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Response of the Rhine–Meuse system (west-central Netherlands) to the last Quaternary glacio-eustatic cycles: a first assessment

Torbjörn E. Törnqvist [a,*], Jakob Wallinga [b,c], Andrew S. Murray [c], Hein de Wolf [d], Piet Cleveringa [d], Wim de Gans [d]

[a] *Department of Earth and Environmental Sciences, University of Illinois at Chicago, 845 West Taylor Street, Chicago, IL 60607-7059, USA*
[b] *The Netherlands Centre for Geo-ecological Research (ICG), Faculty of Geographical Sciences, Utrecht University, P.O. Box 80115, NL-3508 TC Utrecht, The Netherlands*
[c] *Nordic Laboratory for Luminescence Dating, Department of Earth Sciences, Aarhus University, Risø National Laboratory, DK-4000 Roskilde, Denmark*
[d] *Netherlands Institute of Applied Geoscience TNO— National Geological Survey, P.O. Box 80015, NL-3508 TA Utrecht, The Netherlands*

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Abstract

An almost 50-m-deep core from the Weichselian Rhine–Meuse palaeovalley, near the present Dutch coast, reveals new insights into how this continental-scale fluvial system responded to relative sea-level fluctuations associated with the last Quaternary glaciations. A multidisciplinary study of this core included sedimentological and stratigraphic analysis augmented with data on shell, diatom and pollen content to infer depositional environments. Optically stimulated luminescence dating provides a first numerical chronostratigraphy for these strata.

Net fluvial incision due to relative sea-level fall associated with the Weichselian glaciation (notably oxygen-isotope stage 4) is estimated at >10 m, and we argue that this amount of incision decreases both updip and downdip, because our study area is located near the thickest part of the Eemian/Early Weichselian (oxygen-isotope stage 5) highstand coastal prisms that were particularly sensitive to erosion during ensuing relative sea-level falls. Coastal prism geometry, with a relatively steep upper shoreface, is extremely important in promoting erosion, as demonstrated by the Rhine–Meuse system that borders an exceptionally wide, low-gradient continental shelf. Our results show that fluvial deposits associated with relative sea-level fall (80–40 ka) can constitute a considerable part of preserved strata (‘falling-stage systems tract’). Interglacial transgressive and highstand systems tracts tend to have a relatively low preservation potential; in our core these are represented by estuarine deposits scoured into underlying fluvial strata. Furthermore, we note that sequence boundaries in such settings may be relatively undistinct, whereas tidal ravinement surfaces can be more conspicuous and may represent considerably longer time gaps.

Keywords: sequence stratigraphy; sedimentology; OSL dating; palaeoecology; Rhine–Meuse system; Quaternary

1. Introduction

It is widely accepted that substantial sediment packages in subsiding coastal areas consist of

* Corresponding author. Tel.: +1-312-996-3159; fax: +1-312-413-2279.
E-mail address: tor@uic.edu (T.E. Törnqvist).

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palaeovalley fills that have accumulated in response to relative sea-level (RSL) fluctuations. Classical work concerning fluvial incision and subsequent valley filling during the last glacio-eustatic cycle was carried out in the Mississippi Delta, where a Late Quaternary palaeovalley fill was mapped underneath the present-day deltaic plain (Fisk and McFarlan, 1955) and extensively radiocarbon dated (McFarlan, 1961). Several recent studies have stressed that RSL fall need not necessarily lead to fluvial incision, using geometrical arguments based on downdip variations in gradient from alluvial or coastal plain to continental shelf (Summerfield, 1985; Miall, 1991; Posamentier et al., 1992; Woolfe et al., 1998). In addition, fluvial systems are able, to certain degrees, to accommodate variations in gradient by changing their channel pattern (Schumm, 1993). Nevertheless, numerous investigations primarily based on high-resolution seismic studies of shelves and estuaries (e.g., Knebel et al., 1979; Suter and Berryhill, 1985; Colman and Mixon, 1988; Anderson et al., 1996) document the widespread occurrence of palaeovalleys in such environments. In addition, base-level controlled fluvial incision has been identified as a common feature in flume simulations of basin-margin evolution (Wood et al., 1993, 1994; Koss et al., 1994; Paola, 2000).

It is increasingly recognized (e.g., Carter, 1998; Shanley and McCabe, 1998; Blum and Törnqvist, 2000) that the Quaternary offers particularly good opportunities to study stratigraphic sequences and their controls, in the first place due to the availability of independent RSL data. The last glacio-eustatic cycles provide the additional advantage of exceptional numerical dating control. A considerable number of recent sequence-stratigraphic studies have been carried out in Late Quaternary palaeovalley fills, particularly in estuarine and offshore (shelf) settings (e.g., Allen and Posamentier, 1993; and numerous papers in Dalrymple et al., 1994a). Despite the great value of such studies, most of them focus on the last (~ 100 kyr) glacio-eustatic cycle only (usually only the last ~ 20 kyr), and, hence, provide limited insight in the preservation potential of depositional systems tracts (cf. Posamentier and Weimer, 1993). Exceptions include the work by Colman and Mixon

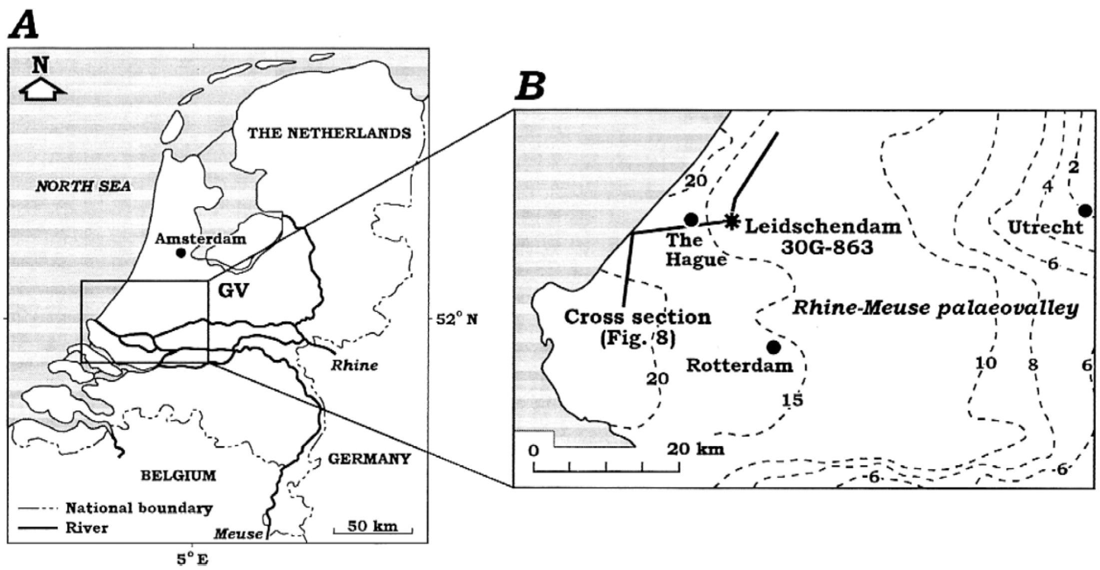

Fig. 1. Location of (A) the Rhine–Meuse delta in the west-central Netherlands and (B) morphology of the Rhine–Meuse palaeovalley with the Leidschendam site. Note that the contours (in meters below Dutch Ordnance Datum; generalized after De Gans and Van Gijssel, 1996) indicate the topography of the *floodplain surface* (not the *thalweg*) and surrounding areas at the end of the Weichselian. The contours therefore represent the transgressive surface and not the underlying sequence boundary. Also note that recent work (De Gans and De Groot, 1995) indicates that Weichselian Rhine–Meuse strata extend further north than the palaeovalley morphology suggests. The higher elevations north of the line Utrecht—The Hague are partly due to accumulation of eolian cover sands. GV = Gelderse Vallei.

(1988), Blum and Price (1998) and Amorosi et al. (1999). The present investigation focuses on the evolution of the Rhine–Meuse system in the west-central Netherlands (Fig. 1A) over the last two glacio-eustatic cycles (i.e., a compound palaeovalley fill or 'compound incised-valley fill' *sensu* Zaitlin et al., 1994). As pointed out by Dalrymple et al. (1994b), palaeovalleys and their fills have been studied primarily in their seaward and middle portions (segments 1 and 2; Zaitlin et al., 1994) whereas the landward, fluvially dominated portion (segment 3) has received less attention. An exception is the recent study by Blum and Price (1998), and the present investigation, despite being located in segment 2, aims to focus particularly on the fluvial component of palaeovalleys.

It has been hypothesized (Törnqvist, 1995) that the Pleistocene succession of the Rhine–Meuse system in the west-central Netherlands consists of vertically stacked lowstand systems tracts (LSTs; terminology following Van Wagoner et al., 1988 and Van Wagoner, 1995), composed primarily of sandy to gravelly braided-river deposits and separated by sequence boundaries. Due to the vertical stacking of relatively homogeneous, coarse-grained fluvial deposits such unconformities are difficult to detect, and have recently been referred to as 'cryptic sequence boundaries' (Miall, 1999). For the Rhine–Meuse system, it has been envisaged (Törnqvist, 1995) that the high frequency and large amplitude of Quaternary glacio-eustatic cycles precluded the preservation of transgressive and highstand systems tracts (TSTs and HSTs). Since these ideas were model-driven rather than data-driven, the purpose of the present study is to test them by means of a multidisciplinary analysis (sedimentology/stratigraphy, palaeoecology, geochronology) of an almost 50-m-deep core located near Leidschendam (Fig. 1B), close to the shoreline of the present-day highstand delta.

2. Geological setting

The Quaternary history of the Rhine–Meuse system in The Netherlands is complex, because advanc-

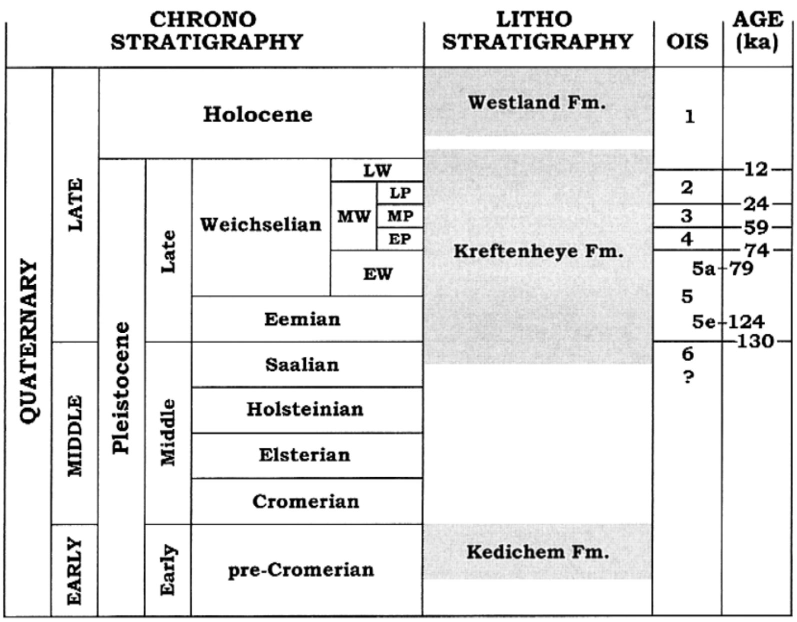

Fig. 2. Late Quaternary chronostratigraphy for northwest Europe (after Zagwijn, 1975, 1992) and lithostratigraphic units in the study area (after Doppert et al., 1975). Oxygen-isotope stage (OIS) ages according to Pisias et al. (1984) and Martinson et al. (1987). EW = Early Weichselian, MW = Middle Weichselian, LW = Late Weichselian, EP = Early Pleniglacial, MP = Middle Pleniglacial, LP = Late Pleniglacial.

ing Pleistocene ice sheets strongly modified the geomorphology, and, hence, fluvial drainage directions. Palaeogeographic reconstructions (e.g., Zagwijn, 1974, 1989; Gibbard, 1988, 1995; Bridgland and Gibbard, 1997) can briefly be summarized as follows. Prior to the Elsterian glaciation (for chronostratigraphy see Fig. 2) the Rhine and Meuse Rivers drained to the northwest and extended their courses onto the continental shelf of the North Sea during RSL lowstands (Fig. 3A). The Leidschendam site is located west of this alluvial plain (Zagwijn, 1974, 1989).

Coalescence of the Fennoscandian and British ice sheets during the Elsterian caused dramatic changes since a big ice-dammed lake was formed in the northern Netherlands and in the present North Sea, ultimately forcing drainage towards the southwest (Fig. 3B) through the Strait of Dover (Gibbard, 1988, 1995; Bridgland and Gibbard, 1997; but questioned by Laban, 1995). Although it remains to be firmly demonstrated, it is now generally assumed that from this moment on the Rhine–Meuse system (along with numerous tributaries) drained through the Strait of Dover during RSL lowstands (but see the critical review by Bridgland and D'Olier, 1995).

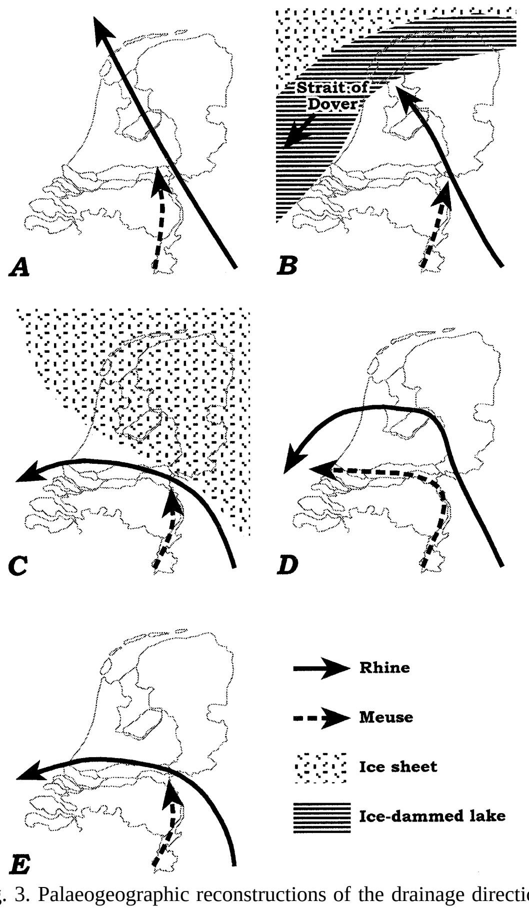

Fig. 3. Palaeogeographic reconstructions of the drainage direction of the Rhine and Meuse systems in The Netherlands during the (A) pre-Elsterian; (B) Elsterian; (C) Saalian; (D) Eemian/Early Weichselian; (E) Middle/Late Weichselian, based on sources cited in the text.

The subsequent Saalian ice sheet covered the northern half of The Netherlands and forced the Rhine–Meuse system to follow a route farther south (Fig. 3C), roughly similar to the present course of these rivers. However, during the latest Saalian, the Eemian and Early Weichselian, the Rhine followed a more northerly route through the country (Fig. 3D) due to the creation of glacially eroded depressions. The present course was reoccupied from the Middle Weichselian onwards (Van de Meene and Zagwijn, 1978; Fig. 3E). Although challenged by Verbraeck (1984: pp. 97, 106–108), this idea is still generally supported (De Gans and Van Gijssel, 1996). It is important to note that the Meuse always approximately followed its present course since the Saalian (e.g., Zagwijn, 1974; Van de Meene and Zagwijn, 1978).

Pleistocene Rhine and Meuse sediments deposited after the peak of the Saalian glaciation belong to the Kreftenheye Formation (Zonneveld, 1958; Doppert et al., 1975; Fig. 2) and constitute the main focus of the present study. The geochronology of the Kreftenheye Formation is poorly understood, particularly in the west-central Netherlands. This is primarily due to the lack of organic matter suitable for dating and because most of its sediments predate the ^{14}C age range. The limited number of usually problematic ^{14}C ages is summarized by De Jong (1995).

3. Methods

The present study is based on a multidisciplinary analysis of an almost 50-m-deep core (Fig. 4). Although the core appears to be located at the northern margin of the palaeovalley (Fig. 1B), recent studies

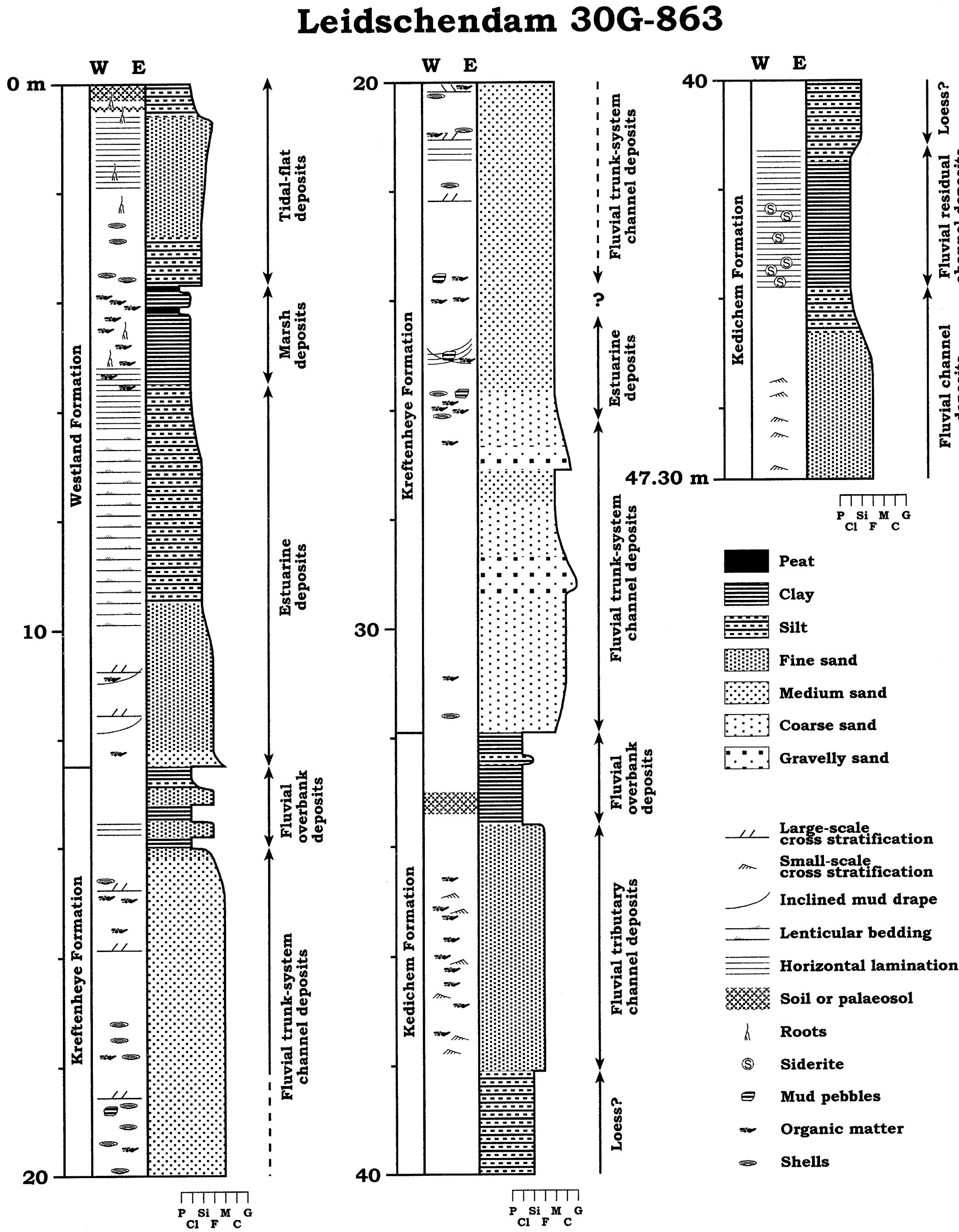

Fig. 4. Sedimentary log of the Leidschendam core (local coordinates 87.540/454.380; surface elevation 4.27 m below Dutch Ordnance Datum). Depth in meters below the surface.

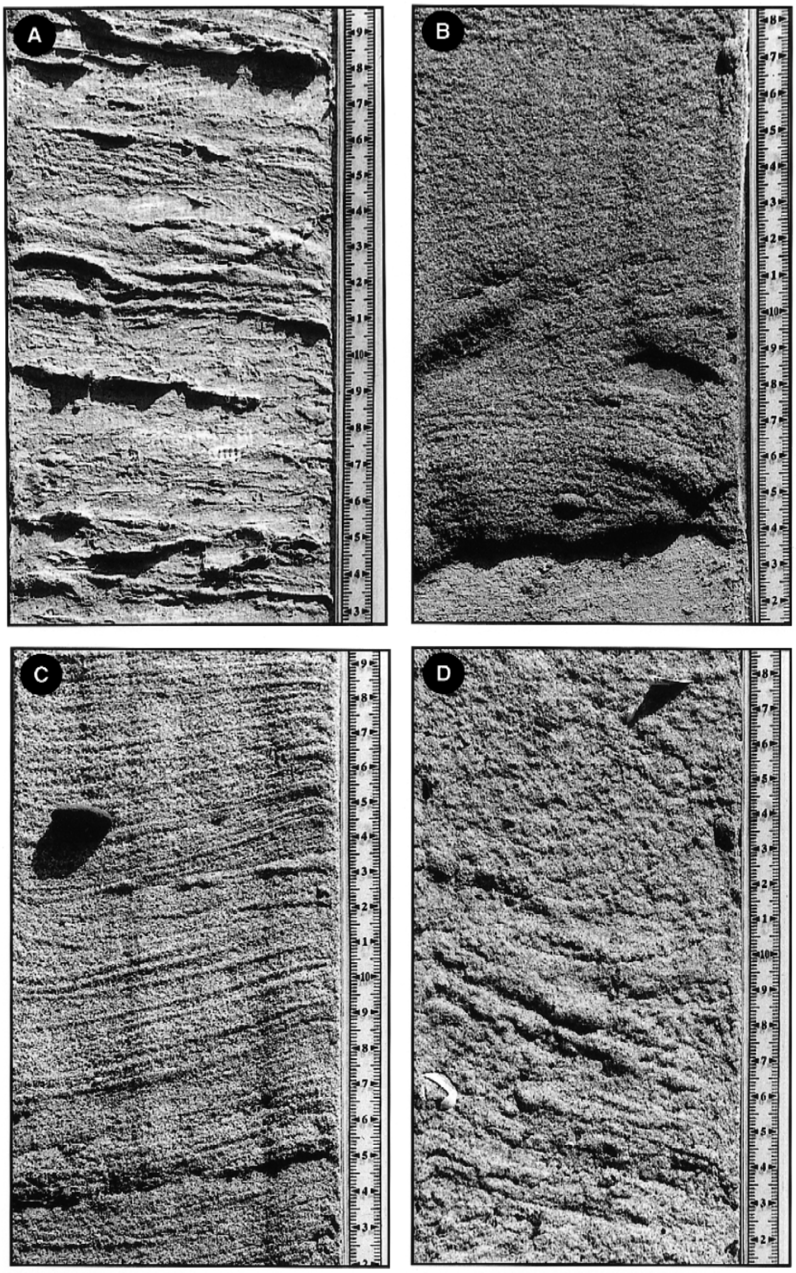

Fig. 5. Key characteristics from lacquer peels of the Leidschendam core, illustrated by (A) lenticular bedding in estuarine (presumably lagoonal) deposits of the Westland Formation (7.5 m); (B) tidal ravinement surface with estuarine channel deposits incised into clayey overbank deposits of the Kreftenheye Formation (12.5 m); (C) multiple sets with large-scale cross stratification and one lamina consisting primarily of reworked organic matter (14.8 m); (D) and (E) cross-stratified fluvial (possibly estuarine) channel deposits with reworked marine shells (20.1 and 20.9 m); (F) estuarine channel deposits with mm-scale inclined mud drapes and fragments of reworked organic matter (24.9 m); (G) faintly cross-stratified gravel-rich channel deposits in the lowermost part of the Kreftenheye Formation (28.3 m); (H) small-scale cross-stratification in fluvial channel deposits of the Kedichem Formation (45.7 m). Scale in cm; lacquer peels oriented W (left)–E (right).

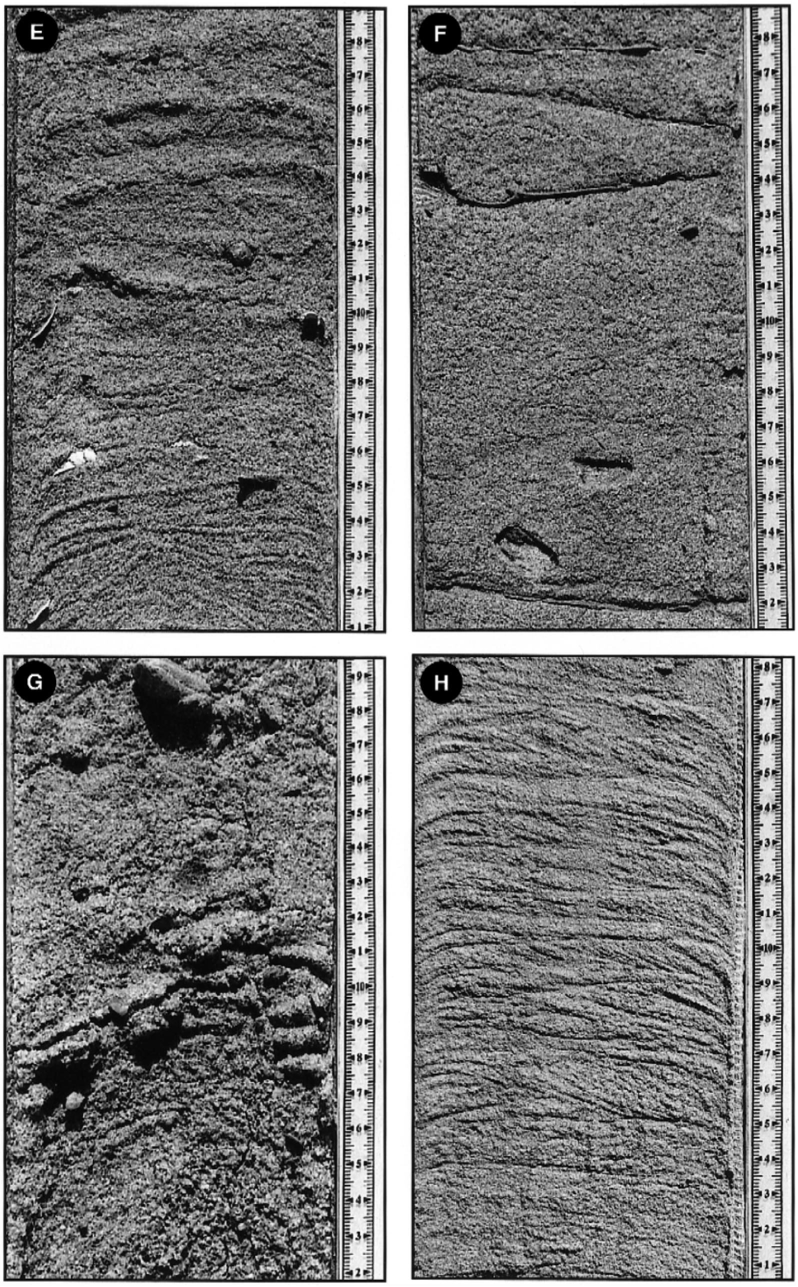

Fig. 5 (*continued*).

(De Gans and De Groot, 1995) propose that Rhine–Meuse deposits of the last glacials extend further north. Therefore, considering the extent of Rhine–Meuse strata along strike, our core site is located in a relatively central position.

Coring was preceded by a cone penetration test (CPT). The core was obtained using a mechanized bailer drilling unit of the Netherlands Institute of Applied Geoscience TNO (Oele et al., 1983), yielding an oriented, undisturbed core with 10 cm diameter. Core recovery was ~85%, but especially in the predominantly sandy and gravelly deposits of the Kreftenheye Formation (12.5–31.9 m) only ~30% of the sediments are completely undisturbed. In the overlying and underlying finer grained sediments this percentage is much higher. CPT data were used to locate marked facies transitions not recovered in the core. The core was split and photographed and one-half was used to produce lacquer peels (Fig. 5). The other half was kept in dark until samples had been taken for optically stimulated luminescence (OSL) dating. In addition, samples were taken from several of the muddy units for pollen and diatom analysis. Intervals rich in shells were sampled for malacological analysis.

4. Results

4.1. Sedimentology and stratigraphy

The Leidschendam section (Figs. 4 and 5) can be subdivided into three broad units (lithostratigraphy after Doppert et al., 1975), including the dominantly fine-grained Holocene Westland Formation (0–12.5 m) which overlies the coarse-grained Kreftenheye Formation (12.5–31.9 m). The lowermost unit, which is again finer grained, constitutes the upper part of the Kedichem Formation.

The Westland Formation consists of estuarine or tidal deposits, including channel, lagoonal (Fig. 5A) and tidal-flat facies. Intercalated in this succession is a freshwater marsh deposit. Cross-sections in the surrounding area (Van der Valk, 1996a) show that basal peats, that usually overlie the Kreftenheye Formation, have commonly been eroded during the initial stage of Holocene transgression. This is also the case at our coring site, where a basal peat is lacking, and an estuarine channel has eroded the top of the underlying Kreftenheye Formation (Fig. 5B).

The Kreftenheye Formation consists primarily of cross-bedded medium to coarse (sometimes gravelly) sands which are interpreted as fluvial Rhine and/or Meuse channel deposits (Fig. 5C). The uppermost part (12.5–14.0 m) consists of a number of alternating sand and clay beds interpreted as overbank deposits, possibly correlative with an overbank deposit that covers much of the Kreftenheye Formation throughout its distribution area (Wijchen Member; Törnqvist et al., 1994). The interval ~15–26 m is characterized by the widespread occurrence of reworked organic matter (Fig. 5C) and reworked marine shells (Fig. 5D and E). Faunal analysis (Table 1) revealed several taxa (*Abra ovata*, *Venerupis aurea senescens*) that are characteristic of the Eemian (Spaink, 1958). Similar facies have been recognized in the west-central Netherlands in the past and have been interpreted as marine, transgressive deposits of the Eem Formation (Schouwen Member; Doppert et al., 1975), an interpretation that is now undergoing revision as will be discussed below. At ~25 m depth in the Leidschendam core, a number of inclined mud drapes are present (Fig. 5F), which might suggest deposition in a tide-influenced environment (cf. Nio and Yang, 1991). However, such phenomena have been described from both Pleistocene (Makaske and Nap, 1995) and Holocene (Makaske, 1998: Fig. 5.15) Rhine and Meuse fluvial deposits. Nevertheless, their fossil content (see below) provides compelling evidence that these are estuarine deposits. The lowermost unit of the Kreftenheye Formation (26.2–31.9 m) is very coarse-grained (Fig. 5G) and differs from the overlying sediments because it essentially lacks reworked marine shells and organic matter. Its contact with the underlying Kedichem Formation is exceptionally distinct.

Table 1
Faunal composition of shell samples from the Kreftenheye Formation

Taxon	17.71–17.84 m	19.86–20.03 m	25.73–25.87 m
Scrobicularia plana	x	x	x
Mytilus edulis	x	x	x
Barnea candida	x	x	x
Macoma balthica	x	x	
Abra ovata	x	x	
Cerastoderma edule	x	x	
Trichia hispida	x		
Ostrea edulis	x		
Cerastoderma glaucum		x	
Bithynia tentaculata		x	
Venerupis aurea senescens		x	
Hydrobiidae		x	
Freshwater gastropods		x	
Lumbricus sp.			x
Ostracods			x

The Kedichem Formation contains a number of facies pointing to sedimentary environments dominated by fluvial deposition in smaller rivers, including channel, residual (abandoned) channel and overbank deposits. Channel deposits are primarily characterized by small-scale cross stratification (Fig. 5H). A massive silt bed at ~40 m depth is tentatively interpreted as a preserved loess deposit. The nature of the Kedichem Formation, as well as the sharp transition with the overlying succession, suggest that major changes in the palaeogeography must have occurred prior to deposition of the coarse-grained Kreftenheye Formation.

4.2. Microfossil analysis

The outcomes of diatom analysis are shown in Table 2; our ecological interpretation follows Vos and De Wolf (1993a,b). The diatom content of thin mud drapes in the basal part of the Westland Formation (9.70–10.92 m) is dominated by the marine-littoral species *Paralia sulcata*, *Cymatosira belgica* and *Thalassiosira decipiens*, as well as *Rhaphoneis amphiceros*, *R. minutissima* and *R. surirella*. *Cyclotella striata* suggests an estuarine environment, which is supported by the occurrence of the freshwater species *Cocconeis placentula* and *Rhoicosphenia curvata*. No diatoms were found in the overbank succession in the upper part of the Kreftenheye Formation; we attribute this to recycling of silica by vegetation. In the mud drapes at ~25 m depth the marine-littoral species *C. belgica*, *P. sulcata*, *R. amphiceros* and *T. decipiens* are abundant. The estuarine species *C. striata*, as well as the freshwater species *Meridion circulare* and *Epithemia zebra* var. *porcellus* indicate either the nearby presence of a river mouth, or deposition in an estuary. The presence of two aerophilous species (*Navicula hungarica* and *N. mutica* var. *nivalis*) points to the latter.

The same clayey sections were sampled for pollen analysis, providing palaeoclimatic and biostratigraphic evidence. The results (Table 3) indicate that the estuarine channel deposit of the Westland Formation belongs to the Holocene pollen zone III (Zagwijn, 1975; De Jong, 1982), ^{14}C dated at 5–8 ka. The uppermost part of the Kreftenheye Formation (12.5–14.5 m) contains a considerable proportion of reworked pollen (including Tertiary and Mesozoic taxa). In view of the dominance of *Pinus* and the relatively high proportion of non-arboreal pollen types (including ~5% *Artemisia*), a Late Weichselian age seems most probable. Hence, overbank deposition occurred under climatic conditions cooler than present. Of particular interest are the thin mud drapes around 25 m depth, dominated by arboreal pollen types (notably *Pinus*, *Quercus*, *Corylus* and *Picea*) which points to a relatively warm climate. Comparison with the biostratigraphy for the Eemian and Early Weichselian (Zagwijn, 1961, 1975) must be done with care, because only one spectrum has a pollen sum of 200 grains. We note striking similarities with the Early Weichselian interstadial pollen zones EW II, EW IV and EW VI, but an Eemian age based on the pollen data cannot be completely ruled out. The Early Weichselian Amersfoort, Brørup and Odderade Interstadials have been ^{14}C dated at 56–73 ka. Since dating occurred by means of the controversial thermal diffusion isotopic enrichment technique (Grootes, 1978) these ages may well be too young (see discussion below).

4.3. Optically stimulated luminescence dating

Optically stimulated luminescence (OSL) dating seeks to determine the last exposure of quartz and feldspar grains to (sun)light (Huntley et al., 1985; Aitken, 1998). The luminescence signal is reset by exposure to light and builds up after burial as a consequence of ionizing radiation from surrounding deposits and a small contribution of cosmic radiation. The OSL age is obtained by determination of the amount of ionizing radiation the sample has received since burial (= equivalent dose), divided by the amount of ionizing radiation the sample received per year (= dose rate).

The recently developed single-aliquot regenerative-dose (SAR) procedure (Murray and Roberts, 1998; Murray and Wintle, 2000) has improved precision relative to previously used OSL techniques and has potentially improved accuracy by allowing for sensitivity changes. The SAR technique has been shown to provide reliable ages for Holocene and Late Pleistocene samples (Strickertsson and Murray, 1999) and ages in accordance with multiple-aliquot and single-aliquot techniques over a time scale up to

Table 2
Diatom content (selected species) of mud drapes in the Leidschendam core

Taxon	9.70 m	9.90 m	10.92 m	24.79 m	24.93 m	25.04 m
Achnanthes delicatula	1–0[a]	0–1		2–0		
Achnanthes exigua			2–0			
Actinocyclus ehrenbergi	3–2	2–1	3–1		0–2	0–1
Actinocyclus normani		2–0	0–1			
Actinoptychus undulatus	1–0		0–2			
Amphora ovalis			3–0			
Amphora ovalis var. pediculus	1–0	2–0	2–0			
Aulacodiscus argus	0–1		0–1			0–2
Biddulphia rhombus	1–0	3–1	2–1		1–1	
Cocconeis pediculus	1–0	2–0	1–0			
Cocconeis placentula	1–1	12–0	3–0			
Cyclotella kutzingiana	2–0					
Cyclotella striata	5–3	5–0	2–1	4–3	7–1	2–0
Cymatopleura solea		1–2				
Cymatosira belgica	10–1	8–1	10–0	7–3	3–1	
Cymbella lacustris	2–0					
Diploneis aestuari	1–0	1–0	0–1			
Diploneis bombus				1–0		
Diploneis didyma	0–2	2–1	5–7		1–0	
Epithemia sorex		1–0				
Epithemia zebra var. porcellus		1–0		1–1	0–1	
Fragillaria pinnata			2–0			
Gomphonema angustata	0–1	1–1	2–0			
Melosira italica	1–0		1–0			
Melosira moniliformis	1–0		1–0			
Melosira westi				1–0		
Meridion circulare					0–1	
Navicula hungarica				2–0	0–1	
Navicula mutica var. nivalis				1–0		
Nitzschia angusta		3–1				
Nitzschia debilis	1–0	1–0	1–0			
Nitzschia navicularis			3–1	0–1	0–1	
Nitzschia panduriformis				1–0		
Nitzschia punctata				1–0		
Nitzschia sigma		0–2				
Nitzschia triblionella		3–1				
Opephora marty			3–0			
Paralia sulcata	9–0	6–1	20–2	8–1	4–0	0–1
Rhaphoneis amphiceros	8–2	6–6	4–2	7–2	1–1	0–4
Rhaphoneis minutissima	8–0	3–2	2–0	1–0	2–0	1–0
Rhaphoneis surirella	7–0	9–1		2–0		
Rhoicosphenia curvata	1–0	3–0				
Synedra tabulata var. faciculata					0–1	
Synedra ulna	0–2		0–1	1–0		
Thalassionema nitzschioides						1–0
Thalassiosira decipiens	7–2	3–2	4–2	5–0	6–0	

[a] Numbers of complete and broken specimens, respectively.

100 ka (Murray and Roberts, 1998). Investigation of fluvial deposits in the Rhine–Meuse Delta revealed good agreement between ^{14}C ages and quartz OSL ages obtained using the SAR protocol for samples ranging from 0.3 to 13 ka (Wallinga et al., 1999; Wallinga and Duller, 2000). These studies indicate

Table 3
Key pollen types in selected muddy intervals of the Leidschendam core, expressed as percentages. All pollen types listed are included in the pollen sum

Pollen type	10.92–11.97 m	12.50–14.50 m	24.79–25.04 m
AP/NAP[a]	80/20	55/45	85/15
Alnus	~ 30	~ 10	2
Corylus	~ 20	~ 5	6
Quercus	~ 15	~ 3	12
Ulmus	~ 5	~ 2	0.5
Carpinus		~ 1	0.5
Betula	~ 3	~ 10	1
Pinus	~ 5	~ 30	56
Picea		~ 3	5
Abies		~ 1	1
Gramineae	~ 10	~ 20	3
Cyperaceae	~ 5	~ 10	8
Ericales		~ 3	1
Artemisia	~ 1	~ 5	

[a]AP = arboreal pollen; NAP = non-arboreal pollen.

that the restricted light intensity and light spectrum in turbid river environments in this area is sufficient to reset the luminescence signal prior to deposition. Isothermal decay characteristics of OSL in quartz show that long-term stability of the quartz OSL signal allows dating up to a million years (Murray and Wintle, 1999), but saturation of the OSL signal commonly limits OSL dating to the last 100 ka. Infrared-stimulated luminescence (IRSL) dating of feldspar has the advantage that the IRSL signal saturates less readily. However, in the study of Holocene and Late Weichselian fluvial deposits in the Rhine–Meuse Delta, IRSL ages underestimated the true age by about 35% (Wallinga et al., 1999; Wallinga and Duller, 2000). Moreover, there are doubts about the long-term stability of the IRSL signal (e.g., Fuller et al., 1996; Wintle, 1997). Considering these complications we preferred to use OSL dating of quartz where possible.

We collected 20-cm-thick samples preferentially from undisturbed parts of the core and dated quartz separates from 12 samples. The quartz equivalent dose was obtained with the latest single-aliquot regenerative-dose (SAR) protocol (Murray and Wintle, 2000). All measurements were made with a Risø TL/OSL reader using blue light emitting diodes for stimulation (Bøtter-Jensen et al., 1999). The dose rate for the samples was obtained by laboratory measurement using high-resolution gamma-ray spectrometry. It is highly likely that the deposits have been saturated with water throughout their lifetimes, which diminishes the dose rate. The contribution of

Table 4
OSL ages from the Leidschendam core

Sample number	Depth (m)	Analyzed grain size (μm)	Dose rate[a] (Gy/kyr)	Equivalent dose[b] (Gy)	Age (ka)
I	14.85	180–212	1.11 ± 0.06	53.5 ± 2.7	48 ± 4
II	16.90	180–212	0.99 ± 0.05	54.2 ± 5.4	55 ± 6
III	19.35	180–212	0.78 ± 0.05	64.0 ± 5.9	82 ± 9
IV	21.25	180–212	1.29 ± 0.06	92.1 ± 6.9	71 ± 6
V	22.25	180–212	0.92 ± 0.05	56.2 ± 3.3	61 ± 5
VI	24.95	180–212	1.13 ± 0.05	65.5 ± 2.7	58 ± 4
VII	25.85	180–250	0.86 ± 0.04	103.5 ± 5.9	120 ± 9
VIII	26.75	180–250	0.79 ± 0.05	123.9 ± 6.9	158 ± 13
IX	28.30	180–212	0.74 ± 0.04	107.0 ± 10.3	145 ± 16
X	31.50	180–212	0.87 ± 0.04	155.5 ± 23.3	180 ± 28
XI	37.70	90–180	1.81 ± 0.17[c]	677.0 ± 24.5[d]	$> 374 \pm 38$[d]
XII	45.70	180–212	2.50 ± 0.13[c]	920.3 ± 33.0[d]	$> 368 \pm 23$[d]

[a]All dose rates calculated for a water content of 20 ± 2% by weight, based on a porosity of 34 ± 3% (Weerts, 1996: fig. 5.5), assuming a density of 2.5 ± 0.1 for the solid fraction. Contributions from internal uranium and thorium based on values reported by Mejdahl (1987) and from cosmic radiation are included.

[b]Uncertainty is the standard error of equivalent doses determined from six aliquots.

[c]Dose rate includes internal dose from potassium in feldspar grains.

[d]Equivalent dose and age obtained by IRSL of potassium-rich feldspar separates.

cosmic radiation to the dose rate was calculated assuming a constant accumulation rate from the time of deposition to the present. The extremely low dose rate for our samples allows us to go further back in time than usually possible for quartz OSL dating.

OSL ages are presented in Table 4 with uncertainties representing 1σ-confidence intervals, including uncertainties in both the equivalent dose determination and the dose rate determination. Samples I to VI are all of Weichselian age, with the youngest ages for the uppermost two samples, whereas samples III to VI exhibit a slightly reversed chronology (Fig. 6). The somewhat higher age of sample III is possibly due to poor bleaching. On the other hand, the relatively young age of sample VI might be caused by an overestimation of the dose rate due to oversampling of mud drapes for the dose rate estimation. Sample VII has an age of 120 $\pm$ 9 ka, suggesting an Eemian age. The ages obtained on samples VIII to X should be interpreted with caution since their OSL signal is close to saturation; consequently, small errors in the sensitivity correction will lead to a large error in the age estimate. Nevertheless, the OSL ages are consistent and considerably older than the overlying samples, pointing to a Saalian age. The quartz OSL signal of samples XI and XII was saturated and therefore unsuitable for dating. As an alternative we dated potassium-rich feldspar separates from these

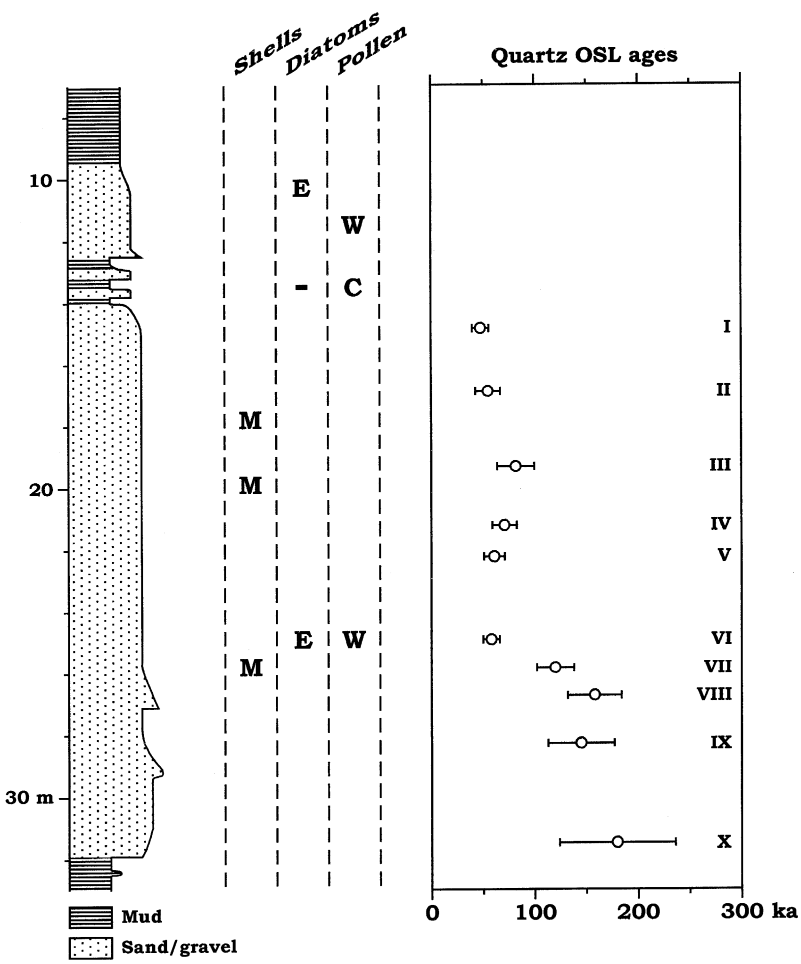

Fig. 6. Generalized sedimentary log of the Kreftenheye Formation in the Leidschendam core with palaeoecological evidence and OSL ages. Error bars represent 2σ-confidence intervals. M = marine, E = estuarine, – = no diatoms, W = warm, C = cool.

samples using a newly developed SAR protocol for IRSL dating of feldspar (Wallinga et al., 2000). The internal potassium content of the feldspar separates was determined using a Risø multicounter system (Bøtter-Jensen and Mejdahl, 1985) in order to calculate the internal dose rate. In view of the problems with IRSL dating described above, the results should be interpreted as minimum ages; the true age is most probably far older than the indicated 370 ka.

5. Discussion

5.1. Palaeogeography

The sedimentary succession in the Leidschendam core (Fig. 4) demonstrates that only during the later part of the Pleistocene large channel belts were present in this area (Kreftenheye Formation). Prior to that, the area was located in a more marginal part of the alluvial plain of the trunk fluvial systems, dominated by smaller (primarily tributary) channel belts and overbank aggradation, presumably alternating with loess deposition (Kedichem Formation). It has been demonstrated elsewhere in The Netherlands that the Kedichem Formation is of Matuyama-age reversed magnetic polarity (Zagwijn et al., 1971; Kasse, 1996). Assuming that the upper boundary of this lithostratigraphic unit is time-correlative throughout the country, this implies an age older than 778 ka (Tauxe et al., 1996).

Our OSL data (Table 4) demonstrate a large break in sedimentation at the Kedichem–Kreftenheye transition. The same unconformity was described from the area south of Leidschendam by Van Staalduinen (1979: p. 29). Zagwijn (1989) reported two widespread unconformities throughout much of the southern Netherlands, with ages estimated around 450 and 900 ka. These unconformities appear to have merged together in the west-central Netherlands. The Leidschendam data are therefore consistent with palaeogeographic reconstructions of Zagwijn (1974) of a Rhine–Meuse system draining to the northwest prior to the Elsterian, and predominantly towards the west from the Saalian onward (Fig. 3).

Since the Rhine–Meuse system was deflected towards the west at the culmination of the Saalian glaciation (Van de Meene and Zagwijn, 1978), the basal coarse-grained trunk channel deposits (Kreftenheye Formation) in the Leidschendam core are most likely of Saalian age. This is supported by OSL ages in the range 115–235 ka (note that we have inferred age ranges from the OSL measurements based on 2σ-confidence intervals) for the lowermost unit of the Kreftenheye Formation (Fig. 6). During the subsequent time interval (Eemian and Early Weichselian), only the Meuse drained towards the west, and it is therefore likely, in view of the limited sediment supply by this smaller river, that during the Eemian transgression the shoreline shifted further inland than during the Holocene.

The estuarine deposits encountered at ~ 25 m depth reveal OSL ages of 58 ± 4 and 120 ± 9 ka (samples VI and VII; Table 4). Although sample VII suggests oxygen-isotope stage (OIS) 5e (Eemian) deposits, the possibility of an overestimated age due to poor bleaching must be considered. This could be the result of a limited transport distance of basal channel deposits in a turbid estuarine environment. The age of sample VI is considerably younger than what would be expected for OIS 5e highstand deposits. This is supported by the pollen spectrum from mud drapes in this unit (Table 3), suggesting an Early Weichselian (OIS 5a–5d) age. We therefore assume that preserved estuarine deposits at this site were primarily formed during OIS 5a, the last highstand prior to a major RSL fall associated with the onset of the Middle Weichselian (OIS 4). Eustatic sea-level curves inferred from oxygen-isotope data in deep-sea sediments (Shackleton, 1987; recently confirmed by U-series dating of corals by Chappell et al., 1996) demonstrate an OIS 5a highstand around 80 ka (Fig. 7). This highstand has been documented worldwide, for instance in Barbados (-15 ± 3 m, 82 ka; Matthews, 1973), Haiti (-13 ± 3 m, 81 ± 3 ka; Dodge et al., 1983) and Huon Peninsula, New Guinea (-19 ± 5 m, 81 ka; Chappell and Shackleton, 1986). Recent work in tectonically stable areas (Ludwig et al., 1996) even suggests that the ~ 80 ka highstand may have been close to present sea level, whereas others identify this highstand level at -9 m (Toscano and Lundberg, 1999). Since the variability amongst these sites clearly demonstrates the role of differential isostatic, tectonic and possibly additional local effects, application of these data to the North Sea

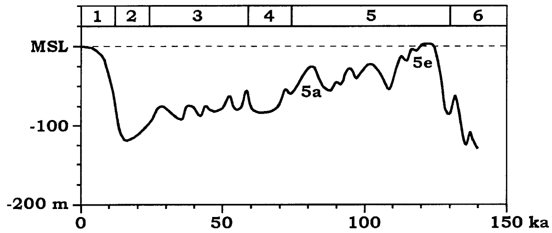

Fig. 7. Eustatic sea-level curve for the last 140 ka (oxygen-isotope stages 1–6), generalized after Shackleton (1987). MSL = mean sea level.

Basin should be done with care. Nevertheless, it seems fair to assume that this RSL highstand caused a significant transgression in the west-central Netherlands around 80 ka. Although sample VI yields a younger age, a marine transgression during OIS 4 or on the onset of OIS 3 must be considered a highly improbable scenario.

As indicated in Fig. 4, the transition of estuarine to overlying fluvial deposits is difficult to determine with accuracy. The sediments with ages of 48 ± 4 and 55 ± 6 ka (above ~ 18 m depth; samples I and II) are very likely of fluvial origin (OIS 3 and 4). Direct indications for tidal influence do not occur above ~ 24 m depth, but our OSL ages of samples III to V from 18–24 m depth do not exclude that these deposits are also estuarine. These sediments contain an abundance of marine shells (Table 1); this, however, does not necessarily indicate deposition in a saltwater environment. As originally hypothesized by Bennema and Pons (1952) and recently confirmed by Bosch and Kok (1994: pp. 55–56, 61) and De Gans and De Groot (1995), Weichselian fluvial channel deposits of the Kreftenheye Formation in the west-central Netherlands contain considerable amounts of reworked marine shells (Fig. 8). This is attributed to erosion and redeposition of Eemian or Early Weichselian highstand strata. Similar observations have been made offshore (Cameron et al., 1984; Laban et al., 1992). OSL ages (Table 4, Fig. 6) indicate that these shell-containing channel deposits were primarily formed within the time interval 80–40 ka.

Since the floodplain in the Rhine–Meuse palaeovalley (Fig. 1B) must have been active during the later part of the Weichselian (Late Pleniglacial and Late Weichselian; < 30 ka), the Rhine–Meuse system appears to have gradually shifted its position from north to south along the present coast (cf. De Gans and De Groot, 1995; Fig. 8). Törnqvist (1998) speculated on the presence of a slightly elevated

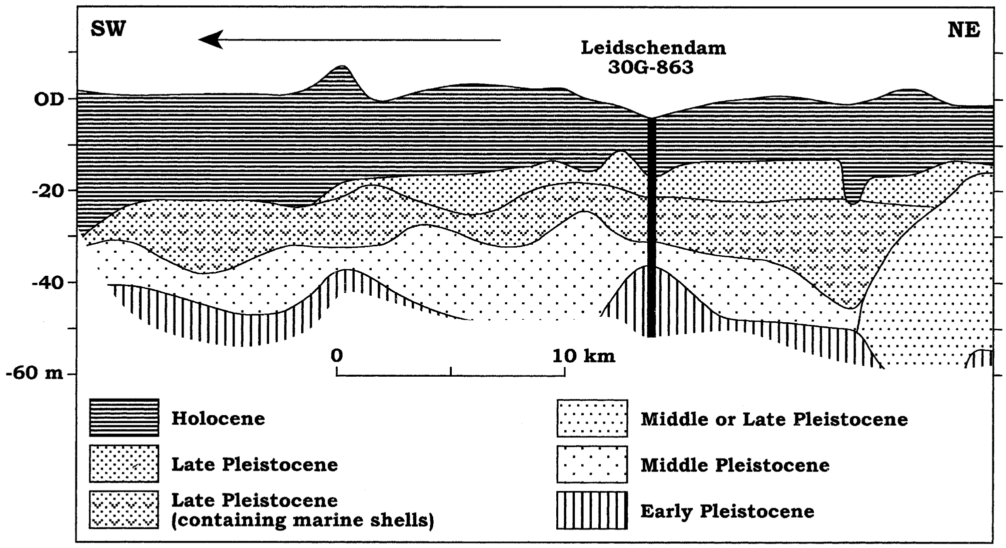

Fig. 8. Strike-oriented cross section with chronostratigraphic units near the present-day Dutch shoreline (for location see Fig. 1), based on 20 boreholes of 30–60 m depth. Arrow indicates presumed southward migration of the Rhine–Meuse system during the Weichselian. Note that Middle and Late Pleistocene Rhine–Meuse strata extend well north of the Leidschendam core. OD = Dutch Ordnance Datum.

terrace remnant of possible Early or Middle Pleniglacial age further updip at the northern margin of the Rhine–Meuse palaeovalley, which might point in the same direction. Although these observations are preliminary, the indications for such a migration of the Rhine–Meuse system during the Weichselian may be related to differential glacio-hydro-isostatic movements. Such crustal movements have been analyzed by means of glacial rebound models for the period of deglaciation since the Last Glacial Maximum. Lambeck (1995) and Kooi et al. (1998) demonstrate an increasing rate of isostatic subsidence in a SE-NW direction throughout The Netherlands during the Holocene, continuing to the present day. Assuming that during the period of build-up of the Weichselian ice sheets the situation was reversed due to the growth of a forebulge (with higher rates of growth towards the northwest), this may have contributed to a southward migration of the Rhine–Meuse system.

It has been argued (Van de Meene and Zagwijn, 1978) that the Rhine reoccupied its course through the central Netherlands from the Middle Weichselian onwards (Fig. 3D and E). Although it is still uncertain when exactly this took place, we tentatively propose that this might be a result of capture by the Meuse, that occupied this area throughout the last glacio-eustatic cycle, by means of headward erosion associated with RSL fall (see below). In addition, differential glacio-isostatic movements, as suggested above, may have reduced the gradient of the northwesterly flowing Rhine in response to Weichselian ice-sheet growth.

5.2. Fluvial incision in response to relative sea-level fall

The stratigraphic evolution of the Rhine–Meuse system since the peak of the Saalian glaciation (OIS 6), as far as can be inferred from our core (Figs. 4 and 6) and cross-section (Fig. 8), is schematically illustrated in Fig. 9, demonstrating alternating construction and degradation of a highstand 'coastal prism' (*sensu* Talling, 1998). It should be kept in mind that this representation is a considerable sim-

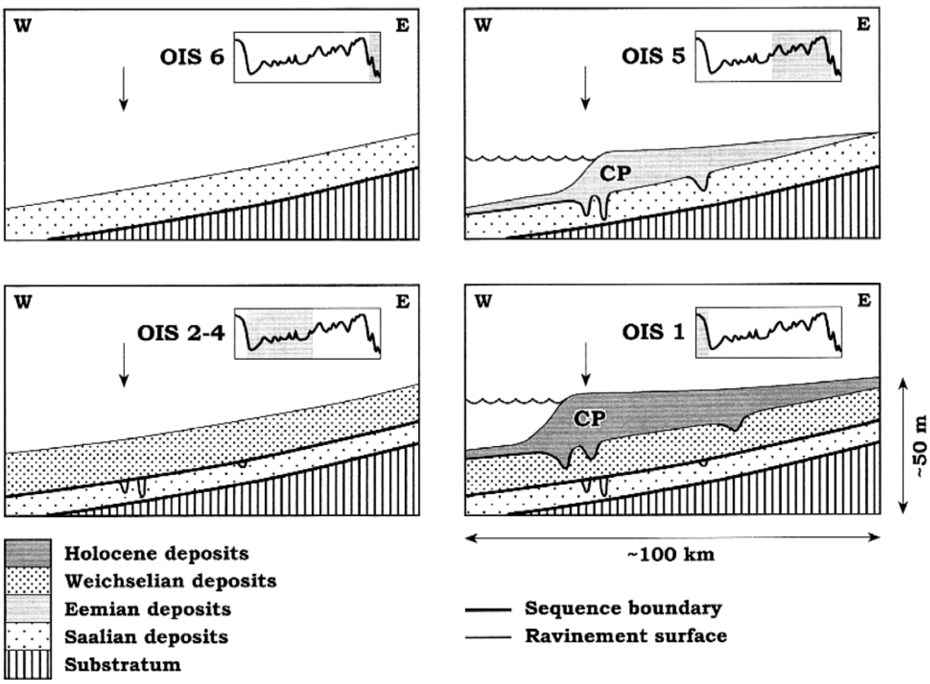

Fig. 9. Schematic dip-oriented section illustrating the evolution of the Rhine–Meuse system in the west-central Netherlands during the last glacio-eustatic cycles. Arrow indicates the position of the Leidschendam core. Horizontal and vertical scales give an impression of dimensions and are not meant to be accurate. Inset shows the eustatic sea-level curve of Fig. 7 and the time interval represented by each cartoon. Note the occurrence of both wave, tidal and fluvial ravinement surfaces. OIS = oxygen-isotope stage, CP = coastal prism.

plification of reality. For instance, our data, along with the global eustatic sea-level curve (Fig. 7), highlight the complexity of the evolution of this area during the Eemian and Early Weichselian. In view of the large amplitude of RSL fluctuations during OIS 5 it can be assumed that construction and degradation of a coastal prism occurred several times during this ~50 ka period (cf. Anderson et al., 1996). In the Leidschendam core primarily sediments belonging to the youngest of these coastal prisms (OIS 5a) are encountered.

Our data provide evidence for significant fluvial erosion associated with the glacio-eustatically controlled Weichselian (OIS 4) RSL fall, and we argue that incision was maximal in this particular area, compared to areas further updip and downdip (Fig. 9). This idea hinges on the fact that our study area is located near the edge of the coastal prism. Earlier work on the Rhine–Meuse system by Zonneveld (1957) already recognized that such a coastal prism is likely to be eroded at the onset of RSL fall during glacials, due to the steeper slope of the shoreface.

Despite the partial preservation of relatively deeply scoured estuarine channel deposits of predominantly Early Weichselian (OIS 5a) age at the Leidschendam coring site, most transgressive and highstand deposits were eroded during the RSL fall associated with OIS 4. As indicated above, the exact nature of the Eemian/Early Weichselian (OIS 5) coastal prisms can only be speculated on. Nevertheless, in view of the fact that the Meuse occupied roughly the same area as it does now (Zagwijn, 1974; Van de Meene and Zagwijn, 1978), such coastal prisms must have existed, although they were probably smaller than their Holocene Rhine–Meuse counterpart. According to Zagwijn (1974), the Leidschendam site may have been located just offshore from the Eemian highstand shoreline. In the Gelderse Vallei (Fig. 1A), where fluvial influence has been essentially absent and the Eemian transgressive succession is well preserved, the altitude of the Eemian RSL highstand is now recorded at 8 m below Dutch Ordnance Datum (OD) (Zagwijn, 1983). Assuming a sequence boundary in the Leidschendam core at 25 m below OD (~21 m below the surface; see below and Fig. 10), this implies that ~17 m of sediments have been eroded. Presently available data from the surrounding area (Fig. 8) suggest that the base of

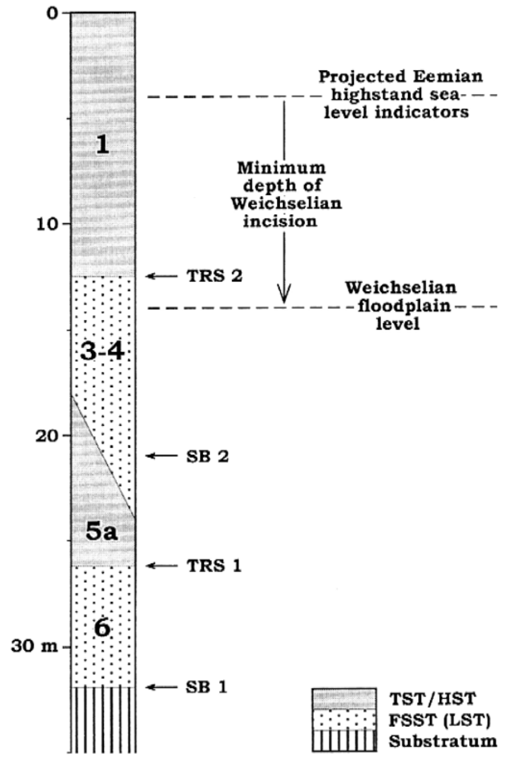

Fig. 10. Sequence-stratigraphic interpretation of the Leidschendam core. Numbers refer to oxygen-isotope stages that are primarily represented in the core. SB = sequence boundary, TRS = tidal ravinement surface, TST = transgressive systems tract, HST = highstand systems tract, FSST = falling-stage systems tract, LST = lowstand systems tract.

Late Pleistocene deposits containing marine shells usually is found at depths down to 45 m below OD. Hence, the amount of erosion may have been larger elsewhere. On the other hand, it must be stressed that we assume that tectonic subsidence rates near Leidschendam have been comparable to those in the Gelderse Vallei, which is by no means certain (cf. Kooi et al., 1998). Nevertheless, the fact that the Early Pleistocene Kedichem Formation is encountered at rather shallow depth in our study area (Fig. 8) lends support to our argument.

In view of the size of the Rhine–Meuse system (maximum depth in present-day channels about 10 m), we believe that ~17 m of erosion cannot be explained solely by autogenic fluvial scour unrelated to RSL fall (cf. Salter, 1993; Best and Ashworth, 1997), and was, at least partly, a result of RSL fall associated with the Weichselian glaciation. This is clearly indicated by the Weichselian floodplain level (overbank deposits; Fig. 4) encountered more than 10 m below the Eemian RSL highstand level (Fig. 10). Our OSL ages show that incision occurred during the initial stage of RSL fall, which exposed the relatively steep shoreface and caused headward erosion of the coastal prism (cf. Talling, 1998). Studies of the evolution of Holocene shoreface (upper 10–20 m) gradients along the Dutch west coast show a tendency of progressive steepening with values typically ranging from 0.001 to 0.01 (measured from Van der Valk, 1996b: Fig. 31). Values for the updip Holocene deltaic plain (Van Dijk et al., 1991; Törnqvist, 1993) are two orders of magnitude lower. Assuming roughly similar conditions during OIS 5 highstands, it seems likely that ensuing RSL falls must have caused fluvial incision.

As has been argued by Posamentier et al. (1992) and Talling (1998), incision was probably most pronounced near the highstand shoreline, and may well have been much more limited farther downdip on the southern North Sea shelf. Offshore mapping (Laban et al., 1992) demonstrates that the Kreftenheye Formation overlies the up to 20 m thick marine Eem Formation in the southern North Sea, whereas it is erosively inset into the Eem Formation closer to the coast and our study area. These stratigraphic relationships indicate decreasing incision in a downstream direction. Both formations terminate farther towards the southwest due to the fact that the Rhine–Meuse system leaves the North Sea Basin and crosses an area (Strait of Dover) of crustal stability or slight uplift (Bridgland and D'Olier, 1995). Uplift may have been amplified by hydro-isostatic rebound (cf. Lambeck, 1995), which has been put forward as a possibly important factor reducing shelf gradients during RSL lowstands (Posamentier et al., 1992). The downdip termination of the Kreftenheye Formation may also be partly a result of marine erosion associated with the Holocene transgression, as suggested by model simulations (Van der Molen and Van Dijck, 2000).

The idea that fluvial systems need not incise a low-gradient shelf despite considerable RSL fall has been proposed by several workers (e.g., Summerfield, 1985; Miall, 1991; Posamentier et al., 1992; Schumm, 1993; Woolfe et al., 1998). In view of the large distance from the highstand shoreline to the shelf break in the Atlantic Ocean ($\sim$1000 km), the Rhine–Meuse system is an exceptional example of a fluvial system bordered by a low-gradient continental shelf. Nevertheless, we observe that substantial incision has taken place locally. Our data support the concept that the amount of incision may be particularly pronounced in the area of the pre-existing coastal prism and decreases downstream, a phenomenon referred to as 'local incision' by Posamentier et al. (1992). Such relationships may also be inferred from outcrop data. For instance, Holbrook (1996) discussed a smooth and subtle Cretaceous sequence boundary overlain by a relatively thin fluvial sheet sandstone, but correlative to palaeovalley fills updip. Since model calculations by Lambeck (1995) suggest that RSL never dropped below the shelf edge during the Last Glacial Maximum, incision may have occurred exclusively at the location of the previous highstand coastal prism (cf. Talling, 1998), although some bedrock incision may have taken place in the Strait of Dover.

In summary, we conclude that in settings with a low-gradient shelf, fluvial incision due to RSL fall is particularly pronounced in the thickest part of the coastal prism (i.e., near the highstand shoreline) and decreases both updip and downdip. These observations demonstrate that in much previous modelling work (both experimental and numerical) basin geometries have been oversimplified, since the important coastal prism is typically not taken into account.

5.3. Sequence-stratigraphic implications

The Rhine–Meuse system in the west-central Netherlands has formed a compound palaeovalley fill (cf. Zaitlin et al., 1994) with two sequence boundaries. In addition, tidal ravinement surfaces (Allen and Posamentier, 1993) constitute conspicuous elements at the site studied (Fig. 9). An interpretation of the observed sedimentary succession and key stratigraphic surfaces is provided in Fig. 10. Compared to the widely used model for palaeovalley fills of Zaitlin et al. (1994) the following comments can be made. Despite the location of the site near the present-day, highstand shoreline (i.e., at the distal side of Zaitlin et al.'s 'segment 2'), the proportion of fluvial deposits is relatively high. Indeed, it can be argued that the preservation potential of the Holocene transgressive/highstand coastal prism is small, and that only the lowermost, if any, estuarine channel deposits may survive erosion during a future RSL fall. Clearly, this only applies to the palaeovalley; adjacent to it, transgressive and highstand strata may have a much better chance of survival, at least in the short term (cf. Blum and Price, 1998). Glacial-age fluvial deposits constitute a considerable component of the preserved sedimentary succession, and we propose that deposits formed during phases of net incision have a higher preservation potential. An additional factor is the high sediment supply characteristic of periglacial conditions. Willis (1997) also argued for a dominance of the fluvial component in palaeovalley fills under conditions of high sediment supply. His study of vertically stacked paleovalley fills underlines the high proportion of fluvial strata when sediment supply and accommodation are reasonably balanced.

Basal fluvial deposits in palaeovalley fills have often been connected to the time interval near RSL lowstand and subsequent initial RSL rise (e.g., Aubrey, 1989; Wright and Marriott, 1993; Shanley and McCabe, 1994; Zaitlin et al., 1994; Feldman et al. 1995; Willis, 1997; Zhang et al., 1997; Ethridge et al., 1998). However, our OSL ages suggest that substantial glacial-age fluvial sediments were deposited during RSL fall, comparable to inferences recently made for Texas Gulf Coast rivers, where alternating terrace formation and incision was an important process during the last RSL fall (Blum et al., 1995). Hence, our findings lend support to the idea of substantial fluvial deposition despite net erosion during RSL fall as proposed by Blum and Price (1998) and Blum (1999), a phenomenon that has also been observed in outcrops (Shanley and McCabe, 1993: pp. 33–34). Strikingly similar inferences have recently been made for the Po coastal plain, Italy (Amorosi et al., 1999). Obviously, our evidence also has implications for the chronostratigraphic nature of sequence boundaries, which are much more complex than first-generation sequence-stratigraphic models predict (cf. Blum, 1994), and were formed, for a major part, during the falling limb of the RSL curve. In addition, this implies that the time gap represented by sequence boundaries can be very small. In our case, numerical ages are unable to resolve the boundary between the falling-stage systems tract (FSST) and the underlying TST/HST, separated by perhaps only a few thousand years, despite the ∼100-kyr period of glacio-eustatic cycles. Compared to the model of Pleistocene stacking patterns of Rhine–Meuse deposits proposed by Törnqvist (1995), the Leidschendam data demonstrate that the situation is considerably more complicated, since (1) preserved strata, at least at the coring site, appear to represent FSSTs rather than LSTs, and (2) basal estuarine channel deposits belonging to the TST/HST can locally be preserved.

We are unable to pinpoint the exact position of the sequence boundary associated with the last glacio-eustatic cycle in the Leidschendam core (sequence boundary 2; Figs. 4 and 10). Amorosi et al. (1999) encountered similar difficulties in identifying sequence boundaries in such settings. As pointed out by Nummedal and Swift (1987) and Zaitlin et al. (1994), sequence boundaries and tidal ravinement surfaces may easily be confused because they share several characteristics. Our OSL ages demonstrate that tidal ravinement surface 1 at ∼26 m depth represents much more time than the overlying sequence boundary 2 (located between 18 and 24 m depth). Nevertheless, data from the surrounding area (Van der Valk, 1996a) indicate that tidal ravinement surfaces like those encountered in the Leidschendam core usually have a limited areal extent. In fact, in much of the Rhine-Meuse palaeovalley the transgressive surface is represented by a conspicuous basal peat bed, that is locally eroded, as is the case at our coring site. Alternative sequence-stratigraphic schemes have been proposed where a ‘forced regressive wedge systems tract’ is underlain by a ‘basal surface of forced regression’ rather than a sequence boundary in the traditional sense, and overlain by a sequence boundary (Hunt and Tucker, 1992). Future work will address whether such alternative concepts are more suitable in our study area, but we have currently no indications that a surface overlying our FSST is easier to identify.

6. Conclusions

This study is based on a multidisciplinary analysis of a core in a compound palaeovalley fill near the present Dutch shoreline, employing a combination of techniques (sedimentological and stratigraphic analysis, palaeoecological analysis based on shells, diatoms and pollen, as well as OSL dating) that has so far rarely been integrated. Although additional cores are essential to gain understanding of spatial variability, we offer the following first conclusions of this ongoing project:

- Construction and degradation of coastal prisms is likely to have occurred repeatedly during alternating RSL highstands and lowstands of OIS 5, indicating much more complexity than traditional glacial–interglacial subdivisions may suggest.
- Fluvial incision near the edge of the highstand coastal prism due to RSL fall during OIS 4 was at least 10 m (excluding autogenic fluvial scour, estimated at <10 m). Comparison with offshore data suggests that incision due to RSL fall decreases downstream. Our results highlight the importance of incorporating coastal prism construction and degradation in stratigraphic models.
- Coastal prism degradation takes place during the initial stages of RSL fall when the relatively steep shoreface is exposed. Although net erosion occurs, fluvial deposition continues and leads to the formation of a falling-stage systems tract.
- In Quaternary glacio-eustatically controlled coastal sequences, falling-stage (and presumably also lowstand) systems tracts have the highest preservation potential. This holds especially for laterally confined systems in settings with relatively low subsidence rates. Transgressive and highstand systems tracts may be only locally preserved, particularly in areas of deep estuarine scour.
- Sequence boundaries that form under such conditions can be relatively undistinct chronologically and may represent time gaps of only a few thousand years, despite dominant 100-kyr RSL cycles. Obviously, the situation would be different if intervening transgressive and highstand systems tracts are not preserved.
- Despite their local nature, tidal ravinement surfaces in such settings may be more conspicuous than sequence boundaries and represent considerably longer time gaps.

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References

Aitken, M.J., 1998. An Introduction to Optical Dating. The Dating of Quaternary Sediments by the Use of Photon-Stimulated Luminescence. Oxford Univ. Press, Oxford, 267 pp.

Allen, G.P., Posamentier, H.W., 1993. Sequence stratigraphy and facies model of an incised valley fill: the Gironde estuary, France. J. Sediment. Petrol. 63, 378–391.

Amorosi, A., Colalongo, M.L., Fusco, F., Pasini, G., Fiorini, F., 1999. Glacio-eustatic control of continental-shallow marine cyclicity from Late Quaternary deposits of the southeastern Po Plain, northern Italy. Quat. Res. 52, 1–13.

Anderson, J.B., Abdulah, K., Sarzalejo, S., Siringan, F., Thomas, M.A., 1996. Late Quaternary sedimentation and high-resolution sequence stratigraphy of the east Texas shelf. In: De Batist, M., Jacobs, P. (Eds.), Geology of Siliciclastic Shelf Seas. Geol. Soc. Spec. Publ., vol. 117, pp. 95–124.

Aubrey, W.M., 1989. Mid-Cretaceous alluvial-plain incision related to eustasy, southeastern Colorado Plateau. Geol. Soc. Am. Bull. 101, 443–449.

Bennema, J., Pons, L.J., 1952. Donken, fluviatiel Laagterras en Eemzee-afzettingen in het westelijk gebied van de grote rivieren. Boor en Spade 5, 126–137.

Best, J.L., Ashworth, P.J., 1997. Scour in large braided rivers and the recognition of sequence stratigraphic boundaries. Nature 387, 275–277.

Blum, M.D., 1994. Genesis and architecture of incised valley fill sequences: a late Quaternary example from the Colorado

River, Gulf Coastal Plain of Texas. In: Weimer, P., Posamentier, H.W. (Eds.), Siliciclastic Sequence Stratigraphy. Recent Developments and Applications. Am. Assoc. Pet. Geol. Mem., vol. 58, pp. 259–283.

Blum, M.D., 1999. Importance of falling stage fluvial deposition: Quaternary examples from the Texas Gulf Coastal Plain and Western Europe. Abstr. Am. Assoc. Pet. Geol. Ann. Conv., San Antonio, Texas, pp. A13–A14.

Blum, M.D., Price, D.M., 1998. Quaternary alluvial plain construction in response to glacio-eustatic and climatic controls, Texas Gulf Coastal Plain. In: Shanley, K.W., McCabe, P.J. (Eds.), Relative Role of Eustasy, Climate, and Tectonism in Continental Rocks. Soc. Econ. Paleontol. Mineral. Spec. Publ., vol. 59, pp. 31–48.

Blum, M.D., Törnqvist, T.E., 2000. Fluvial responses to climate and sea-level change: a review and look forward. Sedimentology 47 (Suppl. 1), 2–48.

Blum, M.D., Morton, R.A., Durbin, J.M., 1995. "Deweyville" terraces and deposits of the Texas Gulf Coastal Plain. Gulf Coast Assoc. Geol. Soc. Trans. 45, 53–60.

Bosch, J.H.A., Kok, H., 1994. Toelichtingen bij de Geologische Kaart van Nederland 1:50.000. Blad Gorinchem West (38 W). Rijks Geologische Dienst, Haarlem, 159 pp.

Bøtter-Jensen, L., Mejdahl, V., 1985. Determination of potassium feldspars by beta counting using a GM multicounter system. Nucl. Tracks Radiat. Meas. 10, 663–666.

Bøtter-Jensen, L., Mejdahl, V., Murray, A.S., 1999. New light on OSL. Quat. Geochronol. (Quat. Sci. Rev.) 18, 303–309.

Bridgland, D.R., D'Olier, B., 1995. The Pleistocene evolution of the Thames and Rhine drainage systems in the southern North Sea Basin. In: Preece, R.C. (Ed.), Island Britain: A Quaternary Perspective. Geol. Soc. Spec. Publ., vol. 96, pp. 27–45.

Bridgland, D.R., Gibbard, P.L., 1997. Quaternary river diversions in the London Basin and the eastern English Channel. Géogr. Phys. Quat. 51, 337–346.

Cameron, T.D.J., Laban, C., Schüttenhelm, R.T.E., 1984. Flemish Bight Sheet 52°N–02°E. 1:250 000 Series. Quaternary Geology. British Geological Survey / Rijks Geologische Dienst, Nottingham / Haarlem.

Carter, R.M., 1998. Will the real sequence stratigraphy please stand up: insights from the Plio–Pleistocene. Sediment. Geol. 122, 1–3.

Chappell, J., Shackleton, N.J., 1986. Oxygen isotopes and sea level. Nature 324, 137–140.

Chappell, J., Omura, A., Esat, T., McCulloch, M., Pandolfi, J., Ota, Y., Pillans, B., 1996. Reconciliation of late Quaternary sea levels derived from coral terraces at Huon Peninsula with deep sea oxygen isotope records. Earth Planet. Sci. Lett. 141, 227–236.

Colman, S.M., Mixon, R.B., 1988. The record of major Quaternary sea-level changes in a large coastal plain estuary, Chesapeake Bay, Eastern United States. Palaeogeogr., Palaeoclimatol., Palaeoecol. 68, 99–112.

Dalrymple, R.W., Boyd, R., Zaitlin, B.A. (Eds.), 1994a. Incised-Valley Systems: Origin and Sedimentary Sequences. Soc. Econ. Paleontol. Mineral. Spec. Publ., vol. 51, pp. 1–391.

Dalrymple, R.W., Boyd, R., Zaitlin, B.A., 1994b. History of research, types and internal organization of incised-valley systems: introduction to the volume. In: Dalrymple, R.W., Boyd, R., Zaitlin, B.A. (Eds.), Incised-Valley Systems: Origin and Sedimentary Sequences. Soc. Econ. Paleontol. Mineral. Spec. Publ., vol. 51, pp. 3–10.

De Gans, W., De Groot, T., 1995. The lower Rijn delta. In: Schirmer, W. (Ed.), Quaternary Field Trips in Central Europe. Friedrich Pfeil, München, pp. 550–557.

De Gans, W., Van Gijssel, K., 1996. The Late Weichselian morphology of the Netherlands and its influence on the Holocene coastal development. Meded. Rijks Geol. Dienst 57, 11–25.

De Jong, J., 1982. Chronostratigraphic subdivision of the Holocene in the Netherlands. In: Mangerud, J., Birks, H.J.B., Jäger, K.-D. (Eds.), Chronostratigraphical Subdivision of the Holocene. Striae, vol. 16, pp. 71–74.

De Jong, J., 1995. Some palaeobotanical data on the fluviatile Rhine/Meuse Kreftenheye Formation in the Netherlands (Weichselian). Meded. Rijks Geol. Dienst 52, 369–386.

Dodge, R.E., Fairbanks, R.G., Benninger, L.K., Maurrasse, F., 1983. Pleistocene sea levels from raised coral reefs of Haiti. Science 219, 1423–1425.

Doppert, J.W.Chr., Ruegg, G.H.J., Van Staalduinen, C.J., Zagwijn, W.H., Zandstra, J.G., 1975. Formaties van het Kwartair en Boven-Tertiair in Nederland. In: Zagwijn, W.H., Van Staalduinen, C.J. (Eds.), Toelichting bij Geologische Overzichtskaarten van Nederland. Rijks Geologische Dienst, Haarlem, pp. 11–56.

Ethridge, F.G., Wood, L.J., Schumm, S.A., 1998. Cyclic variables controlling fluvial sequence development: problems and perspectives. In: Shanley, K.W., McCabe, P.J. (Eds.), Relative Role of Eustasy, Climate, and Tectonism in Continental Rocks. Soc. Econ. Paleontol. Mineral. Spec. Publ., vol. 59, pp. 18–29.

Feldman, H.R., Gibling, M.R., Archer, A.W., Wightman, W.G., Lanier, W.P., 1995. Stratigraphic architecture of the Tonganoxie paleovalley fill (Lower Virgilian) in northeastern Kansas. Am. Assoc. Pet. Geol. Bull. 79, 1019–1043.

Fisk, H.N., McFarlan Jr., E., 1955. Late Quaternary deltaic deposits of the Mississippi River. In: Poldervaart, A. (Ed.), Crust of the Earth. Geol. Soc. Am. Spec. Paper, vol. 62, pp. 279–302.

Fuller, I.C., Macklin, M.G., Passmore, D.G., Brewer, P.A., Lewin, J., Wintle, A.G., 1996. Geochronologies and environmental records of Quaternary fluvial sequences in the Guadalope basin, northeast Spain, based on luminescence dating. In: Branson, J., Brown, A.G., Gregory, K.J. (Eds.), Global Continental Changes: The Context of Palaeohydrology. Geol. Soc. Spec. Publ., vol. 115, pp. 99–120.

Gibbard, P.L., 1988. The history of the great northwest European rivers during the past three million years. Phil. Trans. R. Soc. London B318, 559–602.

Gibbard, P.L., 1995. The formation of the Strait of Dover. In: Preece, R.C. (Ed.), Island Britain: A Quaternary Perspective. Geol. Soc. Spec. Publ., vol. 96, pp. 15–26.

Grootes, P.M., 1978. Carbon-14 time scale extended: comparison of chronologies. Science 200, 11–15.

Holbrook, J.M., 1996. Complex fluvial response to low gradients at maximum regression: a genetic link between smooth sequence-boundary morphology and architecture of overlying sheet sandstone. J. Sediment. Res. 66, 713–722.

Hunt, D., Tucker, M.E., 1992. Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall. Sediment. Geol. 81, 1–9.

Huntley, D.J., Godfrey-Smith, D.I., Thewalt, M.L.W., 1985. Optical dating of sediments. Nature 313, 105–107.

Kasse, C., 1996. Paleomagnetic dating and effects of Weichselian periglacial processes on the magnetization of early Pleistocene deposits (southern Netherlands, northern Belgium). Geol. Mijnbouw 75, 19–31.

Knebel, H.J., Wood, S.A., Spiker, E.C., 1979. Hudson River: evidence for extensive migration on the exposed continental shelf during Pleistocene time. Geology 7, 254–258.

Kooi, H., Johnston, P., Lambeck, K., Smither, C., Molendijk, R., 1998. Geological causes of recent (~ 100 yr) vertical land movement in the Netherlands. Tectonophysics 299, 297–316.

Koss, J.E., Ethridge, F.G., Schumm, S.A., 1994. An experimental study of the effects of base-level change on fluvial, coastal plain and shelf systems. J. Sediment. Res. B64, 90–98.

Laban, C., 1995. The Pleistocene glaciations in the Dutch sector of the North Sea. A synthesis of sedimentary and seismic data. PhD Thesis, University of Amsterdam, 194 pp.

Laban, C., Schüttenhelm, R.T.E., Balson, P.S., Baeteman, C., Paepe, R., 1992. Ostend Sheet 51°N–02°E. 1:250 000 Series. Quaternary Geology. British Geological Survey/Rijks Geologische Dienst/Belgische Geologische Dienst, Nottingham/Haarlem/Brussel.

Lambeck, K., 1995. Late Devensian and Holocene shorelines of the British Isles and North Sea from models of glacio-hydro-isostatic rebound. J. Geol. Soc. London 152, 437–448.

Ludwig, K.R., Muhs, D.R., Simmons, K.R., Halley, R.B., Shinn, E.A., 1996. Sea-level records at ~ 80 ka from tectonically stable platforms: Florida and Bermuda. Geology 24, 211–214.

Makaske, B., 1998. Anastomosing rivers. Forms, processes and sediments. Ned. Geogr. Studies 249, 1–287.

Makaske, B., Nap, R.L., 1995. A transition from a braided to a meandering channel facies, showing inclined heterolithic stratification (Late Weichselian, central Netherlands). Geol. Mijnbouw 74, 13–20.

Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C., Shackleton, N.J., 1987. Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300,000-year chronostratigraphy. Quat. Res. 27, 1–29.

Matthews, R.K., 1973. Relative elevation of late Pleistocene high sea level stands: Barbados uplift rates and their implications. Quat. Res. 3, 147–153.

McFarlan Jr., E., 1961. Radiocarbon dating of late Quaternary deposits, south Louisiana. Geol. Soc. Am. Bull. 72, 129–158.

Mejdahl, V., 1987. Internal radioactivity in quartz and feldspar grains. Ancient TL 5, 10–17.

Miall, A.D., 1991. Stratigraphic sequences and their chronostratigraphic correlation. J. Sediment. Petrol. 61, 497–505.

Miall, A.D., 1999. Cryptic sequence boundaries in braided fluvial successions. Abstr. Am. Assoc. Pet. Geol. Ann. Conv., San Antonio, Texas, p. A93.

Murray, A.S., Roberts, R.G., 1998. Measurement of the equivalent dose in quartz using a regenerative-dose single-aliquot protocol. Radiat. Meas. 29, 503–515.

Murray, A.S., Wintle, A.G., 1999. Isothermal decay of optically stimulated luminescence in quartz. Radiat. Meas. 30, 119–125.

Murray, A.S., Wintle, A.G., 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiat. Meas. 32, 57–73.

Nio, S.-D., Yang, C.-S., 1991. Diagnostic attributes of clastic tidal deposits: a review. In: Smith, D.G., Reinson, G.E., Zaitlin, B.A., Rahmani, R.A. (Eds.), Clastic Tidal Sedimentology. Can. Soc. Pet. Geol. Mem., vol. 16, pp. 3–27.

Nummedal, D., Swift, D.J.P., 1987. Transgressive stratigraphy at sequence-bounding unconformities: some principles derived from Holocene and Cretaceous examples. In: Nummedal, D., Pilkey, O.H., Howard, J.D. (Eds.), Sea-Level Fluctuation and Coastal Evolution. Soc. Econ. Paleontol. Mineral. Spec. Publ., vol. 41, pp. 241–260.

Oele, E., Apon, W., Fischer, M.M., Hoogendoorn, R., Mesdag, C.S., De Mulder, E.F.J., Overzee, B., Sesören, A., Westerhoff, W.E., 1983. Surveying The Netherlands: sampling techniques, maps and their applications. In: Van den Berg, M.W., Felix, R. (Eds.), Special Issue in the Honour of J.D. de Jong. Geol. Mijnbouw, vol. 62, pp. 355–372.

Paola, C., 2000. Quantitative models of sedimentary basin filling. Sedimentology 47 (Suppl. 1), 121–178.

Pisias, N.G., Martinson, D.G., Moore Jr., T.C., Shackleton, N.J., Prell, W., Hays, J., Boden, G., 1984. High resolution stratigraphic correlation of benthic oxygen isotopic records spanning the last 300,000 years. Mar. Geol. 56, 119–136.

Posamentier, H.W., Weimer, P., 1993. Siliciclastic sequence stratigraphy and petroleum geology—where to from here? Am. Assoc. Pet. Geol. Bull. 77, 731–742.

Posamentier, H.W., Allen, G.P., James, D.P., Tesson, M., 1992. Forced regressions in a sequence stratigraphic framework: concepts, examples, and exploration significance. Am. Assoc. Pet. Geol. Bull. 76, 1687–1709.

Salter, T., 1993. Fluvial scour and incision: models for their influence on the development of realistic reservoir geometries. In: North, C.P., Prosser, D.J. (Eds.), Characterization of Fluvial and Aeolian Reservoirs. Geol. Soc. Spec. Publ., vol. 73, pp. 33–51.

Schumm, S.A., 1993. River response to baselevel change: implications for sequence stratigraphy. J. Geol. 101, 279–294.

Shackleton, N.J., 1987. Oxygen isotopes, ice volume and sea level. Quat. Sci. Rev. 6, 183–190.

Shanley, K.W., McCabe, P.J., 1993. Alluvial architecture in a sequence stratigraphic framework: a case history from the Upper Cretaceous of southern Utah, USA. In: Flint, S.S., Bryant, I.D. (Eds.), The Geological Modelling of Hydrocarbon Reservoirs and Outcrop Analogues. Int. Assoc. Sedimentol. Spec. Publ., vol. 15, pp. 21–55.

Shanley, K.W., McCabe, P.J., 1994. Perspectives on the sequence stratigraphy of continental strata. Am. Assoc. Pet. Geol. Bull. 78, 544–568.

Shanley, K.W., McCabe, P.J., 1998. Relative role of eustasy, climate, and tectonism in continental rocks: an introduction.

In: Shanley, K.W., McCabe, P.J. (Eds.), Relative Role of Eustasy, Climate, and Tectonism in Continental Rocks. Soc. Econ. Paleontol. Mineral. Spec. Publ., vol. 59, pp. iii–iv.

Spaink, G., 1958. De Nederlandse Eemlagen. I Algemeen overzicht. Kon. Nederl. Natuurhist. Veren. Wetensch. Meded. 29, 1–44.

Strickertsson, K., Murray, A.S., 1999. Optically stimulated luminescence dates for Late Pleistocene and Holocene sediments from Nørre Lyngby, Northern Jutland, Denmark. Quat. Geochronol. (Quat. Sci. Rev.) 18, 169–178.

Summerfield, M.A., 1985. Plate tectonics and landscape development on the African continent. In: Morisawa, M., Hack, J.T. (Eds.), Tectonic Geomorphology. Allen&Unwin, Boston, pp. 27–51.

Suter, J.R., Berryhill Jr., H.L., 1985. Late Quaternary shelf-margin deltas, northwest Gulf of Mexico. Am. Assoc. Pet. Geol. Bull. 69, 77–91.

Talling, P.J., 1998. How and where do incised valleys form if sea level remains above the shelf edge? Geology 26, 87–90.

Tauxe, L., Herbert, T., Shackleton, N.J., Kok, Y.S., 1996. Astronomical calibration of the Matuyama–Brunhes boundary: consequences for magnetic remanence acquisition in marine carbonates and the Asian loess sequences. Earth Planet. Sci. Lett. 140, 133–146.

Törnqvist, T.E., 1993. Holocene alternation of meandering and anastomosing fluvial systems in the Rhine–Meuse Delta (central Netherlands) controlled by sea-level rise and subsoil erodibility. J. Sediment. Petrol. 63, 683–693.

Törnqvist, T.E., 1995. Discussion: Alluvial architecture of the Quaternary Rhine–Meuse river system in the Netherlands. Geol. Mijnbouw 74, 183–186.

Törnqvist, T.E., 1998. Longitudinal profile evolution of the Rhine–Meuse system during the last deglaciation: interplay of climate change and glacio-eustasy? Terra Nova 10, 11–15.

Törnqvist, T.E., Weerts, H.J.T., Berendsen, H.J.A., 1994. Definition of two new members in the upper Kreftenheye and Twente Formations (Quaternary, the Netherlands): a final solution to persistent confusion? Geol. Mijnbouw 72, 251–264.

Toscano, M.A., Lundberg, J., 1999. Submerged Late Pleistocene reefs on the tectonically-stable S.E. Florida margin: high-precision geochronology, stratigraphy, resolution of Substage 5a sea-level elevation, and orbital forcing. Quat. Sci. Rev. 18, 753–767.

Van de Meene, E.A., Zagwijn, W.H., 1978. Die Rheinläufe im deutsch-niederländischen Grenzgebiet seit der Saale-Kaltzeit. Überblick neuer geologischer und pollenanalytischer Untersuchungen. Fortschr. Geol. Rheinl. Westfalen 28, 345–359.

Van der Molen, J., Van Dijck, B., 2000. The evolution of the Dutch and Belgian coasts and the role of sand supply from the North Sea. Global Planet. Change 27, 223–244.

Van der Valk, L., 1996a. Geology and sedimentology of Late Atlantic sandy, wave-dominated deposits near The Hague (South-Holland, the Netherlands): a reconstruction of an early prograding coastal sequence. Meded. Rijks Geol. Dienst 57, 201–227.

Van der Valk, L., 1996b. Coastal barrier deposits in the central Dutch coastal plain. Meded. Rijks Geol. Dienst 57, 133–199.

Van Dijk, G.J., Berendsen, H.J.A., Roeleveld, W., 1991. Holocene water level development in The Netherlands' river area; implications for sea-level reconstruction. Geol. Mijnbouw 70, 311–326.

Van Staalduinen, C.J., 1979. Toelichtingen bij de Geologische Kaart van Nederland 1:50.000. Blad Rotterdam West (37 W). Rijks Geologische Dienst, Haarlem, 140 pp.

Van Wagoner, J.C., 1995. Overview of sequence stratigraphy of foreland basin deposits: terminology, summary of papers, and glossary of sequence stratigraphy. In: Van Wagoner, J.C., Bertram, G.T. (Eds.), Sequence Stratigraphy of Foreland Basin Deposits. Outcrop and Subsurface Examples from the Cretaceous of North America. Am. Assoc. Pet. Geol. Mem., vol. 64, pp. ix–xxi.

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S., Hardenbol, J., 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), Sea-Level Changes: An Integrated Approach. Soc. Econ. Paleontol. Mineral. Spec. Publ., vol. 42, pp. 39–45.

Verbraeck, A., 1984. Toelichtingen bij de Geologische Kaart van Nederland 1:50.000. Blad Tiel West (39 W) en Blad Tiel Oost (39 O). Rijks Geologische Dienst, Haarlem, 335 pp.

Vos, P.C., De Wolf, H., 1993a. Diatoms as a tool for reconstructing sedimentary environments in coastal wetlands; methodological aspects. In: Van Dam, H. (Ed.), Twelfth International Diatom Symposium. Hydrobiologia, vol. 269/270, pp. 285–296.

Vos, P.C., De Wolf, H., 1993b. Reconstruction of sedimentary environments in Holocene coastal deposits of the southwest Netherlands; the Poortvliet boring, a case study of palaeoenvironmental diatom research. In: Van Dam, H. (Ed.), Twelfth International Diatom Symposium. Hydrobiologia, vol. 269/270, pp. 297–306.

Wallinga, J., Duller, G.A.T., 2000. The effect of optical absorption on the infrared stimulated luminescence age obtained on coarse-grain feldspar. Quat. Sci. Rev. 19, 1035–1042.

Wallinga, J., Murray, A.S., Duller, G.A.T., Törnqvist, T.E., 1999. Infrared stimulated luminescence dating of feldspar: the problem of age underestimation. Abstr. 9th Int. Conf. Luminesc. ESR Dating, Rome, p. 66.

Wallinga, J., Murray, A., Wintle, A., 2000. The single-aliquot regenerative-dose (SAR) protocol applied to coarse-grain feldspar. Radiat. Meas. 32, 529–533.

Weerts, H.J.T., 1996. Complex confining layers. Architecture and hydraulic properties of Holocene and Late Weichselian deposits in the fluvial Rhine–Meuse delta, The Netherlands. Ned. Geogr. Studies 213, 1–189.

Willis, B.J., 1997. Architecture of fluvial-dominated valley-fill deposits in the Cretaceous Fall River Formation. Sedimentology 44, 735–757.

Wintle, A.G., 1997. Luminescence dating: laboratory procedures and protocols. Radiat. Meas. 27, 769–817.

Wood, L.J., Ethridge, F.G., Schumm, S.A., 1993. The effects of rate of base-level fluctuation on coastal-plain, shelf and slope depositional systems: an experimental approach. In: Posamentier, H.W., Summerhayes, C.P., Haq, B.U., Allen, G.P. (Eds.), Sequence Stratigraphy and Facies Associations. Int. Assoc. Sedimentol. Spec. Publ., vol. 18, pp. 43–53.

Wood, L.J., Ethridge, F.G., Schumm, S.A., 1994. An experimental study of the influence of subaqueous shelf angles on coastal plain and shelf deposits. In: Weimer, P., Posamentier, H.W. (Eds.), Siliciclastic Sequence Stratigraphy. Recent Developments and Applications. Am. Assoc. Pet. Geol. Mem., vol. 58, pp. 381–391.

Woolfe, K.J., Larcombe, P., Naish, T., Purdon, R.G., 1998. Lowstand rivers need not incise the shelf: an example from the Great Barrier Reef, Australia, with implications for sequence stratigraphic models. Geology 26, 75–78.

Wright, V.P., Marriott, S.B., 1993. The sequence stratigraphy of fluvial depositional systems: the role of floodplain sediment storage. Sediment. Geol. 86, 203–210.

Zagwijn, W.H., 1961. Vegetation, climate and radiocarbon datings in the Late Pleistocene of the Netherlands. Part I. Eemian and Early Weichselian. Meded. Geol. Stichting N.S. 14, 15–45.

Zagwijn, W.H., 1974. The palaeogeographic evolution of The Netherlands during the Quaternary. Geol. Mijnbouw 53, 369–385.

Zagwijn, W.H., 1975. Indeling van het Kwartair op grond van veranderingen in vegetatie en klimaat. In: Zagwijn, W.H., Van Staalduinen, C.J. (Eds.), Toelichting bij Geologische Overzichtskaarten van Nederland. Rijks Geologische Dienst, Haarlem, pp. 109–114.

Zagwijn, W.H., 1983. Sea-level changes in The Netherlands during the Eemian. In: Van den Berg, M.W., Felix, R. (Eds.), Special Issue in the Honour of J.D. de Jong. Geol. Mijnbouw, vol. 62, pp. 437–450.

Zagwijn, W.H., 1989. The Netherlands during the Tertiary and the Quaternary: a case history of Coastal Lowland evolution. Geol. Mijnbouw 68, 107–120.

Zagwijn, W.H., 1992. The beginning of the ice age in Europe and its major subdivisions. Quat. Sci. Rev. 11, 583–591.

Zagwijn, W.H., Van Montfrans, H.M., Zandstra, J.G., 1971. Subdivision of the "Cromerian" in The Netherlands; pollen-analysis, palaeomagnetism and sedimentary petrology. Geol. Mijnbouw 50, 41–58.

Zaitlin, B.A., Dalrymple, R.W., Boyd, R., 1994. The stratigraphic organization of incised-valley systems associated with relative sea-level change. In: Dalrymple, R.W., Boyd, R., Zaitlin, B.A. (Eds.), Incised-Valley Systems: Origin and Sedimentary Sequences. Soc. Econ. Paleontol. Mineral. Spec. Publ., vol. 51, pp. 45–60.

Zhang, Z., Sun, K., Yin, J., 1997. Sedimentology and sequence stratigraphy of the Shanxi Formation (Lower Permian) in the northwestern Ordos Basin, China: an alternative sequence model for fluvial strata. Sediment. Geol. 112, 123–136.

Zonneveld, J.I.S., 1957. River terraces and Quaternary chronology in the Netherlands. Geol. Mijnbouw N.S. 19, 277–285.

Zonneveld, J.I.S., 1958. Litho-stratigrafische eenheden in het Nederlandse Pleistoceen. Meded. Geol. Stichting N.S. 12, 31–64.