Timing of the last sequence boundary in a fluvial setting near the highstand shoreline—Insights from optical dating

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ABSTRACT

We investigated, by means of optical dating, the chronostratigraphic nature of the sequence boundary associated with the last glacial in a sandy to gravelly compound paleovalley fill, just landward of the highstand shoreline in the Rhine-Meuse Delta (Netherlands). Laterally extensive fluvial strata deposited during oxygen isotope stage 4, coeval with a major sea-level fall, unconformably overlie estuarine deposits from stage 5 or fluvial deposits from the penultimate glacial (stage 6). These chronostratigraphic relationships differ substantially from widely used models and indicate (1) that sequence-boundary formation in this setting was associated with the onset of pronounced sea-level fall, shortly after 80 ka; (2) that the time gap represented by the sequence boundary may be extremely small (<10 k.y.); (3) that the age of the sequence boundary may decrease both updip and downdip of the highstand shoreline; and (4) that our study does not provide viable diagnostic criteria for a sea-level–controlled sequence boundary above the falling-stage systems tract. Despite the high-frequency, high-amplitude glacio-eustatic regime that might be considered ideal for the formation of an unambiguous unconformity, the last sequence boundary in this setting is commonly cryptic.

Keywords: sequence stratigraphy, optical dating, Rhine-Meuse system, Quaternary.

INTRODUCTION

The revival of stratigraphy, largely brought about by the emergence of sequence stratigraphy and its focus on allogenic forcing of sedimentary-basin filling, has drawn considerable interest to the recognition of stratigraphic surfaces in the sedimentary record. Sequence boundaries (Mitchum et al., 1977) currently are the most widely used features for the identification of allostratigraphic units. The sequence boundary is supposed to constitute a widespread unconformity, particularly in the updip (fluvial) realm of clastic stratigraphic successions, rendering it a powerful chronostratigraphic tool for the correlation of strata, the analysis of sedimentary-basin evolution, and the prediction of stratigraphic and sedimentary architecture.

Despite the massive amount of work on the nature of sequence boundaries, surprisingly little is known about their temporal characteristics because the resolution of numerical dating methods, compared to the time span of sequence-boundary formation, is inadequate for the vast majority of geologic history. The late Quaternary offers the only stratigraphic record in which it is possible to study high-resolution age relationships across sequence boundaries. The rapid development of the family of techniques known as optical dating allows direct dating of mineral grains in deposits where alternative means for obtaining chronologic frameworks for the past 100–150 k.y. are virtually nonexistent.

It is commonly thought that in the fluvial realm, sequences consist primarily of deposits formed during relative sea-level (RSL) lowstand, transgression, and highstand, whereas the falling stage would be responsible for subaerial exposure and sediment bypass (e.g., Posamentier and Allen, 1999). Given the sawtooth shape of glacio-eustatically controlled RSL curves, such a timing of deposition implies that time gaps of 50–100 k.y. might be expected during eccentricity-dominated cycles like those of the latter part of the Quaternary.

Following the theoretical analysis by Jervey (1988), first-generation sequence-stratigraphic models related the timing of sequence boundaries to maximum rates of RSL fall, defined by the eustatic-fall inflection point. Diffusion modeling of passive margins by Jordan and Flemings (1991) suggested that the age of sequence boundaries occurs between maximum rate of fall and lowstand, although their model runs also indicate that initial erosion in the updip realm may start earlier during RSL fall. Leeder and Stewart (1996) demonstrated that for conditions of gradual RSL fall and sufficient sediment supply, incision may not occur at all.

A common trait in physical experiments of basin-margin evolution (e.g., Koss et al., 1994; Van Heijst and Postma, 2001) is an updip-migrating knickpoint that develops after base level drops below the shelf edge and a sequence boundary that continues to form in updip areas, even during RSL rise following lowstand. In contrast, Heller et al. (2001) suggested that during rapid RSL fall, sequence-boundary formation is almost instantaneous and tracks the prograding shoreline as base level drops.

Contrasting viewpoints have also been expressed in a series of conceptual papers, commonly inspired by field evidence. Posamentier and Allen (1999) placed the sequence boundary at the initial stage of RSL fall. Plint and Nummedal (2000), following Hunt and Tucker (1992) and Helland-Hansen and Martinsen (1996), advocated that sequence boundaries correspond to RSL lowstand and they defined the sequence boundary as the upper bounding surface of the falling-stage systems tract.

Clearly, theoretical, experimental, and field studies have generated considerable debate about the age of sequence boundaries. Our objective is to assess these contrasting viewpoints in the light of high-resolution geochronologic data from a predominantly fluvial setting. This paper provides the first rigorous, chronostratigraphic test of the timing of sequence-boundary formation, based on a study near the present coast in the Rhine-Meuse Delta, Netherlands (Fig. 1). We have collected five >35-m-deep cores that penetrate paleovalley strata of the last two glacial-interglacial cycles. Three of these cores have been subjected to optical dating. Our results show that in this area, the timing of sequence-boundary formation and deposition differs substantially from that predicted by widely used models.

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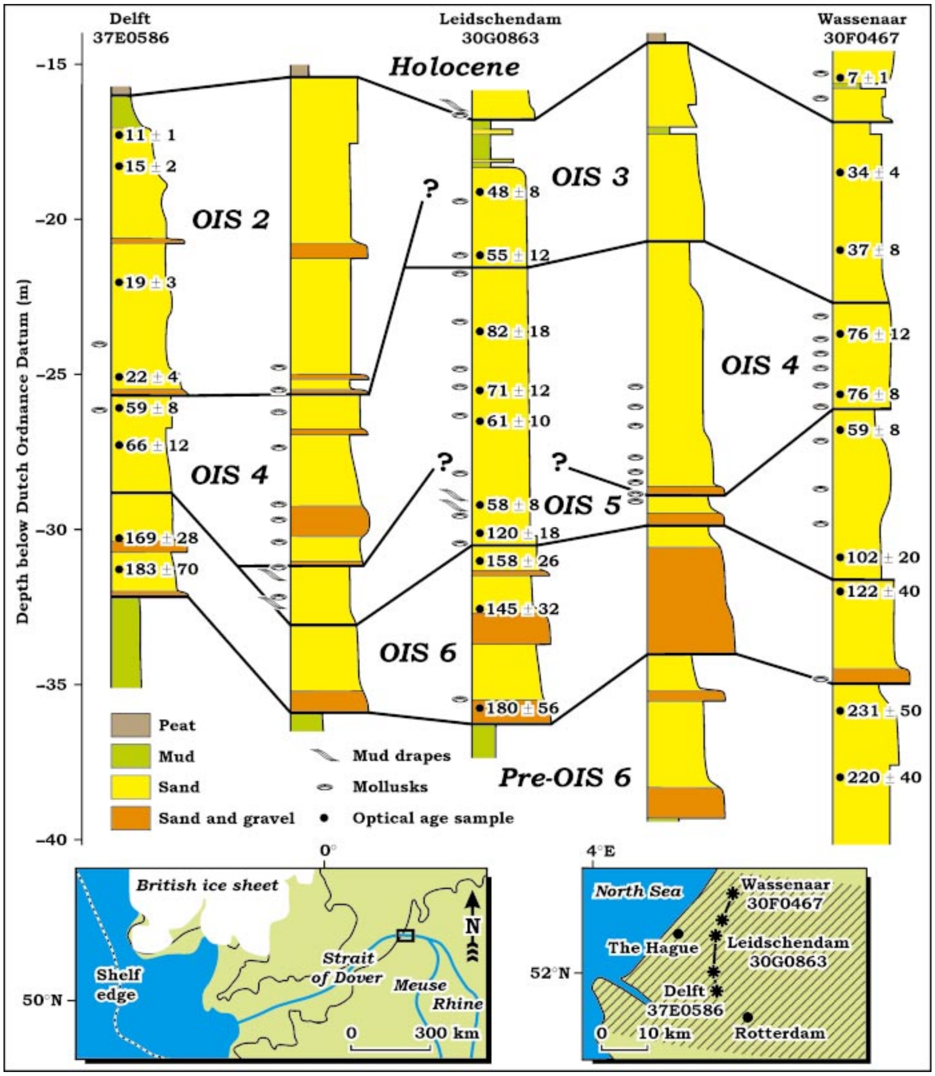

Figure 1. Shore-parallel chronostratigraphic cross section perpendicular to late Quaternary Rhine-Meuse paleovalley, simplified after Wallinga (2001). Combination of fine-grained facies, mud drapes, and marine mollusks indicates transgressive, estuarine conditions during oxygen isotope stage (OIS) 5, sandwiched between fluvial deposits. Younger fluvial strata (particularly OIS 4) contain reworked marine mollusks (Törnqvist et al., 2000; Wallinga, 2001). Optically stimulated luminescence ages labeled with 2σ confidence intervals. Insets: (left) study area relative to shoreline and shelf edge at 22 ka (Lambeck, 1995) and (right) location of paleovalley (diagonal hatching) and cores.

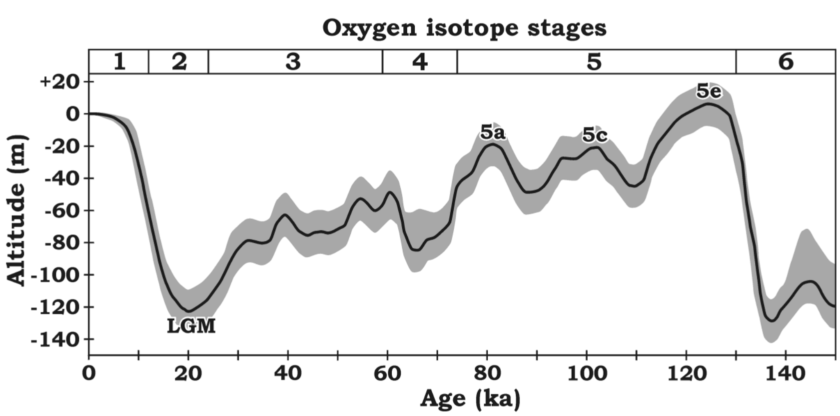

Figure 2. Sea-level change for past 150 k.y. (Waelbroeck et al., 2002). LGM is Last Glacial Maximum.

OPTICAL DATING

Our chronologic framework[1] is based on optical dating of quartz sand, using the single-aliquot regenerative dose procedure described by Murray and Wintle (2000). This technique yielded accurate results by means of extensive cross-checking with independently dated fluvial deposits up to 13 ka from the Rhine-Meuse Delta (Wallinga et al., 2001). However, undetected systematic errors cannot be completely ruled out beyond this age range, and because rigorous verification of this method for older strata in this area has yet to be accomplished, we have practiced utmost care in our data interpretation. We used 95% confidence intervals that are <20 k.y. for most samples that cover the last glacial-interglacial cycle, rendering them adequate to assign the strata in our study area to oxygen isotope stages.

STUDY AREA AND RESULTS

A detailed discussion of the paleogeographic evolution of the study area is provided in Törnqvist et al. (2000). The lowermost part of the paleovalley fill (Fig. 1) was primarily deposited during oxygen isotope stage (OIS) 6, corresponding to the penultimate glacial when the Fennoscandian ice sheet came to a halt halfway into the Netherlands, immediately north of our study area, and forced the Rhine-Meuse system into its present position. In the southern part of our cross section, this coarse-grained, fluvial unit unconformably overlies fine-grained, early Pleistocene deposits.

Subsequent transgressions during OIS 5 (Fig. 2) are likely to have formed highstand coastal prisms (cf. Blum and Price, 1998; Talling, 1998) that were largely eroded during ensuing RSL falls (Törnqvist et al., 2000; Wallinga, 2001). The remnants commonly include basal, estuarine (tide-influenced) channel deposits with mud drapes. The overlying package is dominated by fluvial channel deposits from OIS 4, in turn overlain by fluvial strata from OIS 3 and OIS 2 in the northern and southern part of the cross section, respectively. It is important to note that the Rhine-Meuse system occupied an exceptionally wide, low-gradient continental shelf during the last glacial, and although its length was extended by ~800 km (Fig. 1), its mouth never reached the shelf edge (Lambeck, 1995).

Various pieces of evidence demonstrate that substantial fluvial incision, rather than autogenic scour (cf. Salter, 1993; Best and Ashworth, 1997), occurred during the last glacio-eustatic cycle. Of particular significance is the

[1]GSA Data Repository item 2003028, quartz optical ages, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2003.htm.

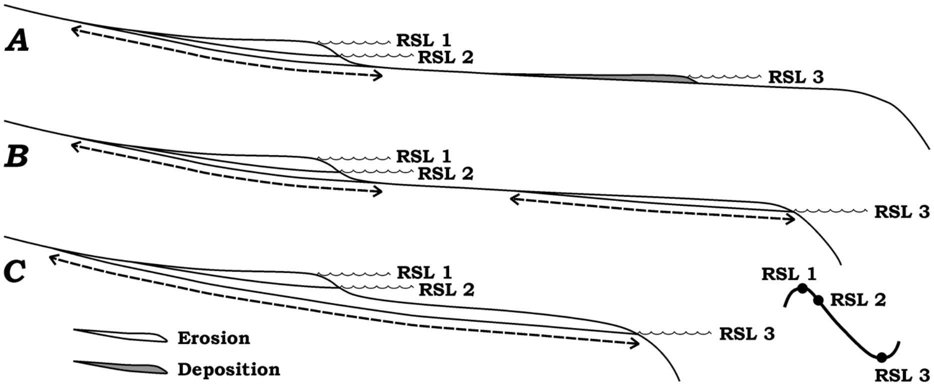

Figure 3. Three scenarios for timing of sequence-boundary formation. Extent of sequence boundaries in areas with true incision sensu Salter (1993) indicated by dashed lines. A: Wide shelf with relative sea level (RSL) remaining above shelf edge limits sequence boundary to highstand coastal prism, temporally corresponding to early RSL fall. B: Wide shelf with RSL dropping below shelf edge may lead to two spatially and temporally distinct sequence boundaries. C: Narrow shelf yields continuous sequence boundary corresponding approximately to RSL lowstand.

presence of fluvial overbank deposits in the Leidschendam core at −18 m (Fig. 1; Törnqvist et al., 2000), indicating at least 10 m of incision during the last glacial, when compared to the present position of OIS 5e (last interglacial) sea-level indicators in the central Netherlands (−8 m; Zagwijn, 1983).

The exact positioning of isochrons (Fig. 1) is somewhat arbitrary as time gaps do not always coincide with grain-size changes, and because of a few problematic optical ages (see footnote one). Nevertheless, there is only limited room for alternative chronostratigraphic interpretations, and the key feature (OIS 4 strata overlying OIS 5 or OIS 6 strata, and underlying OIS 2 or OIS 3 strata) that constitutes the foundation for our sequence-stratigraphic interpretation remains valid for any age model that honors the optical ages.

DISCUSSION

Although the comparatively low sediment supply of the Rhine-Meuse system may have increased at the onset of glacial conditions associated with RSL fall at the transition from OIS 5 to OIS 4, the supply is unlikely to have neutralized the exposure of the steep shoreface (cf. Leeder and Stewart, 1996). Considering the high rates of north-northeast–directed tidal sand transport leading to dominantly erosive conditions offshore of our study area during the Holocene highstand (Van der Molen and De Swart, 2001), presumably representative of previous RSL highstands, incision due to RSL fall was likely inevitable.

We note that deposits from OIS 4 and OIS 3 constitute a large proportion of preserved strata, implying that significant deposition occurred during falling sea level. We infer that incision of the OIS 5a coastal prism took place early during OIS 4 (shortly after 80 ka), followed by net aggradation (discussed in more detail by Wallinga, 2001). Similar chronostratigraphic relationships, with falling-stage fluvial strata overlying the sequence boundary, have been inferred by Blum and Price (1998) and Amorosi et al. (1999). Timing of sequence-boundary formation is also related to tectonic subsidence rates, i.e., how rapidly the sequence boundary enters ''preservation space'' (Kocurek and Havholm, 1994; Blum and Törnqvist, 2000) below the maximum possible depth of fluvial incision. In our case, a subsidence rate of ~12 cm/k.y. (Törnqvist, 1998), combined with a relatively shallow local base level formed by bedrock at −55 m in the Strait of Dover (Fig. 1), protected the initial sequence boundary from erosion later during the last glacial.

Only one of the cores (Delft) provides an unconformity greater than 50 k.y. that unequivocally separates strata of OIS 6 and OIS 4, respectively (Fig. 1). The exact position of this unconformity is difficult to pick due to the absence of grain-size changes, a feature that has recently been referred to as a ''cryptic sequence boundary'' (Miall and Arush, 2001). The erosional base of fluvial OIS 4 strata commonly overlies remnants of OIS 5 deposits, rendering chronological pinpointing of the sequence boundary difficult because the associated time gap may be as little as 10 k.y. or less. As a result, the temporal significance of this surface is equally cryptic.

The erosion surface that separates OIS 2 deposits from older fluvial strata (notably in the Delft core; Fig. 1) coincides with the Last Glacial Maximum (LGM), when ice-volume equivalent sea level approached lowstand (Waelbroeck et al., 2002; Fig. 2) and the coeval shoreline was far downdip of the Strait of Dover (~800 km from our study area, well outside the range of glacio-eustatic control on incision; cf. Blum and Törnqvist, 2000). Hence, this erosion surface is unlikely to be related to RSL. Climate change may have been responsible for cut-and-fill cycles within the OIS 2 to OIS 4 package (Wallinga, 2001) and is thus a possible explanation for this phenomenon. These data therefore indicate, at least for our study area, that the RSL-controlled sequence boundary should be placed at the base of the falling-stage systems tract (i.e., the base of OIS 4 deposits).

Our data suggest that the initiation of sequence-boundary formation occurs at the shoreline of the highstand coastal prism, then tracks the shoreline as sea level continues to fall (cf. Plint et al., 2001), as long as a shoreface profile steeper than that of the coastal plain is being exposed. In the physical experiment by Heller et al. (2001) that included subsidence and essentially self-generated topography, rapid RSL fall led to instantaneous valley cutting and a sequence boundary that nucleated at the highstand shoreline (P.L. Heller, 2002, personal commun.) and propagated both updip and downdip, a scenario that is likely similar to ours (Fig. 3).

Clearly, the issue of whether RSL fall extends below the shelf edge is critical in determining the temporal characteristics of the sequence boundary (Fig. 3). When this is not the case, as for the Rhine-Meuse system, the highstand coastal prism represents the area of maximum fluvial incision (cf. Blum and Price, 1998; Talling, 1998). Except for the scouring of a lowstand channel across the continental shelf, incision farther downdip was minimal (Törnqvist et al., 2000). A similar scenario with ''unincised'' channels downdip of ''incised'' channels has been identified on the Java sea shelf (Posamentier, 2001). Although Koss et al. (1994) and Van Heijst and Postma (2001) mentioned minor incision of the highstand coastal prism during initial RSL fall, this process deserves more explicit attention in future experimental studies (cf. Heller et al., 2001). The advent of numerical models that explicitly take into account the delicate shoreface morphology (e.g., Nummedal et al., 1993; Swenson et al., 2000; Meijer, 2002) is therefore to be applauded.

Blum and Price (1998) discussed the composite and time-transgressive nature of the last sequence boundary in a cross-valley direction. Here, we hypothesize that in a down-valley direction the sequence boundary is equally diachronous. We propose that the spatial and temporal character of the sequence boundary is in large part dependent on the width (and gradient) of the shelf and whether RSL drops below the shelf edge (Fig. 3). In the latter case, the initially formed sequence boundary may be entirely replaced, by means of headward erosion, by a younger one that corresponds more closely to the RSL lowstand.

CONCLUSIONS

The timing of sequence-boundary formation can differ from the predictions of many sequence-stratigraphic models. Our data show that fluvial incision is particularly pronounced during the initial stage of RSL fall and is associated with rapid degradation of the highstand coastal prism.

The age difference between strata that straddle the sequence boundary may be very small and beyond the resolution of numerical dating techniques. In addition, the last sequence boundary in our study area commonly lacks unambiguous sedimentologic criteria. These observations lend support to the concept of cryptic sequence boundaries.

For settings with a wide, low-gradient continental shelf where RSL does not drop below the shelf edge, the area near the highstand shoreline constitutes the nucleus for sequence-boundary formation. The sequence boundary likely becomes progressively younger both updip and downdip of this position.

Despite the presence of a conspicuous erosion surface that happens to be coeval with the LGM, this unconformity is unrelated to eustasy and is more likely climatically controlled. In such cases the RSL-controlled sequence boundary should be located at the base of the falling-stage systems tract.

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