SEDIMENT CHARACTERISTICS AND LATE HOLOCENE EVOLUTION OF THE IJSSELDELTA (THE NETHERLANDS)

(Final version)

Utrecht, July 2010

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1 Introduction

1.1 Background

Deltas all over the world have to cope with climate change since these low-lying areas are becoming more vulnerable as land subsides, sea-levels rise and populations grow. As a consequence, the pressure on densely populated coastal land areas around the world is increasing. Deltas form where a river enters open water (e.g. ocean or sea) and sedimentation takes place as the river flow loses its velocity. Fluvial and coastal processes in response to sea-level rise affect deltaic areas and are essential for understanding past landscape stability and predicting future changes for deltas.

The IJssel River, a tributary of the Rhine River, has formed a relatively small delta near Kampen (the Netherlands). The IJsseldelta is a typical example of a fluvial dominated delta which evolved rapidly due to increased sediment supply from the hinterland, presumably triggered by human cultivation and deforestation.

The IJsseldelta has already been investigated by several scientists (Ente, 1971/1973; Dirkx et al., 1996; Van Engelen, 1924). Ente (1971) assumed a start of delta formation at approximately 1200 AD (ages in this report will be presented in calibrated calendar yr BP = years Before Present, with the use of the year 1950 as present or AD, Anno Domini, referring to the years of the calendar era).

Historical facts suggest that the IJsseldelta evolved rapidly. In 1364/1365 AD the city of Kampen acquired the rights on the first islands: “de Kampereilanden, met aanwas van dien” from the Archbishop of Utrecht in exchange of the polder Mastenbroek (Van Schaick, 1939; Dirkx et al., 1996). Later on, these islands became connected, forming Kampereiland. Floods occurred during times of the northwestern gales, when the saline Zuiderzee water penetrated through the IJsseldelta, preventing the fluvial flow from the IJssel from discharging into the Zuiderzee. Consequently, the delta has been influenced by both fluvial and marine processes. Tidal influence has been relatively small. Near Urk (25 km northeast of Kampen) the tidal range was 0.2 m before closure of the Zuiderzee in 1932 AD (Dirkx et al., 1996). These circumstances made the IJsseldelta a unique environment.

1.2 Objectives and approach

This study aims to expose the fundamental physical processes that formed the IJsseldelta. Since processes like sea-level rise, land subsidence, wave action, erosion, flooding, salinization and sediment supply are of major importance for delta evolution and determine the vulnerability of a delta system, they are of prime interest to predict future changes for deltaic areas. As long as the natural processes in a delta are not disrupted, the delta builds up together with the sea-level rise as it tends to find an equilibrium. The most influential natural processes in a delta are river (fluvial) processes, coastal (marine) processes, climate and tectonics. Sediments transported by the river are deposited to build up the delta when the river enters open water. At the seaward side of the delta marine influence plays an important role with the erosive forces of currents, waves and storms. Climate factors such as temperature and precipitation influences the growth of vegetation and consequently river discharges and sediment supply. When the latter has reached a minimum and flooding has disappeared (at final stage of delta formation) land subsidence may occur.

Sediment characteristics like lithologic composition, grain-size, texture, geometry and sedimentary structures are indicative for the processes mentioned above and reveal the relative importance of fluvial, marine and wave dominance that determines the delta morphology. The relatively small size and extremely rapid expansion provides the IJsseldelta a high potential to be studied in detail. Uncovering the processes that controlled the evolution of the IJsseldelta is valuable for future delta management since this knowledge may contribute to predict future effects for other deltas. Besides the natural processes, described above, human interventions have played an important role in the origin and evolution of the IJsseldelta. Anthropogenic interferences upstream had major influence on flood frequency en sediment supply. Embankments and canalization disturbed the natural dynamics due to changes in sediment supply. One could say this reduces the representativeness of the IJsseldelta to uncover its response to natural processes. On the other hand, these early anthropogenic measures and effects on delta evolution are very unique and revealing these effects is in favour of future delta management of modern deltas all over the world. Lessons need to be learned from these early technical measures and its implications for delta evolution to determine which actions have to be taken in the coming years for increasingly threatened densely populated deltas.

Each process or combination of processes in the IJsseldelta led to distinctive and specific depositional environments (facies). The concept of facies was stated by the German geologist Johannes Walter, as follows: *the vertical succession of facies reflects lateral changes in depositional environment* (Walter's Law of Facies). Thus sedimentary facies units reflect a distinct kind of sediment for its corresponding depositional environment. This specific depositional environment can be revealed by analyzing the sediment characteristics of certain deposits.

Lithostratigraphic classification into formations is complicated for deltaic deposits encountered in the IJsseldelta since they differ from other deposits found in the coastal and alluvial plain of the Netherlands. Moreover, according to the revised lithostratigraphy (see Paragraph 2.4.2), all clastic fluvial Holocene deposits of the Netherlands are assigned to one formation: the Echteld Formation. However, not all sediments of the IJsseldelta were deposited under entirely fluvial conditions and deltaic deposits are not analogous to familiar fluvial deposits of the Netherlands. The complexity of different depositional environments within the IJsseldelta requires a specific approach on a more detailed scale.

Deltaic deposits are therefore described based on facies distribution from the apex of the delta to the former coastline of the ‘Zuiderzee’, starting with the lowest sequence, and subsequently classified in facies associations. Facies associations are often further subdivided in lithofacies units.

1.3 Research questions

To following research questions are formulated:

1. Can a distinction be made between different deltaic deposits according to their specific depositional environment (facies) in the IJsseldelta?

2. What was the relative dominance of fluvial and marine influences to the evolution of the IJsseldelta and how did it have an impact on delta morphology?

3. How did human interventions affect the evolution of the IJsseldelta throughout recorded history?

1.4 Approach

In order to address these research questions and to determine above mentioned sediment characteristics, a large amount of drillings is carried out from the modern delta plain of the IJsseldelta. In spring of 2007 and 2008 students participated in the 2nd year’s fieldwork campaign as a part of the Bachelor program of Physical Geography at Utrecht University. During this fieldwork campaign hand-drillings were carried resulting in hundreds of borehole descriptions, made by students. For an extensive description on how data is obtained for this study, see Chapter 3.

Analyses of borehole descriptions led to classification of deltaic deposits into various (litho)facies based on their specific depositional environment and distribution (Chapter 4). Additionally, a palaeogeographic reconstruction (Chapter 5) of the origin and evolution of the IJsseldelta is made based on obtained field data, a digital elevation map and historical information. Ultimately, recommendations are given for further research (Chapter 8) to determine an accurate chronostratigraphy with absolute dating techniques.

2 Geological and geographical setting

The IJssel River is part of the Rhine fluvial system that drains from the Swiss Alps to the North Sea. This IJssel is a relatively young river, supposed to became active approximately 600-950 AD (Makaske et al., 2008), but follows an already much longer existing valley between Veluwe and Salland. The related IJsseldelta is located in the Netherlands near Kampen where the River IJssel flows into the Lake IJssel (former Zuiderzee, Fig. 2.9). Nowadays, the River IJssel distributes 1/9 of the total Rhine discharge (Berendsen and Stouthamer, 2001). During the Late Saalian, Eemian and Pleniglacial the River Rhine itself had a course through the IJssel valley.

2.1 Saalian

In the Saalian glacial period, approximately 200-130 ka BP, the Scandinavian ice sheet altered the landscape, forming ice-pushed ridges (Fig. 2.1b). A glacier basin of approximately 25 km wide and 50-100 m deep was excavated by glacier tongues. This glacially scoured IJssel basin is positioned within the Saalian ice limit (Busschers et al., 2007). At the base and flanks of this glacier basin, during the ice coverage, a single meters thick layer of clay, sand and boulders was deposited, referred to as 'till'. The Saalian ice front changed the northward course of the Rhine through the IJssel valley, forcing it to flow westward (fig. 2.1a). Sea-level lowered at least 120 m as a consequence of the formation of the Scandinavian ice sheet. After melting of the ice, the River Rhine recaptured its course through the IJssel valley.

2.2 Eemian

During the moderate warm Eemian (~130-120 ka BP) the temperature rose somewhat above present-day values. Arctic vegetation was replaced by deciduous forest and sea-level rose because of the melting of ice. The Rhine flowed through the IJssel valley to the northwest and discharged into the sea (Fig. 2.1c). Although, the basin was largely filled by glacio-lacustrine and fluvial sediments during the Saalian deglaciation, the area remained a Rhine depocenter for most of the Late Pleistocene period (Van de Meene, 1979). During the Eemian interglacial, deposition of channel belts of a meandering type took place. Busschers et al. (2007) encountered paleosoils in the IJssel valley near Deventer, with peat layers covering the soils indicating groundwater table rise. Later a distal flood basin environment evolved characterized, by (shallow) swampy conditions (Busschers et al., 2007).

2.3 Weichselian

During the Weichselian period (ca. 120-10 ka BP), the ice cover expanded but did never reach the Netherlands again. Initially, the Rhine flowed northward through the IJssel valley as a braided river. During the relatively cold phase deciduous forest disappeared and was replaced by tundra vegetation.

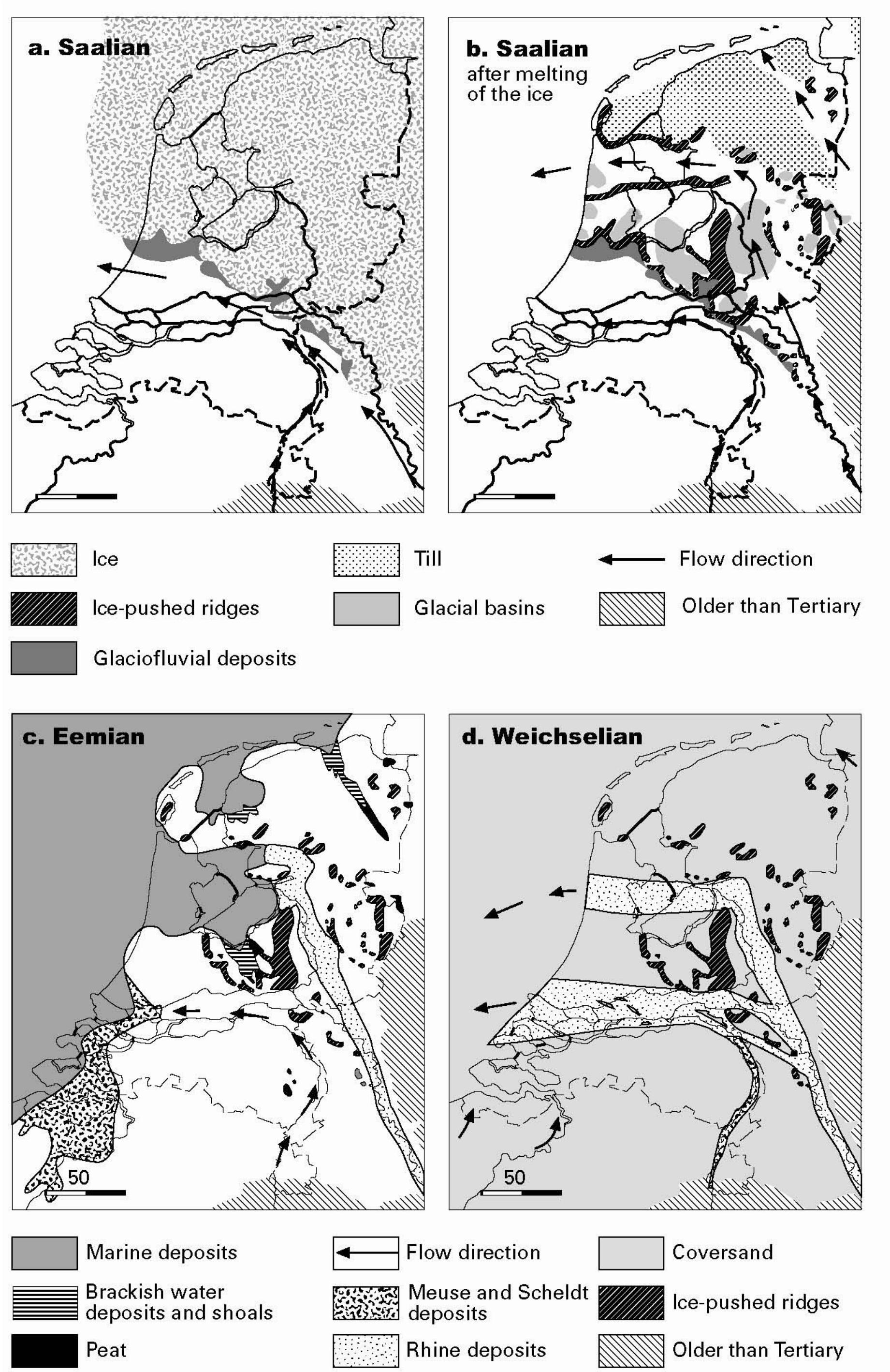


Figure 2.1 Palaeogeographic evolution of the Netherlands during the Late Pleistocene (from Berendsen, 2005).

Approximately 21 ka BP temperatures further decreased and the Late Glacial Maximum (LGM) was reached. Sea-level became approximately 120 m lower than today. The periglacial conditions during the Weichselian, led to a continuous frozen subsoil. Structures (e.g. involutions and cryoturbation structures) were found in the Netherlands, indicating permafrost conditions.

The Late Weichselian period is the transition phase from the coldest part of the Weichselian to the warmer Holocene interglacial. Large ice sheets in Scandinavia and North-America melted rapidly, releasing huge volumes of meltwater, which led to a rise of global sea-level. During the relatively warm Bølling interstadial (~13-11 ka BP), braided rivers changed to meandering incising rivers as a result of an increased vegetation cover and a decreased discharge regime. Later on, during a short cold climate period, called the Younger Dryas stadial (11-10 ka BP), meandering rivers became braided again with higher peak discharges. Due to a dry windy climate, sand got blown up forming aeolian dunes (Dutch nomenclature: 'rivierduinen' = river dunes; Fig. 2.2).

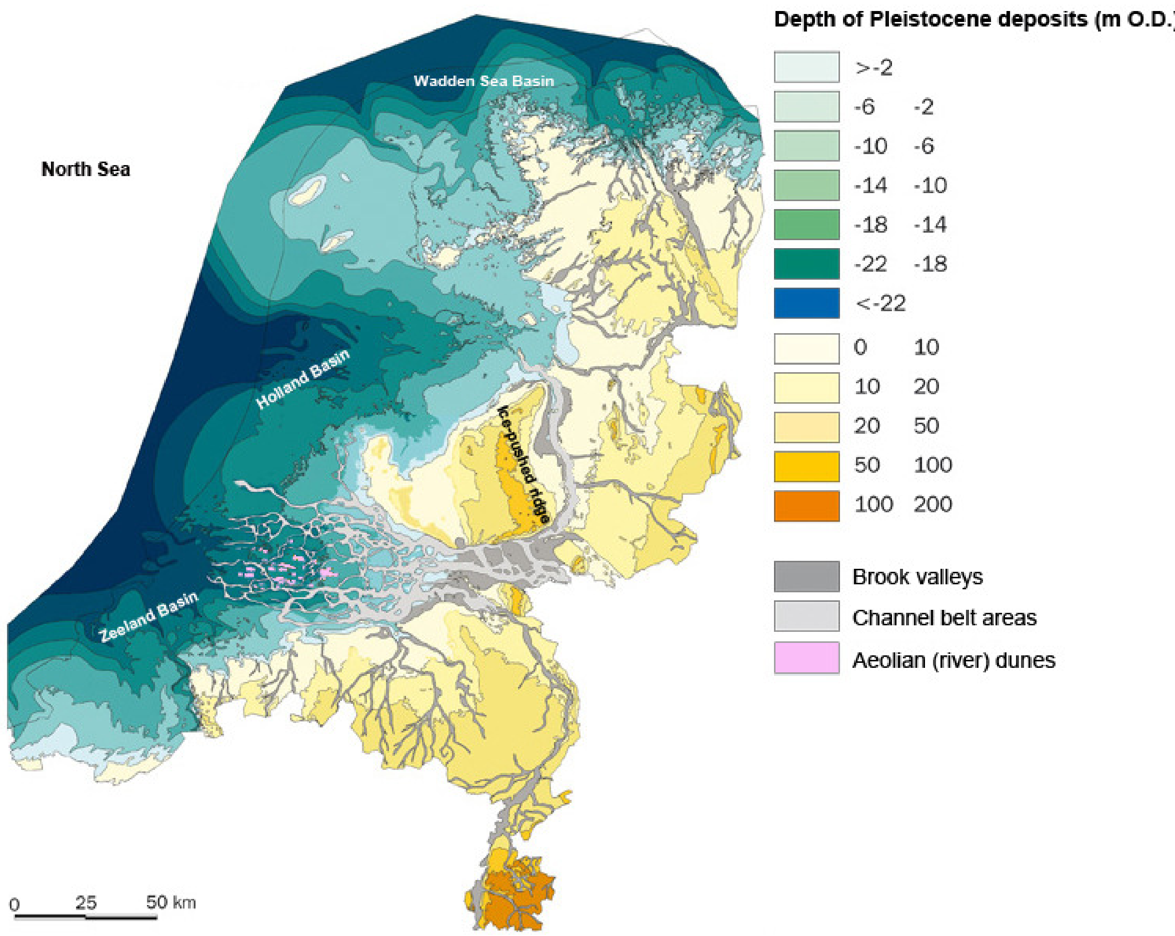


Figure 2.2 Palaeogeographic evolution of the Netherlands during the Late Pleistocene (after Vos, 2008).

2.4 Holocene

From the onset of the Holocene, about 10000 years ago, mean annual temperature increased and sea-level continued to rise. Consequently, vegetation expanded which fixed the sands and ceased the accumulation of coversands. Deciduous forests developed and brook valleys became covered with vegetation which led to a decrease of river discharges. Rivers in channel belt areas had a meandering character and incised the Pleistocene surface. Relative sea-level rise was responsible for an increase in groundwater level (Fig. 2.3).

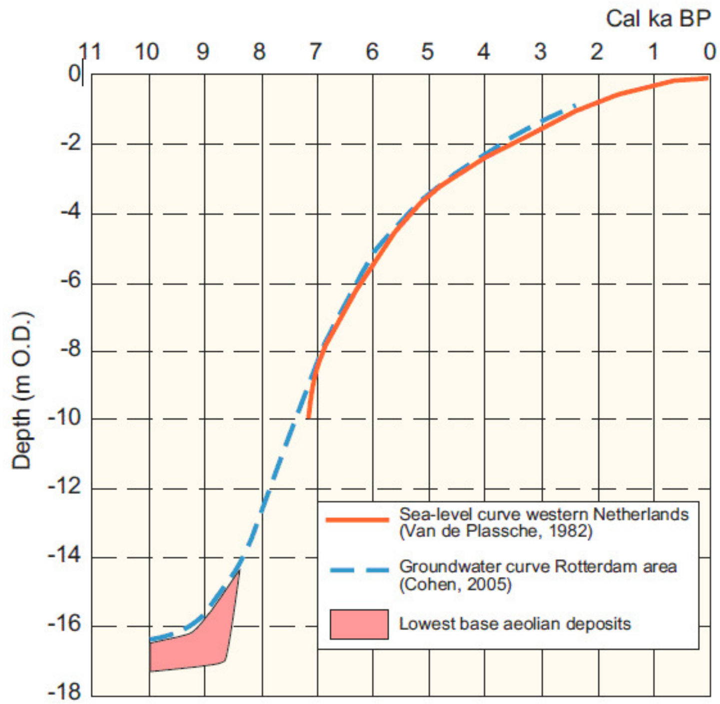


Figure 2.3 Relative sea-level curve during the Holocene for the western Netherlands (Van de Plassche, 1982) and groundwater curve for the Rotterdam area (Cohen, 2005).

2.4.1 Holocene evolution of the Dutch coast

When the groundwater level reached the surface, peat started to develop. Near the Holland basin sedimentation and peat formation could not keep up with the rapid sea-level rise, resulting in a tidal area with salt marshes and tidal flats. Tidal basins were surrounded by peat bogs where basal peat formed on top of Pleistocene sands. Later on as the coastline shifted inland, these peat bogs drowned and changed into lagoons where deposition of clay occurred. The tidal basins of Zeeland and Holland enlarged and the sea penetrated further inland resulting in drowning and peat formation shifting more to the east (Fig. 2.4). At approximately 6500 yr BP peat formation started near Kampen (Makaske et al., 2003) leading to an extensive peat bog area. In the western Netherlands, a tidal inlet (‘Zeegat van Bergen’) formed, where the sea penetrated deep inland (Fig. 2.4b).

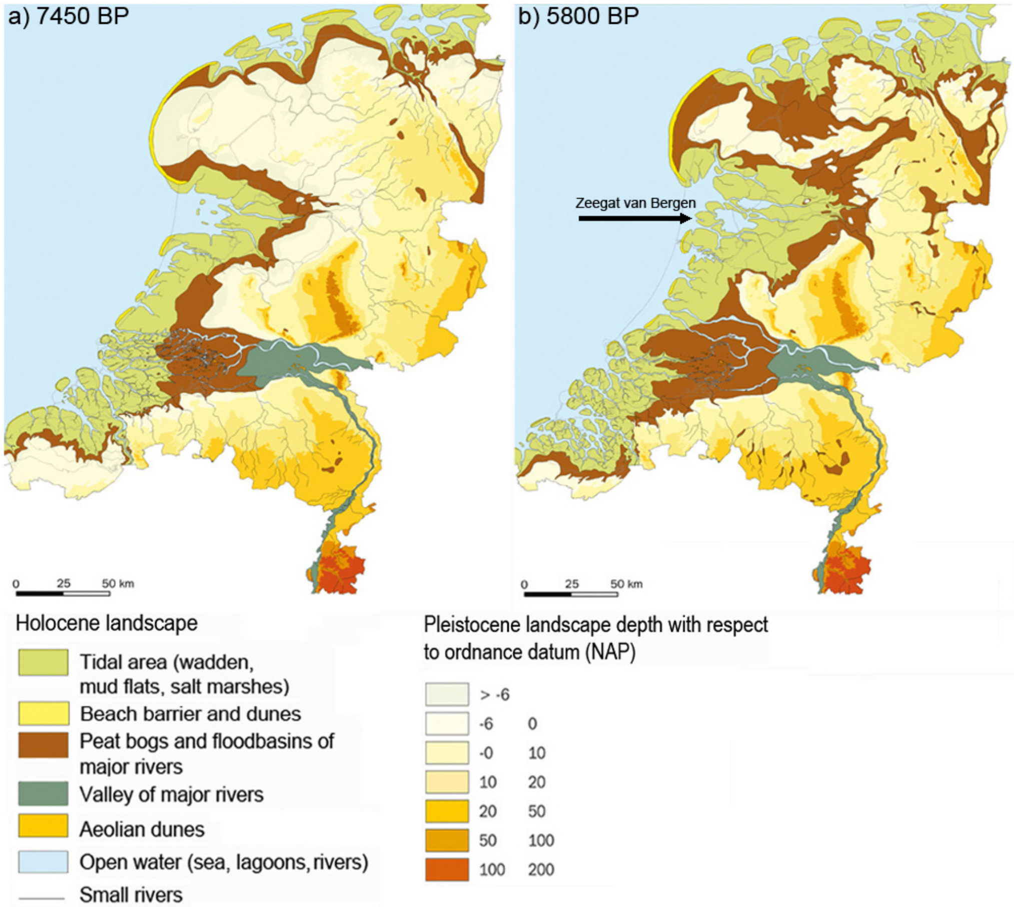


Figure 2.4 Holocene palaeogeographic situation in the Netherlands a) 7450 BP and b) 5800 BP (after Vos, 2008).

Approximately 5000 years ago a beach barrier system evolved at a time the rate of sea-level rise decreased. Inland from the ‘Zeegat van Bergen’, a back-barrier area existed (Fig. 2.5b). Sediment supply of the Rivers Rhine and Meuse was sufficient to fill the tidal basins resulting in closure of the Dutch coast. This stabilized the beach ridge system and offered better protection against marine ingressions. The coastal plain in the western Netherlands was influenced by fresh water supplied by river and rainwater, which enhanced extensive peat formation in the swampy back-barrier area.

Further silting up of the coastal plain and closure of the coast resulted in isolation of the lagoons from the sea and the formation of several lakes in the central part of the Netherlands (Fig. 2.5b) approximately 3500 years ago. Storm surges resulted in erosion of peat and extension of the lakes. Ultimately one inland lake evolved, ‘Lake Flevo’, named by the Romans as ‘Lacus Flevo’ and later ‘Almaere’. Finally, a connection with the North Sea was formed, caused by several heavy floods that broke through the northern barrier, near Texel (Fig. 2.5c). The influence of tides and salt sea water increased at lake Almere and ultimately an inland sea, called the “Zuiderzee” arose in the 12th and 13th century, when large areas of peat were eroded by the turbulent water (Fig. 2.5d).

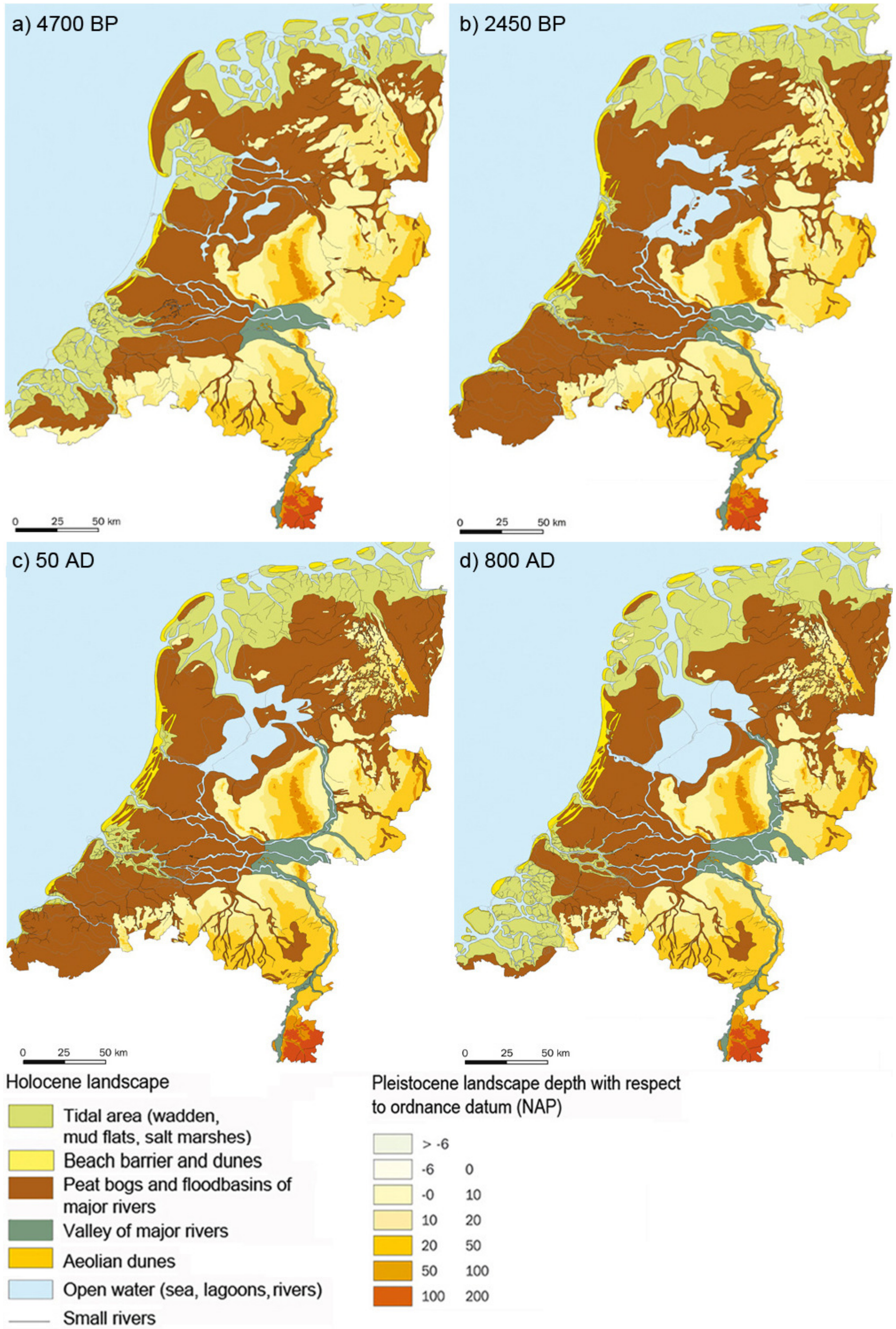


Figure 2.5 Holocene palaeogeographic development of the Netherlands a) 4700 BP; b) 2450 BP; c) 50 AD and d) 800 AD (after Vos, 2008).

2.4.2 Lithostratigraphy

In the year 2003, the Geological Survey of the Netherlands (TNO-GSN) has completely revised the lithostratigraphy of the Netherlands (Westerhoff et al., 2003). New formation names were introduced that can be applied to all Holocene deposits in the Dutch alluvial and coastal plain as well as the adjacent offshore part of the North Sea (Fig. 2.6):

- The Echteld Formation comprises all clastic fluvial deposits in the alluvial plain.
- The Naaldwijk Formation comprises coastal and back-barrier clastic marine sediments.
- The Nieuwkoop Formation comprises all peat beds in the coastal and alluvial plain. In this Formation, the peat beds between and above clastic deposits of the Wormer Member of the Naaldwijk Formation are assigned to the Holland Peat Member. Peat between the top of the Pleistocene deposits and the base of the Naaldwijk Formation is assigned to the Basal peat bed.

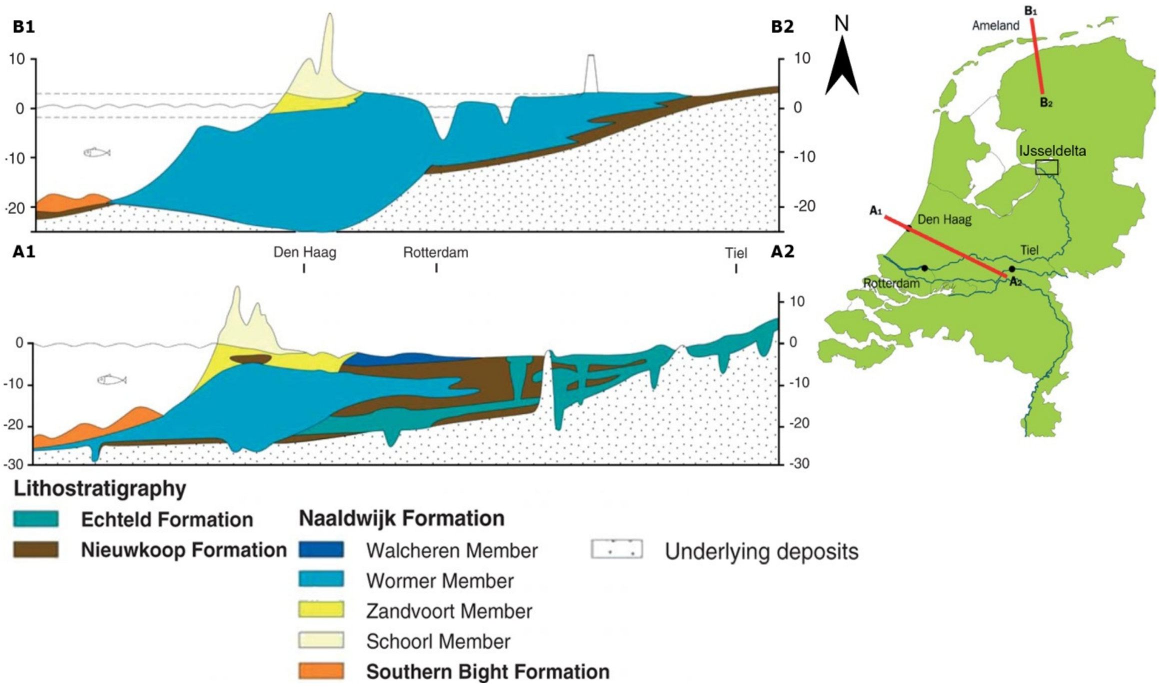


Figure 2.6 Lithostratigraphic interpretation of the Dutch fluvial and coastal plain of the western and northern Netherlands (after Ebbing et al., 2003).

The revised lithostratigraphic classification (Fig 2.7) substitutes the lithostratigraphic classification scheme that was published by Zagwijn and Van Staalduinen (1975) and consists of a hierarchical structure, with the Formation as the primary unit. All Quaternary Formations are part of the Group ‘Boven-Noordzee Groep’, defined by Van Adrichem-Boogaert en Kouwe (1997). Formations can be subdivided in Members (Dutch: Laagpakketten) and Beds (Dutch: Lagen). Nevertheless, according to the revised lithostratigraphy, subdivision in Members and Beds is not mandatory and undesirable

(Weerts et al., 2008). Preferably sediments are subdivided in lithofacies, representing *a specific unit that forms under certain conditions of sedimentation, reflecting a particular process or environment* (Reading, 2006). In the revised lithostratigraphic classification, Formations are assumed to consist of an assembly of facies units (Fig. 2.8).

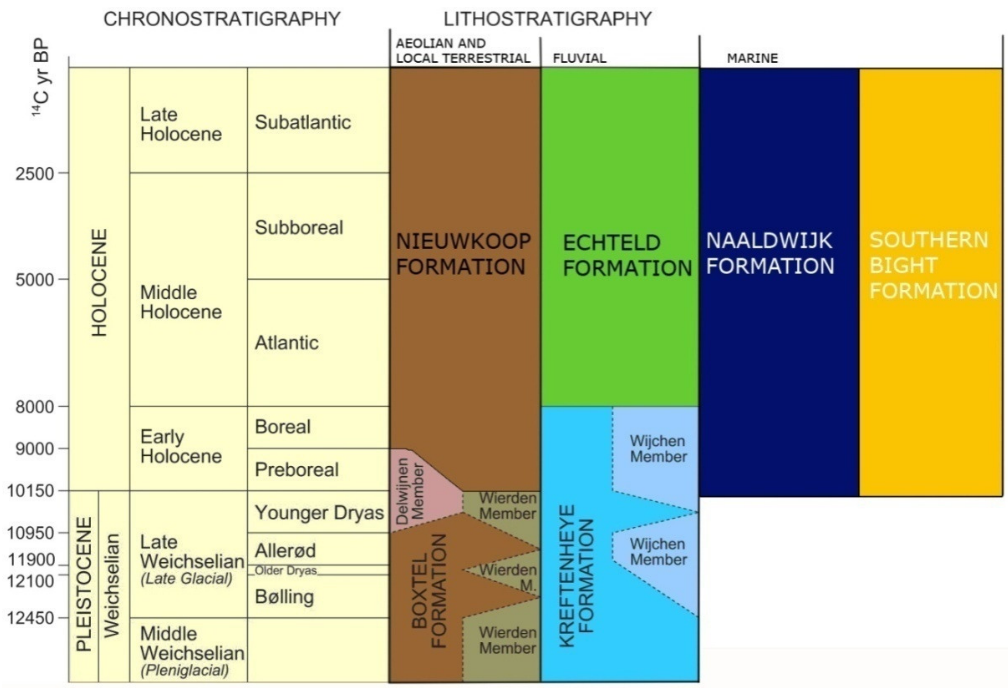


Figure 2.7 Chronostratigraphy and lithostratigraphy of the Holocene Rhine-Meuse delta (after Gouw and Erkens, 2007).

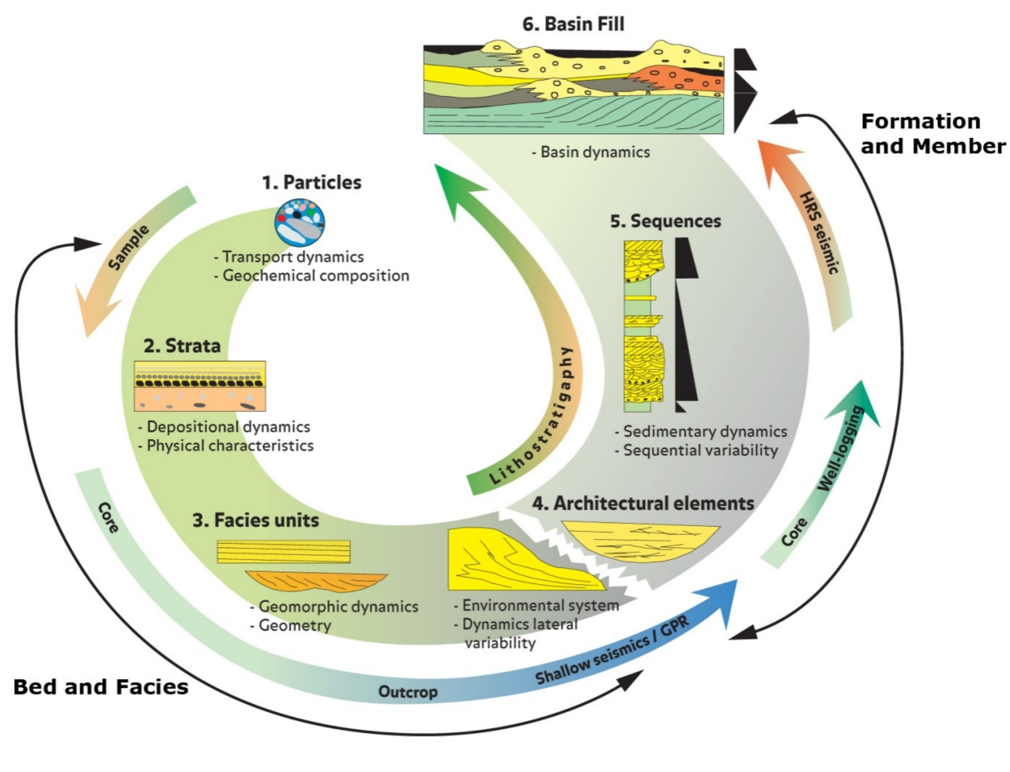


Figure 2.8 Facies units and lithostratigraphic units (from Weerts et al., 2008)

2.5 Study Area

2.5.1 Regional setting

Kampereiland, the modern delta plain of the IJsseldelta, represents the study area where fieldwork has been carried out (Fig. 2.9). The inset of Figure 2.9 shows the location of the IJsseldelta north of Kampen. The IJssel River (or Gelderse IJssel) crosses Kampereiland where it now enters the Lake IJssel (IJsselmeer), which has become a freshwater basin since the closure of the Zuiderzee, in 1932 AD. Since then, parts of the Lake IJssel were reclaimed resulting in the Noordoostpolder and Flevopolder.

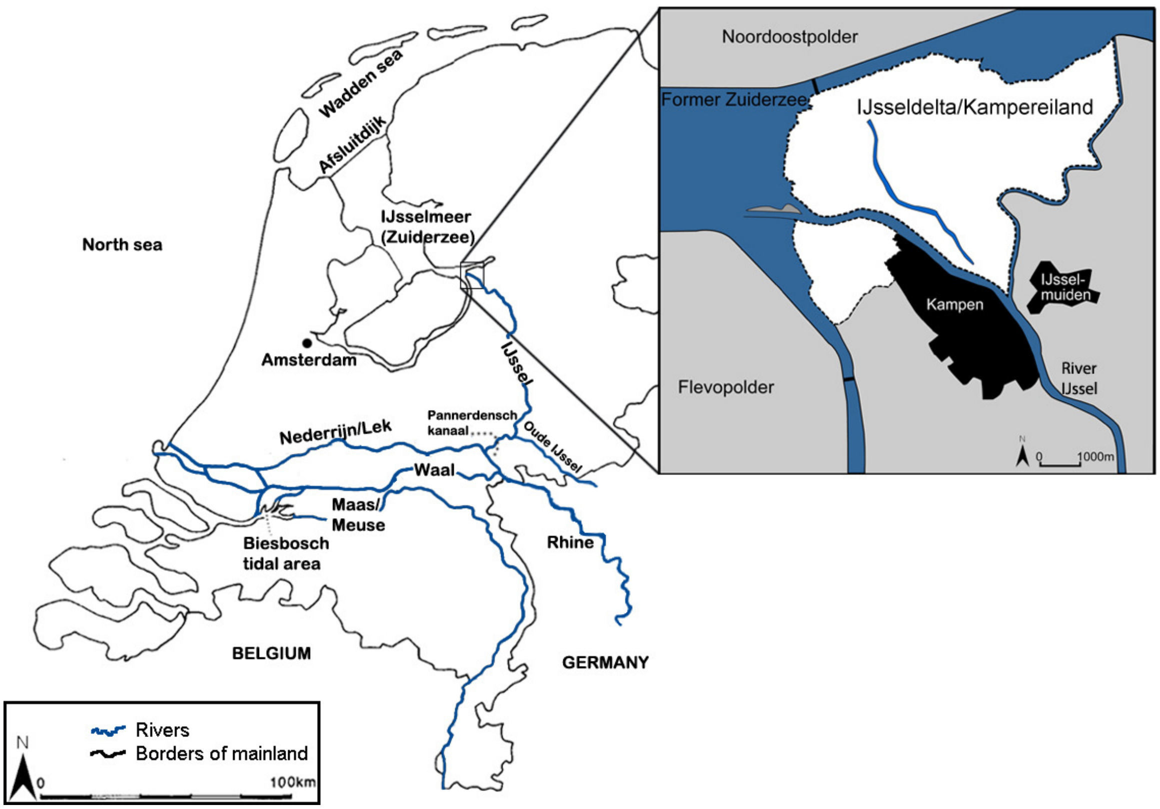


Figure 2.9 Dutch rivers and study area (inset). Main rivers are accentuated in blue.

The Rhine River drains large parts (± 185000 km^2) of central Europe between the European Alps and the North Sea. The length of the main river channel is about 1320 km (Hoffmann et al., 2009) and the river is fed both by rainwater and meltwater from six countries. An average of 2300 m^3/s of river discharge flows through the Rhine at Lobith, near the Dutch border with Germany. From the border with Germany the Rhine flows to the bifurcating point, near Pannerden, where it bifurcates into the Waal and the Pannerdensch canal. This canal was dug in 1707 AD to secure the flow discharge to the IJssel and Nederrijn/Lek branches. Since then, the Rhine discharge is divided into the three distributaries Waal (2/3), Nederrijn (2/9) and IJssel (1/9). The Oude IJssel (Fig. 2.9) originates in Germany under the name Issel and joins to the IJssel near Doesburg.

The subsoil of the Flevopolder is extensively studied by Ente et al. (1986). Pleistocene sands form the base on which peat formed as a consequence of sea-level rise (Fig. 2.10). Later the peat largely eroded, and during the phase of fresh Lake Flevo (~1250 BC - 0 AD), detritus-gyttja/humic heavy loam deposited, under quiet and fresh-water conditions (Ente, 1971). At the central part of the Lake IJssel region this humic facies is overlain by various sandy facies from the Almere phase (~0 – 1300 AD), which were delivered from the north. According to Ente (1971, 1973) these so-called Almere deposits also partly underlie the modern IJsseldelta. Approximately 1300 AD the brackish Almere turned into the saline Zuiderzee (Boon, 1982) when marine clay was deposited. Ultimately, a thin sand deposit of the IJsselmeer phase is distinguished, covering the Zuiderzee deposit (Fig. 2.10).

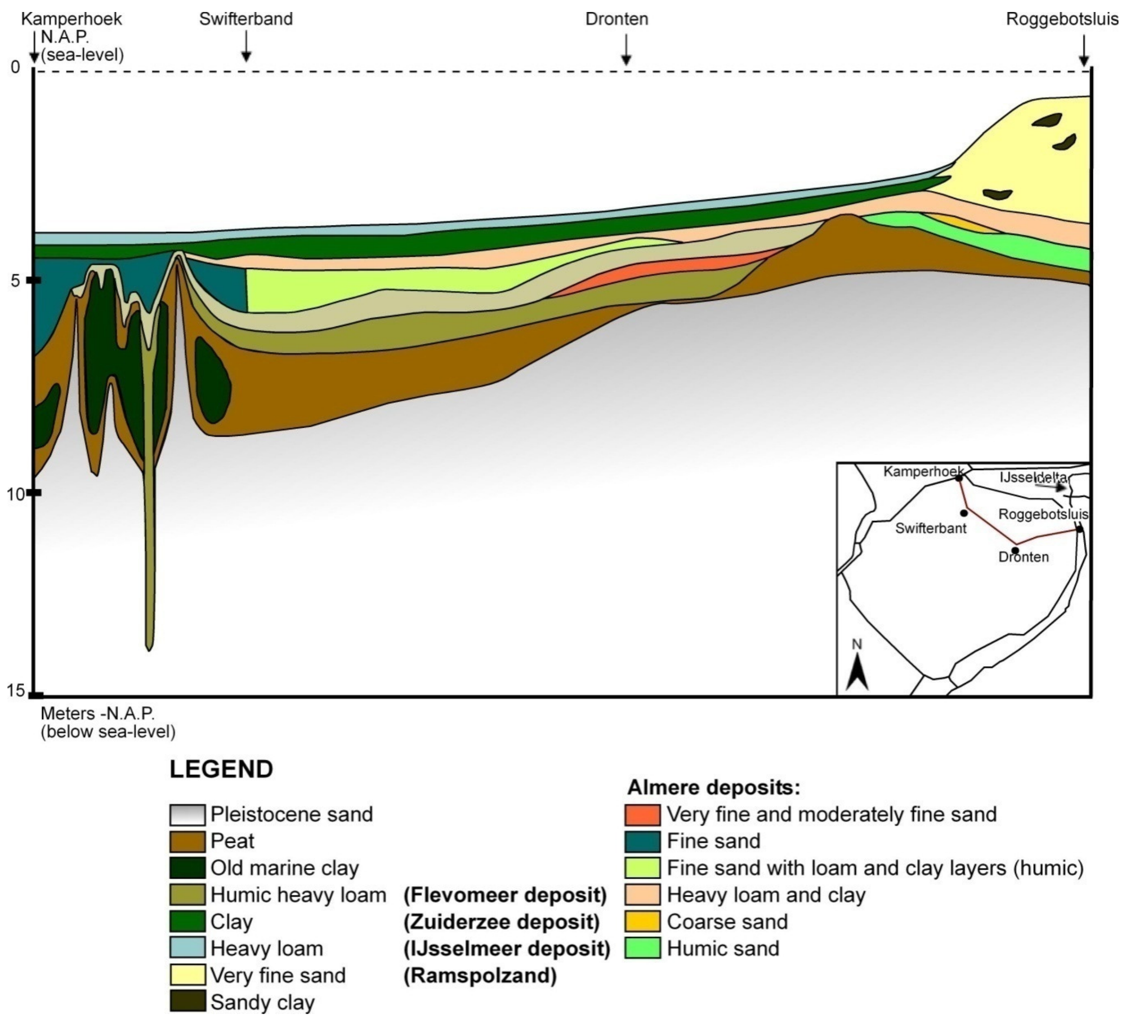


Figure 2.10 Lithologic cross-section of the subsoil of the Flevoland area, west of the IJsseldelta (after Ente et al., 1986).

In the eastern part of the Flevopolder, near the IJsseldelta, calcareous sands (Ramspolzand) are encountered originating from the River IJssel. Apparently, the subaqueous part of the IJsseldelta reached the Flevopolder and Noordoostpolder (Ente et al., 1986).

2.5.2 Historical background of Kampereiland

Inhabitants of Kampen and environs built dikes to protect themselves against floods driven by western gales of the Zuiderzee. Appendix E shows a reconstruction of the embankments around Kampen. The first dikes were built west of Kampen to protect the city against floods of the Zuiderzee. An impulse was given with the construction of ‘De Zwartendijk’ in 1302 AD. At the end of the 16th century more dikes were built at Kampereiland. In spite of this, the lower elevated pastures of Kampereiland were flooded frequently and consequently a natural fertilization of silty clay took place a few times a year. These lower fields were used for grazing, so grassland became the main vegetation and forestry was prevented.

The natural fertilization of the pastures of Kampereiland together with its perfect connection with the open sea made Kampereiland a very interesting place for farmers to settle. Kampen became an important trade center in the 15th century and flourished with a merchant fleet, called “De Kogge”. Kampen joined the famous Hanseatic League, an economic alliance of trading cities in Western and Northern Europe. Products like fish, salt, corns, wood, beer, wine, cloth and pelts were transported to the Baltic Sea, the German North coast, England, France and Holland.

Approximately 1364 AD the delta had already largely extended, when the first islands were given to the city of Kampen by the Archbischop of Utrecht (Ente, 1971). It is unclear if the inhabitants already settled in 1364 AD. Evidence for permanent settlement is obvious during the severe winter of 1502-1503 AD when farmers from Kampereiland came to the city Kampen over the frozen IJssel (Dirkx et al., 1996). From the 15th century, marine influence increased when floods of the Zuiderzee caused drowning of cattle, and meadow and similar crops were lost. Despite of the frequent floods, more and more farmyards were established and each time the higher elevated parts (mouth bars, levees) were used for the construction of farmhouses, mostly built on raised mounds (Dutch: terpen). The amount of farmyards at Kampereiland continued to increase from 26 in 1627 AD to 52 in 1682 AD, and to 71 in 1793 AD (Dirkx et al., 1996).

3 Methods

To reveal sediment characteristics and facies distribution through the IJsseldelta hand-drillings were performed by five fieldwork couples, during twelve weeks of fieldwork in 2007-2008. In addition more drillings were carried out, in the second half of 2008, on sites where data was lacking or insufficient. Moreover, striking sediment characteristics were photographed during this second expedition, enabling facies description and visualization. A coring density of approximately 30 per km^2 (910 drillings, 31 km^2) is obtained from the study area (Fig. 3.1).

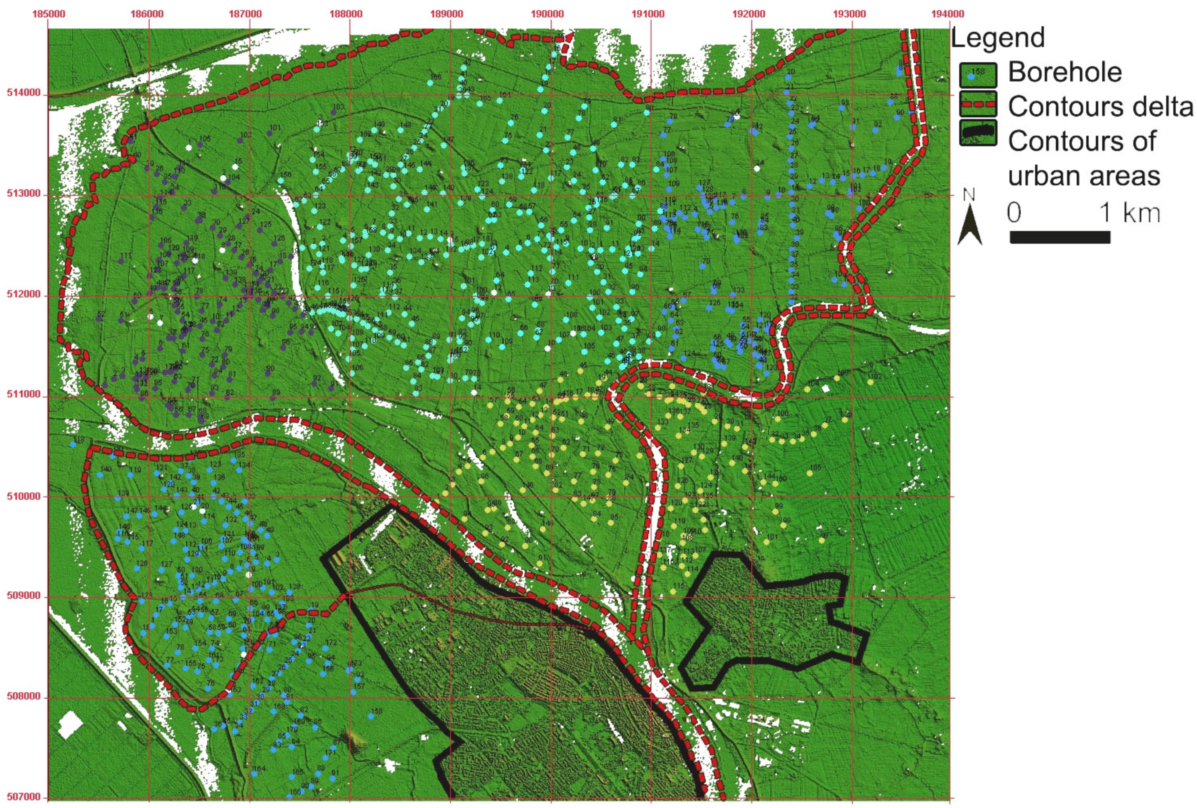


Figure 3.1 Borehole map showing the locations of 910 drillings. RD-Coordinates are shown in red, according to the Dutch coordinate system, consisting of the X and Y coordinates of the ´Rijksdriehoekmeting´. Boreholes are illustrated in various colours according to several fieldwork couples.

Approximately 25 % of the hand-drilled boreholes penetrated the entire Holocene deltaic sequence (> 4 m) with a total average depth of ~3.2 m below surface level. Regularly the Pleistocene subsurface was reached at depths of approximately 5 m –NAP (Dutch Ordnance Datum). Together with data from TNO-GSN (TNO-Geological Survey of the Netherlands) a dataset is generated, with a huge amount of detailed borehole descriptions consisting of texture, lithology, organic matter content, plant remains, colour, grain size, calcium carbonate/iron content, groundwater level and stratigraphy. Sediments were examined accurately and borehole descriptions were made.

Five detailed lithologic cross-sections (Appendix A) with a maximum core spacing of 100 m and two borehole logs (Fig. 4.2) reveal the spatial distribution of different depositional environments (facies) within the studied succession of the IJsseldelta. Cross-sections are made from the deepest drillings which struck the entire Holocene sequence. Two lithologic cross-sections were oriented parallel (cross-sections B-B’ and C-C’) to the former coastline of the Zuiderzee. The remaining three cross-section (D-D’, E-E’ and F-F’) are oriented perpendicular to uncover facies distribution starting from apex of the delta. Of each drilling analysis is performed every 10 cm to make a detailed borehole description comprising sample depth, texture, humic content, plant remains, colour, oxidation/reduction, gravel content, grain size, calcium carbonate content, iron content, groundwater level, lithology and special remarks. Classifications of each sample were based on the system of De Bakker en Schelling (1966) which is altered by Berendsen and Stouthamer (2001), see Fig. 3.2.

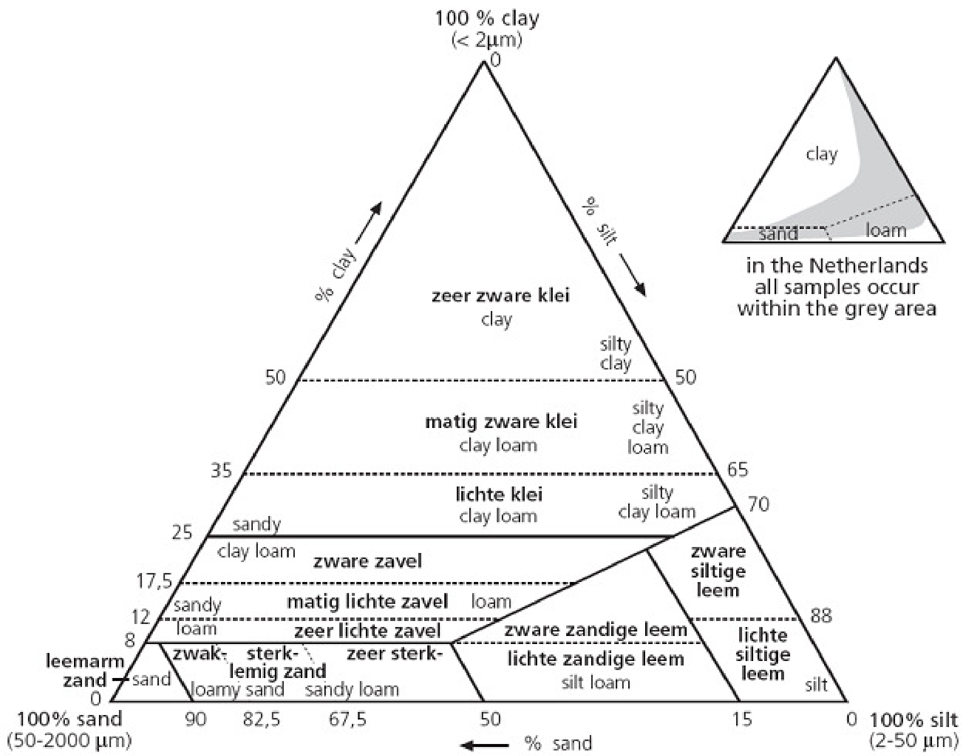


Figure 3.2 Texture classification of clastic sediments, consisting of a mixture of sand, sandy clay loam and clay (after Verbraeck, 1984, from Berendsen and Stouthamer, 2001).

Distinctions are based on the sample characteristics such as: grain-size, sedimentary structures, organic content, plant/shell remains, colour and calcium carbonate. The following drilling equipment was used in the field:

- *Edelman hand auger*: For the upper 1 m or to the depth of the groundwater table;
- *Gauge*: For clay and peat below the groundwater table, up to a depth of 15 m with the use of extension rods of 1 m length. Cores can be taken with a diameter of 3 cm;

- *Van der Staay suction corer* (Van de Meene et al. 1979): This simple, hand operated and inexpensive PVC-corer was used for coring in sand and fine gravel below the groundwater table, up to a depth of 10 m. Sampling rate is rapid and the quality of the results is excellent. The suction corer cannot be used in flood basin deposits like clay and peat, although thin layers of clay or peat can be penetrated, if underlying deposits consist of sand.

With the use of diluted hydrochloric acid (5% HCL) the calcium-carbonate content of sediments has been determined during sampling. A GPS is used to obtain the locations of boreholes. Geomorphology is determined based on observations in the field and a digital elevation model (AHN, Fig. 3.3).

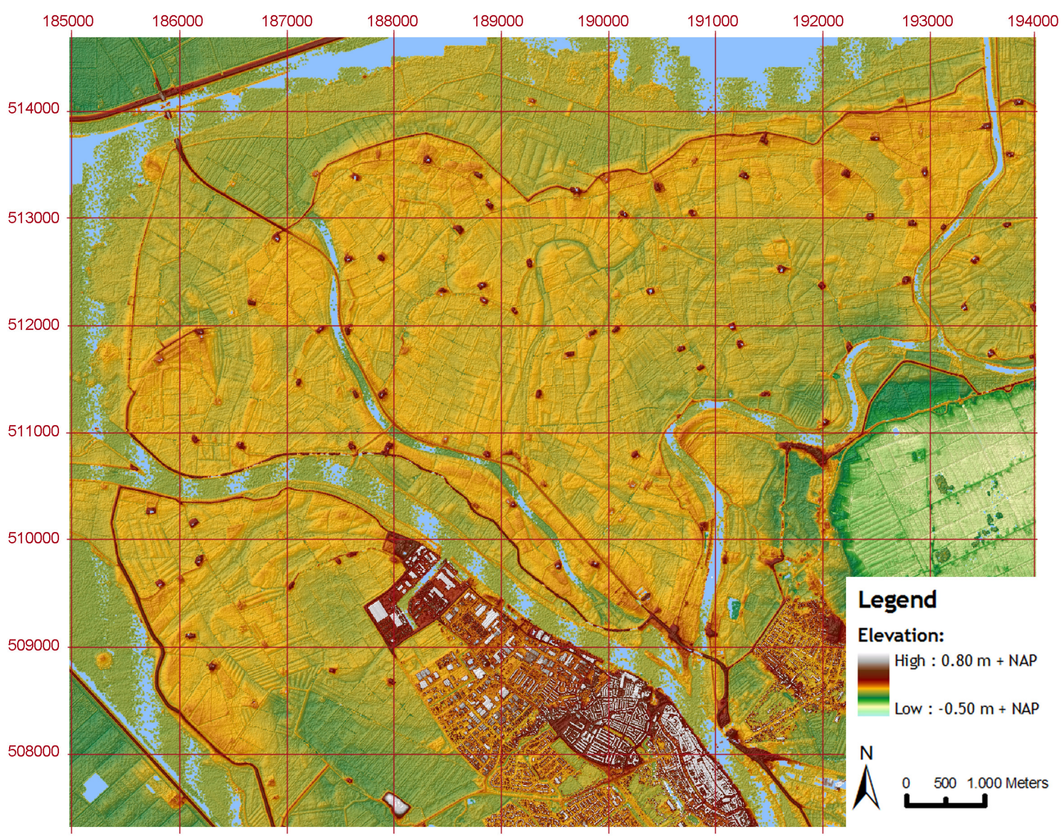


Figure 3.3 Digital elevation model of the IJsseldelta (AHN; after Rijkswaterstaat 2009). RD-Coordinates are shown in red, according to the Dutch coordinate system, consisting of the X and Y coordinates of the ´Rijksdriehoekmeting´.

Historical maps represent a further source of information that is used for palaeogeographic reconstruction of the IJsseldelta (Chapter 5), although it should be noted that the reliability of the older maps is often dubious. A collection of maps is enclosed as Appendix G. All borehole descriptions are stored in a digital database program 'LLG 2008' developed by the Department of Physical Geography of Utrecht University. An example of a borehole form is enclosed (Appendix H).

4 Facies descriptions and interpretations

Deposits are preferably subdivided in facies associations and lithofacies units, as is emphasized by Weerts et al. (2003). This chapter describes all facies units that are classified, based on sediment characteristics of all deposits encountered in the IJsseldelta. Two groups of deposits are distinguished, namely ‘non-deltaic’ and deltaic deposits, formed before the IJsseldelta existed and during delta progradation, respectively. Figure 4.1 shows a simplified cross-section of both ‘non-deltaic’ and deltaic deposits encountered during fieldwork, with corresponding lithostratigraphic classification.

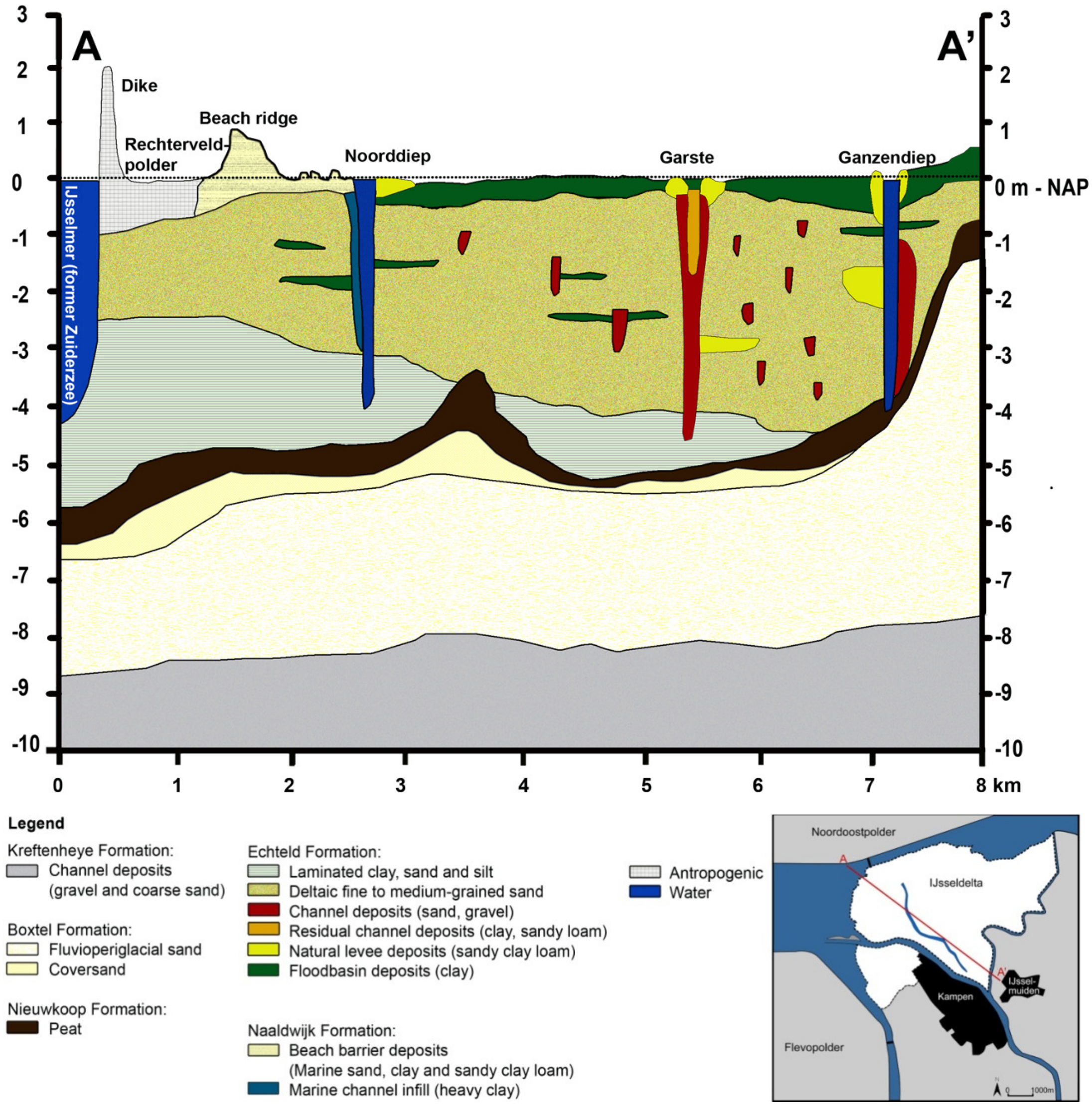


Figure 4.1 Simplified cross-section of transect A - A’. ‘Non-deltaic’ and deltaic deposits are classified into lithostratigraphic formations

4.1 ‘Non-deltaic’ facies descriptions and interpretations

Pleistocene sands form the base of the Holocene sequence of Kampereiland. Figure 4.2 shows sedimentary logs made of two deep hand-drilled cores comprising all Pleistocene (‘non-deltaic’) deposits originating from the Weichselian period onwards. The highest Pleistocene deposits of these borehole logs are also illustrated in most lithologic cross-sections (Appendix A).

4.1.1 Alluvial plain facies association (A)

The deepest deposits (7 - 10 m – NAP), encountered in the study area, consist of carbonate-rich coarse-grained sands in both coarsening- and fining-upward sequences (of 1 - 1.5 m thick), indicating fluvial deposition. These multi-coloured sands consist of different types of minerals, although their grey colour predominates. Deposits accumulated during high flow regimes and reflect a Rhine provenance. Typical is the high gravel content, consisting of rounded greenish-grey sandstone and quartzite derived from the Eifel (Germany) and Ardennes (Belgium).

This facies association is interpreted as fluvial channel belt deposits, belonging to the Kreftenheye Formation. The overall dominance of fining-upward sequences in the upper part of this sedimentary unit indicates channel belt deposition of a meandering river type in the period from Early to Middle Pleniglacial. Channel belt activity in the IJssel valley stopped approximately 40 ka ago when the Rhine River avulsed to the south (Busschers et al., 2007).

4.1.2 Aeolian facies association (E)

The cold conditions during the Weichselian resulted in a dry, windy environment with little vegetation. As a consequence, aeolian transport was abundant, which led to deposition of well-sorted sand grains. These, so-called, coversands represent the top of the Pleistocene fundament on which the delta has developed. Appendix D shows a Pleistocene sand-depth map of Kampereiland, based on TNO-GSN data. The sandy Pleistocene subsurface gently slopes towards the west, from approximately 4.5 to 6.5 m - NAP. A deep depression, running to the northwest, presumably represents a Pleistocene channel that incised the Pleistocene coversands.

Also, two elevated peaks are distinguishable (less than 3.5 m -NAP) in the centre of the delta representing aeolian (river) dunes which evolved in dry windy periods.

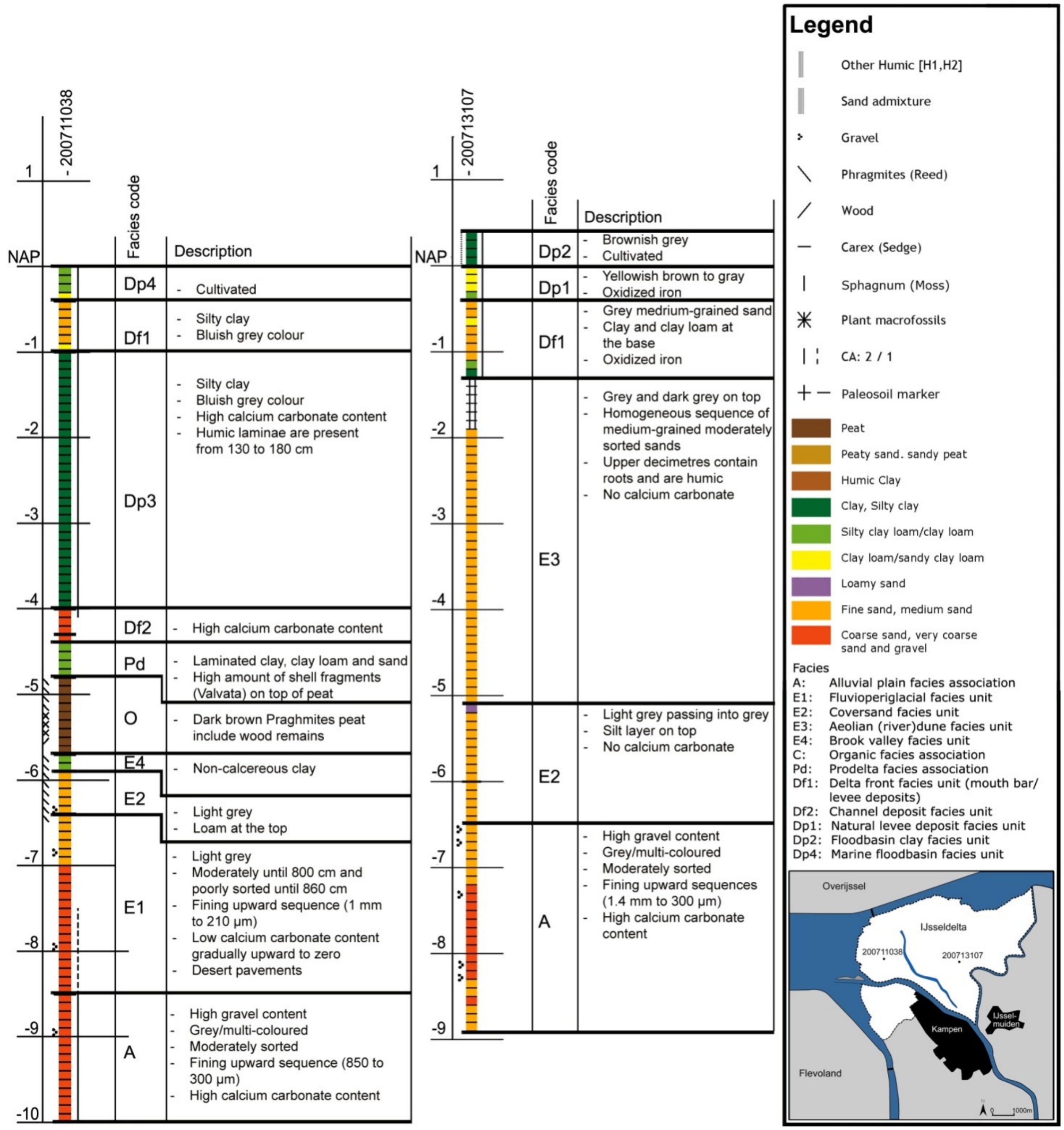


Figure 4.2 Sedimentary logs made of two deep hand-drilled cores (200711038 and 200713107) comprising all Pleistocene deposits and various deltaic facies.

A sharp transition to a light-coloured, coarse to medium-grained sand layer is observed, representing lithofacies unit E1. The yellowish or light grey sands are fine and medium-grained and show a gradual fining-upward trend. White, quartz-rich, carbonate-poor sands with a high content of gravels characterize this sedimentary unit. In core 200711038 (Fig. 4.2) this zone shows a fining upward grain-size distribution and a gradual transition in carbonate content from high to low. This sedimentary unit (E1) is interpreted as a fluvioperiglacial deposit (Boxtel Formation; undifferentiated) and deposited in small scale fluvial systems (Westerhoff et al., 2003) that flowed through the landscape during the cold Weichselian period. Fluvioperiglacial sediments or ‘meltwater’ deposits have a local provenance, deposited under periglacial circumstances by small streams. Characteristic for these small streams was a large fluctuation in flow discharge, which peaked during spring and summer months. When snow melted, the subsurface was frozen and water was not able to infiltrate. Increased surface runoff, directed towards temporary streams, enhanced high discharge. Fluvial and aeolian deposits might have been admixed and were transported to a lower area. The light colour of these deposits can be explained by the fact that the Eridanos river system had flowed in the proximity of the study area. During summer months, when the snow and the top layer of the permafrost disappeared, wind and water were responsible for reworking and redeposition of sediments. After the eroding forces wind and water removed the fine particles, desert pavements (a surface of gravel) formed.

Fluvioperiglacial deposits are mostly covered by lithofacies unit E2, representing finer aeolian sands deposited during the cold phases of the Late Glacial period. These coversands consist of non-calcareous medium and fine, well-sorted sands with a predominately grey colour. Aeolian activity increased due to little vegetation and significant amounts of sand were transported from dry river beds and deposited on the surface. These coversands belong to the Wierden Member of the Boxtel Formation and are deposited in periglacial conditions.

Mainly in the eastern part of the IJsseldelta aeolian dune deposits (lithofacies unit E3) are sporadically encountered (e.g. core 200713107; Fig. 4.2) relatively close to the surface. The rounded sand grains are moderately sorted and have a rather homogeneous grain size of approximately 300 µm. Roots are found in core 200713107 (Fig. 4.2) and core 200810011 (Fig. 4.3a). These aeolian dunes are generally referred to as ‘river dunes’ in the Dutch literature. They are mainly found east of the suggested Pleistocene channel, as a consequence of dominating westerly winds that blew perpendicular to the ancient river bed and reworked fluvial deposits. Thus lithofacies unit E3 is not found everywhere but defined as a local deposit. It is classified as Boxtel Formation (Delwijnen Member), probably originating from the Younger Dryas stadial (~11-10 ka BP) when a dry, windy climate, caused sand-drifts to form the aeolian river dunes. Younger Dryas coversands are called younger coversands in contrast to the older coversands originating from Late Pleniglacial (~15-11 ka BP).

A few centimeters thick layer of sandy clay is encountered sporadically (e.g. core 200711038; Fig. 4.2: ~5.80 m - NAP) on top of lithofacies unit E2. This greyish (often humic) clay contains no calcium carbonate and can be interpreted as a (local) deposit (lithofacies unit E4) of a brook valley. Small streams flowed through the Pleistocene sands at the onset of the Holocene depositing thin clay layers on top of aeolian coversands. This thin layer is interpreted as the Singraven Member of Boxtel Formation.

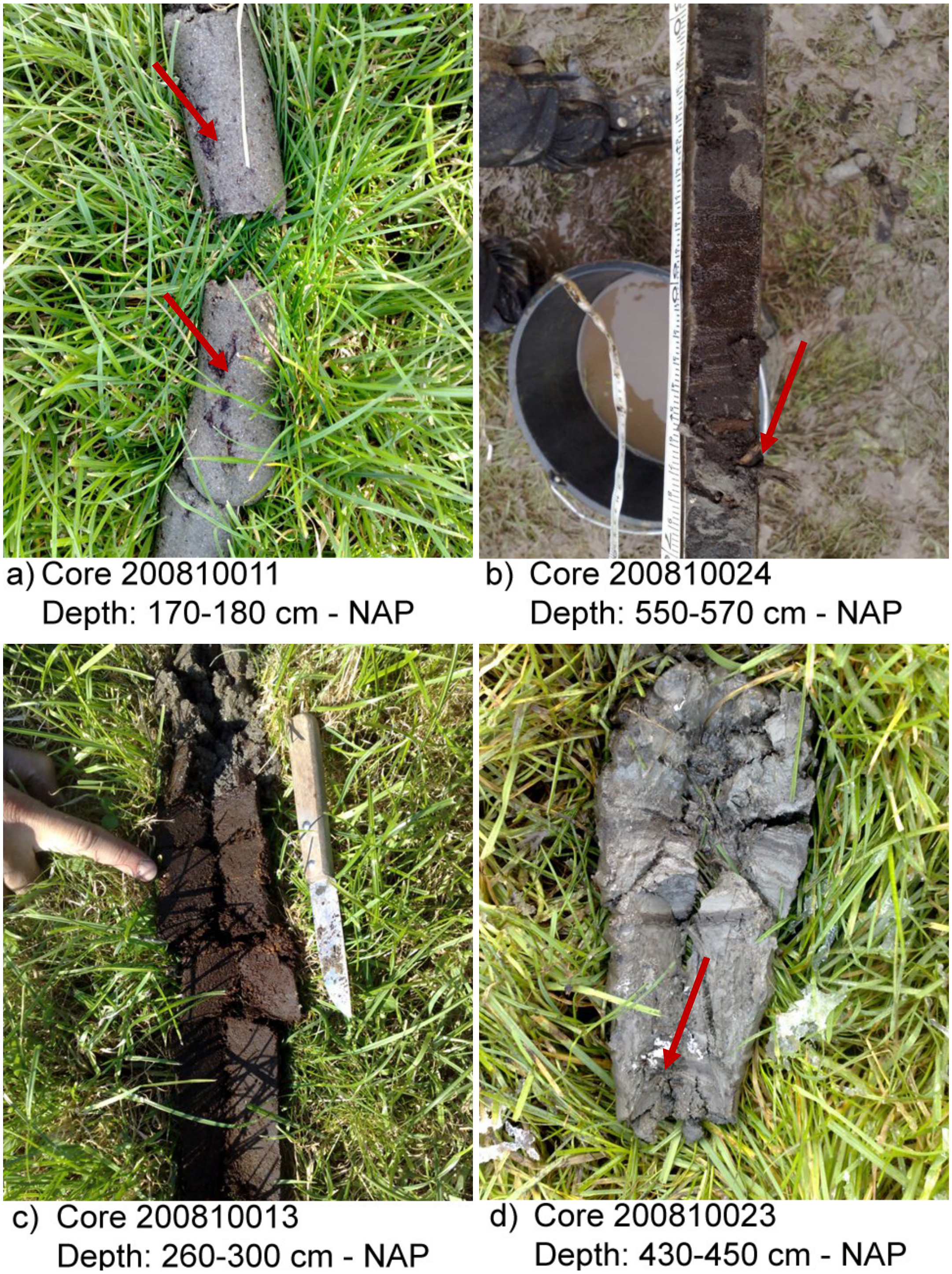
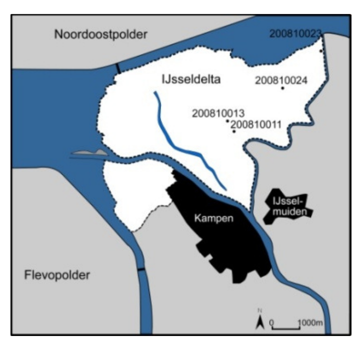


Figure 4.3 Pre-delta deposits. a) Roots are found in an aeolian river dune deposit; b) Large wood fragments indicate a woody marsh environment when basal peat formed due to sea-level rise; c) Compacted Phragmites peat is found relatively close to the surface; d) A layer of freshwater snails (Valvata Piscinalis) is covered by laminated clay.



4.1.3 Organic facies association (O)

A transition from underlying Pleistocene clastics to organic deposits indicates a period of climate warming that represents the Holocene. The lowermost part of this unit occasionally consists of peaty very fine- to medium sand (105-210 μm) or sandy peat including white quartz grains. On top of this sand, pure peat (e.g. core 200711038, Fig. 4.2: ~4.80 m - NAP) is found frequently with distinct wood and bark fragments (Fig. 4.3b) and recognizable plant remains (mainly of reed and alder). Generally two types of peat are discerned all formed in a eutrophic environment: Wood peat and Phragmites peat, both belonging to the Nieuwkoop Formation. The input of clastic material (peaty sand) in the lower part of this unit indicates a partly open landscape in which wind-driven sediment movement and sediment movement by surface runoff occurred.

The presence of macroscopic wood and bark fragments in the sediment cores point to warm climatic conditions during the formation of these organics, with extensive peat formation under the influence of a rising groundwater table. Lithologic cross-sections D-D' and E-E' (Appendix A3 and A4 respectively) show a continuous peat layer from north to south at a depth of approximately 4.5 to 6 m -NAP. The thickness of the peat layer varies from 0.5 to 2.5 m between the south and north of Kampereiland. In the centre of the delta, marine influence was responsible for erosion of peat (see chapter 5), whereas in the southern part of Kampereiland the peat is still undisturbed as peat is encountered relatively close to the surface at depths of approximately 3 m -NAP (Fig. 4.3c). On top of the peat a few centimeters thick layer of shell fragments (*Valvata Piscinalis*, Fig. 4.3d and Fig. 4.4) is frequently found.

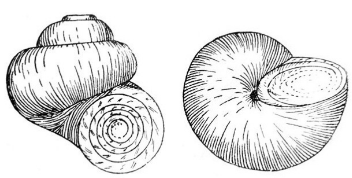


Figure 4.4 Valvata Piscinalis, from http://upload.wikimedia.org/wikipedia/commons/4/4a/Valvata_piscinalis_drawing.jpg (9th of May, 2009).

These molluscs usually live in slowly flowing fresh water with a muddy soil and were washed away from the IJssel when discharge increased. The increased discharge led to bank erosion of the IJssel River. An increased sediment load presumably resulted in burial and rapid extinction of the 'Valvatas'. According to Ente (1973), this Valvata layer can be considered as a chronostratigraphic marker for the onset of the IJsseldelta. In the west of the Noordoostpolder the Almere Member (Naaldwijk Formation) is covered with sand of marine origin ('oude sloef'). In between these two sequences archaeological material (cover of a sarcophagus) is found which dates roughly from the second half on the 12th century. North of

Kampen (at Emmeloord) the identical sand layer is deposited simultaneously, covered by the Valvata layer. Accordingly, the burial of these molluscs is assumed to have taken place in the late 12th century.

4.2 Deltaic facies descriptions and interpretations

Figure 4.5 shows a subdivision of deltaic deposits of transect A-A' (Fig. 4.1) into various deltaic facies associations. The IJsseldelta prograded seaward and 4 to 5 m of deposition of deltaic deposits took place, generally classified into three (vertically) stacked sedimentary sequences (subenvironments).

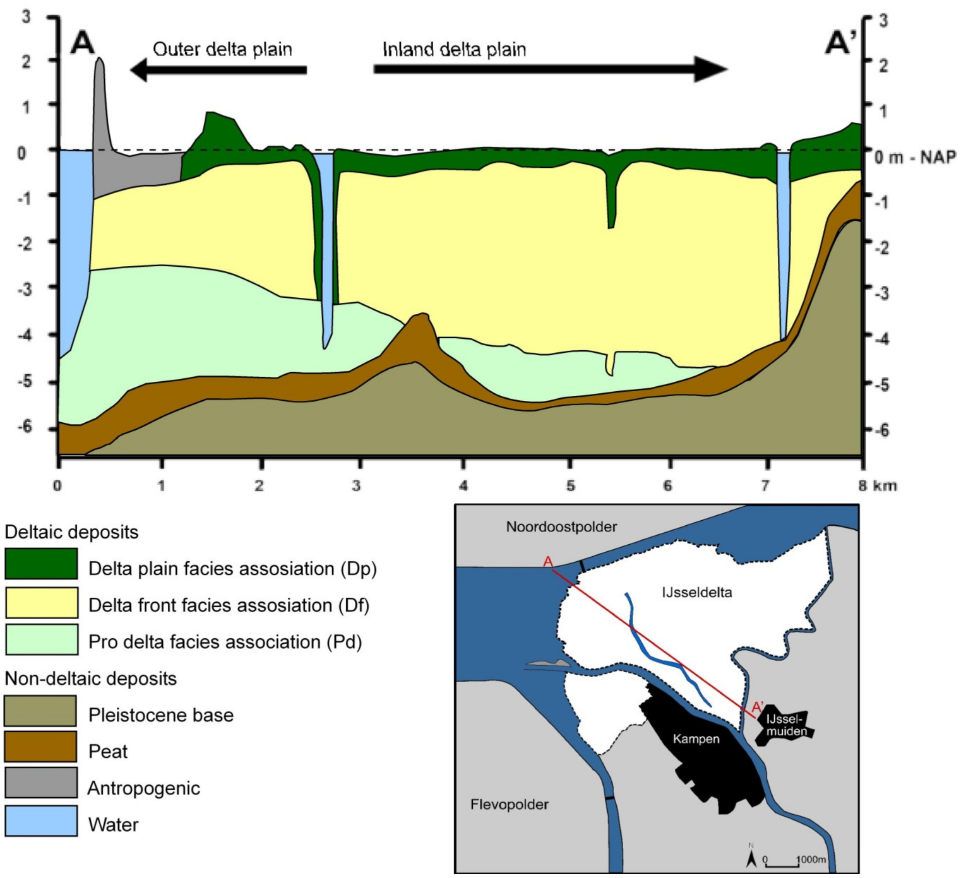


Figure 4.5 Subdivision of deltaic deposits into three main deltaic facies associations.

The lowest deltaic sequence consists of alternations of clay, clay loam and sand and represents the prodelta facies association (Pd). The prodelta subenvironment formed a subaqueous platform for delta progradation. Secondly, a more sandy deltaic sequence is deposited during progradation of the delta front, referred to as delta front facies association (Df). The delta front subenvironment is particularly dominated by a relatively high sediment supply distributed by the IJssel. These aggradational sediments are covered by the delta plain facies association (Dp), the actual platform that has formed at the final stage of delta evolution. Cross-sections in Appendix B1 t/m B5 show the facies classification of all deltaic deposits discerned in the IJsseldelta.

4.2.1 Prodelta facies association (Pd)

The main characteristic of this facies association (Pd) is the presence of well-defined laminae of carbonate-rich clay, silty clay (clay loam) and sand intercalations of a few millimeters to centimeters thick. The high carbonate content indicates a Rhine provenance (Busschers et al., 2007). Microfauna is poor although a layer of shells (*Valvata Piscinalis*) is observed around a transitional boundary to the lower organic facies (facies association O) and therefore marks the onset of the delta. Plant debris and organic-rich material are common within dark laminae and are presumably derived peat beds. These fine sediments have an overall grey colour although laminae show dark and light alternations. Thickness of these laminae varies from 0 to 3 cm (Fig. 4.6a and b) and is presumably related to the deposition rate and the time over which it formed.

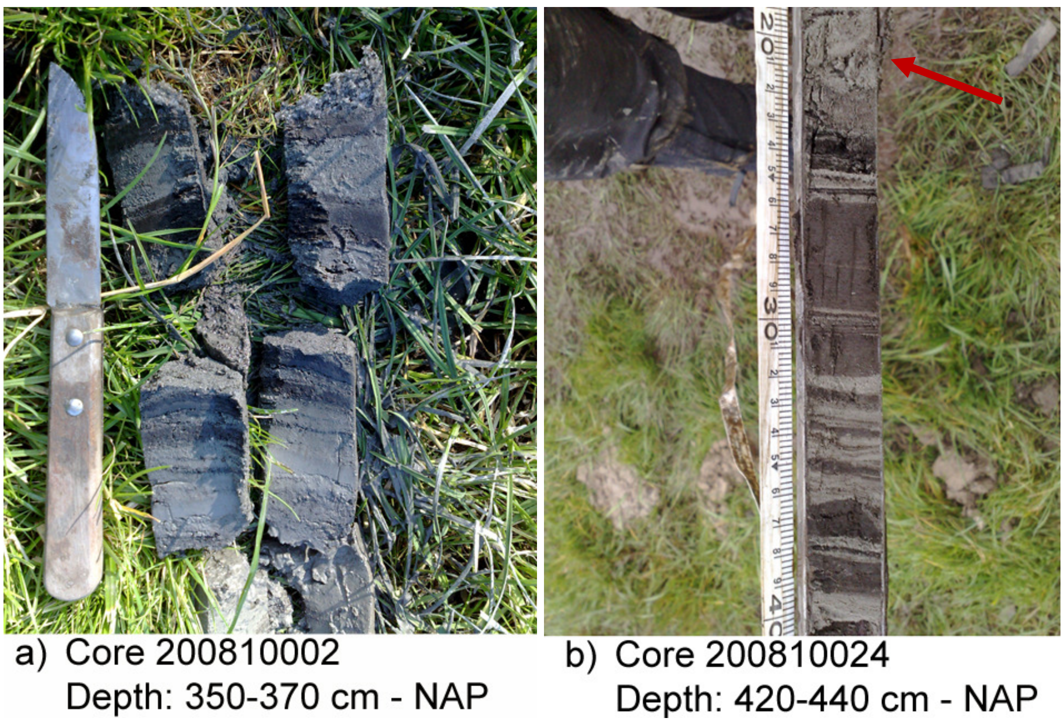
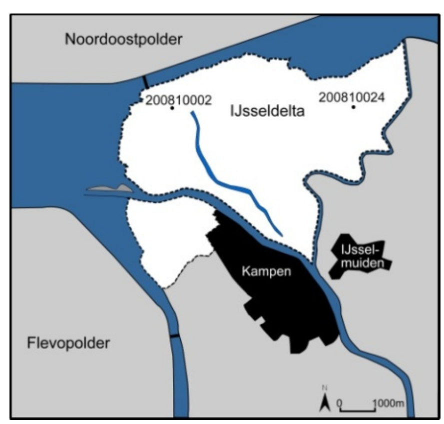


Figure 4.6 Laminae of prodelta facies. a) Dark humic-rich laminae alternate with lighter grey clayey and sandy laminae; b) The gauge is used to penetrate the deepest laminated deposit. Internal structures (arrow) indicate bioturbation in bright laminae found in the outer parts of the prodelta. The difference in colour between a and b is striking and can be explained by a more dominant marine dominance in the west of the IJsseldelta.



Alternations in colour are a result of differences in composition of successive laminae (light-dark couplets) and could be explained by seasonal variations (winter/summer) in sediment supply. Dark laminae are abundant in terrigenous material presumably corresponding with the wet winter (November-April) season when river runoff is high and thus account for the abundance of terrestrial plant debris. According to Asselman et al. (2003), effective supply of eroded soil particles, in the Rhine basin, is relatively high during the end of spring due to higher rain intensities. Moreover, snowmelt in the Alps contributed to high amounts of sediment supply during early spring (March-April), due to enhanced hillslope erosion (Asselman et al., 2003). Despite the fact that snowmelt in the Alps still occurs in summer months, downstream discharges are expected to be relatively small due to high evapotranspiration in the Rhine basin during the growing season. The light (more clastic) laminae are therefore presumably deposited during the dry (summer) season when vegetation expanded and less upstream soil erosion occurred.

Although hardly perceptible with a gauge of 3 cm in diameter, laminae seem to be slightly cross stratified dipping to the north (unidirectional). Mostly a sharp transition to the overlying delta front facies is observed although occasionally intermediate laminae pass into the homogeneous sands of sedimentary unit Df. When the IJssel entered the standing body of the Zuiderzee, the fluid at the margin of the jet mixed with the basin water, spread out and decelerated. Deceleration of the flow resulted in deposition of sediment load. Sand is deposited at the delta front, whereas fines (clay, silt and fine sand) are carried in suspension to be deposited at the subaqueous prodelta portion of the delta.

Cross-sections D-D' and E-E' (Appendix B3 and B4, respectively) show a nearly continuous longitudinal presence of the prodelta facies association from north to south. The depth of this facies association is approximately 3 to 5 m - NAP and 2 to 4.5 m - NAP for cross-section D-D' and E-E' respectively and increases from south to north. Thickness varies from 0 to 1 m in the south to 2-2.5 m in the north of the delta. In the centre this layer is frequently interrupted by sand bodies (cross-section C-C'). Differences in clay content and colour, between the western and eastern part of the delta, indicate a more dominant marine influence in the west. Laminae in the west include a thick succession of blueish clay grading upward into silty clay, whereas in the east greyish silty and sandy laminae are more abundant.

4.2.2 Delta front facies association (Df)

When the IJssel flowed into standing water, deposition of its load occurred in the form of mouth bars and successive bifurcation led to the formation of new distributaries. Mouth bar deposition and channel bifurcation are considered fundamental to the progradation process of the IJsseldelta and is schematically illustrated in three phases (Fig. 4.7). In phase one, flow decelerates at the river mouth resulting in mouth bar deposition and progradation of subaqueous levees towards the bar. Bifurcation of the flow results in creation of a new distributary when the mouth bar emerges above sea level. Secondly, the mouth bar grows and migrates laterally and upstream and phase one repeats to form new subaqueous mouth bars. Distributaries narrowed and subaqueous levees become subaerial. In phase three, accretion of the mouth bars continues and filling of the distributaries reduces the flow velocity and sediment discharge through the channel, which eventually becomes abandoned (Olariu and Bhattacharya, 2006).

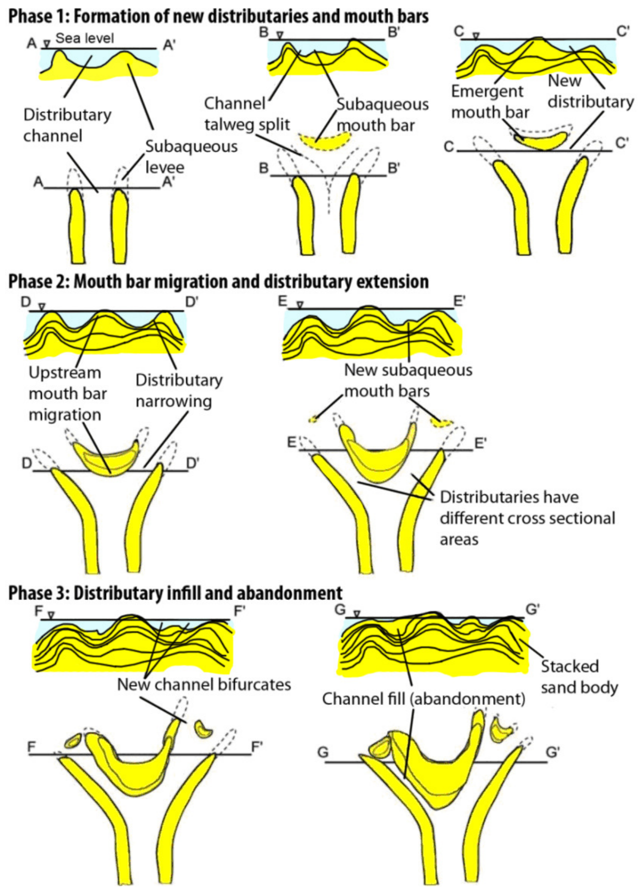


Figure 4.7 Evolution of distributaries and mouth bars in three phases. Lower images represent plan view and the higher images represent cross sections of corresponding situation (A to G). Dotted lines represent subaqueous features. Ultimately a stacked sand body is built up from mouth bars and levees (after Olariu and Bhattacharya, 2006).

Mouth bars are initiated by bedload deposition and many small distributaries are infilled with sands by aggradation and migration of the mouth bars. Izumu et al. (2009) demonstrated with model experiments that flow dominated by bedload transport will lead to river mouth bar construction, whereas flow dominated by suspended load tends to form levees. Ultimately a stacked sand body (Fig. 4.7, phase 3) will form of both subaqueous and subaerial deposition, forming mouth bars and levees, representing facies unit (Df1). Sand grains are usually sub-angular and moderately to well-sorted. This sedimentary unit is entirely carbonate-rich, reflecting an obvious Rhine provenance (Busschers et al., 2007).

Delta front lithofacies unit Df1 consists of fine to medium-grained deltaic sand, named as Ramspolzand by Ente (1971). This facies unit is mainly deposited below seawater level. Mouth bar and subaqueous levee deposits are both classified in facies unit Df1, since they are hard to distinguish from each other, based on their sediment characteristics. A change in colour from (dark)grey to light brown grey from bottom to top is frequently encountered in this facies unit, when a transition from subaqueous (below sea-level) to subaerial deposition occurred (Fig. 4.8b). This colour change may have been developed due to oxidation and reduction processes after sediment burial. Due to the presence of oxygen and light close to the surface an oxidized sediment layer developed which has a yellowish colour. Below this zone, oxygen as well as reduced compounds such as hydrogen sulphide are present in small amounts, resulting in a greyish layer of sediment (Fenchel et al., 1970). A high content of shell fragments as well as wood and plant debris are scattered throughout the facies. Channel deposits (lithofacies unit Df2) are characterized by coarse-grained sands (300-1000 µm) in mostly a fining-upward sequence. Channel lags are often found at the base of the channel deposits with a poorly sorted mixture of sand and gravel, and often containing remains of freshwater bivalves (Fig. 4.8a).

a) Core 200810002
Depth: 320-340 cm - NAP

b) Core 200810012
Depth 250 - 260 cm - NAP

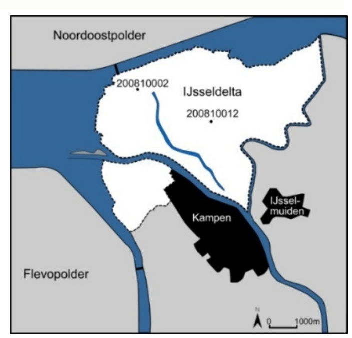


Figure 4.8 Delta front deposits; a) fragments of freshwater bivalves (mussel) and coarse sand and gravel are found in a channel lag on top of silty clay; b) a sharp transition in colour in a channel deposit. Presumably lower (blueish) sand grains are deposited below water level of the Zuiderzee in a subaqueous channel. Later on the delta built up with subaerially deposited sediments which show a more brownish colour after burial.

The absence or limited preservation of overbank facies and small depths of channel deposits indicate that bifurcation occurred repeatedly close to the apex (the starting point of the delta progradation). Consequently, many thin channel deposits are present very close to each other (cross-section B-B’, appendix A1).

Between former distributaries and mouth bars, occasionally clayey and organic layers are found, interbedded within the main delta front sequence, representing a quiet aquatic environment. In these so-called interdistributary areas, with shallow water bodies, humic clays and gyttja are accumulated in a fresh to brackish environment (lithofacies unit Df3, borehole 2007152005; ~4.0 m - NAP). Typical sedimentation units are centimeters thick and were deposited when the interdistributary area was inundated. Small lakes induced the accumulation of sediments rich in organic matter, which formed in a stagnant water body. Distributaries were prone to rapid accumulation when mouth bars partly filled the channel with sand, narrowed and eventually became abandoned (Fig. 4.7, phase 3).

In abandoned channels the sediments become finer upward. In suddenly abandoned channels much greater accumulations of clay and peat occurred. Consequently, residual channel deposits (lithofacies unit Df4) are found in abandoned distributaries when discharge through the channel reduced and eventually ceased. Frequently, the remaining part of the channel was slowly filled in with humic clay during floods of the remaining distributaries (Fig. 4.9a). Abandoned distributaries are often recognized in the field by elongated depressions due to compaction of the humic clay, as is visible on the digital elevation map (Fig. 4.3). This vertical land subsidence occurred mostly where residual channel deposits consist of humic/peaty clay which has a high porosity and lower clastic content. Due to the weight of overlying deposits, air and water is removed out of the pore spaces which led to compression of the subsoil. Such residual channel deposits are for instance found in core 200713025 and 200713002 of cross-section D-D’ at depths of 1.6 to 3.3 m - NAP and 0.5 to 2.2 m - NAP, respectively (appendix B3).

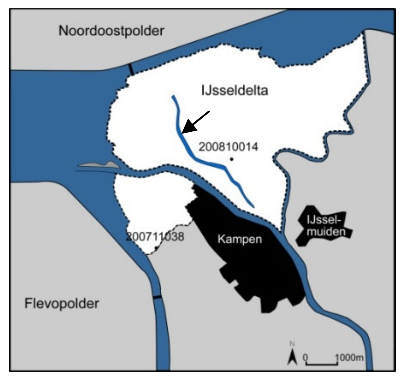
4.2.3 Delta plain facies association (Dp)

The delta plain facies association (Dp) is encountered at the top of the deltaic succession and is mainly composed of clayey or sandy deposits. The modern delta plain can be subdivided into two subenvironments based on fluvial and marine dominance. A fluvial dominated inland delta plain is characterised by superimposed overbank deposits with a maximum thickness of one meter consisting of clay and silt. Secondly, an outer delta plain is distinguished that was primarily dominated by marine influence. Distributaries were active on the modern delta plain when progradation of the delta ceased. The delta plain started to have strong similarities to an alluvial plain with typical fluvial components of lowland meandering rivers (e.g. floodplain, natural levees). However, floods of the Zuiderzee occurred frequently and inundated the delta plain providing marine features. Furthermore, the prevailing westerly winds and wave action affected the delta plain.

a) Core 200810014
Depth: 290-310 cm - NAP

b) Core 200810018
Depth: 0-130 cm - NAP

Figure 4.9 Lithofacies units Df4 and Dp6; a) residual channel deposit consisting of humic clay in the former Garste distributary is encountered and presumably deposition took place during floods of the adjacent Noorddiep distributary (see Fig. 5.5 for locations of these distributaries); b) marine clays are encountered relatively close to the surface in the western part of the delta, where marine influence was most dominant; inset: The inactive Noorddiep (arrow), which is still filled with water today, is found rather close to borehole 200810014.



Natural levee deposits (lithofacies unit Dp1) are formed during river floods when the water flowed outside the margins of the channels. The water spread out and slowed down, leading to deposition of fine sediments. The resulting ridges, parallel to the channels, contain sandy loam and clay loam sediments.

Flood basin deposits (lithofacies unit Dp2) mostly have a brown-grey colour and contain silty clay loam with a thickness that varies from a few decimeters to one meter. Flood basin clay is deposited during periods, when floodwater overtopped levees and the flood basin was inundated. These overbank deposits are rich in calcium carbonate except the very highest centimeters that have been chemically decalcified. Chemical reactions between calcium carbonate ($CaCO_3$) and sulfuric acid (H_2SO_4) may have resulted in the dissolution of $CaCO_3$ releasing aqueous (sulfate and calcium) ions, which are washed away in the water flow:

$$CaCO_3\,(s) + H_2SO_4\,(a) \dashrightarrow Ca^{2+}\,(a) + SO_4^{2-}(a) + H_2O\,(a) + CO_2\,(g)$$

Most likely acid rain have been the reason for decalcification of this layer since H_2SO_4 is the primary component of acid rain.

Occasionally, Dp2 facies units are interbedded within the delta front sequence. For instance in cross-section F- F’ two distinct clay layers are visible originating from floods of the Noorddiep distributary (Appendix B5, southwestern part of the cross-section at 1.0 to 1.5 m and 2.2 to 3.0 m - NAP). The outer delta plain was primarily dominated by marine processes. All marine deposits are classified as the Naaldwijk Formation. Abandoned distributaries are locally filled with marine clays that are predominantly blueish-grey in colour (lithofacies unit Dp3). Such a marine channel fill is found in borehole log 1 (core 200711038, Fig. 4.2: 1 - 4 m -NAP) and is a remnant of the former distributary ‘Regtediep’. Marine clay was also deposited on pastures during floods of the Zuiderzee as marine flood basin clay (lithofacies unit Dp4; Fig. 4.9b).

The blueish-grey colour in marine sediments is presumably caused by sulphate reduction due to the high amount of sulphates in sea water and absence of oxygen (Fenchel et al., 1970). However, marine and fluvial clays are often difficult to distinguish, since they are often admixed due to cultivation for agricultural purposes and are humic-rich due to fertilization. However, Eilander et al. (1990) used various criteria such as colour, sand admixture and stratification, in an attempt to make a distinction between IJssel River clays and clays deposited by the Zuiderzee. Therefore subdivision is largely based on the soil map of the IJsseldelta region (Eilander et al. 1990).

Elevated parts in the northern part of the delta represent beach ridges that were formed under influence of predominating northwesterly winds. This lithofacies unit (Dp5) consists of clay and sandy clay loam with shell fragments in the lowest part. When beach ridges formed a supposed coastal barrier, accretion of clay and clay loam occurred at the side of the Zuiderzee behind the barrier, induced by the production of rush fields (Dutch: biezenvelden), as will be explained next chapter. This resulted in a facies unit (Dp6) outside of the beach ridges consisting of mainly marine clays and silts.

5 Evolution of the IJsseldelta

A prograding deltaic succession with a thickness of approximately 4 to 5 meter developed over a few centuries under influence of a combination of natural processes and anthropogenic operations. This chapter describes and illustrates the origin and evolution of the IJsseldelta. This palaeogeographic reconstruction is made based on historical maps and gathered field data.

5.1 Origin of the IJsseldelta

Holocene sea-level rise resulted in peat formation at great scale near Kampen, approximately 6500 yr BP, based on ^{14}C-ages of basal peat samples obtained from the Schokland area, 10 km North-East of Kampen (Van de Plassche et al., 2005). The landscape evolved in a peat bog area with small brooks from the Overijsselse Vecht and precursors of the IJssel. Mainly wood peat and Phragmites (reed) peat (Nieuwkoop Formation) was formed under influence of eutrophic fresh water.

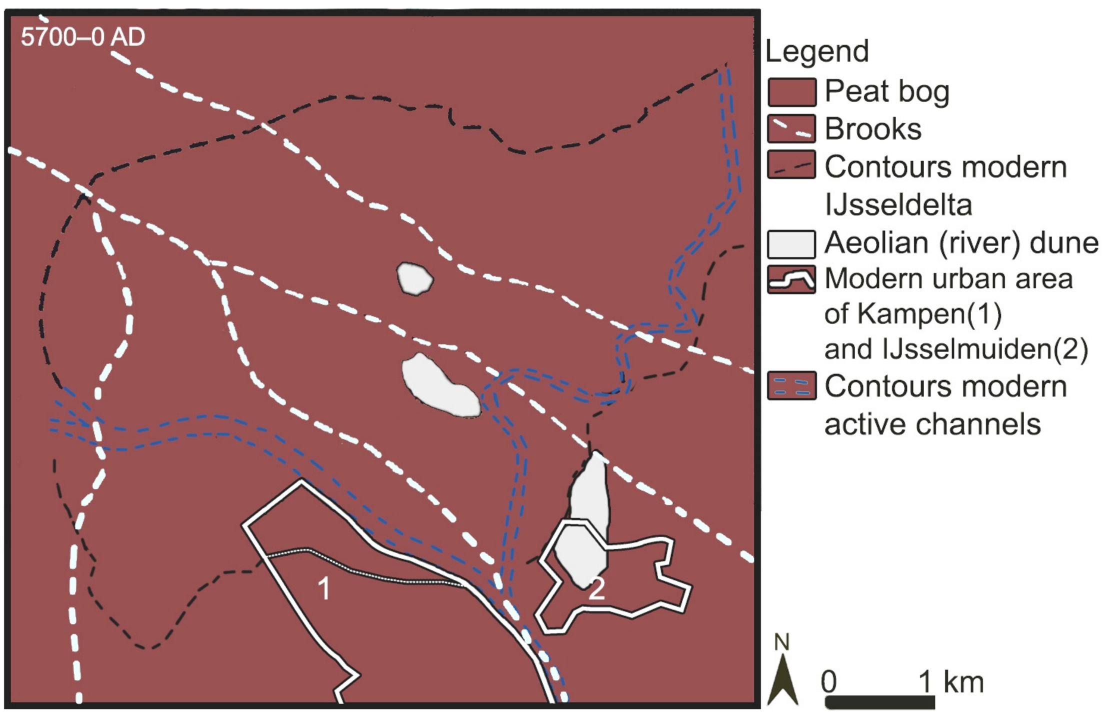


Figure 5.1 Palaeogeographic situation from approximately 5700 to 2000 yr BP.

Small streams flowed, with small flow velocities, through a peat bog area (Fig. 5.1) and finally discharged into the Lake Flevo. (Fig. 5.2a). At the onset of the Roman period the connection between Lake Flevo and the North Sea was, yet partly, established (Fig. 5.2a).

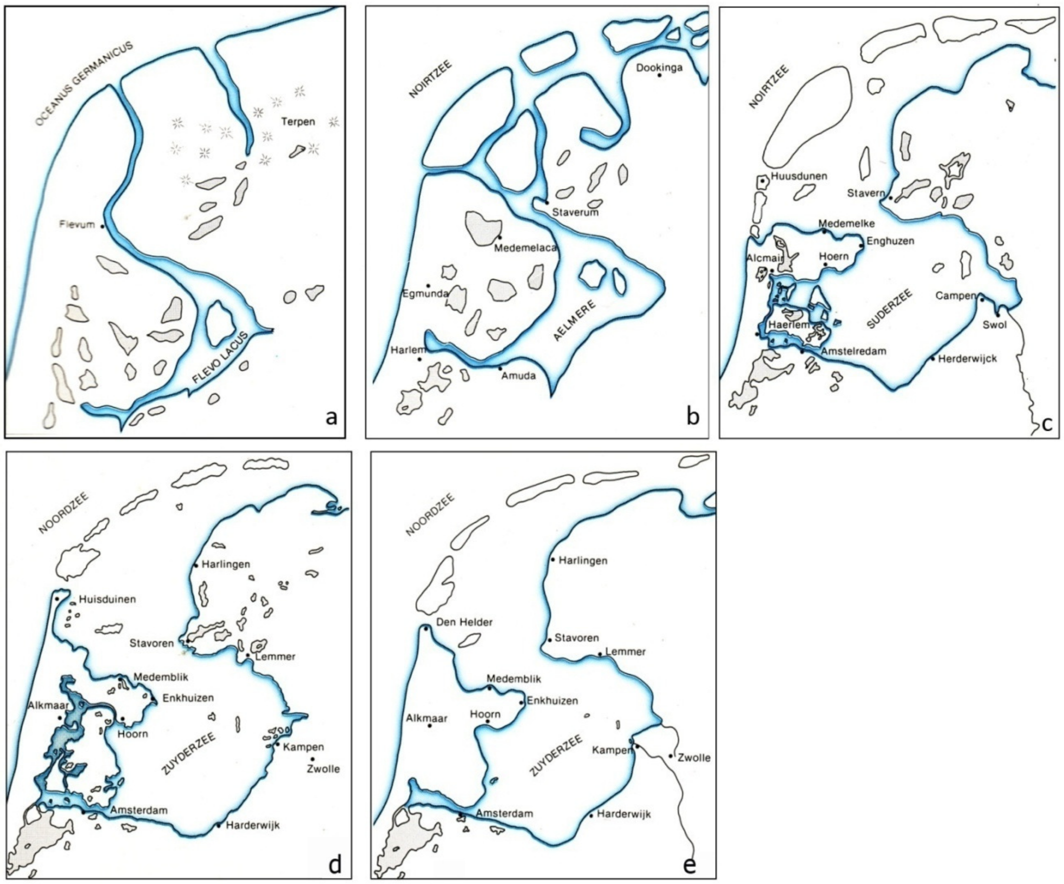


Figure 5.2 Reconstruction of the Zuiderzee basin during Roman times; a) 1st; b) 10th; c) 13th; d) 15th and e) 17th century (after Boon, 1982).

The inland Lake Fevo was a complex of interconnected lakes separated by peat bog areas (Dirkx et al., 1996) which gradually diminished as the lakes expanded due to the erosion. An open (v-shaped) basin developed in the southeastern part of Lake Flevo (Fig. 5.3).

There is much debate on the age and origin of the IJssel as a Rhine distributary among scientists, archaeologists and historians. Makaske et al. (2008) suggested that overbank sedimentation along the lower reach of the river started ~950 AD, based on new AMS radiocarbon age determinations of botanical macrofossils found well upstream of the IJsseldelta. Earlier findings suggest a beginning of upper IJssel overbank sedimentation approximately 600 AD, implying a time lag of ~350 between onset of upper and lower floodplain sedimentation (Makaske et al., 2008). Another ~250 years later the IJsseldelta started to prograde (Ente, 1973). Probably, slow downstream channel-belt progradation accounted for a decreasing age of first IJssel sedimentation (Makaske et al., 2008).

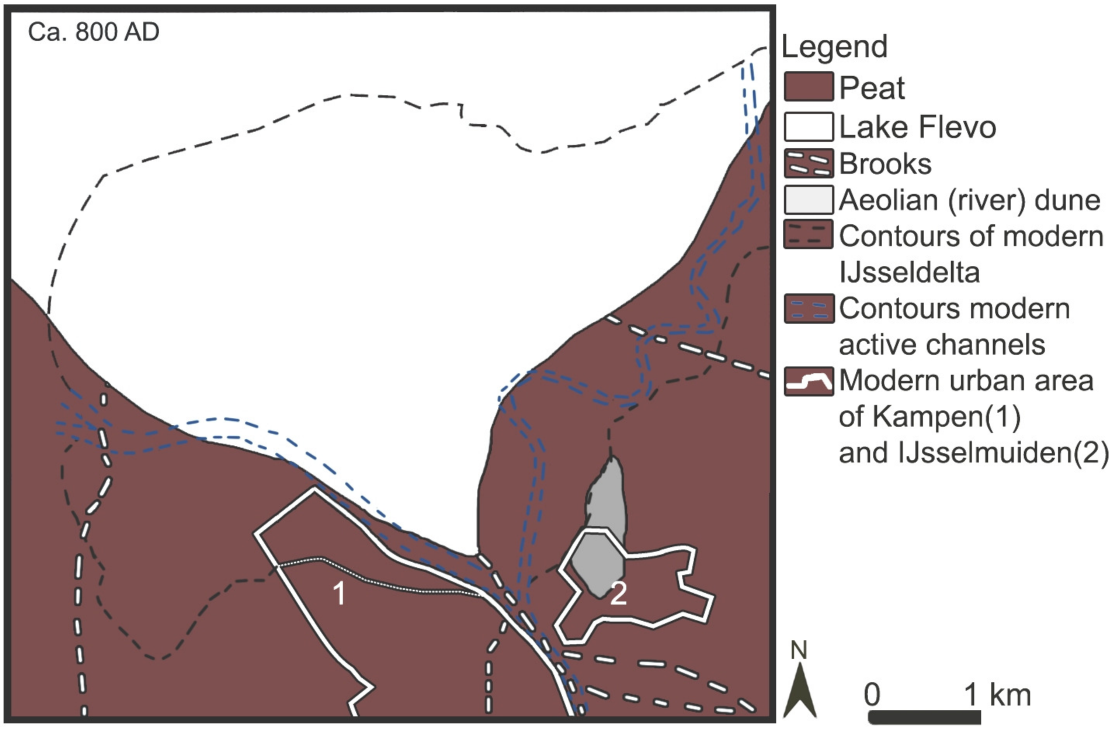


Figure 5.3 Palaeogeographic situation of the former Zuiderzee basin approximately 800 AD. Erosion of peat led to transformation of Lake Flevo to Lake Almere approximately 800 AD.

Approximately 1000 AD, the connection of Lake Almere to tidal inlets of the Wadden Sea was enlarged, which resulted in increased erosion of peat. During storm surges (e.g., St. Julianaflood 1164 AD) enormous landmasses (peat) disappeared. All individual lakes merged forming one vast lake: Lake Almere (Fig 5.2b). Marine influence from the Wadden Sea in Lake Almere increased gradually. According to Dirkx et al. (1996), the Lake Almere near Kampen, was protected from marine influences by a land bridge (Dutch: landengte) which almost connected the Dutch provinces Friesland and Noord-Holland (West-Friesland). Approximately 1300 AD, the land bridge broke and Lake Almere transformed into an inland sea: the Zuiderzee (Fig. 5.2c), a saline to brackish environment due to its connection with the North Sea. Probably, another land bridge (or peat barrier) existed closer to Kampen, as is suggested by Cohen et al. (2010). A rapid breakthrough of the turbulent water, induced by storm events, might have led to a collapse of the land bridge between Kampen and the former island Schokland.

During the High Middle Ages (1000 - 1300 AD) populations grew rapidly. Human activities in the hinterland (Rhine basin), such as cultivation and deforestation, led to increased discharge through the River Rhine and subsequently the River IJssel. Widespread forest degradation, known as the “great clearances”, led to increased rainwater runoff and increased amounts of sediment supply due to soil erosion.

Therefore, the IJssel transported an increased amount of sediments to the river mouth entering open water near IJsselmuiden, a little village that came into existence in 1133 AD. ‘Muiden’ can be interpreted as ‘monding’ (river mouth) and argues that IJsselmuiden was located at the mouth of the River IJssel, where it entered open water. As the IJssel entered the standing water of Lake Almere, approximately 1200 AD, deceleration of the flow resulted in deposition of bed load close to the river mouth in the form of mouth bars and subaqueous levees (Fig 5.4).

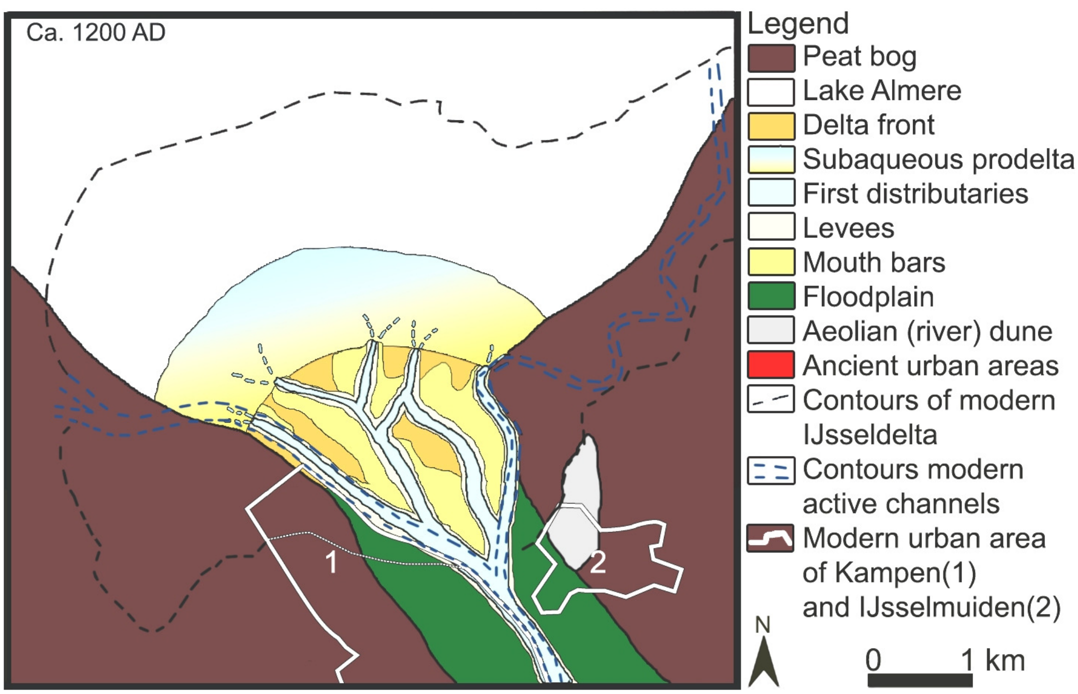


Figure 5.4 Palaeogeographic situation of the IJsseldelta approximately 1200 AD.

The finer sediments in suspension were deposited further in the basin to form a prodelta platform on which the delta front subsequently prograded northwestwards. The presence of mouth bars forced channels to bifurcate into two channels. This process was repeated several times to form various distributaries at the early stage of delta formation, see Paragraph 4.2.2, Fig. 4.7).

5.2 Evolution of the IJsseldelta

Progradation of the subaqueous delta front occurred as sediment supply was sufficient to fill the available accommodation space. The delta built seawards whereas active channels provided sediments as a source for mouth-bar deposition. Levees prograded towards the bars also leading to migration of mouth bars. Consequently, mouth bars and levees formed small islands during delta progradation from approximately 1200 - 1400 AD (Fig. 5.5).

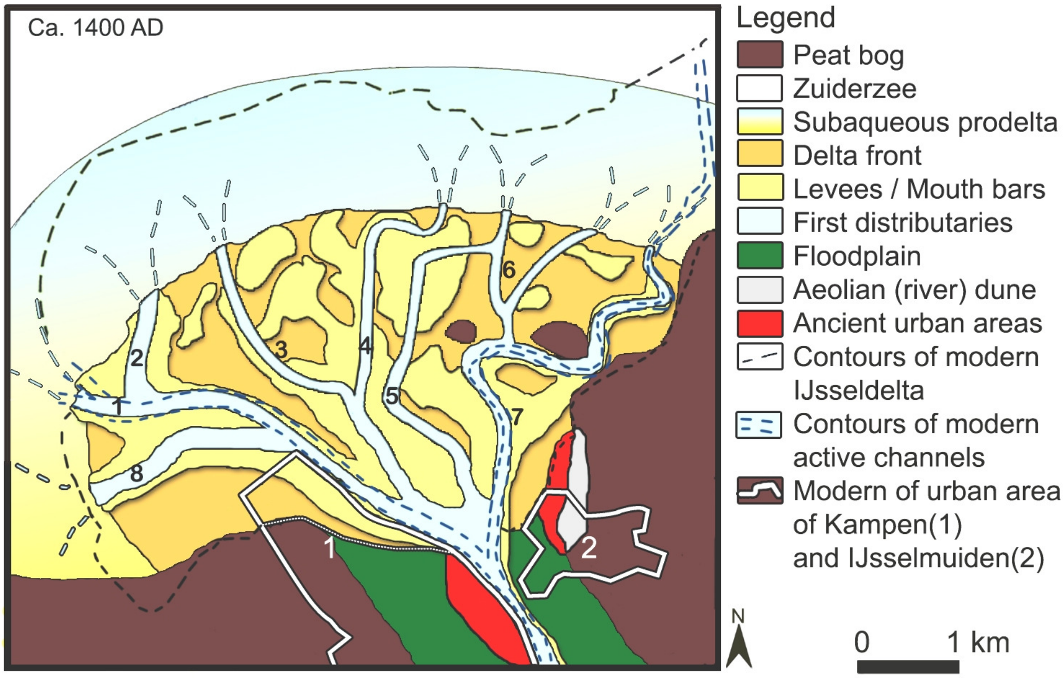


Figure 5.5 Palaeogeographic situation of the IJsseldelta approximately 1400 AD. Mouth bars and levees together grew to islands gradually emerging above sea-level. Distributaries are numbered: 1) IJssel, 2) Regtediep ('t Camperdiep), 3) Noorddiep, 4) Garste, 5) Unnamed, 6) Slenk, 7) Ganzendiep, 8) Zuiderdiep.

The names of the islands are documented and still correspond to the dialectical names given to farmhouses (e.g. weerder, refers to "oeverland = land of levees" and "haegheningher grynt (gravel)" can be interpreted as a sand bar, Dirkx et al., 1996). Eight distributaries were formed (Fig. 5.5) of which the Zuiderdiep became the main distributary around the 15th century, according to Eilander en Heijink (1990).

Embankments and canalizations upstream in the Rhine Basin were carried out by humans from 1350 AD onwards, which increased flow discharge of the River IJssel. Moreover, construction of artificial levees prevented flooding and sediment deposition on floodplains upstream. The majority of sediments was transported to the river mouth until flow discharge ceased and sediments were deposited in front of the delta.

Lower areas between the islands were frequently flooded whereas sediments filled the available accommodation space. The latter might have increased due to compaction of the weak peaty/clayey subsoil and the weight of the overlying deltaic deposits. Gradually, a subaerial delta plain formed which was still prograding to the north into the Zuiderzee. Men raised mouth bars/levees and transformed in mounds where farmers settled. The islands continued to grow and eventually became connected and formed one continuous island called Kampereiland (Fig. 5.7).

In the 16th century the flow discharge of the IJssel diminished. Whereas, there were already complaints about the navigation of the IJssel at the end of the 15th century (Gottschalk, 1977), plausibly caused by the St. Elisabeth's Flood storm surges in 1421 and 1424 AD. Catastrophic inundations and dike breaches led to establishment of a new connection of the Rhine with a southern estuary (Kleinhans et al., 2010) as older fluvial channels in the area SE of Dordrecht eroded (Fig. 5.6; Stouthamer, 2005). This resulted in creation of the Biesbosch tidal area and led to displacement of the mouth of the River Waal which gradually enlarged, while the Lower Rhine-Lek silted up (Fig. 5.6). Consequently, more discharge was assigned to the Waal instead of the IJssel (Ente, 1973), due to the shortening of its course.

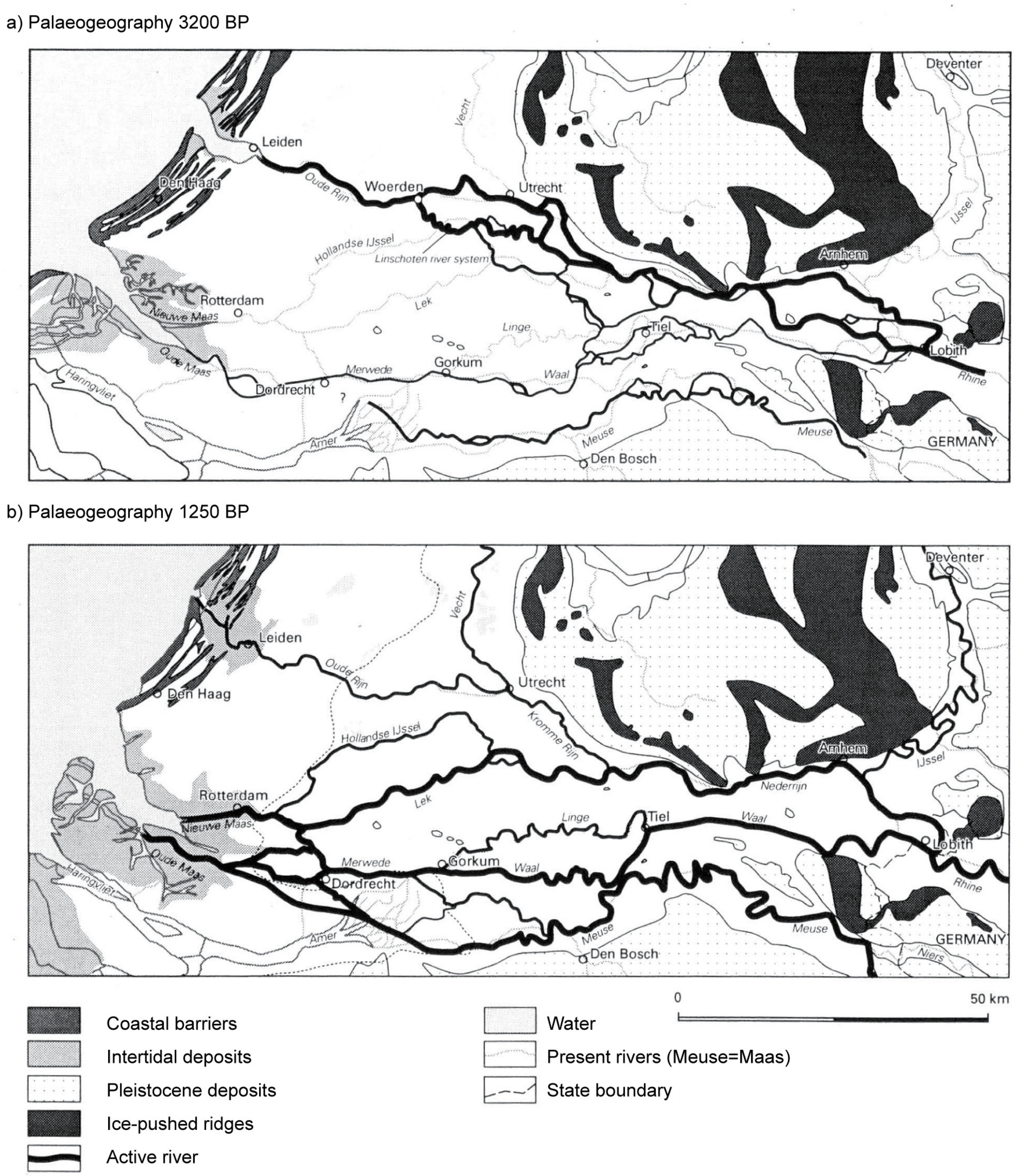


Figure 5.6 Palaeogeographic maps of central Netherlands for the years 3200 and 1250 BP. An obvious change in river diversion is illustrated (from Stouthamer, 2005).

The IJsseldelta silted-up quickly due to the decreased flow discharge. Moreover, the saline seawater was able to drive further inland, through the distributaries, especially during storm surges. Silting up of the IJsseldelta distributaries made shipping more difficult. The city administration of Kampen attempted to prevent the silting up process by damming distributaries (e.g. Noorddiep) to improve the navigation through the Regtediep. This measure should have maintained the channel at depths by directing the flow discharge towards the remaining Regtediep distributary, inducing scouring of this branch (Dirkx et al., 1996). During the years 1624 and 1625 AD dredging was executed (Gottschalk, 1977). Nevertheless, these measures were unsuccessful and ultimately all distributaries silted up, except the IJssel, Ganzendiep and Noorddiep of which the latter continued to be filled with water until present day, although it is inactive.

Simultaneously, marine processes became more dominant as tidal inlets (e.g. Marsdiep and Vlie) enlarged (Gottschalk, 1977). The last remaining peat lands in the Zuiderzee basin were now washed away by storm surges and salinity increased southward (Dirkx et al., 1996). Prevailing northwestern storm surges distributed sediments from the Zuiderzee towards the IJsseldelta. Bank erosion of the delta coast occurred, forced by the turbulent sea water. Consequently, eroded matter was redeposited, under influence of wave action, in the form of beach ridges in front of the delta (Fig. 5.7) consisting of clay/clay-loam material.

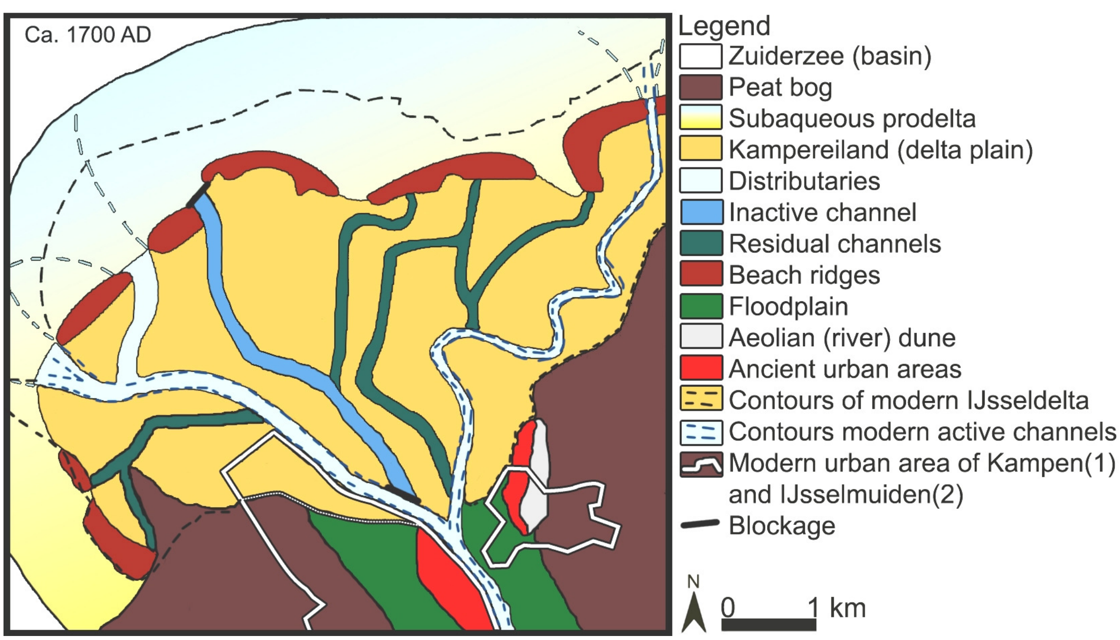


Figure 5.7 Paleogeographic situation of the IJsseldelta approximately 1700 AD.

In 1707 AD the Pannerdensch Kanaal was established upstream near Arnhem, to regulate the distribution of the Rhine discharge towards the IJssel and secure navigability through the IJssel. Since then, discharge and floodings of the IJssel have been more controlled what facilitated dike and water management of the IJssel and its delta. In spite of a more controlled IJssel discharge, floods of the Zuiderzee continued to inundate the subaerial delta plain of Kampereiland because land subsidence was no longer compensated by sedimentation.

The beach ridges extended and became gradually more elongated by the year 1800 AD forming a protective coastal barrier. This barrier was reinforced by significant dike improvements by the year 1862 AD, in order to minimize floodings of the Zuiderzee (Dirkx et al., 1996). On the seaward side of the dikes, accretion occurred in a more saline environment with sand/mud flats and poorly developed salt-marshes. This accretion was stimulated by local farmers with significant dike improvements to reclaim new land (Dirkx et al., 1996). The lack of typical salt marsh vegetation on accreted flats is striking. In contrast to the expected brackish coastal vegetation, rush fields (Dutch: biezenvelden) dominated the area north of the beach ridges which yielded a rich harvest to the local rush industry. Moreover, the rush fields contributed to accretion of clay loam and clay, resulting in further expansion of Kampereiland. When accretion was sufficient the areas were reclaimed and cultivated. Today the beach ridges are located a few hundred meters inland due to this accretion.

In front of the mouth of Regtediep a sand bar formed, called Ramspol (Fig. 5.8).

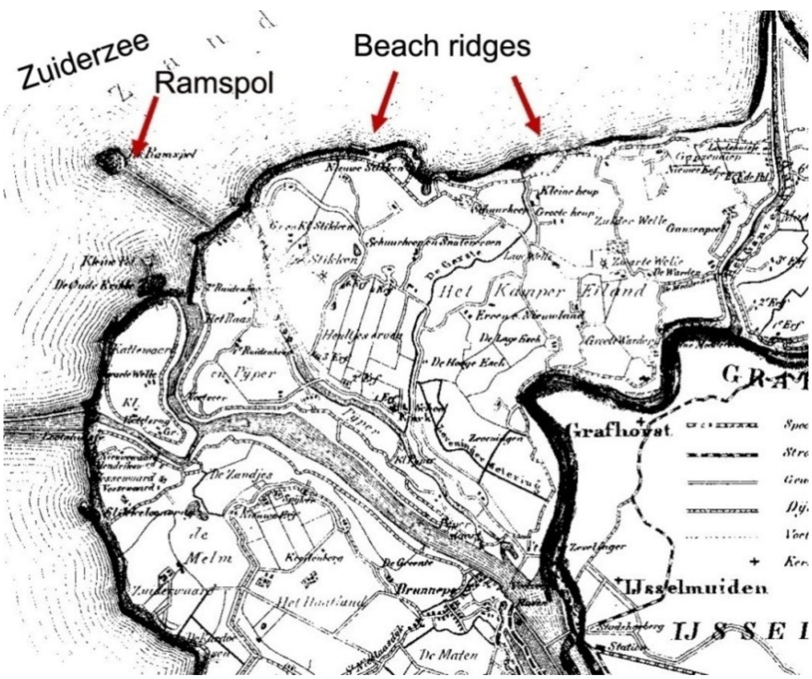


Figure 5.8 Map from city archive of Kampen originating from 1865 AD. The island Ramspol arose as one of the last individual islands.

Despite of the dike reinforcements, floodings still occurred although less frequently. This came to an end in 1932 AD. An enormous project called the ‘Zuiderzeewerken’ started in 1920 AD under the direction of Cornelis Lely, resulting in the construction of a large dam, the

Afsluitdijk. This drastic measure turned the former saline Zuiderzee into the freshwater lake 'IJsselmeer' and floodings became history. Due to the decreased energetic conditions, changes were such that large areas of seawater could be reclaimed as land. The reclaimed areas are known as polders, like the Flevopolder and the Noordoostpolder. Thus, marine influences disappeared completely at Kampereiland and the accretionary fields were transformed in agricultural areas, protected from seawater. In 1940 AD the Regtediep distributary was dammed and filled with sediments from the excavated Kattendiep (Van Schaick, 1939; Appendix G, lower right corner). The surrounding mud flats were elevated with ~0.5 m of these excavated sediments, forming the Rechterveldpolder.

5.3 Delta progradation

The IJsseldelta prograded in a mainly northwestern direction, although not uniformly. Deltaic sand distribution occurred in a triangular shape during delta front progradation. Later when delta front progradation ceased, prevailing westerly winds created a slightly more eastward extension of the delta plain. Obviously, progradation was not constant through time (Fig. 5.9).

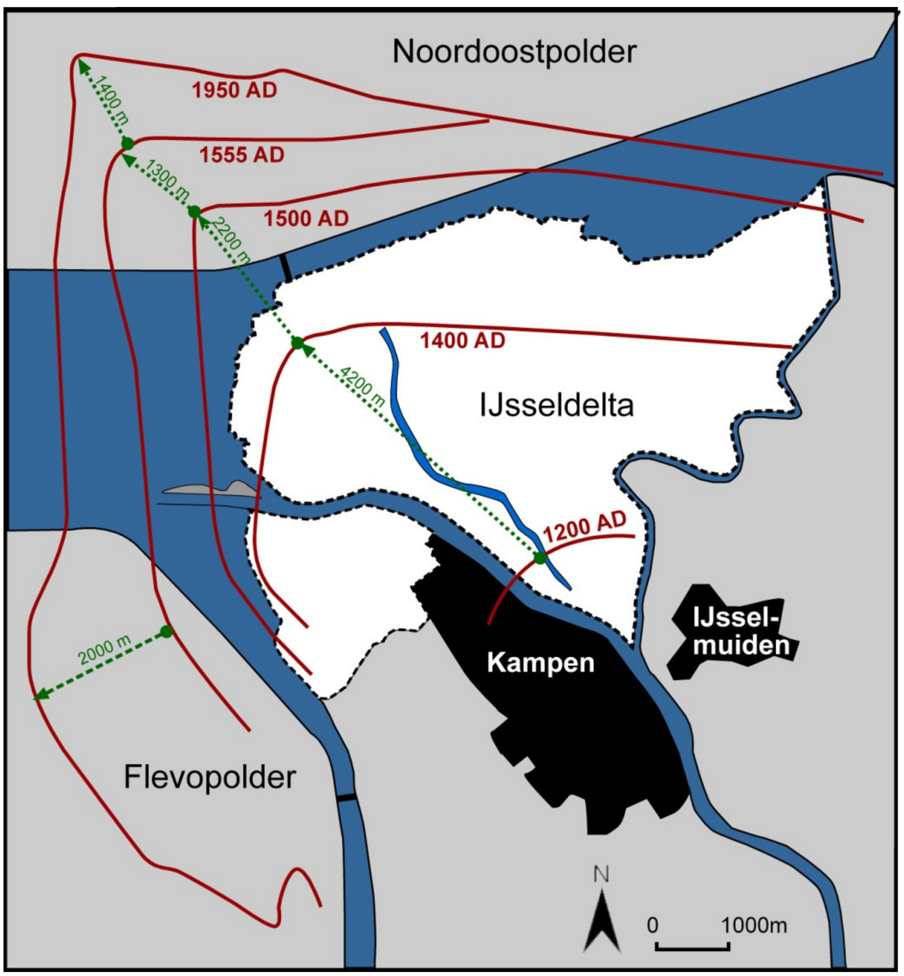


Fig. 5.9 Progradation of deltaic sand through time (After Ente, 1973).

It should be noted that the progradation of the delta is based on the occurrence of deltaic sand (Ramspolzand) in and near the IJsseldelta. The contour lines are derived from Ente (1973), without complete certainty of the provided ages, which are therefore only considered as indicative. The maximum extent of deltaic sand is set to almost 10 km northeast of the former apex of the delta.

Progradation rates are calculated for various time intervals from 1200-1950 AD (Table 5.1).

Table 5.1 Progradation rates of deltaic sand.

Year AD	1200-1400	1400-1500	1500-1555	1555-1950	Total
Progradation (m)	4200	2200	1300	2000	9700
Progradation rate (m/yr)	21	22	24	5	Avg: 13

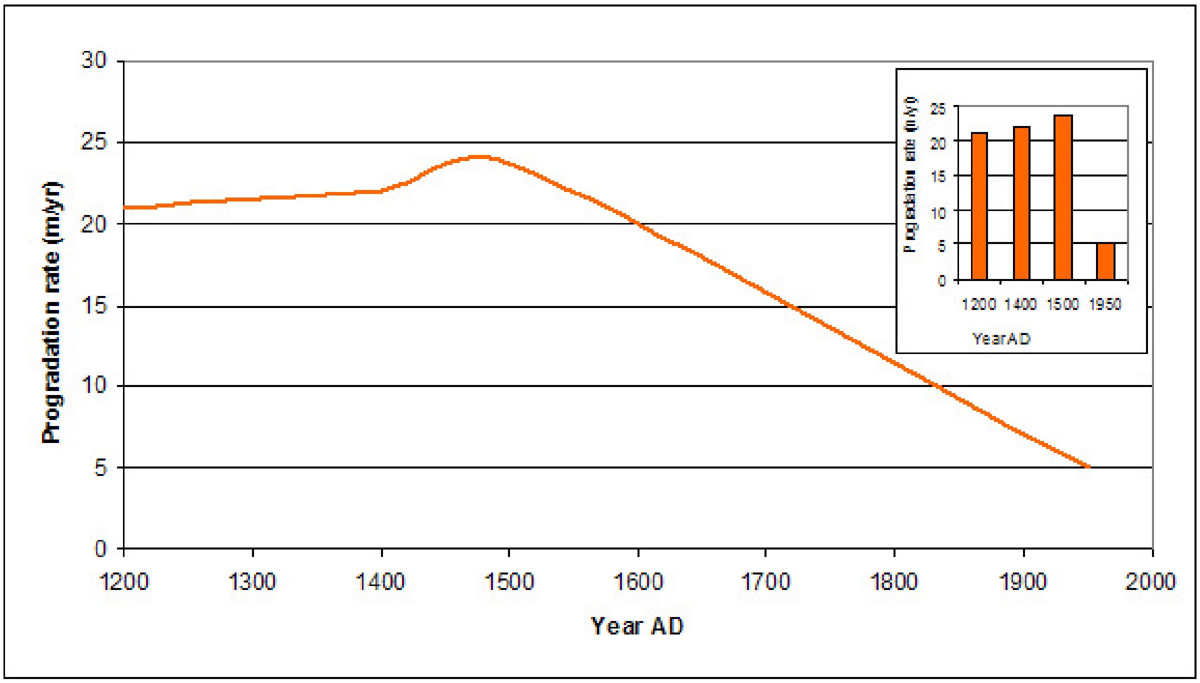


Fig. 5.10 Progradation of the IJsseldelta from 1200 to 1950 AD based on Figure 5.8.

The average progradation rate of the delta was approximately 13 m/yr over a period of 650 yrs. The IJsseldelta had a lightening start from 1200 to 1500 AD. The progradation rate, however, decreased abruptly after the 15th century (Fig. 5.10). Progradation rates dropped from ~24 m/yr to 5 ~m/yr due to a decreased flow discharge of the IJssel River. By that time marine dominance took over.

Already in 1364 AD most mouth bars/levees emerged above sea-level at Kampereiland. The delta already built up approximately 4 m of deltaic deposits within 200 years. Sedimentation rates of the prodelta and delta front facies can be roughly estimated based on average thicknesses obtained from cross-sections (Table 6.1).

Table 5.2 Estimated (vertical) sediment accumulation rates for the IJsseldelta in comparison with other Holocene deltas.

	IJsseldelta		Changjing (Yangtze) delta		Mekong delta		Nile delta
Source	This study		Hori et al. (2001)		Ta et al. (2005)		Krom et al. (2002)
Facies	Prodelta	Delta front	Prodelta	Delta front	Prodelta	Delta front	?
Average thickness (cm)	138	264					
Time (yr)	200	200					
Average accumulation rate (cm/yr)	**0.69**	**1.32**	**0.11**	**0.35**	**0.45**	**0.29-0.42**	**0.6**

* assumed active sedimentation: 200 years

An average sediment sedimentation rate of 0.69 cm/yr (~1.38 m/200 years) and 1.32 cm/yr (2.64 m/200 years) is estimated for the prodelta subenvironment and more active delta front subenvironment respectively. An average sedimentation rate of 0.69 cm/yr for the prodelta endorses the hypothesis that coloured laminae show a seasonal cyclicity, since thicknesses of lamina couplets are often in the same order of magnitude (Fig. 4.6). Sedimentation rates are relatively high compared with other deltas. It should be noted that estimated values are not very certain due to a lack of an accurate chronology of the IJsseldelta. If active sedimentation has taken place for a period of 300 years, the values are more comparable with values of other deltas.

6 Discussion

The onset of the IJsseldelta is most likely caused by human activity in the hinterland. Besides a human-induced increase in sediment supply due to deforestations, other factors downstream could have played role. The enlargement of the brackish Lake Almere and transformation in a more saline Zuiderzee would have definitely played a part. A shorter connection of the IJssel might have enabled the IJssel to withdraw more Rhine water in comparison with the Neder-rijn and Waal. However, the impact of climate changes may not be excluded from consideration. Scientists generally agree that two major climate periods have occurred from the 10th to the 19th century. Namely, when the delta formed, a relatively warm period (Medieval Warm Period or Medieval Climate Optimum), occurred from ~950 - 1250 AD. Increased rainfall, expressed in a higher river flood frequency according to Gottschalk (1971) about the 12th century, might have been influential. Later, the Medieval Climate Optimum was followed by a much colder period, known as the Little Ice Age from the 16th to the 19th century. Gottschalk (1975) suggested the occurrence of ice dams downstream, that could have increased flood frequency, especially where channels narrowed downstream of a bifurcation (Kleinhans et al., 2010). Furthermore, clear evidence of completely frozen distributaries in and near the IJsseldelta is recorded by the famous winter paintings of Hendrick Avercamp, originating from the first half of the 16th century. The influence of these climate fluctuations might have had considerable effects although these are difficult to reveal from sediment characteristics.

The IJsseldelta distributaries silted up quickly, caused by a decreased flow discharge and a consistent sediment delivery of the IJssel River. From ~1350 AD onwards human interventions upstream again played a role in evolution of the IJsseldelta. Embankments prevented flooding and sediment deposition on the embanked floodplains upstream (Middelkoop et al., 2010). Flow discharge increased, inducing bank erosion, which provided an additional sediment source. The question remains what has been the reason for the reduced flow regime of the IJssel. As already mentioned, changes in river diversions upstream in the Rhine system might have been influential. The St. Elisabeth’s Flood storm surges in 1421 and 1424 AD led to catastrophic inundations, dike breaches and river diversions. Consequently, the Waal (a distributary of the Rhine) began to withdraw more water from the Rhine at the expense of the IJssel (Gottschalk, 1977), resulting in silting-up of the other Rhine branches (e.g. IJssel, Nederrijn).

Other factors that could have played a role in the extreme drying-up of the IJssel are imaginable. Changes in climate might have reduced the Rhine flow discharge, although this would have had the same effect on the Waal and Lower Rhine distributaries. This has not been the case since these rivers maintained their navigability. A more plausible explanation is suggested by Gottschalk (1977). The number of dike breaches increased at Nijmegen and Emmerich from 1651 AD onwards as large quantities of sand and silt were carried with the river, blocking its path and diverging the main flow more westwards.

Ente (1971) suggested that Almere deposits are present in the IJsseldelta, overlain with a rather coarse sandy subaqueous delta platform. This is contradictory to the theory that clayey/silty deposits are deposited in a prodelta subenvironment which underlies the sandy delta front facies association, as is suggested in this study. No clear evidence for Almere deposits is encountered during fieldwork in the IJsseldelta. Furthermore, the layer of microfauna (*Valvata Piscinalis*) is mostly found right on top of the continuous peat layer and just below the laminated prodelta facies association. A rapid transition from the 'non-deltaic' to deltaic facies associations seems to indicate that erosion of peat was triggered by major storm events (e.g. 1170 AD; Gottschalk, 1971). It is quite conceivable that a peat barrier has been eroded rapidly that must have created a sudden potential for sedimentation and burial of *Valvata Piscinalis*

To determine a reliable chronostratigraphy of the IJsseldelta, acquire more accurate progradation and sedimentation rates, confirm described assumptions and prove the classification into three deltaic facies associations, absolute dating techniques need to be executed.

7 Conclusions

Detailed analysis of a few hundred borehole descriptions, obtained from the subsurface of the present delta plain, clarified sediment characteristics and resulted in facies classification. Thereupon, palaeogeographic reconstruction of the origin and evolution of the IJsseldelta is made. Major conclusions are drawn as follows:

- All deposits are successfully classified in a total of six facies associations, of which three are interpreted to have a 'non'-deltaic' origin (Fig. 6.1).

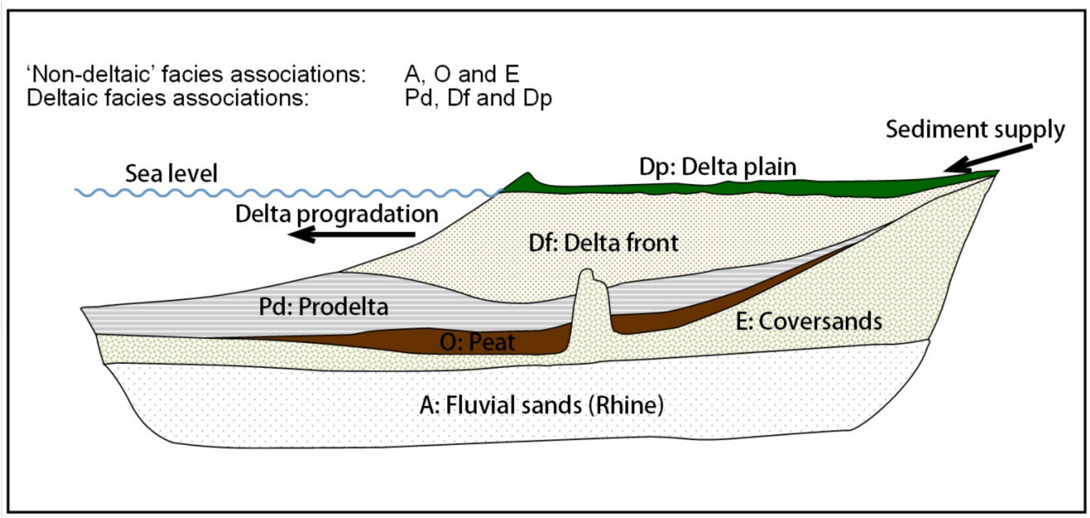


Fig. 6.1 Classification of six facies associations.

Fluvial sands deposited before the Holocene are encountered, covered by aeolian sand. Holocene sea-level rise resulted in a layer of peat which has been struck frequently during fieldwork. The remaining three deltaic facies associations are interpreted as prodelta, delta front and delta plain subenvironments, which were distributed progressively from approximately 1200 AD. Fluvial sedimentation began to overwhelm the marine transgression as the river mouth progradеd seawards. Increased amounts of sediment supply resulted in delta front and prodelta facies distribution. Superimposed delta front and prodelta facies built up about 4 m of deltaic sediments within a few centuries. Approximately 1500 AD delta progradation ceased and marine dominance took over. The resulting delta plain facies was frequently flooded during storm surges of the Zuiderzee. Delta front and delta plain facies associations are further subdivided into lithofacies units according to their depositional environment, as is reflected in distinctive sediment characteristics.

- Many natural physical factors played a role in the development of the IJsseldelta. The most fundamental are:
    - *Sea-level rise,* relative sea-level rise led to an increase in accommodation space, facilitating potential sediment accumulation.
    - *Erosion:* storm surges eroded enormous masses of peat which enlarged the area of the open basin near Kampen, benefitting the potential for deltaic sedimentation. Upstream, soil erosion occurred due to deforestations, delivering an increased amount of sediments to the IJsseldelta. Furthermore, *bank erosion* of the river banks and floodplains occurred, enhancing sediment supply even more. According to Middelkoop et al. (2010), 60% of the IJssel floodplain was reworked between 1300 and 1850 AD.
    - *Wave action,* redistributed sediments were deposited in beach ridges under influence of wave action, generated by northwestern gales.
    - *Flooding:* periodic flooding of the IJssel on the delta plain had a positive effect for Kampereiland inhabitants, since it contributed to a fertile soil. On the contrary, unpleasant floods of the Zuiderzee also occurred which were inconvenient because cattle drowned and damage was made to farmhouses.
    - *Salinization:* increased salinity influenced plant growth and yield. This affected the lower pastures of Kampereiland where considerable amount of crops were lost.
    - *Sediment supply:* variations in sediment supply together with *flow discharge* were of major importance, since sediment was the building material of the IJsseldelta. Sediment was needed to counterbalance the natural degradation by *land subsidence* and *coastal erosion.*
    - *Land subsidence:* it is imaginable that substantial vertical land subsidence has taken place. Cross-sections E-E' and F-F' show preservation of continuous peat layers from south to north. The weight of particularly the sandy delta front facies association must have contributed to a significant compaction of peat what led to increased *accommodation space*.

- Directly and indirectly, people had a great impact on the IJsseldelta. The main effects of human interventions led to disruption of natural processes and particularly changed river discharges and sediment supply. Initially, human activities in the hinterland indirectly modified sediment delivery upstream, which supposedly triggered delta formation. Deforestations and expansion of intensive agriculture in the upstream Rhine basin led to an increase in flow discharge and sediment delivery. People cleared woodlands and constructed canals, which enhanced the increase of river (peak)discharges. Later, human interventions such as embankments and canalization directly led to decreased erosion of upstream floodplains. Less sediments were trapped in the embanked floodplains and more fines were distributed towards the most downstream parts, e.g. the IJsseldelta. In two ways Dutch engineers succeeded to directly control the flood frequency and other dynamic forces that influenced the delta. Flow discharge was regulated by the digging of the Pannerdensch kanaal and marine flooding completely disappeared since the construction of the Afsluitdijk in 1932 AD. Nowadays, Kampereiland is mainly used for agricultural purposes. All physical processes describe above are under control, although land subsidence may still be a thread in the future, possibly enhanced by drainage of pastures. Particularly, when sea level will rise more rapidly the coming decades, as is predicted by many scientists. Sediments to counteract with sea-level rise are no longer supplied to the delta, since all distributaries are embanked or filled. Moreover, the Dutch government is intending to use the modern Lake IJssel as a freshwater basin to secure the demand for freshwater. Consequently, the water level of the Lake IJssel will rise which will threaten the low-lying delta plain of the IJsseldelta even more.

- The delta morphology of the IJsseldelta is influenced by both fluvial and marine dominance. Initially, the delta was fluvial-dominated. Around the 16th century the fluvial-dominated subaqueous delta had reached its final stage and the delta became more wave-dominated (Fig. 6.2). Prevailing (north) westerly winds formed beach ridges under marine influence. Sediment characteristics point to more dominant marine influence in the western part of the delta in comparison to the eastern part. Closure of the Zuiderzee in 1932 AD led to disappearance of both fluvial and marine influence and pastures of Kampereiland became protected from floods.

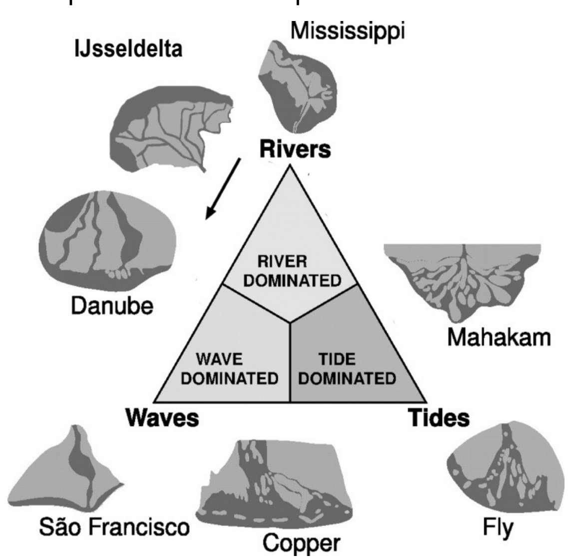


Fig. 6.2 The classification scheme after Galloway (1975) and comparison of the active IJsseldelta with 16 major deltas all around the world. Wave-, tide-, and river-dominated deltas are distinguished in the extremes of the triangle. The IJsseldelta is situated close to the most river dominated deltas, such as the Mississippi delta, although at final stage of delta formation it can be shifted to more wave-dominated deltas.

8 Further research

It is essential to establish an accurate chronostratigraphy to calculate more reliable sedimentation and progradation rates of the IJsseldelta. However, determining ages of deltaic sequences are often problematic and unreliable for several reasons. Traditional radiocarbon ^{14}C-dating is most used to date Holocene deltaic sequences. Ages can be obtained with the use of organic components (e.g. peat, gyttja, macrofossils, humic clay). Radiocarbon ^{14}C-dating might be especially problematic in deltas because of the temporary storage of old carbon. Dates are often too old as a consequence of downslope reworking of upland alluvial sediments, with displacements of old carbon in sediments at the delta front (Stanley et al., 2001). Moreover, contamination can occur due to root penetration through a profile, infiltration by younger humic acids through older peat or soil horizons, and also bioturbation could play a role. By dating macrofossils, such as seeds, botanical contamination (root penetration) can be avoided, which enhances the reliability of acquired ages (Törnqvist et al., 1996, 1998). AMS (Accelerator Mass Spectrometry) dates of terrestrial macrofossils are more accurate than bulk samples of peat or gyttja. The presence of fragments of univalves and bivalves in the deltaic deposits of the IJsseldelta provide opportunities for AMS dating. Molluscs (freshwater mussel) and especially *Valvata Piscinalis* (freshwater snails) are potential to be valuable chronostratigraphic markers within the sediments of the delta.

Residual channels are often filled with humic clay and peat shortly after the sedimentation by the active channel stops. Humic clay, with a huge amount of plant debris, can be used to for dating river activity. If Basal peat is found on top of the (compaction-free) Pleistocene sands, it is possible to reconstruct an age-depth diagram to approach past fluctuations in groundwater level, which was principally driven by relative sea-level rise. Preferably locations featuring a slope in the Pleistocene subsurface have to be chosen, to avoid rising of local paleowater-level relative to regional paleowater-level due to poor drainage.

An alternative dating method is OSL(Optical Stimulated Luminescence)-dating, where the exposure to sunlight prior to burial is measured with the use of minerals (e.g. quartz and feldspars). The exposure to sunlight, called bleaching, sets the clock to zero. During the period of burial, the OSL source accumulates by the action of natural radiation from ambient material including radioactive isotopes (e.g. uranium, thorium, rubidium and potassium). The accumulated dose, called the ‘paleodose’, is the quantity of radiation that the deposit has received since it was last exposed to sunlight. The natural radiation rate during a one-year period is called ‘annual dose’, and the OSL age = paleodose/annual dose. Application of optical dating to sediment deposited in the last few hundred years is of special interest, as the precision of radiocarbon dating in this age range can be extremely poor (Truelsen and

Wallinga, 2003). However, optical dating in this age range can be problematic if light exposure prior to burial was insufficient to completely remove charge from the optical stimulated luminescence traps used for dating (Truelsen and Wallinga, 2003). This may result in overestimation of the burial age and is referred to as partial bleaching. Recently, Wallinga et al. (2010) demonstrated that OSL dating is valid for very young fluvial deposits of the River Waal, no matter the lithology (clay, silt, loam or sand).

Use of a multiple-method approach is recommended to obtain a reliable timing of sediment accumulation. Comparison of different methods (OSL- Radiocarbon dating) on equal deposits provides an opportunity to check if the OSL-method is also applicable for young deltaic deposits in the IJsseldelta. Cross-sections in appendix B show classification into facies units and recommended locations are indicated for potential radiocarbon and OSL-ages. Table 8.1 offers an overview of recommended dating locations and related dating methods. Appendix F shows a map with selected dating locations.

Table 8.1 Recommended locations for dating purposes.

Location nr	Cross-section	Borehole	Coordinates [x,y]	Depth [cm]	Method	Material	Facies code	Objective/special remarks
R1	B-B'	200716007	189419, 510449	440-460	OSL	Sand with grain-sizes varing from 420 to 850 µm	Df2	Determine the beginning of first distributaries. Channel lag might contain fragments of freshwater mussels, which can be used for ^{14}C-dating
R2	B-B'	200716014	189953, 510895	410-440	OSL	Sand with grain-sizes varing from 210 to 1000 µm	Df2	Determine the beginning of first distributaries
				440-460	^{14}C	Wood peat	O	Date Holocene peat
R3	B-B'	200716019	190478, 511133	310-330	^{14}C	Wood peat on a Pleistocene slope	O	Reconstruct groundwater curve triggered by sea-level rise (age-depth diagram)
R4	C-C'	200712005	188018, 512602	410-440	^{14}C	Humic clay, gyttja, wood- and plant remains	Df3	Test suitability of wood-, plant remains and humic layers for ^{14}C-dating. If humic material from interdistributary area can be dated, perhaps also humic laminae of prodelta are able to date
R5	C-C'	200712008	188331, 512629	320-340	OSL	Coarse sand (420-850 µm)	Df2	Date channel deposit
				360-390	^{14}C	Gyttja, humic clay	Df3	Test suitability of wood-, plant remains and humic layers for ^{14}C-dating. If humic material from interdistributary area can be dated, perhaps also humic laminae of prodelta are able to date
R6	C-C'	200712009	188410, 512591	60-80 and 440-460	^{14}C	Medium grained sand (300-420 µm)	Df1	Thickness of delta front facies association to determine sedimentation rates
R7	D-D'	200713033	190657, 511889	170-220	^{14}C	Humic clay with plant remains	Dp3	Date marine deposit (end of active delta)
R8	D-D'	200713002	190411, 512450	450-460	^{14}C	Washed-up peat remains	Df1	Confirm storage of old carbon
R9	E-E'	200714020	189935, 513839	440-460	^{14}C	Valvata microfauna	Pd	Prove that the 'valvatalayer' is a chronostratigraphic marker for onset of the IJsseldelta
R10	F-F'	200711087	185814, 185814	470-490	OSL	Medium grained sand (300-420 µm)	Pd	Date sand intercalation within prodelta deposit
				650-670	^{14}C	Clayey peat	Pd	Determine the age of first prodelta deposit
				690	^{14}C	Valvata microfauna	Pd	Prove that the 'valvatalayer' is a chronostritagraphic marker for onset of the IJsseldelta
R11	F-F'	200711044	187536, 511805	460-470	OSL	Coarse sand (420-600 µm)	Df2	Determine the end of river activity of Noorddiep
R12	F-F'	200711033	186353, 512874	380-410	^{14}C	Clayey peat	Pd	Determine the age of prodelta deposit

When absolute ages are obtained, it would be able to determine more certain progradation and sedimentation rates. Even more interesting, the palaeogeographic reconstruction of the IJsseldelta, presented in this report, can be optimized.

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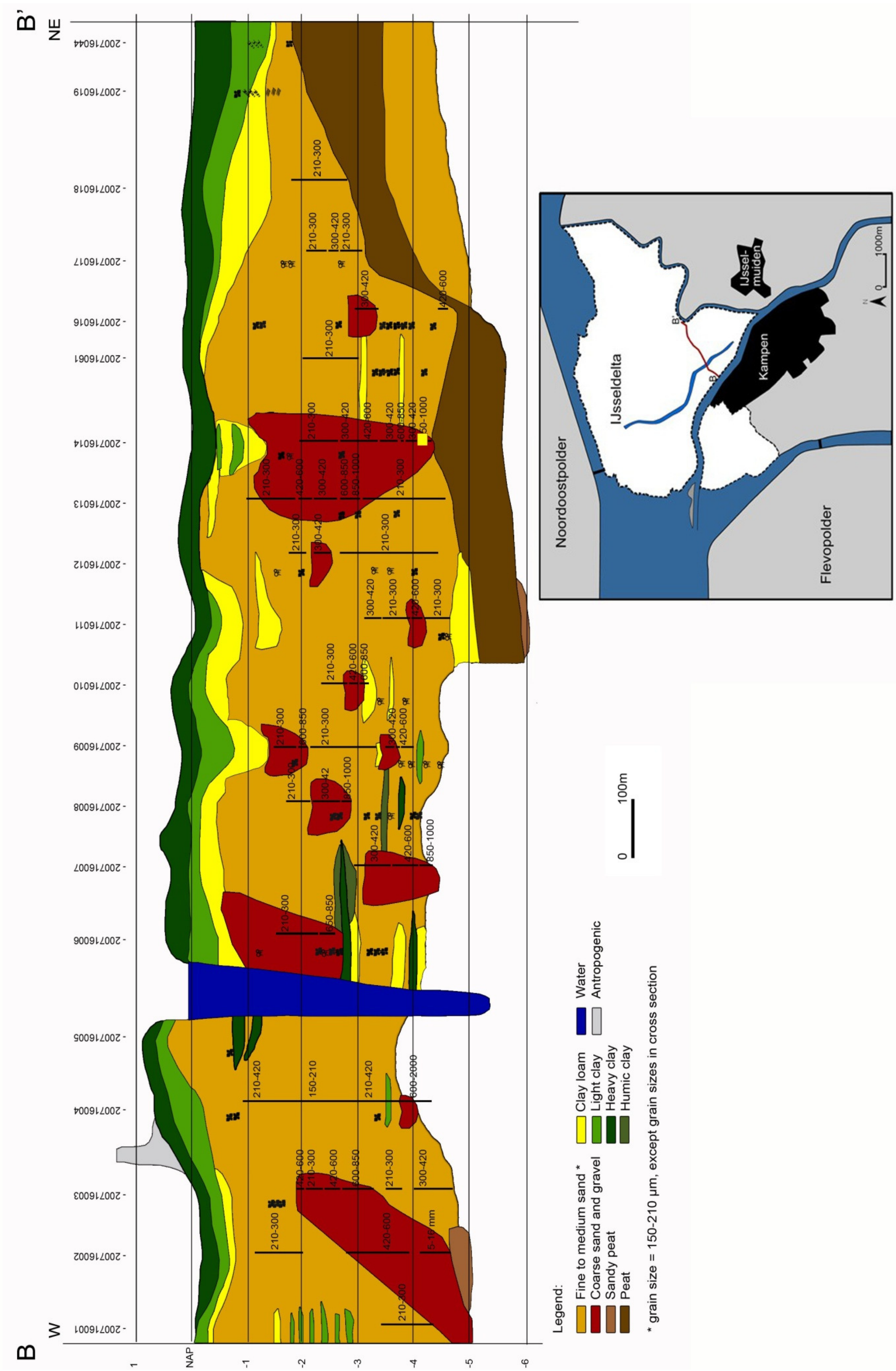
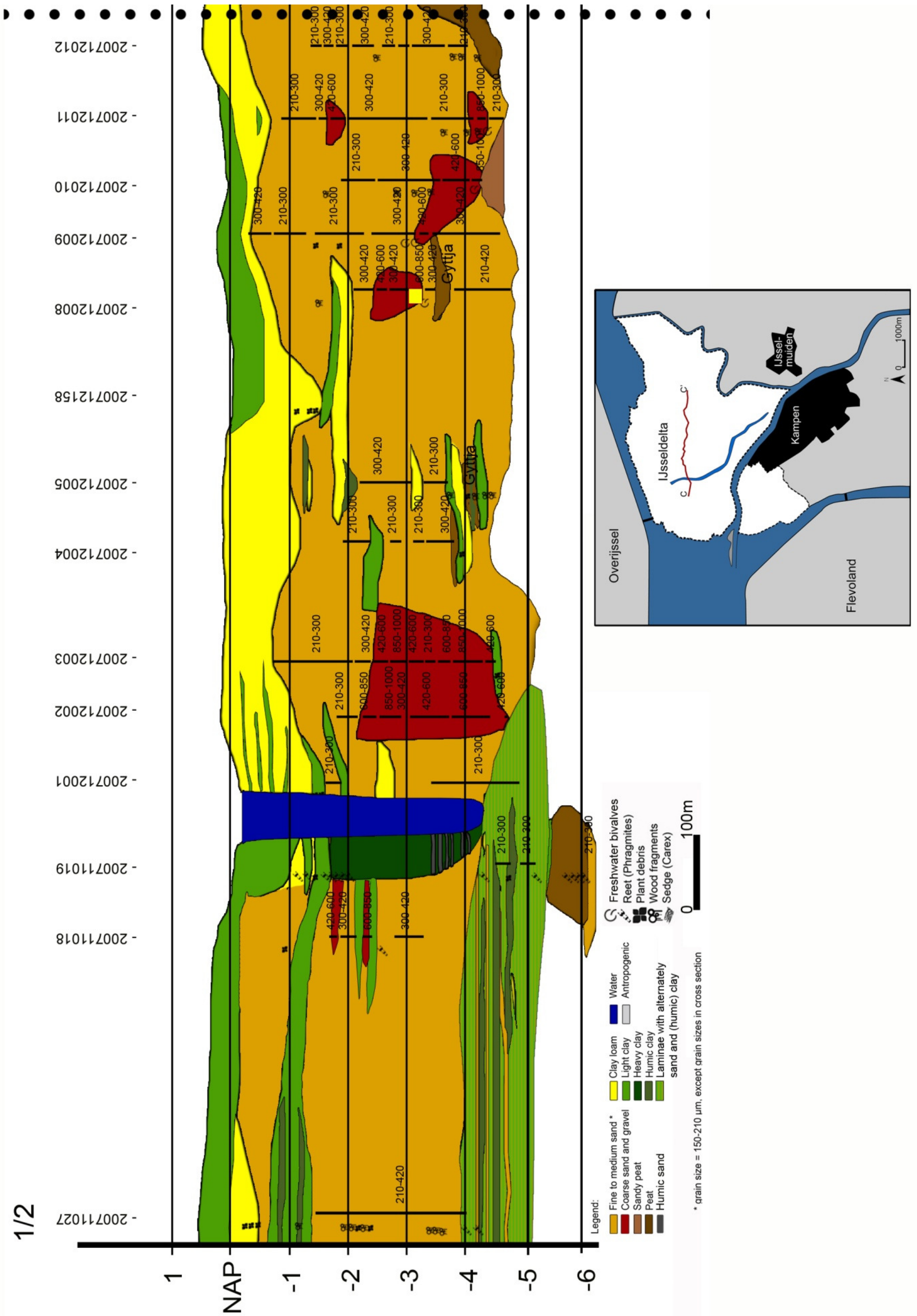
Appendices

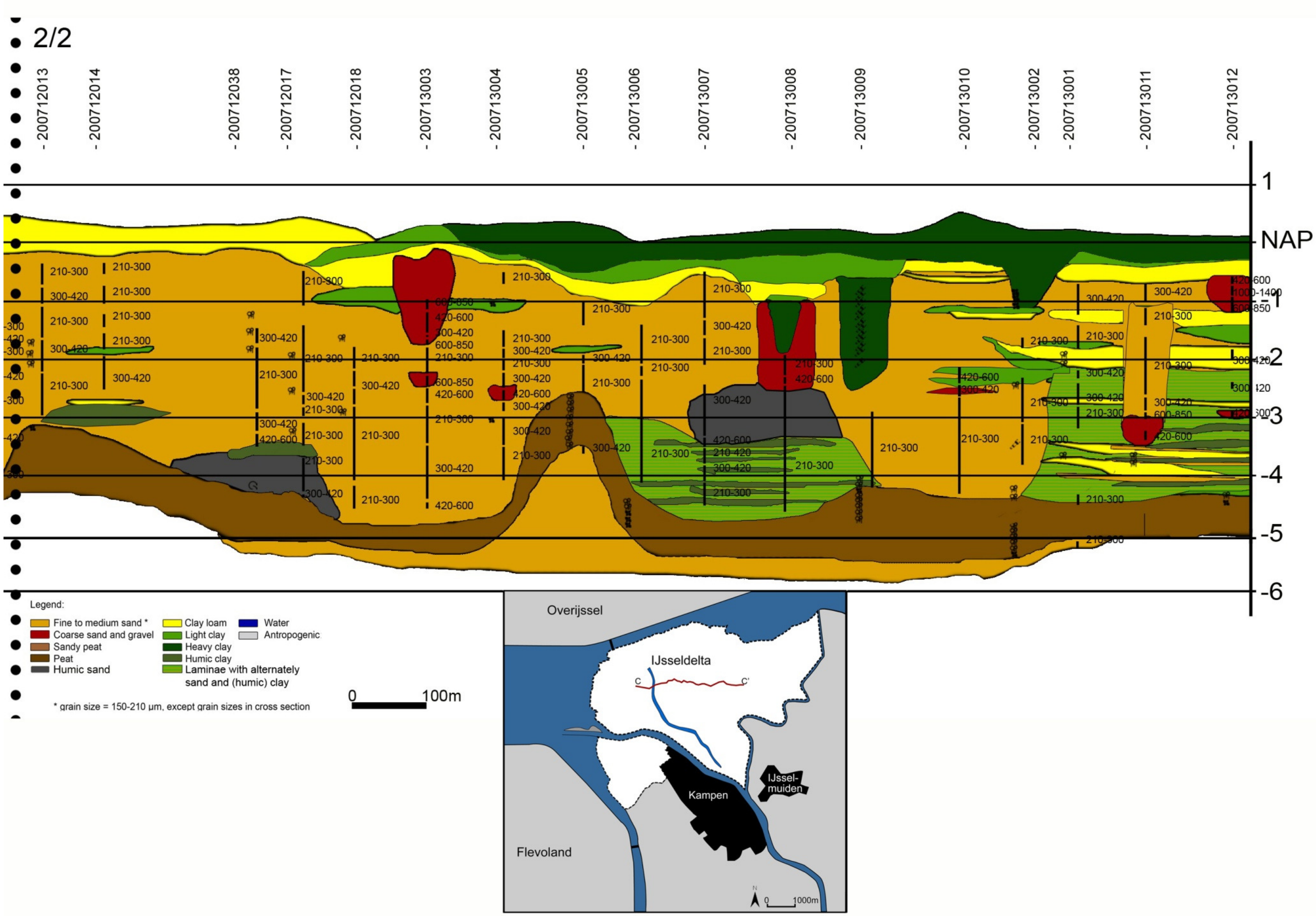
- Apendix A1 Lithologic cross-section B-B’
- Apendix A2 Lithologic cross-section C-C’
- Apendix A3 Lithologic cross -section D-D’
- Apendix A4 Lithologic cross-section E-E’
- Apendix A5 Lithologic cross-section F-F’
- Appendix B1 Cross-section B-B’ with facies classification and recommended dating locations
- Appendix B2 Cross-section C-C’ with facies classification and recommended dating locations
- Appendix B3 Cross-section D-D’ with facies classification and recommended dating locations
- Appendix B4 Cross-section E-E’ with facies classifications and recommended dating locations
- Appendix B5 Cross-section F-F’ with facies classifications and recommended dating locations
- Appendix C Locations of referred boreholes and cross-sections
- Appendix D Pleistocene sand-depth map
- Appendix E Embankments around Kampen (after Eilander et al., 1990)
- Appendix F Map of recommended locations for dating
- Appendix G Example of a borehole log (core 200714006)

Apendix A1 Lithologic cross-section B-B’

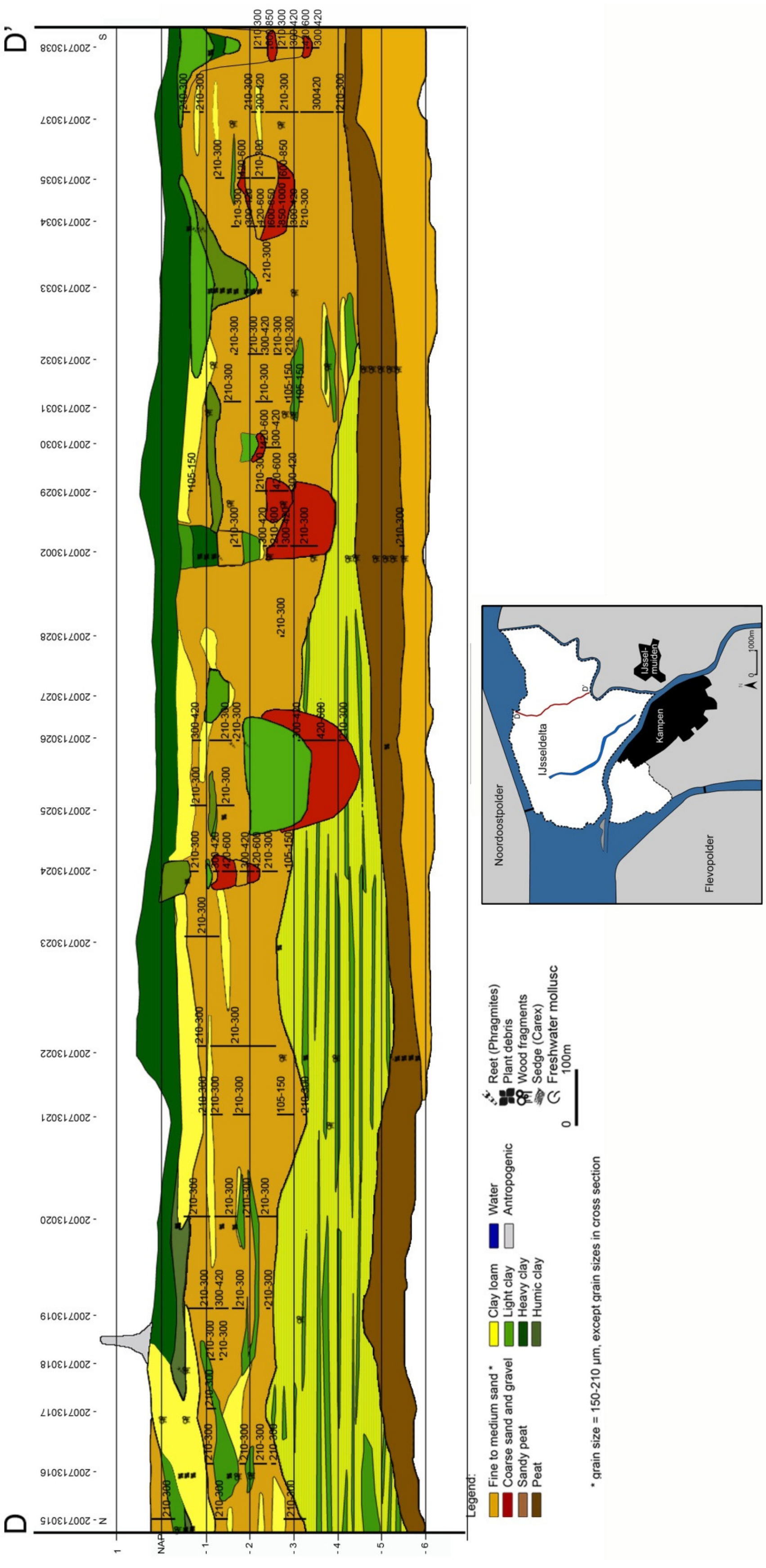


Apendix A2 Lithologic cross-section C-C’

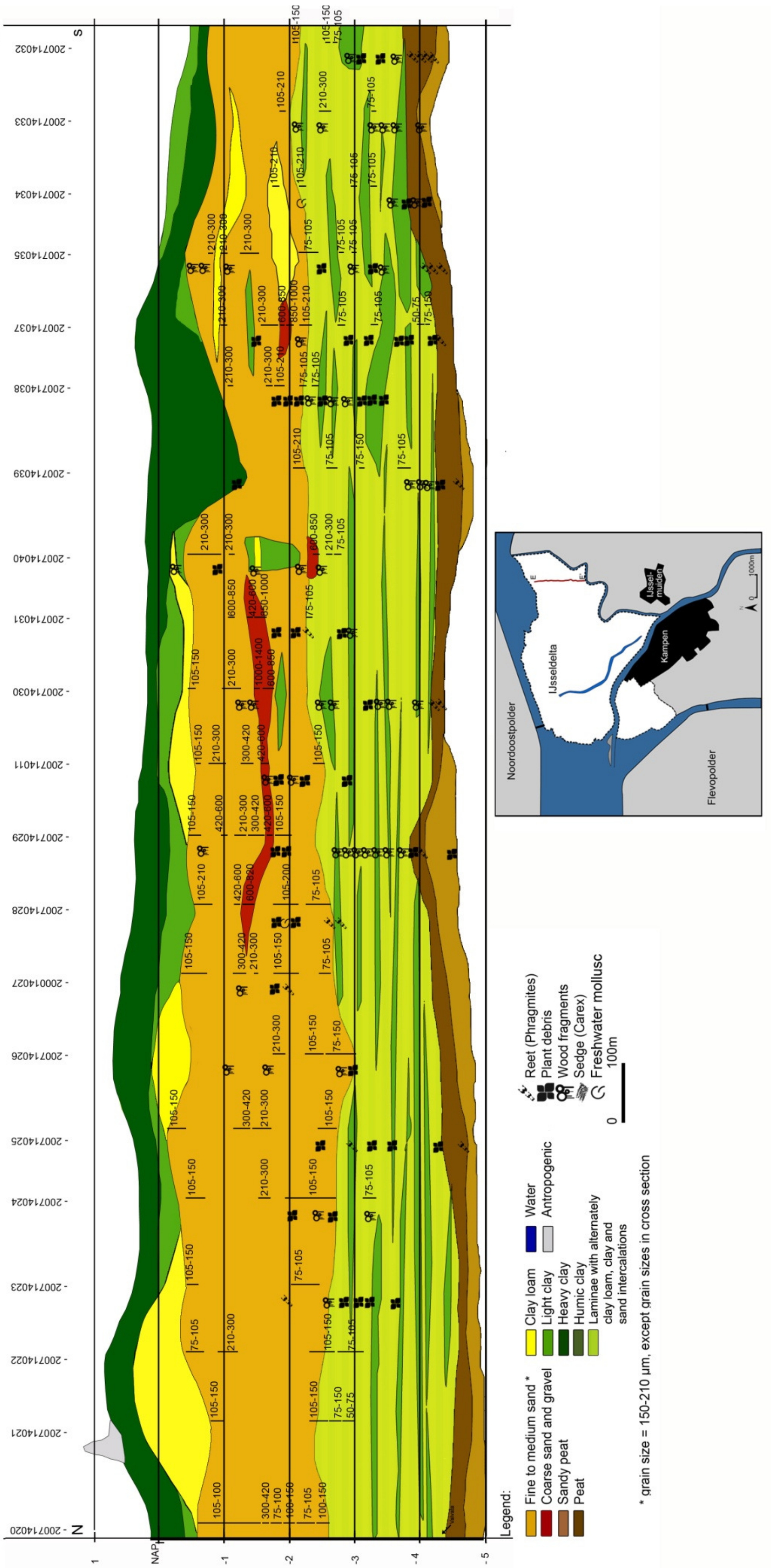



2/2
200712013
200712014
200712038
200712017
200712018
200713003
200713004
200713005
200713006
200713007
200713008
200713009
200713010
200713002
200713001
200713011
200713012
1
NAP
-1
-2
-3
-4
-5
-6
Legend:
Fine to medium sand *
Coarse sand and gravel
Sandy peat
Peat
Humic sand
Clay loam
Light clay
Heavy clay
Humic clay
Laminae with alternately sand and (humic) clay
Water
Antropogenic
* grain size = 150-210 µm, except grain sizes in cross section
0 100m
Overijssel
IJsseldelta
C
C'
Kampen
IJssel-muiden
Flevoland
N
0 1000m

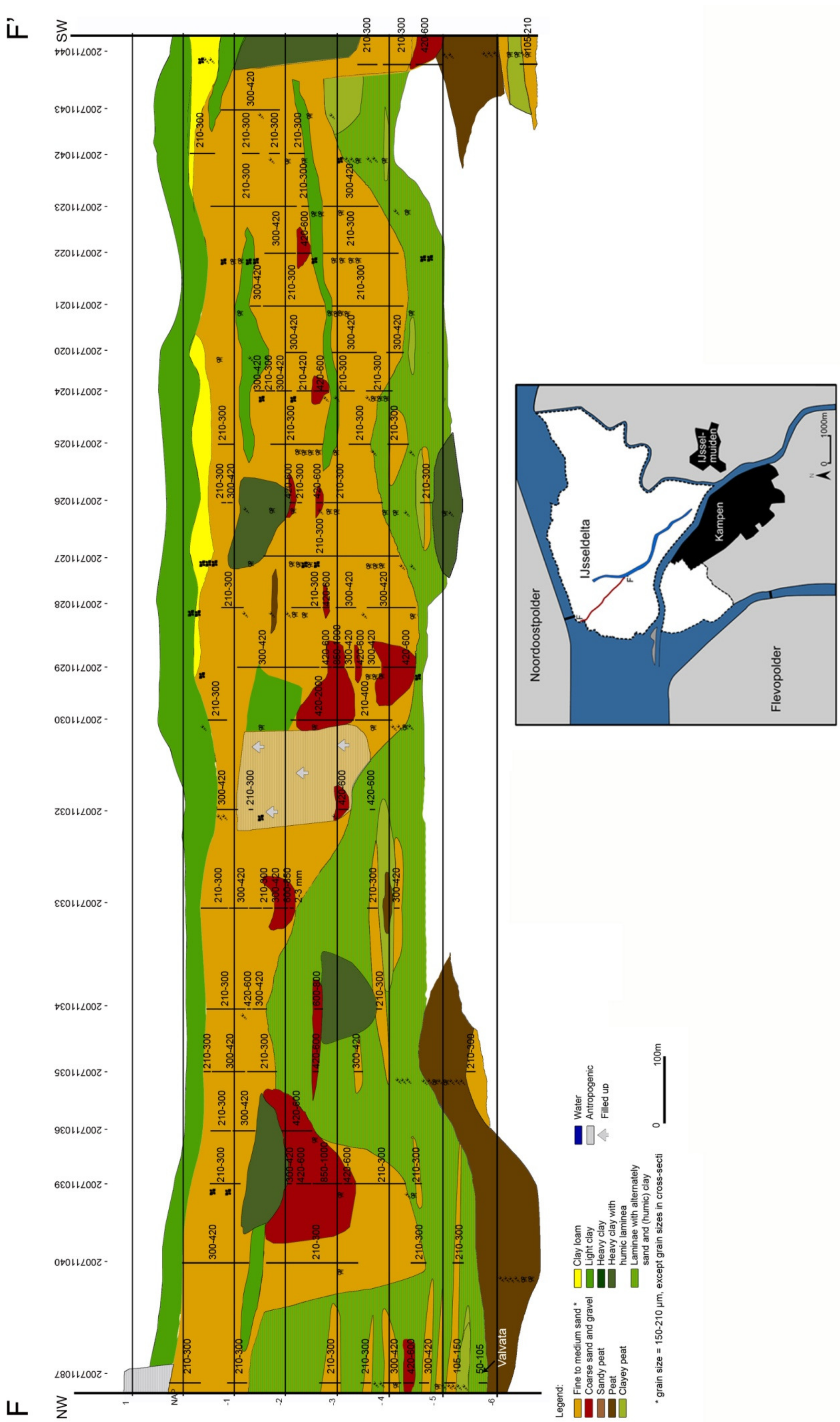
Apendix A3 Lithologic cross -section D-D’



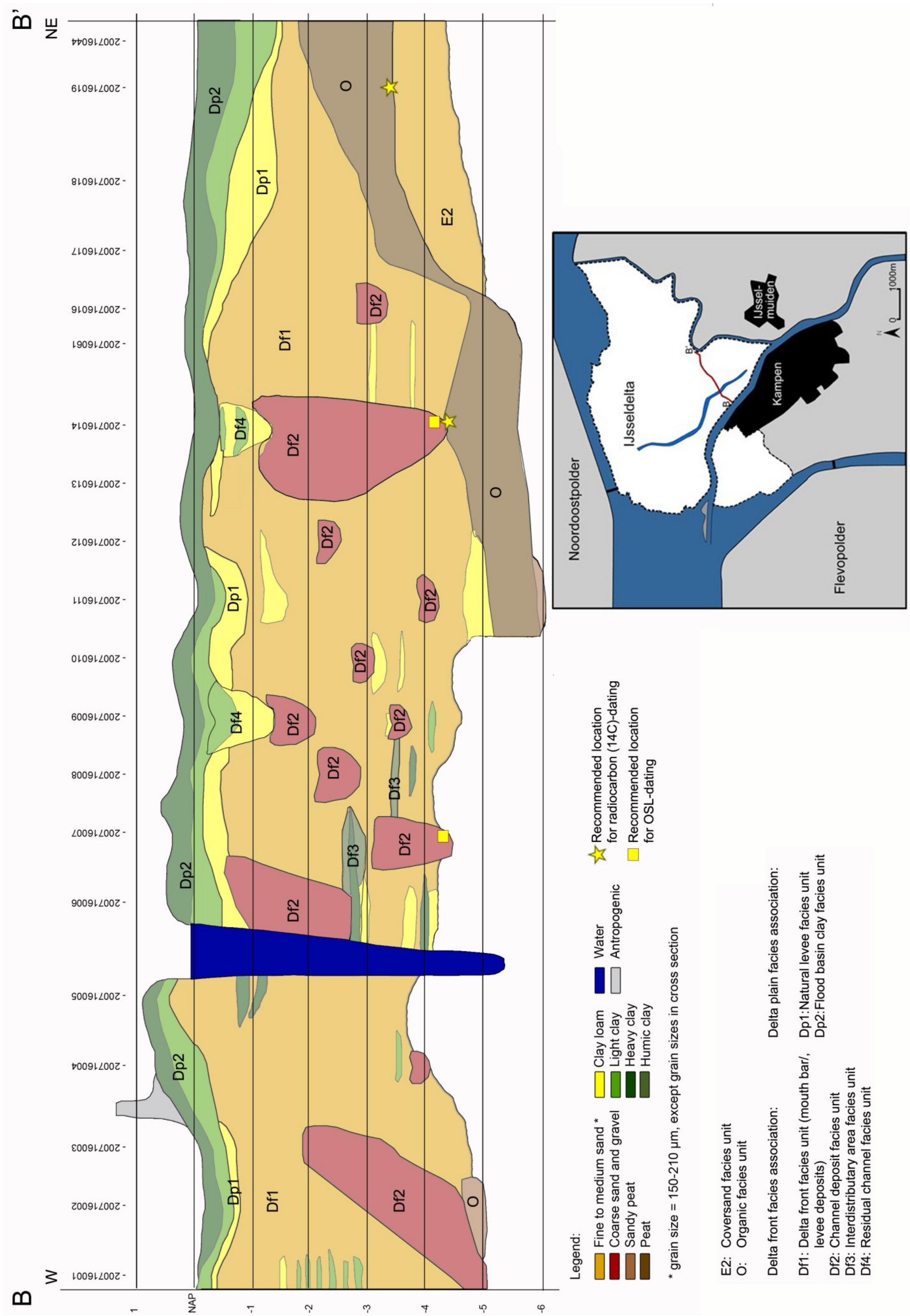
Apendix A4 Lithologic cross-section E-E’



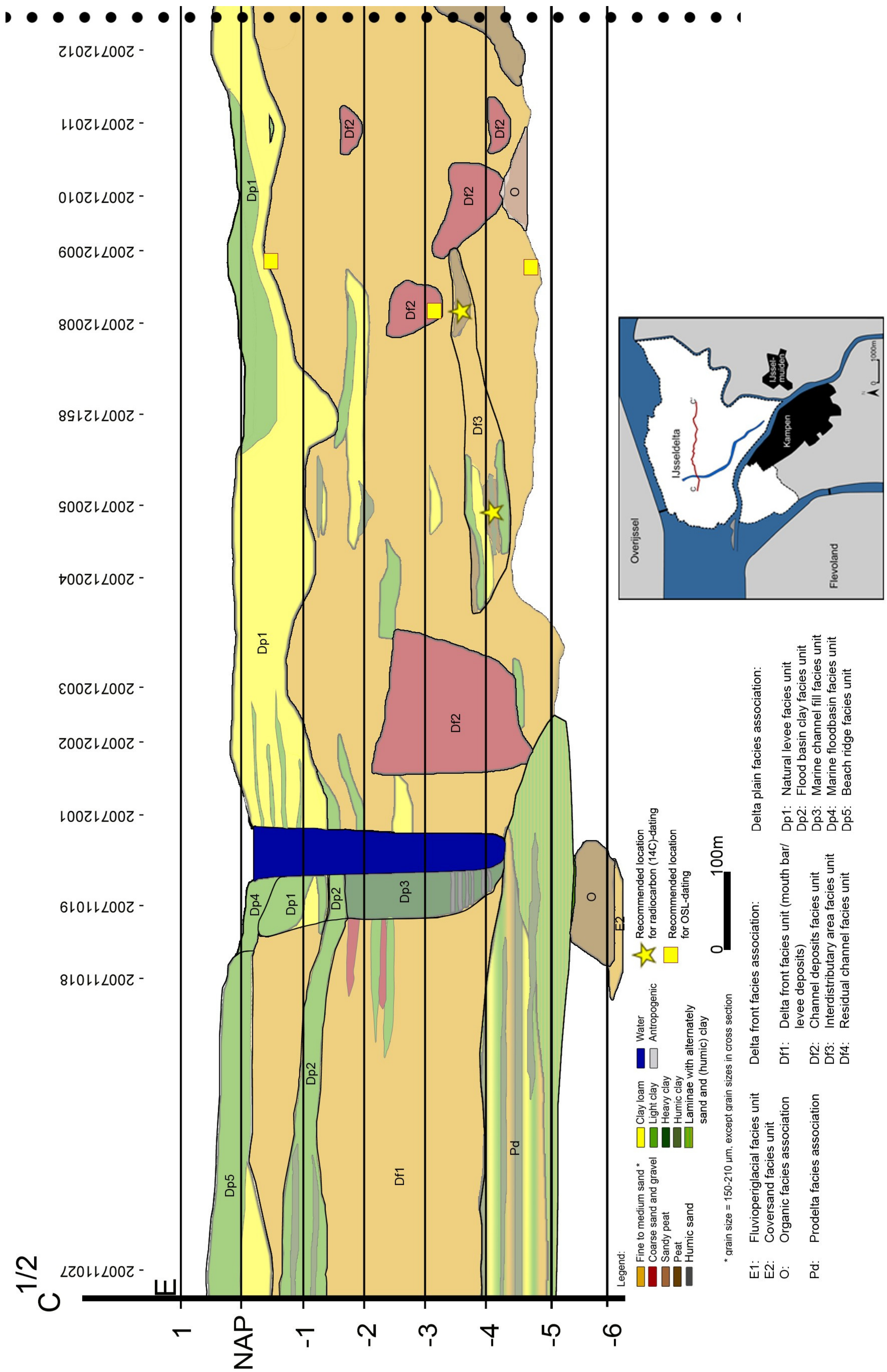
Apendix A5 Lithologic cross-section F-F’

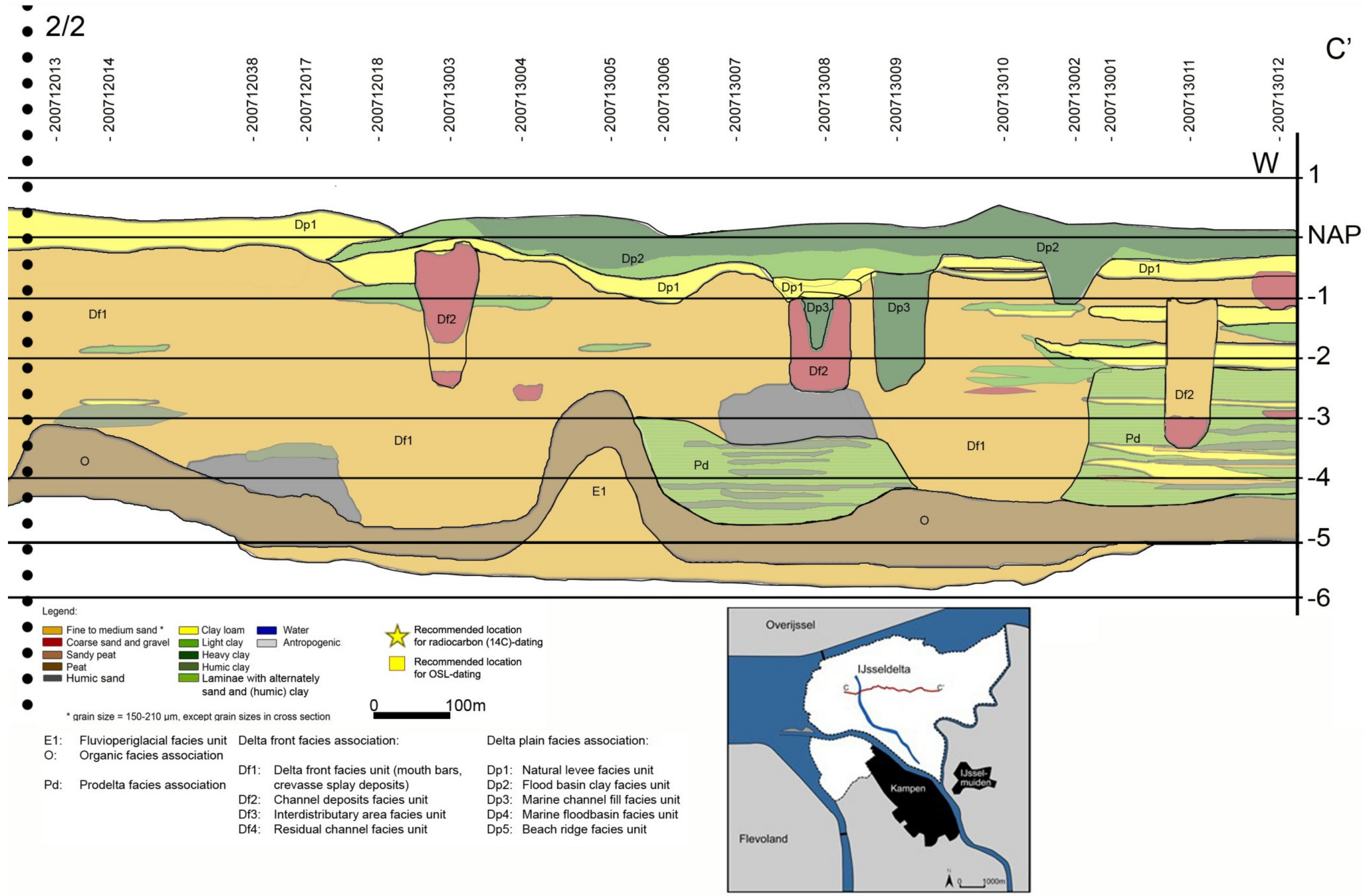


Appendix B1 Cross-section B-B’ with facies classification and recommended dating locations



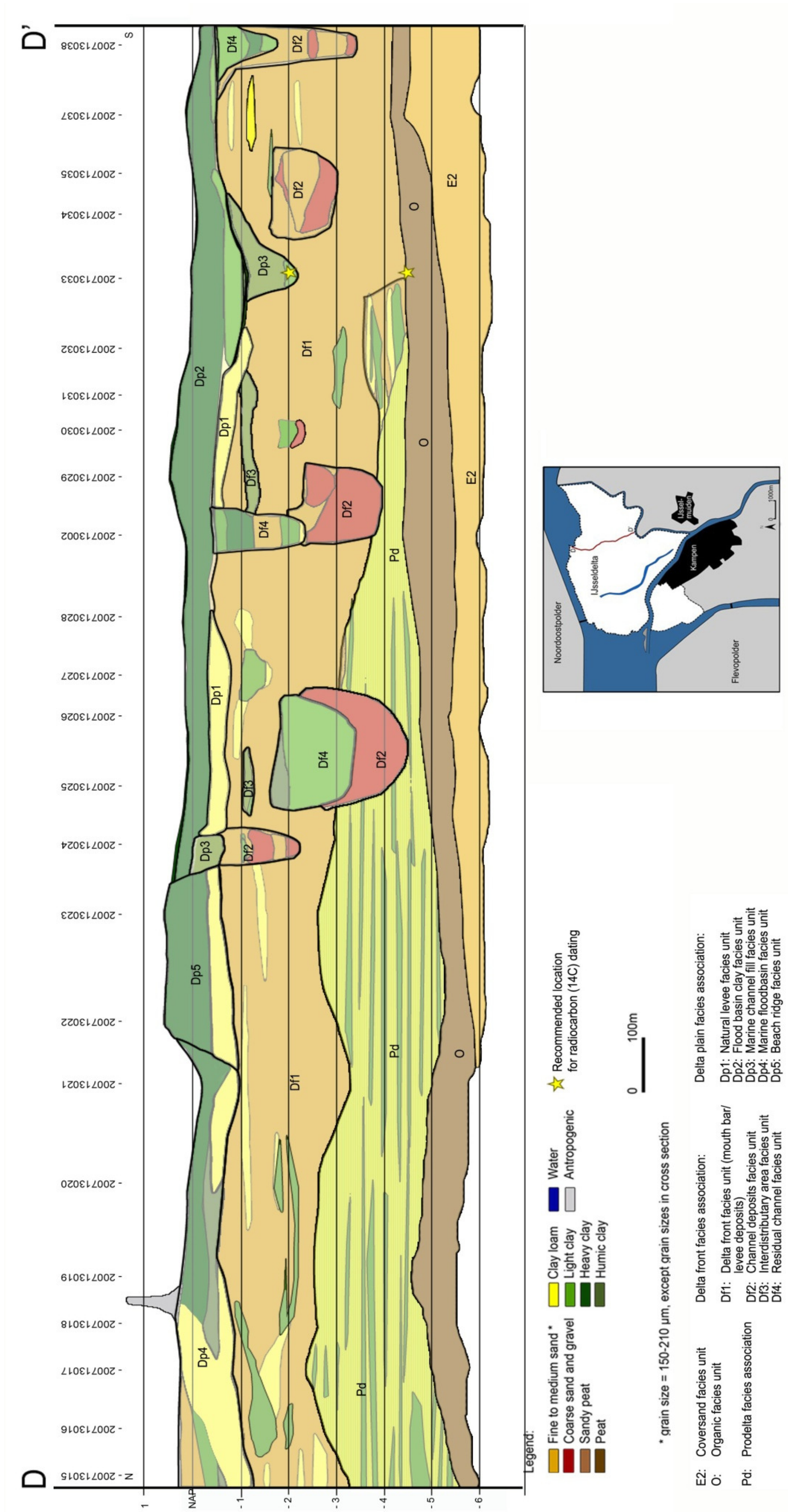
Appendix B2 Cross-section C-C’ with facies classification and recommended dating locations



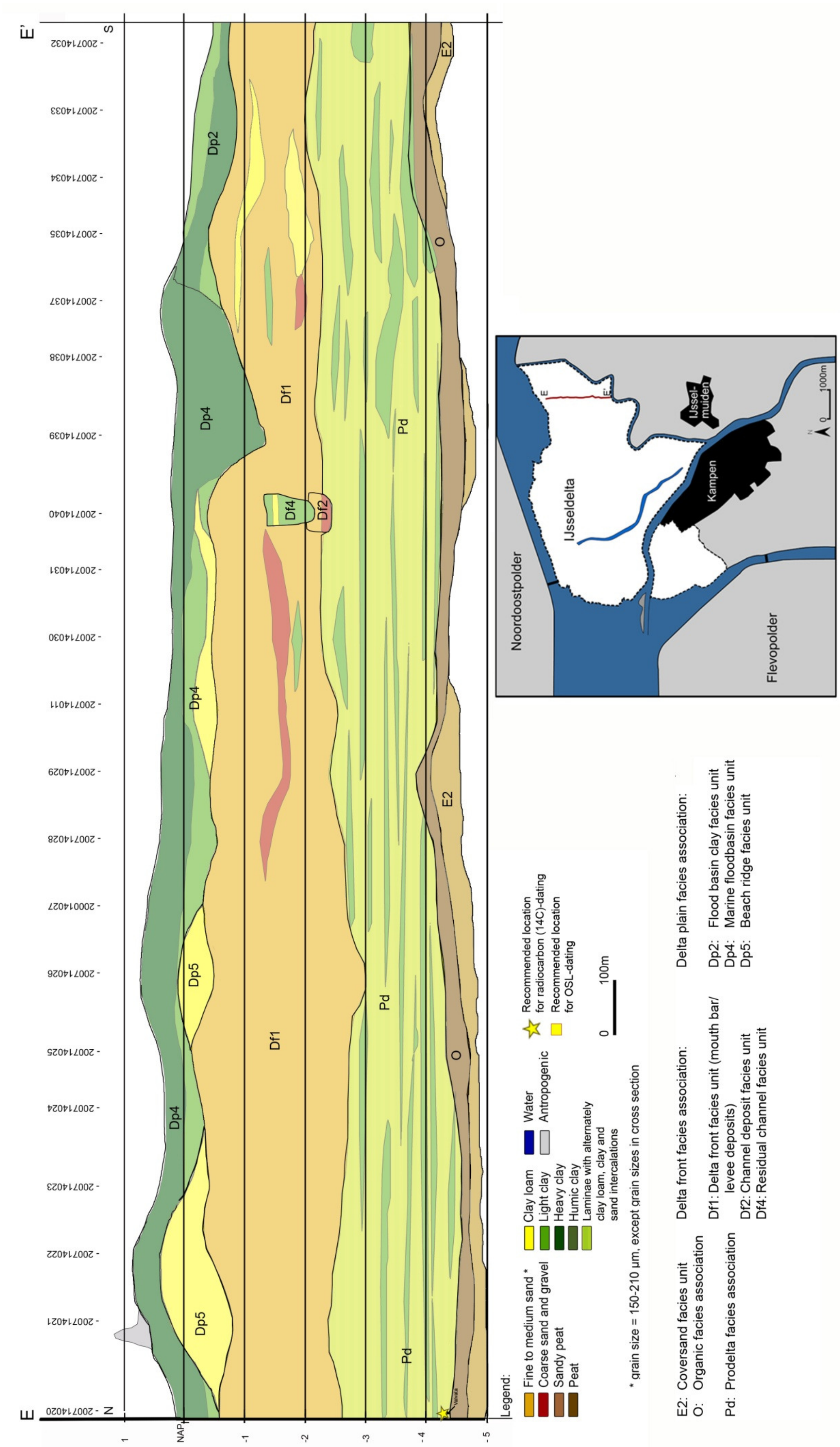


2/2
C'
W
1
NAP
-1
-2
-3
-4
-5
-6
- 200712013
- 200712014
- 200712038
- 200712017
- 200712018
- 200713003
- 200713004
- 200713005
- 200713006
- 200713007
- 200713008
- 200713009
- 200713010
- 200713002
- 200713001
- 200713011
- 200713012
Dp1
Dp2
Dp3
Df1
Df2
Pd
E1
O
Legend:
Fine to medium sand *
Coarse sand and gravel
Sandy peat
Peat
Humic sand
Clay loam
Light clay
Heavy clay
Humic clay
Laminae with alternately sand and (humic) clay
Water
Antropogenic
Recommended location for radiocarbon (14C)-dating
Recommended location for OSL-dating
0
100m
* grain size = 150-210 µm, except grain sizes in cross section
E1: Fluvioperiglacial facies unit
O: Organic facies association
Pd: Prodelta facies association
Delta front facies association:
Df1: Delta front facies unit (mouth bars, crevasse splay deposits)
Df2: Channel deposits facies unit
Df3: Interdistributary area facies unit
Df4: Residual channel facies unit
Delta plain facies association:
Dp1: Natural levee facies unit
Dp2: Flood basin clay facies unit
Dp3: Marine channel fill facies unit
Dp4: Marine floodbasin facies unit
Dp5: Beach ridge facies unit
Overijssel
IJsseldelta
C
C'
Kampen
IJssel-muiden
Flevoland
1000m

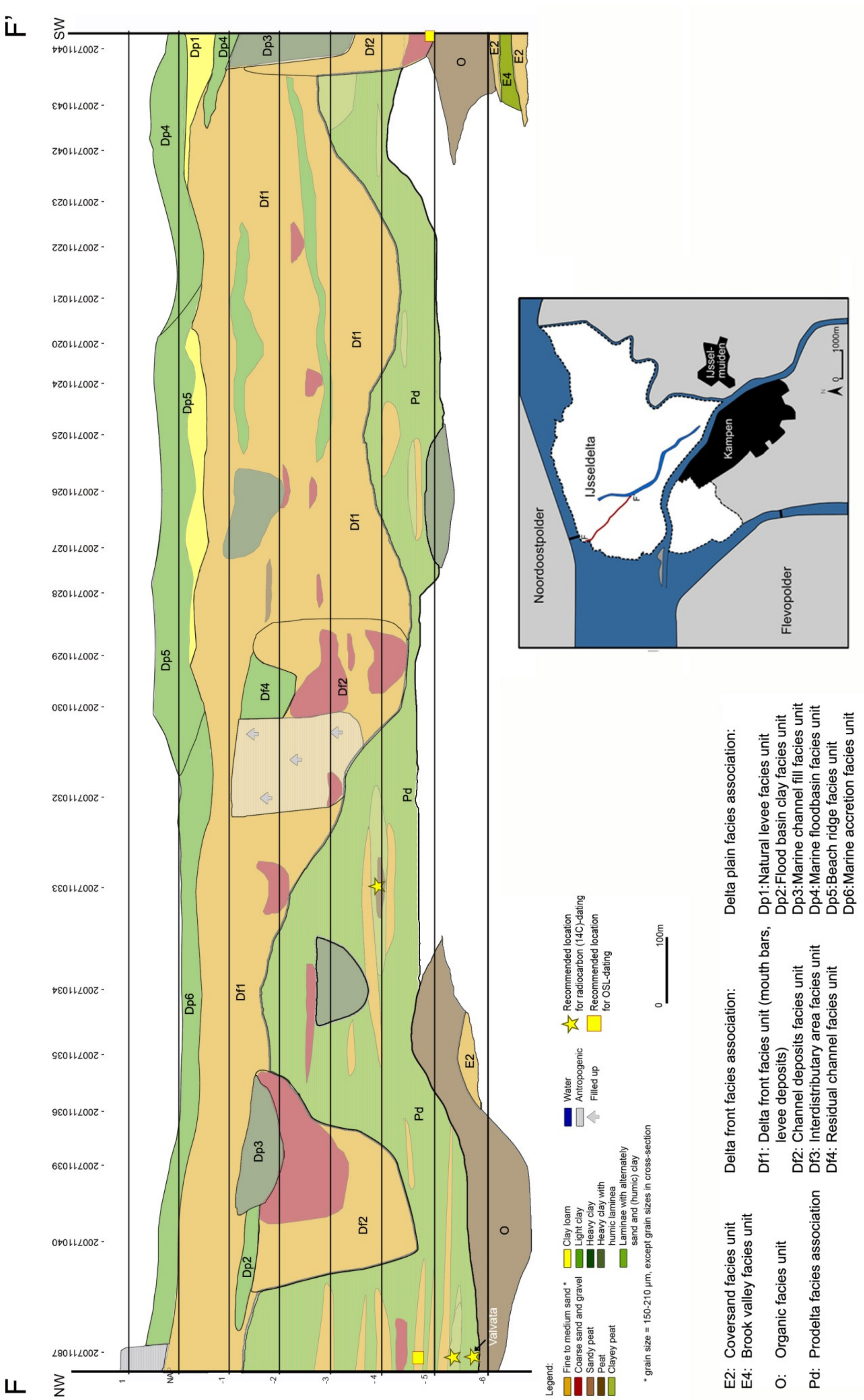
Appendix B3 Cross-section D-D' with facies classification and recommended dating locations



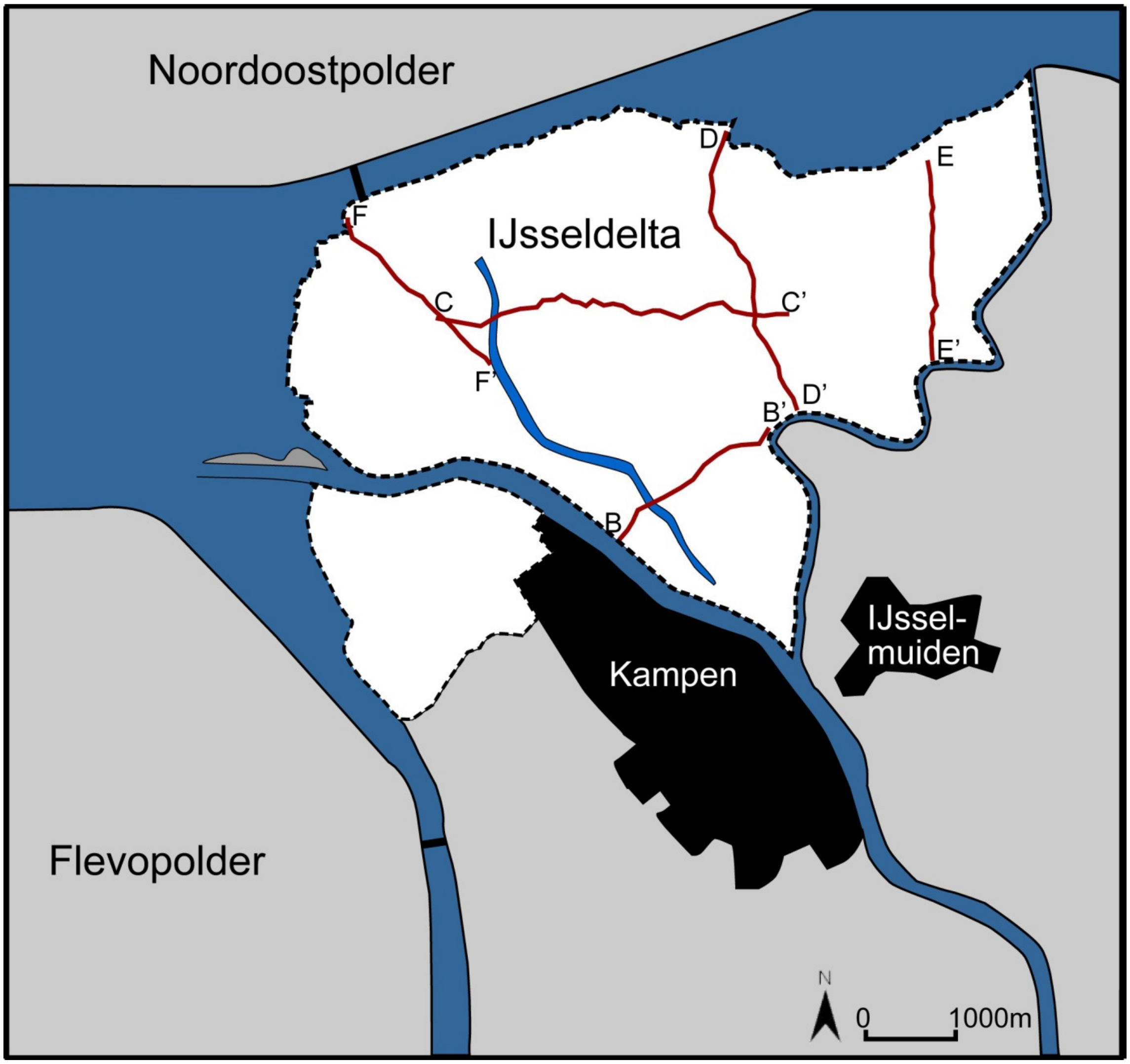
Appendix B4 Cross-section E-E’ with facies classification and recommended dating locations



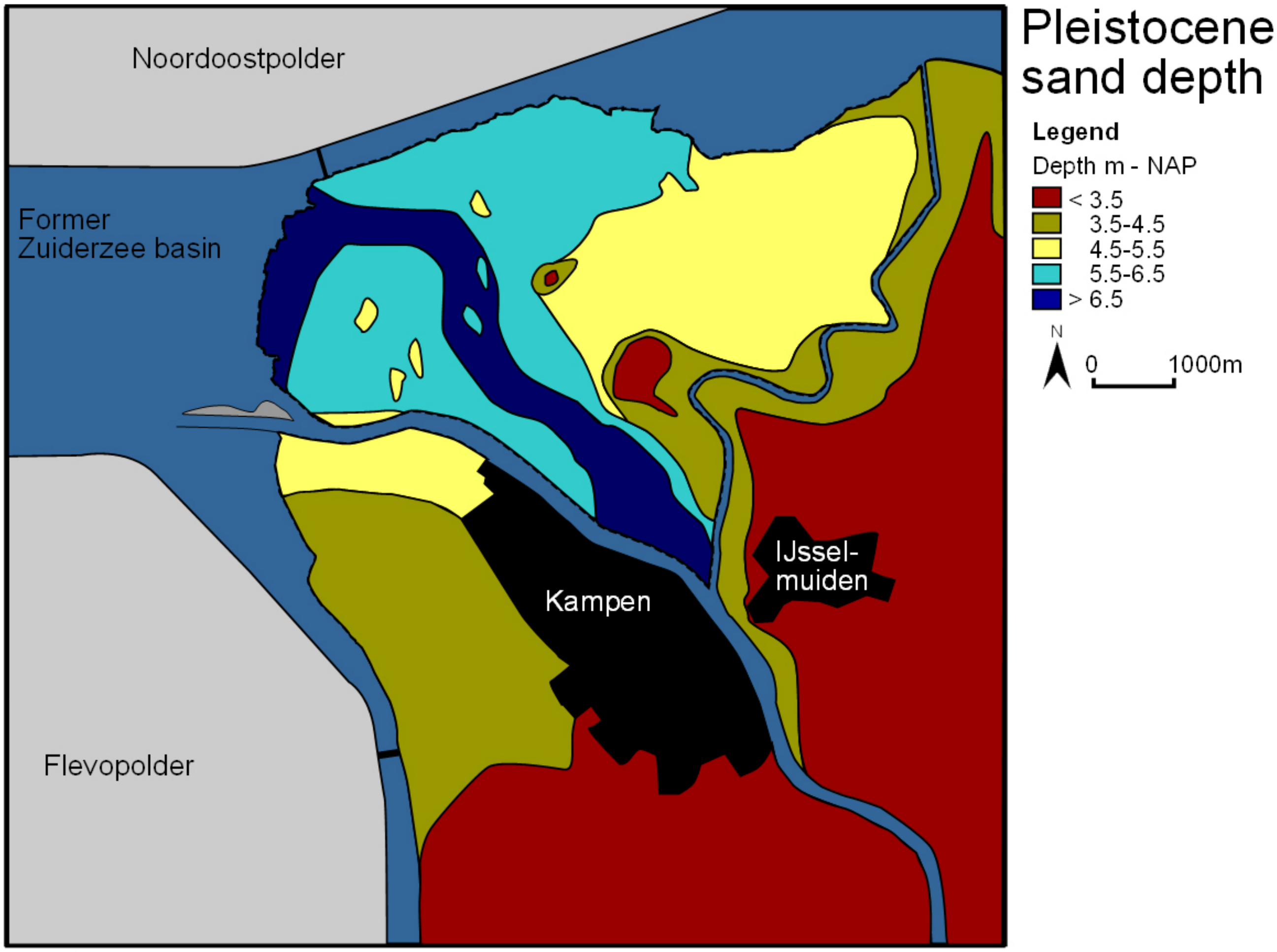
Appendix B5 Cross-section F-F' with facies classification and recommended dating locations



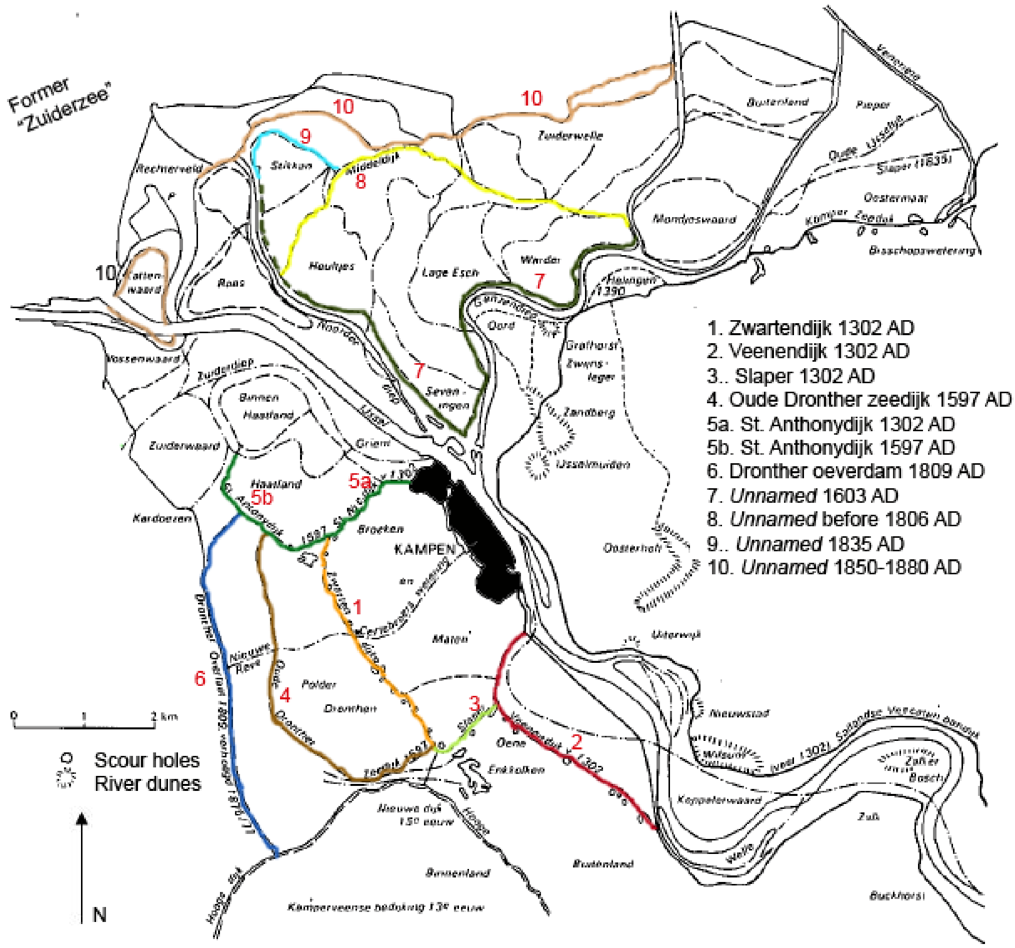
Appendix C Locations of cross-sections



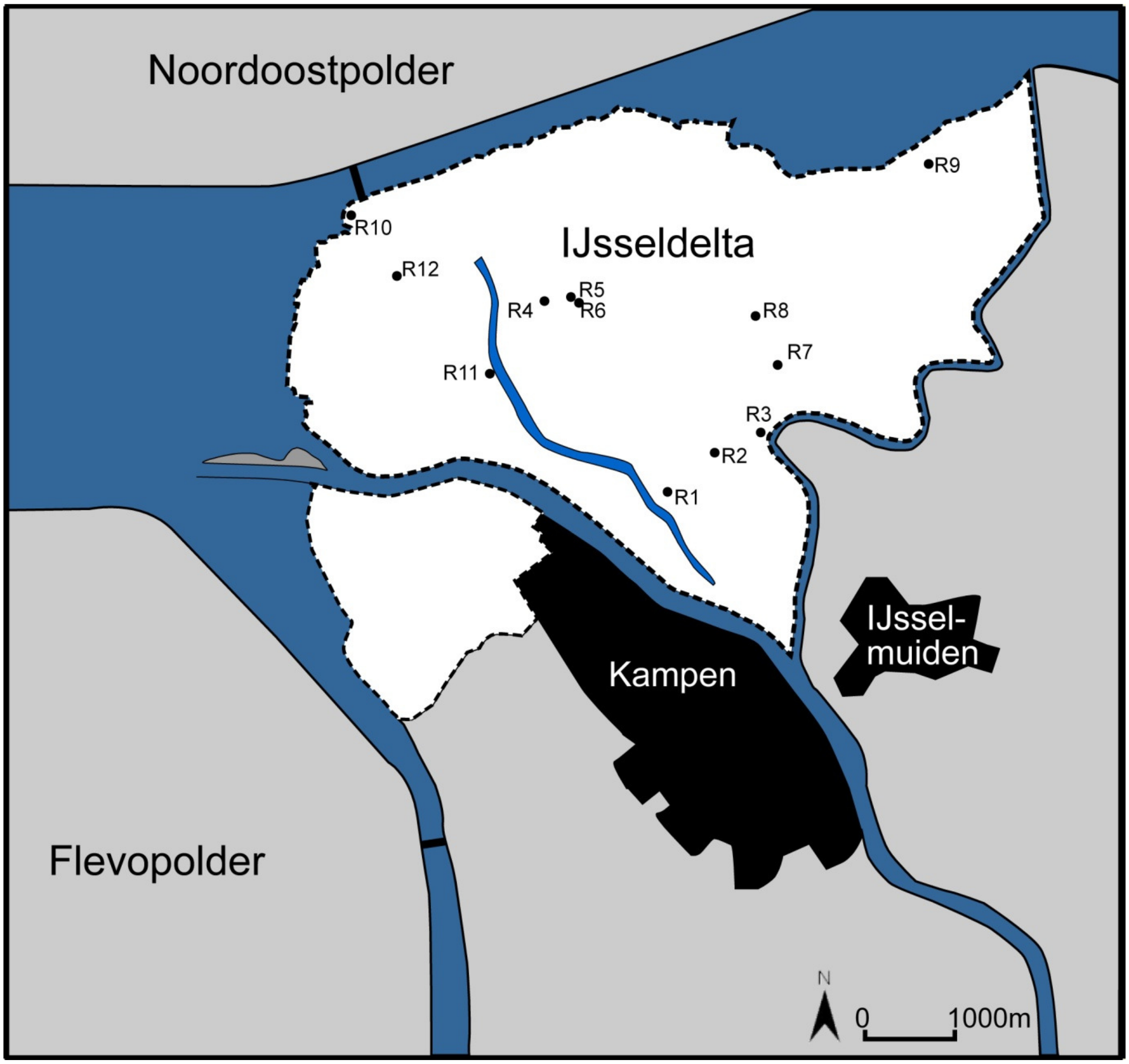
Appendix D Pleistocene sand-depth map



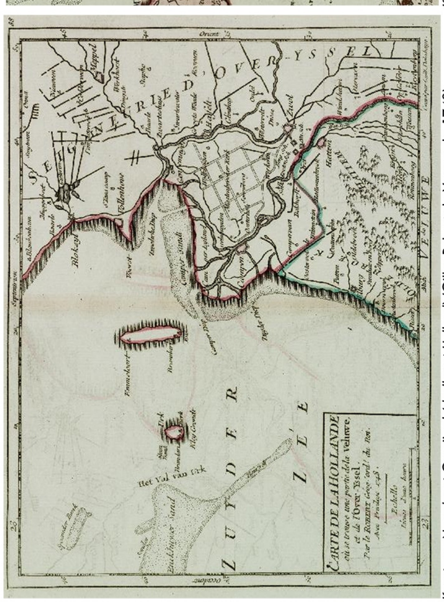
Appendix E Embankments around Kampen (after Eilander et al., 1990)



Appendix F Map of recommended locations for dating



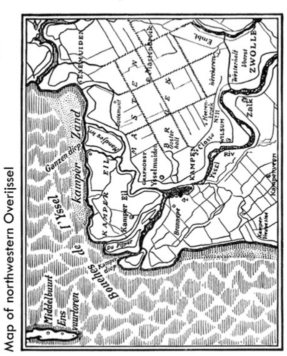
Appendix G Collection of historical maps



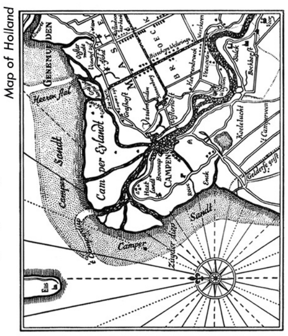
Kaart van Noordwest-Overijssel (deelkaart Holland) (Gilles Robert de Vaugondy, 1748)
Map of northwestern Overijssel

Kaart van Holland (Jacobus Kok en J.C. de Roeder, 1792)
Map of Holland

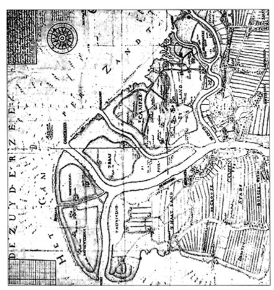
Kaart van Holland, (Nicolaas Visscher II, ~1696 AD)
Map of Holland



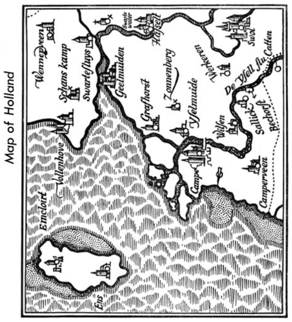
Het Kampereiland en de IJssel monden in 1640 AD (N. ten Have 1652)
Kampereiland and the IJssel mouths in 1640 AD (N. ten Have 1652)



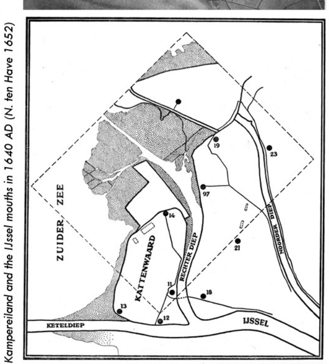
"Het Kampereiland in 1822 AD" (van Baarsel, 1822)
"Kampereiland in 1822 AD"



Fragment van de kaart van Johan Muller (1724 AD)
Fragment of the map of Johan Muller (1724 AD)

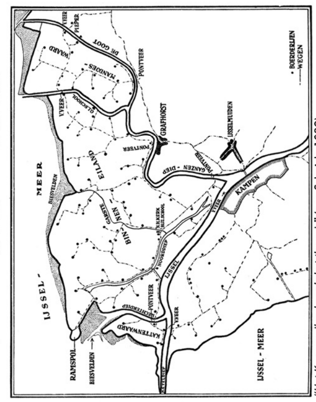


De IJsselmonden (G. Mercator ~1580)
The IJsselmouths

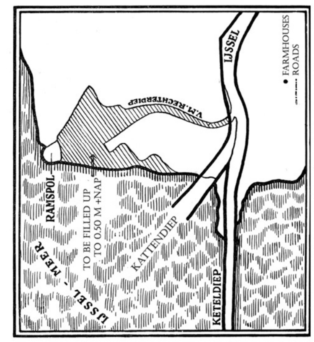


"Rechterdiep, zoals het was" (van Schaick, 1939)
Rechterdiep, as it was"

"Rechterdiep, zoals het was" (foto; van Schaick, 1939)
"Rechterdiep, as it was" (picture)



"Het Kampereiland zoals het thans is" (van Schaick, 1939)
"Kampereiland as it is presently"



"Rechterdiep, zoals het worden zal" (van Schaick, 1939)
"Rechterdiep, as it will be"

Appendix H Example of a borehole log (core 200714006)

Boring: 200714006 Namen: Udo Lavooi Jaar: 2007 Groep: 14 Datum: 31-5-2007

Coordinaten			Hoogte	Diepte
XCO	YCO	Coord. sys	Z [m +/- NAP]	[cm]
191721	512888	RD	0.5	630

KAARTEENHEID	Geomorfogenetische kaart:	Fs33
Geologische kaart: Ed2	Gondwatertrap:5	
Begroeiingskaart: Gwe	Bodemkaart:	

EPE: 4m kwel --> staay komt omhoog samen met C. Roosendaal en K. Volleberg

Diepte	Textuur	Org	Plr	Kleur	RedOx	Grind	M50	Ca	Fe	GW	M	LKL	Strat	Bijzonderheden
10	Z-LK			br	o			0	0				WDk	ger
20	Z-LK			br	o			2	0				WDk	ger
30	Z-LK			brgr	o			2	0				WDk	
40	Z-LK			lbrgr	or			2	1				WDk	Mn-c
50	Z-ZZL			lbrgr	or			2	1				Bo	schgr
60	LZL			lbrgr	or			2	1				Bo	
70	Z-LZL			lbrgr	or			2	1				Bo	schgr
80	Z-LZL			lgr	or			2	1				Bo	
90	FZ			lgr	or		150-210	2	1				Bo	schgr ws a3
100	FZ			lgr	or		150-210	2	1				Bo	schgr ws a3
110	MZ			lgr	or		210-300	2	1				Bo	schgr ps a2
120	ZFZ			lgr	or		105-150	2	1				Bo	schgr ms a3
130	ZFZ			lgr	or		105-150	2	1				Bo	schgr
140	ZFZ			gr	or		105-150	2	1				Bo	
150	ZFZ			gr	or		105-150	2	1				Bo	schgr
160	ZZL		plr	gr	r			2	0				Bo	
170	LK			gr	r			2	0				Bo	schgr
180	LK			gr	r			2	0				Bo	
190	LZL		plr	gr	r			2	0	GW			Bo	
200					r									## gm
210	MZ			gr	r		210-300	2	0				Bc	$ ms a3
220	FZ			gr	r		150-210	2	0				Bc	ms a3
230	FZ			gr	r		150-210	2	0				Bc	ms a3
240	FZ			gr	r		150-210	2	0				Bc	ms a3
250	FZ			gr	r		150-210	2	0				Bc	ms a3
260	FZ			gr	r		150-210	2	0				Bc	ms a3
270	MZL			gr	r			2	0				Bc	org band 1cm
280	MZ			gr	r		210-300	2	0				Bc	
290	ZZL			gr	r			2	0				Bc	
300	MZL			gr	r			2	0				Bc	schgr, kleiband
310	MZL			gr	r			2	0				Bc	gelamin. 4cm vv band
320	MZL			gr	r			2	0				Bc	gelamineerd
330	ZZL			gr	r			2	0				Bc	gelamin. org band
340	ZZL			gr	r			2	0				Bc	gelamin. org band
350	MZL			gr	r			2	0				Bc	$ gelamin. org band
360	LZL			gr	r			2	0				Bc	$
370	LK			gr	r			2	0				Bc	gelamineerd, vv band
380	MZL			gr	r			2	0				Bc	gelamineerd
390	MZL			gr	r			2	0				Bc	gelamineerd
400	LZL			gr	r			2	0				Bc	gelamineerd schgr
410	ZZL			gr	r			2	0				Bc	org band
420	MZL			gr	r			2	0				Bc	$ gelamin. org band
430	MZL			gr	r			2	0				Bc	
440	FZ		h	gr	r		150-210	2	0				Bc	vv band /1
450	LZL			gr	r			2	0				Bc	/1
460	MZL			gr	r			2	0				Bc	gelamineerd org band
470	LK			gr	r			2	0				Bc	gelamineerd schgr
480	ZZL			gr	r			2	0				Bc	$ gelamineerd
490	LZL			gr	r			2	0				Bc	# org bandje 1cm
500	LZL			gr	r			2	0				Bc	
510	MZL		plr	gr	r			2	0				Bc	
520	MZL		plr	gr	r			2	0				Bc	
530	MZL		plr	gr	r			2	0				Bc	
540	LZL			gr	r			2	0				Bc	#
550	FZ			gr	r		150-210	2	0				Bc	3
560	MZL			gr	r			2	0				Bc	
570	MZL			gr	r			2	0				Bc	schgr
580	LZL			gr	r			2	0				Bc	
590				gr	r									# gm
600		V2	h	br	r			2	0				Vb	# /3 schgr