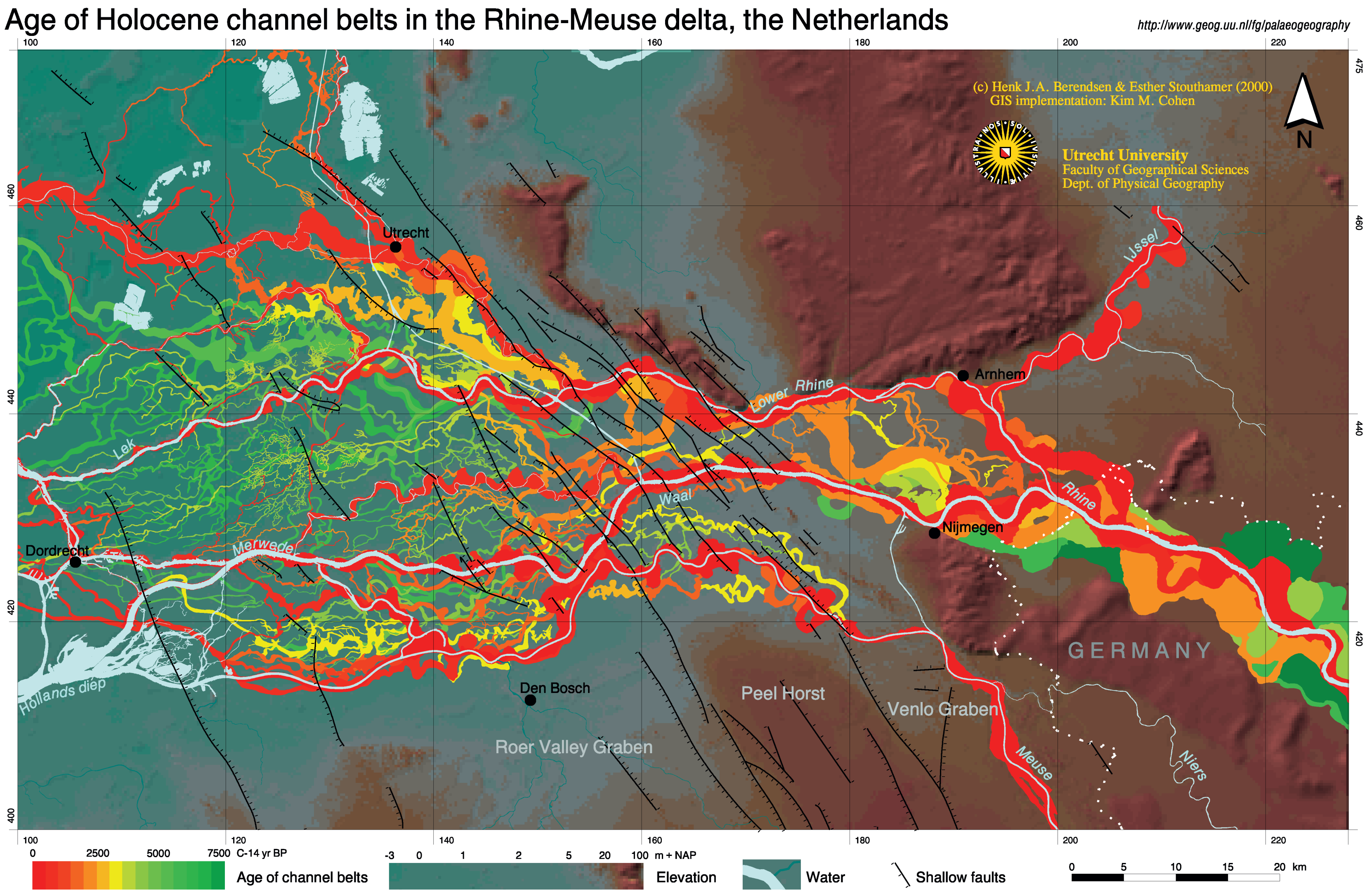
Palaeogeographic development of the Rhine-Meuse delta, The Netherlands

Palaeogeographic development of the Rhine-Meuse delta, The Netherlands

Henk J.A. Berendsen & Esther Stouthamer

Koninklijke Van Gorcum - Assen 2001



[FIGURE 4.12] *Simplified geological map, showing the ages of Holocene channel belts in the Rhine-Meuse delta, The Netherlands. The Peel Horst and the Roer Valley and Venlo Grabens are clearly visible in the topography. The hills between Arnhem and Utrecht and south of Nijmegen are ice-pushed ridges, formed during the Saalian glaciation (Oxygen isotope stage 6 or older). After Berendsen & Stouthamer (2000)*

[5] Maps and cross-sections

[5.1] The geological-geomorphological map and palaeogeographic maps of the Rhine-Meuse delta

by H.J.A. Berendsen, K.M. Cohen & E. Stouthamer

The geological-geomorphological map of the Rhine-Meuse delta (Addendum 1) is essentially based on corings and maps, made by undergraduate and Ph.D. students of physical geography at Utrecht University. The original maps were to the scale of 1 : 10,000. These maps were reduced to the scale of 1 : 50,000, digitized, and stored in a Geographical Information System (GIS), together with information on the age of the mapped phenomena. The printed map has a scale 1 : 100,000. Projection and coordinates are based on the Dutch map coordinate system (Topographical Survey of the Netherlands). The topography is a simplified version of the topographical map 1 : 50,000, made by the Central Bureau of Statistics (CBS) in the Netherlands. For the adjacent part of Germany a simplified topography has been digitized from the topographical map 1 : 50,000 of the Landesvermessungsamt Nordrhein-Westfalen, Germany.

For the geological mapping, many other maps have been used as supplementary sources of information, especially around the fringes of the delta. These include: the Geomorphological map 1 : 50,000 of the Netherlands (Staring Centrum), the Soil map of the Netherlands 1 : 50,000 (Staring Centrum), and maps published by: Edelman et al. (1950), Van Diepen (1952), Van der Sluijs (1956), Van der Schans (1957), Sonneveld (1958), Zonneveld (1960), Pons (1966), Havinga (1969), Havinga & Op 't Hof (1975), Verbraeck (1970, 1984), Louwe Kooijmans (1974), Van de Meene (1977), Braun & Thiermann (1981), Bosch & Kok (1994), Huisink (1999) and Tebbens (1999).

The channel belt width shown on the map is the width of the sandbody. The only exception to this rule are the embanked floodplains: the whole area between the dikes has been indicated as channel belt. This is not always correct: in some embanked floodplains remnants of former floodplains or older channel belts have been preserved, but these have been omitted from the map. More details of the embanked floodplains are given in the 'sand depth-atlas' produced by Berendsen et al. (2001) that also appears as a supplement to the Ph.D. thesis of A.W. Hesselink. Natural levees and residual channels are also not indicated on the map, although these have been mapped in great detail. Crevasse splays have been indicated, because they may be important to understand the mechanism of avulsion. However, the occurrence of crevasse splays is not everywhere known in enough detail. For example, west of x-coordinate 120 virtually no crevasse splays are indicated on the map. This does not mean that they don't exist here; they simply have not yet been mapped in enough detail because they are small and occur often at great depth.

The map (Addendum 1) shows the ages of the Holocene channel belts, organized in 500 yr (± 100 yr) time intervals. Time is expressed as conventional radiocarbon years BP. Datings of the channel belts were carried out using the methods described in Chapter 4. In addition, numerous other sources were used; these are all mentioned in Appendix 1 and 3. The moment of abandonment of a channel belt determines its color on the map. The number of the channel belts refers to Appendix 4, in which the period of existence is indicated, both in radiocarbon years and in calendar years. A summary of all dating evidence is given in Appendix 3, as well as references. The map shows only the fragments of channel belts that survived erosion by younger river systems. In the GIS, reconstructed eroded parts of the channel belts were also implemented, to enable the production of palaeogeographic maps for any given moment during the Holocene. Dates of the upstream and downstream channel belt fragments of a river system may sometimes be slightly different, because the ages of channel belts are usually based on ^{14}C dates. Therefore, it may sometimes seem that a river system has no upstream or downstream continuation during part of its period of existence. This is not an error in the reconstruction, it rather reflects the accuracy of channel belt dating. The palaeogeographic maps are believed to be accurate to within ± 200 years.

Pleistocene deposits and landforms, as well as Holocene intertidal deposits, are represented in distinctly different colors. Late Glacial terraces of the Rhine and Meuse are indicated, as well as eolian coversands and ice-pushed ridges. However, in general, much detail related to the Pleistocene deposits and landforms has been omitted from the map, as the main purpose was to give detailed information on the Late Weichselian and Holocene river systems.

A series of 16 palaeogeographic maps was made (Addendum 2). Channel belts with active rivers at a specific time are shown in yellow; abandoned channel belts are shown in green. Parts of channel belts that have been eroded (and therefore had to be reconstructed) are shown in a lighter yellowish hue.

The 10,000 yr BP map shows the palaeogeography at the onset of the Holocene. Because of the influence of the Late Weichselian topography on the Early Holocene delta, the 7000, 6500 and 6000 yr BP maps show Early Holocene channel belts, backfilling the Late Weichselian valleys. In the later part of the Holocene, the Late Weichselian valleys were largely filled, and eventually were completely covered by Holocene fluvial deposits. The maps of 5500 yr BP – 2000 yr AD therefore focus on the channel belts of the Holocene delta, and Pleistocene deposits are omitted, or only shown where they outcrop at present. Present rivers, canals and lakes have been added in all maps for reference purposes.

The GIS of the channel belt fragments

The geological-geomorphological map of the Rhine-Meuse delta (Addendum 1) and the timeseries of palaeogeographic maps (Addendum 2) are derived maps from a Geographical Information System (GIS). The channel belt fragment GIS is made up of circa 4000 labeled polygons in vector format, and was developed in Arcinfo (ESRI). Additional information on the geology and geomorphology of Pleistocene deposits and of Holocene marine deposits bordering the delta was also incorporated in the GIS. In the GIS, channel belts are identified by the same number as is Appendix 3 and 4. The mapped channel belt fragments (Appendix 1) are also labeled using these numbers. Intersections of channel belts are coded in such a way that the relation to the individual palaeo-river courses is maintained. Other attributes are: name of the channel belt, date of beginning sedimentation, date of ending sedimentation and period of existence (all in ^{14}C yr BP). These attributes are stored in a relational database. If the table of attributes in the database is changed, the system automatically updates the derived maps. New attributes can be added if necessary.

All channel belt fragments have been stored in a single layer as a mosaic of polygons and not as a layered system. Therefore the GIS is a database of channel belt fragments rather than a database of channel belts. In other words, the system is based on raw data and independent of the reconstruction the researcher has in mind. Modifications or alternative reconstructions can be made easily. In this way, the GIS was not only used as a mapping tool, but also as an analysis tool. The time series derived from the GIS (Addendum 2) for example, was used both to visualise and to test the palaeogeographic reconstruction.

To produce the printed maps of Addendum 1 and 2, the GIS data files were subsequently converted to Freehand 8.0 (Macromedia) using MAPublisher 3.5 (Avenza), to cartographically enhance map production at the Cartographic Laboratory of the Faculty of Geographical Sciences, Utrecht University. The GIS is in a vector format, which provides scale-independent map output. Conversion to a raster format is simple. The raster format can be imported in PCRaster (Utrecht University), which implies that derivatives of the map can also be used in dynamic modelling.

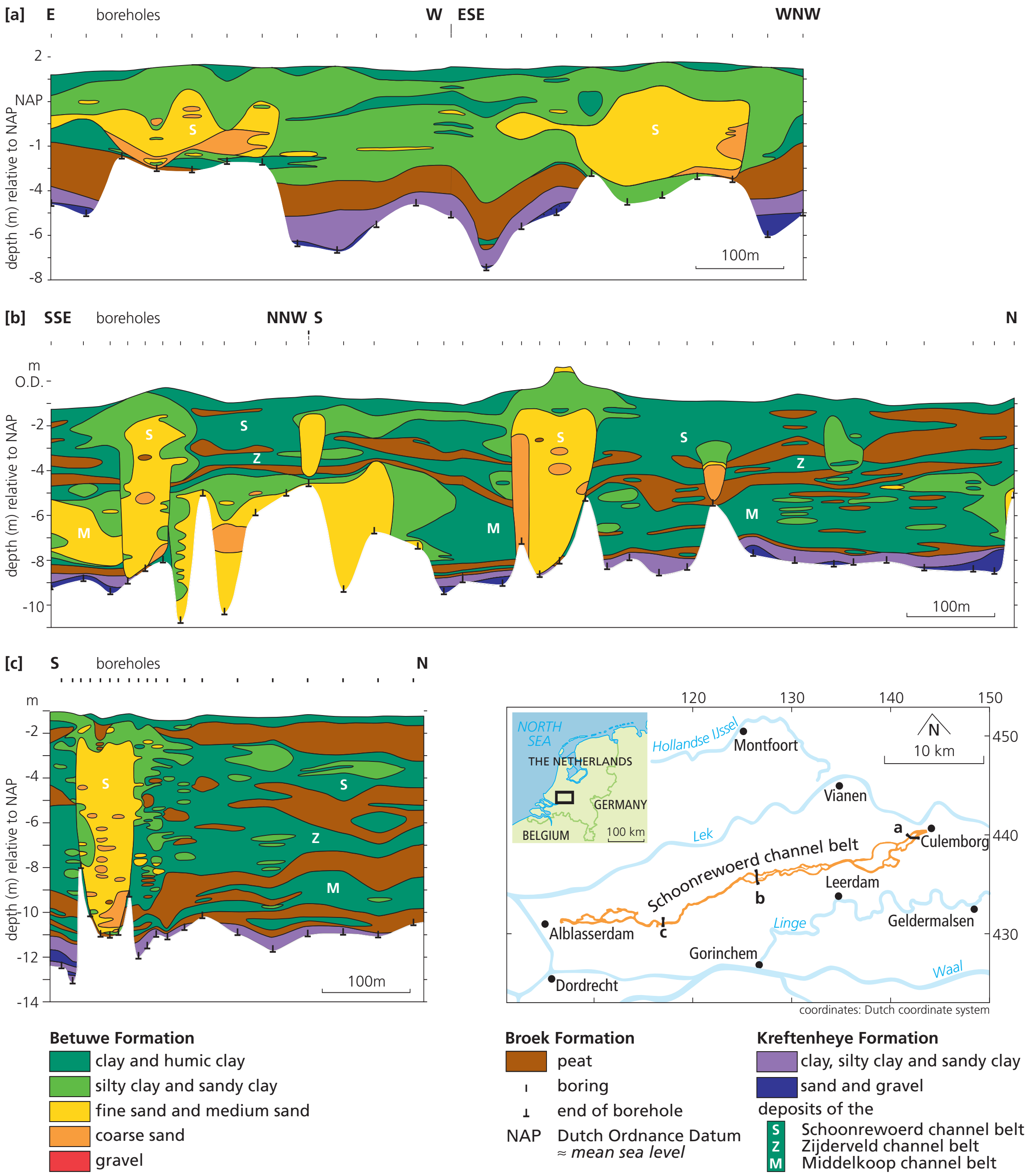
[5.2] Longitudinal (W-E) geological cross-section of the Rhine-Meuse delta

by H.J.A. Berendsen, W. Boasson, K.M. Cohen, R.F.B. Isarin, B. Makaske & E. Stouthamer

Addendum 3 is a W-E cross-section of the Rhine-Meuse delta. N-S cross-sections of the Rhine-Meuse delta are available from our database at intervals of a few km. A detailed N-S cross-section was published by Törnqvist (1993a). Detailed cross-sections of various channel belts were published by e.g. Berendsen (1982), Berendsen ed. (1986), Törnqvist (1993a), Weerts (1996) and Makaske (1998). Generally, these cross sections show a decrease of sandbody width-thickness ratio in a longitudinal direction (Figure 5.1). In addition, cross-sections were published as an addendum to the geological map of the Netherlands, to the scale 1 : 50,000 (Verbraeck 1970, 1984, Van de Meene 1977, Van de Meene et al. 1988, Bosch & Kok 1994). However, a detailed W-E cross-section of the entire delta so far has not been published. Because of its unique character and relatively great depth, a 150 km long longitudinal (W-E) geological cross-section of the Rhine-Meuse delta was included in this book as Addendum 3. The location of the cross-section is indicated in Addendum 3 as well as in Addendum 1.

Construction

The cross section was constructed by Boasson (2000) during his internship as a MSc. student of physical geography, at the 'Archaeology Project Group (APG)', which is a co-operation between the Betuweroute Project Organisation and the State



[FIGURE 5.1] *Three cross sections of the Schoonrewoerd channel belt: (a) near Culemborg, (b) near Noordeloos, (c) near Molenaarsgraaf. Width/thickness ratio of the sandbody decreases from 50-100 near Culemborg to 7.5 near Molenaarsgraaf. After Makaske (1998)*

Service for Archaeological Investigations (ROB). The other authors of this section, both from the APG and Utrecht University, supervised the construction of the profile and provided additional information.

The profile stretches along a planned railroad from Rotterdam harbour into Germany. Several companies are involved in the preparations and geotechnical research for the construction of the railroad, e.g. 'GeoDelft', 'Grontmij-De Weger', 'Arcadis (Fugro) ingenieursbureau', and 'Holland Railconsult'. These companies carried out corings at 500 m intervals, and performed eight cone penetration tests per kilometer to a depth of almost 30 m. Most of the corings were only described from a geotechnical point of view. A geological interpretation of the cores often was not made.

The APG is mainly concerned with archaeological excavations that are associated with the construction of the new railroad. According to new legislation, based on the Treaty of Malta, many archaeological sites around the new railway have to be protected, and, if necessary, excavated, before they disappear forever. In addition, this group carried out sedimentological and morphological studies around known archaeological sites. The cores collected for these studies were described according to the system used in this book (section 4.2).

To construct the W-E cross-section all available geotechnical and geological information has been collected and re-interpreted. The main purposes of this cross-section, as defined by the APG, were:

✧ to be able to interpret the location of archaeological sites in a geological context;
✧ to indicate sites of potential archaeological value, and to predict where new areas of archaeological interest may be found;
✧ to present an overview of the archeological sites in a geological context.

During construction, the section was checked against corings from our archives, and cross sections published by the Netherlands' Geological Survey (TNO-NITG). The Pleistocene formations, indicated in the lower part of the cross section, are based on the information provided by the drilling companies. This information has not been checked by further study, and therefore should be used carefully. For subdivision of the Holocene formations, the geological-geomorphological map (Addendum 1) and the palaeogeographical maps (Addendum 2) were used, as well as the geological map of the Netherlands to the scale 1: 50,000, and the 'sand depth atlas' (Berendsen et al. 1994). Because of difficulties interpreting some of the borehole descriptions and cone penetration tests, some detail was lost. For example, the Wijchen Member could not be indicated, and subdivision of humic clays and peats was not possible. Gyttjas also could not be properly recognized.

General description of the cross-section

To facilitate description, distance is indicated in km at the top of the section (scheduled railroad kilometer marks). For comparison with Addendum 1, also the x-coordinates according to the Dutch coordinate system are indicated. The western part of the section, between km 416 and 434, is outside the geological-geomorphological map (Addendum 1).

The section primarily gives detailed information on the Holocene stratigraphy, but underlying formations are also shown to a depth of 20-30 m. The underlying formations include the Older and Middle Pleistocene Kedichem, Sterksel and Urk Formations, the Saalian Drente Formation (lithostratigraphy according to Zagwijn & Van Staalduinen 1975) and the Kreftenheye and Twente Formations (lithostratigraphy according to Törnqvist et al. 1994). In the deeper substrate glaciotectonically deformed (ice-pushed) deposits occur between km 70-80, and between km 96-100. These deposits have been indicated as Drente Formation. Strictly speaking, they mainly consist of fluvial deposits of Middle and Older Pleistocene age, and only partly belong to the Drente Formation.

The top of the Kreftenheye and Twente Formations is of Weichselian age. The Kreftenheye and Twente Formations underlie the Holocene Westland and Betuwe Formations (lithostratigraphy according to Berendsen 1982), although the Twente Formation sometimes crops out as eolian dunes (Delwijnen Member) that were formed during the Younger Dryas stadial. The sand was blown out of the Younger Dryas braidplain and was deposited on top of the slightly higher Pleniglacial Lower terrace (see section 7.3). In the section numerous eolian dunes occur, but none of them reaches to the surface. Examples are found at km 202, 535, 13, 14 and 103. In the cross-section, the highest dune is found at km 14. The top of this dune is at 4 m –NAP (NAP = Dutch Ordnance Datum ≈ mean sealevel).

The western part of the section, between the coast and Gorkum (km 28), is now below sealevel. This is roughly the area where fluvial sedimentation was influenced by tides. In the eastern part of the section, the land surface rises to an elevation of ~13 m +NAP. In the area upstream of Gorkum the average gradient of the land surface is about 15 cm/km, but the gradient line is deformed where the section crosses the Peel Horst. The Peel Horst clearly stands out as a topographically higher area between km 48 (Geldermalsen) and 66 (Ochten). Addendum 1 shows, that these locations exactly match the main faults bordering the Peel Horst. This suggests, that tectonic deformation still is important for the morphology of the present landscape, a conclusion that is confirmed by our studies of gradient lines and avulsions (Chapter 9). However, in the cross-section, large channel belts of meandering rivers are present in this part of the Peel Horst, which may have built high natural levees. This could in part also explain the higher topography. In other words, the difference in surface elevation may not be caused exclusively by differential tectonic movements.

In the Roer Valley Graben, channel belts generally are narrower and straight, with the exception of the youngest channel belts (Linge, Waal), which are clearly meandering west of the Peel Boundary Fault. This may be explained as a result of increased tectonic activity in recent time (according to Schumm (1986), an increase of gradient may result in an increase of meandering), or as a result of increased discharge (see also sections 9.4 and 9.8). Large meanders, showing considerable lateral migration, occur especially in the area around the Peel Boundary Fault (Addendum 1). The Maas also formed large meanders on the Peel Horst. This is explained as a result of the easily erodible substrate near the southern margin of the delta, which enhanced lateral migration. However, faults may also have influenced the meandering (Cohen, in prep.). The floodbasins east of the Peel Boundary Fault consist essentially of clay, whereas west of the Peel Boundary Fault humic clay and peat prevails.

Differences in elevation of the top of the Kreftenheye Formation are seen at various locations (e.g. at km 55, 67-68, 95-98), but these are not all caused by differential tectonic movements. The top of the Kreftenheye Formation consists of two terraces,

that have a difference in elevation of ~2 m in the east, and ~1 m in the central part of the cross section. However, at other locations, where only the Pleniglacial Lower terrace is present, we found displacements of the order of magnitude of 1-2 m in the top of the surface of the Kreftenheye Formation (Cohen, in prep.).
Between Rotterdam (km 410) and Gorkum (km 28) an almost continuous layer of peat was formed, that is only dissected by narrow channel belts. East of Gorkum, the peat layer is much thinner, and east of Tiel (km 59) almost no peat was found.

In the cross-section, an alternation of fluvial styles can be observed. The top of the Kreftenheye Formation was formed by braided rivers (Berendsen et al. 1995). Directly overlying the Kreftenheye Formation (e.g. at km 306) meandering river deposits are found, characterized by relatively wide channel belt sandbodies. At a higher stratigraphic level, channel belt sandbodies are found with a low width/thickness ratio, especially west of km 47. These generally are straight anastomosing channels, that are characterized by large-scale crevassing. Examples are found near km 0, 5, 15 and 17. This succession of fluvial styles is characteristic for the western part of Rhine-Meuse delta (see also section 9.8 for further explanation). In the eastern part of the cross-section, Holocene aggrading channel belts have always been meandering. These channel belts are also younger, because in this area incision prevailed until about 5000 yr BP (Figure 2.9). Aggradation started only after the terrace intersection of Holocene deposits and the Pleniglacial Lower terrace shifted upstream of this area. It is remarkable that, from about 6000 yr BP to 3000 yr BP, the E-W transition in fluvial style from meandering to straight almost coincided with the Peel Boundary Fault.

Although the approximately 50 cm thick Wijchen Member was not distinguished in the cross-section, we know from other cores in this area that many channel belts eroded down onto the resistant deposits of the Wijchen Member, which is often found immediately underneath the channel lag deposits of small distributaries. Examples are found near km 304, 504, 534, 1, 5, 7, 21, 35, 54. Large channel belts eroded to a depth of a few meters into the Kreftenheye Formation. In those cases the boundary between the Holocene channel deposits and Kreftenheye deposits can only be determined accurately if channel lag deposits are found. The channel lag deposits of the Holocene channel belts often contain a high percentage of gravel, clay pebbles, pieces of wood, rounded 'wood pebbles', fresh-water molluscs, and sometimes large pieces of reworked peat. However, channel lag deposits were not always recognized in the cores, used for this cross-section.

Detailed description of the cross-section

A more detailed description of the cross-section is given below. Numbers between parenthesis refer to the numbers of the channel belts that are extensively described in Appendix 3. In Appendix 4 numbers and ages are indicated (in ^{14}C yr BP and cal yr BP).

Section west of Zwijndrecht (km 534)

In the western part of the delta (km 416-413) the Holocene sequence is about 20 m thick. The variation in the top level of the underlying Kreftenheye Formation is more than 2 m. Similar variations were found elsewhere within the Lower terrace (compare Figure 7.7). In the extreme west, the Kreftenheye Formation is overlain by the Westland Formation, of which marine deposits are visible in the section, namely the older Calais deposits and the younger Duinkerke (= Dunkirk) deposits. These deposits are sometimes separated by a thin peat layer (Broek Formation). There is only one fluvial channel present in this part of the section: the Oude Maas (km 415), which is the downstream continuation of the Oude Maasje (132) channel belt, that is indicated on the geological-geomorphological map (Addendum 1). East of km 408 Duinkerke (= Dunkirk) deposits occur at the surface, but Calais deposits are lacking. Instead, in the lower part of the Holocene sequence, fluvial deposits occur under a layer of peat. Around km 306 an Early Holocene channel belt is present. This channel has not been mapped and is only dated relatively. It belongs to the generation of the Benschop river system (7600-5350 ^{14}C yr BP). Several narrow channels occur at a higher level, e.g. at km 304, 201 and 540, and one large channel: the (former westward continuation of the) Waal (174) channel belt. A low complex of Younger Dryas eolian dunes seems to be present between km 203 and 200. This complex is probably related to the Barendrecht eolian dune, that was used in several sealevel studies (e.g. Jelgersma 1961, Van de Plassche 1982). In recent years, new AMS ^{14}C samples have been collected at the Barendrecht dune complex (Appendix 1, samples Barendrecht), but results have not yet been published.
In general, the section shows less details between km 537 and 534, because this part of the section was drilled by a different company. East of km 537 no marine deposits occur in the section. The oldest Holocene channel belt (km 306) is relatively wide; younger channel belts are narrow and have a low width/thickness ratio of the sandbody (e.g. at km 304). Locally Younger Dryas eolian dunes occur, for example around km 201 and 535.

Section between Zwijndrecht (km 534) and Gorkum (km 28)

The Holocene sequence here essentially consists of two clastic layers, separated by peat. Between km 3 and 4, the Slikkerveer

(154) and Waal (174) channel belts can be recognized (now a channel named 'Noord' is present here), as well as the Papendrecht (140) channel belt (km 6-7), that was inhabited during the Late Iron Age and Roman Age. At km 8, 9 and 16 the Wijngaarden (186) channel belt is present, at a depth of about 9 m –NAP. On the geological map, to the scale 1 : 50,000 (Bosch & Kok 1994) the Wijngaarden (186) channel belt is erroneously connected to the much younger Schoonrewoerd (152) channel belt (not visible in the cross-section). The course of the Wijngaarden (186) channel belt has not been mapped accurately, but channel belts of approximately the same age occur at several locations further to the east (e.g. at km 15-16, 19). This suggests, that the channel can be traced to the east along the profile line. On our geological-geomorphological map (Addendum 1) we presumed that a connection to the Gorkum-Arkel (52) channel belt existed, but this connection remains to be established. Further to the east (km 14-24), the Holocene sequence consists almost entirely of peat. The maximum thickness of the peat is about 8 m. Near km 14-15 Younger Dryas eolian dunes occur, that were inhabited during the Neolithic. Radiocarbon samples were collected from the flanks of these dunes, in order to construct groundwater gradient lines, as shown in Figure 2.8. Results have not yet been published, but the dates are incorporated in Appendix 1 (samples Giessendam and De Bruin). At km 18 the section crosses the Giessen (407) perimarine tidal creek, and at km 20 the Schaik (158) channel belt. The section crosses the narrow Spijk (158) channel belt at four locations, namely near km 20, 21, 22 and 25. The unnamed narrow channel belt at km 24 may be a crevasse channel of the Schaik channel belt. Near Gorkum, the Linge (97) channel belt is crossed (km 27-28).

Section between Gorkum (km 28) and Tiel (km 59)

East of Gorkum, the Holocene deposits consist largely of clay, with thin intercalated peat layers. Here, many narrow channel belts are found, that are similar to the Schoonrewoerd (152) and Zijderveld (197) channel belts, that occur further to the north. The Gorkum-Arkel (52) channel belt is crossed at km 29. The narrow Spijk (158) channel belt is once more crossed at km 31-32, and the Vuren (172) channel belt at km 32-34. Further east, the narrow Broekgraaf (31) channel belt was found at km 36, 39, and 40. The Deil channel belt, at km 43 and 50-51, is of the same age. The Gellicum (51) channel belt is crossed at km 37, the Enspijk (44) at km 38. The younger Eigenblok (43) channel belt, at km 41 and 42, was inhabited during the Neolithic and Bronze age. Inhabitation here is also found on crevasse splays.

The Meteren (110) channel belt is found at km 48; the Esterweg (47) channel belt at km 49. The Linge (97) channel belt crosses the section at km 28, 53 and 58-59, and the Avezaath (13) channel belt at km 56-57. The underlying Kreftenheye Formation is found at a deeper level between km 54 and 59. In this area the Peel Boundary Fault is located. However, the situation here is complicated by the presence of a Younger Dryas braidplain (buried Terrace X) in the subsurface, that is incised into the higher elevated Pleniglacial Lower terrace. The Younger Dryas braidplain is not indicated separately in the cross section, but it can be recognized, because the top of the Kreftenheye Formation is at a lower elevation.

Section between Tiel (km 59) and Zevenaar (km 106)

East of the Amsterdam-Rijnkanaal (km 61) peat generally occurs only in thin layers in the middle of large floodbasins. In the cross-section peat is almost absent. At km 61-64 the Echteld (42) channel belt is crossed. Further to the east, the Ochten (123) channel belt is found at km 65-66 and 67, the Westerveld channel belt at km 70, the Boelenham (24) channel belt at km 76, the Distelkamp-Afferden (37) channel belt at km 77-78, and the Herveld (64) channel belt at km 80-82. Some smaller and older channel belts are found in the cross-section, but these are not indicated in the geological-geomorphological map (Addendum 1).

The large Ressen (146) channel belt is found between km 85-92, the Baal channel belt at km 93 and the Walbeek (178) channel belt at km 94 and 98. Between km 96-98 an incised Younger Dryas braidplain (Terrace X) is crossed again (not indicated in the section). A deeply incised meandering channel occurs at km 96. It was also found in our corings, but it could only be traced over a length of about 1 km. Incised meanders within the Younger Dryas braidplain are common, and have also been found at other locations (Addendum 1 and 2, and Makaske & Nap 1995).

In the easternmost part of the section, the Oude Rijn-Pannerden (135) channel belt is found, just west of the Pannerdens Kanaal that was dug in 1707 AD. Nowadays the Pannerdens Kanaal transports 30 % of total Rhine discharge (Van de Ven 1993). Because a tunnel is projected here, corings are deeper, and reach into the underlying ice-pushed deposits. Near Zevenaar, Weichselian Late Glacial eolian coversands occur underneath a cover of natural levee and dike breach deposits. The W-E cross section ends close to the Dutch-German border. The Holocene cover is only about 2.5 m thick in this area.

[6] Aggrading Holocene river systems

The 206 aggrading Holocene channel belts in the Rhine-Meuse delta have been organized into 'river systems' (cf. Berendsen 1982) in order to facilitate the description of the Holocene evolution. An example is shown in Figure 6.1. A *river system* is defined as a complex of channel belts that have certain common characteristics. These may involve: age, source area, discharge volume, or direction of flow. The following river systems are distinguished: Benschop river system, Utrecht river system, Krimpen river system, Maas river system, Est river system, Graaf river system, Linschoten river system. R*iver courses* are defined as a complex of channel belts that existed simultaneously.

[6.1] The Benschop river system

The oldest aggrading Holocene river system shown on the geological-geomorphological map (Addendum 1) is the Benschop river system (name given by Berendsen 1982). This river system comprises the following channel belts: Winssen (189), Maurik (104), Tienhoven (162), Autena (12), Kortenhoeven (84), Achthoven (3), Benschop (15), Wiersch (183), Willeskop (187), Oudewater (137), Bergambacht (16), Berkenwoude (18), Kadijk (79), Zuidbroek (203), Middelkoop (111), Nieuwland (120), Vuilendam (171), Pinkenveer (142), Gorkum-Arkel (52), Cabauw (35), Gouderak (53), Waddinxveen (177). Details are given in Appendix 3.

The channel belts of the Benschop river system occur at relatively great depth in the western part of the Netherlands, and are shown in the darkest green color on the map (Addendum 1). In the western part of the delta they have only been mapped by the Netherlands Geological Survey (TNO-NITG), and relatively few radiocarbon dates are available pertaining to the age of the individual channel belts. Our age reconstruction is based on the available ^{14}C-data and GTS-lines. Correlations of channel belt fragments are mostly based on the width of the channel belts, GTS lines and lithological cross-sections. For the westernmost channel belt fragments, accurate GTS-lines could not be made, because of the limited number of corings in this area. Our 1999 and 2000 field campaigns, carried out in the area south of Gouda (Figure 1.1), showed that the channel belts in this area are generally correctly mapped by the Netherlands Geological Survey (Bosch & Kok 1994), but the Benschop channel belt is made up of at least three generations of channel belts. This confirmed our expectations, based on the palaeogeographic reconstruction shown in Addendum 2.

[6.2] The Utrecht river system

The Utrecht river system (names and descriptions given by Berendsen 1982) came into being as a result of a major avulsion near the Peel Boundary Fault at Wijk bij Duurstede (Addendum 2, compare the maps of 6000 and 5500 yr BP). This resulted in a new course, that seems to be independent of the Late Weichselian valley. This course initially consisted of the Werkhoven (181) and Oude Rijn (133) channel belts. Characteristic for the Utrecht river system is, that channel belts of different ages occur east of Utrecht (e.g. the Werkhoven (181), Houten (74) and Kromme Rijn (85) channel belts), but they all rejoined and followed the same course to the sea, through the Oude Rijn (133) channel belt.

The Utrecht river system comprises the following channel belts: Werkhoven (181), Houten (74), Kromme Rijn (85), Zeist (195), Oudwulverbroek (138), Vecht (168), Angstel (10), Oud-Aa (129), Oude Rijn (133), and Heldam (62). Upstream contributaries of the system are the Leuth (93), Zandvoort (193), Meerbroek (105), Baal (14), Klein Baal (83), Zandbaal (192), Walbeek (178), Bredelaar (29), Ressen (146), Herveld (64), Wuustegraaf (190), Santacker-Driel (149), Snodenhoek (155), Homoet-Kamp (69), Boelenham (24), Ingen (77), and Lienden (95) channel belts.

The Oude Rijn (133) channel belt existed from approximately 5500 yr BP until the damming of the Kromme Rijn (85) near Wijk bij Duurstede in 1122 AD (828 yr BP) (Berendsen 1982), and therefore is the channel belt with the longest life span (interavulsion period).

[6.3] The Krimpen river system

The Krimpen river system comprises the following channel belts: Oude Rijn-Pannerden (135), Nederrijn (116), Meinerswijk (107), Mars-Oude Rijn (103), Lek (91), Hollandse IJssel (68), Meijerberg (106), Linge (97), Waal (174-175), Tuil (163), Nieuwe Merwede (119), Oude Waal (136), Alblas (5), Oud-Alblas (130), Papendrecht (140), Slikkerveer (154), Nieuwe Maas (118) (formerly called Merwede), and Gelderse IJssel (50).

The river system was essentially formed shortly after the beginning of the Christian Era, and comprises the most recent channel belts in the Rhine-Meuse delta. At present, only three Rhine branches remain: the Nederrijn-Lek, the Waal-Nieuwe Merwede and the Gelderse IJssel. The Hollandse IJssel (69) was dammed in 1285 AD (Vink 1926), the Linge (97) in 1307 AD (Vink 1954). Alblas (5) and Oude Waal (136) were dammed in 1250 AD and 1331 AD respectively (Oude Rengerink 1999). Near the Dutch-German border large meanders occur, due to the sandy substrate, in which the river channel was able to migrate laterally. Further to the west river channels can be classified as ‘straight’ (Makaske 1998), even before meanders were cut off by humans.

It is characteristic that the rivers (with the exception of the Gelderse IJssel) all debouched into the sea through the Maas estuary near Rotterdam.

[6.4] The Maas river system

The Maas river system comprises the following channel belts: Brakel (27), Hill (67), Broek (30), Maas (101), Wijchens Maasje (184), Altforst (8), Molenblok (112), Nieuwe Schans (121), Dreumel (38), Huisseling-Demen (75), Haren (59), Macharen (102), Lith (99), Hoorzik (73), Velddriel (169), Hedel-Wordragen (60), Winkels (188), Oude Maasje (132), Afgedamde Maas (4), Biesheuvel (19), Hank (57), Dussen (40), Gedempte Devel (49), and Bergsche Maas (17).

The age of the channel belts ranges from approximately 6500 yr BP until the present. The oldest channel belts occur west of the Peel Boundary Fault. At the time these channel belts were formed the rivers were still incised in the eastern part of the river district.

West of Heerewaarden (Figure 1.1) all Maas channels got an influx from the Rhine. This is evidenced by the calcium carbonate content: east of Heerewaarden channel belt deposits do not contain calcium carbonate, west of Heerewaarden they are rich in calcium carbonate, as are all Rhine channel belts. Pons (1957: 77-83) explained the difference in calcium carbonate content as a result of the influx of water with a low pH from the peat area of the Peel in the province of Limburg into the Maas. The waters with a low pH would have consumed Meuse carbonate east of the confluence of Rhine and Meuse near Heerewaarden. West of the confluence, Rhine discharge dominated over Meuse discharge, resulting in carbonate-rich deposits. However, this explanation may be challenged, because the difference in calcium carbonate content also applies to Pleistocene deposits that were formed long before the peat in the Peel area was formed. Nevertheless, the difference in calcium carbonate content has been a great help in making palaeogeographic reconstructions: if a connection with Rhine branches existed, the channel belts are rich in calcium carbonate.

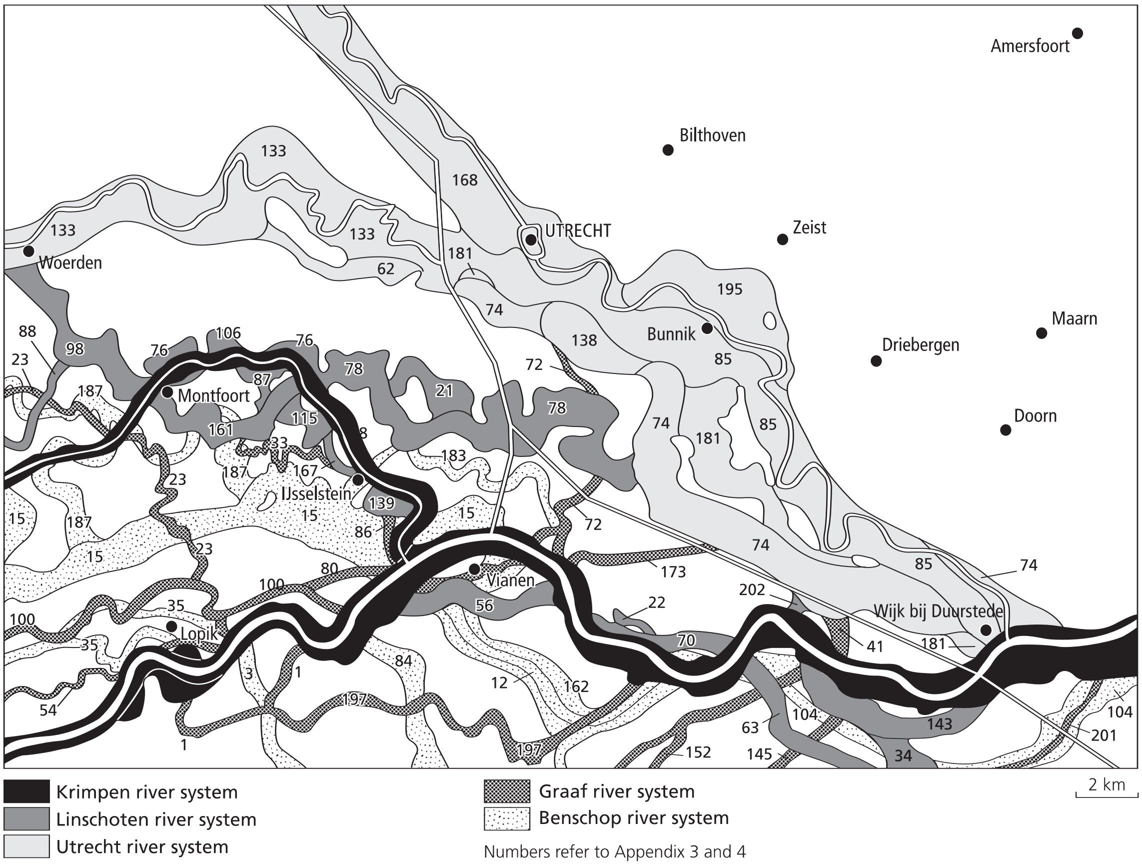
The Maas always joined the much larger Rhine before the river reached the sea. In 1904 AD a canal was dug from the Maas at Well to the Amer (location: see Figure 1.1), a tidal creek at the southern end of the Biesbosch. This gave the Maas an entirely new channel into the tidal inlet of the Haringvliet-Hollands Diep (Figure 1.1), but even in the Biesbosch the river Maas joined a much larger Rhine branch: the Nieuwe Merwede (Figure 1.1), formerly a large tidal creek that was widened by human interference.

Maas channels are concentrated near the southern margin of the delta plain, and are generally incised into coversands of the Twente Formation. This in part explains why the channel sands are very fine grained: they consist largely of reworked coversands. Very characteristic are the large incised meanders of the present Maas river. This is due to: 1) the fine-grained sandy substrate, in which the river could easily migrate laterally, and 2) the upward tectonic movement of the Peelhorst (Van den Broek & Maarleveld 1963) leading to incised meanders.

[6.5] The Est river system

The Est river system comprises the following channel belts: Ooij (127), Zoelen (200), Distelkamp-Afferden (37), Westerveld (182), Ochten (123), Kesteren (82), Echteld (42), Leeuwen (90), Wamel (179), Bommel (25), Est (46), Erichem (45), Tweesluizen (164), Meteren (110), Gameren (48), Rijswijk (148), Hardinxveld (58), Esterweg (47), Zaltbommel-Nederhemert (191), Opijnen (128), Zennewijnen (196), Oensel (124), Oevershof (125), Heesselt (61), Bruchem (32), Leuven-Verdriet (94), Munnikenland (114), Werken (180), Nieuwendijk (122).

Discharge of all channel belts of the Est river system went through the area near Est (Figure 1.1), and all channels eventually emptied in the Maas estuary near Rotterdam. Individual channel belts are relatively small distributaries of the Rhine (compared to the channels of the Utrecht river system). Downstream of Heerewaarden there generally was a confluence with Maas channel belts. All channel belts show lateral accretion, although some (e.g. the Bommel (25) channel belt) may seem rather straight on the map. The sinuosity of the residual channel generally is higher than that of the channel belt.



[FIGURE 6.1] *Example of river systems in the vicinity of Utrecht (Berendsen 1982)*

The situation in the area around Est is extremely complicated, and no comprehensive study on this area has been published so far. Hence, for this study, a large number of new ^{14}C datings were carried out in this area.

[*6.6*] The Graaf river system

The Graaf river system comprises the following channel belts: Vuylkoop (173), Hoon (72), Kapel (80), Lopik (100), Haastrecht (55), Blokland-Snelrewaard (23), Buitenzorg (33), Goyland (54), Bonrepas (26), Stolwijk-Beijersche (159), Achterbroek (2), Dwarsdijk (41), Zijderveld (197), Zoelmond (201), Schoonrewoerd (152), Schaik (150), Liesveld (96), Streefkerk (160), Brandwijk (28), Aaksterveld (1), Langerak (89), Lekkerkerk (92), Schoonhoven (151), Bleskensgraaf (20), Wijngaarden (186), Schuurkamp (153), Herwijnen (66), Varik (166), Deil (36), Molenveld (113), Zeek (194), Kedichem (81), Appelaar (11), Eigenblok (43), Broekgraaf (31), Vuren (172), Passewaaij (141), Enspijk (44), Hooiblok (71), Gellicum (51), Spijk (158), and Mert (108).
The river system consists of narrow, rather straight channel belts, that generally run from NE to SW. All channels except one (Blokland-Snelrewaard) entered the Maas estuary near Rotterdam. At the time the Graaf river system existed, main Rhine discharge still went through the Utrecht river system. Lateral channel migration was very limited. Examples are given by Törnqvist (1993a) and Makaske (1998). Some (but not all) channels are anastomosing. Lateral accretion was common in channel belts with a sandbody width/thickness ratio of > 40. Törnqvist (1993a) showed, that width/thickness ratio decreases westward, in some cases to less than 7 (Makaske 1998). This straight anastomosed river system consisting of narrow channel belts existed roughly between 5000 yr BP and 3700 yr BP (although this varies in space), at a time when the coast was closed, and peat development was at its maximum.

[*6.7*] The Linschoten river system

The Linschoten river system comprises the following channel belts: Avezaath (13), Erichem (45), Hennisdijk (63), Buren (34), Blokhoven (22), Honswijk (70), Hagestein (56), Lage Dijk (86), Over-Oudland (139), Vechgel (167), Neder-Oudland (115), Lampsin (87), Jutphaas (78), Stuivenberg (161), Zuid-Stuivenberg (205), Linschoten (98), Ravenswaaij (143), Redichem (144).
A common characteristic of the channel belts is, that discharge was carried through the Linschoten channel belt, and confluence with the Utrecht river system occurred at Woerden (circa 16 km west of Utrecht, see Figure 1.1). All channel belts

show lateral accretion, although this was sometimes restricted, for example in the case of the Hennisdijk channel belt (Makaske 1998: 225). Although the oldest channel belts may have existed as early as 4500 yr BP, the river system in general is younger than the Graaf river system.