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Stratigraphic analysis and paleoenvironmental implications of the Wijchen Member in the lower Rhine-Meuse Valley of the Netherlands

W.J. Autin

Department of the Earth Sciences, SUNY College at Brockport, Brockport, New York 14420, USA. Email: dirtguy@esc.brockport.edu

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Abstract

The Late Pleistocene Wijchen Member (WM) and its informal stratigraphic precursors have been recognized for decades in the Rhine-Meuse Valley of the Netherlands. Although the WM marks the top of the Kreftenheye Formation (KF) at the boundary between Pleistocene and Holocene lithofacies and provides a confining bed for the regional alluvial aquifer, significant issues remain regarding WM depositional environment and processes of sedimentation. Regional WM chronology suggests a time-transgressive, millennium scale response of the Rhine River to Lateglacial climate oscillations. This paper compares interpretations of sedimentation process, stratigraphic pattern, and paleoenvironmental significance to prevailing viewpoints on the WM mode of origin.

A flood basin in the Over Betuwe between the channel belts of the Neder Rijn and River Waal is investigated to characterize WM stratigraphy. The KF braided stream deposits (Kb) form a regionally extensive sandy to gravelly lithofacies. As Kb aggradation ceased, fluvial channels incised into local braid plain swales. The WM was deposited during episodes of fluvial activity as a suspended load mud drape across segments of the abandoned braid plain. The WM is a gray silty lithofacies that also contains local admixtures of sand. Explanations for the origin of the sand admixed into the mud include variability in hydrodynamic load across the flood plain, eolian mixing, and/or biogenic mixing. In the study area, eolian deposition of sand onto a wet flood plain surface is the most probable cause for the admixed sand fraction. Pedogenesis of the WM in the study area is limited to gleying under reduced wetland conditions and the development of organic rich vegetation horizons that formed on top of relatively unaltered fluvial strata. Similar reduced soil properties and limited pedogenic development occur downdip to the present coast, but updip of the study area, the WM is the parent material for poorly drained to well drained and oxidized profiles that range from Entisols to weakly expressed Alfisols.

The presence of pumice granules in Kb deposits of the study area indicate that channel belt deposition continued after the Laacher See volcanic eruption in Germany at ~12,900 cal yr. Deposition of the WM occurred episodically throughout the Lateglacial and terminated by the early Holocene. The time interval between the end of WM deposition and subsequent burial by flood basin peat reflects a duration of exposure of at least 3500 yrs. Since regional water table rise affected the area ~5000 cal yrs ago, the early Holocene water table must have been maintained by spring fed ground water sources from nearby ice pushed ridges.

Deposition of the WM is associated with transitional braided to meandering fluvial channels during times when the Rhine-Meuse Valley experienced a sensitive response to rapid climate change. The WM is regionally time transgressive and probably formed during flood plain transitions between permafrost and base-flow driven hydrologic regimes. Regional landscape dynamics suggest that WM deposition and subsequent preservation was driven by fluctuations of the southern limit of permafrost during Northern Hemisphere deglaciation.

Keywords: Wijchen Member, Kreftenheye Formation, Late Weichselian, Rhine River, overbank sedimentation, permafrost hydrology

Introduction

The Wijchen Member (WM) is a regionally persistent stratigraphic marker in the Rhine-Meuse Valley of the Netherlands. The unit has been of long standing interest to Quaternary geologists because of its application to geologic and soils mapping, and that it functions as a regional confining bed for the Rhine Valley alluvial aquifer. The unit also records the transition between braided and meandering fluvial deposition in the region. The stratigraphic character of the WM and the associated

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unconformity contains the physical record of significant paleoenvironmental change in the Rhine-Meuse Valley. Berendsen & Stouthamer (2001) and Törnqvist et al. (1994) provide detailed reviews of early stratigraphic investigations. The definition and use of the stratigraphic unit and its environmental interpretations have been varied, if not loosely constrained. Törnqvist et al. (1994) formally defined the WM as part of the Kreftenheye Formation (KF) that overlies Kreftenheye channel belt deposits (Kb).

Previous research has not resolved a number of issues related to the origin of the WM. 1) Although workers offer explanations for the source of the sand in the gritty mud, field and laboratory data constraining the mode of origin is limited. Possible explanations include variability in hydrodynamic load across the flood plain, eolian mixing, and/or biogenic mixing (Berendsen & Stouthamer, 2001; Törnqvist et al., 1994). 2) Both fluvial overbank and channel fill environments are recognized in the WM, but there is no detailed facies reconstruction that explains WM deposition, nor is there a detailed characterization of the environments of deposition (Törnqvist et al., 1994). 3) The WM pedogenic history has been assessed where the unit is exposed on the land surface updip of the Rhine delta (Miedema, 1987), but the duration of exposure of the WM surface is indirectly measured in timescales of a few millennia. No systematic study of weathering properties has been conducted where the WM is buried by Holocene flood basin sediments. 4) Formation of the WM has been associated with transitional braided to meandering fluvial environments at the termination of the last glaciation (Pons, 1957; Berendsen et al., 1995; Berendsen & Stouthamer, 2001). However, investigations suggest that WM deposition is time transgressive (Törnqvist et al., 1994). Inferred fluvial activity spanning several millennia allow for alternative models for how WM deposition responded to specific paleoenvironmental transitions in the Rhine-Meuse Valley.

This study attempts to reconcile some of the issues related to sedimentation process, stratigraphic patterns, and paleoenvironmental significance of the WM in the lower Rhine-Meuse Valley. The objectives of this study are to 1) characterize WM lithofacies in a representative area, 2) determine WM architectural characteristics and association with underlying and overlying lithofacies, 3) assess the WM environments of deposition, and 4) relate WM stratigraphy to potential paleoenvironmental influences during the glacial to post-glacial transition.

Prior investigations of the WM

Stratigraphy

The WM was originally described as a sandy loam stratigraphic unit in Rhine-Meuse Valley soil mapping investigations. Geomorphological mapping defined the geographic extent and stratigraphic position of the loam bed that separates Holocene overbank sediments from the underlying Late Weichselian braid plain (Pons & Schelling, 1951; Pons,1957, 1966). Although the fine grained clastic bed was known as *loam bed* (*Hochflutlehm* of Pons, 1957), lithologically it is rarely loam. Doeglas (1951) interpreted the loam bed as initial overbank deposition from an incipient meander belt around the Pleistocene-Holocene transition. The loam bed consists of firm massive silty clay and clay with a thickness of usually 0.5 to 1.0 m (Berendsen & Stouthamer, 2001). Silty lithofacies found at the base of correlative residual channels fills are included in the WM by Berendsen & Stouthamer (2001).

Zonneveld (1958) established the KF as deposits of the Rhine River. Deposition occurred from the Late Saalian glacial maximum to the Early Holocene to produce a 10-25 m thick deposit. The KF is informally subdivided into 6 units based on petrology (Ruegg, 1994; Busschers et al., 2005; Busschers et al., 2007; Busschers, 2008). Stratigraphic units 1 to 4 predate Late Weichselian, and unit 5 reflects Pleniglacial braided river aggradation. Units 6a and 6b form the uppermost strata. Unit 6a includes fluvial channel and bar deposits (Kb), and the distribution of residual channels reflects the regional braided stream pattern. Unit 6b is the WM, a stiff light gray fine grained overbank deposit with admixed sand grains and a thin cm-scale A-horizon.

Törnqvist et al. (1994) defined the WM as part of the KF. They argue that the term *loam bed* was used for a wide range in textures that occur in the same stratigraphic position, thus the name evolved into informal stratigraphic nomenclature rather than a characteristic of the deposit. The presumed fluvial origin also added a genetic connotation to the term. The intermixing of lithologic, genetic, lithostratigraphic and chronostratigraphic characteristics was considered as ambiguous. While Törnqvist et al. (1994) provide a stratigraphy useful for applied purposes and a framework for future research, the sedimentary history of the deposit remained unaddressed.

Pedogenesis

Koenigs (1949) inferred that the loam bed experienced prolonged weathering due to its firm consistence and low organic matter content. He suggested that early Holocene water table lowering promoted surficial weathering. A dark colored surface layer was interpreted as a vegetation horizon (a buried O or A horizon). Soil formation was assumed to coincide with low fluvial sedimentation rates. Earlier workers assumed the admixed sand in the loam bed originated from the underlying fluvial sands by bioturbation processes (see Törnqvist et al., 1994 for a detailed discussion).

Miedema (1987) assessed the pedogenic history of the loam bed by mapping soil landscape and parent material variability in Rhine Valley flood basins. Lithologic and pedologic characteristics of the loam bed vary locally depending on the degree of weathering, soil formation, and initial lithologic properties.

Soil profiles are completely decalcified and the vegetation horizon is absent where the loam bed overlies fluvial sand and gravel and is locally covered by Holocene deposits. Three soil morphologies were defined based on internal soil drainage and landscape position; well drained profiles, imperfectly drained and mottled profiles, and poorly drained gley soils.

Chronology

The regional distribution of the WM is linked to the evolution of the Rhine-Meuse Valley during the Lateglacial, a time when fluctuating climatic conditions led to the formation of two terraces that are now buried, the Lower Terrace and Terrace X (Pons, 1957; Törnqvist, 1998; Berendsen & Stouthamer, 2001). The Lower Terrace is mostly a Late Pleniglacial age surface (Teunissen & Van Oorschot, 1967; Teunissen & De Man, 1981; Teunissen, 1990) and a minimum age for the Lower Terrace is supported by channels filled with peat dating from the Bølling-Allerød (Berendsen et al., 1995; Kasse et al., 1995). Lateglacial channels changed to a meandering pattern and incised into the Lower Terrace. Pons (1957, 1966) found meandering patterns of residual channels on top of the Pleniglacial braided river flood plain. His observations were later confirmed by Van de Meene (1977), Verbraeck (1984), Teunissen (1990), Makaske & Nap (1995), Berendsen et al. (1995), Huisink (1999), and Tebbens (1999).

Terrace X of Younger Dryas age was initially recognized as inset within the Lower Terrace in the Land van Maas en Waal (Pons, 1957, 1966). Valley incision is marked by a 1 - 2 km wide channel belt that is 2 m lower than the Pleniglacial terrace (Berendsen et al., 1995). Terrace X is underlain by Kb sand and gravel braided river deposits. The Younger Dryas terrace of the Rhine contains pumice granules (Verbraeck, 1984) derived from the Laacher See volcanic eruption in Germany at ~11,000 RC yr BP (~12,900 cal yr).

The Lower Terrace is about 2 m higher than Terrace X in the eastern part of the Rhine delta, but gradient lines converge in a westerly direction, with the terrace intersection located near Rotterdam (Törnqvist, 1998; Berendsen & Stouthamer, 2001). Burial of both surfaces implies that the WM 1) is time transgressive and has two subunits or 2) is a single unit that drapes channel belts of different age. Stratigraphic and chronologic data demonstrate that part of the WM predates eolian river dune formation, but WM deposition also postdates river dune formation (Bohncke et al., 1993; Törnqvist et al., 1994; Berendsen et al., 1995; Tebbens et al., 1999). River dunes generally date to the latter half of the Younger Dryas (Kasse et al., 1995), and dune formation was probably terminated when forest cover emerged in the Early Holocene (Teunissen, 1983).

Study area

An area in the Rhine Valley of approximately 40 km^2 in the Over Betuwe southwest of Arnhem was selected for stratigraphic mapping and lithofacies analysis (Fig. 1). The study area is sufficiently updip of marine influence to minimize effects of sea level rise on sedimentation. The area is also isolated from significant neotectonic effects of subsidence or uplift on alluvial architecture and sedimentation process (Cohen, 2003; Gouw & Erkens, 2007). Study area selection was based on an initial review of published literature, previous mapping projects, and available stratigraphic data from the Laaglandgenese (LLG) data base of the Department of Physical Geography, Utrecht University (Berendsen, 2005) and TNO –

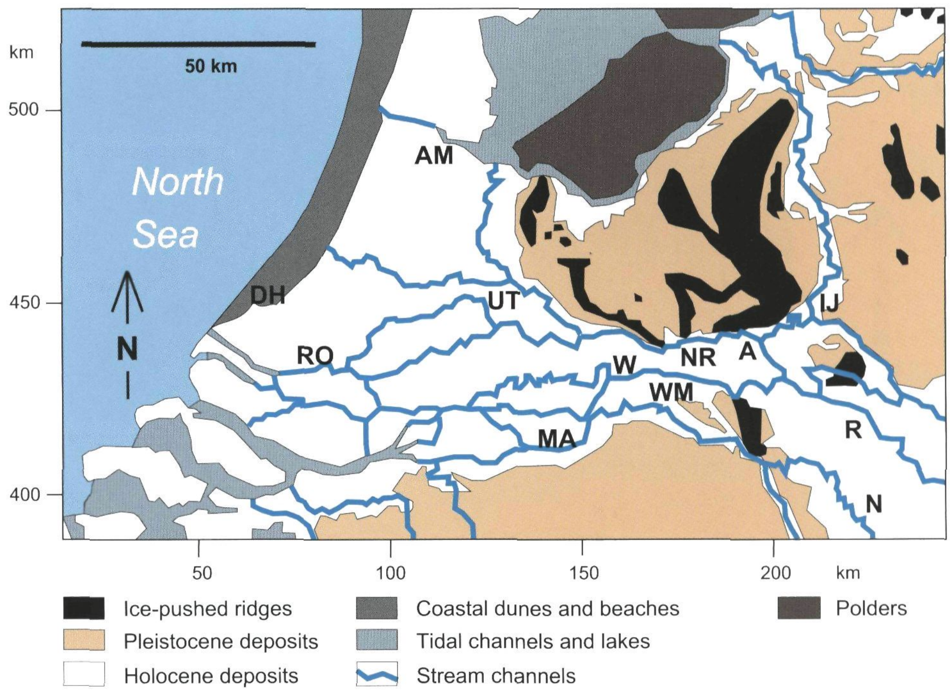

Fig. 1. Principal physical features of the Lower Rhine Valley, central Netherlands. The study area in the Over Betuwe near Arnhem (A) is between the Neder Rijn (NR) and River Waal (W). The Wijchen Member (WM) type area is in the Land van Maas en Waal. Both areas are near the updip limit of the Rhine delta, where the Rhine (R) and Niers (N) enter the delta plain from Germany. Other important channel courses include the IJssel (IJ) and Maas (MA). Principal cities of the region include Amsterdam (AM), Den Haag (DH), Rotterdam (RO), and Utrecht (UT). Distance markings in km correspond to the Rijksdriehoekstelsel grid.

Geological Survey of the Netherlands (NITG) data base. Proximity to the adjacent and well studied Land van Maas en Waal (Fig. 1) facilitates comparison of the study area to geomorphic patterns near the WM stratotype area (Törnqvist et al., 1994).

The study area (Fig. 2) is bounded on the north by the Neder Rijn, which occupies a <500 yr old channel belt that abuts against a Saalian ice pushed ridge and flows along the north edge of the valley. The southern boundary is the 2500 - 4000 yr old Holocene channel belt of the River Waal. Small Holocene stream channels cross the flood basin along the eastern and western sides of the study area and connect the Neder Rijn and River Waal channel belts. Lateglacial fluvial sediments and landforms are best preserved in areas where the WM is buried by Holocene flood basin sequences distal to areas of meander belt occupation, crevassing, and proximal overbank sedimentation. WM preservation is enhanced in areas without significant eolian river dunes or coversands that may bury, interfinger with, or erode the unit. Flood basin stratigraphy is characterized by Holocene overbank deposits that bury and preserve the WM and the underlying Kb deposits.

Methods

This investigation was conducted by developing a database of existing stratigraphic information, then field checking the data with additional borings into the top of Kb deposits. The stratigraphic data base was developed by summarizing 293 LLG and 465 NITG borings into spreadsheets that identified the elevation of the Kb top, WM top, and WM thickness (Table 1). Borings were discarded where the top and bottom of the WM could not clearly be interpreted or Holocene channel belts cross cut and eroded the WM. A total of 49 additional borings (0510 data) were placed along three lines of cross section aligned perpendicular to the valley axis (Fig. 2) to identify lithofacies properties and architectural elements. Coordinates of field borings were located using a hand held GPS and elevations were estimated to 10-cm vertical resolution with DEM data. Contour maps were constructed for elevations on the top of Kb and for WM thickness. The locations of boreholes and relevant database information were plotted with ARCGIS, but contour patterns were manually interpolated and hand drawn to reflect the architecture of the Kb surface and the geometry of the overlying WM.

Detailed core logs were constructed and sampled from two locations representing proximal and distal WM sedimentation. At each location, the WM and the lithofacies directly above and below the unit's contacts were sampled at 5-cm intervals. Sediment particle size distributions were estimated with a Beckman-Coulter LS 230 laser particle size analyzer. The LS 230 uses laser diffraction to calculate particle size distributions from <1 - 2000 µ and lends itself to rapid sample analysis. Mass dependent magnetic susceptibility (MS) were measured with a Bartington MS2B probe. This instrument measures MS at frequencies of 465Hz and 4.65kHz, a technique that aids in

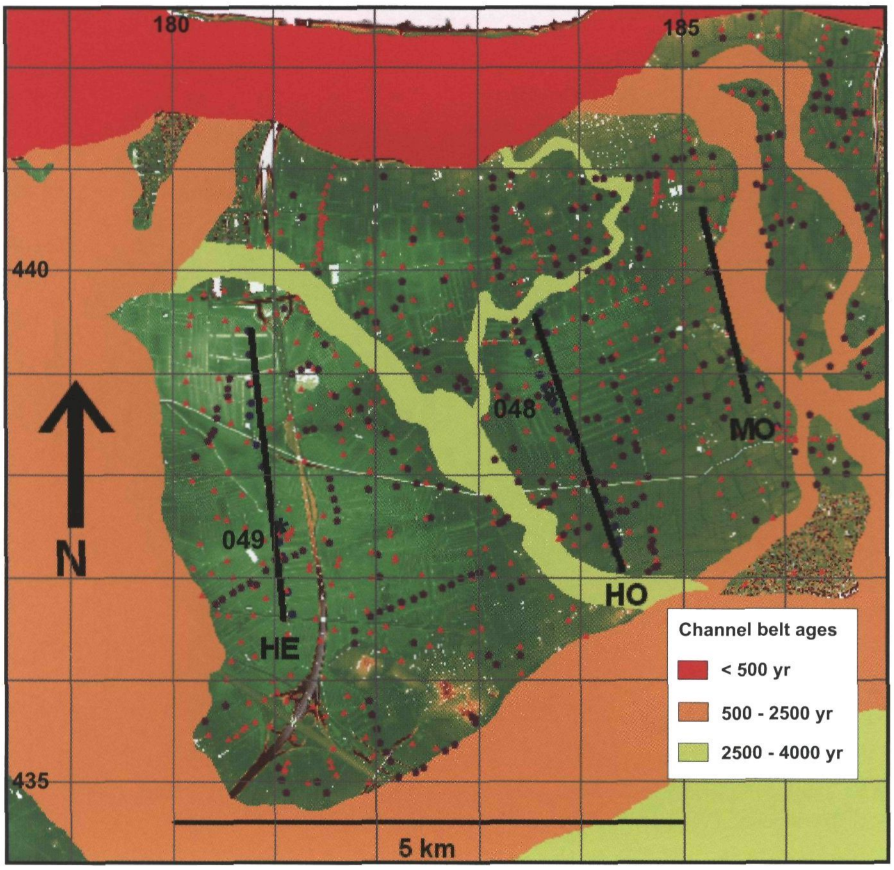

Fig. 2. Combined data distribution for the study area. Boreholes where the WM and Kb were identified in LLG, NITG, and 0510 project data. Location of cross sections Heterensestraat (HE), Hollanderbroek (HO), and Molenstraat (MO) and sampling sites 048 and 049 are identified. Holocene channel belts from Berendsen and Stouthamer (2001). Distance markings in km correspond to the Rijksdriehoekstelsel grid.

Table 1. *Summary statistics of KF stratigraphic data.*

	Kb top (m)				WM top (m)				WM thickness (cm)			
	LLG	NITG	0510	Combined	LLG	NITG	0510	Combined	LLG	NITG	0510	Combined
Maximum	6.7	6.2	5.4	6.7	6.9	6.8	5.9	6.9	160	220	80	220
Minimum	3.0	1.8	1.5	1.5	3.3	2.1	2.1	2.1	10	10	20	10
n	209	446	44	699	280	440	43	763	195	422	43	660
Mean*	4.78	4.66	4.43	4.70	5.23	5.14	4.91	5.18	46.31	49.17	50.47	48.27
Variance	0.50	0.52	0.77	0.52	0.43	0.49	0.73	0.47	618.26	790.17	242.64	736.52
Std. dev.	0.70	0.72	0.88	0.72	0.66	0.70	0.86	0.69	24.86	28.11	15.58	27.14

* Mean values for LLG and NITG are not significantly different from each other at $\alpha = 0.05$.

identifying the presence of depositional and pedogenic MS sources in surficial sediments (Thompson & Oldfield, 1986; Evans & Heller, 2003).

One sample was collected for radiocarbon age estimations using a 7-cm diameter gouge from the basal Holocene organic facies. The radiocarbon age was determined by accelerator mass spectrometry (AMS) in the Van de Graaff Laboratory at Utrecht University.

Samples for optically stimulated luminescence (OSL) age estimations were collected with a Van der Staay suction corer. Four samples were selected from two cores. OSL dating was performed at the Netherlands Centre for Luminescence Dating (NCL) at Delft University of Technology. For equivalent dose estimation, the single aliquot regenerative dose procedure (Murray & Wintle, 2003) was used. Quartz grains of 212 - 250 µ were prepared for analysis. To avoid a contribution to the OSL signal from contaminating feldspar grains, an infrared bleach was applied prior to each luminescence measurement (Wallinga et al., 2002). Based on preheat plateaux tests, a 10 s preheat of 220° C was selected. With the adopted procedure, a laboratory dose could be accurately measured (dose recovery ratio 1.01 ± 0.09) and recycling ratios were excellent (average 1.01 ± 0.01). Dose rate estimation was determined from radionuclide concentrations using gamma ray spectrometry. A saturated water content of 20% water by weight was estimated for the sandy samples. For the loam samples, the water content of 23% water by weight was measured on sample NCL 4306008. Systematic and random errors in equivalent dose and dose rate calculations are taken into account. All OSL ages are reported in cal yr with 1σ confidence intervals. Additional information on OSL dating methods and results is available from the NCL online database (http://www.lumid.nl).

Stratigraphic characteristics of the WM

Characteristics of the WM were determined from 1) lithofacies properties, 2) textural and MS trends, 3) cross sections, and 4) alluvial architecture. This characterization provides a basis for the interpretation of depositional environments for the WM in the Over Betuwe.

Lithofacies properties

The WM overlies the Kb and marks the transition to overlying Holocene overbank deposits (Table 2). The WM is generally grayish in color, has a firm consistence, and varies in texture from clay to loamy sand. Finer grained deposits typically contain admixed sand, roots and stems of wetland reeds, and occasional wood fragments. The WM commonly displays fining upwards trends across its thickness. The Kb lithology is typically stratified lithic sand with occasional granule and pebble gravel. Laacher See (Germany) pumice granules were identified at one location.

Holocene overbank deposits cover the Kb and WM with peat, humic clay, and clay in flood basins, and silt and sand on natural levees and crevasse splays. Vegetation horizons locally mark the top of the WM surface and additional discontinuous buried A horizons occur within organic and clayey flood basin facies.

Flood basin deposits can be subdivided into organic and clayey lithofacies. Organic lithofacies include humic clay to peat that commonly contain abundant wood and grass fragments. Sediments are interbedded layers of varying texture and organic matter content. Changes in the proportion of organic to mineral matter probably reflect variable input of suspended sediment during overbank flooding. Clayey lithofacies are commonly clay to silty clay, massive and lack stratification, occasionally contain wood and grass roots and fragments, and the upper part is typically disturbed by agriculture within 50 cm of the land surface.

Natural levee and crevasse splay deposits range from silt loam to sand. Levee deposits are commonly bioturbated into cambic soil horizons with pedogenically altered soil color and/or soil structure, and the upper part is typically disturbed by agriculture within 50 cm of the land surface. Natural levees are wedge-shaped bodies adjacent to channel belts of the Neder Rijn and River Waal. Crevasse splays have many lithologic properties of natural levees, and can be considered a sub-facies of natural levees. Crevasse splays commonly are fan shaped bodies that coalesce to form aprons adjacent to channel belts and contain ribbon sands encased within the silty fans.

Table 2. Field lithologic and pedologic properties of surficial sediments.

Lithofacies	Horizon sequence	Colour	Texture	Consistence	Comments
Natural levee	Ap - Bwg or Ap - C	10YR 4/2	sandy loam to silt loam	friable	few to common grass roots; upper part disturbed by agriculture
Channel sand (Holocene)	- C	10 YR 5/1	sand	loose	contains loamy interbeds
Flood basin clay	Ap - Bwg - Cg	10YR 4/1 - 5/1	clay to silty clay loam	friable to plastic	few to common grass roots; upper part disturbed by agriculture
Organic flood basin	- Agb - Bgb - Cg (Oei) -	10YR 2/1 - 4/1	humic clay to peat	slightly plastic to friable	abundant reed and grass roots; laminations; OM gradually increases downward, up to 75% OM
Vegetation horizon	- Agb -	10YR 3/1 5Y 3/1	humic clay to silty clay loam	plastic to sticky or greasy	common to abundant reed and grass roots; OM gradually decreases downward
Wijchen Member (WM)	- Cgb -	10YR 4/1 5Y 4/1 - 6/1	clay to loamy sand	firm	fining upward trend; abundant to common reed and grass roots; wood fragments
Kreftenheye Formation (Kb)	- C	5Y 5/1	sand	loose	poorly to moderately sorted; lithic; contains granule and pebble gravel; few to abundant pumice grains

Horizon sequence designations and descriptive terms are adapted from Soil Survey Staff (1999); **Colour** notations from Munsell Soil Colours.

Textural and MS trends in the WM

Sediment cores were collected from two locations (Fig. 2). Borehole 048 is on the Hollanderbroek cross section in a flood basin position distal to WM and post WM sediment sources (Fig. 3). Borehole 049 is on the Heterensestraat cross section proximal to the top bank of a buried WM residual channel (Fig. 3).

The 048 vertical profile consists of a clayey lithofacies over humic clays and peat (Fig. 4). A buried A horizon occurs at the transition between clayey and organic lithofacies. The A horizon has a gradational upper and lower boundary, dark brown to black colour, a slight enrichment in organic matter relative to the overlying clay, and a greasy consistence. The WM is dominantly silty, with very fine sand admixed in the basal interval and very fine to medium sand admixed near the top of the unit. The WM has an abrupt basal contact with the underlying Kb. The Kb is a medium to coarse textured sand with a modal particle size of 250 - 500 μ and occasional granules. Notably, Laacher See pumice granules occur within the stratified sand and gravel below 4 m deep in the profile.

The 049 vertical profile consists of flood basin clay and humic clay that lacks peat (Fig. 4). The WM is dominantly silty, has no sand admixture, and has an abrupt basal contact with the underlying Kb. The Kb is a coarse to medium textured sand with a modal particle size of ~500 μ and lenses and stringers of granules.

The MS trends of profiles 048 and 049 can be explained by depositional processes without significant WM alteration by pedogenesis or diagenesis. Frequency dependant MS was measured through the WM in both the 048 and 049 profiles. The high frequency MS values are essentially identical to the low frequency MS curves (Fig. 4), indicating that the alteration of magnetic mineralogy is insignificant. A minimum of 5 percent decrease in high- versus low-frequency MS indicates magnetic enrichment by pedogenic or diagenetic alteration (Evans & Heller, 2003; Thompson & Oldfield, 1986). Variations in MS of the WM profiles correspond to subtle variations in lithofacies properties, with MS values increasing as grain size increases or with increase in detrital mafic mineral composition. The gradual upward decrease in MS is typical of fining upward texture profiles (Evans & Heller, 2003; Thompson & Oldfield, 1986).

The MS trend of the WM in the 048 profile is typical of muddy sediments and the underlying Kb sand has values higher than the WM. The gradual decrease in MS from the top of Kb, through the WM, to the top of the vegetation horizon reflects the slow aggradation of a flood plain sequence in a position proximal to a channel. A broad sawtooth MS pattern occurs within the Kb below 310 cm. This pattern is common in well stratified sands where MS variation is related to flow dynamic, with MS enrichment corresponding to higher velocity flows necessary to transport denser Fe-Mg siliciclastics. Samples containing pumice granules tend to have suppressed MS values. Volcanism from the Laacher See produces pumice of felsic composition, which has low MS due to lower iron content relative to mafic rocks.

The MS trend of the 049 profile is generally similar to the 048 profile. The MS values increase upwards through the WM interval although the texture trend shows a slight fining upwards tendency. The Kb shows a similar sawtooth pattern associated with variations in the energy of deposition.

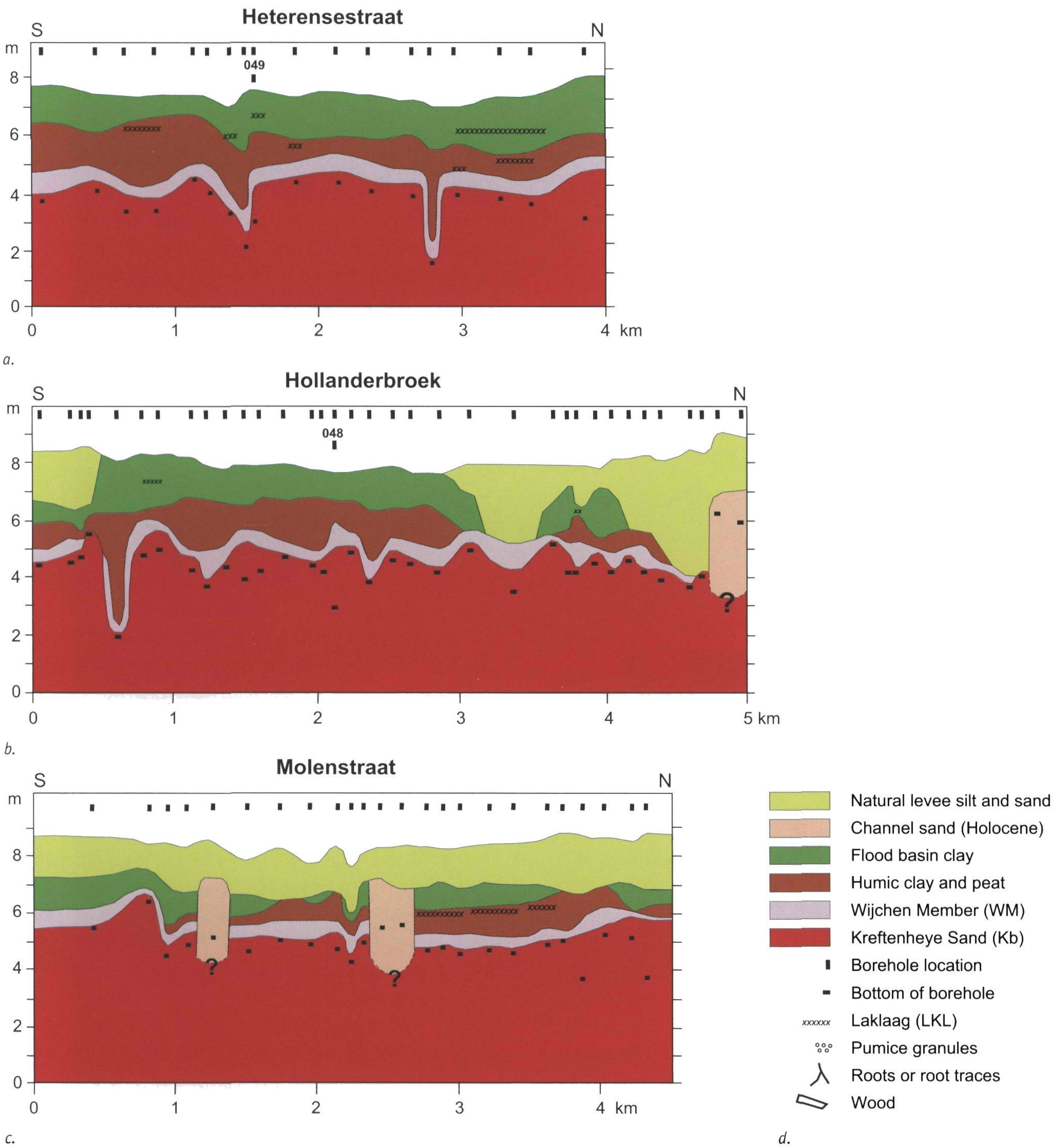

Figure 3. Stratigraphic cross sections: a. Heterensestraat; b. Hollanderbroek; c. Molenstraat; and d. key to cross sections. Elevations are relative to O.D. Locations of boreholes 048 and 049 (Fig. 4) are identified.

Cross sectional geometry

Field work established 3 lines of cross section perpendicular to the valley axis (Fig. 2) at Heterensestraat, Hollanderbroek, and Molenstraat. These locations illustrate downdip, intermediate, and updip architecture across the flood basin.

Heterensestraat (Fig. 3a) is a 4 km cross valley section with land surface elevations between 7 and 8 m. The Kb surface undulates at ~4 - 5 m +O.D. except at two locations where WM residual channels are encountered. In these channels, the Kb top is at 3.0 and 1.8 m +O.D. respectively. The WM drapes the Kb, and the top of WM generally reflects the configuration of the underlying sand body geometry. WM thickness increases slightly between the two residual channels, especially near the channel banks. Humic clays and peats differentially infill the undulating WM surface with 2 - 4 m of organic rich sediment. Clayey flood basin lithofacies cap the flood basin sequence. Scattered discontinuous buried A horizons were identified.

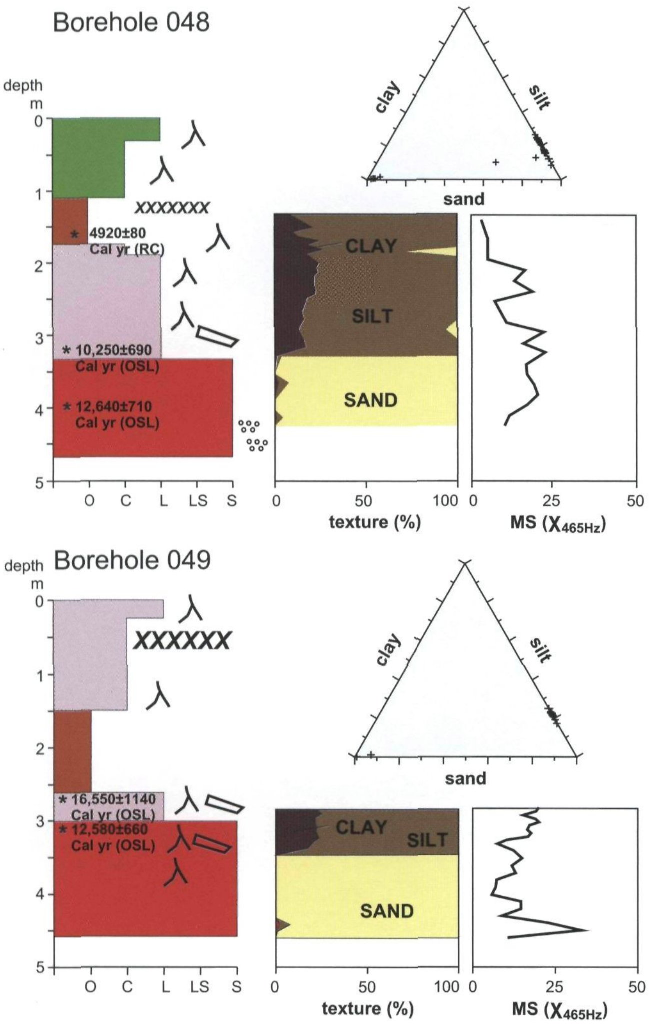

Fig. 4. Lithologic logs, sediment texture, and magnetic susceptibility (MS) profiles of the WM from proximal (048) and distal (049) landscape positions. See Fig. 3d for key to patterns and symbology. The stratigraphic position of radiocarbon and OSL samples are identified. Texture is expressed as per cent and mass dependant MS values are in units of 10^{-8} m^3/kg.

Hollanderbroek (Fig. 3b) is a 5 km cross valley section with land surface elevations between 8 and 9 m +O.D. The northern edge of the section is bounded by an abandoned Neder Rijn channel and the southern edge of the section is bounded by the natural levee of the River Waal. The Kb surface undulates at ~4 - 6 m +O.D., except in one residual channel where the Kb top is ~2 m +O.D. The Kb surface decreases in elevation to the north, as the surface is either aggraded to a differential elevation, differentially cut and filled, or slightly tilted. WM drapes over the Kb tend to thicken in swales and become thin or absent from Kb highs. Humic clays and peats are either absent or thin where Holocene channel belt and natural levee deposition was active. Clayey flood basin lithofacies cap the organic flood basin sequence. Flood basin clays are thickest and most continuous in areas away from the channel belts of the Neder Rijn and River Waal. Natural levees form their thickest wedge-shaped bodies within and near channel belts.

Molenstraat (Fig. 3c) is a 4.5 km cross valley section with land surface elevations between 8 and 9 m +O.D. The section transects a Kb surface buried by Holocene overbank deposits, except for two areas where crevasse channels have eroded the Kb surface and constructed Holocene sand bodies. The Kb surface undulates at ~5 - 7 m +O.D. except at a location where a Kb topographic high produces >1 m of local relief. WM thickness is greatest in areas where the Kb top is flattest and the WM thins across Kb highs. Humic clays and peat deposits are absent or thin where natural levee deposition of the River Waal was active. Flood basin clays are thickest and most continuous in areas away from the River Waal. Two crevasse channels locally eroded the entire flood plain sequence and the base of the crevasse channels probably scoured into the top of Kb sand. Channel sands grade laterally into and are also capped by natural levee deposits. Proximal natural levees from a small channel connecting the Waal to the Neder Rijn drape the entire flood basin sequence.

Topography and thickness of the WM

The WM geometry can be assessed by comparing patterns in the cross sections with a structure contour map of the Kb surface (Fig. 5) and an isopach of WM thickness (Fig. 6). The pattern at the top of the Kb depicts the surface of a sandy braid plain that has been differentially draped by fine grained WM sediments. The Kb surface is locally modified by channels associated with the WM and post-WM Holocene channels.

Frequency distributions of elevation on top of the Kb, elevation of the top of the WM, and WM thickness were extracted from the stratigraphic database (Table 1, Fig. 7). The combined data can be assumed to be randomly distributed, but the project 0510 data used to construct the cross sections is also systematically aligned across the study area (Fig. 2). Mean values of Kb top, WM top, and WM thickness for LLG and NITG data showed no significant differences at α = 0.05. The combined distribution shows an average elevation for the top of Kb at ~4.7 m +O.D., the top of WM at ~5.2 m +O.D., and an average WM thickness of ~50 cm. When the borings from project 0510 were compared to LLG and NITG data, they did test as different from the larger dataset. This situation arises because 1) the size of the 0510 data is <50 borings, and 2) the 0510 data were placed on specific lines of cross section instead of being randomly distributed through the study area.

Elevations on the top of Kb (Fig. 5) are >6 m +O.D. in updip areas and grade to ~4 m +O.D. downdip, except within the axes of post Kb channels. The Kb has ~1 m relief on bar surfaces. Lows in the Kb top are filled with WM residual channel fill. The lowest areas occur in the southwest corner of Fig. 5 near the channel belt of the River Waal and in the northwest corner along the channel belt of the Neder Rijn. The draping of WM over an inset flood plain along the River Waal was documented by Weerts (1996, p. 144, his Fig. 7.4) and Hesselink et al. (2003, p. 236, their Fig. 5).

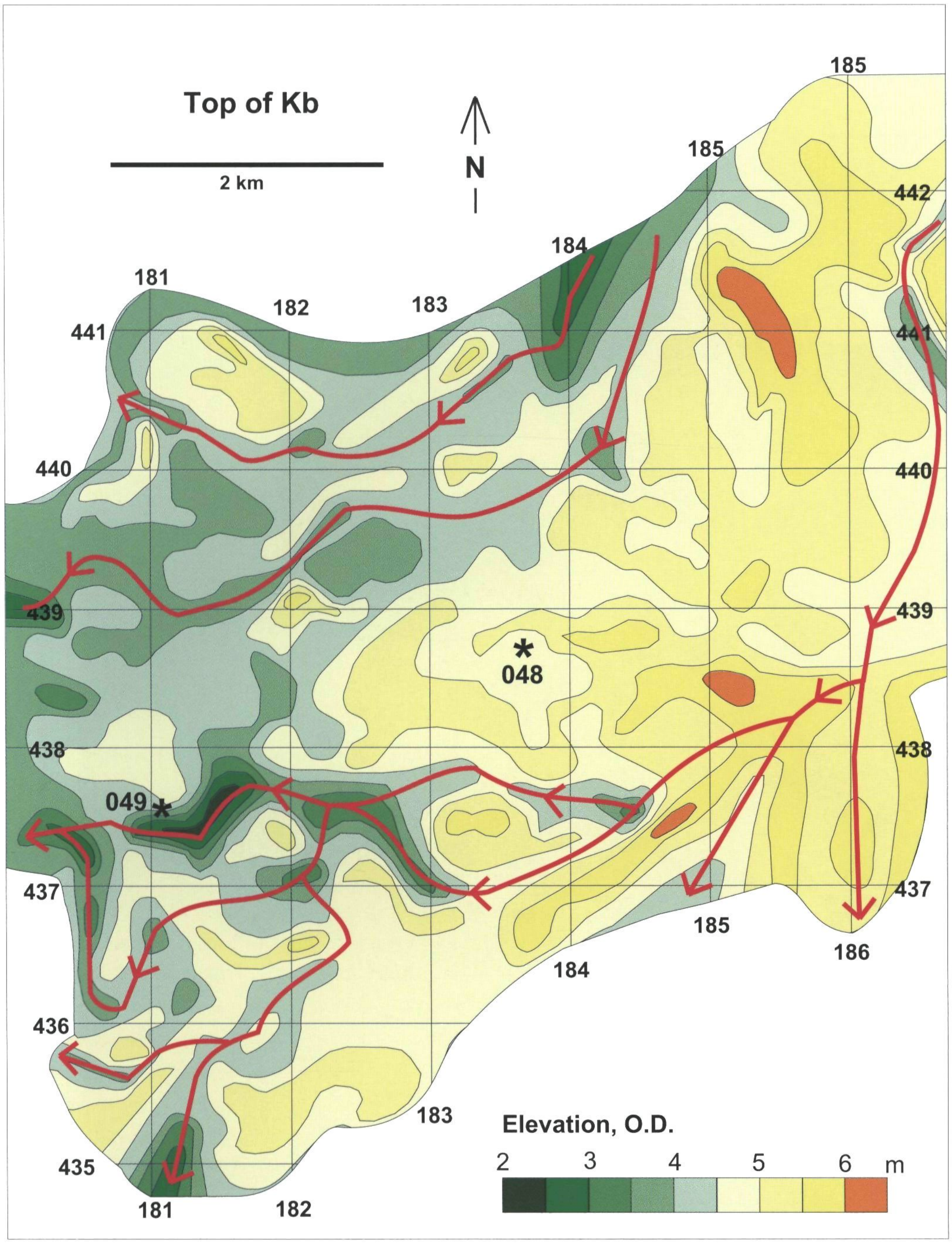

Fig. 5. Elevation on top of Kb. Northern and southern boundaries of the map area are the boundaries of major Holocene channel belts (from Berendsen & Stouthamer, 2001). Smaller Holocene channel belts (see Fig. 2) are omitted. Axes of braid channels (arrows) are inferred from the stratigraphic pattern.

Although the pattern generated from over 600 boreholes provides only an approximate view of the details of the Kb surface, the pattern of Kb elevation difference generally corresponds to the sand atlas mapping of Gelderland Province (Berendsen et al., 2001). The top of Kb decreases across the study area by ~2 m in elevation over ~5000 m downvalley distance for an average slope of ~0.0004. Flood basin fill increases downdip as the flood basin locally widens and thickens into areas more distal to levee sedimentation and crevassing.

The WM is an approximately uniform veneer of ~50 cm (Fig. 6). Areas of anomalous thickness coincide with areas of deepest entrenchment of WM residual channels into the Kb surface. The WM residual channels are more distinct in the west central part of the flood basin. Residual channels are easier to recognize in areas removed from Holocene channel activity.

Chronology

Stratigraphic extent and WM age

Relative stratigraphic relationships between the WM, landform associations, other lithostratigraphic units, and available chronology point to time transgressive WM sedimentation over several millennia. Two lines of stratigraphic evidence demonstrate the regional time-transgressive process of WM deposition

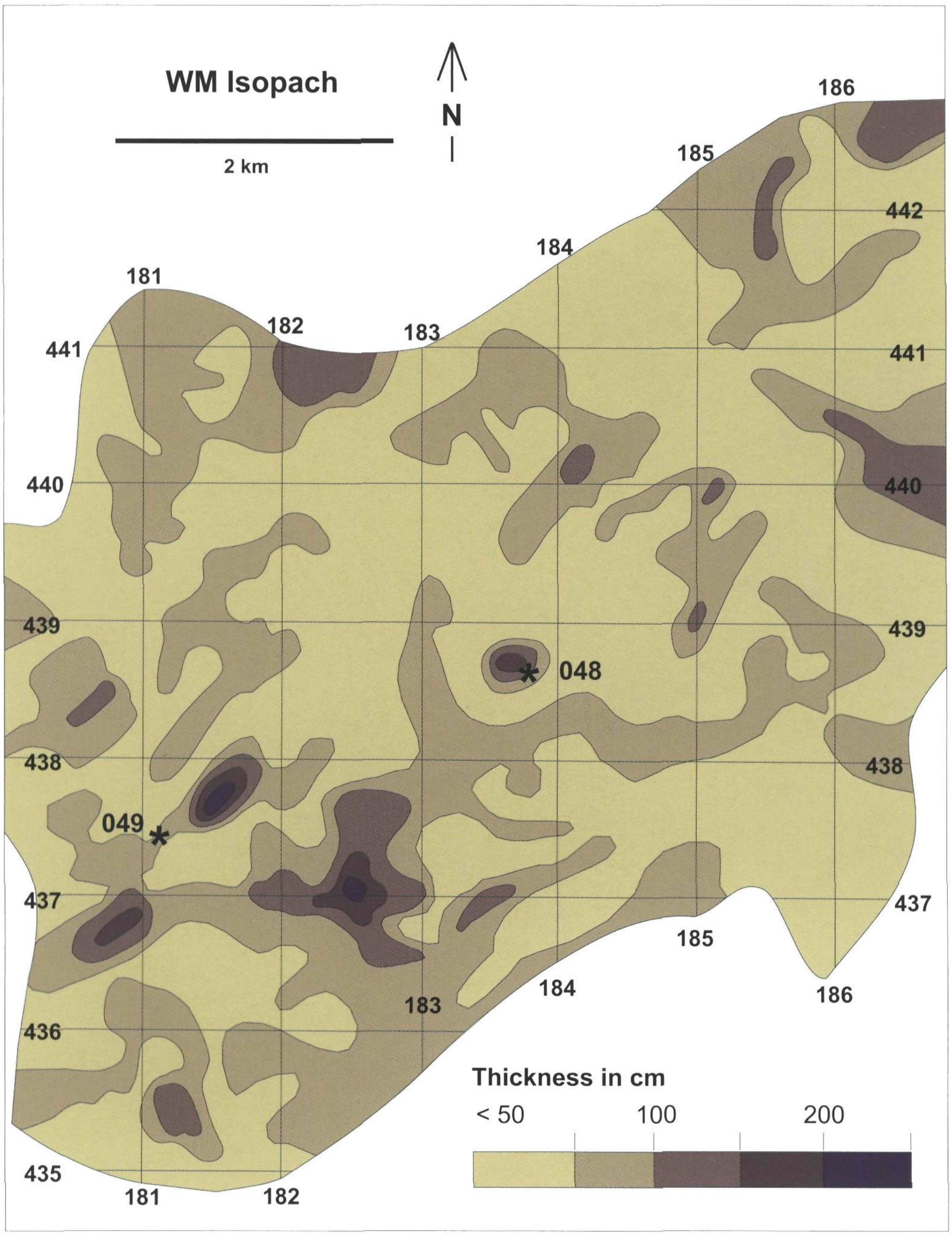

Fig. 6. Isopach of the WM. Northern and southern boundaries of the map area are the boundaries of major Holocene channel belts (from Berendsen & Stouthamer, 2001). Smaller Holocene channel belts (see Fig. 2) are omitted.

and subsequent burial. 1) The WM is widely covered by a variety of younger lithostratigraphic units downdip of the study area (Berendsen & Stouthamer, 2001). Differential burial affects preservation potential, position of the water table within the deposit, and post depositional pedogenic alteration. For example, the WM is exposed as soil parent material updip of the study area (Miedema, 1987), but is essentially unaltered in downdip areas. 2) The WM drapes sand and gravel deposits associated with both the Low Terrace and Terrace X. Sand and gravel deposits from both terraces are part of the Kb (Ruegg, 1994; Berendsen & Stouthamer, 2001; Busschers et al., 2005, 2007; Busschers, 2008).

Relevant radiocarbon and OSL ages in the Lower Rhine Valley apply four different stratigraphic associations to provide age estimations of WM deposition (Table 3). 1) Vegetation horizons are preserved organic rich A or O soil horizons on top of the WM surface. In a pedogenic sense, the WM in the study area is the parent material for buried Entisols (A-C horizon sequence) that form as either gleyed Aquents or stratified Fluvents (Soil Survey Staff, 1999). Vegetation horizons mark abandonment of WM and the preservation of wetland environments that contain datable organic residues from biocycling of organic matter into clayey lithofacies (Törnqvist, 1993). Ages from vegetation horizons provide a minimal age for the termination of WM deposition 2) Basal peat layers reflect wetland aggradation on the WM surface and mark regional ground water level rise (Van Dijk et al., 1991). The basal age marks the time when the water table rises sufficiently to preserve flood basin

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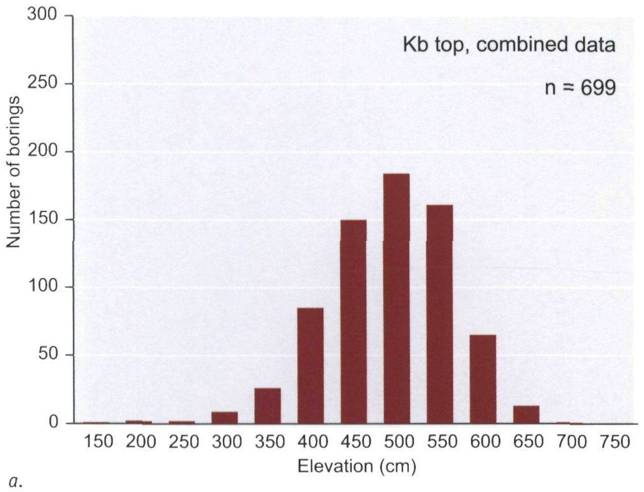
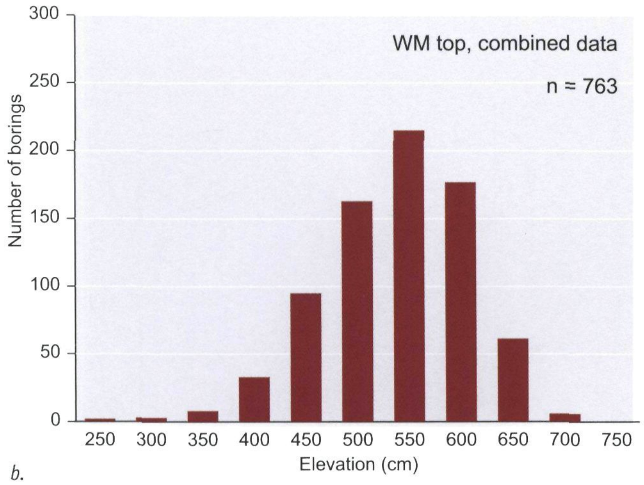
peat. 3) River dunes and coversands bury thin peat layers that drape the WM (Törnqvist et al., 1994; Berendsen & Stouthamer, 2001). Ages from the peats mark WM burial by eolian sedimentation either at fluvial abandonment or when local eolian aggradation rises above levels of fluvial aggradation (Berendsen & Stouthamer, 2001). 4) OSL ages can provide direct estimates of fluvial activity for Kb and WM, respectively. Basal WM sedimentation marks the initial preservation of overbank sediments at a location, provides a minimum age for Kb stream channel activity, and a maximum age for WM meandering or anastomosing channel patterns (Berendsen et al., 1995; Berendsen & Stouthamer, 2001; Kasse et al., 2005).





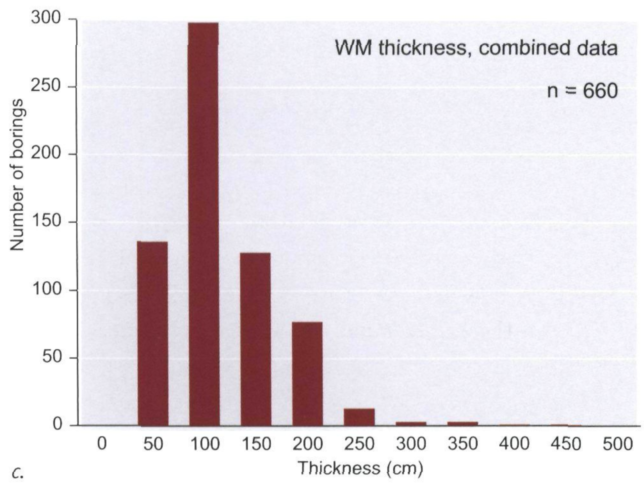


Fig. 7. Frequency distributions of a. elevations at the top of Kb; b. elevations of the top of the WM; and c. WM thickness. Elevations for Kb top and WM top are relative to O.D.

Laacher See (Germany) volcanic eruptions provide additional chronologic evidence by deposition of a widespread marker in the lower Rhine Valley (Berendsen & Stouthamer, 2001). Detrital pumice granules occur in Kb sands near the base of borehole 048 (Fig. 4a), residual channel fills that are probable WM equivalents in the Niers Valley (Kasse et al., 2005), WM of the lower Rhine delta (Busschers et al., 2005), and loamy WM equivalents in the Rhine graben (Dambeck & Thiemeyer, 2002; Houben, 2003; Boenigk & Frechen, 2006). The last eruptive sequence of the Laacher See makes the pumice distribution geologically synchronous (Bogaard & Schmincke, 1985). Sixteen radiocarbon dates associated with the last Laacher See eruption have a mean age of 11,000 ± 50 RC yr B.P. An event scenario is suggested by Park & Schmincke (1997) and Schmincke et al. (1999) where a tephra dam bursts and an ephemeral lake floods the Lower Rhine Valley with detrital pumice. This results in an ~12,900 cal yr time line where pumice granules are found in downvalley fluvial deposits. Friedrich et al. (1999) suggest adjusting the age for the Laacher See eruption to 13,010-13,200 cal yr based on correlation of radiocarbon dates with tree ring, varve, and stable isotope records.

Contrast between Over Betuwe and Land van Maas en Waal

No direct age estimates exist for active WM sedimentation in the Land van Mass en Waal where the WM overlies Kb. Interpretation of landform evolution based on geologic mapping and radiocarbon ages from residual channels suggest that WM activity in Land van Maas en Waal began in the Bølling-Allerød (Berendsen et al., 1995). The assumption is that channel filling reflects a genetic association with braid belt abandonment and flood basin overbank deposition. A succession of multiple channel belt stages are the probable source of the WM veneer draped over abandoned braid belt surfaces.

Stratigraphic and chronologic data from Land van Mass en Waal (Berendsen et al, 1995; Törnqvist et al., 1994) suggest time transgressive WM fluvial activity. An older and a younger phase of WM sedimentation is recognized, with the older loam bed predating river dune formation and a younger loam bed postdating river dune formation. River dunes generally date to the latter half of the Younger Dryas, and dune formation was probably terminated when forests recovered in the Early Holocene (Kasse et al., 1995; Berendsen & Stouthamer, 2001).

An Allerød to Younger Dryas age for the WM suggests potential updip to down dip fluvial response. An OSL age and

Table 3. Summary of chronology related to WM fluvial activity.

Lab no.[1]	RC age	Cal yr[2]	Coordinates[3]	Depth (cm)	Material dated	Stratigraphic significance	References
GrN-18936	7390 ± 140	8210 ± 140	129.100-432.600/-0.30	760-770	Vegetation horizon	Soil formation in WM	Törnqvist, unpublished
GrN-18938	7440 ± 160	8260 ± 160	127.340-439.035/-1.00	690-700	Vegetation horizon	Soil formation in WM	Törnqvist, unpublished
GrN-18924	7675 ± 80	8460 ± 70	127.340-439.035/-1.00	690-700	Vegetation horizon	Soil formation in WM	Törnqvist, unpublished
GrN-18937	7960 ± 290	8840 ± 370	129.100-432.600/-0.30	770-780	Vegetation horizon	Soil formation in WM	Törnqvist, unpublished
GrN-18921	7980 ± 130	8850 ± 200	129.100-432.600/-0.30	770-780	Vegetation horizon	Soil formation in WM	Törnqvist, unpublished
UtC 10857 Core 37E0586	8220 ± 60	9190 ± 100	86.817-442.257/-2.54	1380	*Scirpus* nuts from a vegetation horizon	Soil formation in WM	Wallinga, 2001; Törnqvist et al., 2000, 2003; Wallinga et al., 2004; Busschers et al., 2005
UtC 14291	4360 ± 50	4920 ± 80	183.698-438.770/+5.94	155-160	Basal peat on WM	GW-level	This paper
GrN-18935	4895 ± 40	5620 ± 30	133.405-460.280/-0.10	224-230	*Carex* peat on eolian sand	GW-level	Törnqvist, 1993
GrN- 18103	5660 ± 50	6440 ± 50	147.430-420.500/+2.03	443-453	Peat on WM	GW-level; De Hoevens IV	Weerts, 1996
GrN-11475	5895 ± 35	6710 ± 40	152.308-440.387/+4.00	465-475	Basal peat on eolian sand	GW-level; Zandberg 2	van Dijk et al., 1991
GrN- 18099	6040 ±60	6890 ± 90	147.820-421.180/+2.46	630-650	Peat on eolian cover sand	GW-level; De Vliert	Weerts, 1996
GrN-18928	6270 ± 60	7200 ± 70	130.240-426.550/-0.25	647-652	Strongly clayey *Alnus* peat on WM	GW-level	Törnqvist 1993
GrN-18933	6680 ± 50	7560 ± 40	128.030-432.620/-1.20	581-585	Slightly clayey *Alnus* peat on WM	GW-level	Törnqvist 1993
GrN-11693	6720 ± 70	7580 ± 50	135.215-435.755/+0.04	475-490	Basal peat on eolian sand	GW-level; Leerdam 6	van Dijk et al., 1991
GrN-18929	7125 ± 50	7950 ± 40	128.005-448.590/-0.85	621-626	*Phragmites* peat on Pleistocene sand	GW-level	Törnqvist 1993
GrN-18919	7350 ± 70	8170 ± 80	129.100-432.600/-0.30	748-753	*Alnus-Phragmites* peat (alkali residue) on WM	GW-level	Törnqvist 1993
GrN-18920	8300 ± 90	9310 ± 130	129.100-432.600/-0.30	748-753	*Alnus-Phragmites* peat (alkali extract) on WM	GW-level	Törnqvist, unpublished
GrN- 18105	10800 ±60	12740 ± 70	147.330-421.275/+1.83	473-483	Peat on WM under eolian sand	Burial of WM; Vellingweg I	Weerts, 1996
GrN- 18109	11400 ±90	13320 ± 130	127.250-419.090/-0.5	760-770	Peat on WM under eolian sand	Burial of WM; Den Duyl	Weerts, 1996
GrN-11469	11700 ±100	13610 ± 140	152.621-440.044/+4.01	618-623	Peat on WM under eolian sand	Burial of WM; Zandberg 10	van Dijk et al., 1991
Delft 2 Core 37E0586		11200 ± 600	86.817-442.257/-2.54	1729	Quartz OSL age	Active deposition of WM	Wallinga, 2001; Törnqvist et al., 2000, 2003; Wallinga et al., 2004; Busschers et al., 2005
NCL 4505087		10890 ± 600	184.600-437.138/+8.74	347	Quartz OSL age	Active deposition of Kb	Gouw and Erkens, 2007
NCL 4505088		10410 ± 560	184.600-437.138/+8.74	549	Quartz OSL age	Active deposition of Kb	Gouw and Erkens, 2007
NCL 4505089		11340 ± 610	184.600-437.138/+8.74	639	Quartz OSL age	Active deposition of Kb	Gouw and Erkens, 2007
NCL 4505090		11730 ± 830	184.600-437.138/+8.74	770	Quartz OSL age	Active deposition of Kb	Gouw and Erkens, 2007
NCL 4206006		10250 ± 690	181.040-437.519/+4.25	325	Quartz OSL age	Active deposition of WM	This paper
NCL 4206007		12640 ± 710	181.040-437.519/+3.52	398	Quartz OSL age	Active deposition of Kb	This paper
NCL 4306008		16550 ± 1140	183.698-438.770/+4.90	260	Quartz OSL age	Active deposition of WM	This paper; NCL questions age validity
NCL 4306009		12580 ± 660	183.698-438.770/+4.43	307	Quartz OSL age	Active deposition of Kb	This paper

1 Radiocarbon samples run by Groningen (GrN) and Utrecht (UtC); OSL samples run at Netherlands Centre for Luminescence Dating (NCL), Delft University of Technology.

2 Calendar year estimates from Fairbanks (2008), http://radiocarbon.ldeo.columbia.edu/research/radcarbcal.htm; Quartz OSL ages as reported by NCL.

3 Coordinates relative to O.D.; x-y in km and z in m.

corroborating radiocarbon date (Törnqvist et al., 2000, 2003; Wallinga, 2001; Wallinga et al., 2004; Busschers et al., 2005) suggest active sedimentation of the WM downvalley near Rotterdam at 11,200 cal yr. However, river dunes bury WM surfaces in Land van Maas en Waal from 13,600 to 12,700 cal yr (Berendsen et al., 1995). Clearly, the start of WM deposition overlaps in time with the end of Kb sand and gravel deposition.

In the Over Betuwe, the initial WM deposition post dates Laacher See volcanism and WM deposition terminated as vegetation horizons developed. Laacher See pumice granules deposited within the Kb imply that a Rhine River braid belt was aggrading its uppermost surface at ~12,900 cal yr. The OSL ages on Kb sand suggest Kb aggradation in the Over Betuwe may have persisted as late as ~10,410 cal yr based on nearby ages reported by Gouw & Erkens (2007), although ~12,580 cal yr (Table 3, NCL 4206009) is the youngest age reported in this study. Post Kb incisions occur mostly along the edges of the study area, especially near the channel belt of the River Waal (Weerts, 1996; Hesselink et al., 2003). These incised channels are the probable local source of WM sediments, along with a few smaller residual channels that cross the flood basin. Stratigraphic relations indicate that many local incisions by WM residual channels occurred after Laacher See pumice deposition, however the OSL age only limits active WM deposition to at least ~10,250 cal yr (Table 3, NCL 4306006). Single aliquot equivalent dose distributions indicate that the OSL signal of the vast majority of quartz grains was adequately reset prior to burial, so the measured equivalent doses are expected to be reliable estimates of the burial doses. Samples NCL 4306008 and NCL 4306009 show a large age reversal in borehole 049 (Table 3; Fig. 4). The discrepancy is likely caused by an incorrect dose rate estimation for the upper sample, therefore the age of NCL 4306008 is thought to be unreliable.

Maximum ages for vegetation horizons covering the WM indicate organic matter biocycling was initiated by 9100 to 8200 cal yr and the WM surface was probably regionally abandoned by this time. Ground water level rise affected the Rhine Valley from near Utrecht to the study area from 9300 to 4900 cal yr. A radiocarbon age of 4920 ± 80 cal yr (Table 3; Fig. 4; UtC-14291) from a basal peat corresponds to the highest elevation of the abandoned WM surface. After ~5000 yrs ago, the regional water table in the study area was high enough to support contiguous flood basin wetlands.

Regional channel incision occurred during active WM sedimentation, but vegetation horizon development and gleyed subsoils in the WM suggests that the abandoned braid plain remained as a flood plain wetland. If wetland environments persisted as far up valley as the Over Betuwe, then water tables must be driven in part by ground water seepage. The adjacent Saalian ice-pushed ridges are a probable source of ground water supply, affecting the water table of the alluvial aquifer. This contrasts with interpretations that water table lowering drives downcutting concurrent with WM overbank aggradation (Berendsen et al., 1995; Törnqvist et al., 1994). In the Over Betuwe, the highest local landscape of the Kb surface appears to be of Younger Dryas age based on OSL ages and the presence of Laacher See pumice, and not Bølling-Allerød as implied by the Land van Maas en Waal model. It is plausible that the Low Terrace and Terrace X aggraded to a similar level in the Over Betuwe. Törnqvist (1998) identified areas downvalley where cut and fill produced <1 m of relief, less than the constructional relief identified on the Kb surface (Fig. 5). Active sedimentation of the WM certainly persisted into the Early Holocene.

Regional patterns and WM genesis

The abundant stratigraphic data available for the Rhine Valley (LLG and NITG) allow for a relatively clear delineation of regional Kb fluvial activity and abandonment. When combined with chronologic and other paleoenvironmental records (Hoek, 1997a, b; Hoek & Bohncke, 2002; Berendsen & Stouthamer, 2001; Busschers, 2008; Busschers et al., 2007), lithostratigraphy suggests Kb deposition was during intervals of cold climate in the Late Pleniglacial and Younger Dryas. Consensus is that many Rhine River braided stream channels predate Bølling-Allerød. Stratigraphic mapping divides the Kb of the Rhine Valley into two lithofacies, a) full glacial braid belt that aggraded to form the Low Terrace of Berendsen et al. (1995) and Berendsen & Stouthamer (2001), and b) an inset Terrace X of Berendsen et al. (1995) and Törnqvist (1998). Transitional fluvial systems recognized by Kasse et al. (2005) in the Niers Valley are potentially correlative with Terrace X.

In the Late Pleniglacial, a braided river pattern persisted under permafrost conditions and diminished vegetational cover as cold climate reached a temperature minimum. Fluvial incision was dominant by ~13,000 cal yr when the climate abruptly changed from cold to temperate and vegetation was re-established. In periglacial environments, vegetation recovery first develops an algal cover during initial warming, and then later develops a dense cover of herbs as temperatures moderate (Vandenberghe, 1995, 2003).

The growth and decay of permafrost in NW Europe caused dramatic hydrologic changes in fluvial systems (Renssen, 2001; Renssen et al., 2002; Renssen & Vandenberghe, 2003). Under permafrost conditions, infiltration to the ground water system is limited and active layer melt water goes directly to runoff. Warmer climate with limited freezing allows base flow hydrology to buffer the hydrograph through exchange of ground water and surface water. Periglacial rivers can have a near absence of ground water storage, little contribution of aquifers to base flow, and an impervious frozen surface that maximizes the flashiness of a hydrograph. The hydrology of modern drainage basins that span arctic and subarctic climates like the Mackenzie Basin of NW Canada (Woo & Thorne, 2003) appears to be a reasonable analog to the Lateglacial Rhine River.

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Vegetation cover is partially climate dependant, but is also is a sensitive indicator of broader environmental conditions. River incision was widespread at the beginning of both Bølling-Allerød and Early Holocene. The cause is partially linked to the re-vegetation of a barren or sparsely vegetated landscape. However, fluvial incision predates the full development of shrub and aboreal cover, and fluvial response is not linearly correlated with vegetation changes.

The transition of the Rhine River from glacial to postglacial conditions has been a topic of widespread interest, however, the details of process, timing, and stratigraphic correlation still lack consensus. As Late Pleniglacial braid channels are abandoned, they decrease sand discharge, incise and straighten, and eventually anastomose or meander (Cohen, 2003). Incision of the Low Terrace created a series of younger inset flood plains. The transitional system has been recognized and discussed upvalley (Kasse et al., 2005), and Terrace X is buried downvalley below the Holocene Rhine prism (Törnqvist, 1998).

Environmental controls on WM sedimentation

A fundamental change in sedimentation process occurs at the stratigraphic boundary between Kb and WM. A millennium-scale trend of environmental change transformed the Rhine-Meuse Valley from a dominantly braided river into a meandering river (Fig. 8) as climate ameliorated from the Late Pleniglacial to the Early Holocene (Vandenberghe, 1995; Berendsen & Stouthamer, 2001). The WM stratigraphy provides clues to the details of environmental transitions in the Over Betuwe, the effects on Rhine-Meuse fluvial processes, and the overall causes driving rapid fluvial system change.

The Kb aggraded in the Over Betuwe as a high bedload multiple channel system, forming bars at generally comparable levels across active flood plain areas. Deposition of WM occurred in a low sand and high mud system with fewer active channels than the Kb flood plain. The dominantly silty overbank load drapes the abandoned Kb bar and channel system. The WM sedimentation pattern across the study area shows faint proximal to distal depositional trends associated with its contemporary channel systems. Fining upward trends, although common, are locally interrupted by coarsening upward and uniform textural trends. In the study area, there is no apparent correlation between sand content and proximity to channels or vertical profile trends, making eolian mixing the more plausible explanation. Admixed sand in the WM has a complex distribution that warrants additional study.

In the Lower Rhine-Meuse Valley, Late Weichselian channel patterns in the Over Betuwe, Land van Maas en Waal (Berendsen et al., 1995), and Niers Valley (Kasse et al., 2005) illustrate a complex response to environmental forcing (Fig. 8). Busschers et al. (2007) suggest that Late Pleniglacial aggradation was focused in successive pathways, with fluvial activity progressing to more southerly channel belts over time. It is likely that Kb deposition in the Rhine-Meuse Valley was episodically focused, with one part of the valley rapidly aggrading while other areas experience fluvial abandonment. An upstream control on fluvial aggradation that altered local flood plain gradients probably forced successive abandonment and reoccupation of channel belts. Busschers (2008) considers deglacial forebulge effects to be a significant factor affecting flood plain gradients.

During Bølling-Allerød, the Niers Valley and Land van Maas en Waal developed meandering channels. It is uncertain whether or not the Over Betuwe established a meandering pattern or continued to braid. During the Late Allerød and Younger Dryas, the Niers Valley continued to meander, while Land van Maas en Waal and Over Betuwe braided. By the onset of the Preboreal, meandering channel patterns were established throughout the Lower Rhine-Meuse Valley.

The presence or absence of permafrost exerted a dominant influence on Lateglacial channel morphology, hydrology, and relative sediment load. During Lateglacial cold intervals, the Rhine-Meuse Valley probably developed discontinuous permafrost (Bohncke et al., 1993; Kasse et al., 1995; Busschers, 2008) and fluvial response was sensitive to this environmental control. Under permafrost conditions, summer active layer hydrology provides a limited seasonal discharge, and channels are frozen during cold winter seasons. Permafrost can partially or completely freeze an alluvial

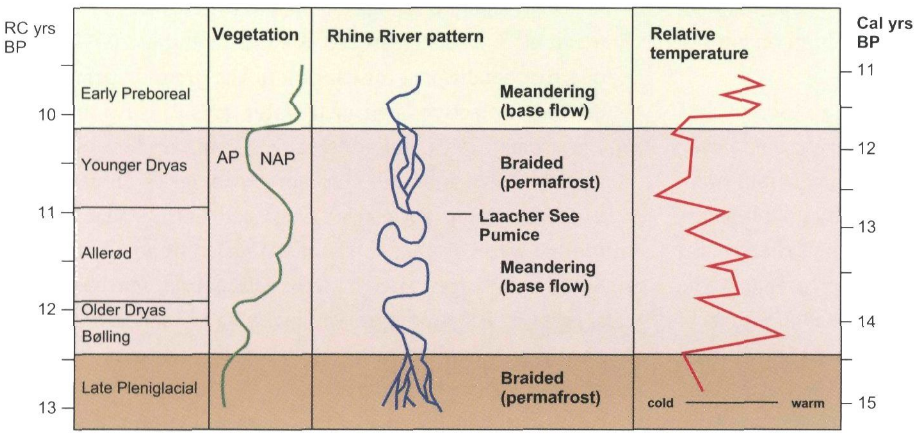

Fig. 8. Generic model for Rhine River fluvial response to environmental conditions in NW Europe from the Late Pleniglacial to Early Preboreal. Associated fluvial pattern response of the lower Rhine River varies for different geographic areas. See text for discussion. Adapted from Kasse et al. (1995, 2005), Berendsen & Stouthamer (2001), and Vandenberghe (1995, 2003).

aquifer. In the Lower Rhine-Meuse Valley, a frozen alluvial aquifer with a partial summer thaw would increase resistance of the channel bed and banks most of the year, limit reworking and transport of available bed load, and decrease the tendency of channels to laterally accrete and incise. The decline of permafrost conditions allows meandering or anastomosing channels to develop. Aquifer thawing allows base flow to be maintained by ground water discharge, regulates a more steady seasonal hydrograph, promotes incision and lateral accretion by seasonal ground water sapping, and allows for increased vegetational cover on the flood plain.

Deposition of the WM continued from the Bolling-Allerød to the Early Holocene. The time transgressive nature of the WM is reflected in its stratigraphic distribution, geomorphic cross cutting relations, and chronology. Throughout the Lower Rhine-Meuse Valley, the WM drapes extensive flood plain areas of Pleniglacial to Early Holocene age. The time transgressive nature and geographic extent of the WM in the Lower Rhine-Meuse Valley suggests multiple episodes of fluvial activity, with periods of aggradation in the Over Betuwe occurring independently from events in the Niers and Meuse valleys.

Conclusions

1. The WM is a dominantly silty lithofacies that differentially drapes Kb sandy lithofacies and formed as a fluvial overbank deposit with a relatively continuous thickness distribution. Variations from average thickness occur with thinning on constructional Kb paleotopographic highs and thickening in landscape lows. Sediments were derived from nearby incised WM paleochannels.
2. The source of the admixed sand in the WM is most likely due to eolian mixing. Substantial bioturbations by either plants or animals are unlikely due to limited pedogenic activity in poorly drained wetland soils that developed on the WM surface. Concurrent deposition of sand and silt by overbank floods are not consistent with the observed lateral or vertical texture patterns.
3. Pedogenesis of the WM in the study area is limited to gleying under reduced wetland conditions and the development of organic rich vegetation horizons that formed on top of relatively unaltered fluvial strata. Similar soil formation properties occur downdip to the present coast, but updip of the study area, the WM has poorly drained to well drained profiles with pedogenic expression ranging from Entisols to weakly expressed Alfisols.
4. Deposition of the WM is associated with transitional braided to meandering fluvial environments during times when fluvial systems experienced a sensitive response to rapid climate change at the termination of the last glaciation. The WM is regionally time transgressive and probably formed during complex responses to fluvial system transitions between permafrost and base flow driven hydrologic regimes.

Acknowledgements

This research stems from an idea of Törbjorn Törnqvist, who encouraged me to investigation of the WM stratigraphy and its depositional environment. Data collection was initiated as a sabbatical research project supported by SUNY College at Brockport and the Department of Physical Geography at Utrecht University. The late Henk Berendsen was a most gracious and informative host during my stay in Utrecht, arranging logistical and field support, providing financial support for radiocarbon and OSL ages, and sharing the wisdom of his experiences in the Rhine Valley. This project would have not been accomplished without Henk's help and generosity. Esther Stouthamer, Kim Cohen, and Wim Hoek provided assistance and advice in implementing various field aspects of the project. Marc Gouw, Gilles Erkens, and Koen Volleberg assisted with field sampling. Special thanks to Koen Volleberg for help with ARCGIS issues. Henk Weerts provided access to and help with the NITG database, and offered countless insightful ideas on the origin and significance of the WM. Jakob Wallinga provided assistance with the reporting and interpretations of the OSL data generated at NCL. Constructive reviews of an earlier draft were provided by Marc Gouw, Andres Aslan, and Albert Fulton. NJG reviewers, Freek Busschers and Leo Tebbens, offered many helpful suggestions for manuscript revision.

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