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Alluvial architecture of the Quaternary Rhine-Meuse river system in the Netherlands

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Abstract

In the Rhine-Meuse river system in the Netherlands, a combination of major tectonic movements and climatic cycles (periglacial to temperate-warm, non-arid) has resulted in different sedimentation patterns on either side of the terrace intersection.

Upstream of this intersection, a vertical series of river terraces was formed by the alternating processes of erosion of the valley by meandering river action and partial refilling of the valley by braided river action. The coarse-grained gravelly deposits within these terrace units show the characteristics of a braided river (Scott-type sequentional model) and reflect general aggradation during cold, i.e. glacial, stages. During interglacials, meandering rivers cut into the previously formed braided river deposits causing net sediment removal. Deposits dating from interglacials are very scarce.

Downstream of the intersection, the average sedimentation rate kept up with subsidence. Sediment was supplied mostly by braided rivers during cold stages and the resulting sequences resemble the Donjek-type sequentional model. During interglacial times meandering rivers mainly caused reworking and erosion of braided river deposits from the preceding glacial stage. Meandering river deposits are more widespread than upstream of the intersection; they are interbedded between braided river deposits.

Futher downstream, marine transgressions during interglacials caused the coast-related anastomosing river zone to shift upstream, sometimes as far as the present-day western Netherlands.

As a consequence of the mechanism responsible for forming fluvial terraces upstream of the terrace intersection, fine-grained overbank and cut-off sediments from meandering rivers that potentially can be dated palaeontologically may be expected underneath coarse-grained 'river-terrace' deposits.

Introduction

A large part of the fluvial deposits in the Quaternary deltaic sequence of the Netherlands was formed by the Rhine-Meuse river system. During the Early Pleistocene this river system competed with another river system which flowed southwestward from the area of the present Gulf of Bothnia and Baltic Sea. This northeastern river system had tributaries from as far as central Scandinavia in the north and Thuringia in central Europe (cf. Bijlsma 1981). When this river system ceased to exist around the transition from Early to Middle Pleistocene, the Rhine-Meuse system prograded northwards into the Netherlands.

During the Quaternary the river Scheldt influenced a small area west of the Rhine-Meuse domain (Kasse 1988).

In northwestern Europe a precursor of the Rhine-Meuse system had been active from as early as Late Miocene (Zagwijn & Hager 1987). In the very Late Pliocene a connection developed between the Rhenish Shield drainage system and rivers flowing from the Alps and Molasse Basin through the Upper Rhine Graben (Boenigk 1978).

The mechanisms that determined the Quaternary alluvial architecture in the Netherlands and the Rhenish Shield are intraplate tectonics and repeated climate changes (e.g. Zagwijn 1989).

Computer simulations of river terrace formation caused by climatic change and uplift patterns, have been published by Boll et al. (1988) and by Veldkamp & Vermeulen (1989). The relation between climatic cycles and astronomical processes was studied by Berger and co-workers (e.g. Berger et al. 1990).

Intraplate tectonics

The North Sea Basin has existed from the Oligocene onward (Zagwijn 1989). During the Quaternary the basin experienced a considerable net subsidence (Fig. 1). At the same time, the Rhenish Shield (Ardennes and Rheinisches Schiefergebirge), the major area of sediment supply for the lower reaches of the river system (cf. Felix-Henningsen et al. 1991), was pushed up by a mantle diapir (Fuchs et al. 1983). The northwestern boundary of this shield, which is a Hercynian massif, is situated just southeast of the area of Fig. 1. The elevation of this shield, a flat upland area, reaches nearly 700 m in the Ardennes and 850 m in the Rheinisches Schiefergebirge.

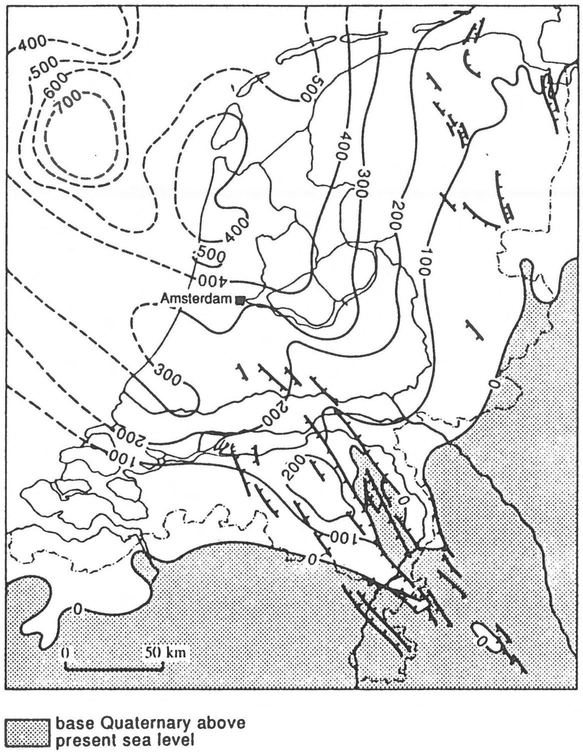

Fig. 1. Depth contours in metres below present sea-level of the base of the Quaternary in the Netherlands (after Zagwijn & Doppert 1978, simplified).

Repeated climate changes

In this part of Europe, between 50 and 56 degrees northern latitude, repeated climatic cycles strongly affected sedimentary processes and the position of the shoreline during the Quaternary (Zagwijn 1989). Warm or at least temperate interglacial times alternated with cold glacial times (Fig. 2). During the latter, periglacial circumstances prevailed over long periods.

Terrace intersection

The terrace intersection is generally understood to be the location where the fluvial terrace landscape (exhibiting net incision) changes downstream into a non-terraced landscape (characterized by net aggradation). In other words, upstream of the intersection the depth of a river's incision exceeds the thickness of its own previous deposits, whereas downstream of the intersection the reverse applies. This terrace intersection is not fixed, but shifts in the course of time depending largely on the tectonic movements, thus forming a diachronous zone. For the Meuse, the 100 km-long intersection zone is situated predominantly in the Netherlands, a minor part of it extends into northeastern Belgium. For the Rhine, the zone is also about 100 km long; the Dutch-German frontier subdivides it more or less equally.

Areas with exposures

Extensive exploitation, mainly of gravel, has led to many exposures upstream of the terrace intersection and especially in Netherlands southern Limburg.

Downstream of the terrace intersection, exposures generally are scarce because of the high position of the groundwater table. Exceptions, however, are the areas with ice-pushed ridges in the central Netherlands. During two Middle Pleistocene cold stages, Scandinavian inland-ice sheets affected the Rhine-Meuse area directly, viz. during the Elsterian (Anglian) and the Saalian (Wolstonian). The Saalian ice sheet shaped basins bordered by ice-pushed ridges. These ridges contain older

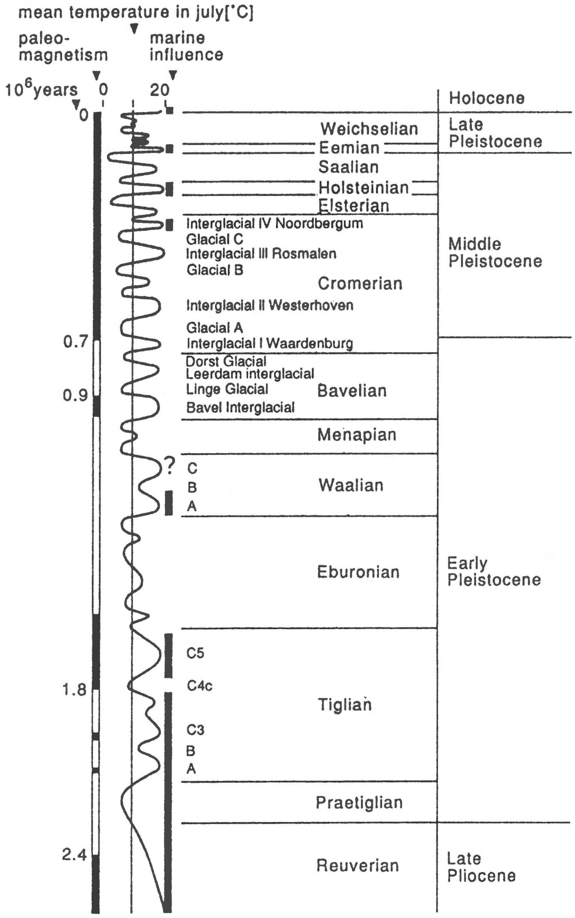

Fig. 2. Correlation of the Pleistocene climate curve with the regional chronostratigraphy (after Zagwijn 1989, simplified).

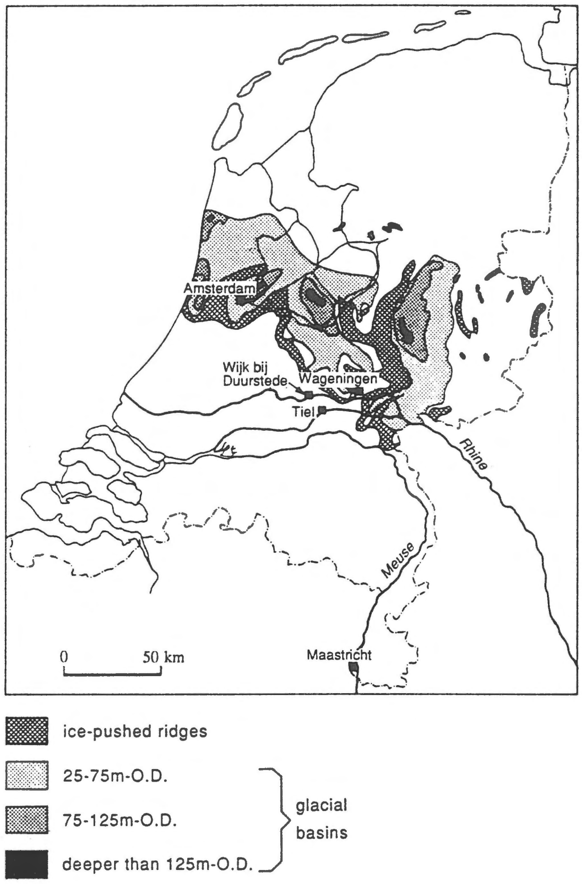

Fig. 3. Position of ice-pushed ridges (Saalian) in the central part of the Netherlands, and topographic names mentioned in the text. Depth contours indicate bottoms of glacial basins.

deposits that partly are not inland-ice related and act as windows into the stratigraphy (Fig. 3).

In addition, information of a more general lithological character is available from many borings.

Characteristics of braiding and meandering rivers

The terms braiding and meandering refer to topographic patterns. Depositionally, braided rivers cause net aggradation, meandering rivers net degradation (cf. Schirmer 1983).[1]

[1] The term 'meandering' refers here to rivers which are actively meandering (and not only have a meandering pattern as is often the case with channels in anastomosing systems) during timespans exceeding many decades, and excludes single channels in braided or alluvial fan systems. See also the paragraph 'Anastomosing and alluvial fan river deposits in the Netherlands'.

Indications for a relation between the braided style and periglacial climatic conditions are:

- The fluvial 'terrace gravel' deposits exposed upstream of the intersection (Fig. 7a) have the same appearance as, for instance, the Thames river gravels of Devensian (= Weichselian) glacial age described by Bryant (1983). According to him these Thames deposits were laid down by a Scott-type river system, such as defined by Miall (1978).
- In Netherlands southern Limburg, east and northeast of Maastricht (Fig. 3), these coarse-grained gravelly deposits invariably display features that indicate a cold-climate origin (Krook 1961, in Zonneveld 1974). Such features are: syngenetic patterned grounds (with ice-wedge casts and/or cryoturbations), ice-rafted sandblocks, isolated outsized stones (often angular), a relatively low per-

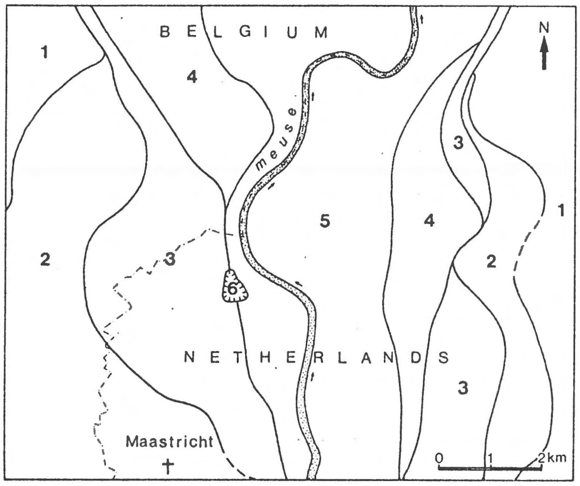

Fig. 4. Pre-loess subcrop map of the terrace deposits of the Meuse north of Maastricht, showing the similarity in dimension of member boundary curves and recent Meuse meanders. 1 = St. Pietersberg Member, 2 = Rothem Member, 3 = Caberg Member, 4 = Gronsveld Member, 5 = Oost-Maarland Member, 6 = Belvédère gravelpit (after Felder & Bosch 1989).

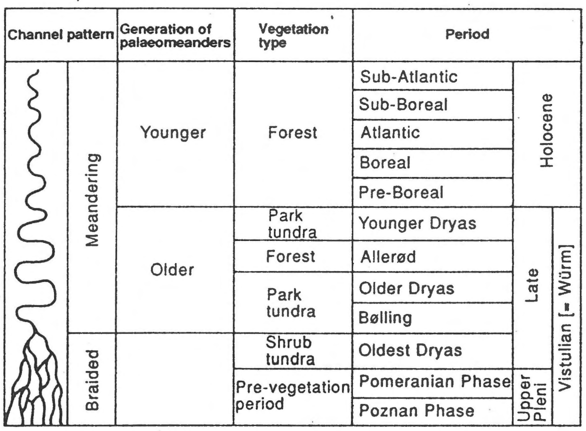

Fig. 5. Change of fluvial channel pattern during the Late Weichselian in western central Poland (after Kozarski 1983, simplified).

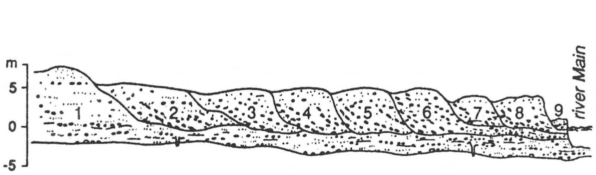

Fig. 6. Schematic cross-section of the Weichselian (Würmian) and Holocene valley fill of the upper Main river in Germany (after Schirmer 1983, simplified). 1: Weichselian Pleniglacial; 2: Late Weichselian; 4–9: Holocene. Notice the difference in layering between unit 1 and units 2–9.

centage of quartz in gravel, a low roundness of the gravel, and in-situ fragmentation of stones.

- In the early 1970s, Weichselian river deposits, dated by C14 (De Jong 1980), were exposed in two excavations for the construction of locks downstream of the terrace intersection, near Tiel and near Wijk bij Duurstede (Fig. 3). These gravelly sands showed vertical aggradation (G.H.J. Ruegg unpublished) and suggest deposition by a Donjek-type river conforming to the outline given by Miall (1978).

The relative positions of Donjek versus Scott-type river sequences within the Rhine-Meuse delta support the lateral relation between the two sequentional types as suggested by Miall (1978).

Indications for a relation between meandering style and temperate climatic conditions are:

- The Holocene Rhine and Meuse river systems upstream of the coast-related anastomosing river zone show a meandering style.
- Virtually all investigated major northwest-European lowland rivers exhibited a change from braiding to meandering around 15 000 to 10 000 years ago, as argued for individual river systems among others by Pons & Schelling (1951), Kozarski (1983; cf. Fig. 5), and Schirmer (1983; cf. Fig. 6). Disappearance of the permafrost seems to be the most plausible cause of this change, in view of its rapid character and early Late Glacial timing.
- An initial laterally accretional setting has been found on top of a Scott-type braided river deposit upstream of the intersection in the Caberg Terrace Member near Maastricht (Figs 4, 7a, b). This initial lateral accretion marks the change from braiding to meandering. This occurred during the transition from a cold stage to a temperate-warm stage, as demonstrated by the mammal fauna (Van Kolfschoten 1985), between the Holsteinian and the Eemian interglacials.
- A temperate-climate meandering river sequence,-aged also between the Holsteinian and the Eemian interglacials, has been found, sandwiched between cold-climate braided river deposits, in a sandpit in an ice-pushed ridge near Wageningen (Ruegg 1991), downstream of the intersection (Figs 3, 8).

The degrading activity of meandering rivers is generally well-known. The following facts are consistent with this degradation.

- In many places in Europe, hard-rock sides of river valleys generally show bends indicating incision by

Fig. 7a. The Early Saalian Caberg Terrace Member in the Belvédère gravelpit, Maastricht, showing Scott-type braided river deposits.

meandering streams. For instance, fossil meander bends have been reported by Rohde (1989) in the Early to Middle Pleistocene Weser river valley in Germany.

- The often curved character of the boundaries between subsequent 'terrace gravel deposits' in southern Limburg can be attributed to the meandering river phases that occurred during the climatic optima between the cold times which are represented by adjoining gravel deposits. Figure 4 is part of a map which shows the similarity in dimension of member boundary curves and recent Meuse meanders (Felder & Bosch 1989).
- Settings in Germany mentioned by Schirmer (1974, 1983) indicate incision by Rhine courses that formed laterally accreted deposits.
- The recent fluvial deposits of the Rhine-Meuse system in the Netherlands are situated at a lower elevation than the adjacent fluvial, older Holocene deposits. The older settlements along river branches, between the anastomosing zone and the terrace intersection, are situated on the outer, erosional banks, presumably because of their relatively elevated position which offered favourable landing and living facilities.

Alternation of braiding and meandering river action

The alternation of braiding and aggradation during cold periods and meandering and degradation during temperate-warm periods has resulted in the well-known terraced river valley landscape upstream of the intersection (Figs 9, 10). On the basis of the above observations the schematic situation is probably as shown in Fig. 11a. The braiding and aggrading river fills the valley to a certain extent. Subsequent meandering deepens the valley even further than during the preceding meandering phase. The alternation of these processes leads to a position of meandering river deposits underneath braided river deposits in individual terraces.

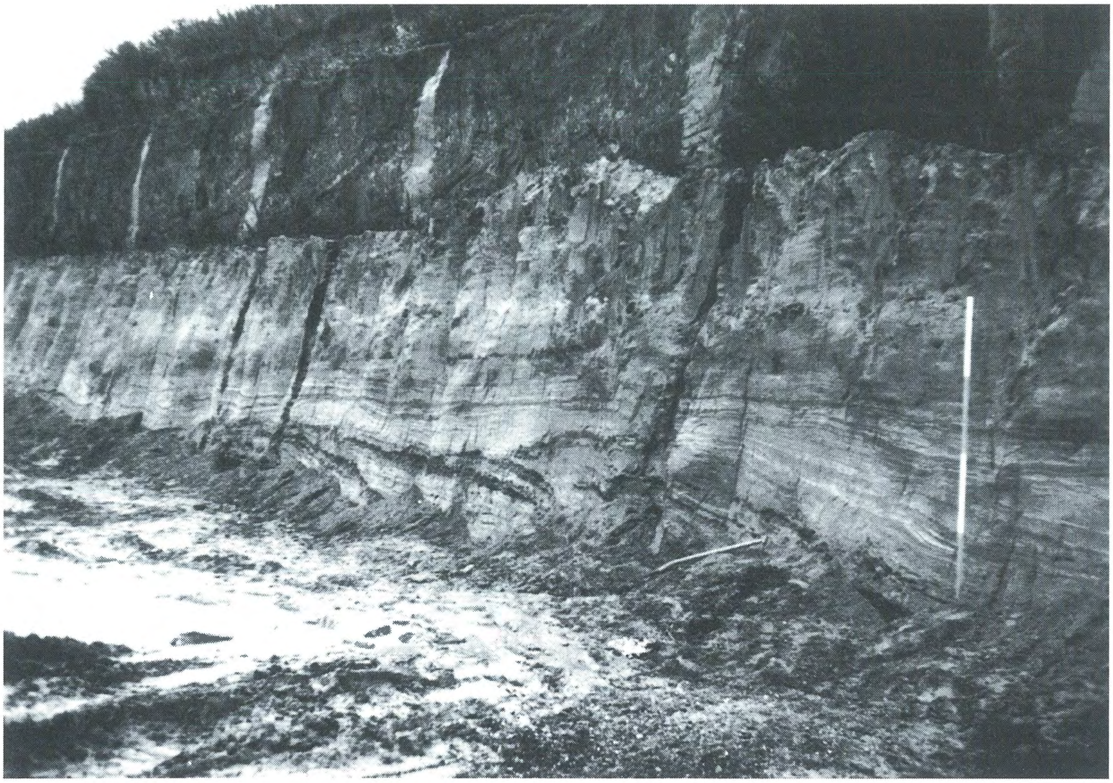

Fig. 7b. Lateral accretion near the top of the Caberg Terrace Member gravels, abruptly overlain by 0.5 to 1.5 m sandy overbank deposits. This sequence is overlain by slope and loess deposits (upper half of photograph); Belvédère gravelpit, Maastricht (bar has a 5-dm division).

Schirmer (1974) describes Middle Pleistocene Rhine deposits from the Frimmersdorf brown-coal pit near Grevenbroich in Germany. Here, a peaty silt complex is intercalated between gravelly strata. A figure by Schirmer shows a lower gravelly part that has a thickness of about 5 m, and that is incised into Miocene strata; the setting of this gravelly part suggests lateral accretion. The overlying peaty silts yield interglacial pollen spectra, which are interpreted as Holsteinian by Von der Brelie et al. (1959). According to W.H. Zagwijn (pers.comm.), this interpretation is still valid on the ground of the pollen data given by Von der Brelie et al. 1959. The overlying 10 m-thick gravelly deposits have a common, parallel-bedded terrace gravel structure; in this deposit intraformational ice-wedge casts and cryoturbations occur.

In a recent study, Maddy et al. (1991) describe this kind of relationship with regard to the fluvial sediments in the Avon valley in England, deposited between Anglian and Devensian (cf. Dawson 1987) (Fig. 12).

A Chinese example of a fluvial aggradation-incision alternation, in many respects comparable with the one discussed here, has been published by Porter et al. (1929).

Downstream of the intersection, the glacial and interglacial river deposits show a normal superposition, i.e. younger upwards, as is shown schematically in Fig. 11b.

Influence of the duration of cold and warm stages

In the geographical framework here described, the thicknesses of braided river deposits and the lateral extensions of braided as well as meandering river deposits are influenced by the durations of successive interglacial and glacial stages. For instance, the warm Eemian stage was very short compared to the preceding and subsequent cold stages. The overall scarcity of Pleistocene fine-grained sediments (fine sands and clays) in the Netherlands may be related to the relative

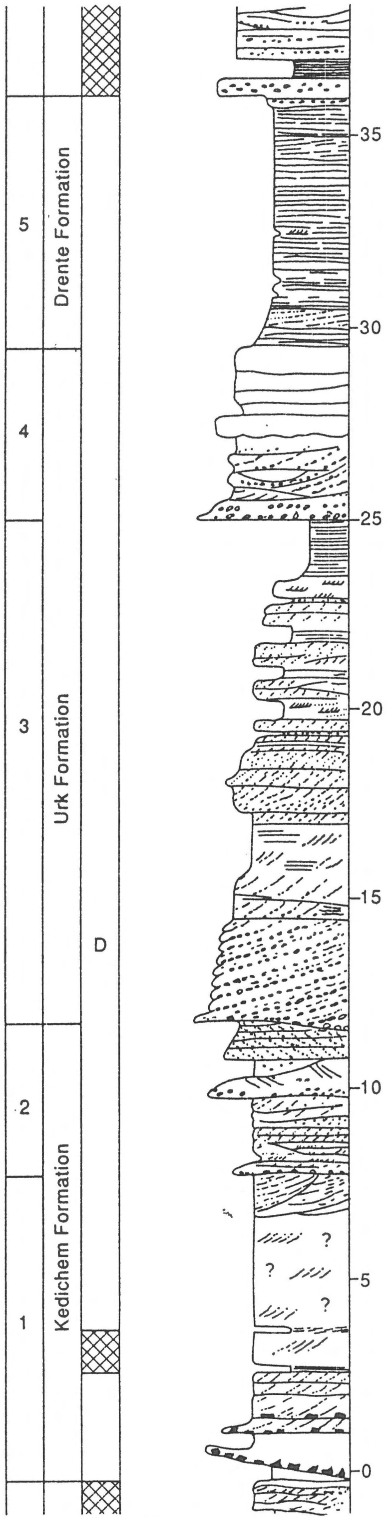

Fig. 8. Sequentional log of Middle Pleistocene deposits in a thrust sheet in the ice-pushed ridge near Wageningen (after Ruegg 1991). Units 2 and 4 are cold-climate braided river deposits; unit 3 is a laterally accreted warm-climate fluvial deposit. D denotes the thrust sheet; cross-hatched areas indicate overturned beds. Vertical scale in metres.

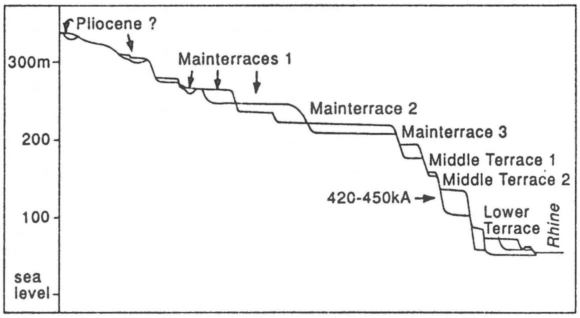

Fig. 9. Quaternary terrace sequence of the river Rhine in the uplift area of the Rhenish Shield between Koblenz and Bonn in Germany; KA = 1 000 years (after Zagwijn 1989).

shortness of the warm stages (with meandering river activity), compared to the much longer duration of the cold stages (with braided river deposition).

Thoste (1974, in Klostermann 1992) mentions a fluvial incision dating from the Allerød interstadial; the subsequent re-establishment of the aggradation during the Younger Dryas cold time not only filled this incision, but also covered the adjacent Weichselian terrace deposits.

Influence of sea-level movement upstream of the anastomosing river zone

During cold times, braided rivers caused aggradation into the then dry southeasterly North Sea area.

During warm times, this area was transformed into a shallow shelf sea. At the same time, the anastomosing river zone (discussed further on) shifted upstream. In turn, the terrace intersection shifted also upstream, be it over a shorter distance. Theoretically, the distance of landward shifting of the anastomosing river zone depends on the maximum height of the interglacial sea-level. However, grading of the river profile was counteracted by uplifting of the area upstream of the terrace intersection. Moreover, at the end of every warm time the grading process ended 'prematurely' when the next cold time began. The interaction of these two counteracting processes, incision versus uplifting, resulted in shifting of the terrace intersection.

Sea-level movements as such do not exert influence on the nature of the fluvial processes upstream of the anastomosing river zone. They only affect the terrace intersection. An in essence similar interpretation is

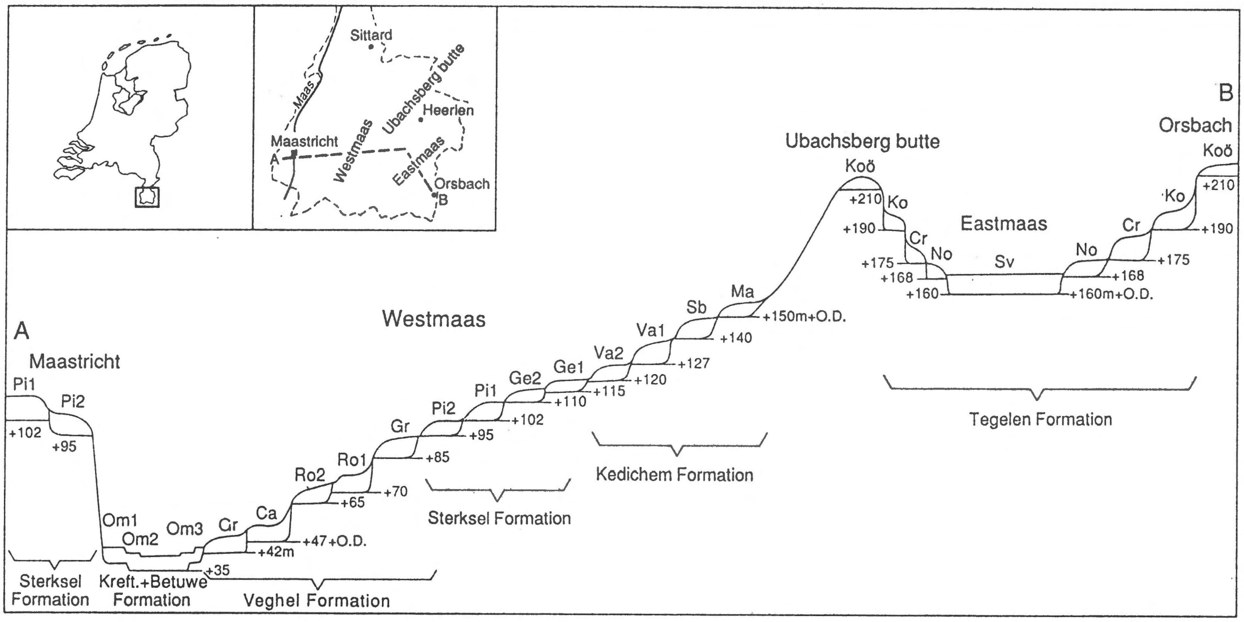

Fig. 10. Quaternary terrace sequence of the river Meuse near Maastricht and Aachen (after Felder & Bosch 1989). Abbreviations refer to local terrace names. Length of profile is 29 km.

advocated by Zonneveld (1974; and by K.M. Clayton in the discussion remarks).

The break from meandering to braiding

Assuming that the here-described changes from braiding to meandering are related to the disappearance of the permafrost, it seems logical to expect a relation between the transition from meandering to braiding, following an increase in instability of subaerial slopes, and a developing permafrost. Further studies will have to be done on the timing of the start of braided river deposition during climatic cooling. Presumably, the dating of the youngest and uppermost fine-grained and peaty meandering river deposits, covered under the braided river sediments, can contribute to such studies.

Anastomosing and alluvial fan river deposits in the Netherlands

Anastomosing rivers and their deposits have been defined by Smith & Smith (1980) and Smith (1983). In the coastal area of the Netherlands, an anastomosing Rhine-Meuse river zone has existed during the Holocene (Törnqvist 1993). At present this zone is a 60 km-wide zone adjacent to the coast, as can be deduced from Van Dijk et al. 1991. In the western part of the Netherlands, deposits resembling those of anastomosing rivers are known from strongly transgressive Early Pleistocene interglacials. A spatial relation exists between meandering upstream and anastomosing downstream. The only effects of sealevel changes on the Rhine-Meuse river system are changes in the location and shape of the anastomosing zone, and in the terrace intersection. A case of upstream shifting of the anastomosing zone was reported by Hageman (1969), with Late Atlantic anastomosing river deposits overlying Early Atlantic meandering river deposits.

Alluvial-fan deposition is connected with meltwater streams from the inland-ice sheets breaking through ice-pushed ridges (cf. Ruegg 1977). This occurred during the Saalian glacial stage. Sandur streams flowed into the Rhine-Meuse braided river system.

Implications with regard to mapping and planning

- A consistent concept is available for river processes and their preserved deposits in the studied area. It can be summarized in the alluvial architecture shown in Figs 11a and b.

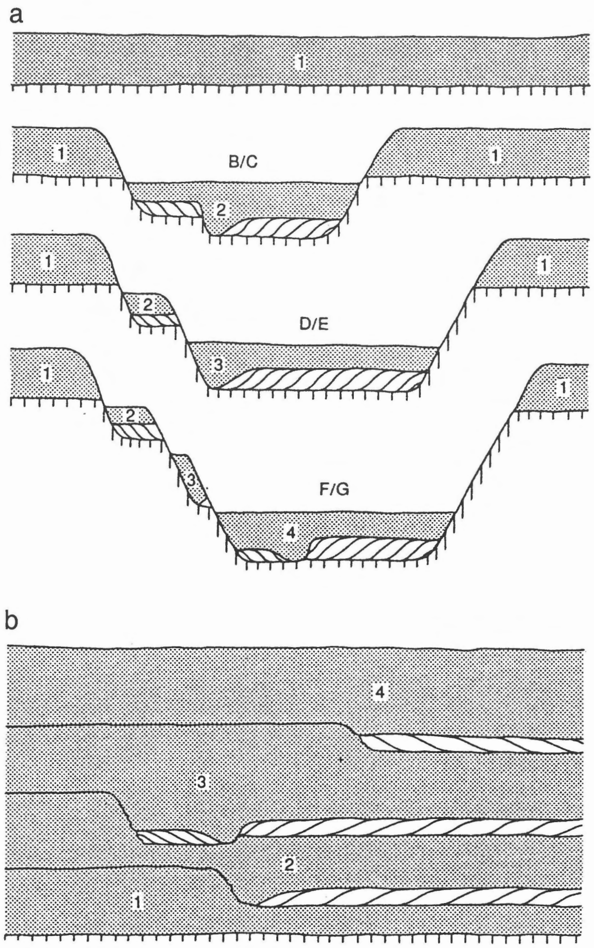

Fig. 11. Schematic diagram of the relation between meandering (with lateral accretion symbol) and braided river deposits (stippled). a. Upstream of the terrace intersection. b. Downstream of the terrace intersection. A to G indicate subsequent stages. 1 to 4 indicate deposits of the same braided rivers in both figures.

- Sealevel movements do not demonstrably affect the synchronous fluvial processes and deposits upstream of the coast-linked anastomosing river zone. They do, however, influence the terrace intersection.
- In the investigated Pleistocene fluvial deposits, aquifers may be split up more effectively by intercalated fine-grained meandering river layers than by fine-grained braided river layers.
- Upstream of the terrace intersection, fine-grained deposits that potentially can be dated palaeontologically (overbank and cut-off sediments of meandering rivers) can be found underneath coarse-grained braided river deposits.

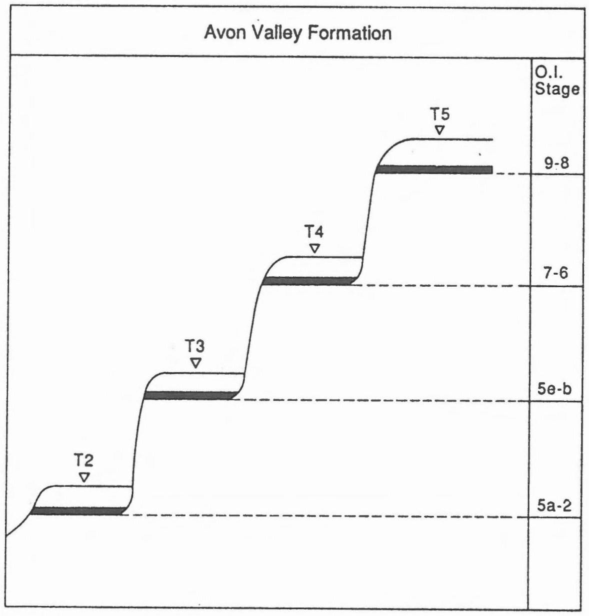

Fig. 12. Outline of post-Anglian to pre-Devensian lithostratigraphy in the Avon valley in England. Temperate-climate fossiliferous beds (in black) are overlain by coarse-grained fluvial terrace gravels (after Maddy et al. 1991, simplified).

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