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Spatial and Temporal Distribution of Sand-Containing Basin Fills in the Holocene Rhine-Meuse Delta, the Netherlands

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ABSTRACT

The quantitative significance of coarse-grained deposits in the overbank realm, such as crevasse-splay deposits, has not been studied at the delta scale or at the Holocene timescale. Such knowledge would be beneficial for understanding and explaining sediment distribution in delta plains. This study addresses delta-scale distribution of sand-containing basin fills and their sand-body proportion variability, based on eight valleywide cross sections in the Holocene Rhine-Meuse delta in the Netherlands. We found that sand-containing basin fills form 7.1% of the fluviodeltaic wedge, of which splay deposits are most frequently observed midway between the delta apex and the coast. Organic-clastic lake fills and bay-head delta deposits, in contrast, are limited to the distal delta plain. Over four successive periods (between 9000 and 800 cal yr BP), the largest proportions of splay deposits remain at 50–150 km downstream of the upstream-shifting delta apex. We show that intermediate floodbasin widths (between 3.1 and 3.6 km in the Holocene Rhine-Meuse delta) yield the highest proportions of splay deposits. High rates of base-level rise and wide floodplains both facilitate the creation of accommodation, which in turn provides conditions for peat-forming wetlands in which organic-clastic lake fills can develop. The results show that sand bodies form 26%–30% of sand-containing basin fills. This proportion is shown to be controlled by, among other variables, channel planform and superelevation of the trunk channel and substrate composition. We conclude that potentially large volumes of nonchannel sand bodies exist in distal delta plains. They constitute up to 39% of the reservoir volume in the distal Rhine-Meuse delta and yield relatively high connectedness ratios.

Introduction

Enormous amounts of exploitable fossil-fuel reserves are stored in ancient delta-plain successions, which has prompted a long history of scientific research of delta deposits. Past work has mainly focused on channel deposits, whereas nonchannel deposits, for example, clastic overbank deposits, and organic accumulations have received much less attention even though they account for significant volumetric proportions of most large delta plains. They form as much as 40% of the delta-plain deposits in the Holocene Rhine-Meuse delta of the Netherlands (Gouw 2008; Erkens 2009) and in the Lower Mississippi Valley (Gouw and Autin 2008). Various studies have reported on the geometry, depositional facies, and formation of nonchannel delta-plain deposits such as natural-levee, floodbasin, and splay deposits (e.g., Fielding 1984; Guion 1984; Mjøs et al. 1993; Jorgensen and Fielding 1996; Miall 1996 and references therein; Cazanacli and Smith 1998; Hornung and Aigner 1999; Farrell 2001; Stouthamer 2001; Ghosh et al. 2006). These and other studies have demonstrated that the depositional-facies variability and lithological heterogeneity of these deposits can be very high (e.g., Fielding 1986; Farrell 1987; Weerts and Bierkens 1993; Willis and Behrensmeyer 1994). Facies variability is especially high in splay deposits, organic-clastic lake fills, and bay-head delta deposits (Farrell 1987; Smith et al. 1989; Tye and Coleman 1989; Weerts and Bierkens 1993; Smith and Pérez-Arlu-

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cea 1994; Pérez-Arlucea and Smith 1999; Stouthamer 2001; Hijma et al. 2009; Bos 2010), which we collectively term sand-containing basin fills.

Sand-containing basin fills form in floodplain depressions and basins that become filled with sediment supplied by fluvial channels, and they commonly contain relatively large amounts of sandy lithofacies. Knowledge of the delta-scale distribution of sand-containing basin fills will contribute to the quality of deltaic-architecture models and hence to the predictability of reservoir characteristics.

The aim of this study is to analyze the spatial and temporal distribution and lithofacies variability of sand-containing basin fills in the Holocene Rhine-Meuse delta and to assess the contingent controlling factors. For a number of reasons, the Rhine-Meuse delta is a suitable area for such a study. First, eight recently compiled valleywide cross sections that cover the delta plain from the apex to the coast offer a unique overview of the alluvial architecture of the Holocene delta-plain succession (fig. 1). Second, thanks to good time control on the deposits, several paleogeographic reconstructions have been made (Berendsen and Stouthamer 2001; Gouw and Erkens 2007; Hijma et al. 2009). The architectural and paleogeographic framework enables determination of the distribution of sand-containing basin fills. Third, allogenic controlling factors such as sea level rise (van de Plassche 1982; Hijma and Cohen 2010), associated groundwater-level rise (Cohen 2005), and sediment supply (Erkens 2009) are well known.

The Holocene Rhine-Meuse Delta

Geological Setting. The Rhine-Meuse delta encompasses the combined delta plains of the River Rhine (mean annual discharge of 2350 m^3/s) and the River Meuse (mean annual discharge of 230 m^3/s; Rijkswaterstaat 2010). The delta is situated at the southeastern margin of the subsiding North Sea Basin. Locally, large differences in relative subsidence rates exist between fault-separated tectonic blocks. For example, Pleistocene and Holocene displacement rates along the Peel Boundary Fault (fig. 1) separating the subsiding Roer Valley Graben from the relatively stable Peel Block, averaged 60 mm/ka (van den Berg 1994). Holocene displacements along the Peel Boundary Fault have influenced fluvial processes in that area, resulting in changing architecture across this fault zone (Cohen et al. 2002; Stouthamer and Berendsen 2000; Stouthamer et al. 2011).

The substratum in the paleovalley (fig. 1), along the east-west axis of the delta, is composed of fluvial sand deposited by a dominantly braiding fluvial system. Associated with these deposits are aeolian sand dunes that regularly formed along active channels. The paleovalley is flanked by Late Pleistocene aeolian so-called coversand deposits, consisting of fine sand.

Holocene onlap in the Rhine-Meuse delta, triggered by base-level rise, is often marked by the presence of organic accumulations at the base of the delta-plain succession. Delta formation has been controlled predominantly by base-level rise and upstream sediment supply (Gouw and Erkens 2007). Until 5000 cal yr BP, eustatic sea level rise was the principal component of base-level rise and thus the dominant controlling factor in the formation of accommodation space for delta-plain sedimentation. By 5000 cal yr BP, eustatic sea level rise had ceased, and from that moment on, base-level rise was governed principally by basin subsidence. After 3000 cal yr BP, increased sediment delivery from the hinterland, related to human activity, controlled sedimentation in the delta plain (Erkens 2009).

Avulsion is one of the major processes that governs delta-plain architecture in the Rhine-Meuse delta (e.g., Stouthamer and Berendsen 2000, 2007). It is a key process for diverting coarse-grained sediments to floodbasins. It commonly initiates by breaching a natural levee along a channel; this is followed by the formation of a crevasse splay. Avulsion is controlled by allogenic or autogenic factors or both. Sites of avulsion in the Rhine-Meuse delta are largely related to allogenic controls, such as rate of base-level rise, fault activity, sediment load, and discharge volume. The average period of activity of newly formed channel belts, however, is mainly controlled by autogenic processes (Stouthamer and Berendsen 2007).

Natural sedimentation in the larger part of the delta plain ended ~800 cal yr BP, when embankment of the river channels limited flooding of the delta plain. Deposits formed after 800 cal yr BP are considered to be associated with regulated river channels and therefore are not included in the study.

Sand-Containing Basin Fills. The dominant coarse-grained lithofacies consists of sand, usually with diameters up to 300 μm. Gravel, if present, is confined to layers of up to 15 cm in the distributary-channel deposits. In the depositional framework of the Holocene Rhine-Meuse delta, three types of sand-containing basin fills are distinguished (e.g., Hijma et al. 2009; Bos 2010):

1. Splay deposits form in periodically inundated floodbasins. They consist predominantly of sand-clay mixtures, although sporadic sand layers may

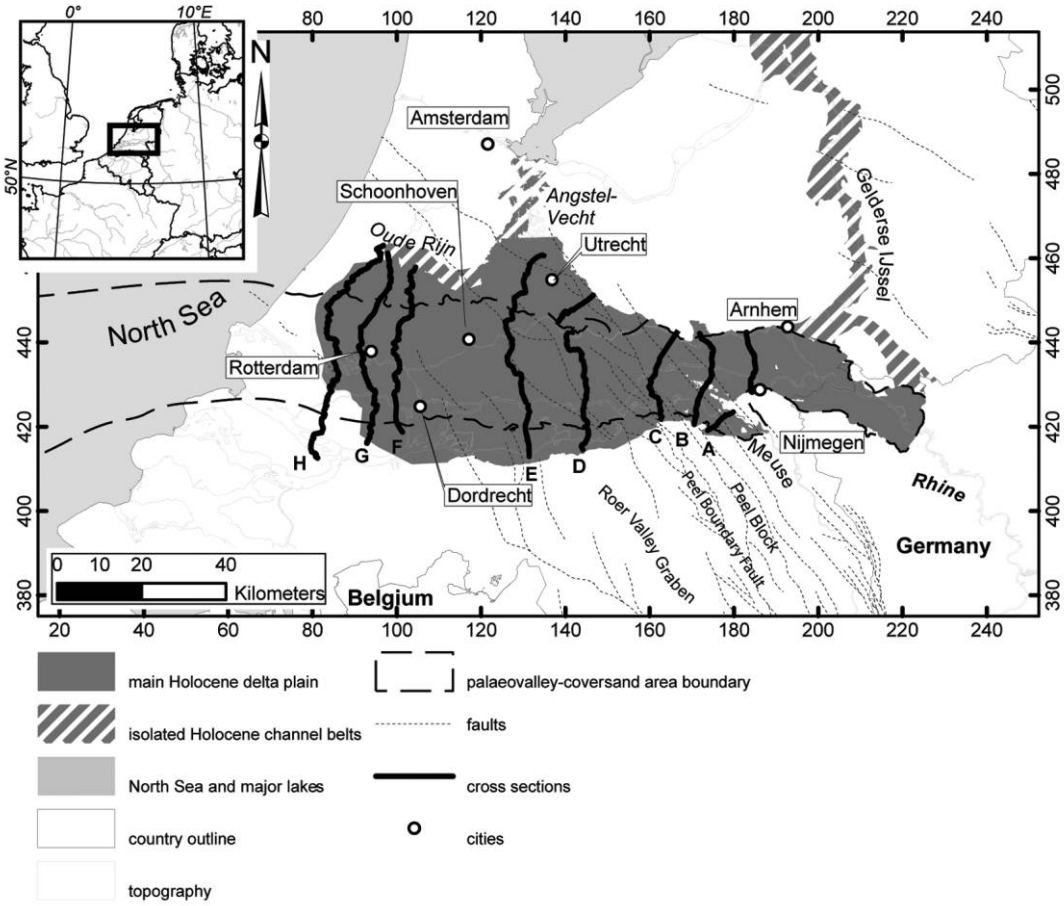

Figure 1. Overview of the Holocene Rhine-Meuse delta. Indicated are the positions of valleywide cross sections. Cross sections A–E were constructed by Gouw and Erkens (2007); cross section C was initially published by Cohen (2003), and the larger part of cross section E was modified after Törnqvist (1993). Cross-sections F–H were all constructed by Hijma et al. (2009). The boundary between the paleovalley and the coversand area is after Berendsen and Stouthamer (2001) and Hijma et. al (2009). Coordinates conform to Rijksdriehoekstelsel.

also occur (Stouthamer 2001). Splay deposits most frequently overlie floodbasin deposits (silty clay) or in situ peat. As a result of intense bioturbation and soil-formation processes during low-stage intervals (e.g., the summer period), sedimentary structures in splay deposits are often disturbed or obscured. Even though most splay sediment is crevasse derived, we could not determine whether all splay deposits were crevasse derived, and therefore we use the general term "splay deposits."

2. Organic-clastic lake fills form as channel-terminus deposits in peat-bounded lakes (i.e., permanently inundated) and include amalgamated mouth-bar deposits composed of sand up to 3 m thick (Bos 2010). These prominent sand bodies overlie deposits of clay to clayey sand (coarsening-upward succession from clay to sand) and organic lacustrine sediments (gyttja), which form the base of these lake fills. Their geometry is defined by the shape of the lake in which they form. The commonly near-vertical lateral boundaries give these deposits a rectangular shape when viewed in cross section (Bos 2010).

3. Bay-head delta deposits form as channel-terminus deposits in upper estuaries, where fluvial sediments are deposited under freshwater but tidal conditions (Dalrymple et al. 1992). In the distal part of the Rhine-Meuse delta plain, five large sand bodies consisting of amalgamated mouth-bar deposits of bay-head deltas have been identified. The deposits occur in a relatively narrow zone, ~30 km wide in the downdip direction, and were formed in a limited period of time, 8000–6000 cal yr BP (Hijma et al. 2009; Hijma and Cohen, forthcoming; K. M. Cohen, unpublished data). The number of individual bay-head delta sediment bodies is thus limited, but when

present, they are a prominent architectural element because they may contain a large volume of sand that affects both the geomechanical properties and the reservoir characteristics of the delta-plain deposits.

Methods

Approach and Input Data. The spatial and temporal distributions of sand-containing basin fills were identified in eight valleywide cross sections (A–H) that cover the Holocene Rhine-Meuse delta from the apex to the present coast (fig. 1). These cross sections are assumed to be representative of the facies architecture of the delta plain, and downstream architectural trends are considered to be recorded in these cross sections. We emphasize, however, that the cross sections represent a sample of the total sediment body and that the results are an approximation of the real architecture. The cross sections have been positioned independently of the configuration of sand-containing basin fills. Errors related to the position of the cross sections are therefore randomly distributed and have no structural effect on the results. If, for example, a cross section covers the distal part of a splay at a certain location, it probably covers the proximal part of another splay elsewhere. Besides, results of earlier studies show that these cross sections yield geologically meaningful patterns concerning, for example, channel-belt architecture (Gouw 2008) and sediment budgets (Erkens 2009).

On the basis of 2756 borehole descriptions (including lithological and sedimentary characteristics) and 724 cone penetration tests (CPTs, exclusively in cross sections F–H), a number of lithogenetic units in the fluvial domain were distinguished, including channel-belt deposits, natural-levee and crevasse-splay deposits, and organic accumulations (see table 1 for a complete list). Average spacing of data points in the cross sections (cores and CPTs) was ~100 m, although it varied considerably in cross sections F–H, being less in built-up areas and at the base of the deltaic wedge. A set of time lines divides the succession into temporal intervals, mostly spanning 1000 years (table 2). Methodological details on the construction of the cross sections are provided by Gouw and Erkens (2007, cross sections A–E) and Hijma et al. (2009, cross sections F–H). On the basis of the geological cross sections and inferred time lines, we calculated the proportions of sand-containing basin fills relative to other lithofacies in order to assess spatial and temporal trends.

Identification of Splay Deposits, Organic-Clastic Lake Fills, and Bay-Head Delta Deposits. Despite the apparent detail in the cross sections, they do not distinguish splay deposits from natural-levee deposits, which show strong similarities lithologically. Furthermore, organic-clastic lake fills were interpreted as crevasse-splay deposits (table 1). Quantitative data on grain-size variations within individual elements, which are essential for assessment of lithofacies distribution, are available only for individual cores archived in two large geological data sets (Berendsen 2005; TNO 2010). The borehole descriptions in these data sets include, among many other variables, information on estimations (occasionally measurements) of grain-size distributions, sedimentary characteristics, admixtures, and rooting.

We conducted the following steps to identify splay deposits, organic-clastic lake fills, bay-head delta deposits, and their lithofacies proportions in the cross sections (fig. 2). (1) We limited our analyses to fluviodeltaic units in the cross sections that included sand-containing basin fills, that is, crevasse-splay deposits and natural-levee deposits (all cross sections) and bay-head delta deposits (cross sections F–H; table 1; fig. 2*A*). (2) We selected sand-containing basin fills in the combined-unit crevasse-splay deposits and natural-levee deposits (fig. 2*A*), which involved two consecutive procedures: (a) elements in the cross sections that occur isolated from channel-belt deposits were interpreted as sand-containing basin fills, and (b) elements that were connected to channel-belt deposits were further examined because they can comprise both nat-

Table 1. Identified Lithogenetic Units in Valleywide Cross Sections and Those Identified in This Study

Cross sections A–E	Cross sections F–H	This study
Channel-belt deposits	Channel-belt deposits	
Abandoned-channel fill	Abandoned-channel fill	
Crevasse-splay and natural-levee deposits	Crevasse-splay and natural-levee deposits	Natural-levee deposits, splay deposits, organic-clastic lake fills
(No equivalent)	Bay-head delta deposits	Bay-head delta deposits
Floodbasin deposits	Humic clay, (silty) clay, silty clay with abundant tree debris	
Organics	Reed peat, wood peat, gyttja	

Table 2. Time Intervals (cal yr BP) Analyzed in This Study and Corresponding Time Intervals as Identified in Existing Cross Sections of Gouw and Erkens (2007; A–E) and Hijma et al. (2009; F–H)

This study	A–E	F–H
Before 9000	Before 9000	Before 9000
9000–7000	9000–8000, 8000–7000	9000–8500, 8500–8000, 8000–7500
7000–5000	7000–6000, 6000–5000	7500–6500, 6500–5000
5000–3000	5000–4000, 4000–3000	5000–2500
3000–800	3000–2000, 2000–800	2500–800

Note. The time intervals in cross sections F–H deviate slightly from the analyzed periods. This means that, for example, the volume of coarse-grained overbank deposits in cross sections F–H is slightly underestimated because deposits that formed between 7500 and 7000 cal yr BP are included in the subsequent time interval.

ural-levee deposits and sand-containing basin fills. To differentiate these, we applied the widely used conceptual model of meandering rivers (Miall 1985), whereby natural-levee deposits become thinner and finer-grained away from the channel belt. For that purpose we used the aforementioned geological databases in combination with the cross-sectional geometry. Most important is the notion that natural-levee deposits are basically wing shaped and commonly exhibit a coarsening-upward succession overlain by a fining-upward succession. (3) We subdivided the sand-containing basin fills into three texture classes (following Nederlands Normalisatie Instituut 1989; comparable to USDA 2005): "sandy clay," "clayey sand," and "sand" (fig. 2*B*). (4) We identified organic-clastic lake fills and bay-head delta deposits (fig. 2*C*). Organic-clastic lake fills were identified through geometrical and lithological properties and properties of the underlying succession (for details, see "Sand-Containing Basin Fills"). The presence of gyttja underlying sand-containing basin fills is a strong indication of the presence of organic-clastic lake fills (fig. 2*C*). It was suggested recently that the quantity of gyttja in the Rhine-Meuse and other delta plains has been underestimated (Bos et al., forthcoming), which further suggests that the proportion of organic-clastic lake fills, for which gyttja is an important indicator, represents minimum values. Lithologically, bay-head deltas are similar to organic-clastic lake fills, and differentiation was based primarily on microfossil (diatoms and pollen) and macrofossil (shells) content (Hijma et al. 2009). For example, the estuarine position of bay-head delta deposits is recorded in diatom and shell associations, whereas in organic-clastic lake fills, marine elements in diatom associations and shells are present, if at all, only in very low numbers. It should be noted that the presence of marine indicators does not necessarily mean that the environment was brackish. In the studied examples, the still-limited number of marine indicators points to freshwater conditions during deposition (Hijma et al. 2009).

Splay-channel deposits were not uniformly identified across the delta plain. Hijma et al. (2009; cross sections F–H) included splay channels in the fluvial-channel architectural element, whereas Gouw and Erkens (2007; cross sections A–E) included them in the crevasse-splay and natural-levee architectural element. Gouw and Erkens (2007) used channel-deposit thickness (T_c) to distinguish (crevasse-)splay channels ($T_c < 5$ m) from mature fluvial channels ($T_c \geq 5$ m), following observations of Gouw and Berendsen (2007). The latter illustrated that the thickness of most channel-belt deposits in the Rhine-Meuse delta ranges between 5 and 9 m. They carried out 35 measurements in cross sections, which yielded an average channel-belt thickness of 6.7 m ($\sigma = 1.5$ m). Accordingly, we used 5 m as an arbitrary dividing value for fluvial and splay channels in cross sections F–H. Gouw and Berendsen (2007) found that channel-deposit thickness increases in the downstream direction. Hence, the use of 5 m as maximum thickness for splay-channel deposits means that calculated proportions of these deposits are minimum values.

Age Estimation. The studied cross sections include time lines based on radiocarbon dates and stratigraphic principles, as outlined by Gouw and Erkens (2007). We analyzed intervals of 2000 years, defined by the time lines 9000, 7000, 5000, 3000, and 800 cal yr BP in cross sections A–E (Gouw and Erkens 2007). In cross sections F–H, some of these time lines were not determined, and instead we used time lines with slightly different ages (table 2). We chose three 2000-year periods for the following reasons: (1) during 9000–7000 cal yr BP, the locus of fluviodeltaic sedimentation was constrained by the paleovalley (fig. 1; Berendsen and Stouthamer 2000); (2) during 7000–5000 cal yr BP, fluviodeltaic sedimentation strongly extended upstream and invaded areas outside the incised paleovalley (Berendsen and Stouthamer 2000; Stouthamer et al. 2011); and (3) during 5000–3000 cal yr BP, beach barriers along the coast protected

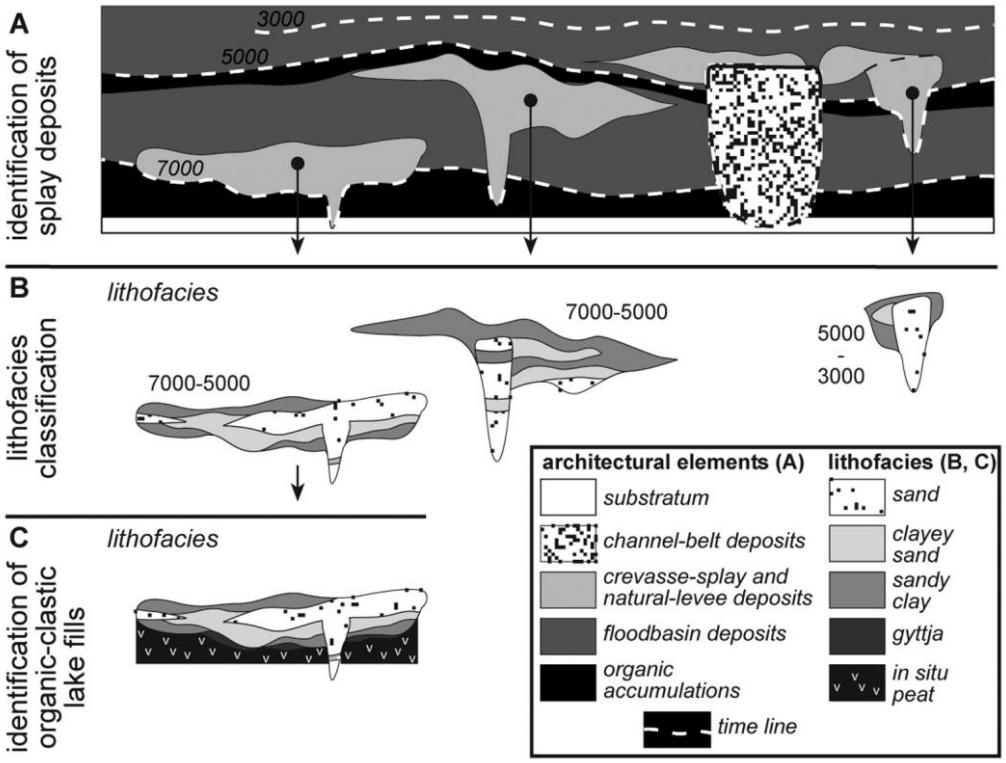

Figure 2. Procedure for the identification of splay deposits and organic-clastic lake fills and their lithofacies composition in the analyzed cross sections. *A*, Identification of sand-containing basin fills in the cross sections where they were combined with lithologically comparable natural-levee deposits. This step was based on geometrical properties and lithofacies composition. *B*, Identification of lithofacies units within the sand-containing basin fills, mainly on the basis of archived descriptions of manually derived cores. In this step, the units are separated into time intervals according to the time lines in *A*. *C*, Identification of organic-clastic lake fills, based on the geometrical properties and lithofacies succession of both the sand-containing basin fill and the underlying deposits. See text for further explanation. A color version of this figure is available in the online edition of the *Journal of Geology*.

the delta-plain area, where peat formation became prominent (Gouw and Erkens 2007).

Proportion and Lithofacies Composition of Sand-Containing Basin Fills. The relative importance of the studied deposits, both spatial and temporal, can be quantified by the sand-containing-basin-fill proportion (SCBFP), defined as the volume of sand-containing basin fills divided by the volume of all Holocene fluvial deposits and organic accumulations in (a specified part of) the delta-plain succession for any specific time interval. Similarly, we also obtained proportions of splay deposits (SDP), organic-clastic lake fills (OCLFP), and bay-head delta deposits (BHDDP). To obtain SCBFP, SDP, OCLFP, and BHDDP, we calculated cross-sectional areas of each of the three architectural elements and compared them with total cross-sectional areas of time slices and cross sections. Cross-sectional areas in this context refer to the combined cross-sectional areas of fluvial deposits and organic accumulations, thus leaving out marine deposits and pre-Holocene deposits. The influence of compaction of organic accumulations on the proportion of sand-containing basin fills has not been corrected for in this study. Proportions thus refer to the present situation. The original thickness of organic accumulations, especially where overlain by clastic sediments, was much larger. In addition, future burial of relatively uncompacted peat by clastic sediments will reduce peat thickness, which means that the proportion of organics will decrease. Furthermore, in peat areas (mainly cross sections E–G), the top part of the delta-plain succession often has been excavated or has oxidized because of groundwater-level lowering. The proportions of clastic deposits (e.g., sand-containing basin fills), therefore, are minimum values. The procedure we applied was modified from an existing method (Erkens 2009, p. 138) and involved rasterizing the units of interest (lithofacies units per cross section,

per interval, and per architectural element). Subsequently, the number of pixels per unit was multiplied by the cross-sectional area represented by one pixel. The number of pixels per unit was counted with photo-editing software (Adobe Photoshop 10.0), and the area represented by a single pixel was calculated.

To obtain SCBFP in the alongstream direction, the cross-sectional areas of sand-containing basin fills (combined areas of splay deposits, organic-clastic lake fills, and bay-head delta deposits) were compared with the cross-sectional area of the Holocene fluvial deposits and organic accumulations per cross section. The cross-sectional areas, therefore, account only for upstream-delivered sediment and ignore reworked sediment of the paleovalley. It should be noted that cross-sectional areas, especially in cross sections F–H, are minimum values because excavation and oxidation of peat since the Middle Ages has lowered the surface and hence resulted in smaller cross-sectional areas.

To obtain SCBFP for time slices, the cross-sectional areas of the deposits within a certain time slice (for each cross section) should be compared with the summed cross-sectional area of that time slice (all cross sections). However, reconstruction of cross-sectional areas of time slices is hampered by erosion during successive time intervals. We could assume erosion to be constant over time and use a fixed value, but a more precise alternative is available. We used reconstructed delivered-sediment volumes per time slice, which were based on extensive database analyses and geographic information system computations in which erosion was taken into account and corrected for (Erkens 2009). Comparing these volumes with cross-sectional areas does not yield true proportions but still enables comparison with other time slices and thus detection of temporal trends.

An important variable affecting delta-plain architecture is floodplain or delta-plain width (e.g., Bridge and Leeder 1979). We measured delta-plain widths at the locations of the cross sections for 11 moments between 7000 and 822 cal yr BP, using a map indicating Holocene delta-plain growth (fig. 6.4 in Erkens 2009). The measurements were used to detect temporal trends in floodbasin widths for the studied intervals (7000–5000, 5000–3000, and 3000–800 cal yr BP).

Results

Sand-Containing Basin-Fill Proportion. In the Holocene Rhine-Meuse delta plain for the interval 9000–800 cal yr BP, the SCBFP is 0.07 (7%), which includes the SDP (0.046), the OCLFP (0.010), and the BHDDP (0.015).

Spatial Variability. In general, the volume of sand-containing basin fills and the SCBFP increase in the downstream direction (fig. 3*C*). Splay deposits occur throughout the delta plain (fig. 3*A*). The SDP in the cross sections, however, is greatest in the proximal delta plain (cross sections B–E) and attains its maximum in cross section D (0.075; fig. 3*A*). Upstream (cross section A) and especially downstream (cross sections F–H) from these cross sections, proportions of splay deposits are considerably lower. Also, within time slices, the SDP is greatest 50–100 km downstream of the corresponding delta apex, which shifted upstream in response to base-level rise. The location of this delta apex for each time slice was published by Berendsen and Stouthamer (2001).

Organic-clastic lake fills occur exclusively in the distal part of the delta plain (cross sections D–H; fig. 3*B*). The OCLFP increases strongly in the downstream direction, reaching 0.04 in the most downstream part of the delta plain (cross section H; fig. 3*B*). Bay-head delta deposits were confined to the most downstream part of the study area (cross section H), where BHDDP is 0.13 (fig. 3*B*).

Temporal Variability. Sand-containing basin fills formed predominantly before 5000 cal yr BP (fig. 3*D*–3*F*). The majority of splay deposits formed between 7000 and 5000 cal yr BP (fig. 3*D*). Organic-clastic lake fills formed most extensively in the period 9000–7000 cal yr BP (fig. 3*E*). The abundance of these deposits in the delta-plain succession strongly decreases thereafter (compare time slices 9000–7000 and 7000–5000 in fig. 3*E*). After 5000 cal yr BP, extensive organic-clastic lake fills were not formed, despite the presence of a relatively wide floodplain (fig. 3*B*). Bay-head delta deposits formed between 7000 and 5000 cal yr BP (fig. 3*E*).

Proportion of Sand Bodies in Sand-Containing Basin Fills. The proportion of sand bodies in sand-containing basin fills varies considerably. The minimum, average, and maximum proportions (per time slice per cross section) of sand bodies in splay deposits are 0.00, 0.26, and 0.77, respectively. For organic-clastic lake fills, we found values of 0.02, 0.28, and 0.38, respectively. The bay-head delta deposits were composed entirely of sand (Hijma et al. 2009). The proportion of sand bodies contained in sand-containing basin fills relative to the total Holocene succession is 0.030, which includes sand bodies in splay deposits (0.012), organic-clastic lake fills (0.003), and bay-head delta deposits (0.015).

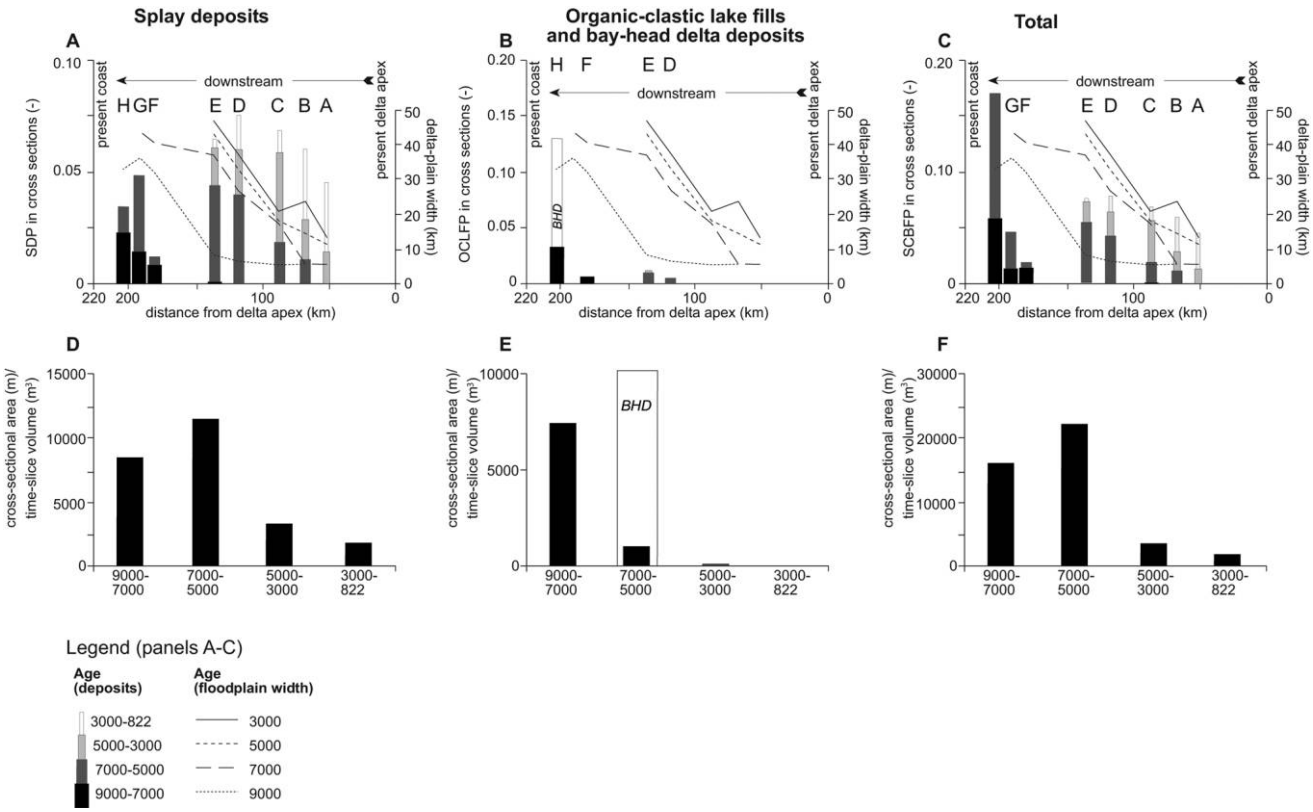

Figure 3. Spatial (*A–C*) and temporal (*D–F*) distribution of the proportions of splay deposits (left) and organic-clastic lake fills and bay-head delta deposits (middle) and their summed values (right). Floodplain width (lines) is given in *A–C*. BHD = bay-head delta. A color version of this figure is available in the online edition of the *Journal of Geology*.

Sand bodies in splay deposits are chiefly channel deposits, whereas those in organic-clastic lake fills are predominantly amalgamated, sheetlike, mouth-bar deposits.

Spatial Variability. Splay deposits, in general, are more sand-rich in the distal delta plain. The proportion of sand bodies, for example, increases from 0.10 (cross section B) to 0.62 (cross section F; fig. 4*A*). The trend within individual time slices, however, is less well expressed or is absent (fig. 4*C*, 4*G*, 4*I*), except for time slice 7000–5000 cal yr BP (fig. 4*E*), where splay deposits in the downstream part (cross sections F, G) are much sandier than those in the proximal part (cross sections B–E). The overall downstream coarsening largely reflects a temporal trend, as follows. The delta-plain area expanded during the Holocene mainly by upstream extension, which means that proximal delta-plain successions overall are younger than their distal counterparts. Simultaneously, splay deposits become finer-grained through time (fig. 5*A*, 5*E*). The combination of these two observations implies that sand-containing basin fills in the proximal delta plain, on average, contain less sand than those in the distal delta plain. The downstream coarsening of splay deposits and organic-clastic lake fills, therefore, is believed to reflect fining through time in combination with an upstream expansion of the delta plain (fig. 6).

Organic-clastic lake fills also exhibit a downstream increase in the proportion of sand, from 0.21 in cross section D to 0.30 in cross section H (fig. 4*B*). Within time slices, there is a maximum of two cross sections where organic-clastic lake fills have been found (fig. 3*E*), which limits detection of downstream trends in the composition of these deposits in time slices (right-hand panels in fig. 4). The upstream shift of organic-clastic lake fills from cross sections F and H (fig. 4*D*) to cross sections D and E (fig. 4*F*, 4*H*) reflects the upstream shift of the entire delta plain. The results, therefore, suggest that organic-clastic lake fills form exclusively in a narrow zone perpendicular to the general flow direction within the distal delta plain (see also "Discussion").

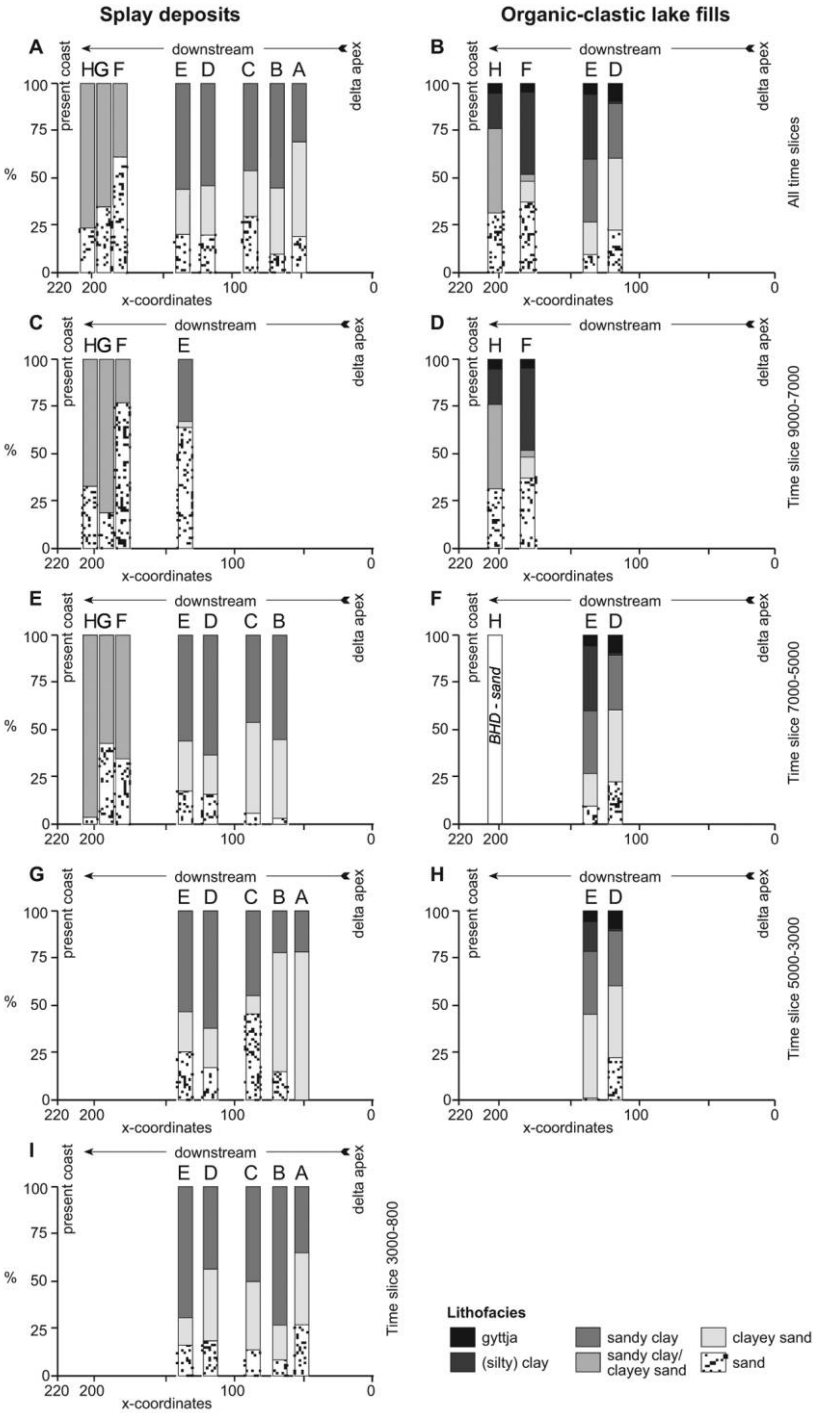

Figure 4. Lithofacies composition of splay deposits and organic-clastic lake fills related to the downstream position in the delta plain. *A* and *B* show the composition for all time slices. The other panels show the composition for the time slices 9000–7000 (*C*, *D*), 7000–5000 (*E*, *F*), 5000–3000 (*G*, *H*), and 3000–800 cal yr BP (*I*). Organic-clastic lake fills did not form after 3000 cal yr BP in the central delta plain. A color version of this figure is available in the online edition of the *Journal of Geology*.

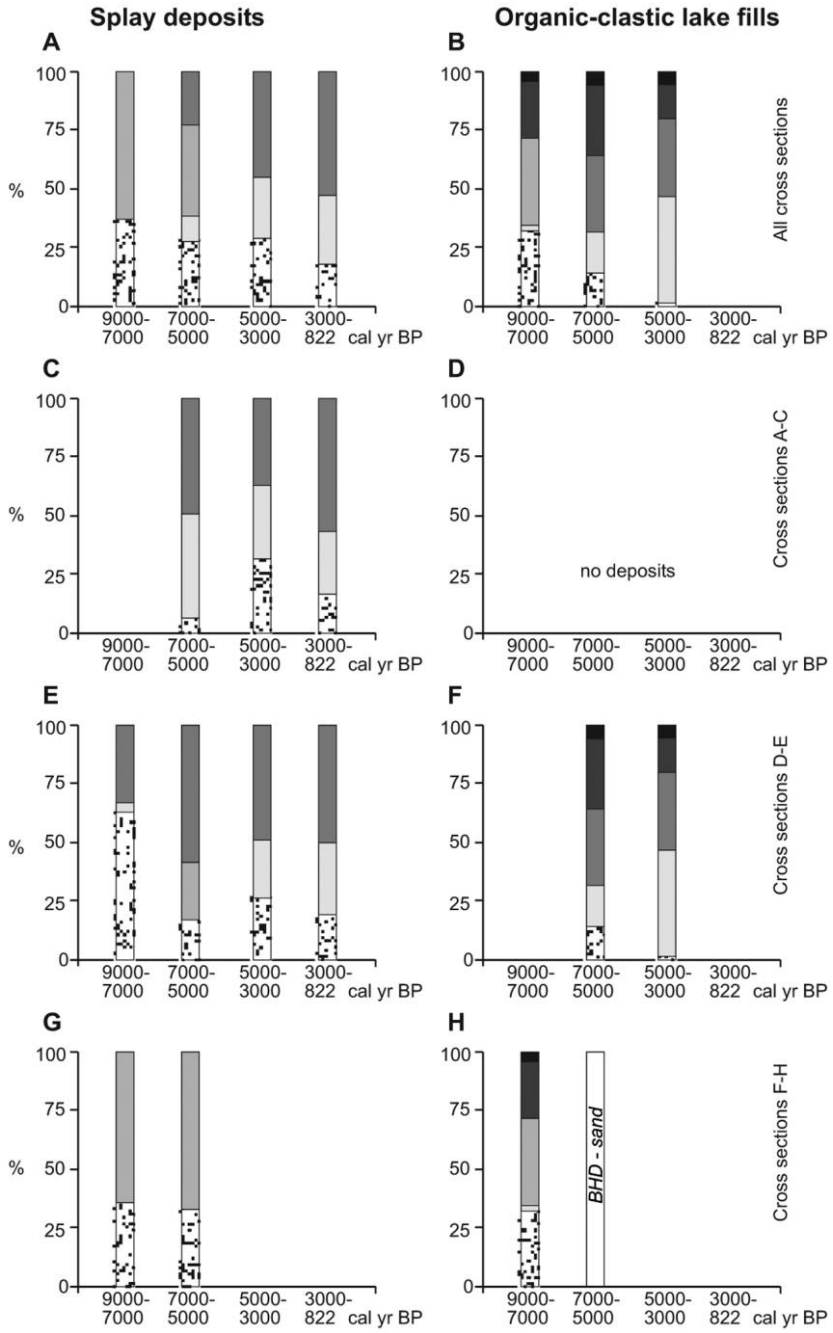

Figure 5. Lithofacies composition of splay deposits and organic-clastic lake fills related to the time slices. *A* and *B* indicate the composition for the whole delta. The other panels show the composition for three parts of the delta: the proximal delta plain (summed values of cross sections A–C; *C*, *D*), the intermediate delta plain (summed values of cross sections D and E; *E*, *F*), and the distal delta plain (summed values of cross sections F–H; *G*, *H*). For key, see figure 4. BHD = bay-head delta. A color version of this figure is available in the online edition of the *Journal of Geology*.

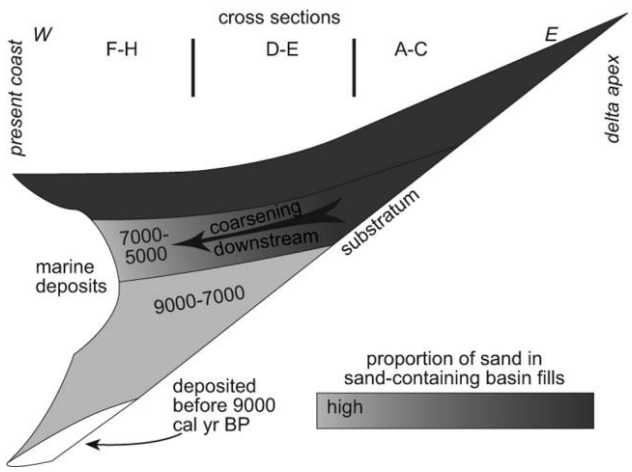

Figure 6. Schematic cross section of observed sand proportions within splay deposits throughout the Rhine-Meuse delta for the period after 9000 cal yr BP. This overview illustrates how a temporal trend affects a spatial trend. For example, splay deposits that formed between 9000 and 7000 cal yr BP are coarser-grained than younger splay deposits. Deposition in the proximal delta plain (cross sections A–C) commenced after 7000 cal yr BP, which means that splay deposits in that part of the delta are, on average, finer-grained than those in the distal delta plain (cross sections F–H). As a result, a general coarsening-downstream trend is observed for splay deposits, but this largely reflects a temporal fining trend (see text for explanation). A color version of this figure is available in the online edition of the *Journal of Geology*.

Temporal Variability. The lithofacies composition of splay deposits becomes finer-grained with decreasing age (fig. 5*A*). For example, splay deposits that formed between 9000 and 7000 cal yr BP are coarser-grained than those formed between 3000 and 800 cal yr BP (fig. 5*A*). This trend is particularly visible in the central part of the delta plain (cross sections D, E; fig. 5*E*), where the proportion of sand bodies is 0.63 in the oldest splay deposits and decreases to 0.19 in the most recent time slice.

Organic-clastic lake fills also become finer-grained with decreasing age (fig. 5*B*). This trend, however, cannot be further resolved spatially (fig. 5*D*, 5*F*, and 5*H*) because of the limited temporal range of the deposits within individual cross sections.

Discussion

Spatial and Temporal Distribution Patterns of Sand-Containing Basin Fills. *Spatial and Temporal Variability of Splay Deposits.* Splay deposits are present throughout the delta plain, with highest proportions within individual time slices occurring 50–150 km downstream of the associated delta apex (fig. 3*A*). We infer that the preservation degree of deposits, the width of floodbasins, and factors such as sea level rise, neotectonic activity and discharge, and within-channel sedimentation affected the present distribution of sand-containing basin fills.

The preservation degree of delta-plain deposits changed during the Holocene. Erkens (2009) published preservation values for floodbasin deposits, which are assumed here to be comparable to those of sand-containing basin fills because they are usually encased in floodbasin deposits. Preservation is shown to be controlled by the number of newly formed channel belts and by the thickness of the Holocene deposits in which they are encased (Erkens 2009). Erkens showed that preservation increases from 57% in cross sections A–C to 74% and 76% in cross sections D–E and F–H, respectively. Correction for erosion would increase the SDPs in cross sections A–C relative to those in cross sections D–E, but the effect on the trends in our results would be minimal. For example, the difference between splay deposits that formed between 7000 and 5000 cal yr BP in cross sections A–C and those in cross sections D–E would become smaller (fig. 3*A*), but a trend of increasing SDP in the downstream direction would still exist, indicating that factors other than preservation (as outlined below) also control SDP variability.

The width of floodbasins, approximated by the spacing between (paleo)channels (or similarly, by the width of the entire floodplain divided by the number of active channels), is another factor that may control the SDP (figs. 7, 8). Measurements of floodbasin widths on paleogeographic maps (app. D in Erkens 2009) suggest that lateral distances between paleochannels of the same age increase in the downstream direction (fig. 9). Further, maximum SDP values for consecutive time slices were found in cross sections D (7000–5000 cal yr BP), C (5000–3000 cal yr BP), and A–B (3000–800 cal yr BP; fig. 3*A*). The floodbasin widths that correspond to these maximum SDP values are remarkably similar and range between 3.1 and 3.6 km (fig. 9). We therefore suggest that average floodbasin widths of 3.1–3.6 km yield maximum proportions of splay deposits (see fig. 8*B*) in the Rhine-Meuse delta. This could be explained as follows. Narrower floodbasins show relatively low SDP values because they tend to limit splay development (fig. 8*A*). The proportion of channel-belt deposits (including natural-levee deposits) increases with decreasing distance

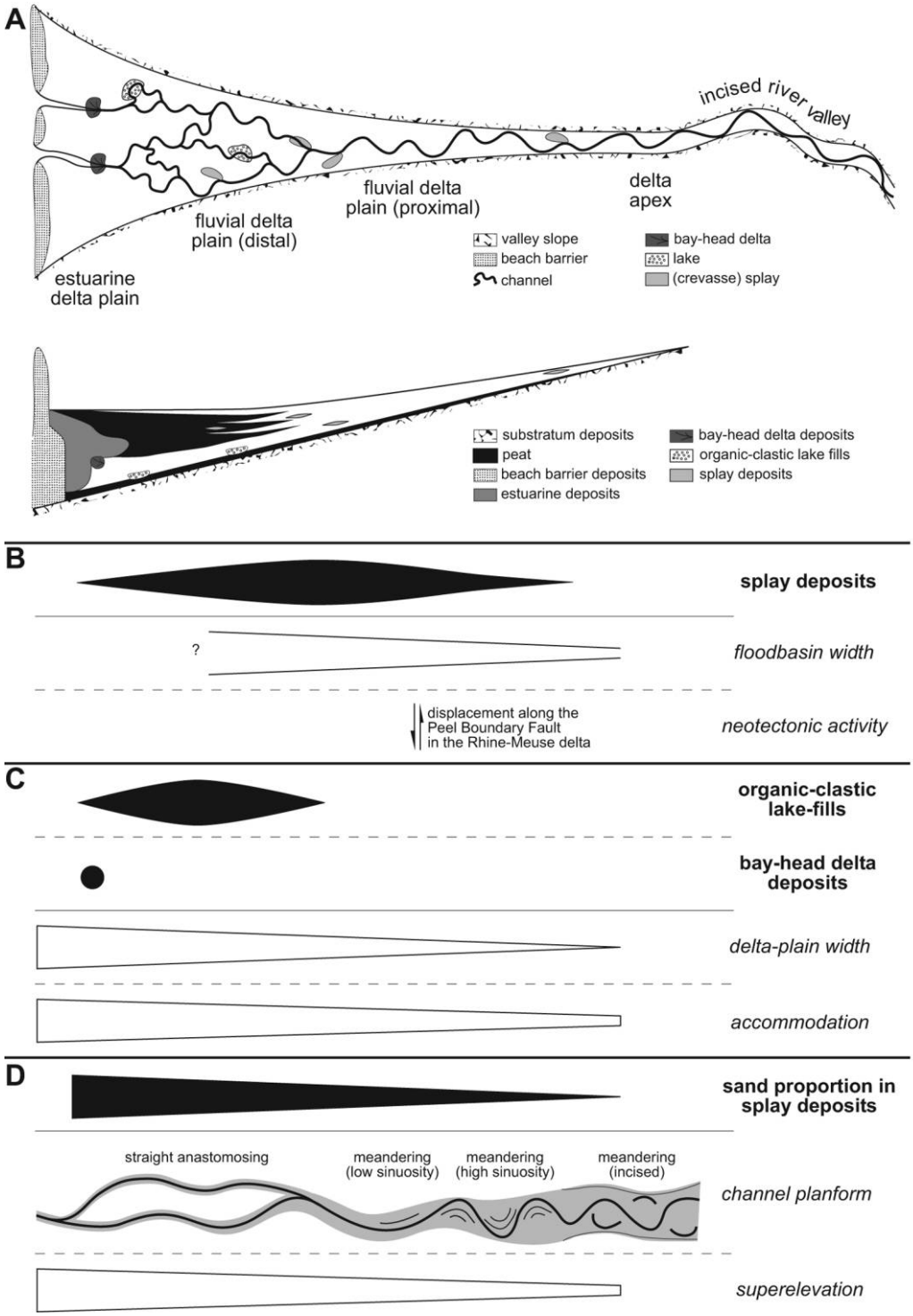

Figure 7. Schematic relationship between observed spatial trends in plan view (*A*) and longitudinal cross sections of splay deposits (*B*), organic-clastic lake fill and bay-head delta deposits (*C*), and the sand proportion in splay deposits along with their controlling factors (*D*; in italics). Note that the downstream changing proportion of sandy lithofacies in splay deposits accounts only for the period 7000–5000 cal yr BP. Thereafter, the proportion of sandy lithofacies in splay deposits is fairly constant in the downstream direction. Channel planform has been modified from Wolfert (2001). A color version of this figure is available in the online edition of the *Journal of Geology*.

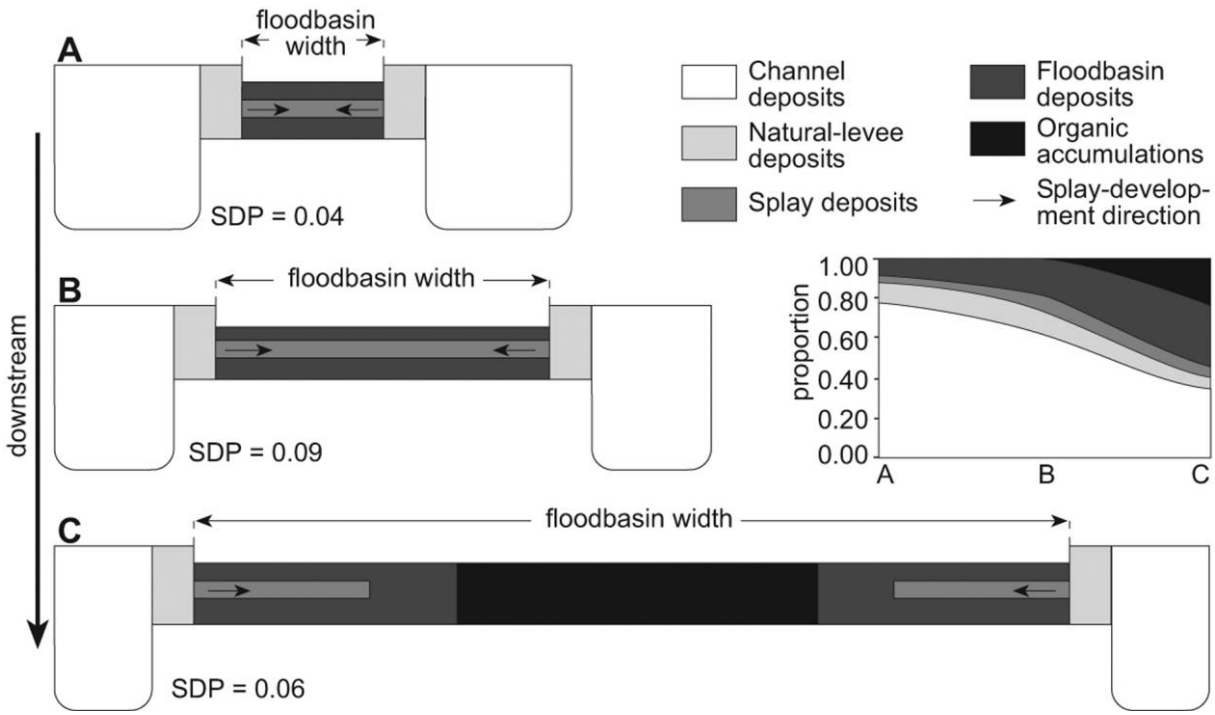

Figure 8. Proposed schematic relationship between floodbasin width and the proportion of splay deposits (SDP), based on characteristics of the Rhine-Meuse delta. Floodbasin width is relatively small in *A*, which limits the areal extent of splay deposits. The proportion of splay deposits increases farther downstream (*B*) as floodbasin width increases. When floodbasin width increases further (*C*), SDP decreases again in favor of floodbasin deposits. A color version of this figure is available in the online edition of the *Journal of Geology*.

between channel belts, that is, decreasing floodbasin width. This means that the proportion of nonchannel belt deposits decreases when floodbasin width decreases (fig. 8*B*). When floodbasins become very wide (fig. 8*C*), splay deposits will not be able to occupy the entire width of the floodbasin, leading to smaller SDP values.

At least three other factors may have controlled the spatial and temporal distribution of splay deposits in the Rhine-Meuse delta, as has been discussed by Stouthamer and Berendsen (2000, 2007). First, relative sea level rise and the resulting upstream shift of the delta apex and lateral expansion of the delta plain are essential for providing accommodation space and an aggradational environment. This, in turn, is a necessary condition for the formation of splay deposits. Second, neotectonic activity may have directly or indirectly controlled the position and timing of splay formation, possibly by means of gradient changes. Cohen et al. (2005) showed that neotectonic activity influenced the distribution of splay deposits. They found an abrupt increase of the abundance of splay deposits across the Peel Boundary Fault (fig. 1). Because of differential subsidence, formation of accommodation space and subsequent aggradation started earlier and at a higher rate in the Roer Valley Graben downstream of the fault than in the Peel Block, situated upstream of the fault (Berendsen and Stouthamer 2000). In the vicinity of this fault, the increased SDP appears to be related to the quantity of accommodation space. Third, discharge and/or within-channel sedimentation may also have influenced the temporal distribution of splay deposits in the Rhine-Meuse delta. When peak discharge volume and sediment load increase, bankfull discharge will be exceeded more frequently, probably resulting in the formation of more splay deposits (Stouthamer and Berendsen 2000).

Spatial and Temporal Variability of Organic-Clastic Lake Fills. Organic-clastic lake fills are limited to the distal delta plain. An example of organic-clastic lake fills near Schoonhoven (Bos 2010), located between cross sections E and F and formed between 7000 and 5000 cal yr BP, fits well in the observed temporal and spatial distribution pattern of the studied cross sections (fig. 3*B*).

High rates of base-level rise and wide floodplains facilitate the formation of organic-clastic lake fills,

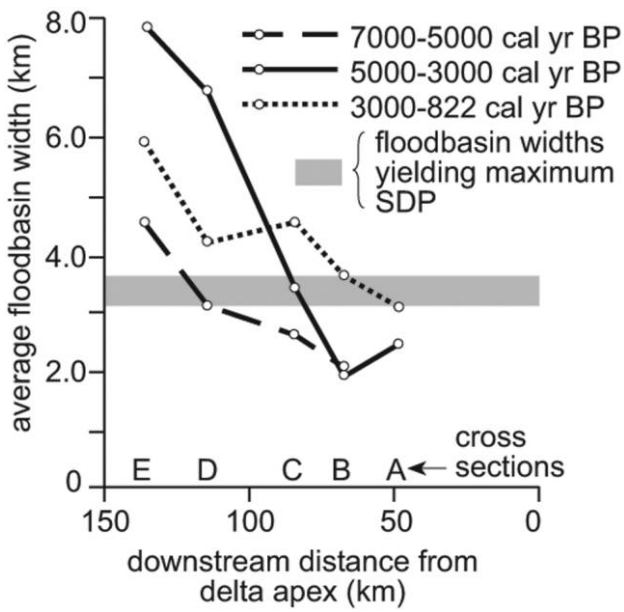

Figure 9. Average floodbasin widths in the Rhine-Meuse delta for three time slices, differentiated for cross sections (fig. 1). Indicated in gray is the range of the average floodbasin width that coincides with maximum SDP (proportion of splay deposits) values. The maximum SDP shifts upstream through time. Measurements were carried out on existing paleogeographic maps (Erkens 2009).

as do low stream gradients. These factors provide the necessary conditions for the formation of accommodation space. When the volume of clastic-sediment input cannot fill the created accommodation space, extensive peat-forming wetlands will form, which in turn are favorable areas for the development of organic-clastic lake fills (Bos 2010). In the central delta plain, OCLFP decreases with time (fig. 3*E*), corresponding to decreasing rates of base-level rise.

Spatial and Temporal Variability of Bay-Head Delta Deposits. Bay-head delta deposits were found only in cross section H (Hijma et al. 2009), but other studies suggest that these deposits likely occur elsewhere in the Holocene Rhine-Meuse delta. Hijma et al. (2009), for example, expect that they may be present at other locations, either between cross sections or as components of current cross sections, unrecognized because of low data quality. This is confirmed by the identification of four other locations where bay-head deltas formed before 6500 cal yr BP (Hijma and Cohen, forthcoming; K. M. Cohen, unpublished data). Two of the five above-mentioned bay-head delta deposits were (largely) eroded by later fluvial-channel activity; the remainder has been preserved because of avulsion (K. M. Cohen, personal communication). Further, a recently formed (~500 cal yr BP) fluvial-tidal sediment body containing 151 × 10^6 m^3 of sand and located slightly east of cross section F (Kleinhans et al. 2010) can also be regarded as a bay-head delta deposit. The spatial distribution of bay-head delta deposits, however, is strongly limited to the narrow transition zone between the fluvial and marine realms (fig. 7). Their relatively large volume, especially of sand bodies, nonetheless points to the significance of these deposits, for example, as reservoir or aquifer.

Temporal and Spatial Lithofacies Variability. *Spatial Trends of Sand-Body Proportions in Sand-Containing Basin Fills.* Sand-body proportions in splays and other sand-containing basin fills in this study, although variable within time slices, do not show clear spatial trends within time slices (e.g., fig. 4*F*, 4*I*). An exception are the splay deposits that formed between 7000 and 5000 cal yr BP, in which the proportion of sandy lithofacies increases from 0.04 (cross section B) to 0.41 (cross section G) in the downstream direction (fig. 4*E*).

Various factors potentially control the spatial trends found in the sand-body proportions of sand-containing basin fills. Below, we discuss the influence of channel planform, superelevation, and substratum composition.

Channel planform is believed to partially determine the composition of splay deposits. A study in the Rhine-Meuse delta (Stouthamer 2001) shows that splay deposits may be finer-grained along meandering river systems than along straight river systems. The first process that could explain this variability is a difference in flow mechanisms between meandering and straight river systems. Helical flow in meandering river channels transports sandy bed load to inner bends (Leopold and Wolman 1960), leaving little sand for diversion into splay channels positioned in outer bends, where they are commonly located (Stouthamer 2001). Hence, splay deposits forming in these settings are relatively fine-grained. Because this mechanism is not effective or is absent in straight river channels, splay deposits along these systems are generally coarser-grained. Helical-flow differences, however, become less effective when crevasse channels are more deeply incised. Then, an increasing amount of bed load in meandering river channels can be diverted to the splay channel. The second explanatory process for the lithological difference between splay deposits along meandering and straight river systems is the nature of sediment transport. Meandering rivers

tend to be suspended-load dominated, which is why these rivers are characterized by relatively fine-grained sediment. Straight rivers, in contrast, tend to transport a comparatively large portion of the sediment as bed load, which is relatively coarse-grained (Slingerland and Smith 2004). Probably both mechanisms contribute to the lithological differences between splay deposits along meandering and straight river systems. In the Rhine-Meuse delta, straight river channels along which large-scale crevassing occurred were dominant in the distal central delta plain between 8000 and 4000 cal yr BP. Meandering rivers were dominant in the proximal delta plain and along the edges of the distal delta plain throughout its formation. The relatively large proportion of sand in splay deposits that formed between 7000 and 5000 cal yr BP in the distal delta plain (fig. 4*E*) is therefore likely controlled by the straight rivers that dominated these areas (fig. 7).

Superelevation differences between straight and meandering river systems might also contribute to differences in lithofacies composition of sand-containing basin fills (fig. 7). Superelevation is the elevation difference between the water level in the river channel at bankfull discharge (i.e., natural-levee crest) and the surface level in the adjacent floodbasin (Heller and Paola 1996). Because lateral migration in meandering river channels prevents natural levees in the outer bends from reaching maximum potential heights, it could be hypothesized that superelevation in these systems is low compared to that in straight river systems. According to this line of thought, floodbasins of straight rivers consequently tend to be deeper and have the greatest water depths during high-discharge events. These water depths allow for relatively high flow velocities, which probably can also transport sand particles. This facilitates deposition of relatively sandy deposits during waning stages of floods in floodbasins of straight river systems. Furthermore, large superelevation (straight rivers) facilitates deep incision of splay channels, which enlarges the chance that they tap coarse-grained bed material of the trunk channel, yielding relatively coarser-grained splay deposits. Splays along meandering rivers, by contrast, will be relatively fine-grained. We therefore contend that fluvial style and superelevation influence the lithofacies composition of sand-containing basin fills.

The properties of the substratum also affect the lithofacies composition of sand-containing basin fills. Splay deposits situated at or near the base of Holocene successions are relatively sandy in various locations in the Rhine-Meuse delta, which is attributed to reworking of sandy substratum material (Stouthamer 2001; Cohen et al. 2009). In particular, when a channel is able to erode topographically elevated substratum deposits (e.g., aeolian river dunes), significant volumes of sand can be added to the upstream-supplied sediment (Cohen et al. 2009).

Temporal Trends of Sand-Body Proportions in Sand-Containing Basin Fills. Sand-containing basin fills within the Holocene Rhine-Meuse delta-plain succession tend to become finer-grained with decreasing age (figs. 5*A*, 6), as has been proposed for splay deposits by Stouthamer (2001). Decreasing water depth in floodbasins possibly results in fining of splay deposits with younger age. Floodbasin water depth is expected to be greater when rates of base-level rise are high, thereby enhancing trap efficiency, which would explain the decreasing proportion of sand in splay deposits with time. This explanation is supported by lithological and palynological observations of van der Woude (1981), who found predominantly waterlogged floodbasins before 4700 cal yr BP and much drier conditions thereafter. The decreasing rate of base-level rise probably is reflected in the fining trend of splay deposits.

Alternatively, downstream fining might have had a larger imprint on the sediment composition of younger deposits because the delta expanded longitudinally with time. This lengthened the pathway for sediment to reach downstream portions of the delta plain, permitting sediment fining to be more effective during younger periods. As a consequence, sediments in a specific region of the delta, on average, become finer-grained with time. Incorporation of sandy substratum material in distal-delta-plain deposits is comparatively limited during later phases of the Holocene because younger channels are not incised into the substratum. The effect of this mechanism (i.e., the incorporation of sandy substratum), however, is not supported by the spatial distribution of the lithofacies composition. The anticipated downstream fining of splay deposits is not reflected in our results (fig. 4*C*, 4*E*, 4*G*, 4*I*). We therefore propose that fining of sand-containing basin fills through time is mainly controlled by decreasing floodbasin water depth.

Influence of Sand-Containing Basin Fills on Reservoirs. Predictions of reservoir exploitability, which partly depend on reservoir volume (i.e., the volume of sand bodies in a geological formation) and connectedness, are commonly based on numerical simulation models (e.g., Mackey and Bridge 1995). These so-called reservoir models, especially

recent ones (e.g., Pyrcz et al. 2009), recognize the potential of splay deposits as reservoirs, but in general they lack field data for model conditioning. Hence, the notion that sand-containing basin fills may form more than 10% of the deposits in distal parts of delta plains (cross section H in fig. 3*B*, 3*C*) emphasizes that they should not be ignored in reservoir models. In this section, we discuss the significance of overbank sand bodies for reservoir volume and connectedness.

Reservoir Volume. In the Holocene Rhine-Meuse delta plain, channel-belt and non-channel-belt sand bodies volumetrically form 40% (Erkens 2009) and 3% (this study), respectively, of the succession. The proportion of channel-belt sand bodies decreases downstream from 70% (cross section A) to 30% (cross section E), whereas the proportion of non-channel-belt sand increases downstream from 1% (cross section A) to 11% (cross section H). The preserved sand body of the bay-head delta deposits in cross section H has a volume of ~120 × 10^6 m^3 (Hijma et al. 2010), which accounts for approximately 11% of the total fluvial sediment in that part of the distal delta plain. In cross section H, channel deposits form 21% of the fluvial deposits (Erkens 2009), indicating that 34% ([11/(11 + 21)] × 100) of the local reservoir volume (i.e., sand-body volume) is formed by bay-head delta deposits. Similarly, preserved sand bodies of organic-clastic lake fills in the relatively isolated and peat-dominated Angstel-Vecht area in the distal delta plain (fig. 1) have a combined volume of 44 × 10^6 m^3 (Bos 2010), whereas the volume of channel sand bodies is 99 × 10^6 m^3. Here, overbank sand bodies account for 31% of the reservoir volume. Another example is the more upstream-positioned Gelderse IJssel (fig. 1), where 60% of the Holocene deposits are sand bodies, consisting of channel deposits and sand-containing basin fills (43% and 17%, respectively; based on Cohen et al. 2009). In the Gelderse IJssel area, sand in sand-containing basin fills constitutes 39% of the total reservoir volume, partly derived from erosion of the locally elevated substratum.

Reservoir Connectedness. The connectedness ratio (CR) is a measure of the degree to which individual channel-belt sand bodies are amalgamated (e.g., Leeder 1978). It is a principal parameter for alluvial architecture, especially concerning reservoir characterization, and it partly determines the exploitability of reservoirs. The CR is defined as "the length of horizontal contact between connected channel belts divided by the total horizontal width (or length) of channel-belt deposits in the transect" within a single cross-valley transect (Mackey and Bridge 1995, p. 14), and it can be expressed as

$$\mathrm{CR} = \frac{\sum_{i=1}^{n-1} c_i}{\sum_{j=1}^{n} w_j}, \tag{1}$$

where c is the shared horizontal width of two channel-belt sand bodies, w is the width of an individual channel-belt sand body, and n the number of channel-belt sand bodies in the cross section. The theoretical limits of CR are 0, where individual sand bodies are completely isolated, and 0.5, where individual sand bodies are all connected over the full width, that is, vertically stacked (fig. 10). In the latter case, the CR is by definition set to 1 (see Mackey and Bridge 1995). Increasing CR values indicate that reservoir elements within a cross section are increasingly well connected, which is generally associated with lower costs for exploitation and therefore more interesting from an economic point of view.

Strictly, CR involves only sand that is deposited in fluvial channels. Practically, however, reservoir connectedness also includes sand bodies contained in overbank deposits (e.g., Larue and Hovadik 2006). Especially when the areal extents of individual sand bodies are large, they may be able to connect isolated channel belts (fig. 11). Despite the relatively large total volume of sand contained in splay deposits, we consider them not very suitable connectors because individual units are relatively small, with sand concentrated in channels that are often isolated in cross sections from other reservoir elements. In contrast, laterally extensive sand bodies in organic-clastic lake fills and bay-head delta deposits may form effective connectors for otherwise unconnected channel-belt sand bodies. In this way, they potentially yield higher CR values (fig. 9). In addition, the presence of overbank sand bodies promotes the local development of wider channel-sediment bodies. Bos et al. (2009) showed that lateral channel migration is enhanced by sandy subsoils contained in organic-clastic lake fills, ultimately resulting in wider channel-belt deposits. Apart from larger reservoir volumes, the presence of overbank sand bodies potentially also enlarges CR values, because younger channel belts are more likely connected to these wider channel-belt sand bodies. Hence, this study confirms and strengthens the observation that the CR sensu stricto, by excluding sand bodies contained in overbank deposits, underestimates the true reservoir connectedness in areas where non-channel-belt sand bodies

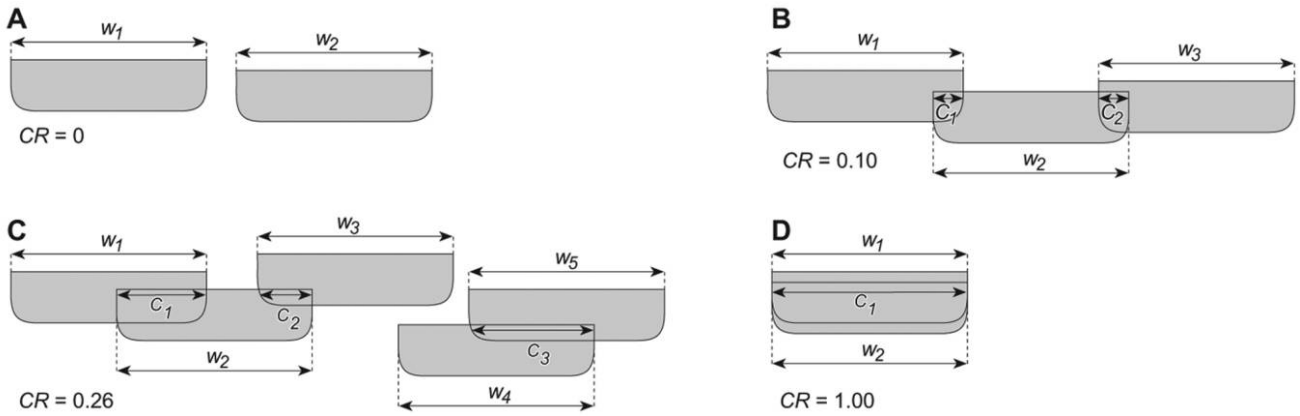

Figure 10. Schematic visualization of possible channel-sand-body configurations. The connectedness ratio (CR) partly reflects this configuration. The CR ranges from 0 (individual channel-sand bodies are completely isolated; *A*) to 1 (channel-sand bodies totally overlap; *D*). In the Rhine-Meuse delta plain, CR values were found to range between 0.08 (cross section E in fig. 1) and 0.21 (cross section A in fig. 1; Gouw 2008), although in model simulations, higher CR values (up to 0.69) were found (Mackey and Bridge 1995).

are present in the subsoil (Larue and Hovadik 2006). We argue that this especially accounts for distal-delta-plain deposits, which generally encompass ribbon sand bodies that potentially are connected by sand bodies present in organic-clastic lake fills or bay-head delta deposits.

Conclusions

Distribution of Sand-Containing Basin Fills. Sand-containing basin fills in the Holocene Rhine-Meuse delta form 7.1% of fluvial delta-plain volume (including organic accumulations) and consist of splay deposits (4.6%), organic-clastic lake fills (1.0%), and bay-head delta deposits (1.5%). Proportionally, splay deposits are most abundant midway between the delta apex and the coast, but they occur throughout the fluvial delta-plain succession. The SDP was found to be related to floodbasin width and affected by neotectonic activity. In the Rhine-Meuse delta, the SDP reaches its maximum value when floodbasin width is between 3.1 and 3.6 km. Narrower floodbasins restrict splay deposit formation, yielding relatively low SDPs. Wider floodbasins also yield lower SDP values, because the increased space between channel belts is occupied by floodbasin deposits and organic accumulations instead of splay deposits.

Organic-clastic lake fills are most abundant in the distal delta plain. The distribution of organic-clastic lake fills is associated with extensive peat accumulations, which form when accommodation creation outpaces sedimentation. This requires high rates of base-level rise (occurring before ~5000 cal yr BP in the Rhine-Meuse delta) and/or wide delta plains (present in the distal Rhine-Meuse delta). Bay-head delta deposits are confined to the upper estuary.

Sand-Body Proportion in Sand-Containing Basin Fills. Volumetrically, sand bodies constitute, on average, 26%–30% of sand-containing basin fills. The proportion of sand bodies in these deposits generally decreases with younger age. Because the upstream limit of aggradation shifted upstream over time, this temporal trend is also reflected spatially: on average, sand-containing basin fills in the distal delta plain contain more sand than those in the proximal delta plain. We attribute the lithofacies variability of sand-containing basin fills to variations in channel planform, superelevation, and substratum properties. In meandering river systems, splay deposits are relatively fine-grained, which can be explained by (1) the presence of helical flow in meandering river systems, which prevents relatively coarse sediment from reaching outer bends, where crevasses predominantly occur, or (2) large superelevation values (related to straight river systems), which permit splay channels to incise more deeply, thereby enlarging the proportion of bed-load material that is contained in these splay deposits. Substratum properties, in addition, may also influence the composition of splay deposits, especially when they form just downstream of an area where the channel has incised into sandy substratum.

Because of the relatively large volume of sand bodies in overbank deposits, especially in distal

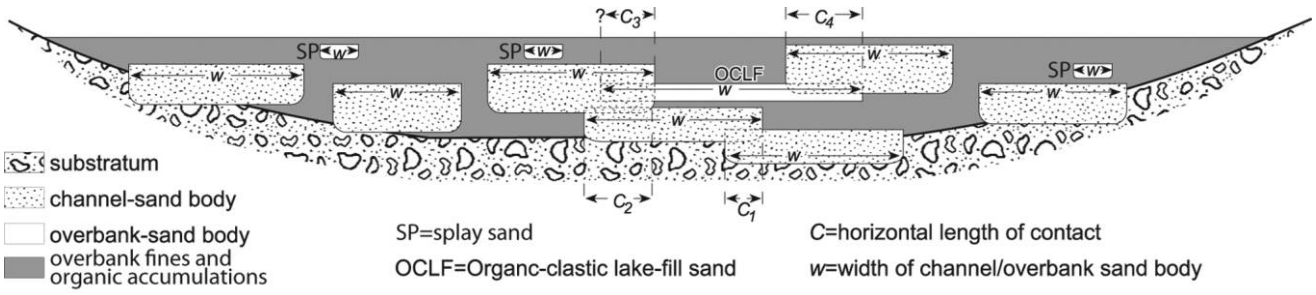

Figure 11. Schematic cross section illustrating the effect of overbank sand bodies on the connectedness ratio (CR) in distal delta-plain successions. The CR of channel-sand bodies, using only the widths of the channel-sand bodies and C_1 and C_2, is 0.09, which is realistic for the distal Rhine-Meuse delta plain (Gouw 2008). The CR increases to 0.17 when overbank sand bodies are considered as reservoir elements, thereby using the width of all sand bodies in the cross section and C_1–C_4. Note that the left-hand edge of the organic-clastic lake fill cannot be determined exactly. The CR, therefore, may vary slightly from what has been calculated. Nevertheless, including overbank sand bodies in CR calculations will lead to higher and more realistic CR values.

delta plains, ignoring sand-containing basin fills in reservoir models potentially leads to underestimation of reservoir volumes. Furthermore, organic-clastic lake fills and bay-head delta deposits potentially form connectors between channel-belt sand bodies in distal delta plains, thereby increasing the overall CR.

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