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Sedimentary architecture and optical dating of Middle and Late Pleistocene Rhine-Meuse deposits – fluvial response to climate change, sea-level fluctuation and glaciation

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Abstract

Eight continuous corings in the west-central Netherlands show a 15 to 25 m thick stacked sequence of sandy to gravelly channel-belt deposits of the Rhine-Meuse system. This succession of fluvial sediments was deposited under net subsiding conditions in the southern part of the North Sea Basin and documents the response of the Rhine-Meuse river system to climate and sea-level change and to the glaciation history. On the basis of grain size characteristics, sedimentological structures, nature and extent of bounding surfaces and palaeo-ecological data, the sequence was subdivided into five fluvial units, an estuarine and an aeolian unit. Optical dating of 34 quartz samples showed that the units have intra Saalian to Weichselian ages (Marine Isotope Stages 8 to 2). Coarse-grained fluvial sediments primarily deposited under cold climatic conditions, with low vegetation cover and continuous permafrost. Finer-grained sediments generally deposited during more temperate climatic conditions with continuous vegetation cover and/or periods of sea-level highstand. Most of the sedimentary units are bounded by unconformities that represent erosion during periods of climate instability, sea-level fall and/or glacio-isostatic uplift.

Keywords: Rhine-Meuse, Netherlands, North Sea Basin, Middle Pleistocene, Late Pleistocene, fluvial, estuarine, subsidence, optical dating, climate, sea-level, glaciation, isostacy

Introduction

Studies on rivers in northwestern Europe indicate that changing climate conditions, sea-level change and tectonics are reflected in depositional characteristics and in changing river patterns throughout glacial-interglacial cycles. Northwest European records of fluvial response over glacial-interglacial time scales primarily involve terraced sequences in river valleys like those of the Rhine (Klostermann, 1992; Boenigk, 2002), Thames (Gibbard, 1994) and Meuse (Van den Berg, 1996) in generally uplifting settings. The Middle and Late Pleistocene Rhine-Meuse system in the west-central Netherlands is a low-gradient fluvial system in a slowly subsiding setting (Zagwijn, 1989; Fig. 1) located downstream of the North Sea Basin hinge line. The hinge line marks the transition between the subsiding North Sea Basin and its uplifting surroundings areas (cf. Törnqvist, 1995). Subsidence creates long term (net) accommodation and as a result the Rhine-Meuse deposits form vertically stacked sand units with locally fine-grained intercalations. Although predominantly basal parts of fluvial sequences preserve in slowly subsiding settings, such sequences suffer considerably less from erosion than fluvial records in uplifting terraced areas and therefore provide a more complete fluvial sedimentary record.

The Middle and Late Pleistocene Rhine-Meuse system experienced major (primarily) North Atlantic driven climate

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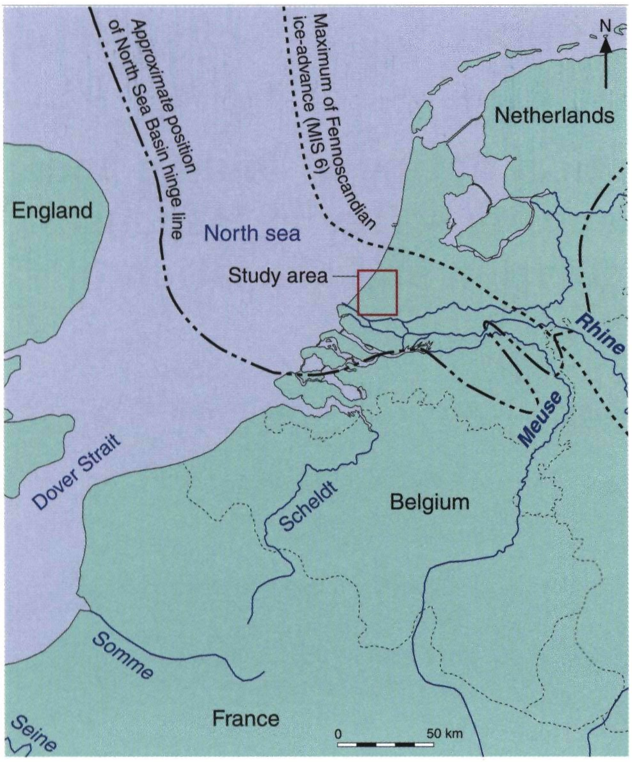

Fig. 1. Location of the study area in relation to the (approximate) position of the hinge line of the North Sea Basin (Zagwijn, 1989). Also shown is the maximum extent of the Late Saalian (MIS 6) ice sheet.

oscillations (Johnson et al., 1998), sea-level changes (Waelbroeck et al., 2002) and invasion(s) and retreat(s) of the Fennoscandian ice sheets (Ehlers, 1996; Houmark-Nielsen and Kjaer, 2003; Ehlers and Gibbard, 2004; Fig. 1). Studies on the Late-Glacial and Holocene Rhine-Meuse river system, have shown that these changes have had pronounced effects on river type, sedimentary composition and erosional-aggradational trends within the lower reaches of the Rhine-Meuse river system (Kasse et al., 1995; Berendsen et al., 1995; Cohen, 2003). These studies mostly involve only the final phases of the Weichselian and give no details on the preceding parts of the last glacial-interglacial cycle. Long term Plio-Pleistocene Rhine-Meuse studies on the other hand (Van den Berg, 1996; Boenigk, 2002) lack high resolution absolute dating control or proxy records, which prevents detailed correlations between forcing factors and fluvial development. Thus, sofar little detail is known about the fluvial responses of the Rhine-Meuse river system during the last glacial-interglacial cycles.

In the present paper we describe the sedimentary development of the lower reach of Rhine-Meuse fluvial system in the west-central Netherlands and relate this development to climate change, sea-level movement and glaciation during the last ~300 kyr. We present the sedimentary architecture of Rhine-Meuse deposits in the west-central Netherlands comprising the Kreftenheye & Urk Formations (cf. De Mulder et al., 2003; Ebbing et al., 2003) and construct a detailed chronological framework by the use of optical dating (Optically Stimulated Luminescence, OSL) (Aitken, 1998; Wallinga, 2002). Lastly, we link the sedimentary architecture of the Rhine-Meuse deposits to conditions of climate, sea-level and glaciation.

Geological setting and general characteristics of the Rhine-Meuse deposits

During most of the Pleistocene the Rhine-Meuse system deposited gravels and sands in a southeast-northwest oriented zone throughout the Netherlands (Zagwijn, 1974; Doppert et al., 1975), hereby following the central axis of the North Sea Basin (Zagwijn, 1989) (Fig. 1). The southeast-northwest flowing Rhine-Meuse system drastically changed its drainage route during the Middle Pleistocene glaciations. The Fennoscandian ice sheet that covered the northern part of the Netherlands during the Late Saalian glaciation (Marine Isotope Stage, MIS 6), forced the Rhine-Meuse system to follow a course through the central Netherlands (Thome, 1959) (Fig. 2).

After retreat of the ice sheet, the Rhine followed a more northerly route draining into a glacially eroded depression (present IJssel Valley, Fig. 2). The Meuse most probably maintained a course through the western Netherlands. During the Eemian (MIS 5e) and parts of the Weichselian Early Glacial (MIS 5d-a) parts of the Netherlands experienced marine conditions (Zagwijn, 1974; Törnqvist et al., 2000) and the Rhine formed a delta at the location of the present IJssel Valley. Hereafter, the Rhine reoccupied the Saalian imposed course through the western Netherlands (Van de Meene & Zagwijn, 1978; Verbraeck, 1984; Törnqvist et al., 2000) (Fig. 2).

The Late Saalian to Weichselian sedimentary record of the Rhine-Meuse system (Kreftenheye Formation cf. De Mulder et al., 2003; Fig. 2) in the central Netherlands consists of a 10 to 25 metres thick unit of medium- to coarse-grained gravelly sands (Doppert et al., 1975). Small rock fragments (Riezenbos, 1971; Verbraeck, 1984), namely green, red and black sandstone and shale fragments from the Eifel and Rheinisch Massif in Germany give the deposits a colourful appearance. The quartz content of the deposits decreases towards the top of the Kreftenheye Formation (Verbraeck, 1984). Locally, glacially derived gravel (e.g. Fennoscandian granite) occurs. Throughout the deposits the volcanic mineral augite is abundant (Zonneveld, 1958; Verbraeck, 1984) while locally the upper few meters of the deposits contain pumice granules (Verbraeck, 1984) that originate from the Laacher See volcanic eruption in the Eifel (~12.9 kyr cal BP, Friedrich et al., 1999). The top of the deposits is mostly capped by a sandy clay layer (Wijchen Member after Törnqvist et al., 1994).

Methods

With a mechanical bailer-drilling system providing undisturbed sediments in tubes of 1 meter length and 10 cm diameter (Oele et al., 1983), three new continuous cores were obtained (Fig. 3,

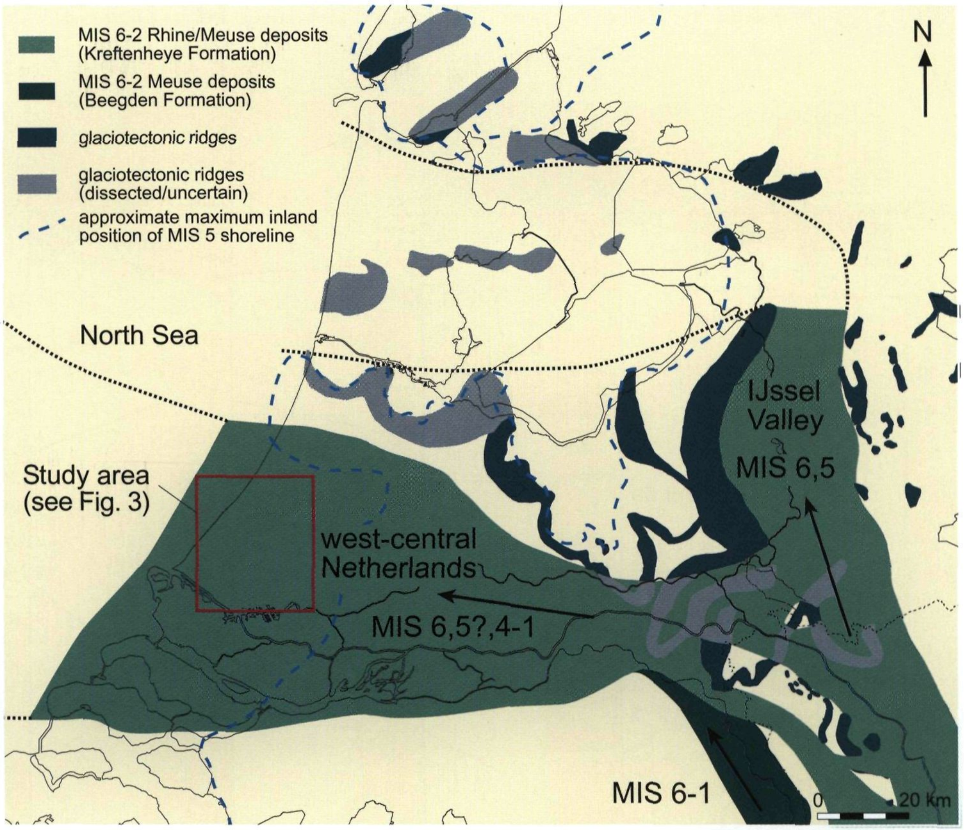

Fig. 2. Late Saalian and Weichselian Rhine-Meuse deposits in the Netherlands and major flow directions (adapted from Doppert et al., 1975). Also shown are the positions of Late Saalian glacio-tectonic ridges (Van den Berg & Beets, 1987; TNO-NITG, unpublished data) and the maximum inland position of MIS 5 highstand deposits (adapted from Doppert et al., 1975).

cores 37E0586, 30G0863 & 30F0490). Information on four other continuous cores were obtained from their archived lacquer peels at the Netherlands Institute of Applied Geoscience TNO – *National Geological Survey* (TNO-NITG) (Fig. 3, cores 37E0547, 30G0854, 30F0467 & 30D0215). The seven cores are correlated in two cross sections through the west-central Netherlands (Fig. 3). The cross sections were completed using 33 coring-descriptions obtained from the database (DINO) of TNO-NITG. The first cross section is oriented tangential to the Late-Pleistocene palaeovalley of the Rhine, the second is oriented longitudinal to the palaeovalley.

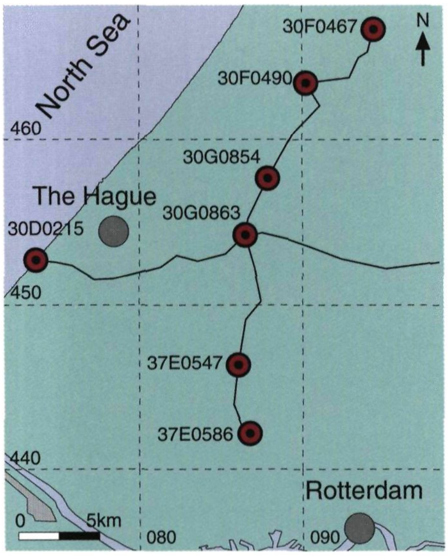

Fig. 3. Location of the cross sections in the study area and positions of the continuous cores.

Sedimentary analysis included macroscopic description of grain size, gravel content, organic and non-organic admixtures, sedimentary structures and colour. Special attention was given to the position and characteristics of sharp contacts (bounding surfaces), marking pronounced sedimentary transitions. Diatom-analysis was carried out on 16 samples and 9 intervals rich in molluscs were sampled for malacological analysis.

Optical dating of sand-sized quartz from 34 samples was applied to obtain chrono-stratigraphical information (Aitken, 1998; Wallinga, 2002). Optical samples were taken from the cores under subdued red light conditions and treated with hydrochloric acid (10%) and hydrogen peroxide (30%) to remove carbonates and organic material. The samples were then sieved to obtain a narrow grain size for analysis (usually 180-250 µm) and treated with hydrofluoric acid (40%) to remove feldspar grains and to etch the quartz grains. The SAR procedure (Murray & Wintle, 2000) was used for equivalent dose determination, the dose rate was determined using high-resolution gamma spectrometry (Murray et al., 1987). Details on the measurement procedure, as well as a discussion on the optical dating results are presented by Törnqvist et al. (2003) and Wallinga et al. (2004). Two ^{14}C datings were carried out for this study. Their ^{14}C ages were calibrated using the INTCAL98 calibration data set of Stuiver et al. (1998) and the Groningen radiocarbon calibration program Cal25 (Van der Plicht, 1993).

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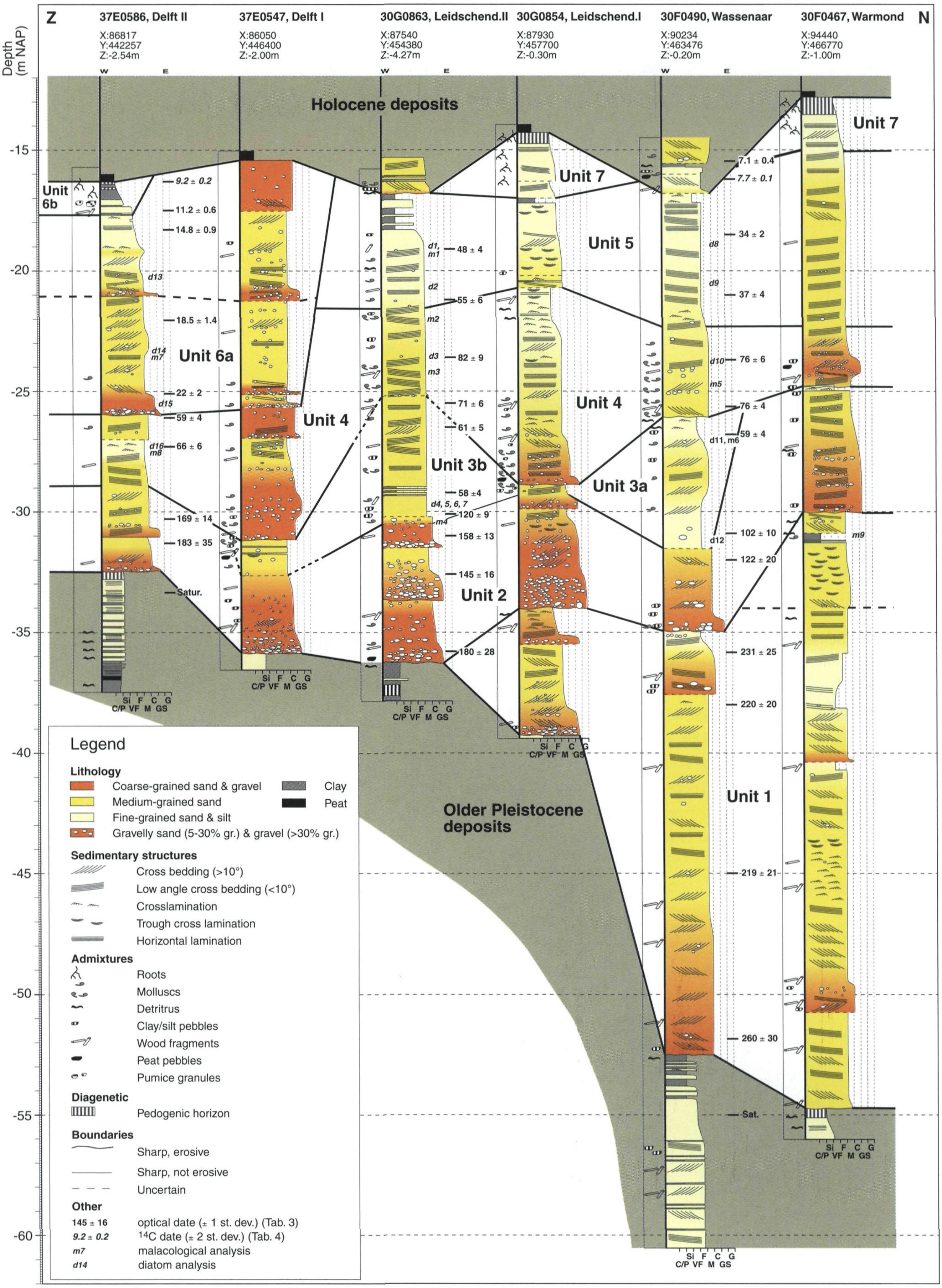

Fig. 4a. Sedimentary logs of cores 37E0586, 30G0854, 30G0863, 30F0490 and 30F0467 (north-south cross section). Geographical positions of the cores are shown in Fig. 3.

Sedimentary facies

The facies characteristics, nature of bounding surfaces and the geometry of sedimentary units are described from bottom to top. Sedimentary logs of the cores are represented in Figs. 4a and 4b. The cross sections are shown in Figs. 5a and 5b.

Unit 1 (Urk Formation)

Description

Unit 1 consists predominantly of medium-grained cross-bedded, grey to light-brown coloured sand with fine gravel. Within the unit the grain size decreases towards the top where fine-grained ripple cross-laminated sands dominate. A clay layer with a marine mollusc (*Cerastoderma sp.*, Table 2) was found in the upper part of the unit in core 30F0467. The unit contains large amounts of centimetre-sized wood fragments and other organic material. The unit is deeply incised in older deposits and its base is characterised by a sharp bounding surface at a level between –40 m and –55 m NAP (NAP = Dutch Ordnance Datum = ≈ mean sea-level). A mixture of wood fragments, coarse sand, gravel and reworked clay pebbles of surrounding older deposits is often found directly above the bounding surface. The thickness of the unit varies between 6 to 30 m.

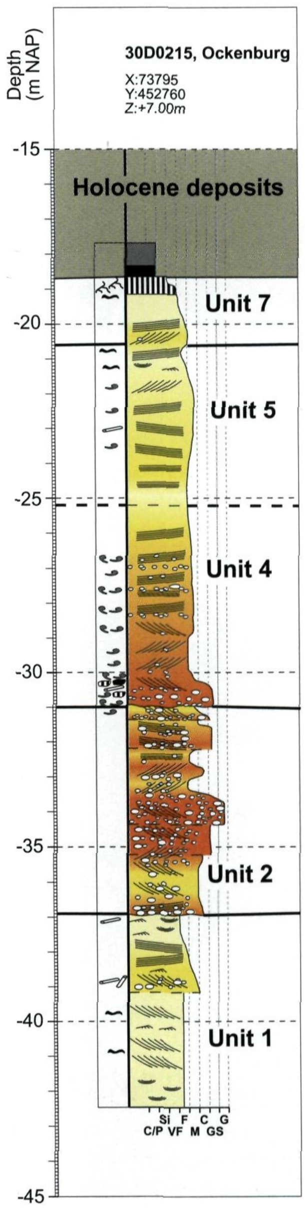

Fig. 4b. Sedimentary log of core 30D0215 (east-west cross section). Geographical position of the core is shown in Fig. 3.

Interpretation

The gravelly medium-grained sands, dominance of cross-bedded structures and the fining upward trend point to a fluvial origin (Miall, 1996). The clayey intercalation with a marine mollusc suggests marine influence towards the top of the unit.

Unit 2 (Kreftenheye Formation)

Description

Unit 2 consists of medium- to coarse-grained sands with 10 to 25% fine to coarse gravel. The unit has a grey to whitish colour. Cross-bedded structures dominate, although ripple cross-laminated beds are present in the upper part of the unit. Within the unit several erosion surfaces form the bases of a number of small-scale fining-upward sequences that could not be correlated between cores. The base of the unit is a sharp bounding surface, found between –32 m and –38 m NAP (Figs. 5a and 5b). The bounding surface is covered by a lag deposit of coarse-grained sands with high concentrations of gravel, clay and peat pebbles and locally some fragments of weathered molluscs (Fig. 4, core 30G0863). The thickness of the unit is 4 to 10 m (Figs. 5a and 5b).

Interpretation

The dominance of coarse-grained sands, high concentrations of gravel, numerous internal scour surfaces and small-scale fining upward sequences and a clear lag deposit at the base of the unit, point towards deposition in a fluvial channel system (Miall, 1996).

Unit 3a (Kreftenheye Formation)

Description

Unit 3a consists of medium-grained to fine-grained, grey sands with a small amount of gravel. The unit is dominated by cross-bedded structures. Locally ripple cross-laminated facies occurs (e.g. core 30F0490). There is no clear lag deposit marking the base of this unit, but the transition from underlying Unit 2 to Unit 3a (at –32m in core 30F0490) is characterised by a sharp drop in grain size. The thickness of the unit is 3 to 5 m. No diatoms were present in the unit (Table 1). The unit does contain fragments of molluscs that lived in brackish and/or marine water in the shallow subtidal to upper intertidal zone of a tidal flat or estuary (e.g. *Cerastoderma glaucum*, *Scrobicularia plana*, Table 2).

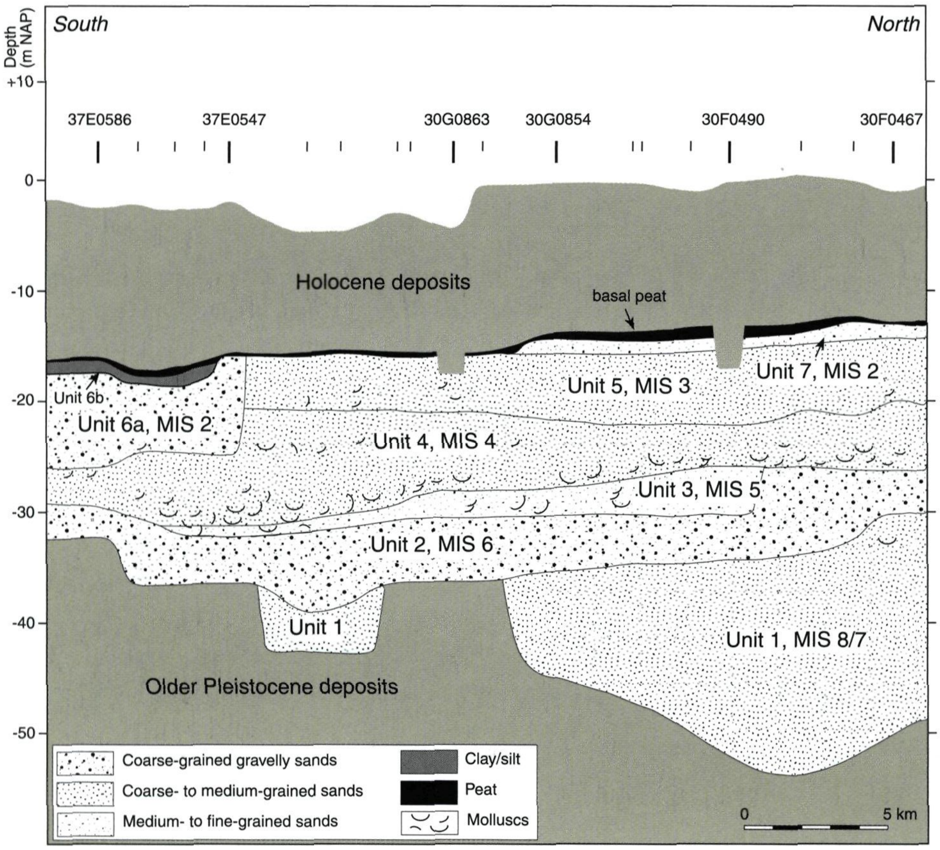

Fig. 5a. North-south oriented cross section (location in Fig. 3).

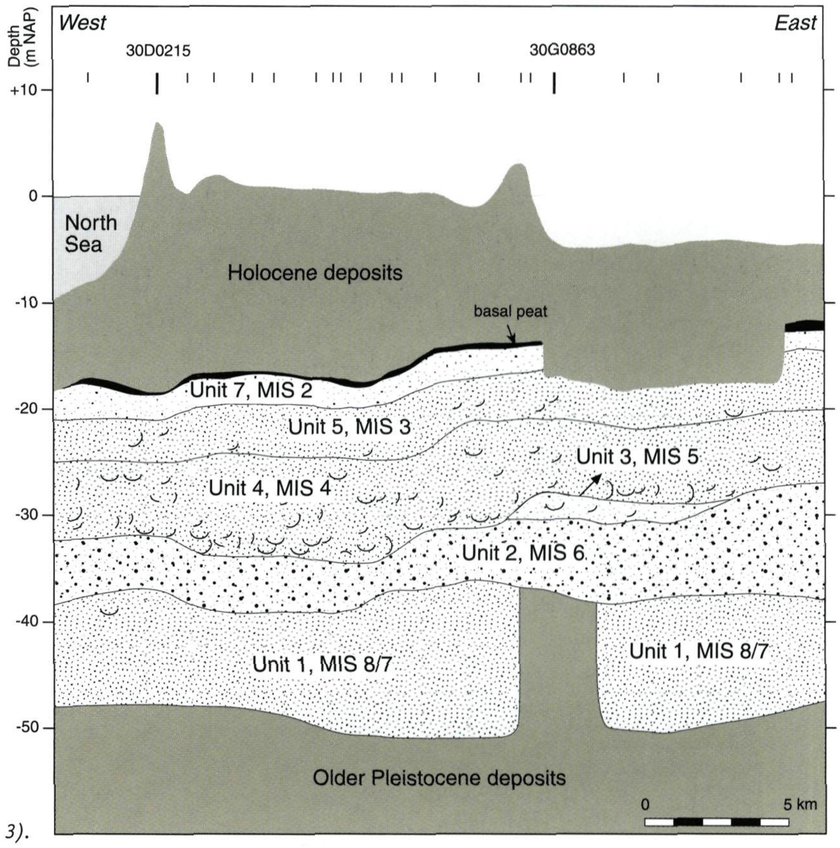

Fig. 5b. East-west oriented cross section (location in Fig. 3).

Core		30G0863							30F0490					37E0586			
Sample		d1	d2	d3	d4	d5	d6	d7	d8	d9	d10	d11	d12	d13	d14	d15	d16
Depth (m)		14.70-15.00	16.55-16.70	20.07-20.17	24.79-25.07	24.79[1]	24.93[1]	25.04[1]	18.66-18.86	20.66-20.89	24.50-24.70	26.84-26.94	30.91-30.94	17.68-17.88	20.76- 20.95	22.70-23.00	24.57-24.88
Depth (m -NAP)		18.87-19.27	20.82-20.97	24.34-24.44	29.06-29.34	29,06	29,20	29,31	18.86-19.06	20.86-21.09	24.70-24.90	27.04-27.14	31.11-31.14	20.22-20.42	23.20-23.49	25.24-25.54	27.11-27.42
Unit		5	5	4	3b	3b	3b	3b	5	5	4	3a	3a	6a	6a	6a	4
Lithology		sand	sand	sand	sand	claydrape	claydrape	claydrape	sand	sand	sand	sand	sand	sand	sand	sand	sand
Species	**Ecological interpretation**[2]																
Meridion circulare	freshwater plankton						•							•			
Cocconeis placentula	freshwater epiphytes				•												
Cocconeis disculus	freshwater epiphytes														•		
Epithemia sorex	freshwater epiphytes		•														
Epithemia turgida	freshwater epiphytes			•	•												
Epithemia zebra var. porcellus	freshwater epiphytes					•	•										
Epithemia zebra/turgida	freshwater epiphytes														•		
Synedra ulna	freshwater epiphytes					•											
Cymbella lanceolata	freshwater epiphytes														•		
Epithemia	freshwater epiphytes															f	
Epithemia gordel	freshwater epiphytes													•			
Gomphonema spec.	freshwater epiphytes														•		
Navicula mutica var. nivalis	freshwater aerophilous					•											
Amphora perpusilla	freshwater aerophilous														•		
Caloneis silicula	fresh epipelon														•		
Fresh spec.	fresh								•								
Actinocyclus normanii	estuarine														•		
Cyclotella striata	estuarine		•	•	•	•	•	•							•		
Achnanthes delicatula	marine/brackish epipsammon				•	•											
Catenula adherens	marine/brackish epipsammon								•								
Rhopalodia gibba	marine/brackish epiphytes														•		
Synedra pulchella	marine/brackish epiphytes				•												
Synedra tabulata var. faciculata	marine/brackish epiphytes						•										
Diploneis bombus	marine/brackish epipelon		•			•											
Diploneis didyma	marine/brackish epipelon						•										
Navicula hungarica	marine/brackish epipelon				•	•	•										
Nitzschia navicularis	marine/brackish epipelon					•	•										
Nitzschia puncata	marine/brackish epipelon					•											
Surirella ovalis	marine/brackish epipelon				•												
Diploneis interrupta	marine/brackish aerophilous														•		
Cymatosira belgica	marine tychoplankton	•		•	•	•	•								•		
Melosira westi	marine tychoplankton		•	•	•	•									•		
Rhaphoneis amphiceros	marine tychoplankton		•	•	•	•	•	•							•		
Rhaphoneis minutissima	marine tychoplankton		•			•	•	•							•		
Actinocyclus ehrenbergi	marine tychoplankton	•	•	•			•	•							•		
Actinoptychus undulatus	marine tychoplankton			•	•												
Aulacodiscus argus	marine tychoplankton	f		•	•			•									
Paralia sulcata	marine tychoplankton		•	•		•	•	•			•				•	f	
Thalassionema nitzschiodes	marine tychoplankton							•									
Thalassiosira decipiens	marine tychoplankton		•	•	•	•	•							•	•		
Triceratium favus	marine tychoplankton		•		•												
Rhaphoneis spec.	marine tychoplankton								f								
Biddulphia granulata	marine tychoplankton		•														
Biddulphia rhombus	marine tychoplankton				•		•								•		
Biddulphia rhombus/rostrata	marine tychoplankton													•			
Rhaphoneis surirella	marine tychoplankton					•								•			
Grammatophora oceanica	marine epiphytes			•	•												
Nitzschia panduriformis	marine epipelon					•											
Marine spec.	marine	f							f		f						
Diploneis spec.											f						
Caloneis spec.														•			
Melosira spec.															•		
Opephora spec.											f			•			
Pinnularia spec.					•												
Synedra spec.		•												•		f	
Pyrite fragments					•				•	•	•	•	•				

• = Species observed
f = Fragment of species observed

1 From Törnqvist et al.(2000)
2 Ecological interpretation following Vos & De Wolf (1993)

Table 1. Diatom content of samples in cores 30G0863, 37E0586 and 30F0490. The sample locations are also depicted in Fig. 4a.

Table 2. *Faunal composition of mollusc samples in cores 30G0863, 37E0586, 30F0490 and 30F0467. The sample locations are also depicted in Fig. 4a.*

	Core	30G0863				30F0490		37E0586		30F0467
	Sample	m1	m2*	m3*	m4*	m5	m6	m7	m8	m9
	Depth (m)	14.70-15.00	17.71-17.84	19.86-20.03	25.73-25.87	24.00-25.00	26.84-26.94	20.76-20.95	24.57-24.88	29,95
	Depth (m –NAP)	18.87-19.27	21.98-22.11	24.13-24.30	30.00-30.14	24.20-25.20	27.04-27.14	23.30-23.49	27.11-27.42	30,95
	Unit	5	4	4	3b	4	3a	6a	4	1
Species	**Ecological interpretation**									
Bithynia tentaculata	fresh water			•						
Freshwater gastropods	fresh water			•						
Succinia oblonga	hygrophile landsnail	•								
Trichia hispida	hygrophile landsnail, park landscape		•							
Lumbricus sp.	land, no saltwater				•					
Cerastoderma edule	brackish to fully marine, inter tidal		•	•			•			
Cerastoderma glaucum	brackish to fully marine, shallow subtidal			•		•	•			
Cerastoderma sp.	brackish to fully marine, shallow subtidal							•	•	•
Abra ovata	brackish to fully marine, subtidal		•	•						
Hydrobiidae	brakish to fully marine, intertidal to subtidal			•						
Peringia ulvae	brakish to fully marine, shallow subtidal to lower intertidal					•				
Barnea candida	fully marine, clear water, subtidal		•	•	•					
Venerupus senescens	fully marine, shallow subtidal			•		•				
Macoma balthica	fully marine, shallow subtidal to lower intertidal		•	•		•		?		
Mytilus edulis	fully marine, shallow subtidal to lower intertidal		•	•	•	•	•			
Scrobicularia plana	fully marine, shallow subtidal to upper intertidal	•	•	•	•	•	•	?	•	
Ostracods	fresh to fully marine				•					
Ostrea edule	fully marine, sub tidal, clear waters		•			•				

• = Species observed
? = Presence of species uncertain

* From Törnqvist et al. (2000)

Interpretation

The medium- to coarse-grained sands with cross-bedded structures suggest deposition in fluvial channels (Miall, 1996). An estuarine interpretation is unlikely because of the absence of tidal characteristics like clay-drapes and bioturbation (Boersma & Terwindt, 1981; Allen, 1991). Although marine molluscs do occur, their fragmented character suggests they must have been reworked from older marine deposits (see also Unit 4 for further discussion).

Unit 3b (Kreftenheye Formation)

Description

Unit 3b consists of fine to medium-grained sand with no gravel. The lower part of the unit shows no sedimentary structure, in the upper part parallel lamination occurs (core 30G0863). A lag deposit with clay pebbles and a drop in grain size marks the transition from underlying Unit 2 to Unit 3b. The unit has a thickness of about 5 m but is difficult to trace in the non-continuous coring-descriptions. A small number of millimetre-thick inclined mud drapes were observed. These mud drapes as well as the sands of Unit 3b contain marine and marine-brackish diatom species (Table 1; Vos & De Wolf, 1993). Fresh-water species (e.g. *Epithemia turgida*) also occur. Molluscs that have lived in marine waters within the subtidal to upper intertidal zone occur scattered throughout the unit (Table 2). The amount of molluscs in this interval is much smaller compared to overlying Unit 4 (Table 2).

Interpretation

We interpret the fine- to medium grained sands and intercalated clay drapes to be deposited under estuarine conditions (Boersma & Terwindt, 1981; Allen, 1991). An estuarine interpretation is supported by both the diatom and mollusc assemblages.

Unit 4 (Kreftenheye Formation)

Description

Unit 4 in cores 30F0490, 30G0854 and 30D0215 consists of medium- to coarse-grained, grey to light-brown sands with fine gravel. Cross-bedded structures dominate. A fining-upward trend is visible in the unit and locally ripple cross-lamination is observed in its upper part (core 30G0854). The lower part of Unit 4 usually contains a concentration of marine molluscs commonly mixed with gravel, wood fragments and peat- and clay pebbles (e.g. cores 30D0215, 30F0490). The concentrate covers a sharp bounding surface between –25 and –34 m NAP.

Molluscs (mostly *Cerastoderma*, Table 2) that have lived in marine water within the subtidal to upper intertidal zone occur scattered throughout this unit. However, freshwater species (*Bithynia tentaculata*, freshwater gastropods, Table 2) also occur and close to the top of the unit hygrophile land-snails were found (*Trichia hispida*, Table 2). Molluscs in living position have not been found. Although most molluscs are not intact, the fragments have sharp edges and their thin non-mineral outer layer (*periostracum*) is generally well-preserved (Table 2). Unit 4 is locally characterised by the occurrence of small fragments of pyrite (core 30F0490, Table 1). Compared to the other cores, in core 30G0863, Unit 4 is finer grained. Also, in this core the amount of molluscs is smaller and the periostracum of the molluscs is less well preserved due to chemical bleaching. Unit 4 is characterised by the occurrence of marine and estuarine diatoms (e.g. *Cyclotella striata*), while marine-brackish and freshwater species only occur sporadically (Table 1).

Interpretation

The assemblages of both the (largely fragile) diatoms and molluscs and the presence of pyrite (common in estuarine/near-coastal sediments), suggests that the sediments of Unit 4 were deposited under tidal conditions. However, sedimentological features pointing towards tidal influence, such as clay drapes, bimodal cross-bedded sets and/or bioturbation features (Boersma & Terwindt, 1981; Allen, 1991) were not found. The absence of these tidal features in combination with the coarse grain size suggests that Unit 4 is of fluvial origin (cf. Törnqvist et al., 2000; 2003; Wallinga et al., 2004). The large fining-upward sequence presented in core 30G0854 indicates that rivers were deep and migrated laterally ('sandy meandering' cf. Miall, 1996) during deposition of this unit.

We interpret the marine molluscs in this unit as fluvial reworked from older deposits, since they are never observed in living position, they are primarily fragmented and occur in large amounts at the base of the unit. Preservation of the fragile periostracum of the molluscs and their sharp-edged (non-rounded) fragments indicates that transport of reworked material has only been minor.

We also interpret the marine diatoms in this unit as being reworked. This is controversial, because the pristine diatoms are often thought not to survive reworking and hence would always indicate in-situ marine or estuarine deposits. However, our descriptions of Unit 4 and especially of Unit 6a later in this paper, clearly illustrate that estuarine and marine diatoms assemblages can occur in coarse grained and gravelly fluvial deposits.

The idea of reworking is supported by optical dating (later in this paper), which shows that some units containing these estuarine diatom assemblages must have been deposited when sea-level was located at least 90m below the channel belt surfaces of that time (Fig. 6).

Unit 5 (Kreftenheye Formation)

Description

Unit 5 consists of fine-to medium-grained, light-brown sands with only small amounts of fine gravel. The deposit has a cross-bedded and ripple cross-laminated facies and shows an upward fining of grain size. Parallel lamination and ripple cross lamination become common towards the top. Occasionally, an alternation of thin clay layers and fine-grained sands occur at the top of the unit (e.g. core 30G0863). The contact with the underlying Unit 4 is difficult to pin-point. Locally, a sharp bounding surface is located at the base of the unit (core 30G0854), but in most corings the contact can only be recognised by a decrease in grain size (core 30F0490). The thickness of the unit is 3 to 7 m. Marine molluscs occur only sporadically, landsnails like Succinia oblonga (Table 2) were also encountered. Marine, marine-brackish and estuarine diatoms species occur at the base of the unit, but strongly decrease in number towards the top.

Interpretation

Unit 5 is interpreted to be of fluvial origin. This is based on the same criteria as given for Unit 4.

Unit 6a and 6b (Kreftenheye Formation)

Description

Unit 6a consists of coarse-grained, brown sands with significant amounts (5 - 25%) of fine to coarse gravel (2 - 63 mm). The sands contain a striking amount of coloured particles, due to less quartz and more rock fragments (mainly green, red and grey sandstone and shale fragments), which makes it easy to distinguish them from older fluvial units. Cross-bedded facies dominate in the lower part, while the upper part of the deposit has a ripple cross-laminated and horizontal laminated facies. The base of the unit is a sharp bounding surface at a level between –24 m and –26 m NAP (Fig. 5a). A gravel lag covers the bounding surface. Except for sporadic reworked weathered specimens at the base of the unit, marine molluscs are absent. A less well-expressed bounding surface is present at –21 m (core 37E0547). This bounding surface is covered by a gravel lag.

The unit is generally covered by a stiff light-grey clay layer (Unit 6b, Figs. 4a and 5a; Wijchen Member cf. Törnqvist et al., 1994) which is characterised by admixed sand grains and two centimetre-thick soil A-horizons. Just below the clay layer small amounts of pumice (core 37E0586) are present that are attributed to the eruption of the Laacher See volcano ~350 km upstream (Eifel region, Germany) at 12.9 ka BP (Friedrich et al., 1999). The thickness of the unit is 8 to 10 m. Unit 6a is characterised by a rich diatom assemblage consisting of estuarine, marine and fresh water species (Table 1).

Interpretation

The coarse-grained, gravelly sands and dominance of cross-bedded structures suggest that the deposits of Unit 6a are of fluvial origin (Miall, 1996). The small-scale fining-upward sequences are interpreted as braid bar deposits. This interpretation is supported by the braided pattern of residual channels found at the top of comparable deposits in the eastern Netherlands (Pons, 1957; Teunissen & De Man, 1981; Berendsen et al., 1995; Kasse et al., 1995). Unit 6b is interpreted as an overbank deposit (cf. Törnqvist et al., 1994).

Although the diatom assemblage encountered in Unit 6a suggests an estuarine sedimentary environment, we consider in-situ deposition of estuarine sediments at this level impossible because of generally accepted sea-level lowstand at time of deposition (Fig. 6) (see also paragraph on dating results). The occurrence of marine and estuarine diatoms in these coarse-grained gravelly sands is best explained by fluvial reworking incorporating older diatom bearing deposits, an explanation supported by the high number of freshwater diatom species (Table 1). Most likely, the source of these diatoms are the deposits of Unit 4.

Unit 7 (Boxtel Formation)

Description

Unit 7 consists of well-sorted, rounded, fine-grained sands that only occur on top of Unit 5. Sedimentary structures in the sands are vaguely developed, but consist mainly of horizontal lamination, wavy lamination and locally some cross-bedding. A well-developed podsolic soil is present at the top of the unit and roots penetrate the unit from the upper parts of the soil (A-horizon). The unit is covered by Holocene peat. Locally the unit is dissected by relative deep tidal and fluvial channels of Middle Holocene age (Figs. 5a and 5b). The thickness of this unit is 2 to 3 m.

Interpretation

The well sorted and rounded sands and vaguely developed sedimentary structures indicate an aeolian origin ('coversands' of Van der Hammen et al., 1967).

Dating results

Optical ages from the deepest part of the sedimentary succession in the study area (Unit 1) suggest deposition during MIS 8 and/or 7 (samples 30F0490 IX-XII, Table 3; Fig. 4a), although dating results of this unit have to be treated with caution because the validity of quartz optical ages in this age range has so far not been demonstrated (Murray and Olley, 2002). The abundant presence of augite in the deposits suggests that Unit 1 postdates 450 ka (Boenigk & Frechen, 1998). Overlying Unit 2 was deposited during the Late Saalian (MIS 6) (Table 3, Fig. 4a: samples 37E0586 VII, VIII; 30G0863 VIII-X; 30F0490 VIII).

Table 3. Quartz optical dating results. For technical details on dose rate and equivalent dose measurements we refer to Törnqvist et al. (2003) and Wallinga et al. (2004).

	Depth (m)	Depth (m –NAP)	Dose rate (Gy/ka)	Equivalent dose (Gy)	Optical age (ka, 1σ)
Core 37E0586					
Sample I	14,75	17,29	2.19 ± 0.07	24.6 ± 1.0	11.2 ± 0.6
Sample II	15,75	18,29	1.05 ± 0.03	15.5 ± 0.9	14.8 ± 0.9
Sample III	19,50	22,04	1.17 ± 0.03	22 ± 2	18.5 ± 1.4
Sample IV	22,55	25,09	1.12 ± 0.03	25 ± 2	22 ± 2
Sample V	23,55	26,09	0.74 ± 0.02	43 ± 3	59 ± 4
Sample VI	24,75	27,29	0.62 ± 0.02	41 ± 3	66 ± 6
Sample VII	27,75	30,29	0.69 ± 0.02	117 ± 9	169 ± 14
Sample VIII	28,75	31,29	0.84 ± 0.03	152 ± 29	183 ± 35
Sample IX	30,80	33,34	2.19 ± 0.07	Sat.	-
Core 30G0863					
Sample I	14,85	19,12	1.11 ± 0.06	54 ± 3	48 ± 4
Sample II	16,90	21,17	0.99 ± 0.05	54 ± 5	55 ± 6
Sample III	19,35	23,62	0.78 ± 0.05	64 ± 6	82 ± 9
Sample IV	21,25	25,52	1.29 ± 0.06	92 ± 7	71 ± 6
Sample V	22,25	26,52	0.92 ± 0.05	56 ± 3	61 ± 5
Sample VI	24,95	29,22	1.13 ± 0.05	66 ± 3	58 ± 4
Sample VII	25,85	30,12	0.86 ± 0.04	104 ± 6	120 ± 9
Sample VIII	26,75	31,02	0.79 ± 0.05	124 ± 7	158 ± 13
Sample IX	28,30	32,57	0.74 ± 0.04	107 ± 10	145 ± 16
Sample X	31,50	35,77	0.87 ± 0.04	156 ± 23	180 ± 28
Sample XI	37,70	41,92	-	Sat.	-
Sample XII	45,70	49,92	-	Sat.	-
Core 30F0490					
Sample I	15,25	15,45	1.05 ± 0.03	7.4 ± 0.4	7.1 ± 0.4
Sample II	18,30	18,50	1.04 ± 0.03	35 ± 2	34 ± 2
Sample III	20,80	21,00	1.10 ± 0.03	41 ± 4	37 ± 4
Sample IV	23,50	23,70	0.53 ± 0.02	40 ± 3	76 ± 6
Sample V	25,45	25,65	0.61 ± 0.02	46 ± 2	76 ± 4
Sample VI	26,60	26,80	0.87 ± 0.02	51 ± 4	59 ± 4
Sample VII	30,70	30,90	0.95 ± 0.03	96 ± 9	102 ± 10
Sample VIII	31,80	32,00	0.61 ± 0.02	75 ± 12	122 ± 20
Sample IX	35,65	35,85	0.61 ± 0.02	141 ± 14	231 ± 25
Sample X	37,80	38,00	0.74 ± 0.02	164 ± 14	220 ± 20
Sample XI	44,80	45,00	0.70 ± 0.02	154 ± 14	219 ± 21
Sample XII	51,65	51,85	0.64 ± 0.02	165 ± 19	260 ± 30
Sample XIII	54,80	55,00	1.16 ± 0.03	Sat.	-

Optical ages of Unit 3 (Table 3, Fig. 4a: samples 30G0863 IV-VII; 30F0490 VI-VII) point to deposition somewhere during the Eemian to Weichselian Early Pleniglacial (MIS 5, 4) period. However, part of the unit shows in-situ estuarine characteristics, pointing to deposition during a sea-level highstand. Estuarine deposition at these observed levels (-25 m to -30 m NAP) would be highly unlikely during MIS 4, since eustatic sea-level has been shown to have been at least 40 meters below present at that time (Waelbroeck et al., 2002; Cutler et al., 2003; Fig. 4a; Fig. 6). Estuarine deposition later than MIS 5 is therefore unlikely, implying that most optical dates from this unit are erroneously young. In cores 30G0863 and 30F0490 optical ages show a reversal, with older ages found for deposits overlying unit 3. This corroborates our conclusion that for some reason, our optical dating underestimated the age of unit 3. A detailed discussion on the aspects related to this underestimation is given in Törnqvist et al. (2003) and Wallinga et al. (2004).

Optical ages of Unit 4 (Table 3, Fig. 4a: samples 37E0586 V, VI; 30G0863 III; 30F0490 IV, V) point to deposition during the later part of the Weichselian Early Glacial (MIS 5a) and during the first part of the Weichselian Early Pleniglacial (MIS 4). The overlying Unit 5 was deposited during the Middle Pleniglacial (Table 3, Fig. 4a: samples 30G0863 I, II; 30F0490 II, III). The lower part of Unit 6a was deposited during Weichselian Late Pleniglacial (MIS 2) (samples 37E0586 III, IV) while the upper part was deposited during the final stage of the Weichselian Late Pleniglacial or during the initial phase of the Weichselian Late Glacial (Bølling) (Table 3, Fig. 4a: sample 37E0586 II). Pumice pebbles (Fig. 4a, core 37E0586) that occur directly below Unit 6b indicate that Unit 6b was deposited after the eruption of the Laacher See volcano (12.9 ka). Optical date 37E0586 I (11.8 - 10.6 ka) located directly below Unit 6b (Fig. 4a) and the ^{14}C date at the base of the peat layer overlying Unit 6b (Table 4: 9.4 - 9.0 cal. ka BP; Fig. 4a), constrain deposition of Unit 6b to the later part of the Younger Dryas and the beginning of the Holocene.

Although we have no direct dates of Unit 7, this aeolian deposit is widespread and well correlated to other areas in the Netherlands where a Late Pleniglacial and locally a Younger Dryas age is derived (Van der Hammen et al., 1967; Van Huissteden et al., 2001; Schokker et al., 2004).

Sedimentary architecture and relation to climate, sea-level and glaciation

The sedimentological and geochronological framework makes it possible to link the fluvial architecture to climatic, eustatic and glacial conditions. We stress that for the older part of the sequence, the resolution of our optical dates only permits us to make correlations to general conditions of climate, sea-level and glaciation for subsequent marine oxygen isotope stages. Correlations with events and/or conditions occurring within marine oxygen isotope stages is only possible for the upper (younger) part of the sequence.

MIS 8-6 (Saalian)

The basal part of the Urk and Kreftenheye Formations in the study area is formed by deeply incised fluvial channel systems correlated to MIS 8 and/or MIS 7 (Unit 1, Figs. 4 and 5). Abundant wood fragments and other organic material suggest that vegetation existed along the river system. Although periods of considerable temperate forest cover were described for MIS 7 (Zagwijn, 1973; De Beaulieu et al., 2001; De Mulder et al., 2003), it can not be ruled out that the wood fragments originate from erosion upstream and that the channel systems are formed during a colder unforested stage (envisaged for MIS 8; De Beaulieu et al., 2001). Marine molluscs, occurring towards the top of Unit 1, indicate high sea-level conditions. High eustatic sea-levels have been reported for MIS 7 (e.g. Waelbroeck et al., 2002).

During the Late Saalian (MIS 6) glaciation, the northern part of the Netherlands became covered by the Fennoscandian ice sheet of which the most southern limit was situated just north of the study area (Fig. 2) (Vandenberg & Beets, 1987; Ehlers & Gibbard, 2004). In front of the ice mass an ice marginal system developed that transported coarse-grained sand and gravel. Unit 2 represents this system (Figs. 4a and 4b). Vegetation reconstructions indicate a discontinuous treeless shrub tundra over most of the Rhine drainage basin (Guiot et al., 1989; Van Andel & Tzedakis, 1996; Fig. 6) and well-developed cryoturbations and frost cracks indicate conditions of continuous permafrost in nortwestern Europe (Vandenberghe, 2001). Sediment supply was high due to periglacial transport processes and supply of fluvio-glacial material that came available in front of the ice-sheet. Transport of the coarse-grained material most probably occurred during peak discharge related to spring release of glacial meltwater and snow melt. High sediment supply and high transport capacity during the Late Saalian made Unit 2 the coarsest unit in the sequence of the study area.

Strong isostatic vertical movement can be expected to have occurred during major glaciations (suppressing crust below main ice masses, and causing forebulge effects along the ice margins) (Lambeck, 1995). Although geophysical models and field evidence indicate these have occurred during MIS 2 (discussed

Table 4. Radiocarbon ages. All ^{14}C dates were calibrated using the calibration dataset of Stuiver et al. (1998) and the Groningen radiocarbon calibration program CAL25 (Van der Plicht, 1993).

Labnumber	Core	Depth (m)	Depth (m -NAP)	Analysed material	^{14}C age (yr, 1σ)	Calender age (yr BP, 2σ)
UtC-10757	37E0586	13,80	16,30	Terrestrial macrofossils (Scirpus nuts)	8220 +/- 60	9422 - 9013
UtC-10758	30F0490	16,00	16,20	Terrestrial macrofossils and charcoal	6889 +/- 49	7816 - 7612

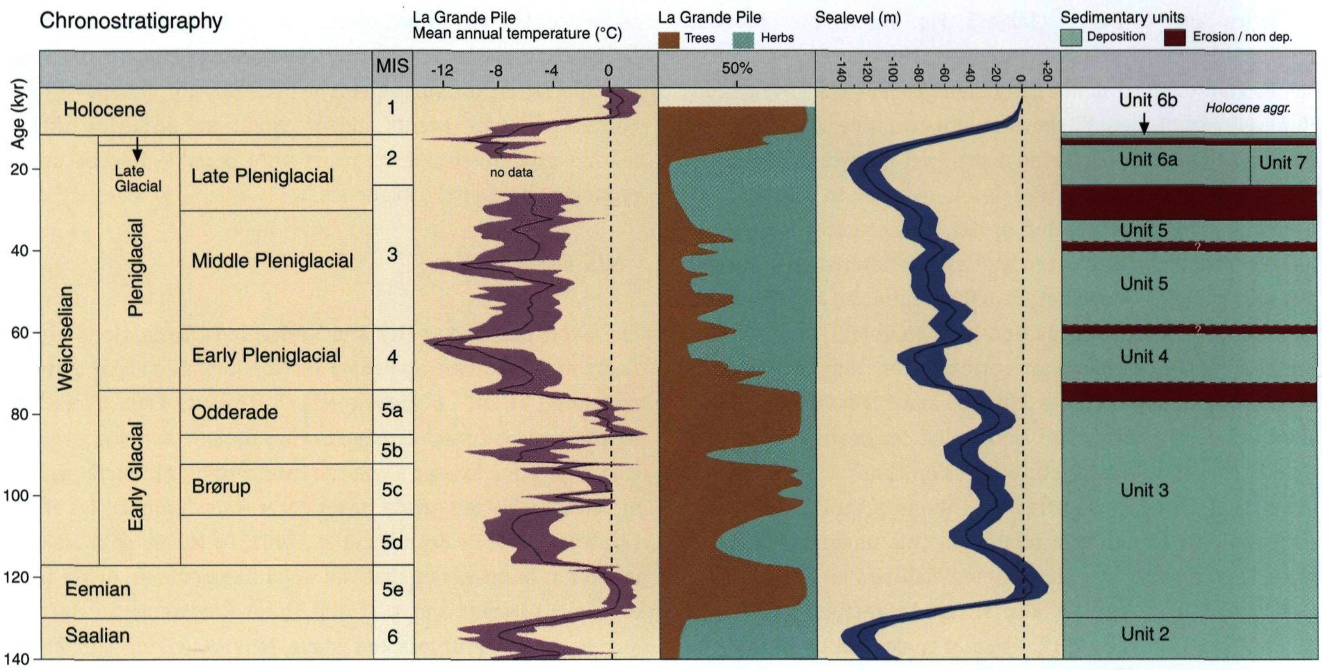

Fig. 6. Northwest European climate conditions and global sea-level during the Late Saalian and Weichselian periods. Chrono-stratigraphical framework for northwestern Europe after Zagwijn (1974), Vandenberghe (1985) and De Mulder et al. (2003). Marine isotope record after Bassinot et al. (1994). Sea-level record derived from North Atlantic and Equatorial Pacific benthic oxygen-isotope data (Waelbroeck et al., 2002). Mean annual temperature and precipitation data derived from a pollen record from La Grande Pile, France (Guiot et al., 1989), located just outside the Meuse drainage basin at 330 m NAP. Error envelopes in all records were taken from the original sources.

The chrono-stratigraphical position of the sedimentary units and unconformities in the study area are shown on the right. Although this figure suggests that deposition was essentially continuous, the exact amounts of time represented by depositional units (as proportion of total covered time), especially for the older units, remains unknown with current dating accuracies.

later in this paper), their magnitudes and effects on incision-aggradational trends during the reported Saalian glaciations in the North Sea area remains to be identified. For these periods it is unclear whether the study area was located in an area of isostatic uplift or suppression during maximum ice advances.

MIS 5-4 (Eemian to Weichselian Early Pleniglacial)

At the end of the MIS 6 glaciation the climate rapidly changed towards warmer interglacial conditions (Eemian). A closed forest vegetation developed and sea-level rose to values close to or higher than present (Zagwijn, 1983; Waelbroeck et al., 2002). Although a sea-level drop of 40 m is described for MIS 5b (Cutler et al., 2003), sea-level during the Weichselian Early Glacial interstadials (Brørup/MIS 5c, Odderade/MIS 5a) was located between -25 to -10 m NAP (Waelbroeck et al., 2002; Cutler et al., 2003). High sea-level conditions during MIS 5 are recorded in (part of) the sediments of Unit 3 (Fig. 4a). This unit is time-equivalent to the fine-grained mostly clayey sediments of the Brown Bank Formation, extensively described in the southern North Sea area (Cameron et al., 1986; Laban, 1995). The distribution of reworked marine molluscs in overlying Unit 4 indicates that marine influence during MIS 5 highstands reached at least 10 km inland from the study area (Fig. 2).

Sea-level fall at the MIS 5/4 transition is reported to have been rapid (Waelbroeck et al., 2002; Cutler et al., 2003; Fig. 6). This sea-level fall (base level drop) is thought to be at least partly responsible for dissection and erosion of marine and estuarine highstand deposits of MIS 5 age (Törnqvist et al., 2000, 2003; Wallinga et al., 2004), reflected by the reworked marine molluscs in the fluvial lag deposit of Unit 4 (Figs. 4a and 4b). Although the original thickness and extent of the MIS 5 highstand deposits (coastal prism) is difficult to reconstruct because of later erosion, it is likely that in the western Netherlands, it was considerably smaller than the Holocene coastal prism. The Rhine was located in the present IJssel Valley for most of MIS 5 (Van de Meene & Zagwijn, 1978), so only the much smaller river Meuse and some small local rivers brought sediment into the western Netherlands. Furthermore, overall sediment supply during MIS 5 may have been lower compared to the Holocene because of general reported vegetation stability (Guiot et al., 1989; Fig. 6) and absence of human deforestation and agriculture. Although changes in type of vegetation from grass-shrub/patchy boreal forest to boreal/temperate full forested conditions did occur throughout MIS 5 (Guiot et al., 1989; Aalbersberg & Litt, 1998; Guiter et al., 2003), these changes have been less dramatic than during the following Pleniglacial period (Fig. 6). Therefore we suggest that although sediments may have been generated (especially in mountain areas) during MIS 5 cold periods, sediment fluxes through the river system were modest and transported sediment was relatively fine-grained compared to the following Pleniglacial period. The lithology of Unit 3 reflects this.

This picture of general stability changed at the onset of MIS 4, when major climate deterioration set in, culminating in a period of severe cold around 70 ka with continuous permafrost and a treeless open vegetation (Huijzer & Vandenberghe, 1998; Guiot et al., 1989; Guiter et al., 2003; Fig. 6). Deposits from this period (Unit 4) show large cross bedded sets and large fining-upward sequences, suggesting that rivers were deep and migrated laterally by meandering. Such conditions could erode/rework marine deposits from MIS 5 age over a wide area, creating a marked erosion surface (base of Unit 4). Under the permafrost conditions, lateral erosion may have been accelerated by processes like thermo-erosional niching and subsequent collapse of frozen banks, frequently observed in recent periglacial systems (Church and Miles, 1982; Vandenberghe & Woo, 2002; Costard et al., 2003) with reported lateral erosion rates up to 40m a year (Lena river, Costard et al., 2003). Lateral erosion at such rates is associated with in-channel deposition of collapsed bank material and such conditions can explain why the marine molluscs and diatoms in this unit show no evidence of major transportation despite being reworked.

We can not exclude that during this period, sediment supply increased as an effect of the avulsion of the Rhine system from its MIS 5 course through the present IJssel Valley towards the western Netherlands (Fig. 2). The effects and timing of this avulsion is subject of further study. Regardless of avulsions in the receiving basin, sediment supply during MIS 4 may have increased gradually because of ongoing deterioration of the vegetation and increase of periglacial transport processes upstream in the drainage basin.

MIS 3 (Weichselian Middle to early Late Pleniglacial)

Vegetation reconstructions for MIS 3 period in northwestern Europe indicate minor vegetation changes with dense tundra vegetation (shrubs) and steppe vegetation (grasses) during temperate climatic phases (e.g. Kolstrup, 1980; Grüger, 1989; De Beaullieu et al., 2001; Guiter et al., 2003). This stability prevented major fluxes of coarse-grained material to occur in the fluvial system, which explains the relatively fine-grained composition of MIS 3 sediments (Fig. 4a and 4b). Time-equivalent smaller fluvial systems show comparable trends (Van Huissteden et al., 2003), but it needs further study, especially on other large fluvial systems in subsiding areas, whether this is a general phenomenon.

Despite the absence of clear erosional features, optical dates indicate a hiatus at the base of the MIS 3 fluvial succession (contact Unit 4/5 in Fig. 4a). Substantial age differences also exist laterally within Unit 5 (compare optical ages of Unit 5 in core 30G0863 with the ages in core 30F0490), a feature suggesting that multiple cut-and-fill cycles are present or that lateral migration of the river occurred. These features may relate to reported millennial scale North Atlantic climate oscillations (Dansgaard et al., 1993; Johnson et al., 1998) with cyclic alternations of warm/wet phases with sediment mobilization and cool phases of sediment deposition. Although correlation with particular climatic events remains difficult because of dating uncertainty, it is tempting to correlate part of our MIS 3 sediments (Unit 5) to a pronounced cut-and-fill cycle that is also reported in several smaller river systems in the Netherlands. Here, a phase of downcutting occurred around 40 - 35 ka (Hengelo Interstadial) followed by a phase of pronounced sediment deposition (Van Huissteden & Kasse, 2001; Van Huissteden et al., 2003), a feature also observed in part of our Unit 5 (optical dates of Unit V in core 30F0490).

MIS 2 (Weichselian Late Pleniglacial to Late Glacial)

Unit 6a was deposited during MIS 2 (Fig. 4). The coarse-grained sediments were deposited in a braided river plain under cold climate conditions and sea-level lowstand (Fig. 6). North of the (seasonally?) active river plain, as well as in other large parts of the Netherlands, fine-grained aeolian sands (Unit 7) were deposited.

At the end of MIS 3 and during MIS 2 the Scandinavian and British ice-sheets strongly expanded reaching their maximum extent in Denmark around 22 ka (Houmark-Nielsen & Kjaer, 2003). Climate reconstructions indicate extremely cold and dry conditions (Kolstrup, 1980; Guiot et al., 1989; De Beaullieu et al., 2001; Guiter et al., 2003) with the most severe period occurring between ~26 and 17 cal ka BP (Last Glacial Maximum). The landscape was characterised by open tundra vegetation (Kolstrup, 1980; Guiot et al., 1989; De Beaullieu et al., 2001; Guiter et al., 2003) and large ice-wedge casts and pingo remains indicate the existence of a continuous permafrost zone to about the latitude of central France (Renssen & Vandenberghe, 2003).

Fig. 4a shows that Unit 6a started to form as an incising system: the base of Unit 6a is located 4 to 5 m lower than the base of Unit 5. The optical age at the top of Unit 5 (sample 30F0490 II), shows that incision started after ~34 +/- 2 ka. The optical age from the base of Unit 6a (sample 37E0586 IV) shows that this incision continued until ~22 +/- 2 ka (Fig. 4a; Table 3).

We relate this incision to changing climate conditions at the MIS 3/2 transition. Around the MIS 3/2 transition the build-up of continuous permafrost (Huijzer & Vandenberghe, 1998) led to increased spring discharges due to snowmelt and a low storage capacity of the active layer overlying the permafrost (e.g. Van Huissteden & Kasse, 2001). Probably, sediment supply was initially low because the pre-existing tundra vegetation may have remained intact for a significant time (multiple millennia), preventing an influx of sediment from hill slopes and river banks into the river system (see also Vandenberghe, 1995). On top of that, it may have taken time before a sediment flux generated in the drainage basin, started to be recorded downstream. Although these mechanisms likely have been important during earlier periods, the MIS 3/2 transition is the only period, for which incision can be clearly demonstrated. This is due to preservation of the older pre-incisional sediment body (Unit 5) north of the incised Unit 6a.

During MIS 2, ongoing deterioration of the vegetation cover, especially in the upland areas, led to an increase in sediment supply. In the study area, incision was followed by net deposition of coarse-grained material (Unit 6a) from ~22 +/- 2 ka onwards. Seasonal thaw of the active layer, especially in the upland sparsely vegetated areas, resulted in a flux of freshly eroded coarse-grained material towards the river system. This material was transported downstream during peak discharges and/or phases of ice-break up (Woo & McCann, 1994).

A second factor that may have influenced fluvial development during MIS 2 is glacio-hydro isostacy. This involves crustal movement on a time scale of 10^3 - 10^4 years, as the result of ice and water loading and unloading due to the growth and decay of large ice sheets. Geophysical models indicate that in response to the build-up of the Fennoscandian ice-sheet (until ~22 ka; Houmark-Nielsen & Kjaer, 2003), a forebulge developed extending from the area between Norway and Britain towards the northwestern Netherlands and northern Germany (e.g. Lambeck, 1995). Our study area likely was located on the southward sloping flank of the forebulge and data from Lambeck et al. (1998) indicate that uplift in the area may have been more than 10 m. Kiden et al. (2002) show that the final phase of forebulge collapse is recorded as spatial differences in Holocene sea-level rise in the southern North sea. Cohen (2003) explains Late Glacial and Early Holocene northward channel shifts in the Rhine and Meuse valleys immediately upstream of the study area, as effects of the collapse of the southern flank of a forebulge. We recognise that in the study area, the Rhine likely reacted to isostatic uplift by incision during forebulge updoming. The base of Unit 6a (MIS 2) is located 4 metres below the base of Unit 5 (MIS 3), the latter reflecting a situation prior to isostatic forebulge updoming (assuming constant channel depth). Unit 6a incised position may reflect a river system that maintained a constant longitudinal profile, as it traversed the study area towards the Dover Strait. Older deposits north and south of the Unit 6a palaeovalley were uplifting while in the Unit 6a valley a constant absolute elevation was maintained. During forebulge collapse the area would have experienced subsidence. Within Unit 6a this may explain the transition to net deposition of coarse-grained from ~22 +/- 2 ka onwards (Fig. 4a). It is stressed that the effects of isostatic uplift and subsidence (also during earlier periods) can not be fully discriminated from the effects of climate related changes in discharge and sediment load. Nevertheless, the Weichselian Middle to Late-Pleniglacial depositional Rhine-Meuse record does allow to attribute features to updoming and initial collapse, and complements indications for forebulge collapse from the Late Glacial and Early Holocene records (Kiden et al., 2002; Cohen, 2003) from the same area.

An age difference of at least 3 kyr exists between the top deposits of Unit 6a and the overbank fines of the overlying Unit 6b (Fig. 4a), indicating a period of non-deposition in the study area that lasted for most of the Late Glacial. The overbank fines (Wijchen Member) originate from Younger Dryas and/or Early Holocene fluvial channel belts located south of the study area. Two soil layers within these overbank fines suggest that its deposition was temporarily interrupted or at least reduced. This feature was also described by Berendsen & Stouthamer (2002), who hypothesised an Allerød age for the lower soil. Our data shows that in our study area the entire Wijchen 'complex' is of Younger Dryas to Early Holocene age, with dark soil horizons developing mainly in the Early Holocene period.

Conclusions

The late Middle and Late Pleistocene (MIS 8-2) fluvial succession of the Rhine-Meuse system in the west-central Netherlands consists of a 15 to 25 meter thick stacked sequence of sandy to gravelly fluvial and estuarine units bounded by basal unconformities. In most cases these unconformities were recognised in the sedimentary record on the basis of lag-deposits and/or sudden changes in grain size.

Most of the sediments were deposited during cold climatic phases in a landscape with low vegetation cover and permafrost conditions. Relatively fine-grained sediments were deposited during more temperate fases and periods of high sea-level. Most of the material deposited during sea-level highstands however occurs in reworked position in younger units. The unconformities are related to phases of climate instability, sea-level fall and glacio-isostacy uplift although not in all cases full discrimination between these forcing factors is possible. Discriminating between forcing factors is complicated because major changes in climate, sea-level and/or glaciation often occurred simultaneously, i.e. forcing factors operated coevally.

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