5 PALAEOGEOGRAPHY

OF THE CENTRAL RHINE-MEUSE DELTA

WITH EMPHASIS ON THE EARLY HOLOCENE

5.1 Introduction

The Peel Boundary Faultzone (PBF) crosses the study area from SE to NW. In the central Netherlands, the PBF separates the Roer Valley Graben (RVG) from the tectonic blocks on its northeastern shoulders (known as Peel Horst, Peel-Venlo block, Maasbommel High). From the deeper subsurface, the PBF is known as an up to 10-km wide faultzone of overstepping normal faults.

The study area (Addendum 1) is located in the heart of the Netherlands’ fluvial district. Channels of the rivers Rhine and Meuse have crossed the PBF zone at least since 60 kyr BP (OIS-4/3) continuously (Törnqvist et al., 2000). The Weichselian-Holocene (OIS-4 to 1) river Rhine followed (and still follows) a course imposed by the Saalian ice sheets (OIS-6). The study area covers the full width of this glacial-imposed valley. In response to the Weichselian-Holocene (OIS-2/1) deglaciation and climatic amelioration, a fairly complete record of fluvial deposits is preserved that spans the last 15,000 years. It is this specific geological setting that produced the study areas’ unique record, from which interaction between active tectonics and deltaic-fluvial sedimentation can be studied over time scales of millennia.

The deposits in the study area document the evolution from a full-glacial (OIS-2) braided-river of the Weichselian Pleniglacial (ca. 20 kyr BP) towards the present situation. Weichselian Late Glacial and Early Holocene (OIS 2/1 transition) incisive stages, with wandering and meandering channels, reworked the Pleniglacial braidplain. This was followed by aggradation in the Middle and Late Holocene, when fluvio-deltaic deposits from several generations of anastomosing meandering and straight (cf. Makaske, 1998) channels buried the palaeovalley.

Aims

During the Late Glacial and Holocene, faults of the PBF have been active, albeit not at constant rates. Differential subsidence occurred in the area over the last 15,000 years. This implies that effects of tectonics should be taken into account when interpreting the sedimentary record and reconstructing the detailed palaeogeography of this area. The aim of this chapter is to discuss what part of the fluvial record may be interpreted as syn-depositional effects of tectonic controls.

To distinguish syn-depositional tectonic effects from those of other controls (e.g. climate change and sea level rise) insight in the latter controls is necessary. Late Glacial fluvial evolution is essentially controlled by climate change. The Middle-Late Holocene evolution is essentially controlled by sea level rise. At the start of this study, it was unclear when the change in dominance occurred and how and where this was recorded in the fluvial record. The palaeogeographic reconstruction therefore concentrated on the Early Holocene part of the record.
Research questions were:
- What is the geometry of the Early Holocene channel deposits? Where were they located? How complete is their preservation?
- What were the external and internal controls that shaped these channels? How do Early Holocene rivers relate to the Weichselian Late Glacial topography? How is their occurrence related to upstream and downstream controls?
- Is there a response to tectonic controls in these deposits? Did rivers respond to active deformation of the Late Glacial surface? Did post-depositional deformation occur?

Solving these questions requires a reconstruction of fluvial evolution over the last 15,000 years, and description of the regional effects of upstream and downstream controls. The syn-depositional effects of local tectonic controls (active differential subsidence) are represented by those parts of the palaeogeographic reconstruction that cannot be explained by upstream and downstream controls.
5.2 The framework

The presented work builds upon a long history of earlier research. Berendsen & Stouthamer (2000, 2001) documented this work and integrated the accumulated data and insights. This produced a well-established framework for the fluvial evolution of the Rhine-Meuse delta that was used as a starting point for the detailed palaeogeographic reconstruction, which was further expanded with new insights from the study area.

The framework covers the fluvial evolution of the study area since the last glacial maximum, ca. 22-18 kyr cal BP. The time span is split into four periods, representing subsequent stages in the evolution: 22-18 kyr cal BP; 18–11 kyr cal BP; 11–8 kyr cal BP; and after 8 kyr cal BP. Each stage has a specific combination of in-channel and overbank deposition, evolutionary trend (system response over time to changes in controlling factors) and resulting alluvial architecture (preservation).

22 - 18 kyr cal BP
During the last glacial maximum of the Weichselian Pleniglacial, approximately 22-18 kyr ago, the Rhine probably discharged through multiple valleys, reoccupying flow paths dating back to the Saalian (OIS-6) glaciation and deglaciation (Cohen et al., 2002: Fig. 5.2c). The Meuse joined the southernmost Rhine distributary (the valley presently occupied by the smaller river Niers) south of the Nijmegen ice-pushed ridge. Further downstream, this Rhine-Meuse branch joined other Rhine branches more to the north in the study area. The wide palaeovalley produced the initial conditions for the developments during the Late Glacial and Holocene. Their deposits are seldom reached by the hand corings that are the primary data source for this study.

Upstream of the study area, slightly (1-5 m) above the present floodplain, a terrace is preserved on both sides of the Holocene valleys of the Rhine and Meuse (Huisink, 1997; Tebbens et al., 1999). Abandoned channel scars in the terrace surface indicate that a braided river system existed. The surface continues in the substrate of the study area as a buried terrace. Downstream fining occurs within the deposits, but all along the longitudinal profile the deposits contain coarser material than younger units. Gravel is present in significant percentages (>10%) in the study area. Absolute dating of the age of this terrace is primarily based on abandoned channel fills that date from ca. 15 kyr BP (Huisink, 1997; Tebbens et al., 1999). Luminescence dating (OSL) has confirmed the age of the terrace’s deposits (Wallinga, 2001:153, core Delft II).

18 - 11 kyr cal BP
Dramatic climatic change characterised the termination of the Weichselian glacial between 18 and 11 kyr cal BP. In the valleys upstream of the study area, the geomorphology indicates the braided river valley contracted its width, by forming a few meandering channel belts, dated to the Bølling/Allerød period (Huisink, 1997; Tebbens et al., 1999). These meandering channels incised into the older deposits. This resulted in the abandonment of large parts of the Pleniglacial palaeovalley.

Late Glacial channels formed a series of cut-terraces within the palaeovalley surface. Abandoned Rhine and Meuse channel belts date from the Bølling/Allerød and earliest Younger Dryas (ca. 15-12.5 kyr cal BP). A meandering Rhine channel existed south of the present river Waal in the east of the study area (Makaske & Nap, 1995). A smaller meandering channel (Pons, 1957; Berendsen et al. 1995) joined this Rhine channel from the SE. In the study area, Rhine and Meuse are believed to have been meandering during the Bølling/Allerød, like the channels are the continuations of meandering systems directly upstream.
Upstream of the study area, the Younger Dryas (ca. 12.7-11.6 kyr cal BP, Litt et al., 2003) channel belt of the Meuse shows a braided pattern of abandoned channels (in-filling started in the Early Holocene). The braided pattern during the colder Younger Dryas formed an incised terrace within the Pleniglacial braidplain. Abandoned channels are straighter than the Bølling/Allerød channels that were largely reworked. The Younger Dryas Rhine channel belt can be discriminated from older deposits based on the occurrence of reworked Laacher See Tephra (between 13.1-12.9 kyr cal BP; Schmincke et al., 1999; Litt et al., 2003): gravel-sized clasts of pumice occur in these deposits. The massive occurrence of pumice within the Younger Dryas channel belt is attributed to a catastrophic flood of the Rhine directly related to the Laacher See volcanic eruption. In the vicinity of the volcano, the Rhine gorge through the Eifel / Rhenish Massif became dammed by the eruption, forming a temporarily lake in the upstream valley (Litt et al., 2003). Shortly thereafter the dam breached, unleashing a catastrophic flood through the Rhine that produced a pumice-rich bed within the then-active river.

A last phase of incision (ca. 11.6 – 11.0 kyr cal BP) occurred at the onset of the Holocene (Hoek & Bohncke, 2002). The oldest Holocene channel deposits are at a deeper level than the Weichselian channel deposits, and largely reworked the Younger Dryas deposits. Upstream of the study area, the Early Holocene Rhine was meandering (Berendsen & Stouthamer, 2001; Shala, 2001).

The dynamics of the Late-Glacial Meuse producing a series of incisive channel belts has primarily been explained as a fluvial response to climatic amelioration (Vandenberghe, 1995; Berendsen et al., 1995). In the Rhine, the dimensions of the channel belt may not solely reflect the climatic control because of the catastrophic flood event following the eruption of the Laacher See volcano. Below the Laacher See Tephra-containing beds, finer deposits occur (Verbraeck, 1984). These are found at depths well below the surface of the Pleniglacial palaeovalley, and suggest incision of the Rhine during the Bølling/Allerød (ca. 15-13 kyr cal BP), prior to the Laacher See eruption.

11 – 8 kyr cal BP
The Early Holocene (ca. 11.6 – 8 kyr cal BP) is the least studied in the Rhine-Meuse delta. Studies on the Holocene Rhine-Meuse delta are primarily based on dense networks of hand-corings. In borehole descriptions Early Holocene channel deposits usually are not recognised as such, because they occur within the Weichselian palaeovalley. Together they form the substratum for the Middle and Late Holocene delta. Only few borings penetrated Early Holocene sediments, and early Holocene river-courses at the base of the Holocene delta have only been roughly mapped (e.g. Berendsen et al., 1994, 2001). Often it is not clear if channels recognised in the palaeovalley surface date from the Early Holocene or from the Weichselian Late Glacial. Common mapping practice has been to lump Early Holocene and Weichselian Late-Glacial deposits into one unit.

The most detailed work on the Early Holocene systems has been carried out in the Meuse valley upstream of the study area (SE Land van Maas & Waal and Land van Cuijk). In this area, fills of deeply incised (2-3 m) Early-Holocene channels were mapped (Berendsen et al. 1995). The Early Holocene deposits occur within the Younger Dryas channel belt. In individual cores, Early Holocene channel fills are relatively easily recognised, but (sandy) channel deposits are not. Sections and maps can reveal which channel deposits must have formed in the Early Holocene based on stratigraphic and geographic positions, and whether channel fills relate to incised channel belts or to channel scars on abandoned terrace surfaces. The Early Holocene channel-fills occur at stratigraphic positions below the Late Glacial floodplain level. Channel-fills at such
depths are known to locally occur all over the Rhine-Meuse delta. Palynological (e.g. Teunissen, 1990; Berendsen et al., 1995) and radiocarbon datings (Berendsen & Stouthamer, 2001) usually date the base of such fills to 11-8 kyr cal BP (10,300-8,000 ^14C yr BP; Berendsen & Stouthamer, 2001:251; all ^14C dates are calibrated using INTCAL98, Stuiver et al., 1998). These are dates of abandonment and indicate that active fluvial incision and reworking by the channel belts occurred before that date.

Overbank deposits of Early Holocene (and Late Glacial) rivers occur over the full width of the palaeovalley. They are known as the Wijchen Member (Törnqvist et al., 1994). The Wijchen Member differs from younger overbank deposits, because it experienced some pedogenesis prior to being buried by fluvio-deltaic sediments. The Wijchen Member usually represents overbank deposition in a floodplain setting, with a groundwater level below the surface (except during flooding). The overlying Middle Holocene deposits represent a floodbasin setting, with water average levels close to or above the surface. Upstream where Wijchen-Member deposits are at the surface, mature Holocene soils occur (grey-brown podzolics or Dutch: ‘Brikgronden’; Miedema, 1987). Downstream of the study area, where these deposits are buried several meters below the surface, palaeosoils are far less mature. Here, two organic horizons may be recognized (Berendsen & Stouthamer, 2001), suggesting that aggradation occurred in between two phases of soil formation. The study area is in an intermediate position, with some pedogenetic maturation of the Wijchen Member deposits.

**Since 8 kyr cal BP**
Similar to Early Holocene channel belts, older Middle Holocene channel belts of the Rhine and Meuse have hardly been mapped in the study area. Their stratigraphic position within the Weichselian palaeovalley prohibited easy identification. Late Holocene channel belts are still visible in the terrain. They were mapped at high resolutions (Berendsen & Stouthamer, 2001; Berendsen et al., 1994, 2001).

Middle Holocene back-filling resulted in upstream migration of the delta apex. Aggradation occurred downstream of the delta apex. During the Middle Holocene, a shift from net incision to aggradation took place in the study area. The oldest distributary channel belts (i.e. channel belts that ‘aggraded’ above the palaeovalley surface) occur downstream of the study area. In the northwest of the study area (near Maurik, Fig. 5.1), aggradation started about 7 kyr cal BP (Cohen et al., 2003). Upstream from the study area Middle Holocene channel belts were reworking the palaeovalley for a longer period of time.

In the Late Holocene aggradation continued. In the floodbasins, extensive peat formation stopped and clay deposition dominated. Relative sea-level rise was modest in the Late Holocene (0.3-0.5 m/kyr over the last 3,000 yr). Compaction of Middle Holocene floodbasin sequences provided additional space for deltaic sedimentation (Chapter 3). Multiple cycles of avulsion were needed to distribute sediment evenly over the widening central delta. Probably climatic variation and growing human impact (deforestation, agriculture) increased water and sediment loads of the rivers during the Late Holocene: channel belt dimensions (width, depth, meander length) increased considerably (Weerts & Berendsen, 1995; Stouthamer & Berendsen, 2001).
5.3 New data

Results from key locations (Dreumel, Maren, Berghem; Fig. 5.1) visited in the 1999-2001 field campaigns are discussed below. The digital map of Berendsen & Stouthamer (2001, scale 1:100,000) was used as a starting point. For the study area an updated version was made (Addendum 1). Parts (ca. 200 km²) of the polders ‘Neder-Betuwe’, ‘Land van Maas en Waal’ and ‘Maaskant’ (Fig. 5.1) were mapped in more detail, at a much larger scale (1:5,000, 1:10,000). The Late Glacial and Early Holocene subsurface in the study area has been re-mapped, and six channel belts of Late Weichselian and Early Holocene age were identified that cross the PBF (Addendum 2). They were encoded according to their time of formation (W = Late Weichselian, H = Early Holocene) and source (Rhine: R, Meuse: M) and order of formation (1,2,3), e.g. ‘WM-3’ (Appendix 1). The Middle Holocene channel belts in the study area were also reinterpreted and remapped (Addendum 1). Names and numbers of Middle and Late Holocene channel belts (e.g. ‘Dreumel (38)’) refer to Berendsen & Stouthamer (2001). As a consequence some of the descriptions of individual channel belts (Berendsen & Stouthamer, 2001; their App. 3) were revised (Appendix 2).

Site ‘DREUMEL’
The area around the ‘Dreumelse berg’ Younger Dryas dune was visited to (1) obtain a detailed section across Late Glacial and Early Holocene channel belts; (2) to obtain a series of index points for palaeo groundwater rise, representative for the central delta; (3) to investigate tectonic deformation of the Dreumel (38) channel belt (Stouthamer & Berendsen, 2000) and (4) to identify a possibly active fault in the Weichselian Pleniglacial terrace overlain by the aeolian dune. Three detailed sections (see Fig. 5.1 for section locations) are presented here: (a) a SE-NW section (Fig. 5.2), that crosses the Early Holocene channel belts. This section is incorporated in the cross-valley section Oss-Rhenen (Addendum 2); (b) A detailed SE-NW section (Fig. 5.3) with the locations of the basal peat dates for reconstruction of groundwater rise; (c) a SW-NE section across the dune, that shows the deformation of the buried Weichselian Pleniglacial terrace surface, attributed to fault activity (Fig. 5.4).

Early Holocene Meuse channels (section Dreumel-1)
Section Dreumel-1 (Fig. 5.2) shows the Early Holocene Meuse deposits in the subsurface directly south of the ‘Dreumelse berg’ Younger Dryas dune. These deposits occur between 7 and 0 m – O.D., below the buried Late Weichselian terrace surface (at 0.5 m – O.D. in the south, 0.5 m + O.D. in the north). Two Early Holocene Meuse channel belts (HM-1 and HM-2) are stacked within a Late Glacial Meuse channel belt (WM-3). Based on the low calcium carbonate content, absence of any pumice and mapping of the upstream continuations, a Rhine source is excluded. A Middle Holocene Meuse channel belt (Nieuweschans 121) is found in the section, with its top at 2.5 m + O.D. Other Middle Holocene Meuse channel belts in the direct vicinity are Molenblok (121), south of the section, and Dreumel (38), north of the section (see Addendum 1, 2). At the location of the section, Middle Holocene channel belts did not reoccupy Early Holocene river courses, in contrast to locations to the north and south (Addendum 1).
Channel belt HM-1 appears to be older than HM-2. In the section, HM-1 is a meander bend that prior to abandonment had laterally migrated northward, eroding parts of the Pleniglacial terrace deposits and aeolian dune. Its channel scar is sinuous and filled with gyttja and peat. The preserved fragment of HM-1 is only 1-km long and shares both its upstream and downstream continuations with HM-2 (Addendum 1). Between channel belts HM-1 and HM-2, peat is found that overlies sandy-loams and coarse sands at the top of WM-3. This indicates that floodplain lowering by this channel belt was about 2.5 m relative to the Pleniglacial terrace surface. Probably WM-3 had incised to this level at the very beginning of the Early Holocene (ca. 11.6-11.0 kyr cal BP). Date 1 in Fig. 5.2 indicates HM-1 was abandoned by 9.0 kyr BP (8,140±60 14C yr BP, UtC-10182). This coincides with the date 4 to the south (8,100±50 14C yr BP, UtC-10754). Date 1 is from a channel-fill gyttja, date 4 is from a floodbasin setting. Their elevation difference is 0.50 m (Appendix 3). Channel belt HM-2 has a clastic channel fill at its northern side, suggesting that the channel migrated northward, and eroded part of the peat south of date 4 after HM-1 became abandoned.

A clay bed occurs at 0 m +O.D., that has a slickenside facies attributed to palaeosoil formation. This is the natural levee of channel belt HM-3, that is found downstream of the section (Addendum 1, 2). A small crevasse channel of HM-3 has reoccupied the HM-2 channel belt, but the channel belt itself must have avulsed to a more southern course than HM-1 and HM-2. Samples 2 and 3 date the beginning of activity of this channel to ca. 8.0 kyr cal BP (6,980±50 resp. 7,170±60 14C yr BP; UtC 10183, UtC 10187). The depth of the palaeosoil can be used to estimate the age of abandonment. From the overlying peat, dates are available (Fig. 5.3) and soil formation must be older. The 0 m +O.D. level was the groundwater level by the time HM-3 was abandoned. Dates of overlying peat show that by 5.5 kyr cal BP (4,800 14C yr BP) the groundwater level had risen to 1.25 m +O.D. A rate of groundwater rise of 1 m/kyr for the area is a reasonable estimate (Ch. 4). Applying this rate suggests an age of ca. 6.5 kyr cal BP (ca. 5,700 14C yr BP) for the abandonment of HM-3.

Middle Holocene Meuse channel belts in the area are considerably smaller than their Early Holocene predecessors. The Nieuweschans (121) channel belt in the south of the cross section produced a 1.5-m thick crevasse splay to the north of it. Near the ‘Dreumelse berg’ dune, peat formed in between subsequent clay beds of Middle and Late Holocene systems. In this part of the section samples were taken to pinpoint palaeo groundwater levels.

**Middle Holocene groundwater level rise (section Dreumel-2)**

The section (Fig. 5.3) is located 200 m downstream of section Dreumel-1. It shows the Dreumelse berg Younger Dryas dune deposits overlying Weichselian Rhine-Meuse sands and gravels with a 20-50 cm thick loam bed (Wijchen Member) in between at 0.5-1 m -O.D. In the south, channel belt HM-2 laterally eroded the terrace and the overlying dune in the Early Holocene. Between 0-1 m +O.D. the aeolian dune sands are overlain by an Early Holocene loam, deposited by channel belts HM-1 and HM-2 (Addendum-1).

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**Figure 5.2 (previous page):** Lithological section Dreumel-1. The N-S section crosses Early Holocene channel belts of the Meuse (HM-1, HM-2; 0-5 m below O.D.). These are stacked within Late Glacial channel belt (WM-1; >3 m below O.D.) that incised into the Weichselian OIS-2 terrace ( >0.5 m below O.D.). The Younger Dryas aeolian dune covers this terrace north of WM-1. An over 4-m thick floodbasin sequence accumulated since Middle Holocene, deposited by deltaic distributaries. Peat did form locally.
Figure 5.3: Detailed section Dreumel-2. The section crosses the southern flank of the ‘Dreumelse Berg’ inland dune. The dune is buried by Middle and Late Holocene floodbasin deposits. Locally peat overlies in situ dune sand. Basal peat dates from these virtually compaction-free locations are index-points for palaeo groundwater levels. In sampling basal peat for $^{14}$C dating (Appendix 3), peat that buried slumped sand (not in situ) was avoided.

Middle Holocene deposits of the Molenblok (112) and Nieuweschans (121) channel belts overly the Early Holocene deposits. At the dune flank, an Alnus peat developed in between these deposits, at 1-1.5 m +O.D. Further to the south a palaeosol within in the lower clay bed separates the deposits of these two channel belts. Following activity of the Nieuweschans (121) channel belt, a second more widespread peat layer developed. It is found between 1 and 2 m +O.D. all over the section and occurs slightly higher (2.5 m +O.D.) on the dune flank. During formation of this peat, Meuse discharge was probably routed north of the dune, following the Dreumel (38) channel belt: little sediment entered the relatively protected area south of the dune.

Holocene clays and peat overly the southern flanks of the Younger Dryas dune. Cores were collected to sample the base of the peat that overlies dune sands, to minimise effects of compaction. This proved extremely hard to do, since the dune flank turned out to have been subject to slumping during peat formation. Nevertheless, four reliable samples for groundwater level-index points were taken (dates a, c-e; Fig. 5.3). These samples are from peats that were underlain by A-horizons of palaeosoils developed in the dune sand. That ensures they were ‘in situ’. Dates d and e come from the lower peat bed.
Figure 5.4: Detailed section Dreumel-3. The section crosses the Late Weichselian buried terrace in a longitudinal direction. A 2-m displacement exists below the ‘Dreumelse Berg’ dune, reflecting fault offset since abandonment of the surface ca. 15.0 kyr cal BP.

Their elevation difference is 0.11 m and their radiocarbon age is virtually the same (4,800±50 \(^{14}\)C yr BP, UtC-10186; 4,797±42 \(^{14}\)C yr BP, UtC-11128). This consistent result confirms the quality of these index points. Dates a and c differ 0.55 m in elevation and ca. 360 \(^{14}\)C yr in age. Date b (UtC-10185) proved to be not a good index-point. It was displaced ca. 30 cm while being reworked in a slump: its age is in between a and c, but the sample was taken from an elevation below c. Dates a-c show that slumping occurred at the same time as peat formation. Results of palaeo groundwater rise at site ‘Dreumel’ are discussed in comparison with data from site ‘Maren’ later in this section.

Local fault displacements (section Dreumel-3)
This SW-NE section shows a ca. 2-m drop in elevation of the Late Weichselian palaeovalley underneath the ‘Dreumelse berg’ aeolian dune. Within a kilometre, the terrace surface drops from 1 +O.D. to 1-O.D. This drop is found in the top of sandy deposits (i.e. Weichselian Pleniglacial terrace) and in the top of overbank loam (Wijchen Member). The observed 0.5-1.0 m thickness is
exceptionally thick for a loam underlying Late Glacial dunes in the study area. However, some 300 m to the north a Weichselian Late Glacial channel is present (Addendum 1) that may have deposited the loam as a natural levee, explaining the larger thickness. In the southwest, the Dreumel (38) channel belt cuts the section. It has eroded parts of the dune upstream (Addendum 1) and has reworked aeolian dune sand, underlying terrace deposits (sand, gravel, loam) and older Holocene clays. The scour base is in the Late Glacial loam at 1.5 m -O.D.

The ‘Dreumelse berg’ dune overlies a less than 1-km wide fragment of the Weichselian Pleniglacial terrace. In boreholes east of the section, the Late Weichselian surface always occurs above 0.5 m +O.D. West of the section the surface is always reached below O.D.; mostly below 1 m-O.D. Channel belts WR-1 and WM-3 have eroded the terrace in the north and the south. WM-3 occurs at a distinctly (2-3 m) lower level, and had its northern bank ca. 300 m south of the section. Channel belt WR-1 had its southern bank ca. 500 m north of the section.

The observed drop in the dune’s subsurface is related to a fault. Alternatively it may be attributed to fluvial activity: the lower and higher parts resemble two phases within the Weichselian Late Pleniglacial. However, palaeo-hydrological observations support a fault-related origin: in the section two vertical oxidised zones occur that crosscut deposits of widely different age. Commonly, sediments below the groundwater level are in a reduced state, and have typical greyish colors (Fe²⁺). In the two zones however, sediments below the groundwater table are in an uncommon oxidised state, with typical orange colors of oxidised iron (Fe³⁺). The zones crosscut the Weichselian fluvial deposits and the Younger Dryas dune sands, but also the much younger Dreumel (38) channel belt deposits. This indicated they have a local hydrological cause rather than a pedogenetic cause. Similar phenomena have been observed along fault-lineaments in the Eastern Maaskant area (Cohen et al., 2002). The palaeo-hydrological features are thought to indicate the presence of a fault. This hypothesis seems to be confirmed by the construction of Late Glacial and Holocene longitudinal profiles (next section).

**Deformed longitudinal profiles near Dreumel**

Late Weichselian gradient lines show a marked deformation at the position of the Dreumel site. The 2-m drop below the ‘Dreumelse Berg’ dune (Fig. 5.4) appears to be a local feature: Fig. 5.5 shows that within 3 km to the southwest, the palaeovalley surface rises again. Over a downstream distance of 6 km from the ‘Dreumelse Berg’ dune the palaeovalley surface drops 2.5 m in elevation (ca. 0.4 m/km). Upstream of the site, gradients appear much lower (ca. 0.2 m/km). This indicates that the area downstream of the ‘Dreumelse berg’ dune is a zone of deformation: the inferred fault is the most upstream fault of the PBF in this area. Within this zone, the first 2 km downstream of the dune, is a back tilted block (local gradient –0.05 m/km). The presence of two other faults within the PBF is inferred. The most downstream of these faults is thought to correlate with the PBF as identified south of the study area in the polder Maaskant (Cohen et al. 2002:Fig. 5).

In the area upstream of PBF, channel belts have roughly parallel gradient lines, indicating that this is a relatively stable block. It is thought to represent the Maasbommel High structure known from the deeper subsurface (e.g. Verbreack, 1984; Dirkzwager et al., 2000). Within this block, the channel belts WM-3, and HM-2 have steeper gradients over their last kilometre before they enter the PBF. It suggests that these rivers were actively adapting their longitudinal profile in response to deformation and that considerable fault displacement occurred in the period between 15.0 and 11.0 kyr BP. Gradients of younger channel belts have a more gentle deformation. The gradient lines of Molenblok (112) and HM-3 show a relative low where the channel belts leave the Maasbommel High and cross the PBF. This seems to be caused by back tilting of blocks within the PBF.
Figure 5.5: Longitudinal profiles of Late Weichselian and Holocene channel belts.
(a) Late Weichselian gradient lines show deformations related to tectonic activity of the PBF. The top of sand-gravel channel deposits is plotted.
(b) 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 (following Cohen et al. 2002).

Only datapoints of the Pleniglacial terrace to the area north of channel belt WM-3 were used to construct the gradient line of Fig. 5.5a. Datapoints of the Pleistocene terrace to the south plot slightly above this gradient line (Fig. 5.5b). This indicates a SE-NW tilting of the Maasbommel High block and tilting of blocks within the PBF. To the south this tilt was quantified by comparing the gradient lines of Fig. 5.5 to gradient lines in the Maaskant area (Cohen et al., 2002: Fig. 5.5 and the site ‘Berghem’ discussed below). The elevation difference upstream of the PBF is ca. 2.5 m over 10 km in a SE-NW direction. Part of this elevation difference is the syn-depositional valley-gradient, the remainder is post-depositional tilt. For example: for a palaeovalley with a gradient of 0.25 m/km, that crosses the block at 45° relative to the strike of the tilt, and an observed elevation difference of 2.5 m over 10 km, the post-depositional tilt is 2.5 - (sin(45°) x 10 km x 0.25 m/km) = 0.75 m.
The gradient lines of the younger Dreumel (38) and especially the Nieuweschans (121) channel belts seem to be little deformed. Dreumel (38) and Nieuweschans (121) are downstream continuations of the Wijchens Maasje (184) channel belt. Stouthamer & Berendsen (2000) found considerable deformation of the Wijchens Maasje (184) channel belt, especially of the part upstream of the Dreumel site. Based on this gradient line, Berendsen & Stouthamer (2000) suggested that abandonment of the Dreumel channel belt was followed by a period of high rates of tectonic movement. This is not confirmed by the gradient lines across the PBF. Deformation, if real at all, may be attributed to deformation across upstream faults (i.e. of the Tegelen Faultzone).

Site ‘MAREN’

The site ‘Maren’ was visited to obtain a series of palaeo groundwater rise index points representative for the south-eastern part of the central delta. A SE-NW section was cored (Fig. 5.6). The site is in the RVG part of the polder Maaskant, downstream of the PBF (Cohen et al., 2002). The Late Weichselian subsurface consists of coversand, and slopes towards the North. A palaeo soil is found at the top of the coversand. The morphology of the Late Weichselian surface flattens towards the north and grades into the fluvial palaeovalley. Below the coversand surface
fragments of older Rhine-Meuse terraces may be present. An isolated aeolian dune (cores 25, 111, 112; Fig. 5.6) has developed on top of the palaeovalley deposits. At the base of the dune a palaeosoil was found. A Younger Dryas age of the dune surface and a Bølling/Allerød age of its buried palaeosoil is presumed, based on similarities elsewhere (Berendsen & Stouthamer, 2001). A Late Glacial loam (Wijchen Member) was not recognised within the section but is found to the NW, N and NE.

Three distinct levels of Holocene fluvial clay, interbedded in peat are recognised. These clays are floodbasin deposits of channel belts directly north of the section. The lower two are connected to levees and channel belts of the Lith-Maren (99) channel-belt complex. Sample b (UIC 10192) dates the beginning of the Maren phase of the Lith-Maren (99) channel-belt complex. The upper clay wedge is connected to the present Meuse (102) channel belt. To reconstruct groundwater rise, 5 samples of basal Alnus peat were collected for $^{14}$C dating (b-f; Fig. 5.6).

![Figure 5.7: Holocene relative groundwater level (GW) rise at sites 'Dreumel' and 'Maren'.](image-url)

Peat dates (GW index-points) and 3D-interpolated curves of GW rise are plotted. For non-basal peat samples, vertical bars indicate a GW above sample depth.

The Dreumel data consist of Early Holocene (Fig. 5.2, estimated water depths 0.5-1.5 m), Middle Holocene (Fig. 5.3) and Late Holocene (Verbraeck, 1984:211, palaeosoil A-horizon dates, estimated compaction 0.3-0.5 m) data points.

The Maren data set consists of basal peat dates only (Fig. 5.6). Sample details in Appendix 3.
Holocene groundwater rise at ‘Maren’ and ‘Dreumel’

Local groundwater rise at Maren and Dreumel (Fig. 5.7) appears to have been rapid, compared to groundwater rise at other locations. ‘Maren’ groundwater level index-points plot below those of the more inland ‘Dreumel’ site that is located 8 km north and 6 km east. Over this distance a considerable gradient in groundwater levels exists: the present elevation difference is approximately 1.2 m, the EW gradient is 0.2 m/km. Radiocarbon dates of groundwater level index points were calibrated to calculate rates of rise. The ‘Maren’ data suggest that the highest rates of rise (up to 1.5 m/kyr) occurred between 6.0 and 5.0 kyr cal BP. 3D interpolated curves (Ch. 4) are smoother and give lower rates (1.15 m/kyr for 5.4 kyr BP). Relatively high aggradation rates also occur between 4.0 and 3.5 kyr cal BP, the same period of the slumping at the ‘Dreumelse berg’ dune.

At ‘Maren’ basal peat formation started approximately 6 kyr cal BP at 1.2 m below O.D. (Fig. 5.6). At ‘Dreumel’ this moment roughly coincides with the abandonment of the WM-3 channel belt (estimated age 6.5 kyr BP) and the formation of peat at about O.D. The elevation difference and gradient appear to have been constant since 6 kyr cal BP (Fig. 5.7): they have remained constant since deltaic aggradation started. Further back in time, curves of relative groundwater rise (Ch. 4) converge. Before 6 kyr cal BP, at the ‘Maren’ site a groundwater level above that of ‘Dreumel’ may have occurred. At ‘Maren’, near the delta margin regional groundwater levels were above those of the ‘Dreumel’ in the centre of the palaeovalley.

Site ‘BERGHEM’

The site ‘Berghem’ was visited in 2001. The aim was to detail earlier palaeogeographic reconstructions for the Maaskant area and to study the influence of fault-related lineaments (Cohen et al., 2002) on Late Glacial lateral river migration. The section (Fig. 5.8) shows a buried natural levee and channel belt of a Late Weichselian Meuse channel. Mapping suggest a sinuous shape of the abandoned channel. The relatively large scour depth (down to 3 m-O.D.) and the 5-m thick, relatively fine channel fill resembling other channel fills, and the sinuous shape of its abandoned channel suggest it essentially formed during the Allerød. Older Weichselian deposits may have been incorporated in the channel belt. On top of the channel fill, between 1.5-3.5 m +O.D. a fining upward sequence is found, with a relatively coarse lag, that may be of Younger Dryas age. Within this upper unit, two small channel scars were filled with peat in the Holocene.

The Allerød channel deposits are finer than the deposits in its outer bank. These are older Rhine-Meuse deposits (Weichselian, OIS 3-2; possibly Saalian, OIS-6 or older). At their top (4 m +O.D.) a thin veneer of aeolian coversand is found, probably of Late Weichselian age. At about 1 m +O.D. a continuous gravel bed was found. These gravels are oxidised (orange coloured, Fe3+), as are the overlying sands in the southernmost core. To the north, deposits are generally in a reduced state (greyish, Fe2+), except for two levels within the Allerød channel fill.

The peat in the abandoned Late Glacial channels is overlain by overbank deposits of the Haren (59) channel belt. Samples (a) and (c) date the onset of activity by this channel belt, about 600 14C yr earlier than estimated by Berendsen & Stouthamer (2001). At +4.5 m+O.D. Carex peat overlies the Meuse overbank deposits. This peat buried a palaeosoil in the Weichselian coversands, which indicates that the groundwater level locally must have risen considerably. The present river Meuse deposited the upper 0.7-1.0 m of clays.
Figure 5.8: Detailed section Berghem. The section crosses an Allerød meandering channel belt in the southeastern rim of the Weichselian Rhine-Meuse valley. Stratigraphy and palaeohydrological features suggest the meander scar lined up with a fault line of the Tegelen fault zone.

The base of the peat-fill (sample (b), Fig. 5.8) in the most southern channel was dated to ca. 11.0 kyr cal BP (9,560±60 ^14C yr BP, UtC 11759, 2.69 m+O.D.). This may indicate that the channel was abandoned as late as the Early Holocene. However, the elevation of the channel belt surface, relative to incised younger channel belts makes this improbable. Early Holocene channel belts are only known at deeper levels further north. Channel fills in these channel belts are much thicker (e.g. 3 m, section Dreumel-1, Fig. 5.2). An approximately 300-m wide, and 5-m thick Early Holocene channel fill is found 6 km north of the section (Berendsen et al., 1995:163). From this fill a date of 9,420±120 ^14C yr (GrN-18095; Appendix 3) similar to sample b was obtained from a depth ca. 5 meters lower (3 m-O.D.). In a small incised channel (Raam valley, Pons, 1957; Cohen et al., 2002), 2 km north of the section, a Middle Holocene date (6,870±130 ^14C yr; UtC-7866; Berendsen & Stouthamer, 2001) was obtained from 2.35 m+O.D., i.e. 0.34 m lower than sample b. Lastly, the top of the fill, only 0.6 m higher, shows an age difference of over 5,000 yr
The large age difference over a small depth, and the relative high position of the Early Holocene basal peat, indicate that the peat is not a typical channel fill, nor a deltaic floodbasin peat as known from other parts of the Rhine-Meuse delta. Early Holocene organics at the base of this channel fill must have originated below a locally higher groundwater table, probably above the regional groundwater level in the Early Holocene palaeovalley.

Changes in the hydrological setting may explain the local occurrence of peat at relative high positions in the section ‘Berghem’. During the Early and Middle Holocene, groundwater outflow (seepage) is thought to have occurred in the channel scar. Possibly, outflowing water formed a small brook that followed the channel scar towards the NW. This preserved the dated material at the base, but did not raise the water table, so no new peat was formed. Late in the Middle Holocene, when regional groundwater levels had risen to ca. 3 m +O.D., peat started to accumulate. Subsequently, in the Late Holocene, deposits of the Haren channel belt sealed the former outflow area. Late Holocene groundwater outflow did occur further south, and facilitated a *Carex* peat to form on top of the Weichselian sand. This peat formed above the apparent floodbasin level of the Haren (59) channel belt. The peat in the channel scars (2.7-3.3 m+O.D.) and the *Carex* peat at 4.5 m+O.D. can be explained by the same local groundwater hydrological setting (i.e. seepage), at different stages of regional groundwater rise.

It has been suggested (Cohen et al., 2002) that banks of Allerød channel belts aligned to fault lines of the Tegelen Fault zone in the eastern part of the Polder Maaskant (Addendum 1). The presumed position of a fault is indicated in Fig. 5.8. The presence of a fault may explain the local palaeo hydrological conditions and the relatively high position of the gravel in the outer bank of the Allerød channel (1 m +O.D., Fig. 5.8). There are no indications for tectonic offsets in the Late Glacial sediments. If the presumed fault exists, Late Glacial fluvial alignment to its lineament is the result of a passive tectonic control, and not necessarily indicates syn-depositional fault activity. Regardless of the hypothesised presence of a fault, the contrasts in grainsize between the fine Allerød channel fill and the coarse deposits to the south, will have influenced the local palaeo hydrology.

### 5.4 Late-Glacial to Middle-Holocene palaeogeography

**GIS based palaeogeographic reconstruction**

The palaeogeographic reconstruction is based on approximately 20,000 original borehole descriptions that were re-interpreted. This is different from the reconstruction made by Berendsen & Stouthamer (2001), who essentially used student’s maps and only occasionally reinterpreted the 200,000 borehole descriptions. By re-interpreting all borehole descriptions, Middle Holocene channel belts could be identified, that were not mapped during the original fieldwork in the 1980’s and 1990’s. The reason for this is that these buried Middle Holocene channel belts are harder to map than the younger channels, because they are not visible in the morphology. The number of borehole descriptions that has accumulated since the first field campaigns made revised mapping of channel belts in the subsurface possible for this study.

Due to erosion by subsequent channel belts, older channel belts are progressively eroded and dissected. Only fragments of channel belts are mapped, that have to be correlated to reconstruct channel belts over larger distances. In many cases, these correlations are straightforward, for example because clear differences in the elevation and/or width of the channel belts occur, or because their floodbasin deposits occur at different levels. However, where larger systems (e.g. 1-
2 km wide channel belts like Waal (174), Addendum 1) eroded smaller systems (e.g. 50-200 m wide channel belts like Dreumel (38), Addendum 1), correlation is less straightforward. Over large distances, correlation of fragmented channel belts cannot be based purely on geometric relations, but has to include:

1) Analysis of dates of channel activity, at multiple locations along a channel belt;
2) Construction of longitudinal gradient lines
3) Considerations on the conservation of discharge over simultaneously active (coeval) channel belts

A GIS database was set up by the author, that combined maps of channel belts (spatial database) with the radiocarbon dates (Berendsen & Stouthamer (2001; their Ch. 5). In this study, the Berendsen & Stouthamer (2001) GIS-database was detailed and expanded. The GIS was used to evaluate the palaeogeographic reconstruction on internal consistency.

Geological-geomorphological map
The map (Addendum 1) presents a complete record of channel belts that existed over the last 15,000 yr. Twelve Late Glacial and Early Holocene channel belts of Rhine and Meuse are identified (Appendix 1). Colours of Holocene channel belts represent time of abandonment. Middle-Late Holocene channel belts (Appendix 2) are referenced following Berendsen & Stouthamer (2001, their App. 3). Appendix 2 contains updated descriptions of individual channel belts.

Over the width of the Weichselian palaeovalley, narrow (1-2 km) Late Glacial and Early Holocene channel belts occur that dissected the Weichselian Pleniglacial terrace. In earlier reconstructions the palaeovalley was considered as a large Late Glacial braidplain with local islands of older terraces (e.g. Verbraeck, 1984:101, his fig. 33). Within the study area, upstream from the PBF zone, this is clearly not the case: the Late Glacial ‘braidplain’ essentially encompasses three separate channel belts that dissected the Pleniglacial braidplain. The surface of these channel belts occurs below the Pleniglacial surface. The incised Late Glacial channel belt contains Early Holocene channel belts with channel fills, that are interpreted as discontinuous clay-plugs in palaeo oxbow-lakes.

Previously, these Early Holocene channel fills were interpreted as narrow valleys (‘Boreal valleys’ cf. Pons, 1957) or, as narrow essentially stable channels (e.g. Berendsen et al. 1995). Now it seems that the Early Holocene channel belts were considerably wider than their channel-fills. The Early Holocene floodplain was below the Pleniglacial terrace level, and occupied most of the Younger Dryas channel belt surface. The so-called ‘Boreal-valleys’, at least in the area studied, are in fact in-filled fragments of Preboreal and Boreal meanders. This implies that dating of their base of these channel fills is not a good measure to time the onset of regional aggradation. The considerable spread that occurs in these dates (2,000 $^{14}$C yr; Berendsen & Stouthamer, 2001:251, their Terrace X terminus ante quem dates), indicates that these reflect multiple local meander cut-offs rather than a regional onset of aggradation. Downstream of the study area influence of rising sea level may have triggered regional aggradation already in the Early Holocene. For the area upstream of the PBF this is not the case.

Cross-section ‘Oss-Rhenen’
The cross-section (Addendum 2) spans the full width of the Holocene delta at the position where it is narrowest. The section has a major knick point in the centre, at the location of the buried Late Glacial dune ‘Dreumelse Berg’. The northern part of the section runs mainly NE-SW, the southern part of the section runs mainly NW-SE. In the extreme south of the section, near the margin of the Holocene area, a knick to NE-SW makes the section cross the Peel Boundary Fault
(sensu stricto): this is the fault line that is expressed in the topography south of the study area. The section is essentially located upstream of the Peel Boundary Fault, on blocks known as the Peel Horst and Maasbommel High (Van Montfrans, 1975; Dirkwzager et al., 2000).

To draw the section, 290 borehole descriptions from the archive of Utrecht University were the primary data source. Used boreholes are located within 50 m of the line of section. An exception is the 1.5 km stretch directly North of the river Waal; here cores from larger distances (max. 400 m) were projected on the transect. Most boreholes have their base in sandy channel deposits of Holocene or Weichselian age. Architectural elements in the section are based on age (Holocene/Late Weichselian) and lithogenic subdivision (channel / overbank deposits), following Berendsen (1982); Weerts (1996); Makaske (1998) and Stouthamer (2001). Eleven architectural units were recognised. A description of these units is given in Appendix 4.

Plotted in the cross-section are the radiocarbon datings that directly apply to the section. Most dates were collected from cores within the section, some are projected from some distance downstream or upstream, but from the same architectural element. Numerous other dates indirectly apply to the section. The period of activity (the time between onset of sedimentation and abandonment) of most Middle and Late Holocene channel belts is accurately dated (see Berendsen & Stouthamer, 2001). For each numbered channel belt for which new dating evidence has been collected, an updated description is given in appendix 5.1 and 5.2.

**Palaeogeography 18 – 11 kyr cal BP**

*WR and WM channel belts*

Several channel belts formed between 15-11 kyr cal BP. As a result of incision, the Pleniglacial terrace surface, that had largely become abandoned by 15 kyr cal BP, acted as a floodplain. In the Younger Dryas (11.7 kyr cal BP), the WR-3 and WM-3 channel belts were the only active courses. These are the northernmost channel belts of the Rhine, respectively the Meuse valley. WR-3 and WM-3 formed in the Late Glacial, and continued to exist into the Early Holocene. At the start of the Early Holocene they further lowered their channel belt surface, to a final level ca. 2 m below the Pleniglacial terrace surface (Addendum 2). Subsequent Early Holocene activity (HR and HM channel belts) remained concentrated in channel belts WR-3 and WM-3 (Addendum 1). Therefore, only the basal part is preserved of channel belts that were active during the transition from Late Glacial to Early Holocene (WR-3, WM-3; Addendum 2).

Earlier abandoned channel belts (WM-1 and 2, WR-1 and 2) are better preserved. They are capped by Late Glacial-Early Holocene floodplain deposits and, occasionally, by Younger Dryas aeolian deposits. An example is WR-1 in the centre of the cross section (Addendum 2). The ‘Dreumelse berg’ dune partly overlies WR-1 that therefore must have been abandoned before the Younger Dryas (<12 kyr cal BP). The channel belt has a deep channel fill that is interpreted as an abandoned meandering channel. The top of channel belt WR-1 is at a slightly lower level than the Pleniglacial terrace to its north. Downstream, the channel continues into the Tielerwaard (Addendum 1). Based on the scour depth / thickness of the channel fill, the system is thought to have been meandering. This suggests that WR-1 was essentially formed in the Bølling/Allerød interstadiol. Makaske & Nap (1995) describe a similar Late Weichselian meandering channel, ca. 10 km upstream of the ‘Dreumelse berg’ dune. At this site, a calcareous gyttja at the base of a channel fill was dated to the Younger Dryas (bulk: 10,720±60. GrN-15023; CaCO$_3$-fraction: 10,690±230, GrN-16038; Berendsen et al., 1995). WR-1 is the downstream continuation of this Allerød channel belt. Its course is now mapped further downstream (Addendum-1) over a distance of 10 km, revising previous maps (Berendsen et al., 1995).
Laacher See pumice has been found in the channel belts WR-2 and WR-3. This indicates activity in the Late Allerød and Younger Dryas. Based on the pumice occurrence, Verbraeck (1984) mapped two coeval Younger Dryas Rhine channel belts in the study area: one underlying the Nederrijn, one underlying the Waal. Pumice in channel belt WR-2 only occurs higher up in the channel deposits (Verbraeck 1984:104; his cores 39G-72; 39D-84) To the north pumice occurs down to the channel lag deposits in channel belt WR-3 (Verbraeck 1984:102; his core 39B-277). WR-3 is deeper incised than WR-2 and Early Holocene channel belts only appear within WR-3. This implies that WR-3 was the main channel at the Younger Dryas-Holocene transition (11.6 kyr cal BP), a situation that may already have existed by the time of the Laacher See eruption (13 kyr cal BP). The pumice within channel belt WR-2 was deposited in a channel that did not incise, implying it was abandoned before the Younger Dryas-Holocene transition, i.e. within 1500 yr after the Laacher See event. It is suggested that in channel belt WR-3, pumice was deposited and reworked by the main Rhine channel, and that WR-2 was a secondary channel at the time of the Laacher See eruption. This has implications for pumice finds downstream of the study area. Thick pumice finds, near the base of main Late Glacial Rhine channel belts (e.g. 40 km downstream at Alblasserdam; De Jong, 1995; his core 38C-864) would imply an upstream connection to the main Rhine channel (i.e. WR-3). Thinner beds of pumice may occur higher up in the channel belts in downstream continuations of channel belts like WR-2.

Three Late Weichselian channel belts of the Meuse appear in section Oss-Rhenen (Addendum-2). WM-1 and WM-2 were abandoned before the Early Holocene, the northernmost channel belt WM-3 hosted the Early Holocene Meuse. Based on relative elevation of the channel belt surface and the surrounding floodplain / terrace, WM-1 is presumed to have been abandoned in the Bølling/Allerød interstadial (<13 kyr cal BP) and WM-2 in the Younger Dryas (Cohen et al., 2002). However, no direct dates are available yet to date these channels.

**Tectonic deformation of the Pleniglacial terrace**

In most of the section, the Pleniglacial terrace and overlying Late Glacial floodplain loams occur at a rather constant elevation of 0.5-1 m+O.D. South of the Dreumelse berg, the Pleniglacial terrace is at a 1-2 m lower level. A tilt (northward dip) is visible in the Meuse floodplain, that may be somewhat exaggerated due to the (SE-NW) orientation of this part of the section. The tilting suggests that active tectonic deformation occurred in the southern half of the section. Considerable tectonic deformation of the Pleniglacial terrace in this area is observed (Cohen et al., 2002). The cross-section indicates that the Weichselian Pleniglacial subsurface in the ‘Maaskant’ polder may have been uplifted ca. 1 m relative to the centre of the section (‘Dreumelse Berg’). Interplay of tectonic tilting and fluvial incision may explain the northerly position of the eventual Early Holocene course.

The Pleniglacial terrace to the south of the ‘Dreumelse berg’ dune (Meuse side) also has subsided relative to the terrace in the north (Rhine side). A fault beneath the ‘Dreumelse berg’ is thought to be present (Fig. 5.4). The area directly south of the ‘Dreumelse berg’ dune is a small graben that opens to the west, related to ‘en-échélon’ positioned faults (Van Montfrans, 1975). The tilted block to the south is seen as the most northern extent of the Peel Horst.

The block north of the ‘Dreumelse berg’ seems to be a second horst: the Maasbommel High. In Addendum 2 the pleniglacial terrace surface over this block is remarkably level: considering palaeoflow direction (E-W), river gradient and section orientation (SW-NE), one would expect the terrace surface to rise. It suggests that the Maasbommel High has tilted similar to the Peel Horst: the north of the block is lowered relative to the south.
Figure 5.9: Tectonic deformation of the palaeovalley surface. Map of the study area showing the width of the OIS-2 LGM palaeovalley and the locations of faults with quantified offsets over the last 15 kyr. Displacement occurred along 3 faults of the PBF zone. The active faults mark the boundary between the relatively stable Maasbommel High and Peel Horst blocks and the PBF zone. Faults in the deeper subsurface (Tertiary-active, Van Montfrans, 1975) indicated to illustrate the tectonic structure. Minor displacements along these faults may have occurred. Differential subsidence across the PBF zone decreases northward. The Peel Horst and Maasbommel High blocks are tilted to the North.
The PBF in the study area can be considered a zone of overstepping fault activity: the active faults in the northern part of the PBF are other faults than the active faults further to the south. This view on tectonic structure matches earlier mapping by the Netherlands’ Geological Survey (Van Montfrans, 1975; Verbraeck, 1984; see Dirkwzager et al., 2000). The exact location of the faults, interpreted from the upper 10 m of sediment, only slightly differs (1-2 km) from published maps that are primarily based on boreholes penetrating deeper strata (100-1500 m) and seismic data. Recent mapping of the Geological Survey (TNO-NITG) has resulted in updated fault-maps, incorporating new data on the deeper substrate. Fig. 5.9 does not contain the new TNO-NITG data, and hence may be used to crosscheck the implied locations of faults.

**Palaeogeography 11 – 8 kyr cal BP**

*HR and HM channel belts*

Early Holocene channels largely reworked the northernmost Meuse and Rhine Late Glacial channel belts (WM-3, WR-3). For the Meuse, this is better documented in the section (Addendum 2) than for the Rhine. Incision seems to have occurred at the onset of the Holocene (11.6-11.0 kyr cal BP). After that, the HM and HR channels formed, as new channel belts within the incised WM-3 and WR-3 channel belts.

Channel belt HM-1 represents a meandering system (see above, site ‘Dreumel’). By the time that channel belt HM-1 became abandoned (ca. 9.1 kyr BP, 8,140 ± 60 14C yr, sample 1, Fig. 5.2/Addendum 2) it was already aggrading to a level above that of WM-3. HM-2 may have been present coeval with HM-1, but is thought to have developed its final width by lateral migration after abandonment of HM-1. By 8.0 kyr BP (7,170 ± 60 14C yr, sample 3, Fig. 5.2/Addendum 2) rapid aggradation set in (Fig. 5.7). Channel belt HM-3 formed shortly thereafter and may be considered the first Middle Holocene channel belt.

For the larger Rhine a similar evolution applies. Meandering Rhine channels have laterally reworked the Late Glacial channel belt almost completely. No direct datings for the Early Holocene Rhine channel belts are available. Ages (Appendix 1) were estimated, based on relative dating and rough correlation with the Early Holocene Meuse channels in the south. A slightly lower elevation of the top of HR-1 channel deposits, and more distal (peaty) facies of the floodbasin deposits overlying it, discriminate HR-1 from HR-2. HR-2 evolved from HR-1 by northward lateral migration; HR-1 may have evolved from WR-3 by southward migration. Channel belt HR-3 is a younger secondary channel. Its trunk channel was the Maurik (104) channel belt. In the line of section (Addendum-1), a small fragment of Maurik (104) has preserved between the Mars-Nederrijn (103) and Nederrijn (116) channel belts. Downstream of the section, the Maurik (104) channel belt is better preserved (Cohen et al., 2003). Its onset of activity is estimated 7.0 kyr cal BP Holocene, based on the onset of regional aggradation downstream of the section.

**Floodplain deposition**

Following WR-3 and WM-3’s incision to 1-2 m below the Late Weichselian surface, Early Holocene overbank deposition primarily occurred within their confined valleys. The width of these HR and HM channel belts is smaller than that of the WR-3 and WM-3. Consequently, part of the Early Holocene floodplain was preserved, at levels in between the Pleniglacial terrace surface and the top of Early Holocene channel deposits (above 3 m–O.D. on top of WM-3, HM-1 and HM-2; above 2 m-O.D. on top of WR-3, HR-1 and HR-2, Addendum 2)

During peak discharge, overbank deposition on the higher elevated Weichselian Pleniglacial terrace has occurred. Towards the Middle Holocene rates of deposition on top of the terrace may
have increased, because aggradation of Early Holocene channel belts reduced the elevation
difference between their confined ‘valleys’ and the terrace. The upper part of the Weichselian
Late Glacial floodbasin deposits (Wijchen Member) may actually have been deposited in the
Early Holocene. Downstream of the section, radiocarbon dates of A-horizons in the top of the
Wijchen Member (Berendsen & Stouthamer, 2001) all give Early Holocene results. However,
these are just terminus post quem dates (minimum age) for the deposition of the clay.

**Palaeogeography since 8 kyr cal BP**

**Rhine channel belts**

During the Middle Holocene, the main Rhine discharge followed the same course as its Early
Holocene predecessors. Rhine channels (Maurik (104); Werkhoven (181); Houten (74)) formed
stacked channel belts in the study area. They have their scour base in Early Holocene channel
belts (HR-1 and HR-2). Smaller, secondary channel belts came into existence that invaded the
floodbasins to the south (Winssen-Veedijk (189); Schuurkamp (153); Ochten (123) and Ommeren
(126)). These must have originated from partial avulsion of the trunk channel (upstream of the
section for (189) and (123); just downstream of the section for (126)). These channels deposited
clay that filled considerable volumes of the accumulation space. Nevertheless, accumulation
space was created so rapidly in the Middle Holocene that it could fill with peat rather than
sediments.

Towards the Late Holocene, the main channel of the Rhine (Houten (74), Lienden (95), Mars-
Nederrijn (103)) was gradually abandoned in favour of a southern course (Distelkamp-Afferden
(37), Ochten (123) Leeuwen (90), Echteld (43), Waal (175), Addendum-1). At present, the river
Waal carries 6/9 of the total Rhine discharge, the remainder is routed along the river Nederrijn
(2/9) and river IJssel (1/9, not in section, Fig. 5.1). This southward switch was essentially
triggered by an avulsion that created the Distelkamp-Afferden (37) channel belt (Addendum 1),
with Echteld (42) as a secondary channel. The later Leeuwen (90) and Waal (175) channel belts
probably gradually evolved from the Distelkamp-Afferden (37) channel belt, i.e. they did not
originate from new avulsions. In the section (Addendum 2) the southern main channel overlies
WM-2. Upstream of the line of section, WM-2 can be traced north of Distelkamp-Afferden (37)
and Waal (175) (Addendum 1). Laacher See pumice within these channel belts indicates local

**Meuse channel belts**

The Meuse south of the Dreumelse berg had a similar evolution. A difference is that a major
avulsion at the Meuse apex diverted the Meuse trunk channel out of its Late Glacial channel belt:
the Meuse course directly south of the Dreumelse berg (WM-3, HM-1 and HM-2) became
abandoned by the end of the Early Holocene. The Meuse trunk channel must have been diverted
to the south. Its new course has been preserved as channel belt HM-3. A coeval channel possibly
existed at the location of the present river Meuse, that later evolved into the Molenblok (112)
channel belt. It reoccupied the WM-2 channel belt: mapping upstream of the section shows that
WM-2 had dissected the Pleniglacial terrace and formed a relative low within the floodplain.
HM-3 was abandoned ca. 6.5 kyr BP, in favour of Molenblok (112). Channel belts HM-3 and
Molenblok (112), and subsequently the Haren (59), Macharen (102) and present Maas (101) were
the main channels of the Maas; Nieuweschans (121) and Dreumel (38) are considered to represent
secondary channels (Addendum 1, 2).

In the absence of clastic input from nearby channel belts, the floodbasin area directly south of the
‘Dreumelse Berg’, could fill with humic clays and peat. This floodbasin overlies the Early
Holocene trunk course (WM-3/HM-1/HM-2). Upstream and downstream from the ‘Dreumelse
berg’ dune, channel belts Dreumel (38) respectively Nieuweschans (121) invaded the floodbasin. These channel belts are downstream continuations of Wijchens Maasjë (184) and probably have carried similar discharges. Dreumel (38) locally reworked aeolian dune sands, which resulted in a greater width compared to Nieuweschans (121). Upstream of the section, the width and depth of the Dreumel (38) and Nieuweschans (121) are similar.

**Floodbasins**

In the Middle Holocene, floodbasins came into existence as the river system transformed from a valley to an aggrading delta. The lowest elevated parts were the areas occupied by Early Holocene incised channel belts (Meuse WM-3/HM-1/HM-2; Rhine WR-3/HR-1/HR-2). Here, floodbasin aggradation (peat formation) first set in and aggradation occurred at the highest rates. In the higher elevated areas of the Pleniglacial terrace, floodplain aggradation started slightly later. Since aggradation rates over the Middle Holocene were generally decreasing (Ch. 4), slower rates of aggradation occurred in these areas. The elevation difference of basal peat on the Early Holocene floodplain and on the Pleniglacial terrace is about 2 m for the Meuse and about 1 m for the Rhine (Addendum 2). Rates of aggradation during the first half of the Holocene were 1-2 m/kyr (e.g. Fig. 5.7). The estimated age difference between peat overlying Early Holocene deposits and basal peat overlying the Pleniglacial terrace is about 1000 yrs (Cohen et al., 2003).

In the floodbasins, the major difference between the Late Holocene and the Middle Holocene is the absence of organic beds. Late Holocene humic clays only occur locally, in distal settings (e.g. near the ‘Dreumelse Berg’). These upper organic beds are found at approximately 2.5 m + O.D. The clays above this level locally contain palaeosoils. Roman and Medieval archeological artefacts locally occur within these palaeosoils, in the upper 1.5 m of floodbasin sediments. The base of the upper clay dates to ca. 3.0 kyr BP (2,500-3,000 14C yr BP); it has been dated at many locations in the delta (e.g. dates (f),(h),(i) and (10) in addendum 2). In many cases these dates are related to avulsions. Avulsion intensity peaks at this period (Stouthamer & Berendsen, 2000; 2001).

By 1200 AD all rivers were embanked. Since then, inundation of the ‘polders’ (parts of floodbasins protected by dikes) only occurred when dikes breached. Sedimentation was concentrated in the embanked floodplains. The area south of the river Meuse was part of the ‘Beerse Overlaat’: a spillway that was used in 18th-early 20th century. Lowering of groundwater tables resulted in compaction of underlying strata: the present surface may be up to 1 m below 1000 AD levels at some locations.

**5.5 Discussion and conclusions**

A summary of the last 15,000 years of fluvial evolution in the study area is presented in Table 5.1. The Weichselian Late Glacial and Holocene evolution of the Rhine and Meuse is remarkably similar, although there are differences in timing.
Table 5.1: Summary of fluvial evolution in the central Rhine-Meuse delta, the Netherlands

<table>
<thead>
<tr>
<th>Chrono stratigraphy</th>
<th>Sedimentary style</th>
</tr>
</thead>
</table>
| **SUBRECENT** | • Since ~1200 AD  
Strongly human dominated  
• After 4 kyr cal BP |
| **LATE HOLOCENE** | Channel: sand  
Overbank: clay,  
sandy crevasse channels,  
peaty residual channel fills |
| **EARLY HOLOCENE** (OIS-1) | Channel: gravelly sand,  
abandoned channel fills (‘oxbow lakes’)  
Overbank: silty loam, pedogenesis |
| **MIDDLE HOLOCENE** | Channel: sand  
Overbank: peat, clay,  
sandy crevasse channels,  
peaty residual channel fills |
| **EARLY HOLOCENE** | Anastomosing system (cf. Makaske, 1998)  
of meandering, confined-meandering  
and straight distributary channels |
| **LATE GLACIAL** (OIS-2) | Channel: sand-gravel  
Overbank: sandy loam,  
abandoned channel fills,  
Allerød pedogenesis,  
Younger Dryas aeolian dunes,  
Anabranching wandering and  
meandering channels |
| **WEICHSELIAN** (OIS-2) | Channel: Sandy gravel, gravel  
Overbank: rare  
Braidplain |
<p>| <strong>LGM 22 kyr cal BP</strong> | |</p>
<table>
<thead>
<tr>
<th>Evolutionary trend</th>
<th>Alluvial architecture</th>
<th>Seq.Str.</th>
<th>GW</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Since ~1200 AD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• After 4 kyr cal BP</td>
<td>Continued aggrading</td>
<td>Multiple coeval channel belts, confined by - floodbasin deposits</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frequent avulsion,</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>conservative trunk channels</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stable number of channels, increasing W/D ratio, increasing sinuosity.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• 8-4 kyr cal BP</td>
<td>Rapidly aggrading</td>
<td>Multiple coeval channel belts, confined by - floodbasin deposits, - peat</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frequent avulsion,</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>conservative trunk channels</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increasing number of channels, decreasing W/D ratio, decreasing sinuosity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• 11-8 kyr cal BP</td>
<td>Mainly laterally reworking; slight incision upstream, slight aggradation downstream</td>
<td>Single channel belt</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stable number of channels, stable W/D ratio, relative high sinuosity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• 18-11 kyr cal BP</td>
<td>Incisive, ‘flow contraction’, northward deflection</td>
<td>Cut-terraces; several coeval channel belts</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Short aggradation phases, e.g.: - Younger Dryas 12.7-11.6 kyr cal BP - Laacher See event 13 kyr cal BP</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Decreasing number of channels</td>
<td>Decreasing W/D ratio, increasing sinuosity</td>
<td></td>
</tr>
<tr>
<td>• 22-18 kyr cal BP</td>
<td>Aggrading</td>
<td>Fluvial terrace; stacked within older terraces</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: Seq.Str. = Sequence stratigraphy; GW = groundwater; LGM = Last Glacial Maximum
At the start of the Weichselian Late Glacial (ca. 15 kyr cal BP) six channels crossed the PBF. The Rhine and Meuse may be characterised as anabranching, with multiple coeval channel belts. During the Bølling/Allerød the channel style seems to have been meandering, or transitional between braided and meandering (‘wandering’). Incision of the Late Glacial channel belts produced a series of cut-terraces, very similar to the upstream Meuse valley (Berendsen et al., 1995, Vandenberghe 1995). Simultaneously to this incision, the Bølling-Allerød anabranching channel belts were successively abandoned (Fig. 5.10a). This is explained as the result of ‘flow contraction’: the southern channel belts became secondary channel belts, and discharge was concentrated in the northernmost channel. Flow contraction turned these northernmost channels into the more effectively incising channels, which eventually caused abandonment of the southern channel belts. By the end of the Late Glacial, the Rhine and Meuse in the PBF had become single channels. The northernmost channel belts lowered their surface well below the surrounding Weichselian terrace. This lowering must have occurred during the later part of the Younger Dryas and the earliest part of the Holocene, based on datings and stratigraphic relations with earlier abandoned Late Glacial channel belts.

Major incision occurred in the earliest Holocene, within the northernmost Late Glacial Rhine and Meuse channel belt. Despite their age difference the surfaces of WM-1 and HR-1 are at similar depths below the Pleniglacial terrace to the south (Addendum 2). This indicates that the top level of Early Holocene channel belts was at the same level to which Late Glacial channel belts incised at the transition to the Holocene. Following initial incision, between 11 – 8 kyr BP, the Rhine and Meuse mainly reworked the deeply incised channel belts, by lateral migration of their meanders (Fig. 5.10b). Early Holocene channel fills in the PBF are local features that represent meander cut-offs. Lateral migration and meander cut-off locally preserved older channel belt fragments (HM-1, HR-1, Addendum 2). Distinct boundaries between different generations seldom exist. By 9 kyr BP the Meuse south of Dreumelse Berg (Addendum 2) had aggraded, but this may be a local feature related to differential tectonics in the area (as indicated by local deformations in the longitudinal profiles, Fig. 5.5). Upstream of the study area, the Rhine incised for a longer period of time (e.g. Shala, 2001). In the study area, downstream controls (sea level) interplayed with upstream controls (discharge, sediment load), resulting in a stable situation (no incision, no aggradation) between ca. 11-8 kyr BP. Avulsions like in the later Middle Holocene did not yet occur.

At the end of the Early Holocene, the Rhine and Meuse show a different behaviour: the Meuse had avulsed upstream of the PBF and thereby had abandoned its Early Holocene course across the PBF (Fig. 5.10b). In contrast, the Rhine maintained its course. The Rhine may have avulsed upstream, but resulting channels rejoined the Early Holocene course before crossing the PBF.

Between 7.5 and 5.5 kyr BP regional aggradation set in and the fluvial valley changed into a back-barrier delta. Initial aggradation filled the valleys that were formed by the incised Late Glacial channel belts, to the level of the Late Weichselian surface. After that (by ca. 6.0 kyr BP) several new channel belts were formed that cross the PBF (Fig. 5.10c). These were secondary distributaries that avulsed from the main trunk channel upstream of the PBF. This transformed the Rhine and Meuse single channel belt systems to deltaic anastomosing systems. Across the PBF, the Rhine trunk channel remained in its Early Holocene position well in to the Late Holocene (the present trunk channel Waal (174) only evolved to this size after 1.8 kyr BP). The Meuse trunk channel is in its present position since 7.5 kyr BP. For a deltaic system where the average period of existence is ca. 1250 yr (Stouthamer & Berendsen, 2001, Berendsen & Stouthamer, 2001), the stable position of the main channel belts for many thousands of years is remarkable.
Figure 5.10: Palaeogeographic maps for 15 – 11 kyr BP, 11 – 7.5 kyr BP, 7.5 - 5 kyr BP.

a) 15 – 11 kyr BP. In this period of incision, southern Rhine and Meuse channel belts are abandoned in favour of the northernmost channel belts. At the onset of the Holocene (11.6-11.0 kyr BP) this northernmost channel belts further incised. The northward deflection is caused by SN tectonic tilting of the Peel Horst and Maasbommel High blocks and activity of the Tegelen Faultzone.

b) 11 – 7.5 kyr BP. The Early Holocene meandering channel belt evolved within the northernmost Late Glacial channel belts. By the end of this time frame, the Meuse had avulsed southward. The Rhine maintained its northern course.

c) 7.5 – 5 kyr BP Middle Holocene deltaic distributaries cross the PBF zone at several locations. Despite repeated avulsions, directly upstream of the PBF, the trunk channels of Meuse and Rhine conservatively maintained their positions.
Regional syn-tectonic effects

It is striking that in both the Rhine and the Meuse valley the northernmost Late Glacial channel belts transformed into the Early Holocene trunk systems. The other Late Glacial channel belts became abandoned, the southernmost the earliest. It is suggested that active SN tilting has controlled flow-contraction in the northernmost channel. This in addition to differential movement of the Tegelen Faultzone (Fig. 5.9), that has a similar deflection effect because of its SE-NW orientation (Cohen et al., 2002). That SN tilting occurred in the Peel Horst and Maasbommel High blocks is clear from the tectonic deformation of the Pleniglacial terrace (Fig. 5.5). It appears that the tilting occurred for its major part during the Late Glacial. Approximately 8 kyr BP, the Meuse first avulsed out of channel belt WM-3, to a more southern position (channel belt HM-3, Fig. 5.10b/Addendum 1). The Meuse occupied a new position across the PBF. To reach this new position, it crossed the Pleniglacial terrace, at a higher level than channel belt WM-3. This suggests that differential subsidence since 15 kyr cal BP, by 8 kyr cal BP had lowered the Pleniglacial terrace relative to more upstream parts, over a vertical elevation similar to the Early Holocene incision depth (ca. 1-2 m). Because of differential subsidence in a longitudinal direction (fault offset), by ca. 8.0 kyr cal BP the Meuse trunk channel could leave its northerly position, to which it was earlier forced by differential subsidence in the lateral direction (Tegelen Faultzone activity, SN tilting).

The occurrence of other channels is not explained by differential subsidence within the PBF. All later courses essentially formed as deltaic distributaries. Nevertheless, until far into the Holocene no new deltaic distributary across the Peel Horst and Maasbommel High blocks evolved into a trunk channel: their coeval trunk channel conservatively maintained its stable Early Holocene position. Approximately 1.8 kyr cal BP (Berendsen & Stouthamer, 2001) the present river Waal, was the first Rhine distributary that evolved into new trunk channel across the PBF since, ca. 13 kyr cal BP. Flow directions of the Late Glacial and Holocene channel belts are surprisingly constant: NE-SW across the PBF. This may be explained by the tectonic setting: the channel belts crossed the PBF zone faults at an angle of ca. 90°. In the Middle and Late Holocene the Maasbommel High and Peel Horst blocks were uplifted, relative to the subsiding areas downstream (Roer Valley Graben) and upstream (Venlo Graben). In other river systems and in lab experiments (Ouchi, 1985) a more straight course across relatively uplifted blocks appears to be a common fluvial response (Holbrook & Schumm, 1999; Schumm et al., 2000). Upstream of the PBF zone, many channel belts converge, e.g.: Late Glacial Meuse channels in the Venlo Graben; Middle-Late Holocene Rhine channel belts Ommeren (126) and Houten (74); Meuse channel belts Haren (59) and Maas (101) and Macharen (102) and Maas (101). Downstream of the PBF channel belts diverge: flow directions range from NE-SW to SE-NW (Appendix 2). Widening of valleys in more subsiding areas and contraction towards less subsiding areas appears a common fluvial response (Ouchi, 1985; Holbrook & Schumm, 1999; Schumm et al., 2000).

The moment that deltaic aggradation locally set in, is influenced by tectonics (Berendsen & Stouthamer, 2000). In the north of the study area, groundwater levels rose above the Late Weichselian surface relatively early, and deltaic conditions set in at ca. 7.0 kyr BP. Further to the south, this occurred later, approximately 6.0 kyr BP. This is explained as an effect of combined lateral tilting and longitudinal deformation of the Weichselian surface. Tilting lowered the north relative to the south, and in the south, longitudinal deformation created a steep palaeovalley gradient (e.g. Fig. 5.5) that stalled back filling between 6.8 and 6.3 kyr BP (Cohen et al., 2002). Note that the stalling of back filling was not a syn-depositional effect of active tectonics around 6.8 kyr cal BP. It rather was a passive response to earlier post-depositional deformation (15-6.8 kyr cal BP), and initially steeper gradients in the area (syn-depositional response, 22-15 kyr BP).
Conclusions
The framework for fluvial evolution in the PBF zone integrates the Late Glacial evolution that was dominated by upstream controls and the Middle-Late Holocene evolution that was dominated by downstream controls.

- Incision as a response to climatic amelioration of the Last Glacial Termination continued into the Early Holocene, up to 11.0 kyr cal BP.
- In the Early Holocene incision stopped in the PBF zone. Early Holocene rivers mainly reworked the deepest incised channel belts between 11.0 and 8 kyr cal BP. Subsequently, aggradation, forced by sea level rise, started in the incised Early Holocene valleys.
- In the Middle Holocene, deltaic aggradation set in over the full width of the Late Glacial valley. New distributary channels avulsed from the trunk channels. The trunk channels were conservative: they crossed the PBF at the same location for thousands of years (Rhine Nederrijn-course: 13 – 2 kyr cal BP; present Meuse course: since 8 kyr cal BP). In contrast, upstream and downstream of the PBF, trunk channels avulsed many times.

The fluvial record of the PBF, in its Late Glacial ‘alluvial valley’ setting as well as its Middle-Late Holocene ‘delta’ setting has clear syn-depositional features related to differential subsidence.

- Deformations of the Late Weichselian surface show that differential subsidence caused local offsets across faults of the PBF and tilting of blocks within the PBF and directly upstream (Maasbommel High, Peel Horst).
- Regional offset across the PBF decreases to the northwest and tilted blocks are dipping towards the northwest. Late Glacial river flow contracted in the northernmost channel belt of the Meuse and Rhine valley in response to tilting and differential subsidence. This caused other Late Glacial channel belts to become abandoned, the southernmost channel belts first.
- Across the PBF zone, The Middle-Late Holocene trunk channels of Rhine and Meuse were ‘conservative’, they remained in their positions for 8-11 kyr, whereas upstream and downstream trunk channel belts were short-lived.
- All Late Glacial and Holocene channel belts cross the PBF perpendicular to the faults. Incisive ‘alluvial valley’ and aggrading ‘delta’ channel belts show the same response.

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