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Climate-driven fluvial development and valley abandonment at the last glacial-interglacial transition (Oude IJssel-Rhine, Germany)

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Abstract

In the Weichselian, the Lower Rhine in the Dutch-German border region has used three courses, dissecting ice-marginal topography inherited from the Saalian. In the Late Weichselian, the three courses functioned simultaneously, with the central one gaining importance and the outer ones abandoning. This study aims to reconstruct the fluvial development and forcings that culminated in abandonment of the northern branch 'Oude IJssel-Rhine', at the time of the Lateglacial to Holocene transition. The fluvial architecture is studied using a cored transect over the full width of the valley, detailed cross-sections over palaeochannels and geomorphological analysis using digital elevation and borehole data. Biostratigraphy, radiocarbon dating and OSL dating provide a timeframe to reconstruct the temporal fluvial development. In its phase of abandonment, the fluvial evolution of the Oude IJssel-Rhine course is controlled by the ameliorating climate and related vegetation and discharge changes, besides by intrinsic (autogenic) fluvial behaviour such as the competition for discharge with the winning central branch and the vicinity of the Lippe tributary confluence. The rapid climate warming at the start of the Late Glacial resulted in flow contraction as the initial response. Other fluvial geomorphic adjustments followed, with some delay. An aggrading braided or transitional system persisted until the start of the Allerød, when channel patterns finally changed to meandering. Floodplain incision occurred at the Allerød - Younger Dryas transition and a multi-channel system developed fed by Rhine discharge. At the start of the Holocene, this system transformed into a small-scale, local meandering system, which was abandoned shortly after the start of the Holocene.

The final abandonment of the Oude IJssel-Rhine and Niers-Rhine courses can be attributed to deep incision of the Central Rhine course in the earliest Holocene and is considered to be controlled by flow contraction induced by climate and related vegetation and discharge changes.

Keywords: fluvial geomorphology, Lateglacial, Lower Rhine, river pattern change, vegetation development, complex response

Introduction

Although numerous studies have been performed on fluvial system change over the last glacial-interglacial transition, the response of river systems to allogenic (climate) and autogenic forcing mechanisms and timing of this response are still not completely understood (e.g. Starkel, 1983; Vandenberghe et al., 1995; Rose, 1995; Blum & Törnqvist, 2000; Gibbard & Lewin,

2002; Vandenberghe, 2008; Erkens, 2009). The valleys of the Rhine and the Maas in the Lower Rhine Embayment have a long research history on this topic (Pons, 1957; Van de Meene, 1977; Verbraeck, 1984; Klostermann, 1992; Schirmer, 1995; Berendsen & Stouthamer, 2001; Cohen et al., 2002; Busschers et al., 2007; Erkens et al., 2011). In this area, a well-preserved terraced morphology exists, with OSL-datable fluvial sequences with aeolian cover and with palaeochannel fills that allow vegetation

reconstruction and ^{14}C dating of the time of abandonment (e.g. Berendsen et al., 1995; Kasse et al., 1995; Huisink, 1997; Tebbens et al., 1999; Erkens et al., 2011). This is particularly true for those Rhine valleys that were abandoned at the start of the Holocene: the valley of the local river Oude IJssel and the valley of the Niers, on either side of the modern Rhine (Fig. 1).

The fluvial development and final abandonment of these valleys occurred concurrently with the climatic variability and vegetation succession of the glacial-interglacial transition. Leading up to its abandonment, the Niers valley shows morphological change: a Lateglacial channel belt of meandering style developed from a braidplain precursor of Late Pleniglacial age (Kasse et al. 2005). Such morphological change is also seen in the Lower Maas valley (e.g. Kasse et al., 1995; Huisink, 1997), the Lower Rhine (e.g. Van de Meene, 1977; Erkens et al., 2011) and buried below the Holocene Rhine-Maas delta (Pons, 1957; Makaske & Nap, 1995; Berendsen et al., 1995; Berendsen & Stouthamer, 2001; Busschers et al., 2007; Hijma et al., 2009). It is also seen in the Lateglacial Rhine branch that is subject to this study: the Oude IJssel-Rhine between Wesel and the Dutch-German border, which has not been subject to detailed geomorphological-geological scientific investigation before.

This study aims to investigate the spatial and temporal response to allogenic forcings (climate and vegetation change affecting discharge and sediment besides concurrent autogenic processes) and to relate this to the abandonment of the branch. It is based on MSc thesis work of the first author and part of collaborative research of staff and students of the Vrije Universiteit Amsterdam and Utrecht University on river development in response to climate change in the wider Lower Rhine Valley / Rhine delta apex region. Knowledge of the Oude

IJssel-Rhine abandonment, given the context of simultaneous development of the other Rhine courses, offers better understanding of the typical fluvial response mechanisms to climate change observed over mid-latitude Europe.

Study area

At the apex of the Rhine-Maas delta, three Late Weichselian river courses have existed (Fig. 1): the central Rhine course (also known as Gelderse Poort Rhine), the Niers-Rhine course to the west and the Oude IJssel-Rhine course to the north, also known as 'Rond Montferland' Rhine (Van de Meene & Zagwijn, 1978; Verbraeck, 1984). The study area is part of the bifurcation area of the central Rhine and Oude IJssel-Rhine courses (Fig. 1).

We define the Weichselian Oude IJssel-Rhine valley to be located between the former bifurcation area at Wesel (Germany, coordinates: $51^{\circ}40' \text{ N}$, $6^{\circ}37' \text{ E}$) and the confluence point with the IJssel at Doesburg (the Netherlands, coordinates: $51^{\circ}1' \text{ N}$, $6^{\circ}8' \text{ E}$), with a total length of about 45 kilometres. The valley has a mean width of approximately 10 km, increasing in north-westward direction. The longitudinal gradient is ca 30 cm/km and in the study area (Fig. 2) the average surface elevation of the Weichselian valley is ca 20 m above mean sea level. The Oude IJssel valley has formed as the product of deglaciation in the Saalian (Thomé, 1959; Van de Meene & Zagwijn, 1978; Klostermann, 1992; Busschers et al., 2008). The valley is located in the hinge zone area of the North Sea Basin (Cohen et al., 2002), on a relative stable block on the very northeastern edge of the Roer Valley Graben Rift System (Van Balen et al., 2005), the tectonic structure that hosts the Lower Rhine Embayment (Boenigk & Frechen, 2006).

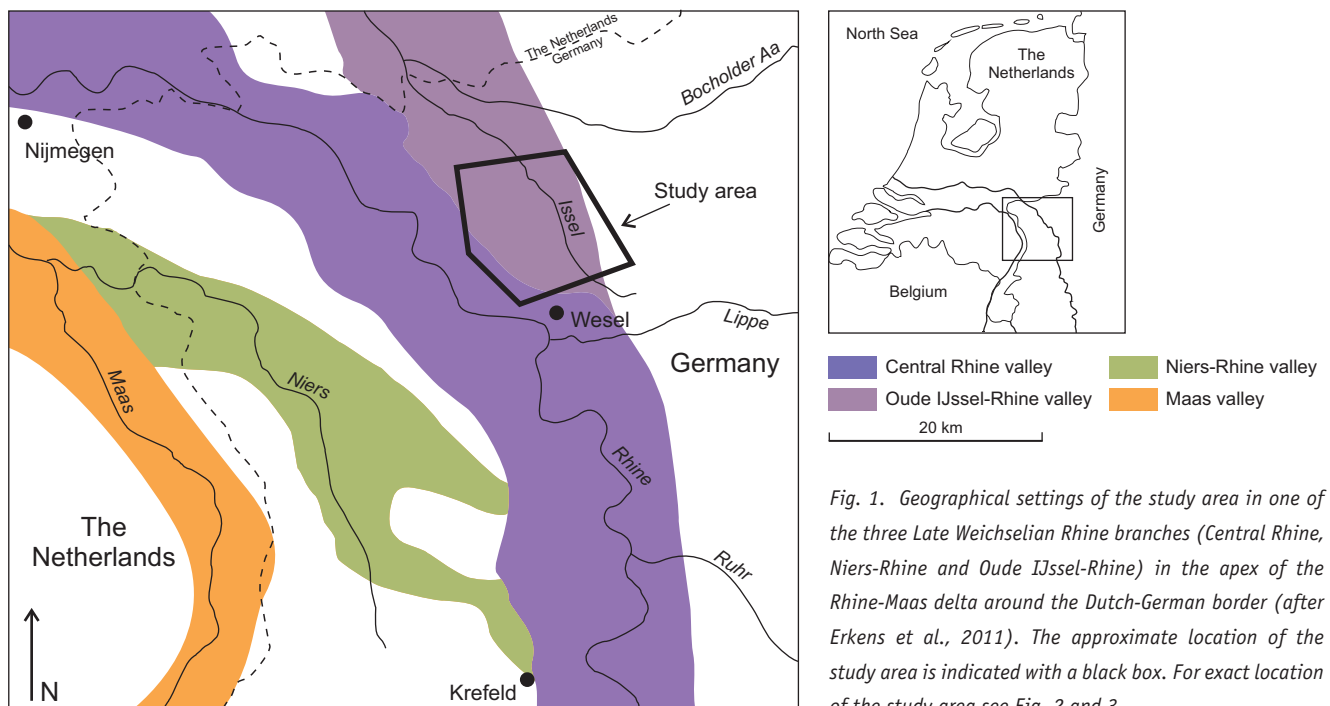


Fig. 1. Geographical settings of the study area in one of the three Late Weichselian Rhine branches (Central Rhine, Niers-Rhine and Oude IJssel-Rhine) in the apex of the Rhine-Maas delta around the Dutch-German border (after Erkens et al., 2011). The approximate location of the study area is indicated with a black box. For exact location of the study area see Fig. 2 and 3.

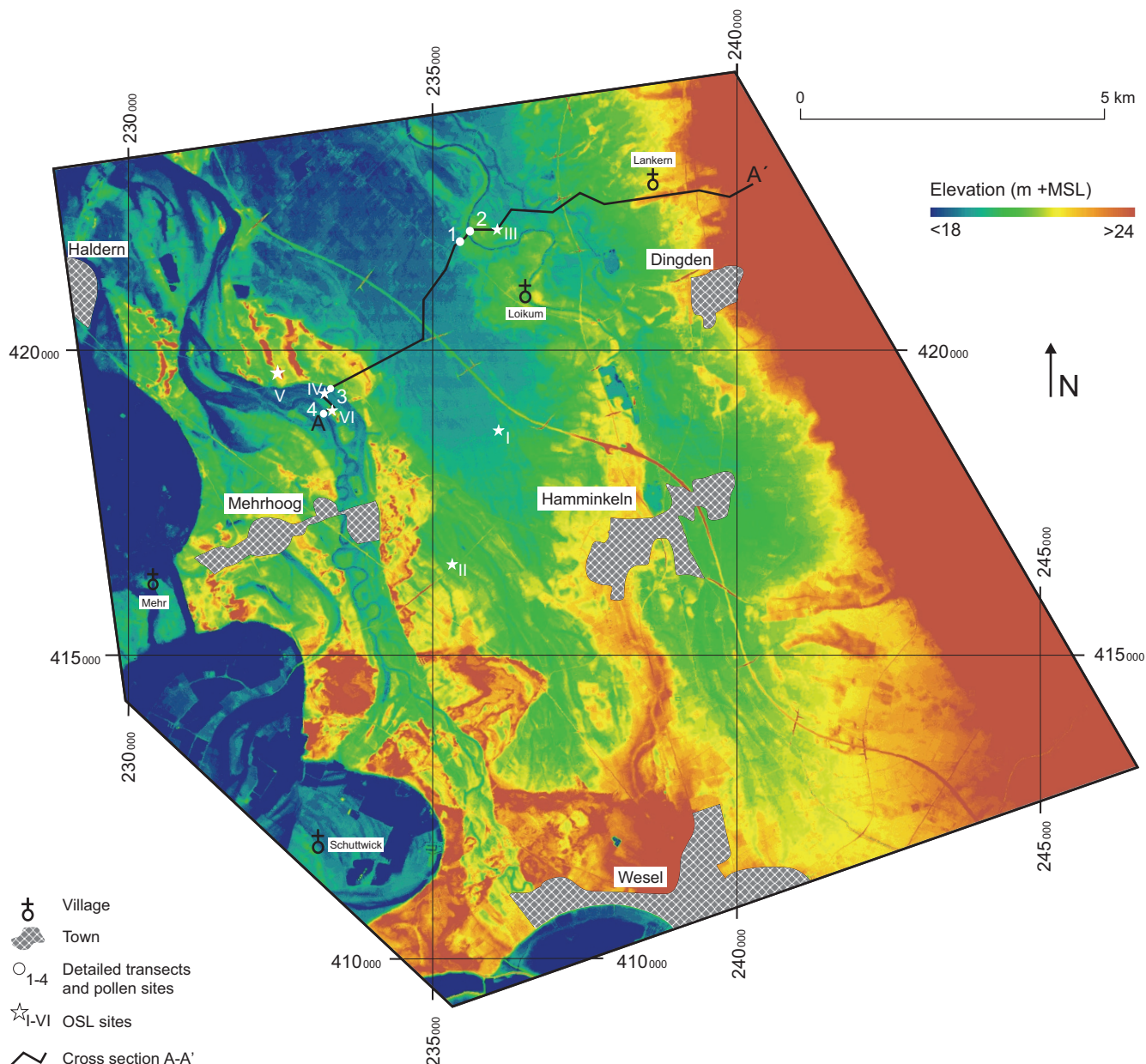


Fig. 2. Digital elevation model of the study area and location of sampling sites. For general location see Fig. 1. Locations of detailed cross-sections and sampling sites for pollen analyses and radiocarbon dating are indicated with white circles (1. Site Eckerfeld; 2. Site Isselau; 3. Site Schlederhorst; 4. Site Berckermann). Locations of OSL sampling sites are indicated with white asterisks (I. Site Hufen; II. Site Hulshorst; III. Site Mehrbruch; IV. Site Schlederhorst; V. Site Wittenhorst; VI. Site Berckermann). Coordinates are given in Dutch National Grid (RD).

At present, the abandoned Oude IJssel-Rhine course is occupied by local underfit streams (Fig. 1). The Issel enters the valley from the east. The southwestern part of the valley is drained by the Wolfstrang. North of the study area the Issel and Wolfstrang join and continue into the Netherlands as the Oude IJssel. The study area lies immediately north of the confluence of the Rhine and the river Lippe (Fig. 1), a larger regional river with pronounced Late Weichselian and Holocene terraced morphology (Herget, 1997). At present the Lippe channel enters the Rhine at straight angle near Wesel. During the Lateglacial, channels of the Lippe possibly ran parallel to the main channel of the Rhine, through our study area (Cohen

et al., 2009). The Oude IJssel valley in historical times has carried floodwaters of the Rhine, but only during passage of rare-magnitude discharge peaks. In the study area, the Weichselian terraces have no significant Holocene Rhine floodplain cover, in contrast to the Oude IJssel valley further north (e.g. Van de Meene, 1977; Cohen et al., 2009).

The Holocene meanders of the central Rhine course to the SW of the study area have been studied recently by Erkens et al. (2011) providing new cross-sections and ^{14}C dating control. Here, we present new biostratigraphical, ^{14}C and OSL dating results for the adjacent Weichselian terraced surfaces: a longer transect over the full width of the valley and detailed cross-

sections over palaeochannels, besides geomorphological analysis using digital elevation data. We focus on Late Pleniglacial, Lateglacial and early Holocene developments, from approximately 20,000 to 9000 years ago.

Methods

The geomorphology of the area was studied using topographical maps (1:25,000, Topographische Karte Landesvermessungsamt Nordrhein-Westfalen, 4104, 4105, 4204, 4205, 4305), a geological map (1:100,000, Geologische Karte Nordrhein-Westfalen, Blatt C4302; Klostermann, 1997), lidar-based digital elevation data (Landesvermessungsamt Nordrhein-Westfalen; as used in Cohen et al., 2009) and field observations. Several floodplain, channel and aeolian units have been distinguished based on architectural relationships (geometry, dissective relationships, relative elevation) and sedimentary characteristics (grain size, facies, planform channel style).

A hand-cored main transect (A-A', Fig. 4), covering all morphological units and running perpendicular to the main flow direction, was constructed to characterise the lithology and architecture of their sediments. Borehole descriptions used the classifications of Verbraeck (1984) for clastic sediments and De Bakker & Schelling (1966) for organic material. More detailed cross-sections were made over four palaeochannels, one from each morphological unit, aiming to sample the deepest and the oldest channel fills. Cores were collected from each of the four palaeochannels with a piston corer (6 cm diameter) or gauge (3 cm diameter). The cores were subsampled and prepared for thermo-gravimetry (TGA), pollen analysis and radiocarbon dating in the laboratory at Vrije Universiteit, Amsterdam. For the thermo-gravimetric analysis 10 mg of sample was dried and crushed and subsequently analysed on organic matter and carbonate content using a Leco TGA 601. Pollen samples were prepared according to the standard method of Faegri & Iversen (1989) and examined under a light microscope with phase contrast (Zeiss axioscop 50). The pollen sum (>150) includes trees, shrubs and upland herbs. The palynological results have been correlated with well-dated palynological records of the Netherlands and surroundings (Hoek, 1997b; van Geel et al., 1981) in order to construct a biostratigraphic framework to date channel abandonment and phases of fluvial sedimentation. Absolute chronological constraints were obtained through six AMS radiocarbon dated samples of selected plant macrofossils, taken from basal channel fills and at biozone boundaries. Radiocarbon ages were calibrated using IntCal09 (Reimer et al., 2009). Calibrated radiocarbon ages are given in cal. yr BP \pm 1 σ .

To determine the time of activity of the fluvial systems and formation of associated aeolian dunes, we used optically stimulated luminescence (OSL) dating. The OSL method determines the time of deposition and burial of the sediments, provided that light exposure prior to burial is sufficient to reset the OSL signal of at least part of the grains (e.g. Wallinga et al.,

2007; Rittenour, 2008). To obtain an OSL age, two quantities are determined: 1) the amount of ionising radiation received by the sample since the last exposure to light; i.e. the equivalent dose (D_e , Gy); 2) the millennial radiation dose the sample was exposed to in its natural environment; i.e. the dose rate (Gy/ka). The age is then obtained through:

$$\text{Age (ka)} = \text{Equivalent dose (Gy)} / \text{Dose rate (Gy/ka)}.$$

Samples were obtained through piston coring of sandy deposits; where possible samples were taken at least 20 cm from lithological boundaries to avoid gamma dose contributions from adjacent material with different activity. Material from the centre part of the sample tube was used for equivalent-dose estimation. This sediment was sieved to obtain grains in size range 180-212 μm and chemically treated with HCL, H_2O_2 and concentrated HF to obtain a pure and etched quartz extract. All luminescence measurements were made on a Risø TL/OSL-DA-20 TL/OSL reader (Bøtter-Jensen et al., 2003). This machine is equipped with an internal Sr/Y source delivering a dose rate of ~ 0.11 Gy/s to quartz grains at the sample position. The machine is equipped with an array of blue diodes (470 nm, ~ 35 mW/cm²) for stimulation. Tests with infrared stimulation indicated that no feldspars remained in the refined extracts. Equivalent doses were measured on small (3 mm) aliquots, each (containing a few hundred grains). The Single-Aliquot Regenerative dose (SAR) procedure (Murray & Wintle, 2003) was used for equivalent dose determination. A preheat of 220° C for 10 s (applied to Natural and regenerative doses) in combination with a 200° C cutheat (applied to testdoses) was chosen based on a preheat plateau test. Data was accepted for analysis if the recycling ratio was within 10% from unity. With the adopted procedure, a laboratory dose could be recovered although there was a slight underestimation of the given dose (dose recovery ratio 0.92 ± 0.02 ; $n = 24$) and recycling was near perfect (1.014 ± 0.004 ; $n = 268$). Equivalent dose distributions showed relatively tight distributions, indicating that light-exposure prior to deposition and burial was sufficient to reset the OSL signals of all grains. The Central Age Model (Galbraith et al., 1999) was used to obtain the equivalent dose from the measured distribution. Based on the sample characteristics and equivalent dose distribution we expect this to be an accurate estimate of the dose received by the sample since deposition and burial.

Sediment from the light-exposed outer ends of the sample tubes was used for dose-rate estimation. It was dried, ashed and then cast in wax pucks for measurement of radionuclide activity concentrations using a broad energy gamma-ray spectrometer; results were converted into infinite matrix dose rates. Based on the elevation of the samples and their sedimentation history, the average water content during burial was estimated with generous uncertainties to reflect the crudeness of the estimate. The effective dose rates to the quartz grains used for age estimation were then calculated taking into

account grain size attenuation, water attenuation, and small contributions from cosmic rays and internal alpha radiation.

The burial age is calculated from the equivalent dose and dose rate, using the age equation presented above. The quoted age uncertainties reflect one-sigma errors and include all systematic and random uncertainties in equivalent dose and dose rate.

Results

The morphological mapping identified four floodplain levels associated to the Weichselian Oude IJssel valley (Fig. 3). These are interpreted in chronological order: a complex braided level (with three sublevels, A-C), a pair of levels from two meandering channels (Issel-Lippe and Wolfstrang), a relatively narrow

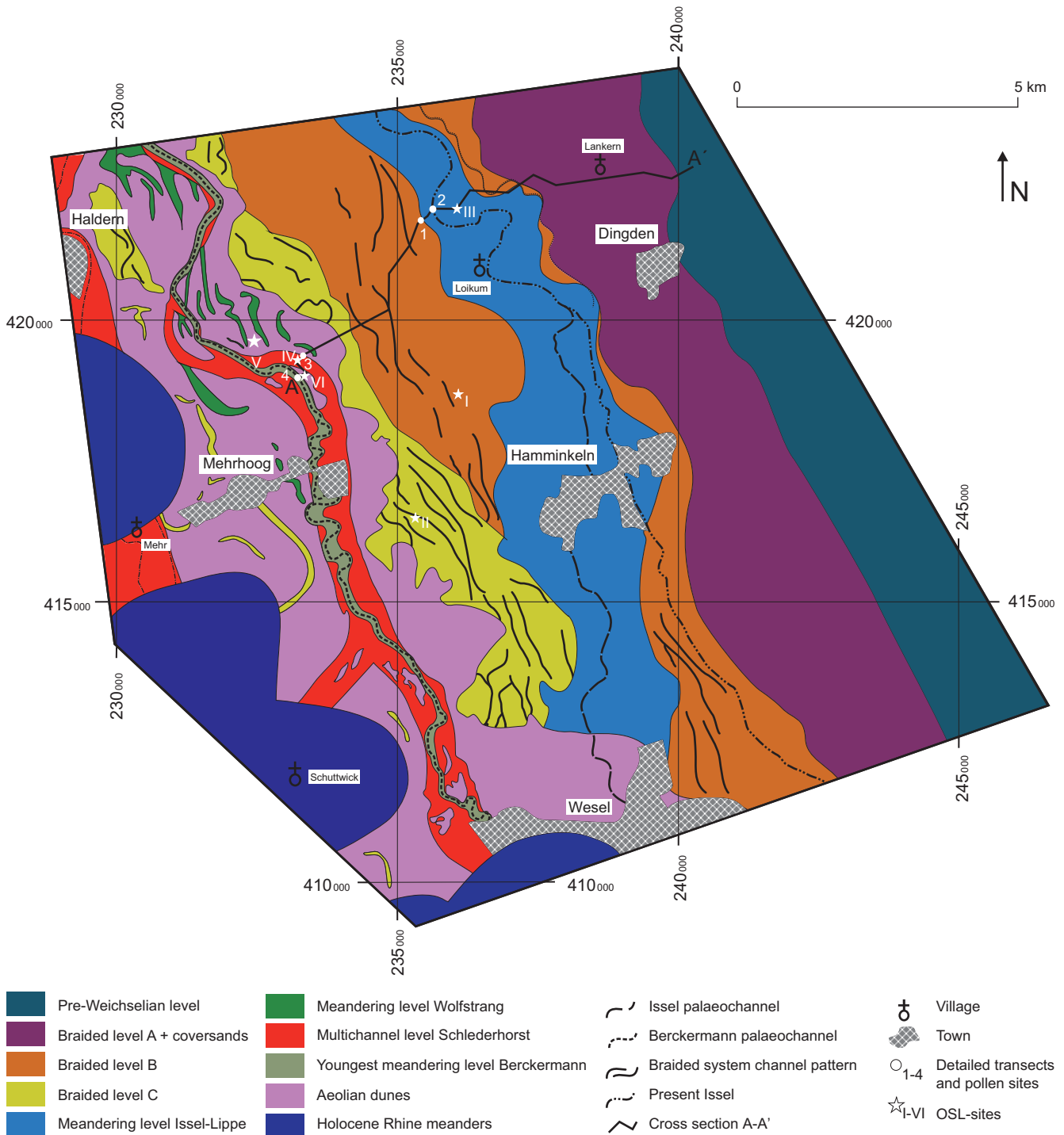


Fig. 3. Late Pleniglacial and Holocene floodplain levels and aeolian levels in the Oude IJssel-Rhine valley. For location see Fig. 1. Locations of detailed cross-sections and sampling sites for pollen analyses and radiocarbon dating are indicated with white circles (1. Site Eckerfeld; 2. Site Isselaeu; 3. Site Schlederhorst; 4. Site Berckermann). Locations of OSL sampling sites are indicated with white asterisks (I. Site Hufen; II. Site Hulshorst; III. Site Mehrbruch; IV. Site Schlederhorst; V. Site Wittenhorst; VI. Site Berckermann). Coordinates are given in Dutch National Grid (RD).

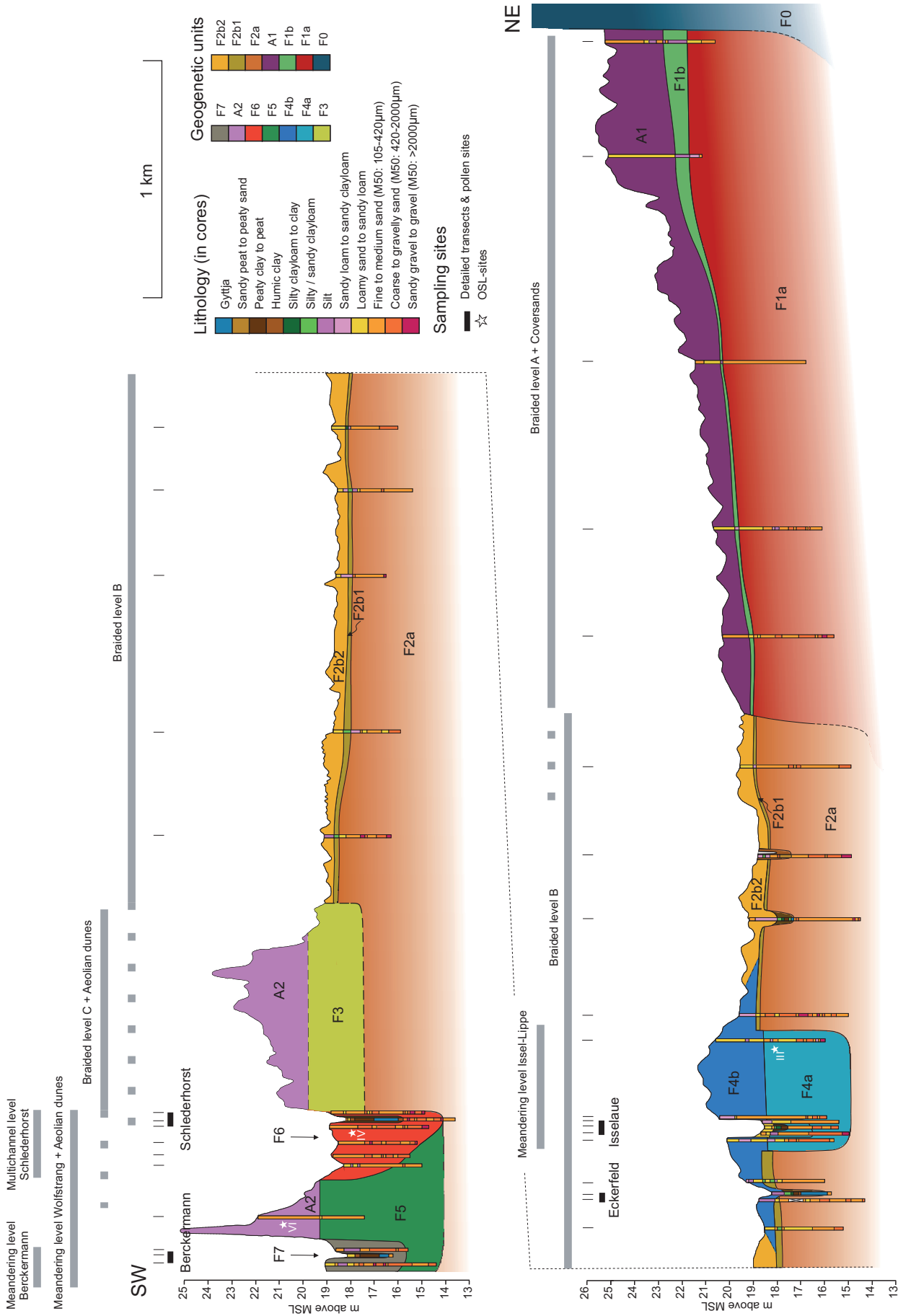


Fig. 4. Lithostratigraphic cross-section A-A' over the Oude IJssel-Rhine valley. For location see Fig. 2 and 3. Grey-coloured bars indicate fluvial and aeolian levels as indicated in Fig. 3. Black-coloured bars indicated location of detailed cross-sections in Fig. 6.

multi-channel level (Schlederhorst) and an underfit last meandering level within it. This ordering was based on their geomorphologic position and cross-cutting relationships amongst others in cross-sections and lidar zoom-ins (Fig. 4, 5) and were validated with new dating results. In the cross-sections, each of the fluvial levels associates with lithological units, which show measurable differences in elevation of the bar tops in former channel bed / the base of topping overbank deposits and eolian overburden. Two aeolian blanketing units with dune field topography mask the fluvial geomorphology in parts of the study area: Coversands overly the Braidplain Level A and appear to be locally sourced from Braidplain B and C. Source-bordering aeolian dune fields overly Braidplain level C and the Wolfstrang and Issel-Lippe meandering levels, formed coeval with the Schlederhorst multi-channel level, apparently sourced from the Central Rhine course braidplain channels that parallel it to the west of the study area. The sedimentary and morphological properties and dating results for these units are summarised in Tables 1 to 3. This section further describes the valley's fluvial units, and their contained channel fills.

Braided levels

Morphology, lithology and sedimentary environments

Braided levels A, B and C were successively abandoned. The preservation of some 2.5 km of width of Braidplain A and a further 3-4 km of Braidplain B towards the direction of the Central Rhine course, indicates that braidplain activity in the bifurcation area shifted laterally to the west, and that remaining flow through the Oude IJssel valley (e.g. Braidplain C) was concentrating over smaller active width. Eolian Unit A1 is of homogenous lithology (fine-grained sand, 150-210 μm), better sorted and lacking coarse-grained lenses and silty drapes. In combination with the undulated morphology and in agreement with mapping in neighbouring areas, it is recognised as coversand and explained as aeolian sand sheets or low dune deposits (Kasse, 2002).

Braidplains B and C show a clear straight multi-channel morphology (Fig. 2 and 5a), although slack water deposits from younger times have attenuated the original relief. Palaeochannels of level C crosscut the channels of level B (Fig. 5a) and Level C is therefore considered the youngest. At transect A-A', the elevation of level A decreases from 22-23m +m.s.l. in the northeast to 19 m +m.s.l. in the southwest (Fig.4). In the same transect, level B has an elevation of 18-19 m +m.s.l. The top of braided level C is slightly higher (0.5 to 1 m) than that of braided level B. This is a peculiar feature in the Lower Rhine region, unknown in similar aged sequences of the other Rhine courses.

The sedimentary units of level A and B (Unit F1 and F2, Fig. 4) generally consist of medium to coarse grained sand (210-600 μm) and gravel (max. 70 %, max. \varnothing : 1.5 mm). The top of the unit

shows fining-upwards sequences of about 1 to 2 metre thick. Gravel depths are generally below ~2m. This indicates a high energy sand-gravel braided fluvial sedimentary environment, in which bar tops are preserved as last in-channel aggradations associated to the dynamic shifting of the braid channels during and towards the end of the braidplain activity.

In braided level C, only one coring has been described which is not incorporated in the cross-section (Fig. 4) because of its large distance to transect A-A'. Based on morphology and lithology in this coring, unit F3 is identified and projected to the cross-section in Fig. 4. The fluvial sands are finer grained than in units F1 and F2 (mainly medium sand: 210-420 μm) and of lower gravel content.

All fluvial levels are topped with a finer-grained layer (silty to sandy clay-loam, silt loam and fine to medium sand (150-300 μm) Units, F1b, F2b and top of unit F3). These mainly formed as slack water deposits of younger systems. The overbank deposits on level B show a clear coarsening-upwards trend, allowing to divide them in a lower subunit F2b1 (silty clay-loam) and an upper subunit F2b2 (sandy loam to fine or medium sand (150-300 μm), Fig. 4).

Channel fill and biostratigraphy

A palaeochannel of braided level B at location Eckerfeld (Fig. 3, 4) was sampled for TGA (Fig. 7) and pollen analysis (Fig. 8). The morphological expression of this channel is limited because it is covered by levee deposits of the nearby Issel-Lippe system (Fig.3). The channel is 1.5 to 2 metres deep and of symmetrical shape (Fig. 6). The channel fill starts with 45 cm of fine-grained clastic material at the base, followed by 45 cm of gyttja, a 10 cm clay layer and 15 cm of peat. Above that, flood basin clays and overbank loamy sand deposits were found.

The lower part of diagram Eckerfeld (Fig. 8, 224-182.5 cm) shows high Poaceae and heliophilous herb values. In particular Artemisia values are high (up to ca 10%). *Betula* values are generally low (13-23%), but dominant over *Pinus* values (1-8%). Furthermore, *Juniperus* (~5%) and *Salix* (~10%) values are high. These characteristics point to a relative cold and dry period and probably reflect the Older Dryas biozone (PAZ 1c, ca 12.1-11.9 k ^{14}C yr BP; Hoek, 1997a). The *Alnus* and *Corylus* pollen in this interval can be attributed to reworking of older sediment, supported by the loamy character of the sediment. In the Netherlands the Older Dryas is known as a dry period with low groundwater levels (Bohncke, 1993). This is reflected in the absence of most of the aquatic species. *Potamogeton*, however, shows extremely high values (up to 50%) in this interval, probably due to over-representation by local influences, since these pollen grains tend to occur in aggregates.

The interval from 182.5 to 135 cm depth shows a decrease in herbs, combined with an increase in *Betula* (~30%) and aquatic species. This indicates a change from dry conditions during the preceding period to more humid conditions, which is supported

Table 1. Summary of the lithological and geomorphological characteristics and interpretation of the sedimentary units. For spatial distribution of the sedimentary units see Fig. 3 and 4.

Unit	Lithology	Geomorphogenetic level (Fig. 3)	Morphology	Details	Interpretation	OSL age (ka)
F1a	Alternating medium to coarse sand, gravelly sand and gravel	Braided level A	Braided, attenuated by overbanks (F1b) and heavily masked by coversands (A1)	Gravel at shallow depth. Several fining-upward sequences of ~2 meter	High energy braided fluvial system. Bed load dominated deposition	-
F1b	Loam and loamy sand	Braided level A	Heavily masked by coversands (A1)	Grain size decreasing eastwards	Overbank deposits, sourced from braidbelt B	-
A1	Moderately sorted medium to fine to loamy sand	Coversands masking Braided level A	Slightly undulating with shallow (~1 m) and wide depressions	Homogeneous lithology	Aeolian coversands, partly sourced from braidbelt B, partly locally sourced and reworked	-
F2a	Poorly sorted coarse grained sand and gravel	Braided level B	Straight multichannel, attenuated by unit F2b, partly masked by unit F4b	Weakly developed fining-upwards sequences. Gravel at shallow depth	High energy braided fluvial system. Bed load dominated deposition.	12.7±0.6 OSL sample I, Hufen
F2b	Loamy sand to sandy or silty clay loam	Braided level B	Following straight multichannel morphology of unit F2a	Divided into two subunits; units F2b2 being slightly coarser grained than F2b1	Overbank deposits, sourced from braidbelt C	-
F3	Medium sand with a loam layer on top	Braided level C	Straight multichannel, masked by dune complex (A2)	Small offset in main channel direction compared to unit F2a	Braided fluvial system. Bed load dominated deposition	10.7±0.5 OSL sample II, Hulshorst
F4a	Gravel and gravelly coarse sand at base. Fine sand at top	Meandering level Issel-Lippe	Single channel meandering. Sinuosity 1.3-15	Fining upwards sequences (thickness: 5-6 m). Clear channel lag at the base	Meandering channel belt. Bed load deposits from mixed-load river	13.0±0.8 OSL sample III, Mehrbruch
F4b	Loamy sand to sandy loam	Meandering level Issel-Lippe	Natural levee ridge bordering the channel	Elevation decreases with distance to the meandering channel	Natural levee, laterally grading to floodbasin. Suspended load deposits from mixed-load river.	-
F5	Medium to coarse sand. Silty at the top	Meandering level Wolfstrang	Complex meandering pattern. Partly masked by dune complex (A2)	Channel lag at 3.5 m depth. Pointbar fining upward sequence. Various types of channels: swales, cut-off oxbows, chute channels.	Meandering channel belt. Bed load deposits from mixed-load river	-
A2	Moderately to well sorted fine to medium sand	Source-bordering aeolian dune field: so-called river dunes	Irregular and parabolic shaped dunes, up to 10 m high	Homogeneous lithology. Present on the east side of the Central Rhine course and the multi-channel Schlederhorst system, indicating a southwestern wind direction	Aeolian dunes, sourced from the Rhine active channel bed, nearby to the west of the study area	10.8±0.7 OSL sample V, Wittenhorst 11.0±0.5 OSL sample VI, Berckermann
F6	Poorly sorted medium to coarse sand and gravelly sand	Multichannel level Schlederhorst	Straight to low-sinuosity multichannel pattern, constrained in precursor more-sinuosity system	5-m thick fining-upward sequence in bars filling 700m-wide inherited belt, leaving multiple 50-m wide channels	Transitional fluvial system between meandering and braided. Bed load deposits from mixed-load river, lowering its bed level.	10.3±0.5 OSL sample IV, Schlederhorst
F7	Poorly sorted medium to coarse sand and gravelly sand	Meandering level Berckermann	Small-scale highly sinuous single channel meandering pattern	Fining-upward sequence	Laterally migrating meandering fluvial system	-

Table 2. Results of OSL dating of sandy pointbar and channel sediments. (For locations see Fig. 2, 3 and 4).

Field Code (and number)	Sedimentary unit	Location (X/Y coordinates (m) in Dutch National Grid (RD))	Altitude land surface (m rel. to Dutch Ordnance Datum (NAP))	Sample depth (m below surface)	Sample number NCL	Water content* dose (Gy)	Equivalent dose (Gy)	Dose Rate (Gy/ka)	Age (ka)
Hufen (I)	F2a (braided level B)	236075/418735	19.2	1.1	NCL-4209156	15±3	19.4±0.7	1.53±0.05	12.7±0.6
Hulshorst(II)	F3 (braided level C)	235491/416559	20.9	1.9	NCL-4209155	20±4	16.9±0.6	1.57±0.06	10.7±0.5
Mehrbruch (III)	F4a (oldest meandering level)	235975/421958	20.6	2.5	NCL-4209157	20±4	21.2±1.1	1.63±0.06	13.0±0.8
Schlelderhorst (IV)	F6 (multi- channel level)	233339/419364	18.7	1.1	NCL-4209158	15±3	12.5±0.4	1.21±0.04	10.3±0.5
Wittenhorst (V)	A2 (aeolian dunes)	232503/419652	28.7	1.1	NCL-4209160	5±2	15.8±0.8	1.45±0.04	10.8±0.7
Berckermann (VI)	A2 (aeolian dunes)	233376/419012	25.7	1.1	NCL-4209159	5±2	17.3±0.6	1.57±0.05	11.0±0.5

* The water content is expressed as the weight of water divided by the weight of dried sediment.

Table 3. Radiocarbon dates of macro remains from organic channel fills in abandoned fluvial channels. For locations see Fig. 2, 3 and 4.

Field code	Location (X/Y coordinates (m) in Dutch National Grid (RD))	Altitude land surface (m rel. to Dutch Ordnance Datum (NAP))	Depth below surface (cm)	GrA number	Dated material ((#)number of individuals)	Radiocarbon age in ¹⁴ C yr BP	Calibrated age in cal. yr BP ± 1σ (68% confidence interval)
Berckermann BM-1	233260/418966	18.1	166-168	49479	<i>Betula alba</i> fruits (35), <i>Betula alba</i> female catkin scale (1)	9470±75	11,063-10,585
Schlelderhorst SH-1	233350/419394	18.2	197-199	49477	<i>Betula</i> fruits (25), <i>Betula</i> bud scales (1), <i>Betula</i> female catkin scales, <i>Salix</i> buds (5)	10,015±65	11,692-11,338
Isselaeue IA-1	235609/421957	18.5	137-139	49580	<i>Salix/Betula</i> twig (no bud scales)(2), <i>Salix</i> buds (5,5), <i>Betula nana</i> female catkin scale (1), <i>Betula nana</i> female cone basis (1), <i>Betula nana</i> fruit (1), <i>Betula alba</i> fruits (3), <i>Betula alba</i> male catkin scales(2)	10,105±50	11,954-11,505
Eckerfeld EF-3	235431/421770	18.2	108-110	49478	<i>Betula alba</i> fruits (1), <i>Carex</i> cf. <i>vesicaria</i> (8), <i>Carex</i> sp. <i>biconvex</i> (2)	12,060±60	13,985-13,827
Eckerfeld EF-2	235431/421770	18.2	176-179	49484	<i>Betula alba</i> fruits (9), <i>Betula alba</i> female catkin scales (3,5), <i>Carex aquatilis</i> (2), <i>Scirpus lacustris</i> (0,5), <i>Phragmites australis</i> (1), <i>Sparganium</i> sp. (1)	12,130±110	14,115-13,836
Eckerfeld EF-1	235431/421770	18.2	215-224	49482	<i>Salix</i> buds (2), <i>Betula alba</i> fruits (2), <i>Betula alba</i> bud scale (1), <i>Carex rostrata</i> (16), <i>Carex aquatilis</i> (1), <i>Alisma plantago-aquatica</i> (2,5), <i>Mentha aquatica</i> (1)	15,260±85	18,667-18,207

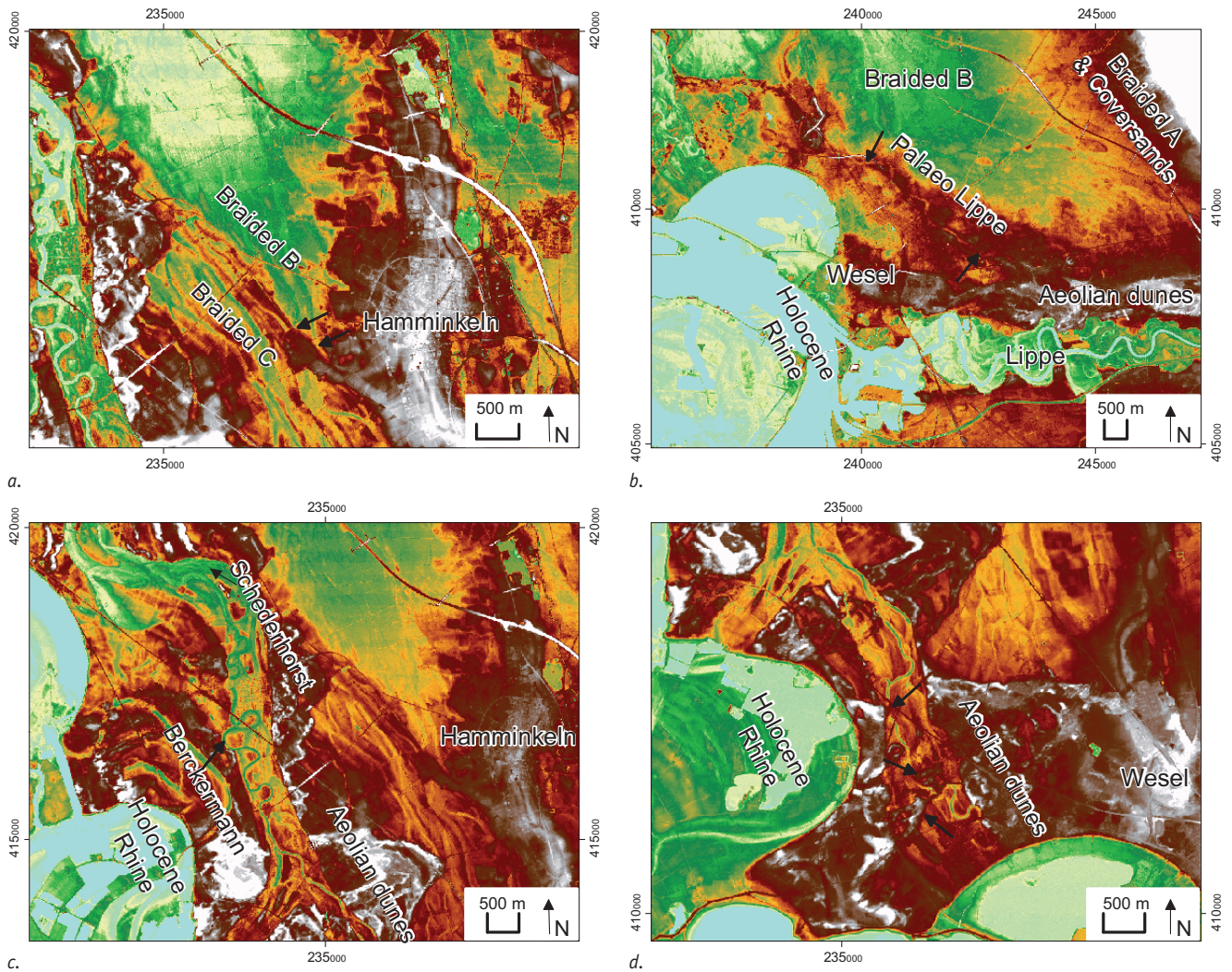


Fig. 5. Detailed parts of the digital elevation model. A. Slightly higher elevated braided level C, crosscutting the channels of braided level B (indicated with black arrows); B. The Issel-Lippe meandering system entering the Oude IJssel-Rhine valley from the east, suggesting that this system was formed by both Lippe and Issel. Aeolian dunes cover the meandering channel, probably explaining the abandonment of the meandering system during the Younger Dryas; C. The Schlederhorst multichannel level and the small-scale meandering Berckermann channel crosscutting the aeolian dunes; D. The Schlederhorst multichannel level and the small-scale meandering Berckermann channel partly overlain by the aeolian dunes. C and D together indicating that dune formation occurred mainly during the activity phase of Schlederhorst system, but continued locally after the abandonment of the Berckermann system. Coordinates are given in Dutch National Grid (RD).

by the change in lithology from fine-grained clastic sediments to gyttja accumulation in open water. The lithological and palynological changes both point to a warmer and wetter interval, supported by a peak in calcium carbonates (Fig. 7) marking calcareous gyttja deposition, which forms more-favourably at relatively higher temperature. Therefore, this interval is interpreted as zone 2a (11.9-11.25 k ^{14}C yr BP; Hoek, 1997a), the *Betula* phase of the Allerød interstadial. This interval shows a peak in Poaceae at 168.5 cm depth. The high Poaceae values (up to 80%) in this interval can be attributed to over-representation of Poaceae by local occurrence, since reed macro-remains were found over the complete interval. Towards the top of this interval the calcium carbonate percentage decreases, while the percentage of organic matter increases (Fig. 7). This coincides with a decrease in aquatic species and an increase in

wetland herbs, pointing to a natural hydrosere succession from a full open water environment towards a riparian environment.

In the interval from 135 to 105 cm *Pinus* values increase and become more dominant over *Betula*. This probably reflects the Allerød Pine phase (PAZ 2b, 11.25-10.95 k ^{14}C yr BP; Hoek, 1997a). Elsewhere in the Netherlands and surroundings, this period is characterised by low lake levels (Hoek & Bohncke, 2002). In the pollen sequence, this period is reflected by the absence of aquatic species, mosses and fungi and in the lithology by the presence of peat. Also the oxidised state of the peat in this interval points to low lake levels. In the uppermost interval (105-101.5 cm), *Pinus* values show a distinct drop, indicating the start of the Younger Dryas phase (PAZ 3a, 10.90-10.55 k ^{14}C yr BP; Hoek, 1997a). This coincides with a lithological change from peat to clay, suggesting increased fluvial activity.

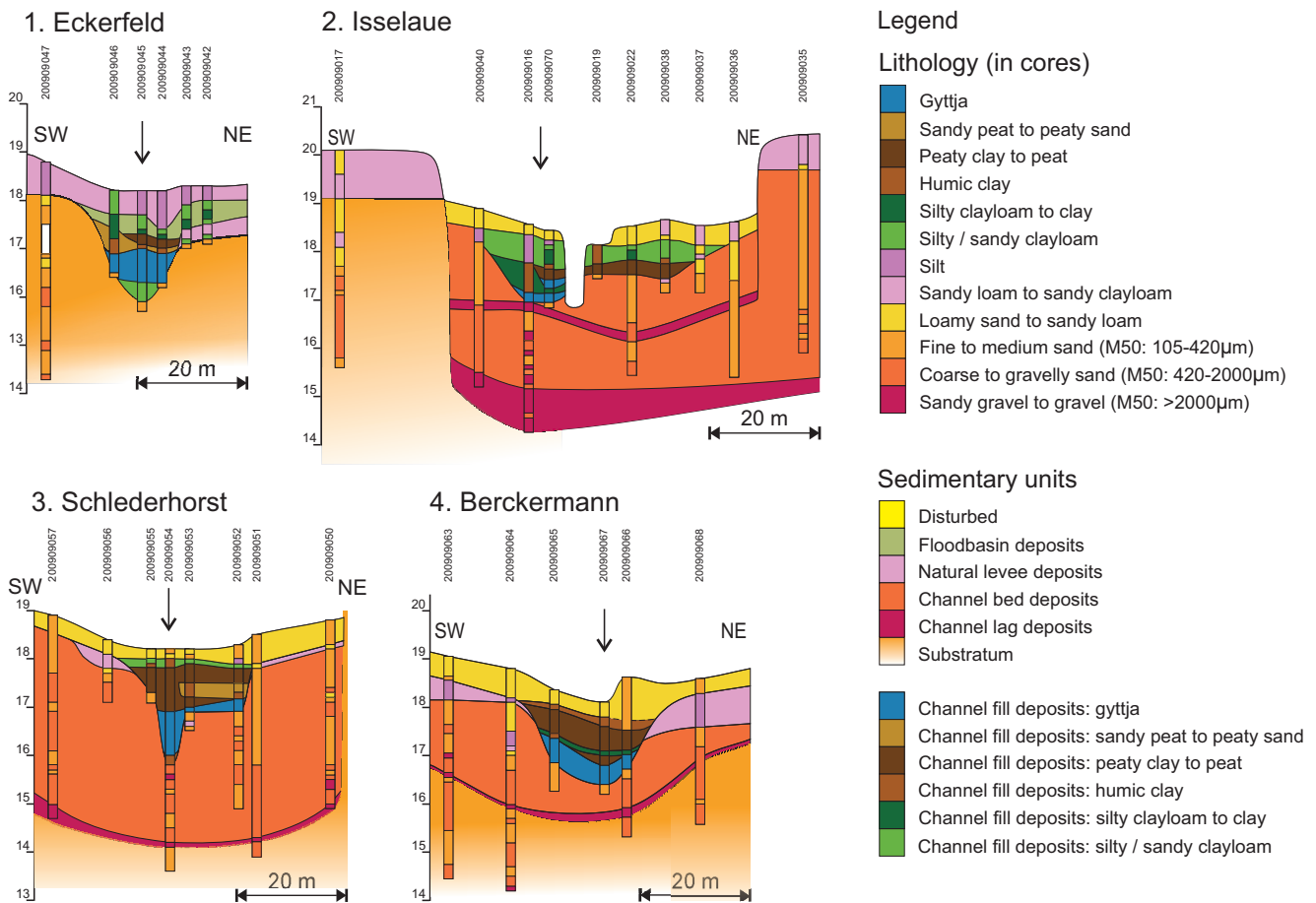


Fig. 6. Sedimentological architecture in detailed cross-sections over palaeochannels of four successive fluvial levels: Braided level B (Eckerfeld), meandering level (Isselae), multichannel level (Schlederhorst) and youngest meandering level (Berckermann). Vertical arrows indicate location of sampling sites for pollen analyses and radiocarbon dating.

Chronology

We have obtained age constraints for the braided levels B and C using three methods: OSL dating, pollenzone biostratigraphy and radiocarbon dating.

To obtain absolute ages for the activity of braided levels B and C, and test the relative dating based on the geomorphology, two samples were dated by OSL (Table 2). Sample Hufen (OSL site I in Fig. 3, Table 2) was obtained from level B (Unit F2a) and returned an age of 12.7 ± 0.6 ka. Sample Hulshorst (OSL site II in Fig. 3, Table 2), obtained from level C returned 10.7 ± 0.5 ka. A further OSL sample (see below) is available from the younger Issel-Lippe channel belt which dissects braided level B. The OSL age derived from the meandering system, however, is slightly older than that derived from level B.

To date the abandonment of level B, and phases of subsequent floodplain development, radiocarbon dates were obtained from the channel fill of the braided level at three different depth intervals (Fig. 8 and Table 3). The age returned for the basal channel fill (224-215 cm below surface, sample EF-1: $15,260 \pm 85$ ^{14}C BP ($18,667$ - $18,207$ cal. yr BP)) is not in agreement with the biostratigraphic results, which indicated an age of 12.1-11.9 k

^{14}C yr BP (PAZ 1c, Older Dryas). This can be attributed to redeposition of older macroremains and/or to a hard-water effect. No older organic deposits from which uptake would have occurred are known in the area. The major part of the dated material from this level consisted of *Carex rostrata* remains (Table 3). While terrestrial species are assumed to take up carbon from the atmosphere, this wetland species might have taken up dissolved carbon from groundwater, containing old carbon due to groundwater seepage (Nilsson et al., 2001). A second age was obtained from the interval of 179-176 cm below the surface (sample EF-2). This interval is biostratigraphically interpreted as the start of the birch phase of the Allerød interstadial (11.9-11.25 k ^{14}C yr BP). The radiocarbon age of $12,130 \pm 110$ ^{14}C BP ($14,115$ - $13,836$ cal. yr BP) obtained on *Betula* remains, is slightly older than expected, but in good agreement with the biostratigraphic interpretation. A third sample (EF-3) was taken from the interval of 110-105 cm below the surface, just below the biostratigraphic Allerød to Younger Dryas boundary (10.9 k ^{14}C yr BP) and the lithological change from organic to clastic channel fill deposits. The radiocarbon age ($12,060 \pm 60$ ^{14}C BP, $13,985$ - $13,827$ cal. yr BP) obtained from this interval is not in agreement with biostratigraphy. As in sample

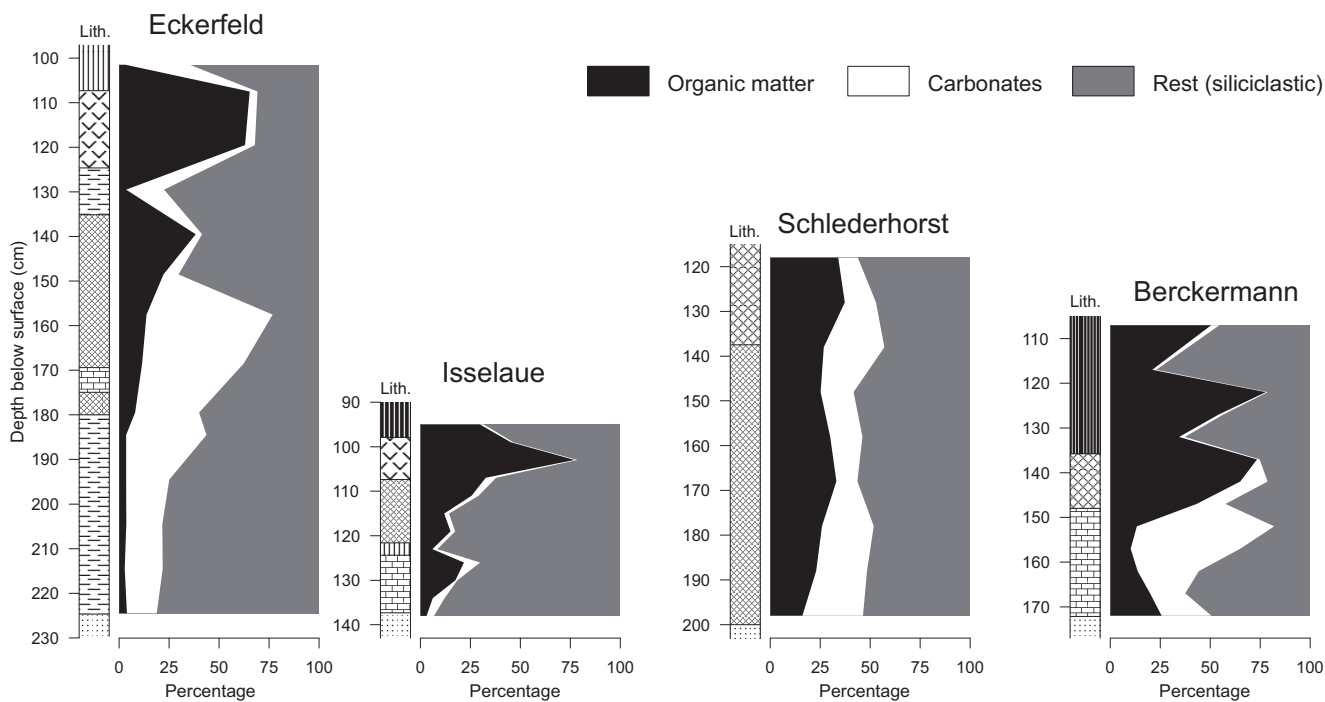


Fig. 7. TGA-results of sample cores from four successive fluvial levels: Braided level B Eckerfeld), meandering level (Isselaue), multichannel level (Schlederhorst) and youngest meandering level (Berckermann). For location see Fig. 2 (map) and 4, 6 (cross-sections). For legend see Fig. 12.

EF-1, the major part of the dated material consists of *Carex* macro-remains, possibly suffering from a hard-water effect. The results for the timing of abandonment of the channel (radiocarbon and biostratigraphy) give older dates than the OSL date for the fluvial activity.

Oldest meandering levels

Morphology, lithology and sedimentary environments

The two main meandering systems of the Weichselian valley, the Issel-Lippe system and the Wolfstrang system (Fig. 3), share the meandering style but have otherwise dissimilar morphological characteristics.

The Issel-Lippe system, in the eastern part of the valley, enters the study area near Wesel and flows via Hamminkeln to the north (Fig. 3). This meandering system is characterised by distinct natural levees, of up to 4 metre high in the south, diminishing in height to about 1.5 m in the north. Levee width is considerable, varying between 400 to 1300 metres. The sinuosity of the Issel-Lippe system varies between 1.13 to 1.51. Northeast of Wesel, the meandering system can be traced towards the east until it becomes covered with aeolian dunes related to the Lippe (Fig. 5b). This tracing suggests that this meandering system is a Lippe course, rather than a former Rhine course. Downstream of Hamminkeln, the continuation of the meandering course is occupied by the river Issel.

The channel belt of the Issel-Lippe system (Unit F4a, Fig. 4) is 5 to 6 metres thick (~4 metres excluding the levees), with a distinct gravel lag (max Ø: 2.5 cm) at the base and a single

fining-upwards sequence from coarse to fine sand (1000 to 210 µm) above it, characteristic for pointbar-forming meandering systems. Organic channel fill deposits were found directly on top of gravelly sand in the residual channel. This indicates abrupt abandonment of this system. The natural levee (Unit F4b, Fig. 4) mainly consists of loamy sand (150-210 µm) and sandy loam.

The Wolfstrang meandering system in the west of the study area does not show natural levee topography (Fig. 2), partly because of the aeolian cover, partly because of dissection by the younger Schlederhorst multi-channel system. In the dune area around the Wolfstrang meander (~3 km north of Mehrhoog, Fig. 2, 3), however, sinuous palaeochannel scars are seen in the lidar data (Fig. 2, 3), which may be swales, chute channels or cut-off oxbows. The channel belt of the Wolfstrang system (unit F5, Fig. 4) mainly consists of medium grained sand (150-420 µm). A distinct channel lag consisting of gravel (max Ø: 2.5cm) has been found at about 5 metre below the top of the unit.

Channel fill and biostratigraphy

The channel fill sediments of the Issel-Lippe system (Fig. 3, 4, 6) were sampled in cross-section Isselaue for TGA and pollen analysis (Figs 7, 9). The infill of the palaeochannel (Fig. 6) mainly consists of clayey gyttja, interrupted by a loamy clay layer. The upper part consists of sandy peat with humic clay on top.

From 139 to 124 cm depth the pollen diagram (Fig. 9) is characterised by relatively high (up to 53%) non-arboreal pollen (NAP) percentages, consisting of Poaceae and upland herbs. A notable characteristic of this interval is the presence of

obtained, a result very similar to that of the Wittenhorst sample. The OSL chronology obtained from the dunes and the Schlederhorst system (OSL date of 10.3 ± 0.5 ka) is in agreement with the morpho-stratigraphically inferred coeval age of the aeolian and fluvial system. Compared to the biostratigraphic and radiocarbon ages of the Schlederhorst channel fill, the OSL ages are slightly younger.

Youngest meandering level

Morphology, lithology and sedimentary environments

This youngest system is a small-scale single meandering channel (the Berckermann channel, Fig. 3) with a high sinuosity (up to 2.03), dissecting the Schlederhorst system and the dune area (e.g. south of Mehrhoog, Fig. 2). The morphology is perfectly preserved because of the absence of any younger fluvial activity. The pointbar tops in this system are of similar elevation as its precursor fluvial system (ca 19 m +m.s.l.). Its small dimensions (Fig. 2, 3) seem to indicate that this meandering channel represents an underfit local river, of much smaller discharge and catchment area than the river(s) that formed the hosting Schlederhorst system. It is possible that the Lippe (or a flood-plain secondary branch of it) created this morphology: younger erosion by migrating meanders of the main Rhine have wiped out direct morphological evidence for possible Lippe and Rhine connections in the Wesel area (Figs 3, 5c). This erosion due to meandering of the main Rhine does explain the sudden abandonment and undissected preservation of the Berckermann channel.

The channel belt (Unit F7, Fig. 4) generally consists of poorly sorted medium to coarse-grained sand (210-600 μm) with a clear fining-upwards trend and a gravelly channel lag (up to 80 % gravel, max \varnothing :1.5 cm) at about 3 m deep.

Channel fill and biostratigraphy

Channel fill sediments from the Berckermann palaeochannel (Fig. 6) were sampled for TGA and pollen analysis. The results are summarised in Figs 7 and 11 (Diagram Berckermann). The infill of the palaeochannel (Fig. 6) starts with calcareous and siderite gyttja at the base, followed by peat and peaty clay, interrupted by a slightly humic clay layer. Sediments above this clay layer are oxidised and could not be used for pollen analysis.

The lower spectrum of the pollendiagram (174-169 cm depth) is characterised by a dominance of *Betula* over *Pinus* and a high NAP percentage (47%), mainly reflecting high values for Poaceae (44%) and *Artemisia* (2%). In particular the high Poaceae values are typical for PAZ 4b (9.95-9.75 k ^{14}C yr BP; Hoek, 1997a), the Rammelbeek phase of the Preboreal.

From 169 to 159 cm depth the percentage of NAP decreases rapidly, mainly because of the decrease in Poaceae. *Betula* percentages have increased, but are still dominant over *Pinus*.

This interval probably reflects PAZ 4c (9.75-9.5 k ^{14}C yr BP; Hoek, 1997a) of the Late Preboreal. *Populus* pollen, which are characteristic for this biozone and are present in the nearby Schlederhorst channel, are absent in this diagram. This can be attributed to the poor pollen production, dispersal and preservation of this species, causing an under-representation, which has also been seen in recent surface samples of *Betula-Populus* forests (Huntley & Birks, 1983).

The TGA-results (Fig. 7) for the interval from 174-159 show an increase in carbonate percentages, possibly pointing to an increase in temperature. Zagwijn (1994) also described a relatively rapid increase of mean summer and winter temperatures since 9750 BP (Late Preboreal, PAZ 4c) in the Netherlands. The appearance and increase of *Nymphaea* and *Typha latifolia*, indicating minimal mean July temperatures of respectively 12°C and 13°C (Isarin & Bohncke, 1999), also support the rapid temperature increase during this period. The decreasing calcium carbonate from 152 to 137 cm can probably be attributed to a change in the depositional environment towards less open water conditions.

The interval from 159-144 cm depth represents the top part of the calcareous gyttja. This interval is strongly dominated by *Pinus* (up to 62%) while *Betula* values have decreased. This transition is typical for PAZ 5 (9.5-9.15 k ^{14}C yr BP; Hoek, 1997a) of the Late Preboreal. In the interval from 144-135 cm, where lithology has changed from calcareous gyttja to coarse detritic gyttja and peat, the first presence of *Corylus* occurs, indicating zone VI of the early Boreal (9.15-9.0 k ^{14}C yr BP; Van Geel et al., 1981).

In the interval from 135 to 129 cm depth *Quercus* appears, indicating the start of late Boreal PAZ VII (9.0-7.9 k ^{14}C yr BP; Van Geel et al., 1981). Zone VII is also characterised by the presence of *Tilia*, appearing shortly after *Quercus*, at 8300 BP (van Geel et al., 1981). The analysed sample in this interval does not show presence of *Tilia*, indicating that this sample is from after the start of PAZ VII, but before 8300 BP. The transition from zone VI to zone VII coincides with the transition from peat to humic clay. In the top part (<129 cm) *Tilia* is present, but here also *Alnus* shows high percentages, indicating the start of PAZ VIII (7.9-5.1 k ^{14}C yr BP; Van Geel et al., 1981), the Atlantic.

Chronology

The small-scale meandering system is morphologically the youngest fluvial system of the study area. Because the basal sediments in this channel contained insufficient terrestrial macro-remains for reliable radiocarbon dating, a sample 6-8 cm above the base of the channel (BM-1), at the base of PAZ 4c of the Late Preboreal phase has been used. This sample returned 9470 ± 75 ^{14}C BP (11,063-10,585 cal. yr BP, Table 3), in good agreement with the biostratigraphic interpretation (PAZ 4c: 9.75-9.5 k ^{14}C BP).

Discussion

Channel abandonment

The four pollen diagrams and radiocarbon samples were taken from the deepest parts of abandoned channels from different floodplain levels. The biostratigraphical results of the basal fills and the radiocarbon ages enable to reconstruct the timing of channel abandonment and fluvial system change. The results have been combined in Fig. 12, showing the relative ages of the different channel-fill deposits. It shows that the channel fills cover the major part of the Lateglacial and Early Holocene. Based on the biostratigraphic results it can be stated that braided level B, represented by the Eckerfeld diagram, was abandoned just before or during the Older Dryas (PAZ 1c). The Issel-Lippe system (diagram Isselau) and possibly also the Wolfstrang system of the meandering level were active from the start of the Allerød onwards and were abandoned during the Younger Dryas. The multi-channel system, reflected in the Schelderhorst diagram, was active during the Younger Dryas and was abandoned at the Younger Dryas to Holocene transition. Finally, the last channel within the Oude IJssel valley, reflected in the Berckermann diagram, was abandoned during the Preboreal phase of the Early Holocene, indicating a short phase of activity during the very early Holocene.

Chronology

In this study three approaches were used in parallel, to attach an absolute timeframe to the fluvial system changes as observed in morpho-stratigraphic order. The results of biostratigraphic analysis, radiocarbon and OSL dating have been summarised in Table 4. Timing of channel abandonment and fluvial system change are based on both biostratigraphy and radiocarbon ages of basal channel fill sediments. OSL dates are obtained from sandy sediments and date burial by deposition, thus timing the activity of fluvial and aeolian systems.

The timing of abandonment, as derived from the PAZ biostratigraphic results, is internally consistent and satisfies the morphostratigraphic constraints to chronological order. It is further supported by the radiocarbon dates collected at the base of the channel fills, although the dates derived from *Carex* macro remains appear to suffer from a reservoir age effect, attributable to calcareous ground water seepage (Nilsson et al., 2001).

The OSL dating results are also internally consistent when taking into account the uncertainty on the individual estimates. For the Issel-Lippe meandering system, the obtained activity age is only slightly older than abandonment age, in line with the expected relation. For the multi-channel system and braided level B, however, the OSL activity dates postdate the PAZ and ^{14}C derived abandonment date. At this stage, we do not know why the OSL results from fluvial sand returned

slightly younger ages, differing 1000-1500 years with ages from PAZ and ^{14}C . Also for Braided level C, the OSL result is younger than was expected based on the stratigraphic position. Since no abandonment dating evidence is available for this unit, its age follows from bracketing older and younger units, and dating accuracy for this unit is not further discussed.

As the local biostratigraphy and radiocarbon ages of this study are in general in good agreement with the regionally established chronostratigraphy of the Netherlands (Hoek, 1997a/b), these have been used in the following description of the palaeogeographic development.

Palaeogeographic development

Late Pleniglacial, Bølling and Older Dryas

During the Weichselian Late Pleniglacial, glacial climatic conditions last reached their maximum (Last Glacial Maximum, LGM). The study area developed a cold and dry periglacial climate with a very sparse vegetation cover and within the limit of continuous permafrost (Kolstrup, 1980). The combination of a nival discharge regime dominated by snowmelt peaks, hill slope soil instability and limited infiltration due to permafrost, the lack of vegetation cover in catchment and valley and, in smaller river systems, relative high aeolian input, caused the formation of vertically aggrading braided river systems in the alluvial reaches of many larger and smaller mid-latitude European rivers (Berendsen et al., 1995; Busschers et al. 2007 (Kreftenheije Fm., Lower Rhine); Klostermann, 1992; Erkens et al., 2011 (Rhine: Niederterrasse NT2, Fig. 13); Kasse et al., 2005 (Niers-Rhine); Huisink, 1998 (Vecht, Maas); Kasse et al., 1995 (Maas); Van Huissteden, 1990 (Dinkel); Rose, 1995 (Thames); Mol, 1997 (Niederlausitz); Kozarski, 1983 (Warta)). Although its braided character is disguised by coversand, we correlate Braided level A to the Late Pleniglacial (following Klostermann, 1992; Van de Meene, 1977; Verbraeck, 1984; Erkens et al. 2011).

The river systems of the Late Pleniglacial are generally of exceptional wide lateral extent and a relative wide braidplain terrace preserved from this time owing to reduced active valley widths from younger times. The wide systems point to effective rapid lateral erosion of larger braided channels at the edge of the braidplain, in which bar systems and secondary channels of low width/depth ratio could subsequently aggrade and vertically rework sediments, producing the traditional braided-style deposits of the Rhine valley (V-schotter of Schirmer, 1990). Our braided level A shows a decrease in grain size and gravel-admixture towards its top, which may be characteristic for the Late Pleniglacial braidplain patches of the Oude IJssel-Rhine course.

In the Lower Rhine system, aggradation during the Pleniglacial is enhanced by the high sediment supply from the Schiefergebirge, evident from the coarser and more angular gravel admixtures in younger Weichselian Rhine units

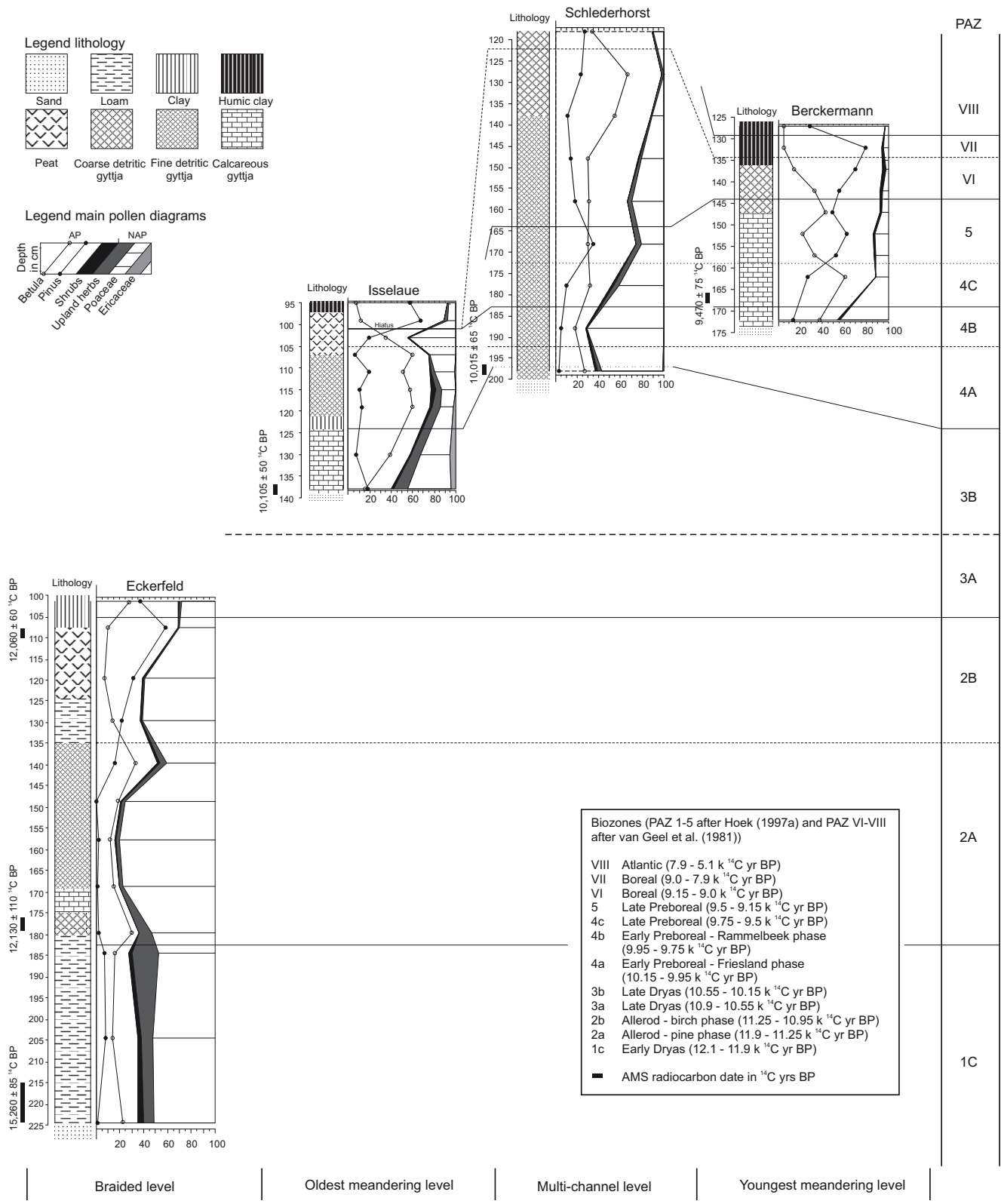


Fig. 12. Correlation of pollen diagrams of this study with the established biostratigraphy of the Netherlands (vertical axis) showing the timing of channel abandonment and fluvial system change (horizontal axis).

Table 4. Overview of dating results obtained from biostratigraphy, radiocarbon dating (given in ka BP) and OSL dating (given in ka). OSL ages are obtained from sandy channel sediments and indicate timing of the fluvial activity. Biostratigraphy and radiocarbon ages are obtained from channel fill sediment and indicate channel abandonment and fluvial system change. Radiocarbon ages of biostratigraphic zone boundaries (given in cal. yr BP $\pm 1\sigma$) after Hoek, 1997a, calibrated using Intcal09 (Reimer et al., 2009).

Floodplain level	Timing of fluvial system abandonment (biostratigraphy of basal fill and calibrated zone boundary ages cf. Hoek, 1997a; Hoek 2008)	Timing of fluvial system abandonment (calibrated radiocarbon ages and majority of analysed macro-remains, sampling depths in Fig. 12)	Timing of fluvial activity (OSL)
Youngest meandering level	Early Preboreal 4B (11.6-11.3 to 11.2)	11.1-10.6 (<i>Betula</i>)	-
Multi-channel system and aeolian dunes	Early Preboreal 4A (12.0-11.7 to 11.6-11.3)	11.7-11.3 (<i>Betula</i>)	10.3 \pm 0.5 11.0 \pm 0.5 (dune) 10.8 \pm 0.7 (dune)
Oldest meandering level	Younger Dryas 3 (12.9-12.7 to 12.0-11.7)	12.0-11.5 (<i>Betula</i>)	13.0 \pm 0.8
Braided level C	-	-	10.7 \pm 0.5
Braided level B	Older Dryas 1C (14.0-13.9 to 13.8-13.7)	14.0-13.8 (<i>Carex</i>) 14.1-13.8 (<i>Betula</i>) 18.7-18.2 (<i>Carex</i>)	

compared to older systems, downstream of the study area (Busschers et al., 2007). Fluvial modelling experiments for Rhine and Meuse also demonstrated gradual coarsening and increasing valley aggradation downstream of the mountain front of the Schiefergebirge and Ardennes respectively (Van Balen et al., 2010). Longitudinal propagation of aggradation might have controlled the routing and partitioning of the Rhine over its three Late Pleniglacial courses.

The coversands overlying Braided level A are assigned to the final phase of the Weichselian (Kasse, 2002: aeolian phase II, c. 15-12.5/11.9 ^{14}C ka BP). This aeolian phase marks the end of the Late Pleniglacial and continues into the Bølling and Older Dryas periods, when interfluvial permafrost had decayed and snowmelt infiltration capacity was restored. Better infiltration reduced overland flow and sheet erosion, enabled the regional preservation of aeolian sediments (Kasse, 1997). In the Oude IJssel valley area, the active braidplains of Rhine and tributaries were additional sources for windblown sand (Van de Meene, 1977; Cohen et al., 2009).

A decreasing active braidplain width and terrace formation towards the end of the Late Pleniglacial has been described frequently in the Netherlands and Germany (Berendsen et al., 1995 (Rhine & Maas); Kasse et al., 1995 (Maas); Van Huissteden, 1990 (Dinkel)). In the study area, this contraction can be recognised in the accumulation of floodplain Unit F1b on top of Braided level A, and subsequently in the abandonment of Braidplain B (preserving Unit F2), leaving only the area occupied by Braidplain C active (Unit F3).

Schirmer (1990), Klostermann (1992) and Erkens et al. (2011) describe braided levels of Pleniglacial age in the central Rhine valley (referred to as the NT2-terrace). Although a morphological connection between the NT2 terrace in the central Rhine valley and braided levels A, B and C in the Oude

IJssel-Rhine valley cannot be established due to erosion by younger fluvial systems, it is likely that these terraces were connected during the Pleniglacial and formed one braidplain at this reach. Assuming that this Pleniglacial braidplain covered both the Central Rhine valley and the Oude IJssel-Rhine valley, it can be stated that the eastward shift of braidplains A, B and C suggests a decrease in lateral extent of the braidplain, indicating flow contraction over a smaller width.

The Older Dryas age of the first channel fill in braided level B (Fig. 8, 12) and the attribution of overbank deposits of the meandering IJssel-Lippe system to the residual channel of Braidplain B, imply that flow contraction in the Oude IJssel-Rhine course had set on before the Older Dryas. This is in good agreement with a channel fill sequence in the NT2-terrace of the Central Rhine, which indicated a first infill of Older Dryas age (Diagram Ratingen-‘Pieperkamp’ in Schirmer, 1990). The cause for the contraction of the river system is sought in the various effects of progressing climatic amelioration in the hinterland: decayed permafrost, restored hydrological infiltration and a less peaked discharge regime of mixed nival and pluvial character. In our study area, changed partitioning of Rhine discharge between the central course and the Oude IJssel valley may have further accentuated contraction and preservation of multiple Late Weichselian braidplain levels. The biostratigraphic results indicate that these braiding conditions continued over the Pleniglacial to Late Glacial transition (onset Bølling) despite the significant warming that occurred at this transition (Renssen & Isarin, 2001). It shows that contraction of flow into a narrower zone is a relative fast way of river response to a (hydrologically) changing climate. Depositional style changed only subtly, showing that true morphological and depositional style transitions (e.g. from bed-load deposition dominated braided to levee-building

mixed-load meandering systems) required longer time. Because autogenic processes in the river valley can modulate the propagation of climatic impacts on upstream elements on the river system, climate-induced transitions in downstream reaches of larger rivers with multiple branches may take different form and longer time to settle than smaller rivers with less complex catchments (e.g. Erkens et al., 2009). The delayed response to the early Lateglacial warming and related transition from braided to meandering in the Oude IJssel-Rhine valley can be estimated at circa 700 year (Bølling period), which is in agreement with previous results for the Niers-Rhine valley (Kasse et al., 2005)

Allerød

By the time of the Allerød, permafrost had disappeared completely from our latitudes and most of the hinterland to the south. Precipitation now could infiltrate unfrozen soil everywhere and peak discharges diminished further, even though precipitation may have increased (Renssen & Bogaart, 2003). The progressive recovery of vegetation during the Bølling and Allerød increased the evapotranspiration and soil water retention capacity and discharge probably decreased gradually. Where barren, unfrozen soils initially may have continued to deliver sediment to the rivers, developing vegetation stabilised soils and decreased hinterland sediment delivery to the river (Vandenberghe, 1995; Berendsen et al., 1995; Gibbard & Lewin, 2003). This explains why many European rivers transformed from multi-channel braided, through transitional phases, to eventual single-channel meandering systems that used part of the abandoned braidplain as their floodplain (all aforementioned studies of Rhine and Meuse). Meandering palaeochannels located in the Pleniglacial braidplain (NT2) of the Central Rhine valley suggest a comparable river system style change to meandering, although it is unclear whether these meandering channels reflect former Rhine channels (Erkens et al., 2011) or smaller local streams (Schirmer, 1990).

In the Oude IJssel-Rhine valley two meandering courses are well preserved (Unit F4 and F5, Fig. 4). The start of the activity of the meandering systems is determined by the biostratigraphy and radiocarbon age of the basal fill of a channel in braided level B (site Eckerfeld, Fig. 3, 4). The Eckerfeld pollen diagram (Fig. 8) shows that the first organic and carbonate deposition in the residual channel (~180 cm depth), related to the abandonment of the braided system and onset of the meandering system, has been dated at the Older Dryas - Allerød transition. This indicates that despite the abrupt climatic change at the start of the Lateglacial, the Oude IJssel-Rhine system did not respond instantaneously by changing fluvial system style (Fig. 13). The delayed response in fluvial system style to the abrupt climatic change can be explained either by the gradual development of the vegetation cover and related discharge and

sediment supply changes or by intrinsic (autogenic) adjustments of the river and the time required for flow contraction and system style transformation (Erkens et al., 2011).

The meandering system probably persisted during the Allerød. In the IJssel-Lippe system, levee deposition increased at the end of the Allerød and onset of the Younger Dryas (indicated by clastic sedimentation in core Eckerfeld, Fig 7, 8). Both Allerød meandering systems of the Oude IJssel-Rhine show no channel belt incision. This is a remarkable difference with other large Allerød meandering systems in northwestern Europe (e.g. the Meuse valley (Huisink, 1998) and downstream continuations of Rhine and Meuse in the central Netherlands (Cohen et al., 2002), which are found in relative incised position). The Allerød meander belt in the Niers-Rhine course, carrying a minor proportion of the Rhine discharge at the time, as did the Wolfstrang system of the Oude IJssel course, also shows no floodplain incision. According to the model of Starkel (1983) meandering systems at climatic transitions start to incise when their decrease in sediment load exceeds their decrease in discharge. This would apply to the main channels of the Rhine and Meuse, but apparently not to secondary branches carrying small proportions of water, such as those in the Oude IJssel-Rhine and Niers-Rhine systems. This size-induced difference in (slow) incisional response to climate change has implications for the further concentration of flow in the Lateglacial. The deepening channels of the Central Rhine course would draw increasingly more water from the secondary courses, retarding these secondary systems even more in positive feedback (Cohen, 2003; Busschers et al., 2007; Hijma et al., 2009; Erkens et al. 2009; 2011). This drove the eventual abandonment and slowly transformed the Oude-IJssel and Niers-Rhine into systems used at flood stage only and then not even flooded anymore – but this process was interrupted by the Younger Dryas climatic cold spell and by events associated with the eruption of the Laacher See volcano some 200 years before the onset of the Younger Dryas.

Younger Dryas

The climatic cooling of the Younger Dryas triggered major fluvial response in many river systems in Europe, including the Rhine (Pons, 1957; Kasse et al., 1995; Rose, 1995; Antoine, 1997). Lower temperatures resulted in an opening of the vegetation cover (Hoek, 1997a), increased natural soil erosion, local re-establishment of permafrost conditions (Bohncke et al., 1993; Isarin, 1997) and a return to a nival discharge regime. A major increase in effective precipitation combined with the lowered soil infiltration capacity caused larger peak discharges, in particular during spring snow melt, besides increased delivery of sediment to the river. This explains the (re)establishment of multi-channel and braiding systems that is seen in many European valleys in this time period (e.g. Huisink, 2000). There are counterexamples of European valleys, however, that did not

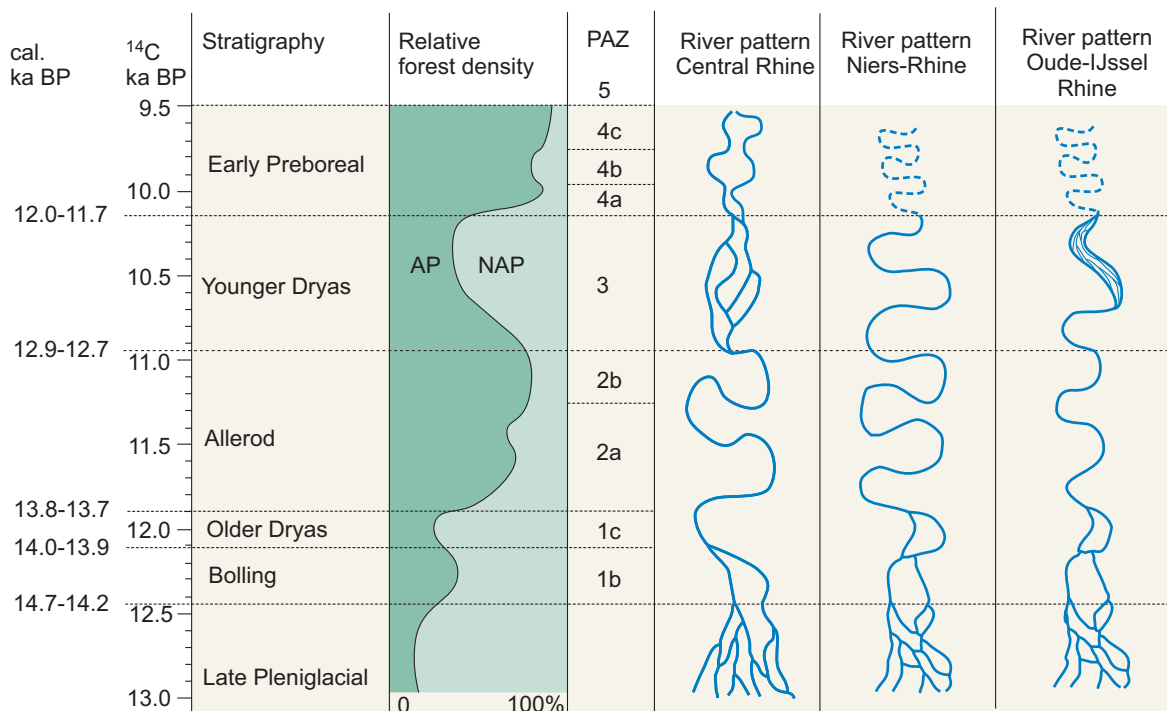


Fig. 13 Synthesis of climate and vegetation-related fluvial pattern evolution of the Oude IJssel-Rhine compared to fluvial pattern changes of the Maas, Central Rhine and Niers-Rhine. Relative forest density and pollen assemblage zones after Hoek (1997a); Fluvial pattern evolution of the Niers-Rhine after Kasse et al. (2005). Fluvial patterns evolution of the Central Rhine based on Erkens et al. (2011). Calibrated radiocarbon ages of biozone boundaries after Hoek, 1997a, calibrated using Intcal09 (Reimer et al., 2009).

see a braidplain re-establish. For example, the Warta in Poland (Vandenberghe et al., 1994), the Scheldt in Belgium (Kiden, 1991) and the Tisza in Hungary (Kasse et al., 2010). The Rhine has examples of both these behaviours.

The Younger Dryas channel through the Niers-Rhine course did not transform into a braided system (Kasse et al., 1995), unlike the main Central Rhine (NT3 terrace cf. Erkens et al. 2011) and unlike the Wolfstrang meandering channel (Unit F5) of the Oude IJssel-Rhine course (this study). The latter transformed into the multi-channel Schlederhorst system (Unit F6), whereas the second Oude-IJssel Allerød meandering system (Issel-Lippe, Unit F4) shows increased levee build up. Just prior to the Younger Dryas onset, a major flood passed the Rhine due to the breaching of a temporal pumice dam in the Middle Rhine, formed by the Laacher See eruption (Schmincke et al., 1999; Baales et al., 2002; Litt et al., 2003). In the Lower Rhine Embayment, this may have helped to transform the Allerød floodplain into the braidplain that it was in the Younger Dryas (Erkens et al., 2011) and may have played a role in the focusing of Rhine discharge in the Central Rhine and the Schlederhorst system.

In comparison to the gradual fluvial response (braided to meandering transitional system) to the early Lateglacial warming, the fluvial response to the Younger Dryas cooling seems to be more instantaneous as transitional channel patterns have not been documented. However, preservation of such warm to cold transitions will be low because their traces will

have been removed by the laterally eroding high-energy braided system. In the Central Rhine valley an up to 10 km wide braidplain (NT 3) developed (Erkens et al., 2011).

The Issel-Lippe system in the northeast did not transform into a braided system but remained meandering and formed well-developed natural levees (Fig. 2, 3, 4). The palynological analysis on the nearby Eckerfeld core (Fig. 8) shows the transition towards the Younger Dryas at the lithological break from peat to clay at the top of the diagram. The cross-section (Fig. 4) shows that this clay is part of the levee deposits, belonging to the Issel-Lippe system, overlying the analysed Eckerfeld core, suggesting that the natural levees of the Issel-Lippe system were formed during the Younger Dryas. The first infill of the Issel-Lippe meandering system dates from the second part of the Younger Dryas, framing the abandonment of the Issel-Lippe system around the transition from the first to the second part of the Younger Dryas. We relate this to the dune field activity in the southwest of the study area during the second phase of the Younger Dryas: newly formed river dunes probably blocked the northward Lippe flow (Fig. 5b), resulting in the abandonment of this Issel-Lippe system. From that moment onwards the Lippe connected to the Schlederhorst system and/or the Central Rhine.

The meandering Wolfstrang system transformed into an incising multi-channel to braided Schlederhorst system (Fig. 2, 3). It is envisaged that an already relatively deep and confined main meandering channel widened itself with successive

Younger Dryas floods, laterally eroding precursor fluvial sediments and aeolian overburden, lowering the bed surface.

The first infill of the Schlederhorst multi-channel system was dated at the Younger Dryas - Holocene transition (Fig. 10), framing the activity of the Schlederhorst system to the Younger Dryas.

The difference in fluvial behaviour of the Issel-Lippe and the Schlederhorst systems is probably best explained by their difference in catchment and position in the Rhine drainage network. The Issel-Lippe system was mainly build by the river Lippe river and will not have carried discharge of the Rhine except during extreme peak discharges. The Schelderhorst system, on the other hand, had clear connections with the main Rhine system (Fig. 2, 3) and can be regarded to have captured the Lippe tributary, probably increasing its baseflow during low stage. Furthermore, the dimensions of the Lateglacial fluvial and aeolian morphology in the Dutch part of the Oude IJssel valley is too large to be formed by local rivers (Issel and smaller) only, suggesting Rhine or Rhine-Lippe activity in the Oude IJssel valley (van de Meene, 1977; Cohen et al., 2009). In addition, occasional finds of Laacher See pumice encountered in the downstream continuation of the Schlederhorst system (unpublished data Utrecht University) confirm Rhine floodwaters to have used the Oude IJssel valley following the Laacher See eruption, i.e. in the Younger Dryas. The different morphological response in the first part of the Younger Dryas cooling can be attributed to differences in sediment composition (relative role of bed load and fines), and differences in the degrees of regime change. The discharge/sediment ratio in the Issel-Lippe system seems to have been more constant over time.

Early Holocene

During the early Holocene, meandering and incising systems developed in the Netherlands as a result of the rapid recovery of forest (Bohncke, 1993; Hoek, 1997a; van Geel et al., 1981). More evapotranspiration and higher water retention capacity of the soil caused a decrease in discharge, while sediment load decreased due to higher soil stability by the denser vegetation cover. In the Oude IJssel valley the multi-channel Younger Dryas system (Schlederhorst) was abandoned because discharge was concentrated in large-scale meandering channels of the Central Rhine course (Fig. 1, 3 (west of Mehrhoog), 13). The abandonment of the multi-channel system is dated by the first organic infill of the Schlederhorst channel at the transition from Younger Dryas to Early Holocene (Fig. 10). A small highly sinuous meandering channel (Berckermann, Fig. 3) remained active in the former multi-channel Schlederhorst system during the start of the Holocene. The strong Holocene erosion around Wesel leaves it unclear whether this Berckermann channel was the full Lippe (the most simple explanation), or a branch of it, or a very small secondary Rhine channel. South of Mehrhoog the Berckermann channel seems to be covered locally

with aeolian deposits (Figs 2, 5c, d). These sediments have not been dated, so it is unclear whether these aeolian deposits were formed by local continuation of aeolian activity after the Younger Dryas to Holocene-transition (as has been reported for other European river system by Kasse et al., 1995; Bateman et al., 1999; Kozarski, 1990; Manikowska, 1991, 1994; Schlaak, 1997) or by local medieval reactivation due to anthropogenic influences.

The organic infill of the Berckermann channel started during the Rammelbeek phase (Fig. 11). Since this is the last channel generation in the Oude IJssel-Rhine valley, it can be concluded that the Oude IJssel-Rhine valley was finally abandoned during or just before the Rammelbeek phase, although throughout the Late Weichselian, Rhine and Lippe discharge was progressively lost to the Central Rhine, stepwise and gradually. In that respect, the development is similar tot that of the Niers-Rhine valley, where very last minor fluvial activity would date to the Early Preboreal too (Kasse et al., 2005), and it is suggested here that the abandonment of both Rhine courses echoes the same ruling mechanisms.

It has been postulated that the secondary Rhine courses abandoned as the outcome of incisional competition with the evidently bigger channels of the Central Rhine as the winner (Erkens et al., 2011). The gradual warming within the Late Pleniglacial and the stepwise warming at the start of the Bølling-Allerød initiated the competition. The climate warming at the start of the Holocene, and its regulating effect on discharge, vegetation development and sediment supply (Kasse et al., 1995; Erkens et al., 2011) would have accelerated the incision and turned out the decisive event for the Oude IJssel abandonment. The single channel Berckermann system functioned an estimated 300 years in the Early Holocene only. Note that the Early Holocene abandonment of the Oude IJssel valley does not mark the completion of the glacial-interglacial transition of the Rhine system as a whole. Within the Central Rhine system, several parallel meander belts were functioning at the onset of the Holocene and in the reach upstream of Wesel it lasted a further 2000 years before the Rhine was truly a single-channel system (Erkens et al., 2011)

Conclusions

1. The Oude IJssel-Rhine valley reveals a fluvial archive of environmental change spanning the Late Pleniglacial to early Holocene period. A braidplain complex with two set in meandering systems is well-preserved and documents sequential fluvial system change of an eventually abandoned course.
2. The fluvial development of the Oude IJssel-Rhine course is interrelated with that of the Central Rhine and Niers-Rhine courses. Gradual flow and discharge concentration into the Central Rhine course, which has a gradient advantage, explains how the Oude IJssel-Rhine and Niers-Rhine were abandoned.

3. The pacing at which the discharge repartitioned to the Central Rhine, however, relates to fluvial response to climatic amelioration and interrupting events such as the Younger Dryas. We dated the fluvial developments in the Oude IJssel-Rhine valley during the glacial-interglacial transition and explained these as the direct and indirect results of climate forcing and associated vegetation and discharge changes, with additional attention to autogenic fluvial behaviour and study area particularities such as bifurcations and tributary confluence.
4. The main fluvial response to the Late Pleniglacial and Lateglacial climate warming is contraction of flow to a narrower zone in the valley, leaving former braidplains as abandoned floodplain levels.
5. A second, slower, response is transformation of fluvial style. In the Oude IJssel-Rhine valley, transformation from a braided to a meandering system appears to have completed shortly before the Older Dryas.
6. The duration and degree of morphological expression of the transitional phases varies between the different systems of the three Rhine courses.
7. The river Lippe had a separate courses into the Oude IJssel valley, notably the Issel-Lippe meandering system, that functioned across the Allerød - Younger Dryas transition. The successor Lippe system of the Younger Dryas was confluent with the last Rhine branch through the Oude IJssel course (Wolfstrang/Schlederhorst system).
8. The Rhine-connected Wolfstrang and Schlederhorst system was meandering in the Allerød and during the Younger Dryas enlarged and incised to become a multi-channel system. This pattern change was accompanied by extensive fields of parabolic dune formations. Neighbouring periodically emergent river beds acted as a their sediment source.
9. At the start of the Holocene, discharge in the Oude IJssel-Rhine valley strongly declined and a local meandering channel developed, which was abandoned just before or during the Rammelbeek phase of the Early Holocene, circa 300 years after the Lateglacial to Holocene transition.
10. The abandonment of the Oude IJssel-Rhine and Niers-Rhine courses can be mechanistically attributed to deep incision of the Central Rhine course in the earliest Holocene and is considered to be controlled by climate-induced flow contraction.
11. The fluvial response and final abandonment of the smaller Oude IJssel and Niers-Rhine courses was fast compared to the slow transformation to a single-channel meandering system of the Central Rhine.

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