Fig. 2d). Within the Pleniglacial valley, the incised series of Bølling/Allerød, Younger Dryas and Early Holocene Meuse-valleys show a progressive shift towards the northeast. In the eastern part of the Maaskant the transitional Bølling/Allerød terrace is preserved, with a single narrow Younger Dryas valley incised in it. Further to the northeast a Bølling/Allerød terrace was never recognized, Younger Dryas valleys are wider and Early Holocene incision is present (Berendsen et al., 1995). This northeastward deflection (cf. Holbrook & Schumm, 1999) seems to be caused by the subsidence of the Venlo Graben and the relative uplift of the Peel Horst. A similar deflection is observed within the stacked Cromerian-Weichselian Meuse-deposits of the Peel Horst and Venlo Graben, which is a response to tilting of the blocks (Van den Berg, 1996). The larger Late Weichselian Meuse channels cross the Peel Horst, but upstream of the Peel Horst smaller Meuse channels in the Venlo Graben rejoin the larger Meuse channels. Downstream of the Peel Horst, where the Allerød, Younger Dryas and Holocene channels of Rhine and Meuse joined, no deflections could be recognized.

(2) *Fault-related alignments of terrace margin scarps.* In the eastern part of the study area, the Meuse crosses the fault zone between Venlo Graben and Peel Horst at a low angle. Differences in bank substrate on both sides of the faults promoted downstream migration of the braided river in favor of lateral migration, and aligned the terraces to the fault pattern. Late Holocene, westward migrating meanders of the Meuse are aligned to the same faults. Part of these Holocene alignments might be the result of differences in bank material due to the inherited terraced subsurface. Independent indications for the presence of faults along these alignments are hydro-chemical features such as iron oxides far below the groundwater table. In the eastern Maaskant many corings with such characteristics were found along these alignments.

(3) *Preservation of terrace remnants.* In the eastern part of the study area, terrace fragments are frequently preserved as islands within younger channels, while further downstream less fragments occur. A similar pattern of preservation is found in the upstream Meuse valley near Roermond (Fig. 1), where the Meuse also crosses the Peel Horst: maps show a straight and narrow Weichselian val-

ley across the Peel Horst, and a much wider valley with meanders both upstream and downstream of this reach. Van den Broek & Maarleveld (1963) attribute the change in valley width to neotectonic influence. Coversands and Younger Dryas aeolian dunes generally overlie the Pleniglacial and older terrace remnants. The spatial distribution of dunes reflects the spatial distribution of underlying terrace fragments. Dune complexes are much smaller in the west than in the central and eastern parts (Fig. 4). In the Maaskant, the spatial distribution of dunes indicates a dissected, multiple terrace level valley in the east, and a single terrace level in the west. Channels in the subsiding setting of the RVG were more effective in eroding laterally compared to their upstream parts in the relative uplifted setting of the Peel Horst. The Wijchen Member on the Late Pleniglacial terrace in the central Maaskant is very thin, compared to the area further north. Stouthamer & Berendsen (2000) attribute this to a relatively elevated position during the deposition of the overbank loam.

Quantifying neotectonics from longitudinal profiles

Neotectonic deformations can be quantified using relative displacements within the longitudinal profiles (Table 1). The Pleniglacial terrace is the best-preserved terrace over the whole study area and used for quantitative analysis. The offset along the PBF is 1.38 ± 0.21 m for the Late Pleniglacial terrace (Fig. 5c). This *local* offset is a minimum estimate for the displacement of the Peel Horst relative to the RVG. The *regional* relative displacement is the tectonic offset between the most upthrown and most downwarped locations. This includes effects of tilting and movements along unrecognized minor faults, and can be considered a maximum estimate of differential movements. To estimate this regional displacement, an initial profile needs to be assumed. The shape of this initial profile is arbitrary. In our case we cannot simply use the present profile as an initial profile (see Discussion). We quantified neotectonic displacements using a linear regression over all datapoints of the Late Pleniglacial terrace (Fig. 5c) that was abandoned 15 kyr BP (Berendsen et al., 1995; Huisink, 1997). Systematic deviations from the regression represent the displacements since 15 kyr BP. Summing the largest deviations on both sides of the PBF results in a maximum displacement of 2.28 ± 0.36 m. For the Peel Horst – Venlo Graben transition, a maximum value of 1.61 ± 0.36 m was found.

The use of an initial linear profile implies that deformation only occurred after deposition. This is not necessarily true, because the profile may initially have been slightly convex-up. In that case the relative displacements are smaller than the maximum values that we quantified. Averaged over 15 kyr rates of relative displacement are 0.09-0.15 mm/yr for the Peel Boundary Fault and 0.02-0.11 mm/yr for the Tegelen Fault zone (Table 1). For the area north of the river Waal, Stouthamer & Berendsen (2000) and for the southern part of the Netherlands, Geluk et al. (1994), Van den Berg (1994, 1996) and Houtgast & Van Balen (2001) reported similar values, based on independent data.

Discussion

Quaternary fluvial terraces are frequently used to quantify tectonic rates. Rates are usually based on elevation differences between the surfaces and/or bases of subsequent terrace levels that are related to cyclic Quaternary glaciations. Along the Meuse near Maastricht (Fig. 1), Van den Berg (1994) used this approach, yielding mean tectonic rates for the Late Tertiary and Quaternary. Age differences between subsequent Quaternary terrace levels are 100-500 kyr, and reconstructed tectonic rates are mean rates over periods covering a similar time. In contrast, we focussed

Table 1. Relative displacement rates quantified from deformations of the longitudinal profile of the Late Pleniglacial terrace.

Late Pleniglacial terrace (abandoned 15 kyr BP)	Relative displacement (m)		Displacement rate (mm/yr)	
	Estimate	Std.Err.	Estimate	Std.Err.
Roer Valley Graben – Peel Horst: Peel Boundary Fault zone				
At fault (minimum estimate)	1.38	± 0.21	0.09	± 0.01
Regional (maximum estimate)*	2.28	± 0.36	0.15	± 0.02
Peel Horst – Venlo Graben: Tegelen Fault zone				
At faults (minimum estimate)**	< 0.30*	± 0.21	0.02	± 0.01
Regional (maximum estimate)*	1.61	± 0.36	0.11	± 0.02

* Calculated as the maximum difference of deviations from a linear regression applied to the data points of the Late Pleniglacial longitudinal profile (Fig 5a). ** Displacements along single faults of the Tegelen Fault zone are within the vertical resolution of our data.

on the surfaces of a series of cut-terraces formed within the Weichselian Pleniglacial terrace during post glacial climatic amelioration. Age differences between the terraces are small (1-3 kyr, Huissink, 1999; Tebbens et al., 1999, 2000) and post-depositional neotectonic deformation along the fault zones occurred since 15 kyr BP. Essentially, we focussed on longitudinal gradients of the Weichselian terrace level, rather than on elevation differences between separate terrace levels. Our approach concentrates on spatial variation in uplift rates rather then on fluctuating trends at a single location.

Holbrook & Schumm (1999) reviewed different aspects of fluvial response to tectonic deformation and presented them as a 'collection of tectonic indicators'. According to them deformed longitudinal profiles are the strongest indicators of tectonic influence, though a tectonic interpretation should be strengthened by accumulating as many indicators as possible, eliminating alternative explanations for each of them. We treated the indicators described in this paper accordingly. In the Rhine-Meuse delta we found neotectonic indications preserved in the incisive systems of the Weichselian Lateglacial, with supportive indications from the Holocene systems. For the Maaskant, the deformed longitudinal profiles of the Lateglacial terraces are the strongest neotectonic indicators. They can be used to quantify neotectonic movements along the recognized faults.

In this study, the correlation of terrace fragments is based on height, stratigraphy and geomorphology only, and some parts of our palaeogeographic reconstruction may remain disputable. We quantified displacement rates using the most-widespread, best-recognized Late Pleniglacial level. Our results in terms of displacement rates are dependent on the correlated Late Pleniglacial age. Its date of abandonment was taken from the well-dated chronostratigraphic framework of the Rhine-Meuse delta. Organic matter is rare in Late Pleniglacial deposits. From an excavation in the upstream Meuse valley, Tebbens et al. (1999) conventional radiocarbon-dated twigs and leaves exposed in a sandy channel fill, covered by a Bølling dated loam. The samples (GrN-21881, GrN-21882) yielded 13,280 respectively 13,780 ± 70 ^{14}C yr BP, which is calibrated to 15,700-16,750 cal yr BP. Huisink (1999a) AMS dated a similar sample ~1 kyr younger (GrA-7484, 12,390 ± 100 ^{14}C yr). For the downstream Rhine-Meuse delta, Berendsen & Stouthamer (2001, their appendix 1) mention 14 other *terminus ante quem* dates supporting the Late-Pleniglacial age. The date of abandonment of the Late Pleniglacial terrace in this study is set at 15 kyr BP. This is a minimum age, giving a maximum estimate when used to calculate displacement rates.

Another assumption that was made is that the initial Late Pleniglacial longitudinal profile was graded (i.e. had a linear profile without any initial neotectonic deformation). At present, the Meuse has a concave-up profile across the Peel Horst, but it may not have developed such a profile until as late as ca. 5.5 kyr BP, when sea level started to influence the river profile as far upstream as the study area. The possibility cannot be ruled out, that older profiles *initially* were neotectonically deformed, although the main channels of the Late Pleniglacial Rhine-Meuse probably had a higher stream power, compared to the Late Holocene Meuse, which implies that they may have been able to maintain a graded profile. In conclusion, the steeper gradient over the Peel Horst is not necessarily caused by post-depositional tilting only, but may partly be due to different rates of subsidence during deposition (syn-depositional deformation). That neotectonics influenced Late-Weichselian channels is clear from the channel deflections and fault alignments observed in the palaeogeographic reconstruction. At-fault displacements are purely post depositional, hence the minimum rates are insensitive to syn-depositional deformation. A syn-depostional component in longitudinal profile deformation would lower the maximum estimated rate (Table 1), because it is based on regional elevation differences. The large variations in local gradient (0.3-0.7 m/km, Fig. 5a) within the constructed longitudinal profiles may indicate that a combination of syn- and post-depositional deformation has occurred.

In general, terraces tend to develop and are preserved better in uplifted regions than in regions of subsidence (Veldkamp & Van den Berg, 1993; Holbrook & Schumm, 1999). In the Rhine-Meuse delta, the Late Weichselian formation of terraces is of climatic rather than of tectonic origin, but the terrace levels are separated most over the Peel Horst (Fig. 5b), and converge in the Roer Valley Graben (Törnqvist, 1998). In the Venlo Graben, the alignment of terrace borders is associated with fault lines. Post-depositional deformation in combination with an oblique crossing of a fault zone locally caused Lateglacial terraces to become more separated in the east than in the central part. This is reflected in the irregularities in the eastern part of the Late Weichselian longitudinal profiles. However, quantification using longitudinal profiles in this case is not easy, due to the fact that the terraces are partly aligned to individual faults and cross the Tegelen fault zone at a low angle. Due to the projection of several terraces on one central axis, vertical elevation differences along a single fault are 'smeared out' over a larger downstream distance. A combination of cross sections and longitudinal sections (3D approach) should be used to quantify neotectonic deformation in this region. Comparing terrace-level elevations may also result in better estimates of differential movements in the Tegelen Fault zone. In our case the quantified elevation differences in the eastern part are close to the vertical accuracy of our data set. However, results are promising and more detailed profiling, incorporating more accurate leveling and extra diagnostic features for the different terrace levels (dating, mineralogy), can be applied to further quantify neotectonic activity since the Late Pleniglacial in this region.

The 15 kyr timeframe that can be studied using Late Weichselian and Holocene deposits in this region is close to the maximum estimated recurrence interval of large earthquakes with a Richter magnitude exceeding the Roermond-1992 earthquake (Camelbeeck & Meghraoui, 1998). We know that movements along the Peel Horst are partly caused shockwise by episodic earthquakes like Roermond-1992, but constant tectonic creep might also cause a significant part of the vertical movements. We quantified relative displacements, in an area that was subsiding over the whole Quaternary. Because the structural blocks within the study area are located in the hinge zone of the North Sea Basin, shifts between net uplift and net subsidence can be expected over longer time scales. Because of the non-linearity of neotectonic movements and events, on shorter time scales like the 15 kyr of this study, estimated movement rates can also vary considerably from average rates over longer time scales. Whether it is just “normal” tectonics or a combination with glacial tectonics (cf. Thorson, 2000) that drives the Late Quaternary displacement is not differentially recorded in fluvial sediments. Comparing neotectonic movements in more river valleys, scattered over NW-Europe, and comparing Early Quaternary to Late Quaternary situations is needed to break down fluvial recorded net vertical displacements into different driving components. Tectonic modelers can use the results from the Rhine-Meuse fluvial archive as validation data to help answer these questions.

Conclusions

Neotectonic movements have caused differential subsidence in the central Netherlands during the Late Quaternary. In literature, direct evidence for seismic activity is available from palaeoseismology (trenches), historic sources and modern seismic monitoring. For the central Netherlands, average displacement rates over widely ranging time scales are available from seismology, backstripped cores, the Rhine-Meuse fluvial archive and modern leveling. Within the Neogene, the Late Quaternary is a phase of above-average displacement rates (Van den Berg, 1996). The Late Quaternary is also the period of major glaciations in the North Sea Basin. The Quaternary Rhine and Meuse periodically shifted courses in response to both tectonics and glaciation. Possibly, the latest major shift of the Rhine was triggered by Weichselian forebulge glacial tectonics.

Neotectonic influences are recorded in the sediments of the Lateglacial and Holocene Rhine-Meuse system as secondary effects in a sedimentary wedge that is primarily controlled by sea-level rise and climate change. As a result of Late Pleistocene glaciation, downstream of the Peel Horst the Holocene delta widens into the West Netherlands Basin and the northern part of the RVG. This is an exceptional situation compared to most other periods of the Quaternary, during which the Rhine flowed parallel to the Peel Horst rather than across. Upstream of the Holocene delta, in the Venlo Graben, Weichselian Lateglacial valleys follow the main structural trend. During the Weichselian Lateglacial, climatic amelioration and river incision resulted in the formation of a series of terraces. Their gradients were affected by post-depositional vertical displacements of the Venlo Graben, Peel Horst and Roer Valley Graben. Neotectonics also caused Late Weichselian Meuse channels in the southeast Rhine-Meuse delta to be deflected around the relatively uplifted Peel Horst. Neotectonic deformations were quantified from deformed longitudinal profiles of the Weichselian Lateglacial terrace levels. For the study area, average displacement rates over the past 15 kyr are calculated to be 0.09-0.15 mm/yr at the PBF and 0.02-0.11 mm/yr at the Tegelen Fault zone. This is in agreement with earlier estimates of Late-Quaternary displacement rates for adjoining areas.

Acknowledgments

We thank all students that carried out fieldwork in the Maaskant in 1984, 1987 and 1995. We thank Dr. L. Tebbens, Dr. W. Hoek, Drs. J. Schokker and Drs. M. Kleinhans for commenting on an earlier draft of this paper. Dr. A. Veldkamp and an anonymous reviewer are thanked for reviewing the manuscript. This research is part of a PhD project ‘Neotectonics in the Rhine-Meuse delta’, sponsored by the Netherlands Organization for Scientific Research (NWO) – Earth and Life Sciences (ALW). This is a contribution to the NEESDI (Netherlands Environmental Earth System Dynamics Initiative) research programme.

References

Alexandre, P., 1994. Historical seismicity of the lower Rhine and Meuse valleys from 600 to 1525: a new critical review. Geologie en Mijnbouw 73: 431-438.

Allen, J.R.L., 1965. A review of the origin and characteristics of recent alluvial sediments. Sedimentology 5: 89-101.

Beets, D.J. & Van der Spek, J.F., 2000. The Holocene evolution of the barrier and the back-barrier basins of Belgium and the Netherlands as a function of late Weichselian morphology, relative sea-level rise and sediment supply. Geologie en Mijnbouw / Netherlands Journal of Geosciences 79 (1): 3-16.

Berendsen, H.J.A., 1982. De genese van het landschap in het zuiden van de provincie Utrecht. Ph.D. Thesis. Utrechtse Geografische Studies 25, Faculty of Geographical Sciences, Utrecht University (Utrecht): 255 pp.

Berendsen, H., Hoek, W. & Schorn, E., 1995. Late Weichselian and Holocene river channel changes of the rivers Rhine and Meuse in the Netherlands (Land van Maas en Waal). In: Frenzel, B., (ed.): European river activity and climate change during the Lateglacial and Holocene. ESF project European Paläoklimaforschung. Palaeoclimate Research 14: 151-172.

Berendsen, H.J.A., 1998. Birds-Eye View of the Rhine-Meuse Delta. Journal of Coastal Research 14 (3): 740-752.

Berendsen, H.J.A. & Stouthamer, E., 2000. Late Weichselian and Holocene palaeogeography of the Rhine-Meuse delta, The Netherlands. Palaeogeography, Palaeoclimatology, Palaeoecology 161: 311-335.

Berendsen, H.J.A. & Stouthamer, E., 2001. Palaeogeographical development of the Rhine-Meuse delta, The Netherlands. Van Gorcum (Assen): 250 pp.

Bijlsma, S., 1981. Fluvial sedimentation from the Fennoscandian area into the North-West European Basin during the Late Cenozoic. Geologie en Mijnbouw 60: 337-345.

Bridgland, D.R. & D'Olier, B., 1995. The Pleistocene evolution of the Thames and Rhine drainage systems in the southern North Sea Basin. In: Preece, R.C. (ed.): Island Britain: a Quaternary perspective. Geological Society Special Publication No. 96: 27-45.

Camelbeeck, T. & Meghraoui, M., 1998. Geological and geophysical evidence for large palaeo-earthquakes with surface faulting in the Roer Graben (northwest Europe). Geophysical Journal International 132 (2): 347-362.

Cleveringa, J., 2000. Reconstruction and modeling of Holocene coastal evolution of the western Netherlands. Ph.D. Thesis. Geologica Ultraiectina – Mededelingen van de Faculteit Aardwetenschappen Universiteit Utrecht 200: 197 pp.

Dirkzwager, J.B., Van Wees, J.D., Cloetingh, S.A.P.L., Geluk, M.C., Dost, B. & Beekman, W.W.W., 2000. Geo-mechanical and rheological modelling of upper crustal faults and their near-surface expression in the Netherlands. Global and Planetary Change 27: 67-88.

Friedrich, M., Kromer, B., Spurk, M., Hofmann, J. & Kaiser, K.F., 1999. Palaeo-environment and radiocarbon calibration as derived from Lateglacial/Early Holocene tree-ring chronologies. Quaternary International 61: 27-39.

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

Gibbard, P.L., 1995. The formation of the Strait of Dover. In: Preece, R.C. (ed.): Island Britain: a Quaternary perspective. Geological Society Special Publication No. 96: 15-26.

Holbrook, J. & Schumm, S.A., 1999. Geomorphic and sedimentary response of rivers to tectonic deformation: a brief review and critique of a tool for recognizing subtle epeirogenic deformation in modern and ancient settings. Tectonophysics 305: 287-306.

Houtgast, R.F. & Van Balen, R.T., 2000. Neotectonics of the Roer Valley Rift System, the Netherlands. Global and Planetary Change 27: 131-146.

Huisink, M., 1997. Lateglacial sedimentological and morphological changes in a lowland river in response to climate change: the Maas, southern Netherlands. Journal of Quaternary Science 12: 209-223.

Huisink, M., 1999a. Lateglacial river sediment budgets in the Maas valley, the Netherlands. Earth Surface Processes and Landforms 24: 93-109.

Huisink, M., 1999b. Changing river styles in response to climate change – Examples from the Maas and Vecht during Weichselian Pleni- and Lateglacial. Ph.D. Thesis. Faculty of Earth Sciences, Vrije Universiteit (Amsterdam): 127 pp.

Jelgersma, S., 1979. Sea-level changes in the North Sea basin. In: Oele, E., Schüttenhelm, R.T.E. & Wiggers, A. (eds.): The Quaternary history of the North Sea. Acta Univ. Ups. Symp. Univ. Ups. Annum Quingentesimum Celebrantis (Uppsala) 2: 233-248.

Kasse, C., 1995. Younger Dryas cooling and fluvial response (Maas river, the Netherlands) (ext. abstr.) Geologie en Mijnbouw 74: 251-256.

Kooi, H., Cloetingh, S. & Remmelts, G., 1989. Intraplate stresses and the stratigraphic evolution of the North Sea Central Graben. Geologie en Mijnbouw 68: 49-72.

Klostermann, J., 1992. Das Quartär der Niederrheinische Bucht. Geologisches Landesamt Nordrhein-Westfalen (Krefeld): 200 pp.

Maddy, D. & Bridgland, D.R., 2000. Accelerated uplift resulting from Anglian glacioisostatic rebound in the Middle Thames Valley, UK?: evidence from the river terrace record. Quaternary Science Reviews 19: 1581-1588.

Makaske, B., 1998. Anastomosing Rivers. Forms, processes and sediments. Ph.D. Thesis. Nederlandse Geografische Studies 249. The Royal Dutch Geographical Society, Faculty of Geographical Sciences, Utrecht University (Utrecht): 298 pp.

Mangerud, J., Andersen, S.T., Berglund, B.E. & Donner, J.J., 1974. Quaternary stratigraphy of Norden, a proposal for terminology and classification. Boreas 3: 109-127.

Posamentier, H.W., Allen, H.W., James, D.P. & Tesson, M., 1992. Forced regressions in a sequence stratigraphic framework: Concepts, examples, and sequence stratigraphic significance. American Association of Petroleum Geologist Bulletin 76: 1687-1709.

Pons, L.J., 1957. De geologie, de bodemvorming en de waterstaatkundige ontwikkeling van het Land van Maas en Waal en een gedeelte van het Rijk van Nijmegen. 's-Gravenhage: Verslagen van Landbouwkundige onderzoekingen 63.11. Dissertatie Wageningen. Bodemkundige studies 3: 156 pp.

Quitzow, H.W., 1974. Das Rheintal und seine Entstehung. Bestandsaufnahme und Versuch einer Synthese. In: Macar, P. (ed.): L'Évolution Quaternaire des Bassins Fluviaux de la Mer du Nord Méridionale – Liège: 53-104.

Stewart, I.S., Sauber, J. & Rose, J., 2000. Glacio-seismotectonics: ice sheets, crustal deformation and seismicity. Quaternary Science Reviews 19: 1367-1389.

Stouthamer, E. & Berendsen, H.J.A., 2000. Factors controlling the Holocene avulsion history of the Rhine-Meuse delta (The Netherlands). Journal of Sedimentary Research Section A 70 (5): 1051-1064.

Talling, P.J., 1998. How and where do incised valleys form if sea level remains above the shelf edge? Geology 26: 87-90.

Tebbens, L.A., 1999. Late Quaternary evolution of the Meuse fluvial system and its sediment composition. Ph.D. Thesis. Wageningen Agricultural University, the Netherlands: 155 pp.

Tebbens, L.A., Veldkamp, A., Westerhoff, W. & Kroonenberg, S.B., 1999. Fluvial incision and channel downcutting as a response to Late-glacial and Early Holocene climate change: the lower reach of the River Meuse (Maas), the Netherlands. Journal of Quaternary Science 14 (1): 59-75.

Tebbens, L.A., Veldkamp, A., Westerhoff, W. & Kroonenberg, S.B., 2000. Reply: Fluvial incision and channel downcutting as a response to Late-glacial and Early Holocene climate change: the lower reach of the River Meuse (Maas), the Netherlands. Correspondence, Journal of Quaternary Science 15: 95-100.

Thorson, R.M., 2000. Glacial tectonics: a deeper perspective. Quaternary Science Reviews 19: 1391-1398.

Törnqvist, T.E., 1993a. Fluvial sedimentary geology and chronology of the Holocene Rhine-Meuse delta, The Netherlands. Ph.D Thesis. Nederlandse Geografische Studies 166. Royal Dutch Geographical Society. Faculty of Geographical Sciences, Utrecht University (Utrecht): 176 pp.

Törnqvist, T.E., 1993b. Holocene alternation of meandering and anastomosing fluvial systems in the Rhine-Meuse delta (central Netherlands) controlled by sea-level rise and subsoil erodibility. Journal of Sedimentary Petrology 63 (4): 683-693.

Törnqvist, T.E., 1994. Middle and Late Holocene avulsion history of the river Rhine (Rhine-Meuse delta, Netherlands). Geology 22: 711-714.

Törnqvist, T.E., 1995. Discussion: Alluvial architecture of the Quaternary Rhine-Meuse river system in the Netherlands. Geologie en Mijnbouw 74: 183-186.

Törnqvist, T.E., 1998. Longitudinal profile evolution of the Rhine-Meuse system during the last deglaciation: interplay of climate change and glacio-eustasy? Terra Nova 10: 11-15.

Törnqvist, T.E., Weerts, H.J.T. & 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.

Törnqvist, T.E., Van Ree, M.H.M., Van ‘t Veer, R. & Van Geel, B., 1998. Improving methodology for high-resolution reconstruction of sea-level rise and neotectonics by palaeoecological analysis and AMS ^{14}C dating of basal peats. Quaternary Research 49: 72-85.

Törnqvist, T.E., Wallinga, J., Murray, A.S., De Wolf, H., Cleveringa, P. & De Gans, W., 2000. Response of the Rhine-Meuse system (West-central Netherlands) to the last Quaternary glacio-eustatic cycles: a first assessment. Global and Planetary Change 27: 89-111.

Van de Meene, E.A. & Zagwijn, W.H., 1978. Die Rheinläufe im deutsch-niederländischen Grenzgebiet seit der Saale-Kaltzeit. Überblick neuer geologischer und pollenanalytischer Untersuchungen. Fortschr. Geol. Rheinld. u. West. 28: 345-359.

Van den Berg, M.W., 1994. Neotectonics of the Roer Valley rift system. Style and rate of crustal deformation inferred from syn-tectonic sedimentation. Geologie en Mijnbouw 73: 143-156.

Van den Berg, M.W., 1996. Fluvial sequences of the Maas: a 10 Ma record of neotectonics and climate change at various time-scales. Ph.D. Thesis. University Wageningen, the Netherlands: 181 pp.

Van den Berg, M.W., Groenewoud, W., Lorenz, G.K., Brus, D.J. & 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 den Broek, J.M.M. & Maarleveld, G.C., 1963. The Late-Pleistocene terrace deposits of the Meuse. Mededelingen van de Geologische Stichting Nieuwe Serie 16: 13-24.

Van der Valk, L., 1992. Mid- and Late-Holocene Coastal Evolution in the Beach-Barrier Area of the Western Netherlands. Ph.D. Thesis. Vrije Universiteit Amsterdam. Febodruk (Enschede): 235 pp.

Van Dijk, G.J., Berendsen, H.J.A. & Roeleveld, W., 1991. Holocene water level development in The Netherlands’ river area; implications for sea-level reconstruction. Geologie en Mijnbouw 70: 311-326.

Vandenberghe, J., 1995. Timescales, climate and river development. Quaternary Science Reviews 14: 631-638.

Vanneste, K., Meghraoui, M. & Camelbeeck, T., 1999. Late Quaternary earthquake related soft-sediment deformation along the Belgian portion of the Feldbiss Fault, Lower Rhine Graben system. Tectonophysics 309: 57-79.

Veldkamp, A. & Van den Berg, M.W., 1993. Three-dimensional modelling of Quaternary fluvial dynamics in a climo-tectonic dependent system. A case study of the Maas record (Maastricht, The Netherlands). Global and Planetary Change 8: 203-218.

Veldkamp, A. & Tebbens, L.A., 2001. Registration of abrupt climate changes within fluvial systems: insights from numerical modelling experiments. Global and Planetary Change 28: 129-144.

Verbraeck, A., 1984. Toelichtingen bij de Geologische kaart van Nederland, schaal 1:50.000, Blad 39, Tiel West, Tiel Oost. Rijks Geologische Dienst (Haarlem): 325 pp.

Verbraeck, A., 1990. De Rijn aan het einde van de laatste ijstijd: de vorming van de jongste afzettingen van de Formatie van Kreftenheye. Koninklijk Nederlands Aardrijkskundig Genootschap, Geografisch Tijdschrift 23: 328-339.

Weerts, H.J.T. & 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.

Zagwijn, W.H., 1974. The Palaeogeographic Evolution of The Netherlands during the Quaternary. Geologie en Mijnbouw 5: 369-385.

Zagwijn, W.H., 1986. Nederland in het Holoceen. Staatsdrukkerij (‘s-Gravenhage): 46 pp.

Zagwijn, W.H., 1989. The Netherlands during the Tertiary and the Quaternary: A case history of Coastal Lowland evolution. Geologie en Mijnbouw 68: 107-120.

Ziegler, P.A., 1994. Cenozoic rift system of western and central Europe: an overview. Geologie en Mijnbouw 73: 99-127.