Unravelling the Rhine

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ENGLISH SUMMARY

GENERAL AIMS AND METHODS

This study focused on the 10-35 m thick coarse-grained fluvial record below the Holocene Rhine-Meuse delta in the Netherlands (Kreftenheye, Urk and Beegden Formations cf. Westerhoff *et al.,* 2003). The sediments were deposited by the Rhine and Meuse in the southern North Sea sedimentary basin which has been one of the main northwest European depocenters of fluvial, shallow marine and glacial sediments throughout the Quaternary. An important part of the Dutch subsurface is formed by these fluvial sediments and they are of great economic value in terms of aggregate mining, construction works and groundwater extraction. The aims of the study were to describe the internal sedimentary variability of these deposits (lithology, geometry, petrology), to describe the palaeogeographical developments during deposition and to understand the depositional history in relation to climate, sea-level, tectonic and glacial forcing mechanisms.
The study was performed by means of multidisciplinary analysis of newly drilled continuous cores and archived core data. The data were primarily collected from two areas in the Netherlands that together represent the depositional record of the Rhine-Meuse system formed during the late Middle and Late Pleistocene. The record was described as twelve sedimentary units that were identified based on grain size trends, sedimentology and position of bounding surfaces. The units were placed in a geo-chronological framework by using Optically Stimulated Luminescence dating (OSL) and biostratigraphy (pollen) after which correlations were made to records of climate change, sea-level oscillation and glaciation history (Chapters 2-4). One of these forcings (climate change) was evaluated in more detail by means of a process-based numerical modelling study of sediment transport in the Rhine drainage basin (Chapter 5).

IMPRINTS OF CLIMATE CHANGE

Most of the Saalian sediment units that were described in this dissertation were deposited during the youngest stadial phase of the Saalian (equivalent to MIS6). The coarse-grained nature of these sediments indicates that deposition occurred under cold periglacial conditions with a high supply of sediment from the catchment as well as from glacial sources. For the older part of the Saalian, correlation between the record and specific intra Saalian stages remains speculative due to the current resolution of the OSL-dates at these time-intervals. Much more detail about the interaction between climate variation and Rhine-Meuse development can be given for the last interglacial-glacial cycle (Eemian-Weichselian). Sediment reworking dominated the beginning end of the climate cycle while during the intervening phase, a stepwise increase in sediment supply is observed. The interaction between Eemian-Weichselian climate change and Rhine-Meuse fluvial development can be summarized as follows:

Phase 1(Eemian-Early Glacial)
The Eemian is characterised by sediment reworking and limited input of fresh bed load sediment from the catchment due to vegetation development and soil formation. Deposition of clays dominated the Eemian although this is primarily related to coastal prism formation. During the Weichselian Early Glacial (~115 ka), conditions of limited bed load supply persisted and organic (floodplain) components increased. The climate oscillations that are reported for this period clearly had a limited impact, a feature that was explained (Chapter 3) as an effect of regolith protective soil complexes in the drainage basin.

Phase 2 (Early Pleniglacial, Middle Pleniglacial)
The Early Pleniglacial is characterized by reworking of Eemian and Early Glacial coastal prism deposits. The increase in channel mobility is related to high discharges due to permafrost

development and snowmelt regimes. Large-scale input of fresh sediment from interfluve areas was still limited during the Early Pleniglacial. Early Middle Pleniglacial avulsion of the Rhine from its former course through the northern Netherlands indicates that channel belts were in an aggrading mode and that bed load sediment supply into the lower reaches of the Rhine had strongly increased. The increase in sediment supply coincided with the onset of major climate cooling from ~50-45 ka onwards. The fact that sediment supply increased in this phase and not during the (much colder) Early Pleniglacial stage, may be explained by the final breakup of Eemian-Early Glacial soil complexes which were still largely intact during the Early Pleniglacial. It shows that relic features like soils can strongly influence and buffer landscape response to climate change.

Phase 3 (Late Pleniglacial)

The earliest phase of the Late Pleniglacial (~30-24 ka) is characterized by channel belt shifting followed by incision. Although the incision phase could have a climatic origin, the combination with shifting features strongly suggests that glacio-isostatic uplift of the study area played a dominant role. After ~24 ka, a strong input of coarse-grained gravelly sediments was observed resulting in infill of the incised system. This major sediment input indicates a strong increase in physical weathering processes and periglacially driven supply of bed load in the catchment. The time-delay between the climate transition (~30 ka) and aggradation of the system (<24 ka), is explained as a result of the long transport path between the main sediment source area (Rhenish Shield) and depocentre (study area). Alternatively, it could indicate that the main aggradation phase is primarily related to the phase of increased runoff rates and (temporal) permafrost thaw that was reported for the post 22 ka period, triggering increased sediment supply towards the river systems.

Phase 4 (Late Glacial)

At the onset of the Late Glacial, the Rhine started to incise and rework older sediment. This phase shows some analogy to conditions that existed at the onset of the Late-Pleistocene climatic cycle (late Saalian - Eemian transition). It indicates that imprint of climate change on the fluvial record of the Rhine-Meuse system shows cyclic components.

FLUVIAL RESPONSE TO CLIMATE CHANGE: MODEL RESULTS

3D simulations with the Channel-Hillslope Integrated Landscape Development model (CHILD) gave additional insights into the mechanisms of how climate controls aggradation-incision patterns and grain size variation in a large fluvial system like the Rhine (Chapter 5). The simulations indicate that climate-controlled channel (belt) aggradation and incision of the Rhine-Meuse system are strongly time-diachronic processes. Delays of several thousand years were observed between the release of (periglacial) produced coarse-grained material in the upstream reaches of the network (Rhenish Shield) and associated aggradation in the downstream areas (study area). This is the result of transport path length and the associated amount of time that is needed to transport the bed load. A similar complex response pattern was observed for the subsequent channel belt incision phase due to gradual sediment depletion of the network. The model results also indicate that out of an initial (catchment wide) homogenous grain size distribution (sand, gravel), a wave-like change in grain size is predicted along the main fluvial network indicating time-diachronic input from different sub-areas of the Rhine catchment.

The simulations outcomes provided valuable new explanations for some observations that were made for the Late Pleniglacial and Late Glacial Rhine-Meuse system (Chapters 2 & 3):

1) In chapter 3 it was shown that deposition of coarse-grained gravelly sands in the Netherlands occurred several thousand years after the onset of the Late Pleniglacial cold

stage. The simulations indicate this feature could be explained by (a transport controlled) time-delay between sediment release in the upper catchment and deposition of these sediments in the lower reaches of the system.

2) A staircase of terrace levels shows that from the onset of the Late-Glacial onwards both Rhine and Meuse channel belts incised. Although other authors generally ascribed this incision to intra Late-Glacial climate change, the simulations show that it may alternatively be explained as a delayed response to a single major climate transition that occurred at the Late Pleniglacial-Late Glacial boundary (~15 ka). This climate transition and associated stabilisation of hillslopes by vegetation, caused gradual sediment depletion of the fluvial network due to ongoing transport of sediment within the rivers without new sediment being put into the rivers.

Imprints of Sea-level variation

Direct evidence for Late Pleistocene sea-level control is reflected in the record of the IJssel Valley area (Area A in Chapter 3). Here, peat formation followed by gyttja deposition, reflects gradual drowning of the area due to rise of the groundwater table as a response to early Eemian sea-level rise. The organic deposits are overlain by overbank sediments that reflect coastal prism formation upstream of a shallow marine embayment. Influence of sea-level control is supported by the fact that this succession shows strong analogy to developments described for the early Holocene Rhine-Meuse delta. The preservation of Eemian and Early Glacial near-coastal deposits is strongly controlled by their geomorphological position. The sediments are primarily preserved as (upper) infills of Saalian ice-sheet created depressions which provided extra accommodation space after the Saalian glaciation and by later compaction of underlying Saalian basin fills. Outside of these depressions, near-coastal sediments were only encountered sporadically (western part of Area B).
The overall poor preservation potential of Eemian-Early Glacial near-coastal sediments is related to reworking of near-coastal deposits during the Early Pleniglacial. In previous studies this erosion was primarily related to sea-level fall, resulting in steepening of the rivers gradient and erosion of the coastal prism, a vision that was expressed in sequence stratigraphic interpretations (e.g. Törnqvist *et al*., 2003). However, the spatial scale at which Early Pleniglacial reworking occurred is difficult to explain by base-level lowering alone. A quick drop in sea-level would lead to local erosion only. Therefore, reworking was likely a combination of base-level lowering and an increase in lateral channel migration rates as a result of climate controlled increases in seasonal discharge (Chapter 2, 3).

Imprints of glaciation

In chapter 4 it was shown that ice sheet progradation during the late Saalian Drente (Marine Isotope Stage 6) glaciation had an overwhelming influence on the sedimentary development of the Rhine-Meuse system. The partial glacial override of the northern Rhine-Meuse catchment triggered total (syn-glacial) drainage re-organisation (Chapter 2, 4) while glaciotectonic ridges, subglacially formed depressions and incised fluvial valley systems controlled the position of Rhine-Meuse channel belts until far into the Eemian-Weichselian period (Chapter 2, 3). The Saalian and Weichselian glaciations also indirectly affected the Rhine-Meuse system by means of glacio-isostatic crustal movements and formation of proglacial lakes. The (potential) magnitudes of both these processes make them critical factors that cannot be set aside when the Rhine or any other ice-marginal system is concerned.

Glacio-isostacy

Raised beach systems in the formerly glaciated area of Scandinavia and the British Isles indicate that under the Late Pleniglacial ice-sheet, the lithosphere was depressed (‘depression zone’) and that it has rebounded since the maximum phase of glaciation (e.g. Lambeck, 1995; Peltier, 2004).

Relative sea-level rise inferred from stratigraphic records of the non-glaciated foreland parallel to the ice-margins testify for enigmatic postglacial subsidence which indicates collapse of a peripheral upwarped zone some distance around the former ice sheet ('forebulge zone'). Since the Rhine-Meuse palaeovalley from this period was situated immediately south of the zone of maximum upwarping, glacio-isostacy can be expected as an extra external control to the fluvial system in the study area in terms of lateral tilting effects and incision-aggradation behaviour. In Chapter 3, the marked southward shift of the Rhine after 35 ka is explained as a response to lateral tilting of the river valley, because the north of the valley was updoming slightly more than the south. Once the Rhine-Meuse got positioned in the south it formed a distinct incised valley system which was explained as ongoing response to the glacio-isostatic upwarping and adaptation of the Rhine's longitudinal profile in order to maintain equilibrium profile as it traversed towards the Dover Strait. A phase of subsequent aggradation could reflect accommodation of initial forebulge collapse although this probably coincided with a strong increase in sediment supply from the upper catchment area.
For the late Saalian Drente glaciation, however, the situation was different. The study area was located much closer to the ice mass which was estimated to have been at least several hundred meters thick just north of the study area. The fluvial Rhine-Meuse sediments were deposited under glacio-isostatically suppressed conditions and subsequent glacio-isostatic rebound during the deglaciation phase can be expected to have brought deposits to relatively shallow depths. In Chapter 4 it was postulated that enigmatically elevated parts of the former proglacial Rhine-Meuse river plain could reflect such rebounded deposits (Chapter 4, Unit S4). Dissection of these proglacial sediments by the Meuse during the deglaciation stage (Chapter 4, Unit S5) may be explained as adaptation of the Meuse-longitudinal profile as a response to rebound (uplift) of the study area during and after ice melt.

Proglacial lake formation

Another major indirect effect of ice-sheet expansion on the Rhine-Meuse record is the formation of ice-marginal lakes during coalescence of Scandinavian and British ice masses. Glacial reconstructions of Saalian and Weichselian ice-sheet dynamics in the North Sea area indicate that such coalescence phases occurred during the Saalian Drente glaciation (MIS6), the Weichselian Late Pleniglacial (late MIS3, MIS2) and probably also during the Weichselian Early Pleniglacial (MIS4). The presence of proglacial lakes in the southern North Sea area is promoted by the funnel-shaped topography and the presence of a bedrock sill in the Dover Strait that during earlier periods was probably higher than at present. It would mean that high-stand conditions, which normally exist during interglacials with high eustatic sea-levels (i.e. Eemian), could also apply to phases with low eustatic sea-level. It can be expected that in such a situation, the ice-marginal Rhine-Meuse system graded towards the contemporary lake level, triggering deposition at enigmatic high levels compared to conditions as they existed prior to lake formation. In Chapter 4 it was postulated that alternatively to (post)glacial glacio-isostatic rebound (see the previous paragraph), the enigmatic elevated position of the proglacial Rhine-Meuse sediments that were formed during the maximum ice-sheet expansion of the Drente glaciation (Chapter 4, Unit S4) could also reflect deposition in the marginal setting of a large proglacial lake. The record shows that lake levels were positioned close to present sea-level. A phase of strong channel belt incision by the river Meuse (Chapter 4, Unit S5) could mark lake-spill controlled dissection and permanent opening of the Dover Strait. An MIS6 'opening' event of the Dover Strait agrees with biostratigraphical data and patterns of human migration into the British Isles which indicate the Strait was open from MIS5e onwards (Meijer & Preece, 1995; White & Aston, 2006).

Imprints of tectonics

The Middle and Late Pleistocene Rhine-Meuse sediment series accumulated under gradual subsiding conditions along the southern margin of the North Sea rift basin. In the study area, long-term subsidence rates vary between 0 m/kyr (hinge line) and ~0.1m/kyr (Kooi *et al*., 1998). The expression of this subsidence on the Rhine-Meuse record is best illustrated in the area south of the former Saalian ice limit. Here, the thickest Rhine-Meuse sediment record occurs at the location of the Roer Valley Graben (RVG) and the West Netherlands Basin while the sequence becomes thinner in eastern and offshore directions (Chapters 2-4). Spatial differences in subsidence rates also explain the deformation of the longitudinal gradient lines of Rhine-Meuse sedimentary units (Ch. 6). Figure 6.1a (Ch. 6) shows that at the location of the RVG and West Netherlands Basin area, the base of older units (i.e. late Saalian Unit S5) are more convex shaped than younger ones (i.e. Weichselian Unit B6b). The position of strongest tectonic deformation and hence highest subsidence rates fit with major subsidence zones predicted by Kooi *et al*. (1998). All units also show a step at the location of the Peel boundary fault zone indicating major fault activity in this area.

The thickness differences and deformation patterns indicate that long-term tectonics controlled the large-scale architecture of the sediment record described in this dissertation. In addition, tectonic movements strongly controlled preservation by bringing deposits below the scour depth of younger fluvial systems.