



Fluvial evolution of the Rhine during the last interglacial-glacial cycle in the southern North Sea basin: A review and look forward



Jan Peeters^{a,b,c,*}, Freek S. Busschers^b, Esther Stouthamer^a

^a Department of Physical Geography, Faculty of Geosciences, Utrecht University, Heidelberglaan 2, P.O. Box 80115, 3508 TC Utrecht, The Netherlands

^b TNO – Geological Survey of the Netherlands, Princetonlaan 6, P.O. Box 80015, 3508 TA Utrecht, The Netherlands

^c Deltares, Unit Subsurface and Groundwater Systems, Princetonlaan 6, P.O. Box 85467, 3508 AL Utrecht, The Netherlands

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ABSTRACT

This paper presents the current state of knowledge on the evolution and depositional history of the River Rhine in the southern part of the North Sea basin during the upper Middle and Late Pleistocene, and its response to climate change, sea-level oscillation and glacio-isostasy. The study focuses on the development of the Eemian interglacial lower-delta in the central Netherlands and its relation to records of climate and sea-level rise, and uses the Saalian and Weichselian pre- and postdating periods to place its development in context.

The Rhine fluvial system fills the gradually subsiding North Sea basin, but its development has strongly been affected by the Saalian glaciation and its remaining topography. Ice-pushed ridges originating off the limit of maximum glaciation basically divided the central Netherlands into two sedimentary depocentres: a central depocentre within the former ice-limit, and a southern depocentre south of it.

The sedimentary record of the central depocentre, including an incised-valley fill, shows a 20–40 m thick stacked sequence consisting of three units. The incised-valley fill consists of a Late Saalian to early Eemian age lower fluvial unit and a Weichselian age upper fluvial unit, both composed of coarse-grained channel deposits. Sandwiched in-between is a 5–15 m thick record composed of fine-grained fluvial and estuarine (tidal) floodbasin and shallow-marine deposits. It is of Eemian interglacial and Early Weichselian age, and comprises transgressive and highstand deposits that show the drowning of a fluvial system. Inland parts transformed from fluvial to deltaic and estuarine environments, and the most downstream parts transformed to a shallow-marine embayment. Preservation of these units occurred, despite considerable sea-level fall and climate-controlled erosion taking place in the last-glacial. Preservation potential was increased by the fact that the Rhine system avulsed away to the southern depocentre, halfway the Weichselian Pleniglacial. Consequently, the infill of the southern depocentre is of an entire different nature, and last-interglacial transgressive or highstand units are hardly preserved.

Because of glaciation and resulting depocentre configuration, the Netherlands in NW Europe thus offers a very good opportunity to study the transgressive interglacial lower-deltaic records and falling-stage preservation thereof – both key elements for understanding sedimentary development over full 100-ky glacial-interglacial cycles of climate and base-level change.

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1. Introduction

Strong lithological variability, high clay-sand ratios and short-range porosity changes, make thorough understanding of estuarine and deltaic records (here integrated in the term lower-delta;

Fig. 1) of vital importance for exploitation of both the deep (e.g. hydrocarbon reservoirs) and shallow subsurface (e.g. aggregate resources and groundwater). Although a number of well-studied modern (Holocene) lower-deltaic records exists (e.g. the Rhine-Meuse delta in The Netherlands (Berendsen and Stouthamer, 2000; Hijma et al., 2009; Hijma and Cohen, 2011; Martinus and Van den Berg, 2011; Stouthamer et al., 2011); the Lower Tagus Valley in Portugal (e.g. Vis et al., 2008; Vis and Kasse, 2009); Po delta in Italy (e.g. Amorosi et al., 2003; Antonioli et al., 2009) and the Lower Mississippi Valley in the USA (e.g. Saucier, 1994; Aslan

* Corresponding author. Department of Physical Geography, Faculty of Geosciences, Utrecht University, Heidelberglaan 2, P.O. Box 80115, NL-3508 TC Utrecht, The Netherlands.

E-mail address: j.peeters1.uu@gmail.com (J. Peeters).

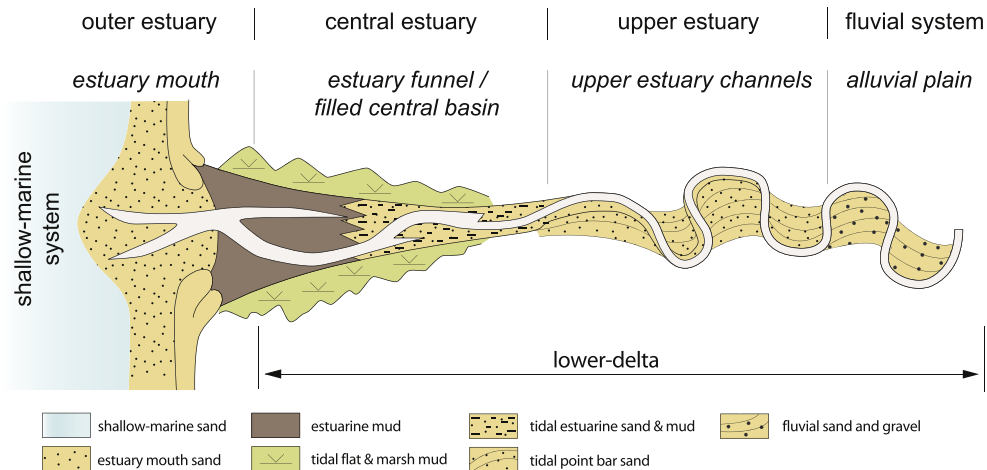


Fig. 1. Schematic illustration of terminology applicable to the Eemian interglacial Rhine in the central Netherlands. Different morphological units indicate different depositional environments within a partially-closed wave-dominated microtidal filled estuary (definition cf. [Reinson, 1992](#), modified from [Allen and Posamentier, 1993](#); [Van den Berg et al., 2007](#)).

and [Autin, 1999](#))), determining the long term (>10 ka) stratigraphic position, sedimentary architecture and in particular the preservation potential of lower-deltaic systems remains a major challenge.

To study these long-term process-relations and controls of lower-deltaic systems, sedimentary records originating from the Last Interglacial (\approx Marine Isotope Stage (MIS) 5e ([Shackleton et al., 2003](#)); [Fig. 2](#)) are arguably in a more relevant state of preservation than Holocene sequences are, especially since Last Interglacial lower-deltaic records experienced severe truncating effects of the full glacial-interglacial cycle of climatic and base-level change that occurred over the last 100 ka. Thereby, Last Interglacial lower-deltaic records are commonly situated within the practical ranges of data collection and dating techniques, enabling good correlations to independent high-resolution proxy-records, making them the ultimate natural laboratories to determine process relations and to test concepts of facies distribution, preservation (potential) and allogenic forcing.

In Europe, the Last Interglacial is known as the Eemian. Eemian interglacial records have been recognised and studied for longer and in greater detail in NW Europe than in any other region ([Turner, 2000](#)), at least in the terrestrial realm. Shallow-marine and estuarine Eemian interglacial deposits have also been identified in many records along the southern North Sea coast-line from Denmark (e.g. [Seidenkrantz et al., 2000](#); [Funder et al., 2002](#)), to Germany (e.g. [Höfle et al., 1985](#); [Streif, 2004](#)), to The Netherlands (e.g. [Harting, 1874, 1875](#); [Jelgersma et al., 1979](#)), to Belgium (e.g. [Mostaert and De Moor, 1989](#); [Mathys, 2009](#)) and the UK (e.g. [Jardine, 1979](#); [Bridgland and D'Olier, 1995](#); Ipswichian stage). Across the Atlantic Ocean, along the East Coast of the USA, more or less similar Last Interglacial (Sangamonian stage) lower-deltaic deposits are encountered (e.g. [Colman and Mixon, 1988](#); [Knebel and Circé, 1988](#); [O'Neal and McGeary, 2002](#); [Parham et al., 2007](#); [Harris et al., 2013](#)).

To study the effects of base-level and climatic change on the development and preservation of a lowland river system in a shelf-connected setting through the last glacial-interglacial cycle, the Rhine delta record in the southern North Sea basin (The Netherlands: [Fig. 3A–B](#)) is a very suitable location in NW Europe (e.g. [Törnqvist, 1998](#); [Törnqvist et al., 2000, 2003](#); [Wallinga et al., 2004](#); [Busschers et al., 2005, 2007, 2008](#)).

Here, the River Rhine, at present draining $\sim 185,000$ km² of the northwest and central European foreland, deposited several tens of metres of mostly sandy deposits during the upper Middle and Late

Pleistocene. Sandwiched in-between these fluvial sands, a 5–15 m thick Eemian unit of mainly lower-deltaic and shallow-marine fine-grained sediments is found. This Eemian interval is encountered in literally tens of thousands of individual boreholes. An overview of only the highest-quality cores penetrating the entire Eemian interglacial sequence (~ 3300 cores) is shown in [Fig. 3C](#). In the areas where the interval is thickest developed and preserved, it is composed of several stacked and lateral occurring units of fluvial, estuarine and shallow-marine origin. Sedimentary architecture and deposit characteristics of the shallow-marine system (e.g. [Harting, 1874, 1875](#); [Steenhuis, 1933](#); [Wiggers, 1955](#); [Jelgersma et al., 1979](#); [Cleveringa et al., 2000](#); [De Gans et al., 2000](#); [Van Leeuwen et al., 2000](#)) and the more upstream fluvial part of the Eemian interglacial Rhine system (e.g. [Van de Meene, 1977](#); [Busschers et al., 2007](#)) have been thoroughly studied. The area where the Rhine entered the Eemian interglacial estuary has however never been studied in detail. Earlier efforts to investigate the Eemian interglacial Rhine estuary resulted (only) in the preliminary identification of marine and terrestrial depositional extents (e.g. [Steenhuis, 1933](#); [Burck, 1951](#); [Wiggers, 1955](#); [Busschers et al., 2007](#)). A coherent overview of the complete Eemian interglacial depositional system of the Lower Rhine has not been presented so far.

In this review, we present the current state of knowledge on the sedimentary development of the Rhine depositional-system in The Netherlands during the upper Middle and Late Pleistocene, and on the response of this system to climate change, sea-level oscillation and glacio-isostasy. We focus on the lower-deltaic environments as they established during the Eemian Interglacial in relation to sea-level rise. The developments during the pre- and postdating periods are used to place the evolution of the Eemian depositional system in context. This review examines consolidated ideas and highlights gaps in the existing knowledge. Moreover, it presents a framework for future research in order to obtain better insights and improve our knowledge in the long-term sedimentary architecture and preservation (potential) of lower-deltaic systems.

2. Regional geological setting

The Netherlands and the adjoining southern North Sea are situated at the margin of the Cenozoic North Sea basin ([Ziegler, 1994](#)). The basinal Cenozoic sediment sequence reaches a maximum thickness of 3500 m ([Anell et al., 2012](#)), where Quaternary deposits, mainly consisting of fluvial, marine and estuarine sediments,

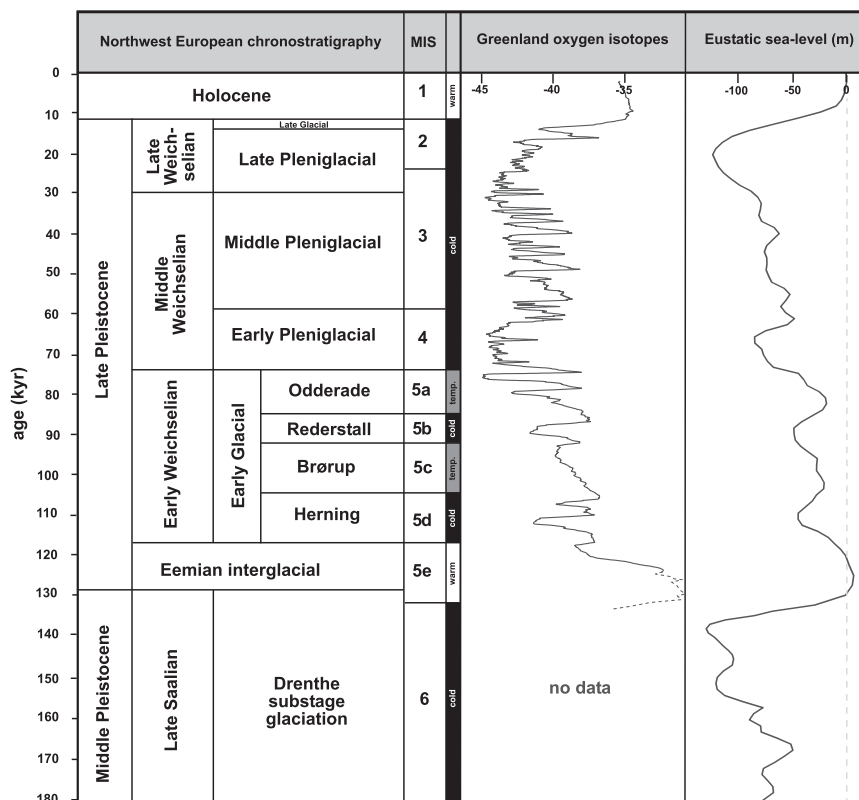


Fig. 2. NW European chronostratigraphical subdivision of the upper Middle and Late Pleistocene (after Van Huissteden and Kasse, 2001 and Busschers et al., 2007, 2008) and correlations with the marine isotope record (Bassinot et al., 1994) and with the NGRIP oxygen isotope record (solid-line) (NGRIP-members, 2004), supplemented for the Eemian interglacial with results (dashed-line) from NEEM-members (2013). The composite eustatic sea level record is from Waelbroeck et al. (2002).

account for a thickness of up to 900 m (e.g. Zagwijn, 1974, 1989; Caston, 1979). The main Cenozoic depocentres of the North Sea basin are formed by the Roer-Valley-Rift system (RVR) in the south-eastern Netherlands and the Central Graben (CG) (Fig. 3A). These depocentres are structurally linked with the Lower Rhine Graben (LRG) in central Germany and the Upper Rhine Graben (URG) in southern Germany (Fig. 3A). The Rhine system follows these linked tectonic structures, which activated during the Late Eocene in response to the Alpine orogenesis, and continue to be active today (Ziegler, 1994). The grabens thereby acted as important depocentres resulting in large-scale stacking of fluvial sediments. The Pleistocene Rhine sequence in the central part of the RVR reaches a thickness of up to 500 m and is mainly made up of coarse-grained gravelly sands (e.g. Zagwijn, 1989; Westerhoff et al., 2008).

The pattern of gradual basinal infill changed markedly during the Middle Pleistocene due to glacial expansion and (partial) cover of most of the North Sea basin by ice-sheets especially during the Elsterian and Late Saalian periods (Passchier et al., 2010; Laban and Van der Meer, 2011; Lee et al., 2012). This resulted in a major distortion of the former SE–NW directed drainage pattern (Fig. 4A) and hence stepwise shifts of deposition locations (e.g. Busschers et al., 2008; Cohen et al., 2012). This process culminated during the final opening of the Dover Strait for which most evidence now suggests it occurred during the Saalian (e.g. Meijer and Preece, 1995; Busschers et al., 2008; Hijma et al., 2012; Mellett et al., 2013; Rijdsdijk et al., 2013).

Late Pleistocene fluvial deposition was strongly affected by the inherited Saalian glacial morphology, basically creating two depocentres, separated by a complex of Late Saalian ice-pushed ridges. The Southern Netherlands depocentre (SND) is situated beyond the Saalian ice-limit, while the Central Netherlands depocentre (CND)

is located within (Fig. 3B). The SND record shows a 10–25 m thick stack of Late Pleistocene sediment, initially deposited by the Meuse only, but later by both the Rhine and Meuse rivers (Van de Meene and Zagwijn, 1978; Busschers et al., 2007). The CND record contains a stacked sequence of 20–40 m of primarily coarse-grained sediments that were deposited by the Rhine only (Van de Meene and Zagwijn, 1978; Busschers et al., 2007) (Fig. 5). In the CND, sediment accumulation was particularly affected by the presence of Late Saalian scoured glacial basins, creating large accommodation-space. Long-term preservation of Late Pleistocene sediments however is in both areas controlled by (background) subsidence, ranging from ~0.2 m/ka in the most downstream parts to near zero in the upstream parts (Kooi et al., 1998; Wallinga et al., 2004; Cohen et al., 2005), which are close to the North Sea basin hinge-line both in the CND and in the SND.

This review focusses on the CND, where Rhine lower-deltaic deposits occur in the subsurface of, from east to west, the present-day IJssel valley, Noordoostpolder, Lake IJssel, province of North Holland and North Sea (Fig. 3B). During the Late Saalian, the River Rhine formed a major east-west orientated incising river valley-system (palaeo-Vecht valley: Fig. 4E). The Eemian interglacial Rhine lower-delta is positioned in this drowned river valley, filling it partially. Around the position of the former river mouth, the incised-valley fill contains estuarine sediments of both marine and fluvial origin. Due to its narrow entrance and scattered shallows in the west, tidal-influence in the enclosed-bay is considered to be (relatively) low (De Gans et al., 2000). The Eemian interglacial Rhine system, occupying the funnel-shaped drowned palaeo-valley, can therefore presumably be regarded a wave-dominated microtidal filled estuary (cf. Reinson, 1992; i.e. with few or no barriers at its mouth) (Fig. 1). Upstream the river mouth, the

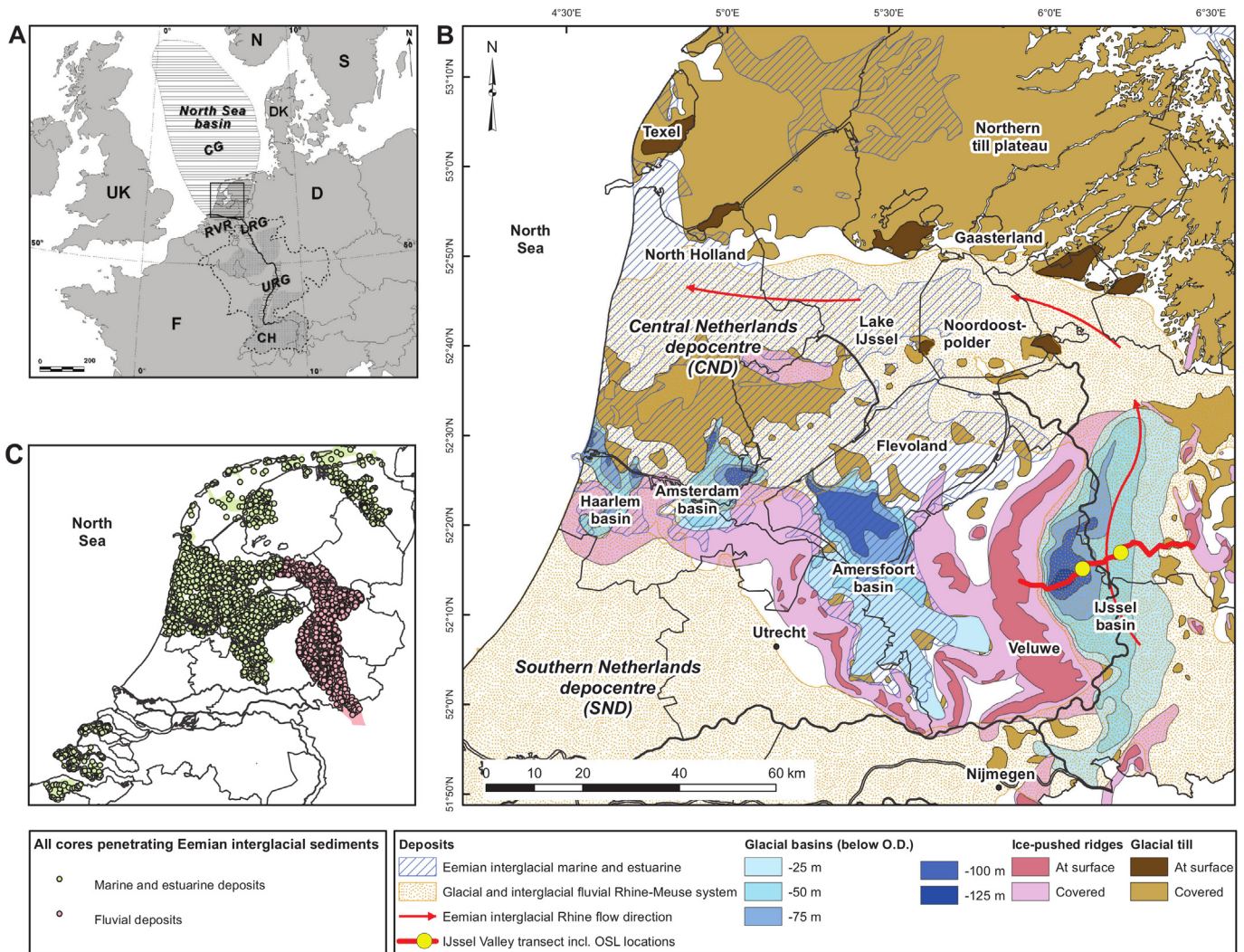


Fig. 3. A) Present-day Rhine drainage basin and its tectonic setting (cf. Ziegler, 1994). URG = Upper Rhine Graben; LRG = Lower Rhine Graben; RVR = Roer Valley Graben; CG = Central Graben. B) Late Pleistocene Rhine and Eemian interglacial marine and estuarine deposits in relation to the inherited (glacio-) topography in the Netherlands. After Busschers and Bakker (2009) and Gunnink et al. (2013). C) Overview of all highest-quality cores (ca. 3300) penetrating Eemian interglacial fluvial, estuarine and marine deposits in the study area (data from TNO-GSN subsurface database: TNO, 2013; Van der Meulen et al., 2013).

Eemian interglacial fluvial sequence extends into the fill of the IJssel glacial tongue basin, where it covers latest Saalian fluvial deposits, underlain by lacustrine-deltaic and glacio-fluvial deposits (Fig. 5) of the Saalian deglaciation phases (Fig. 4D–E).

In general, the Eemian interglacial Rhine lower-deltaic sequence is found at depths varying between 10 and 40 m below the surface, with a thickness of 5–15 m, and is covered by sediments of the Weichselian River Rhine and local drainages (Fig. 5; Huisink, 2000; Busschers et al., 2007). Lagoonal and fluvio-deltaic deposits of Holocene age top the entire sequence (e.g. Wiggers et al., 1962; Ente et al., 1986; Makaske et al., 2008; Cohen et al., 2009).

3. Evolution of the Rhine during the upper Middle and Late Pleistocene

3.1. Saalian glaciation (MIS 6)

A transition from interglacial conditions towards a colder climate occurred around 190 ka (Dutton et al., 2009), marking the onset of ice-sheet expansion over the North Sea basin. The Fennoscandian ice-sheet reached The Netherlands shortly after 170 ka (Kars et al., 2012). The ice-sheet ultimately covered most of the

northern Netherlands by several hundreds of metres of ice (Schokking, 1990; Lambeck et al., 2006). This phase of glaciation, referred to as the Drenthe substage within the Saalian, left a marked imprint on The Netherlands' landscape by formation of glacially scoured basins, ice-pushed ridges and glacial till complexes (Fig. 3B) (e.g. De Waard, 1949; Ter Wee, 1962, 1983; Maarleveld, 1983; Ruegg, 1983; Van den Berg and Beets, 1987). These landforms remained to have a major impact on fluvial development for the remainder of the Pleistocene.

During a first glacial-advance phase, overridden till accumulations and small ice-pushed structures formed on the Texel-Gaasterland line in the northern Netherlands (Fig. 4B) (e.g. Van den Berg and Beets, 1987). The Rhine-Meuse sediments from this time, best recognized in outcrops in the later formed ice-pushed ridges, are very coarse-grained sands which are rich in gravel and (large) boulders. These sediments occur in a wide SE–NW oriented range throughout the CND (Fig. 4B), and were dated at 168 ± 19 ka (Busschers et al., 2008). The Rhine-Meuse system probably merged with a proglacial system along the southern margin of the ice-sheet.

Continuing ice progradation in south-westward direction eventually slowed down and presumably stopped due to the

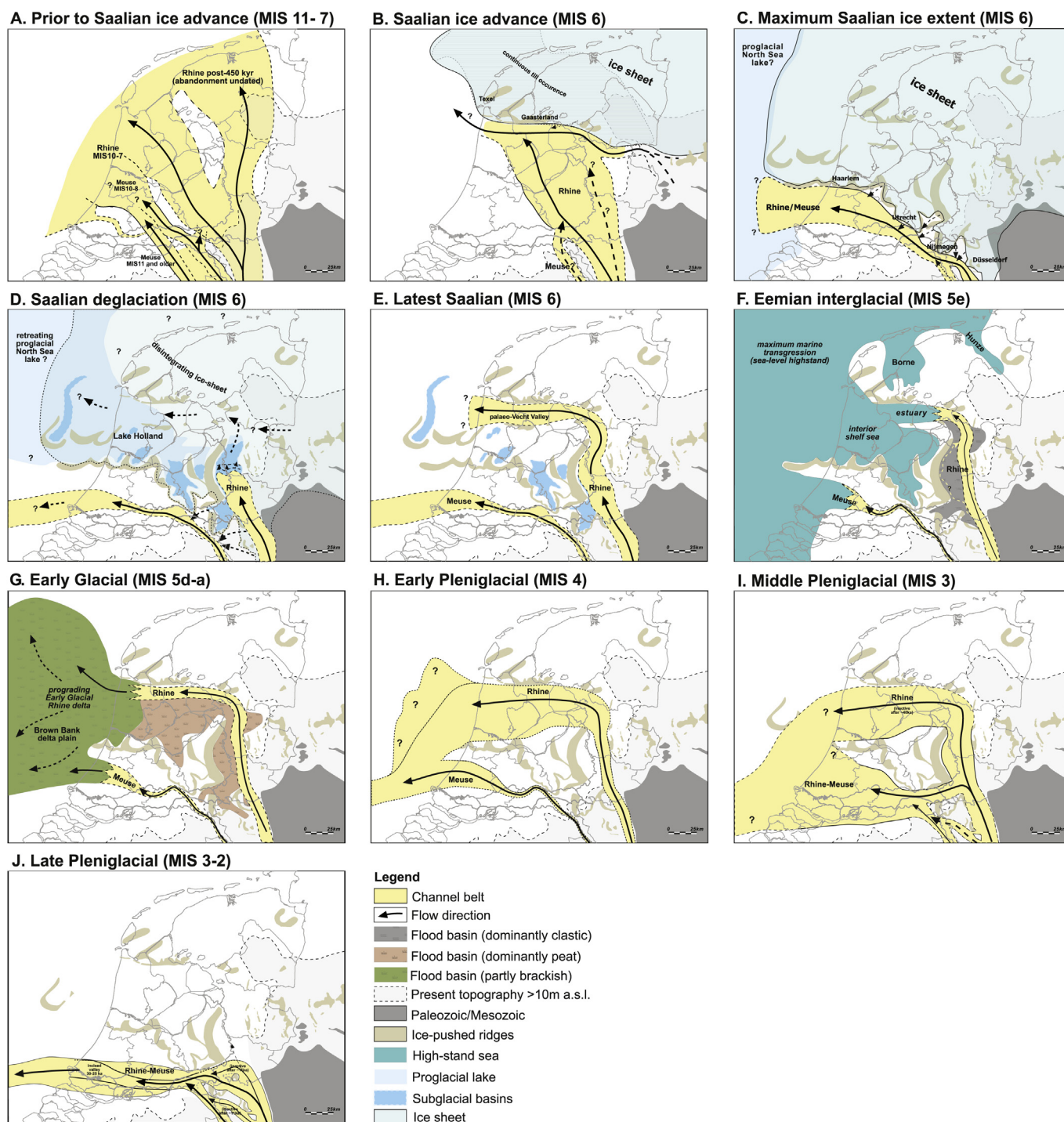


Fig. 4. Palaeogeographical reconstruction of the lower Rhine during the Middle (MIS 11-6) and Late Pleistocene (MIS 5-2) illustrated by 10 successive time frames. The palaeogeographical maps are principally based on Busschers et al. (2007, 2008) and modified with use of Jelgersma et al. (1979), Hijma et al. (2012), Rijsdijk et al. (2013) and supplemented with data from the TNO-GSN subsurface database (TNO, 2013; Van der Meulen et al., 2013). A) Rhine-Meuse drainage configuration prior to the Drenthe substage glaciation (see Busschers et al. (2008) for further detail). B) Drenthe ice-sheet advance into the northern Netherlands up to the Texel-Gaasterland line. The Rhine probably made contact with proglacial drainage directly south of the ice-mass, and was joined by the Meuse. C) Maximum Saalian ice-sheet extent up to the Haarlem-Utrecht-Nijmegen line. The Rhine had its course through the Niers-valley and confluenced with the Meuse south of the large ice-pushed ridges. D) During the initial Drenthe deglaciation phase, the Rhine diverted its course to the north and entered the inundated IJssel basin, while the Meuse continued towards the west. E) During and after presumed Late Saalian lake drainage, the deglaciation-river Rhine extended its course into the east-west oriented palaeo-Vecht valley, while the Meuse held its position in the SND. F) Eemian interglacial maximum transgression during sea-level highstand. The Rhine flowed through the IJssel basin, in a solely fluvial dominated setting, before it deflected to the west where it entered the upper estuary in the area of the present-day Noordoostpolder. In the south, the Meuse had its own Eemian interglacial estuary. G) During the Weichselian Early Glacial the Rhine remained at its position through the IJssel basin where organic-rich deposition increased. More to the west, the prograding Rhine delta entered a lower-deltaic floodbasin environment (Brown Bank delta plain), which also comprises the outlet of the Meuse. H) The Rhine persistently kept its position through the IJssel basin during the Early Pleniglacial, thereby laterally reworking former coastal prism deposits before connecting with the Meuse in the south. I) During the Middle Pleniglacial the Rhine partly avulsed towards a shorter higher-gradient course and merged with the Meuse in the south. The avulsion was completed ~40 ka BP. J) The Rhine-Meuse system abandoned the northern part of the SND in the Late Pleniglacial–Late Glacial around ~35 ka BP, resulting in the configuration of the Rhine-Meuse system similar to today's. Deposition in the CND was dominated by local river and aeolian activity only.

change of the glacier substratum to coarser-grained sands and associated permeability changes (Fig. 4C) (Van den Berg and Beets, 1987). Exceptionally large ice-pushed ridges were formed in the central Netherlands (Haarlem-Utrecht-Nijmegen), reaching heights of over 100 m above sea-level (e.g. Van den Berg and Beets, 1987; Kluiving et al., 1991). Formation of this series of ice-pushed ridges was accompanied by deep scouring of glacial basins, to depths of 125 m below sea-level (Fig. 3B). The volume of the different glacial basins and their coherent ice-pushed ridges is related and increases from west to east. The main large glacial-basins across this west–east transect are referred to as the Haarlem and Amsterdam basins (De Gans et al., 1987, 2000; Van Leeuwen et al., 2000; Beets and Beets, 2003), Amersfoort basin (Zagwijn, 1961; Cleveringa et al., 2000) and IJssel basin (Verbraeck, 1975; Busschers et al., 2007, 2008) (Fig. 3B). These glacial basins all show more or less similar basal infills, with in many places glacial till at the bottom, covered by several tens of metres of glacio-lacustrine clays of Late Saalian age. The lower part of these clays often shows an annually laminated varve-signature (Jelgersma and Breeuwer, 1975; De Gans et al., 2000; Van Leeuwen et al., 2000). During maximum glaciation, the Rhine (and Meuse) system was forced into an ice-marginal position in the SND, south of the Haarlem-Utrecht-Nijmegen ice-pushed ridges line (Fig. 4C) (e.g. Thomé, 1958; Van de Meene and Zagwijn, 1978; Busschers et al., 2008), where it made direct contact with sandur outwash complexes (Verbraeck, 1984). Sediments from this phase within the Saalian are gravelly and coarse-grained with sporadic admixture of Scandinavian granites, and were dated with optically stimulated luminescence (OSL) to within MIS 6 (ages ranging between 157 and 130 ka; Busschers et al., 2008). The ice-marginal Rhine maintained this course towards the western Netherlands for a relative short period. After the Rhine abandoned this maximum ice-limit course during the following Saalian deglaciation (see below), the Meuse remained at this position up to present (Busschers et al., 2008; Hijma et al., 2012).

In response to the on-going disintegration of the Saalian ice-lobe of the IJssel tongue basin, the Rhine diverted its course to a position north of the ice-pushed ridges, towards the CND (Fig. 4D). This avulsion of the Rhine occurred relatively early in the deglaciation sequence, and introduced a gradually northward prograding delta-system in the now melt-water filled IJssel basin (Fig. 3B; Fig. 4D). Deposition of fine-grained lacustrine-deltaic sediments (clays, fine sand) led to a near complete infill of the basin, already before the onset of the Eemian interglacial (Van de Meene and Zagwijn, 1978; Busschers et al., 2007; Fig. 5). This IJssel valley lake appears to have connected with the larger lake system (Holland Lake) that had formed in the tongue basins of the CND (De Gans et al., 2000; Beets and Beets, 2003). Busschers et al. (2008) suggested it was part of a much larger deglaciation retreat North Sea lake during this stage (Fig. 4D).

During the Late Saalian, the Rhine deposited ~10 m of coarse-grained gravel-rich sands on top of the lacustrine-deltaic sequence in the IJssel basin (Fig. 5) (Busschers et al., 2008). These coarse-grained sediments span the entire valley and are assumed to be deposited by a braided fluvial system (Van de Meene and Zagwijn, 1978). After drainage of the Late Saalian lake(s), the Rhine extended its course into the 30 m deep and 10 km wide east–west orientated palaeo-Vecht valley (Fig. 4E). Here, the Rhine sediments overlay coarse-grained gravel-rich glacio-fluvial deposits (Wiggers, 1955; Van den Berg and Beets, 1987). Although a postglacial age of this valley is indicated by the cross-cutting relationship with the underlying fine-grained glacio-lacustrine sediments and Drenthe substage till (Van den Berg and Beets, 1987; Westerhoff et al., 1987), its position may have initially been controlled by the presence of an older ice-marginal structure that developed during ice-sheet progradation.

Glacio-isostatic adjustment-modelling results (Lambeck et al., 2006, 2012) position The Netherlands in between the crustal depressed region and the crest of the peripheral forebulge

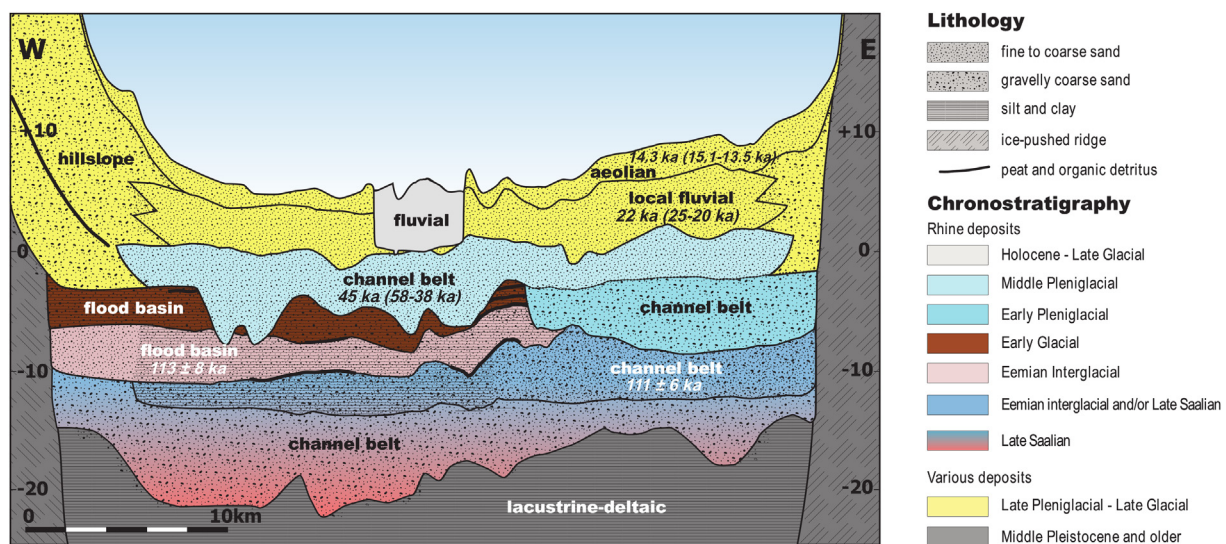


Fig. 5. Geological transect showing the stratigraphical position, stacked geometry and OSL-ages of the IJssel basin fill (after Busschers et al., 2007), see Fig. 3B for its location and Busschers et al. (2007) for detailed information on the individual OSL-datings. Lacustrine-deltaic deposits partly consisting of laminated clay are found from the base of the fill upward. Being over 100 m thick in some places, they span the complete width of the former glacial tongue basin. The top of these fine-grained deposits dates to the Late Saalian, and is partly eroded by fluvial activity, depositing coarse-grained sediments during the latest Late Saalian. Coarse-grained Rhine channel-belt sedimentation continued into the Eemian interglacial, when contemporaneously clastic floodbasin fines were deposited in the western half of the IJssel basin. More organic-rich floodbasin deposits, including peats, were formed at the same western position during the Weichselian Early Glacial, while the main Rhine channel belt was probably located in the east during both periods. At this eastern position, the presumed Early Pleniglacial coarse-grained Rhine channel belt is encountered, probably reworking the Eemian interglacial and Early Glacial channel belts. The Early Glacial organic-rich floodbasin deposits were partly eroded by more centrally positioned Middle Pleniglacial river channels. The Middle Pleniglacial channel belt deposits overlay the older Weichselian Early Glacial floodbasin and Early Pleniglacial channel belt deposits. The Holocene fluvial system incised into local Late (Pleni-) Glacial fluvial and aeolian sediments, resulting in a stacked sequence of at least 5 major Rhine channel belts at this particular location.

(Busschers et al., 2008). For the sequence in the SND area, a complicating factor is that the ice-marginal Rhine-Meuse system appears to have experienced base-level effects due to the development of a proglacial North Sea lake during Late Saalian ice-sheet expansion, probably at the same time that it also experienced effects of the glacio-isostatic warping (Busschers et al., 2008). This lake developed due to ponding of melt water in between the ice-sheet front and Paleogene and Mesozoic topography in the south, a situation also assumed to have existed during the Elsterian (Gibbard, 1988; Toucanne et al., 2009; Murton and Murton, 2012). It would have caused erosion in its southern sill area (e.g. Gibbard, 1988; Busschers et al., 2008; Hijma et al., 2012) and therefore base level lowering during the time of maximum ice extent (e.g. Fig. 4C–D). Lake-level rise and fall are exchangeable for responses to glacio-isostatic compensation as explanations for observed aggradations and incisions in the SND (Busschers et al., 2008). The deglacial Rhine route into the IJssel basin and towards the CND is not affected by these proglacial complications.

In conclusion, during the prolonged cold Saalian period, large and widespread glacial geomorphology (e.g. ice-pushed ridges, glacial till complexes and glacial basins) was formed by land ice-masses, thereby shaping the important bounding topography for the Rhine system in the subsequent Eemian interglacial period.

3.2. Eemian interglacial (MIS 5e)

At the very end of the Saalian, the NW European climate ameliorated, defining the onset of the Eemian interglacial. Temperatures rapidly increased towards values as high or higher than present-day (e.g. Kukla et al., 2002; Kaspar et al., 2005; Bakker et al., 2012), reaching an early optimum (Zagwijn, 1996), followed by a slight cooling and eventually a sharp drop in both temperatures and precipitation (e.g. Guiot et al., 1989; Kühl et al., 2007; Brewer et al., 2008). Global sea-level at maximum highstand within MIS 5e exceeded modern levels by more than 5.5 m (Kopp et al., 2009; Dutton and Lambeck, 2012), with eustatic sea-level rise rates being 1.6 m per century on average (Rohling et al., 2008). The Netherlands' relative sea-level curve as constructed by Zagwijn (1983) shows a maximum sea-level position at 8 m below modern sea-level during the second half of the Eemian interglacial.

Eemian vegetation development in the Netherlands' setting has a long research history and is studied in great detail (e.g. Florschütz, 1930; Zagwijn, 1961, 1996; Cleveringa et al., 2000; Van Leeuwen et al., 2000). The Netherlands' Eemian interglacial is basically subdivided by partly-coinciding succession-assemblages of characteristic tree taxa: *Betula*, *Pinus*, *Ulmus*, *Quercus*, *Corylus*, *Taxus*, *Carpinus*, *Picea* and *Pinus* respectively. Shrub and herb dominated assemblages preceded and succeeded this succession. These characteristic groups of different taxa are captured in Regional Pollen Assemblage Zones (RPAZ E1–E6; cf. Zagwijn, 1961), with each RPAZ being a distinctive biostratigraphic marker horizon.

The duration of the Eemian interglacial in The Netherlands was estimated on basis of the German Bispingen varve-record (Müller, 1974) at ca. 11 ka by Beets et al. (2006). They also presented an inferred age of ca. 131 ka for the onset of the Eemian. Van Leeuwen et al. (2000) U–Th dated the uppermost part of The Netherlands' Eemian interglacial sequence at 118 ± 6 ka. Recently, Sier et al. (2011) used the position of the palaeomagnetic Blake event to determine an age of ca. 121–110 ka for the timing of the Eemian interglacial in Neumark, Germany. This relatively young age contradicts the earlier derived older age assignments for the Eemian interglacial, but is supported by several independent luminescence-dating results (e.g. Murray and Funder, 2003; Schokker et al., 2004; Busschers et al., 2007; Buylaert et al., 2011).

Detailed information on the Rhine lower-deltaic development comes from lithostratigraphical geological mapping. During the Eemian interglacial, the Rhine flowed through the IJssel basin before it deflected downstream to the west where it entered the estuary in the area of the present-day Noordoostpolder and Lake IJssel (Fig. 3B). More to the west in the CND, below the present-day Lake IJssel and the province of North Holland (Fig. 3B), the outer estuary and shallow-marine system of the Eemian interglacial interior shelf sea (Fig. 4F) were located.

3.2.1. Fluvial system

Fluvial Eemian Rhine deposits are especially well preserved in the IJssel basin (Burck, 1949; Van de Meene, 1979, 1990; Busschers et al., 2007), where they overlay the Late Saalian fluvial and lacustrine-deltaic fill of the Drenthe Substage glacial tongue basin (Fig. 5). In the early Eemian, the Rhine main channel belt (sands) is thought to have been positioned in the eastern side of the IJssel basin, whereas floodbasin deposits (clays and peat; RPAZ's E1, E2 and/or E3) are encountered on the western side, at the margin of the Veluwe ice-pushed ridge (Figs. 3B and 4F; Van de Meene, 1979, 1990; Busschers et al., 2007). The mean thickness of the floodbasin deposits is ca. 3.5 m, whereas the channel belts are on average ca. 4.5 m thick (Fig. 5). One OSL date from the channel sediments is available (Busschers et al., 2007), with a relatively young age of 111 ± 6 ka.

From the later part of the Eemian (RPAZ's E4, E5 and E6), predominantly floodbasin deposits appear to be preserved, forming a second unit that overlays the older floodbasin deposits (Fig. 5). It is finer grained and contains less sand. One OSL date is available (Busschers et al., 2007: 113 ± 8 ka). The base of this unit is a several decimetres thick compacted peat layer, covered by clay, clay-gyttja and peat-detritus. These floodbasin deposits change upwards into alternations of laminated clay and silt, with some rooted soil horizons. No channel belts related to these (presumed) floodbasin deposits have been identified and it was therefore assumed that these belts were located in the eastern part of the basin where they were later eroded by younger (Pleniglacial) channel belts (Busschers et al., 2007).

The sedimentology of the early Eemian interglacial fluvial unit indicates a meandering river system, through the presence of fining-upward sequences and overbank deposits (Fig. 5), and is thought to reflect a response to early Eemian interglacial climate warming (Busschers et al., 2007), in analogy to such behaviour observed in the Late glacial and Early Holocene in the SND (e.g. Hijma et al., 2009; Hijma and Cohen, 2011). Decrease of spring snow-melt and increased infiltration of precipitation due to permafrost disappearance likely resulted in a more evenly distributed discharge with fewer discharge-peaks. Development of a closed deciduous forest throughout NW Europe after the onset of the Eemian interglacial (e.g. Zagwijn, 1961, 1989), together with soil development at the top of early Eemian interglacial channel belts (Busschers et al., 2007) suggests that fluvial discharge must have gradually concentrated, causing valley-wide sedimentation to have reduced, if not ceased.

The sedimentology of the later Eemian interglacial fluvial unit indicates deltaic deposition in accommodation space created by sea-level rise downstream. In the IJssel basin, this reactivated sedimentation across the full width of the valley, from the beginning of RPAZ E4b/E5 onwards. Also this situation is strongly analogous to the Rhine-Meuse delta in the SND, at the beginning of the Middle Holocene (Cohen et al., 2005; Hijma et al., 2009; Hijma and Cohen, 2011; Bos et al., 2012). Upstream of the river mouth, ground-water rise resulted in the formation of swamps and freshwater lakes. This allowed the distal floodbasins to fill with peat, gyttja and clayey floodbasin fines (Busschers et al.,

2007). On-going Eemian interglacial sea-level rise resulted in drowning of the fluvial system and development of the Rhine estuary within the protective setting of the inherited Saalian topography, probably tens of kilometres upstream of the river mouth in the CND embayment of that time.

3.2.2. Upper and central estuary

Evidence for widespread estuarine transgression is found in the CND below the present-day Lake IJssel and Noordoostpolder (Figs. 3B and 4F) (Steenhuis, 1933; Burck, 1951). Here, mollusc-rich fine-grained estuarine sediments of Eemian interglacial age are encountered at a depth of 20–25 m below sea-level, directly on equally fine-grained freshwater sediments from the Eemian Rhine lower-deltaic floodbasin (Wiggers, 1955). The latter clay unit is more humic and has thin peat-layers within. The transgressive unit of lower-deltaic deposits gradually thickens westward (Wiggers, 1955). Combined with Eemian coastline reconstructions (Jelgersma, 1979) this identifies the present-day Noordoostpolder as the probable location of the river mouth at the time of highstand within the Eemian interglacial (Fig. 4F; Van de Meene, 1979, 1990; De Gans et al., 2000; Busschers et al., 2007), and upper and central estuarine depositional environments would thus project here. This location of the Eemian interglacial Rhine lower-delta is in agreement with observations in areas to the south (Flevoland polders; Ente et al., 1986), which have Eemian mollusc levels indicating it to be part of the marine embayment, but which lack any signs of deposits of lower-deltaic or fluvial signature. A relative northerly location of the Eemian interglacial Rhine lower-delta system thus is the consensus (Figs. 3B and 4F). No sedimentary or palaeoenvironmental details are available for this area, prohibiting the investigation of the inland reach of saline and tidal influences and maximum flooding surfaces.

In the SND, south of the ice-pushed ridges, tidal sediments with both coastal-estuarine and freshwater diatoms indicate the former presence of the interglacial Meuse estuary in this region (Törnqvist et al., 2000; Busschers et al., 2005). Eemian-indicative marine molluscs also occur extensively in reworked position in Weichselian fluvial units, and the inland limit of these deposits is indicative for former upper estuary positions. Most of these deposits are reworked during the Early and Middle Pleniglacial by fluvial activity, therefore only a few small patches have been preserved (Törnqvist et al., 2000, 2003; Wallinga et al., 2004). OSL-dating of these sediments suggests that part of the mollusc bearing units is of Weichselian Early Glacial rather than Eemian age. All but the very bases of Eemian interglacial channels of the Eemian interglacial Meuse estuary may have been eroded.

3.2.3. Outer estuary and shallow-marine system

In the CND, the Eemian interglacial Rhine outer estuary and shallow-marine system are found below the province of North Holland and adjacent parts of Lake IJssel (Figs. 3B and 4F). This more downstream reach of the Late Saalian/earliest Eemian Rhine palaeo-valley, would be North-Sea transgressed somewhat earlier during the Eemian, than regions upstream. Consequently, a lower-deltaic environment may have established here earlier in the Eemian. In the highstand situation, the interior shelf sea environment has covered this area and made it the entrance of an embayment (Fig. 4F). Shallow-marine sediments from this stage are routinely recognised as they are mollusc-rich (e.g. *Bittium reticulatum*, *Venerupis aurea senescens*; Spaijk, 1958), and consist of moderate to coarse-grained sands, locally intercalated with silty clay-layers. These sediments often contain reworked fine and coarse-grained gravel at their base, originating from the underlying Saalian glacial deposits. The shallow-marine deposits are often

strongly eroded by younger fluvial activity (De Gans et al., 1987; Westerhoff et al., 1987).

The most complete Eemian interglacial shallow-marine record is found in the south of the CND, in the former glacial basins of Amersfoort (e.g. Zagwijn, 1961, 1983; Cleveringa et al., 2000) and Amsterdam (e.g. Zagwijn, 1983; De Gans et al., 2000; Van Leeuwen et al., 2000; Beets and Beets, 2003; Beets et al., 2006) (Fig. 3B). The CND glacial basins are topographically separated from the open Eemian sea by sills at depths of 35–40 m below present-day sea-level (Cleveringa et al., 2000; De Gans et al., 2000). In Late Saalian and earliest Eemian time (RPAZ E1–E2), they formed lake environments fed by rainfall and groundwater flow. Prior to being transgressed, the groundwater and lake-level began rising, attributed to sea-level rise and the approaching coastline (during RPAZ E3). After overtopping of the sills and inundation by the interior shelf sea (during RPAZ E4a), the basins remained relatively protected low-energetic deep depositional environments with sheltered brackish waters (De Gans et al., 2000; Van Leeuwen et al., 2000).

In the Amsterdam glacial basin, these changes in depositional environment are reflected in a transition from varved glaciolacustrine clays into a diatom-rich sapropel (Harting Layer; Zagwijn, 1983). This diatomite is overlain by laminated lagoonal clays, deposited at low sedimentation rates. Overlying these lagoonal clays is a wedge of mollusc-rich medium- to coarse-grained sands, thought to represent barrier and washover deposits. The sequence indicates uninterrupted transition from transgression to highstand conditions during RPAZ E4b–E5. Considerable dissipation of the tide, which was also promoted by the irregular palaeo-bathymetry of the embayment, is presumed (De Gans et al., 2000).

In the CND glacial basins, the Eemian deposits are overlain by Weichselian sands, reflecting an erosive fluvial-regime in the western part of the CND, during the Weichselian Pleniglacial (Fig. 4H–I). Occasionally, the marine Eemian interglacial deposits are overlain by a peat, in particular at the margins of the Amersfoort glacial basin. Peat growth started here during RPAZ E6 and continued into the Weichselian Early Glacial (Louman, 1934; Zagwijn, 1961; Cleveringa et al., 2000).

In the SND and adjacent areas beyond the Saalian ice-limit, presumed Eemian shallow marine and lower estuarine deposits are found downstream and south of the earlier discussed Meuse estuary (Fig. 4F), mainly as fills of incised structures, comprised of coarse-grained marine-mollusc bearing sands, interbedded with clays (e.g. Bennema and Pons, 1952; Van der Heide, 1957; Van Rummelen, 1970, 1972; Hijma et al., 2012).

Lastly, in the north-eastern Netherlands, Eemian shallow-marine sediments are composed of reworked coarse-grained sand to mollusc-rich clay. These sediments fill depressions created by the Drenthe ice-masses and regional Saalian rivers (Boorne and Hunze) (Bosch et al., 2000) (Fig. 4F). The estuarine and littoral sediments wedge out against the northern till plateau, reaching a thickness of 10–20 m (Ter Wee, 1976; Bosch, 1990).

3.3. Weichselian (MIS 5d-2)

3.3.1. Early Glacial (MIS 5d-5a)

At the end of the Eemian interglacial, sea-level lowering (Zagwijn, 1983) and climatic cooling (e.g. Kukla et al., 2002; Brewer et al., 2008; Bakker et al., 2012) marked the onset of a period of alternating cold stadials (Herning, Røderstall) and more temperate interstadials (Brørup; Odderade; e.g. Zagwijn, 1961; Caspers and Freund, 2001), known as the Weichselian Early Glacial (Fig. 2).

During this period, the Rhine maintained a course through the IJssel basin and continued through the northern part of the CND

(Fig. 4G; Busschers et al., 2007). In the IJssel basin, Weichselian Early Glacial sediments show up as an alternation of decimetre thick humic-clay and peat layers and cross-bedded concentrations of organic debris (Fig. 5). This indicates deposition in a floodbasin environment dominated by peat growth, with only sporadic inundation by Rhine waters. In previous studies, no coarse-grained Rhine channel belts of Early Glacial age have been identified. Busschers et al. (2007) attribute this to younger Pleniglacial erosion, implying the same channel belt location as during the Eemian highstand. Alternatively, (part of) the Pleniglacial channel belt sands is older than thought. Busschers et al. (2007) suggested that during the Weichselian Early Glacial, established vegetation cover and the presence of soils, prevented major sediment fluxes towards the Rhine system, promoting incision and reworking rather than deposition in the IJssel basin.

Below the province of North Holland and off the North Sea coast, lower-deltaic floodbasin clay- and peat layers of Weichselian Early Glacial age occur on top of the Eemian shallow-marine and estuarine sequence (Fig. 4G) (Busschers et al., 2007; Hijma et al., 2012). Data from the North Sea (Brown Bank Formation cf. Laban, 1995) suggest that at least part of the area experienced brackish conditions, under relatively high sea-level. Such is in agreement with reported eustatic sea-level positions of 15–20 m below present-day sea-level for the Brørup and Odderade interstadials (Fig. 2; Waelbroeck et al., 2002), and with inference of upper estuarine channels of that age in the SND area (Törnqvist et al., 2000; Busschers et al., 2007).

3.3.2. Early Pleniglacial (MIS 4)

At the onset of the Middle Weichselian, sea-level dramatically dropped (Fig. 3; Waelbroeck et al., 2002), initiating deep (>10 m) fluvial incision near the margin of the Eemian highstand coastal prism, especially in the SND (Törnqvist et al., 2000; Hijma et al., 2012). Strong climate deterioration at the beginning of the Early Pleniglacial (Fig. 2) (Huijzer and Vandeberghe, 1998) caused the development of continuous permafrost in large parts of NW Europe, decreasing soil permeability (Vandenberghe and Pissart, 1993). This led to intensified discharges in the Rhine-Meuse catchment, resulting in extensive lateral migration of deep channels, erosively reworking the Rhine channel belt zone along the eastern side of the IJssel basin (Busschers et al., 2007). Downstream of the IJssel basin in the CND, the zone of reworking widened considerably to the south and southwest. In the very southwest, the Rhine established a connection to the SND and the River Meuse (Fig. 4H). The combined Rhine-Meuse system continued towards the Strait of Dover (Laban, 1995; Busschers et al., 2007; Hijma et al., 2012; Rijdsdijk et al., 2013).

At the onset of the Early Pleniglacial the Rhine started reworking Eemian interglacial and Early Glacial sediments. Fining-upward sequences found in the IJssel basin suggest that during this period the Rhine was a meandering river (Busschers et al., 2007). Downstream of the IJssel basin, lateral erosion appears to have been particularly efficient in areas of mollusc-rich sandy coastal prism and shallow-marine Eemian interglacial deposits, a phenomenon also reported for the SND (Busschers et al., 2007). Erosion is evident by large concentrations of reworked (fragmented) marine molluscs and marine-clay pebbles at the base of the Early Pleniglacial fluvial units (Westerhoff et al., 1987; De Gans and Wassing, 2000; Busschers et al., 2007).

3.3.3. Middle Pleniglacial (MIS 3)

The first part of the Middle Pleniglacial (~60–50 ka) is characterized by temperate climate conditions (Fig. 2), while lower temperatures and snow cover-rich conditions prevailed throughout the second part (~50–30 ka; Fig. 2) (Caspers and Freund, 2001).

Middle Pleniglacial Rhine sediments in the IJssel basin (OSL-dated 58–38 ka; Busschers et al., 2007) consist of cross-bedded, coarse- and medium-grained gravel-containing channel belt sands, often showing an erosive base (Fig. 5). These sediments and their architecture mark valley-wide migration and aggradation by the Rhine, indicating increased trapping of sediment. Similar increased aggradation is thought to have occurred just upstream, and in that region induced a partial avulsion towards the SND and the River Meuse (around ~50 ka; Busschers et al., 2007), creating a severe shortcut (Fig. 4I). Here, the mixed Rhine-Meuse deposits consist of cross-bedded medium-grained sands with only small amounts of gravel. OSL-dating indicates an upper Middle Pleniglacial age (48–30 ka; Busschers et al., 2007).

The Rhine entirely abandoned its CND's northern course through the IJssel basin and its incised palaeo-valley after ~40 ka (Busschers et al., 2007). This major change in drainage configuration is related to a strong climatic driven increase in sediment supply (Hasselo Stadial: Van Huissteden et al., 2003) which strongly favoured aggradation and hence the possibility for the Rhine to avulse and follow a shorter course through the SND. Busschers et al. (2007) assume that the high sediment supply originates from the final breakup of Eemian interglacial soil complexes, initiated by the on-going climate cooling and intensified runoff after ~50 ka.

3.3.4. LGM, Late Pleniglacial and Late Glacial (MIS 2)

Strong climate cooling commenced during the latest phase of the Middle Pleniglacial (Fig. 2). Continuous-permafrost developed in large parts of the Rhine-Meuse catchment, inducing a highly peaked discharge regime (Van Huissteden et al., 2003). The run up to the LGM in the SND area is marked by a southward shift of the Rhine-Meuse system (Fig. 4J), thereby abandoning the northern part of the SND by ~35 ka (Busschers et al., 2007). The LGM itself is marked by narrowing and strong incision of the Rhine-Meuse braided channel belt (Fig. 4J). The Late Pleniglacial is marked by net aggradation and widening of this braided belt, burying the LGM unit. In Late glacial and early Holocene times, northward shifting of the Rhine system followed (Busschers et al., 2007; Hijma et al., 2009). This series of developments is seen as a response to glacio-isostatic-controlled forebulge upwarping towards the LGM, with ice-mass build-up from about 35 ka onwards (Lambeck et al., 2010), and collapse afterwards, starting ~24 ka (Cohen et al., 2002; Busschers et al., 2007). Glacio-isostatic model-predictions suggest 5–10 m of relative uplift along the Rhine in our study area, compared to central Germany and France (Peltier, 2004; Steffen and Wu, 2011).

The glacio-isostatic warping compensating fluvial responses (incision/aggradation; south/north lateral migration) are overprinted by climatic induced river style and sediment load changes, which helped to map out the successive subunits. The Rhine-Meuse sediments in the SND from the LGM and Late Pleniglacial period (24–16 ka BP; Busschers et al., 2007) consist of cross-bedded, medium to coarse-grained gravelly sands with large grain-size variation. An erosive basal bounding surface is found at many locations (Busschers et al., 2007). The coarse grain-size of the sediments reflects cold climate conditions with continuous permafrost, periglacial slope activity and physical frost weathering processes (Huijzer and Vandeberghe, 1998). The channel incision described above may be related to initial climate instability during the Late Pleniglacial cooling (Vandenberghe, 1995, 2003).

4. Synthesis and look forward

In this review we explored the upper Middle and Late Pleistocene evolution of the River Rhine in the southern part of the North

Sea basin. We thereby focussed on the development of the Rhine lower-delta during the Eemian interglacial. For aspects of setting inheritance and state of preservation, developments during the preceding (Saalian) and following (Weichselian) periods were also included, while comparisons with the Holocene Rhine-Meuse delta supported sedimentological inferences regarding the positioning and architecture of the Eemian interglacial Rhine deltaic system. Despite earlier research, various parts of this sedimentary system have only received fragmented attention. This paper provides a first coherent overview of data from the fluvial, estuarine and shallow-marine domains in the central Netherlands. Fig. 6 and accompanying text serves as a summary for this.

During the upper Middle and Late Pleistocene, lower-deltaic deposition was strongly affected by the position of the inherited Saalian glacial morphology and its former ice limit, which basically divided the Netherlands into two separate depocentres (CND and SND respectively). The ice-pushed ridges, glacially scoured basins and the Late Saalian palaeo-valley through the CND together provided an irregular initial topography for the Eemian interglacial deposition. This resulted in a relative inland position of the Rhine's lower-delta during the sea-level highstand in the Eemian, which is much unlike the setting for the Meuse in the SND. Here, a smoother and steeper-gradient palaeo-valley existed which resulted in limited accommodation-space for Eemian transgressive and highstand lower-deltaic deposition and a far more limited inland extent of the coastal prism. During the subsequent last-glacial lowstand, major parts of the Eemian lower-delta were eroded, leaving larger parts of the CND preserved than of the SND. These differences in preservation between the CND and SND may in part be (glacio-) tectonically controlled. Regional differences in net subsidence might have enlarged CND accommodation-space compared to SND although this is a hypothesis that needs further study.

Sedimentary and chronological research on the Eemian interglacial Rhine system so far, almost entirely focused on the upstream fluvial system, while the central lower-delta (central and upper estuary) received less attention, resulting in an incomplete picture of the sedimentary record (see question marks in Fig. 6). To increase our knowledge about the sedimentary characterisation and chronological control of the Rhine lower-deltaic setting, collection of new material and construction of geological transects crossing the Rhine's incised palaeo-valley is compulsory. This would lead to the same level of sedimentary detail as obtained in previous work in the SND (Busschers et al., 2007, 2008; Hijma et al., 2012), enabling comparison of the infill of the two depocentres and more detailed reconstruction of the evolution of the lower Rhine and Meuse associated deposits. Collecting new cores will allow construction of a robust chronostratigraphic framework based on luminescence-dating, biostratigraphy and possibly magnetostratigraphic research (cf. Sier et al., 2011). Improved constraints on the timing and duration of the Eemian interglacial in our Netherlands' setting will allow better correlation to existing sea-level reconstructions and climate records and hence a better understanding of the Rhine's Eemian depositional system. Especially investigation of the effects of glacio-isostatic crustal movements is of major importance, as this might lead to new insights in how the regional Eemian sea-level curve relates to the eustatic sea-level curve and what falling stage and lowstand erosive truncation driving forces were.

The thick Eemian interglacial coastal-prism that developed as a result of abundant accommodation-space available in the CND at that time, together with the enormous amount of available sub-surface data (tens of thousands of borehole descriptions: Van der Meulen et al., 2013), makes the Netherlands' setting, amongst our neighbouring Eemian interglacial embayments along the present

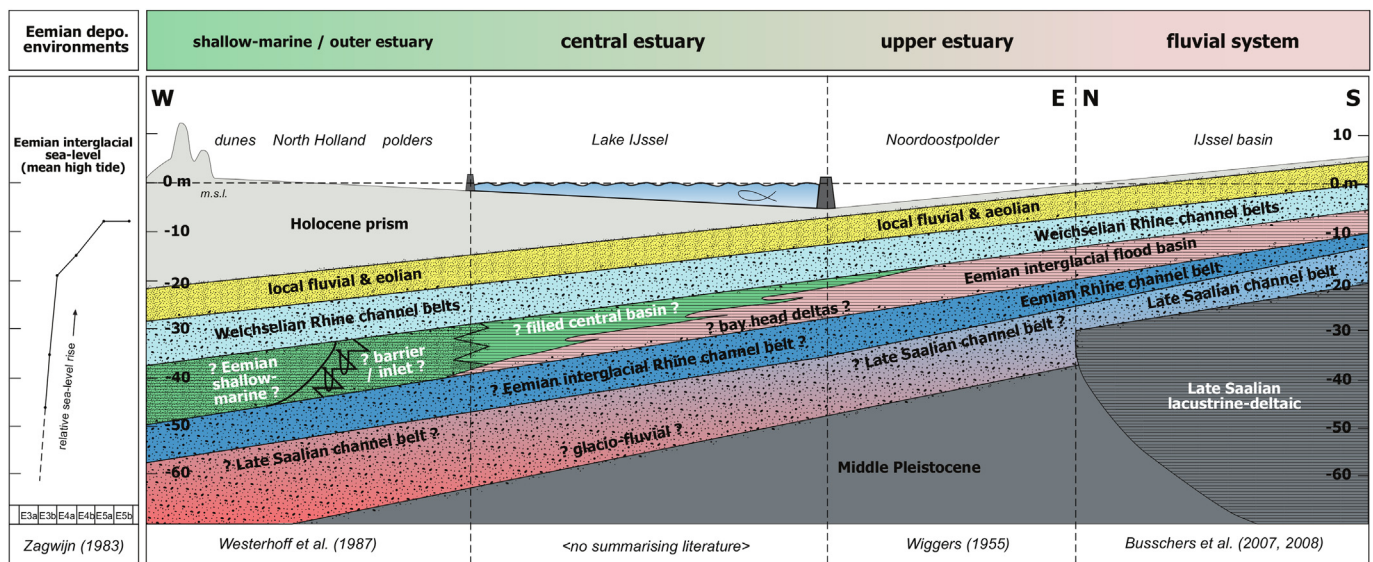


Fig. 6. Synthesizing schematic longitudinal section along the Rhine's incised palaeo-valley, illustrating its upper Middle and Late Pleistocene fill, with emphasis on the Eemian interglacial lower-deltaic environment. See Fig. 5 for legend. The upper Middle and Late Pleistocene CND incised-valley fill generally consists of three stacked sequences with a total thickness of 20–40 m. The lower sequence is of Late Saalian (MIS 6) and early Eemian age (MIS 5e) and primarily consists of two to three separate units of gravely coarse-grained channel belt sands that were deposited during progradation of the Rhine into a glacially eroded landscape during and following deglaciation. The upper sequence is of Weichselian Pleniglacial age (MIS 4–2) and also consists of two to three different units, which are also dominated by coarse-grained channel belt sands. Sandwiched in between these coarse-grained fluvial sediments is a 5–15 m thick record of Eemian interglacial and Weichselian Early Glacial age (MIS 5). This part of the record is dominated by fine-grained floodbasin, estuarine and shallow-marine deposits, and locally floodbasin peats. We observed that during sea-level rise, fluvial deposition shifted upstream and was concentrated in the IJssel basin. Major fluvial sedimentation took place in this basin and a delta formed downstream, partly positioned below the present-day Noordoostpolder, while estuarine conditions prevailed in the downstream regions of the present-day Lake IJssel and province of North Holland. During and after sea-level fall at the Early Glacial to Pleniglacial transition, major parts of the Eemian highstand coastal prism were eroded by the falling-stage fluvial system. Despite Pleniglacial erosion, significant amounts of Eemian interglacial sediments have been preserved in the CND due to the effects of the inherited irregular glacial topography. Lower-deltaic sediments, as well as a major volume of shallow-marine sediments, were preserved below and possibly alongside the Pleniglacial river system in the central Netherlands.

southern North Sea coastline (e.g. Thames estuary in UK (Jardine, 1979; Bridgland and D'Olier, 1995); Ems and Elbe tidal bays in Germany (Höfle et al., 1985; Streif, 2004) and the Flemish Valley in Belgium (Mostaert and De Moor, 1989; Mathys, 2009)), a highly interesting location to study and compare interglacial lower-deltaic evolution, sedimentary architecture and preservation. In this light, comparison to the East Coast of the USA is of special interest, since interglacial estuarine depositional systems are found here as well (e.g. Delaware Bay (Knebel and Circé, 1988; O'Neal and McGeary, 2002); Chesapeake Bay (Colman and Mixon, 1988) and the Albemarle Sound (Parham et al., 2007)), in more or less similar positions as in the Netherlands' setting (Fig. 6).

A final way to improve our insights in the sequence stratigraphic and sedimentary architectural development of lower deltas is to compare the Eemian interglacial (MIS 5e) Rhine system with its well documented Holocene (MIS 1) Rhine–Meuse equivalent. The Eemian interglacial record has experienced a full glacial-interglacial cycle of sea-level and climate change in a subsiding tectonic setting, and is therefore arguably in a more relevant state of preservation when it is to be used as a reservoir analogue. To test this hypothesis, process relations and preservation (potential) of the Eemian interglacial lower-deltaic depositional setting need to be determined and compared with the Holocene lower-delta.

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