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The geology of the Amstel river in Amsterdam (Netherlands): Man versus nature

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Abstract

The Amstel river is located in the peat-covered coastal plain of the Netherlands and gives Amsterdam its name (Amstel dam). It is a small secondary branch of the repeatedly bifurcating Rhine delta system. Historically, the Amstel debouched into the peat-fringed former Oer-IJ estuary, which was connected to the North Sea, but after the closure of this inlet the estuary was transformed into an inland sea (IJ) due to erosion of the adjacent peat. The Amstel river was active between 3000 BP and 1122 AD after which time the supply water from the Rhine was stopped due to the construction of a dam far upstream near Wijk bij Duurstede. On the basis of borehole data from various sources, four cross-sections were constructed in the Amstel branch to study the unknown lithology and lithostratigraphy of the Amstel sediments in the Amsterdam area. The deposits show the Amstel was a low-energy river which carried mainly clay. The cross-sections reveal that the Amstel in its downstream part was flanked by two lithologically identical layers of overbank clay, intercalated by a peat layer. The lowermost overbank clay was deposited from 3000 BP to about 1000 AD. The intercalated peat layer is estimated to have developed between the 11th and 12th centuries AD, indicating a decreased sediment supply in the Amstel, and rise of water level in the downstream river caused by Zuiderzee influences such as storms and tide. The uppermost overbank clay was deposited during major storm surges such as those documented in 1164 and 1170 AD, and was derived from the brackish Zuiderzee; it has been traced upstream along the Amstel for over 10 km. Near the mouth of the Amstel channel in the Oer-IJ estuary its bottom has been scoured by estuarine processes to a lower level. On the basis of archaeological and geological data it is argued that the Amstel channel of medieval Amsterdam had a water depth of about 6 m before the construction of a dam in the 13th century. Soil scientists, historical geographers and historians have argued that the Amstel once consisted of two separate rivers: a northern Oer-IJ connected channel draining from the Amsterdam Stopera to the north, and a southern peat draining channel draining from the Amsterdam-Watergraafsmeer to the south. The relatively straight stretch of the present-day Amstel now positioned within the urban area has been hypothesised to be man-made between the 11th and 13th centuries AD. In this paper, on the basis of geological arguments such as channel depths, overbank clays, peat composition and other characteristics, it is concluded that the Amstel had a natural channel in the Amsterdam area.

Keywords: Amsterdam, Amstel river, sedimentary history, overbank deposits, storm surges, lagoonal channels, back-barrier deposits, human impact, urban geology

Introduction

Knowledge of the geological history of the Amstel river in Amsterdam is hampered by poor access to natural sediments in the urban area, where buildings and bitumen on top of thick layers of anthropogenic fill make up the foundations of the town since medieval times onwards. In addition, the top of the underlying natural sediments is generally disturbed by digging and reworking. The geological stratigraphy and history of the Amstel, between Ouderkerk aan de Amstel and where it drains into the IJ (Fig. 1), is described in this paper on the basis of four cross-sections based on data from several databases.

The Amstel is the northwesternmost downstream channel of the bifurcating Rhine delta system in the Netherlands. The river is located in an extensive coastal peat area (Fig. 1) and is potentially an important link between the freshwater/peat environment and the marine/estuarine environment. The Amstel has a meandering planform, but it is questionable whether this is an initial meandering path or otherwise restricted lateral migration (Makaske, 2001).

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Fig. 1. Detail of the geological map produced by Staring in 1860. The course of the estuary is added in blue after data from Güray (1952) and de Gans & Bunnik (2012). Ouderkerk aan de Amstel is identical with Ouder Amstel.

The river initiated in the Rhine delta as one of the bifurcating channels at about 3000 years BP (Berendsen & Stouthamer, 2001; Bos, 2010; Cohen et al., 2012). In the upstream direction it is connected via the Angstel/Vecht and Kromme Rijn with the Nederrijn (Weerts et al., 2002; Vos et al., 2011). Between 2500 and 2400 BP the major discharge shifted from the Angstel/Amstel towards the Vecht river, further to the east (Fig. 1; Bos et al., 2009). This may have impeded discharge and sediment load in the Amstel. The Amstel drained until 220–400 AD via the Oer-IJ estuary into the North Sea (Fig. 1). After the closure of the Oer-IJ estuary, the Amstel continued to drain into the remnants of the estuary that is now connected to the central Netherlands lagoon in the east. This remnant of the estuary continued to enlarge as a result of storm surges, causing lateral erosion of its banks, and is named 'IJ' ('IJe'). This is also true for the peat-fringed lagoon which became Zuiderzee (Fig. 1).

Before 1000 AD the peat surface was positioned 2–2.5 m above Dutch Ordnance Datum (NAP). Cultivation of the swamps and bogs, and cutting of the peat resulted in substantial subsidence of the surface (de Bont, 2008). At present the peat surface is situated at 1–2 m –NAP. Consequently, the building of dykes along the major waterways, and dams and locks in minor channels had become a necessity during the Middle Ages. The Amstel became inactive as it was fully disconnected from the Rhine system in 1122 AD when humans dammed the silted-up river Kromme Rijn near Wijk bij Duurstede (Berendsen, 1982; Weerts et al., 2002; Bos et al., 2009) and also constructed a dam (lock or discharging sluice) in Amsterdam. The latter structure was also constructed because of the intrusion of water from the former Zuiderzee into the Amstel during storms. Historians date the construction of this dam (now located below Dam Square) in Amsterdam to between 1265 and 1275 AD, whilst archaeologists date it to early in the 13th century (de Bont, 2008). The construction of dykes along the Amstel near Amsterdam is tentatively dated to between 1100 and 1275 AD, but it remains unclear whether dykes were indeed raised along the Amstel before the construction of the dam (de Bont, 2008).

Soil scientists, historical geographers and historians argue that the relatively straight part of the river between Watergraafsmeer and Stopera (Fig. 2) is anthropogenic (man-made) and as such should be interpreted as a canal. In their view, before the digging of a canal, between the 11th and 13th centuries, the Amstel was divided into two parts: one flowing from the Stopera to the north and one from the Watergraafsmeer to the south (de Bont, 2008). However, in this paper it will be argued that this Amstel stretch has a natural origin.

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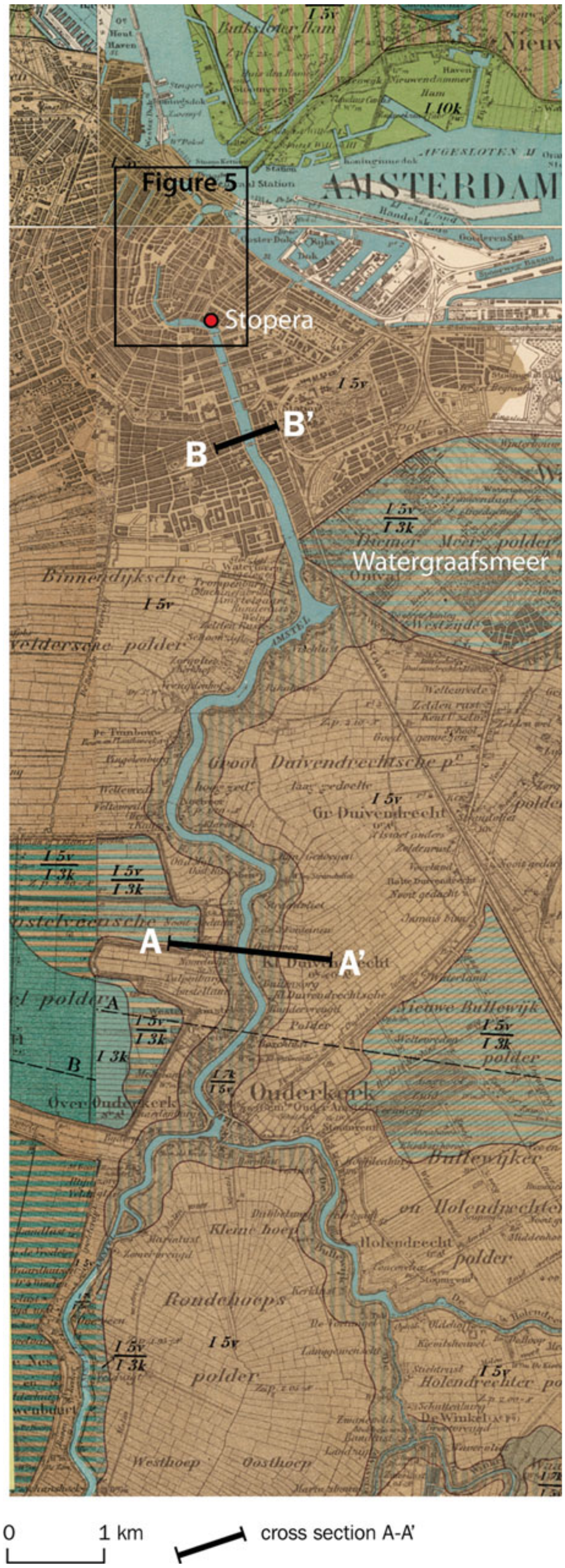

Fig. 2. Part of the Geologische kaart 1:50.000 Blad 25 kwartblad IV Amsterdam (1927/1928) with the locations of section AA′ (Ouderkerk aan de Amstel) and BB′ (Torontobrug). Overbank clay is indicated by I 7k/I 5v. Note the straight Amstel course between Diemer Meer polder/Watergraafsmeer and the Stopera building.

The reclaimed former lake Watergraafsmeer or Diemermeer (Fig. 2) originated by wave erosion of peat along the eastern Amstel bank, driven by predominantly southwesterly and westerly winds. The lake was partly filled up with Rhine clay derived via the Amstel. The clay layer was deposited, on the basis of palynological data, between Roman times and 700 AD (de Gans & Bunnik, 2011), but sedimentation of this clay may have continued after 700 AD since the uppermost layer of this deposit was not sampled for palynological research.

The Oer-IJ estuary pre-dates the Amstel system and originated about 5000 BP. At that time the sedimentation of coastal barriers resulted in the gradual transformation of a wide tidal channel system into a relatively narrow estuary. The inlet of the estuary was completely closed by the development of beach barriers in Roman times, in the first centuries AD (Vos et al., 2011; de Gans & Bunnik, 2012). The depth of this estuary was, after closure of the coast, up to 25 m. West of the mouth of the Amstel it was filled with clay and gyttja from that time. By 1000 AD much of the estuarine channel here was completely filled. After seaward closure of the estuary the excess water delivered by the Amstel had to take an easterly course towards the Zuiderzee area (Fig. 1). From this time onwards the peat adjacent to the former estuary was affected by wave erosion, and eventually a wide brackish interior sea originated: 'the IJ' (Fig. 1). In the IJ, parts of the overbank clay along the former estuary were preserved as islands such as Ruigoord and Den Hoorn (Fig. 1; de Gans & Bunnik, 2012). In the 19th century the IJ was transformed into a polder area in order to facilitate the digging of the Noordzee Kanaal connecting Amsterdam harbour with the North Sea.

The general geological sequence in the Amstel area is as follows (see legend of Fig. 3), with lithostratigrahical terminology following de Mulder et al. (2003). Late Pleistocene sediments (aeolian sands forming part of the Boxtel Formation) are situated at approximately 12–13 m –NAP. On top of these sands is a basal peat layer which is overlain by 5–7 m of lagoonal or tidal back-barrier deposits (Naaldwijk Formation; formerly Oude Zeeklei or Calais deposits). These latter lagoonal/tidal deposits are composed of clays, silty clays and fine sands with local thin peat layers intercalated. The top of the lagoonal deposits is located at a depth of about 5 m –NAP. These deposits are capped by a thick peat layer, known as 'surface peat' or 'Holland peat', which started to grow around 4400 BP (Zagwijn, 1986). The basal peat layer, intercalated peat layers and the surface peat layer are assigned to the Nieuwkoop Formation whilst the deposits of the Amstel which will be discussed below are assigned to the Echteld Formation.

Method and materials

This study is based on lithostratigraphical data described for boreholes in the study area. As the urban subsurface is largely

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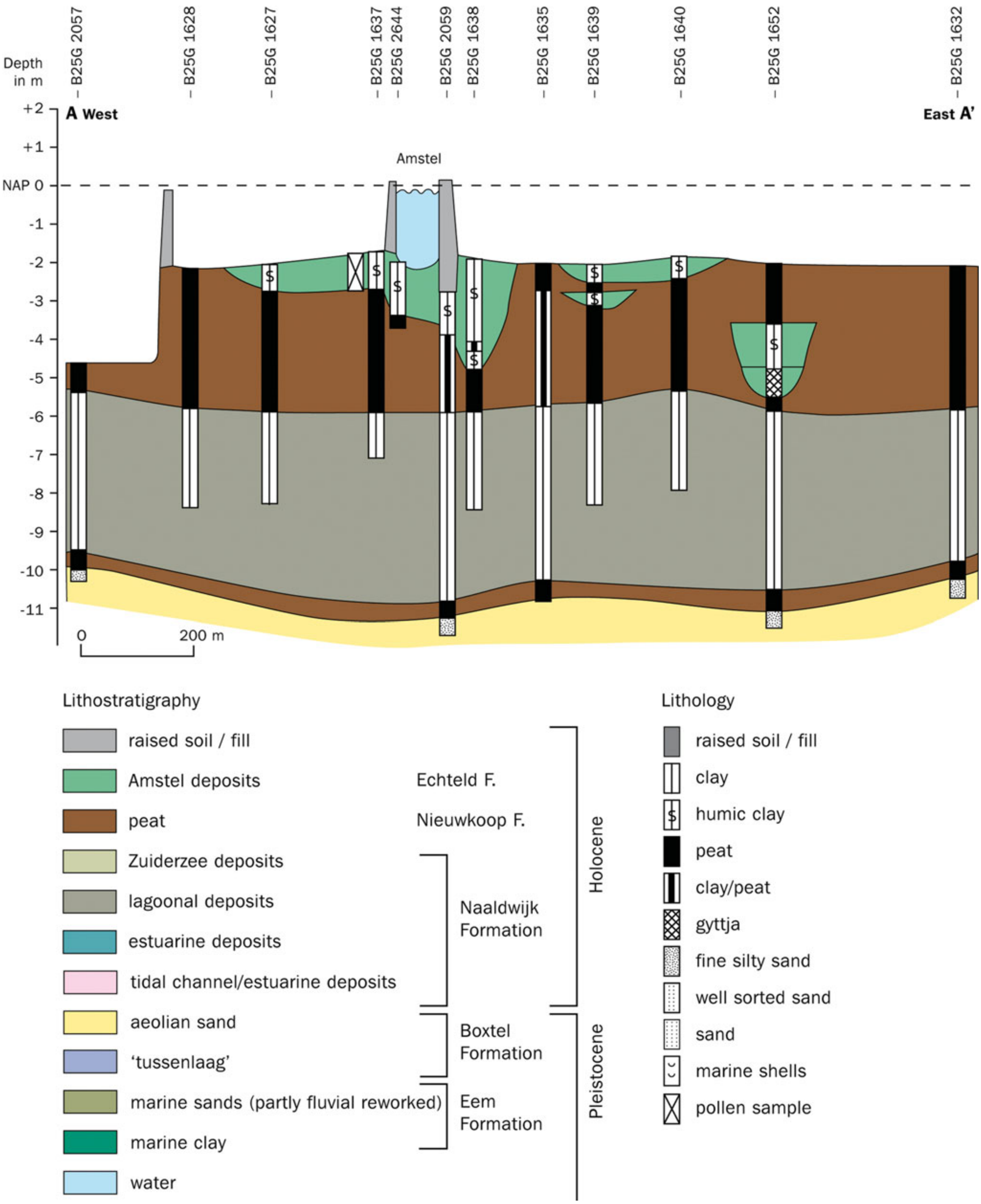

Fig. 3. Geological section AA′. Ouderkerk aan de Amstel. Location Fig. 2.

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inaccessible for drilling activities because of the presence of an anthropogenic fill (made ground) of up to 6 m, data were predominantly obtained from the public website of the archives of the TNO Geological Survey of the Netherlands (*www.DINOloket.nl*; in the sections indicated as B25GXXXX). Further data was retrieved from the non-public archives of Waternet (E06.XXX), Omegam (OMEGAM) and Ingenieurs Bureau Amsterdam (IBA). Finally, some data were obtained from Stadsarchief Amsterdam (Amsterdam City Archives; SA). Both the quality of the drilling techniques and the description and detail of the sedimentary deposits varies to a large degree in each of these databases. Some only have a simple discrimination between peat, clay and sand. Others have more information, but data on peat composition, the percentages of clay in the peat and *vice versa* or the calcium carbonate content are absent. A small number of published palynological analyses (de Gans & Bunnik, 2011) and one radiocarbon date formed the basis of the chronostratigraphical interpretations.

The downstream Amstel sediments are composed of humic clays. The clay is silty in places but sands are generally absent since the sands were laid down in former lakes along the river (Bos et al., 2009; de Gans & Bunnik, 2011, 2012). The humic character and the brownish colours facilitate in general the discrimination between the Amstel sediments and the underlying lagoonal deposits. In places the lateral discrimination between Amstel clay and adjacent clayey peat is gradual.

Four new cross-sections

Section AA′ near Ouderkerk aan de Amstel The first section to be discussed is located near Ouderkerk aan de Amstel (Figs 2 and 3), outside the reach of the thick fill layers which are found further to the north in the urban area. Here the Amstel is at present 60–70 m wide. The channel on either side is accompanied by a humic, brownish, overbank clay layer around 300–400 m wide and up to 1 m thick. The top level of these clays is situated at 2 m –NAP. The gyttja and clay located in the peat east of the river (B25G1639; B25G1652) may be part of the Amstel system (Fig. 3).

The Amstel channel is embedded in the 'Holland' peat unit. Its deposits are composed of brownish humic or peaty clay which is silty in places. The discrimination between humic or peaty Amstel clay and adjacent or underlying clayey peat is in places problematic, as in boreholes B25G2059 and B25G1635. However, the Amstel channel did not erode into the underlying lagoonal deposits. Thus the bottom of the Amstel channel is positioned no deeper than 4.5 to 5.5 m –NAP. Sands or sandy clays are in general absent in the Amstel deposits in agreement with the far downstream position of the branch in the Rhine delta network (Bos et al., 2009).

Directly west of the present Amstel, a borehole with additional palynological data is available (Fig. 3). On the basis of these data it is concluded that the initial overbank clay deposition started in the late Subboreal (at about 3000 BP) and came to an end at about 1000 AD. However, the uppermost 50 cm of the investigated core was not sampled and analysed (de Gans & Bunnik, 2011) so the upper age may be later. These results are in accordance with palynological data from boreholes several kilometres north of section AA′ (de Gans & Bunnik, 2011). These findings are in accordance with C^{14} dating and palynological work in the Vecht-Angstel region immediately upstream also (Weerts et al., 2002; Bos, 2010). The presence of pollen of *Abies* and *Picea* indicate that the Rhine system was the source of the overbank sediment (de Jong, 1968; de Gans & Bunnik, 2011).

The soil map (Bodemkaart van Nederland, 1965) features a small area of a brackish water clay ('Zuiderzee klei') along the banks of the Amstel south of Amsterdam. The area extends as far south as Ouderkerk aan de Amstel. As the name of the clay suggests it must have been derived from the former Zuiderzee area, northeast of Amsterdam (Fig. 1). The available borehole data do not permit discrimination between (fluvial) Amstel clay and (brackish) 'Zuiderzee clay' in this section. However, the Zuiderzee clay layer must have a thickness of less than 50 cm as no marine or brackish water diatoms were found in the analysed samples below this level (de Gans & Bunnik, 2011). This brackish clay was tentatively dated to between 250 and 500 AD by soil scientists (Bodemkaart van Nederland, 1965), but, on the basis of palynological data, the Zuiderzee clay layer was deposited after 1000 AD.

The soil map (Bodemkaart van Nederland, 1965) also shows in the area south of Amsterdam a 1 km wide zone on both sides of the Amstel where the peat composition changes from eutrophic clayey wood peat near the river via a mesotrophic sedge peat to oligotrophic Sphagnum peat.

Section BB′ near Amsterdam Toronto brug The Amstel, between the former lake Watergraafsmeer (reclaimed in the 17th century) and the Stopera in Amsterdam's historic centre, is 70–100 m wide (Figs 1 and 2). Because the river here is relatively straight, soil scientists, historians and historical geographers have suggested that this stretch of the Amstel is a man-made connection, dug in several phases between the end of the 11th century and the middle of the 13th century (de Bont, 2008).

Cross section BB′ near Torontobrug (Fig. 4) shows thick (up to 6 m) layers of ground fill. The present Amstel is completely encased in this fill, but below this fill natural overbank clay deposits are present, which are best preserved east of the river. Here two overbank clay layers are present with a width of about 300 m and a thickness of up to 1 m. The clay is intercalated by a peat layer 0.5–0.7 m thick. The peat layer extends laterally over the channel deposits along the eastern side of the Amstel (core E06.157). The uppermost level of the topmost overbank clay is situated at 2–2.5 m –NAP. The altitudinally lower position of this unit in relation to section AA′ (Fig. 3) may be due to compaction caused by the thick fill layer.

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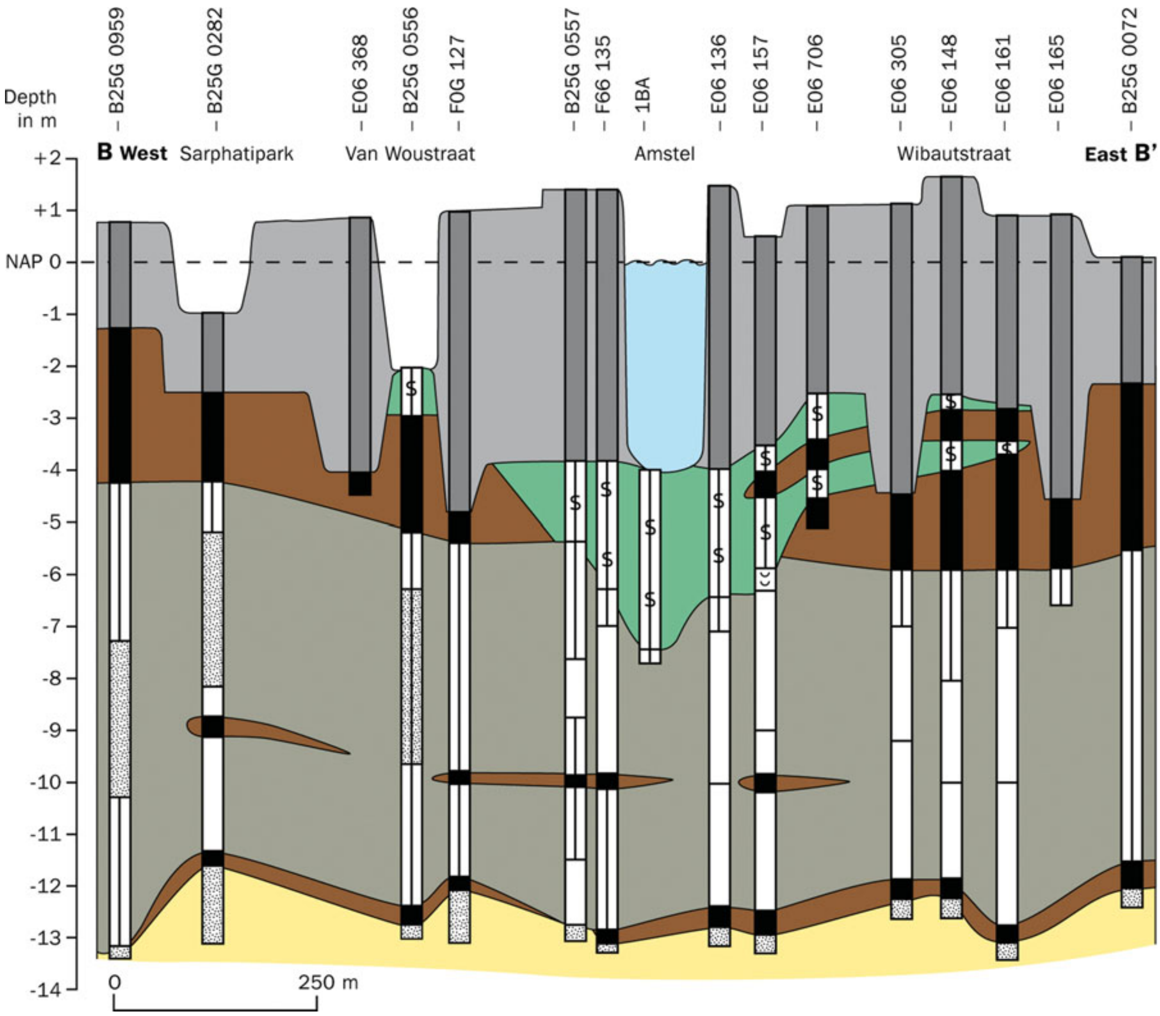

Fig. 4. Geological section BB′. Toronto brug. Location Fig. 2, legend Fig. 3.

The Amstel deposits are composed of humic clays similar to those recorded in section AA′ (Fig. 3). The humic and brownish character of the Amstel sediments was used to discriminate between them and the underlying greyish/blue lagoonal deposits of the Naaldwijk Formation. Locally discrimination of the two was difficult as the top 1 m of the lagoonal deposits may also be humic (core B25G0557). Where the Amstel channel had eroded deeper than this humic level the distinction between the two was clear (core IBA). The bottom of the Amstel channel fill deposits is positioned at a maximum depth of 7.5 m –NAP, although a clear erosional surface is absent except at one location (E06.157), where a layer of shells was recorded at the base of the Amstel channel at 6 m –NAP. This layer is interpreted as channel lag deposits of the Amstel channel, composed of reworked shells from the underlying lagoonal sediments.

Section CC′ crossing the Dam The Dam section (Figs 5 and 6) is located in the centre of Medieval Amsterdam at the aforementioned 13th century dam. In this section a thick layer of anthropogenic fill (up to 7 m) is again present. On the basis of photographs found in the Stadsarchief Amsterdam (Amsterdam City Archives) taken during an early 20th century excavation, the position of the former Medieval lock floor was established at 6 m –NAP, at the base of the anthropogenic fill.

The width of the Amstel between the dykes is greater than in the upstream section AA′ (Fig. 3). This may be due to the tidal processes operating in the nearby IJ and Oer-IJ (Fig. 1). The bottom of the river channel fill is positioned at 11–12 m –NAP (Fig. 6) distinguished on the basis of a difference in colour and organic matter content. This depth is deeper than in the upstream sections. In one borehole (D0.0679) a shell layer interpreted as a channel lag deposit is found at 10 m –NAP.

The Amstel channel fill is composed of clay or humic clay and is silty in places. Overbank deposits are again recorded on top of the adjacent peat, which are lithologically similar to the channel deposits. Along the western side of the Amstel these overbank clays have a width of about 500 m and are intercalated by a peat layer. In several boreholes this intercalated peat layer contains clay (B25G2625; B25G2634). The

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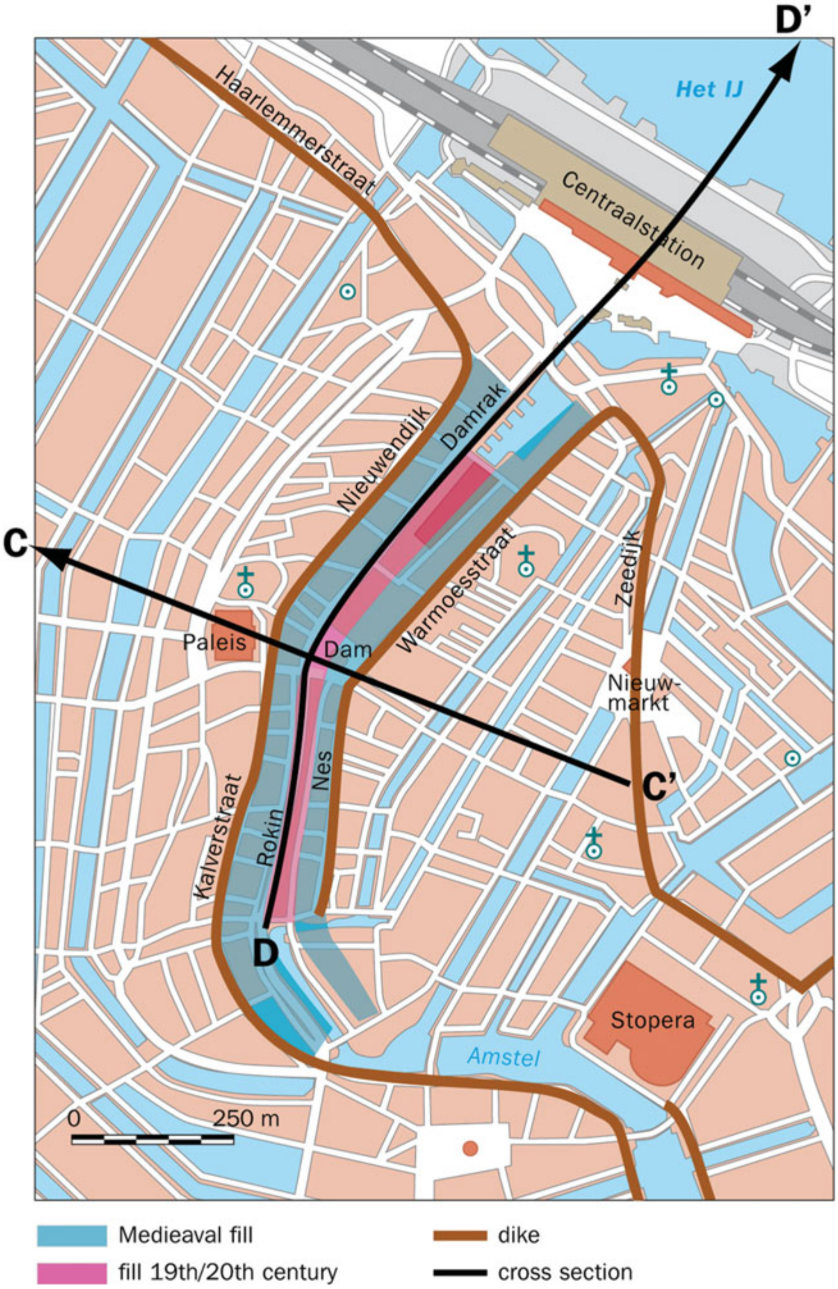

Fig. 5. Map of the city centre of Amsterdam and location of sections 3 (Dam) and 4 (Rokin-IJ) (after de Gans, 2011).

top of the overbank clay is situated here at 1.5 m –NAP. At its base it is sandy. East of the Amstel the overbank clay is up to 2 m thick. The elevation here is locally as high as mean sea level (0 m NAP; boreholes D06.1048 and SA). These high positioned laminated clays are presumably man-made as a result of the construction of small dwelling mounds composed of sods (van Regteren Altena, 1966). Elsewhere in Amsterdam the earliest dwelling mounds date from 1200 AD (Veerkamp, 1998).

The overbank clay on top of the peat at the western side of the Amstel and the uppermost level of overbank clay at the eastern side are thought to have been deposited during storm surges in 1164 and 1170 AD (van Regteren Altena, 1966; Veerkamp, 1998). During these storm surges sediments derived from the extending Zuiderzee were deposited along the Amstel far inland (Veerkamp, 1998). However, in the section, on the basis of the available borehole data, no lithological distinctions could be made between Zuiderzee deposits and Amstel sediments.

Below the Amstel channel deposits, a layer composed of grey silty clay or grey silty sand with shell concentrations near its base is located. These deposits are tentatively correlated with the tidal channel or estuarine deposits in the Oer-IJ. The base of these deposits is cut into a late Pleistocene layer of cryoturbated peat, clay and fine sands, locally called ‘Tussenlaag’ (Fig. 6). The ‘Tussenlaag’ is thought to have originated in a thermokarst lake environment dated to a Weichselian Interstadial (de Gans & Wassing, 2000).

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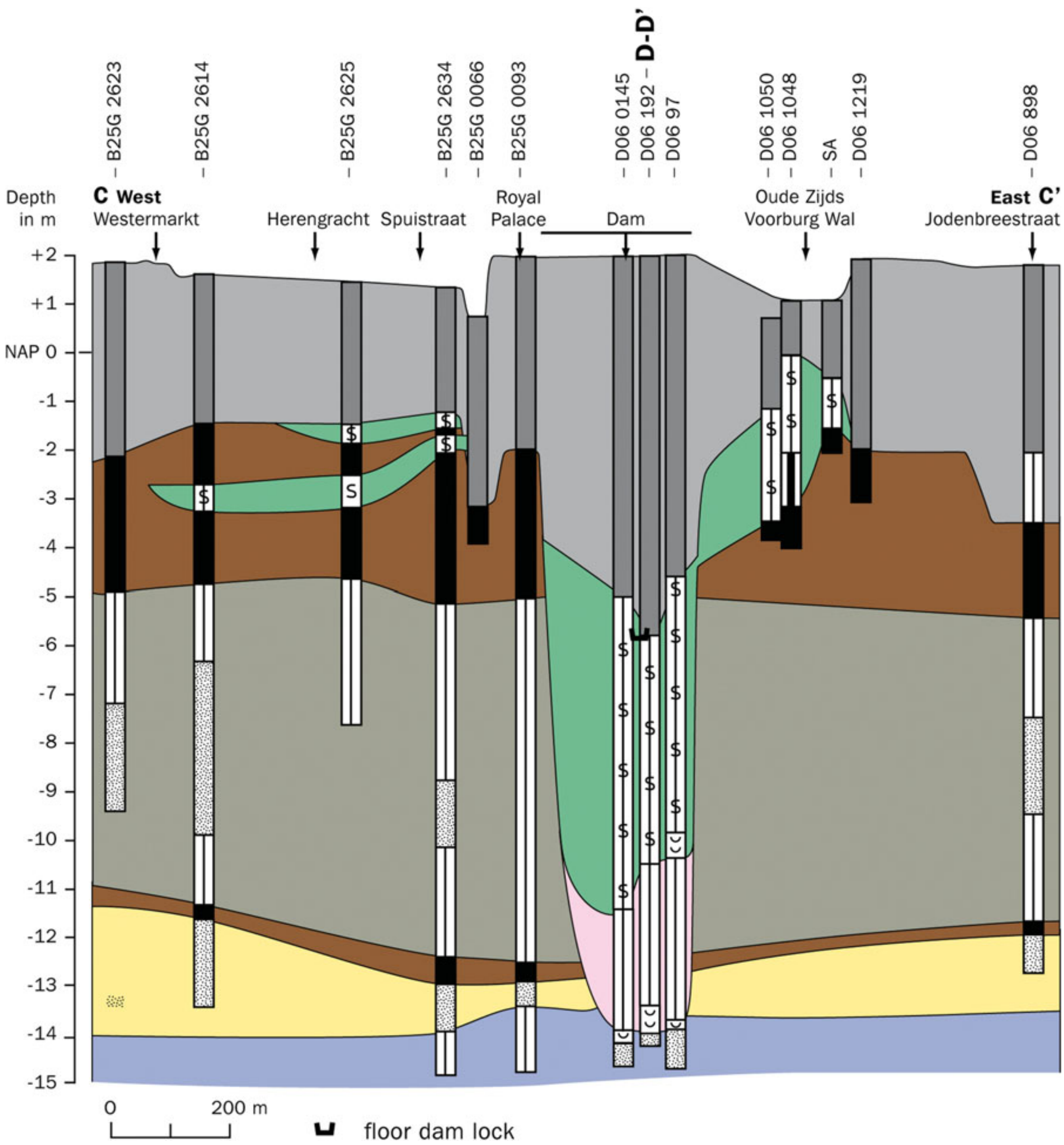

Fig. 6. Geological section CC′. Dam. Location Fig. 5; legend Fig. 3.

Section DD′: Longitudinal section from Rokin into the Oer-IJ estuary In this section from Rokin to IJ (Figs 5 and 7) the Amstel deposits are completely covered by a sandy fill. From the 13th century onwards the banks of the Amstel floodplain were infilled with clayey and peaty sods of earth to create new building spaces, thus constraining and narrowing the river. Six centuries later the remaining narrow channel was infilled with sand. The segment north of the Dam (Damrak) was infilled in phases between 1845 and 1883. The part south of the Dam (Rokin) was infilled between 1933 and 1939 (Figs 5 and 7).

Below the thick fill layer humic Amstel clay deposits can be traced as far north as the former estuary. From here they cannot be identified further. The top of the Amstel deposits is located at about 5 m –NAP. Because of the weight of the overlying fill the original depth will have been less. The bottom of the Amstel deposits increases from 9 m –NAP in the southern part of the section to 16 m –NAP in the north.

Palynological data from the Amstel sediments are available from a core at Beursplein (B25G0943; Fig. 7; Cleveringa, 1998; de Gans & Bunnik, 2011). These data suggest initial sedimentation of the Amstel in the late Subboreal (about 3000 BP), with the top (latest) level (5.5 m –NAP) deposited in the 12th/13th centuries. Younger sediments have presumably been removed by dredging. The presence of pollen of *Picea* and *Abies* indicate a Rhine source of the Amstel sediments (de Jong, 1968; de Gans & Bunnik, 2011). In the channel fill archaeological remains were found. The Rokin excavation pit dug in advance of a new metro line (Noordzuidlijn) revealed the lowermost Medieval

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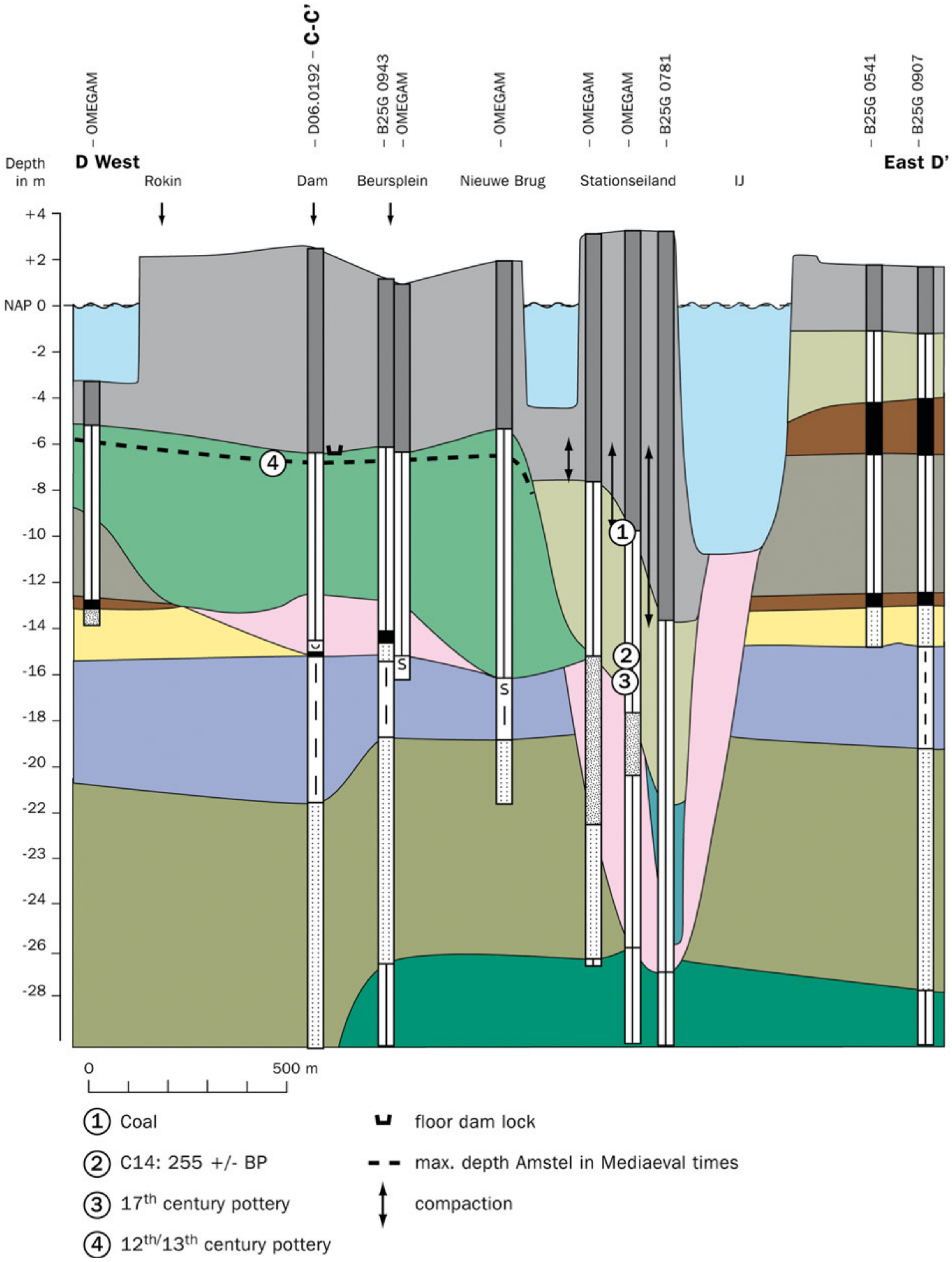

Fig. 7. Geological section DD'. Rokin-IJ. Location Fig. 5; legend Fig. 3. Note the condensed vertical scale compared to Figs 3, 4 and 6.

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finds in the Amstel deposits at 6 m –NAP; in the Damrak metro pit near Nieuwe Brug, the lowermost Medieval finds were at 6.5 m –NAP (pers. comm. Peter Kranendonk). Close to the dam a stone jar from about 1200 AD was found at 6 m –NAP (Veerkamp, 1998).

Below the Amstel sediments, tidal channel or estuarine deposits were found associated with the Oer-IJ, as described in section CC′ (Figs 6 and 7). The sediment is composed of grey silty clay or grey silty fine sands and contains marine shells. This deposit can be traced southwards until Rokin, although further south its presence is unclear. To the north it fades into the tidal and estuarine deposits.

Below the IJ the former tidal channel and estuarine sediments are composed of fine sands, silty clay and clay, which cannot be discriminated. The abandoned inactive estuarine channel (the Oer-IJ) was filled with a thick layer of basal clay, which was deposited after closure of the North Sea mouth. The thick clay fill of this 'rest gully' is in contrast with the surrounding sediments. The fill of the channel is described as estuarine clay in the section (Fig. 7). The channel bottom is located at 25 m –NAP. The initial sedimentation in this estuarine channel west of this section was dated between 200 and 400 AD (late Roman Period; de Gans & Bunnik, 2012). It is assumed that the initial sedimentation of the clay in the estuarine channel in section DD′ (Fig. 7) started in the same period. This means that in the late Roman Period the depth of the estuarine channel in front of the Amstel confluence was also about 25 m.

During the end of the 19th century the Central Railway Station of Amsterdam was constructed on an artificial island (Stations eiland) directly in front of the former mouth of the Amstel, on top of the former estuarine channel. To construct the Stations eiland a large amount of sand was used which subsided because of compaction of the underlying unconsolidated clay (Fig. 7). A borehole (Omegam, drilled in the middle of Stations eiland) revealed the presence of coal and lead (possibly from whitelead) at a depth of 10 m –NAP (tentatively dated to the end of the 19th century), a nut at a depth of 14 m –NAP (dated to the 18th century: GrA 22502: 255 ± 35 BP) and fragments of pottery (dated to the 17th century) at a depth of 16 m –NAP. These sediments are, given their age, assigned to the Zuiderzee deposits as this was the only possible source for sediments since the construction of the Amstel Dam in the 13th century. The transition from estuarine clay to Zuiderzee deposits in the section is drawn tentatively.

Discussion

This section seeks to compare and contrast the upstream section AA′ (Fig. 3) and the downstream sections BB′, CC′ and DD′ (Figs 4, 6 and 7) to investigate natural channel connection.

The four cross-sections reveal complex intercalations of Amstel clay, peaty clay/clayey peat and peat, indicating a fluvial environment where peat growth and clay sedimentation alternate. The clayey character of the Amstel sediments suggests a low water flow and transport capacity, therefore the winding character of the Amstel is not the result of active meandering. The curves in the Amstel are most likely related to irregularities in thickness and composition of the underlying peat.

The base of the Amstel channel deposits has an increasingly lower position northwards: in the Ouderkerk aan de Amstel section (4.5–5 m –NAP), in the Toronto brug section (7–8 m –NAP), in the Dam section (11–12 m –NAP) and 16 m –NAP near the confluence with the Oer-IJ (Figs 3, 4, 6 and 7). From the Toronto brug section and further to the north, lag deposits composed of reworked shells are found in some places. They are absent in the Ouderkerk aan de Amstel section as here the base of the Amstel channel did not cut into the lagoonal deposits. This suggests higher energy in the channel in the stretch north of Toronto brug. This may possibly be the result of tidal processes in the deep estuarine channel (Oer-IJ) during the initial phase of the Amstel. The channel sediments below the Amstel deposits in sections 6 and 7 are composed of grey sands and silts containing marine shells. They are thought to represent a tidal or estuarine channel that was located here before the Amstel river followed this course.

The Amstel river in section AA′ is accompanied by one overbank clay layer (Fig. 3) whilst north of this section two overbank clay layers are present separated by a peat layer (Figs 4 and 6). In a northward direction, towards the confluence with the Oer-IJ estuary, the zone where the lowermost overbank clay layer is present becomes wider. This may be the result of tidal processes in the estuary. The channel fill becomes more silty in the northward direction also, which supports the hypothesis that tidal processes have been in play. The intercalated peat layer is locally absent (Figs 4 and 6), which is probably due to human reworking and digging. We assume there is synchronism in the development of the intercalated peat layer. The presence of this peat layer, even locally on top of Amstel channel deposits (Fig. 4; core E06.157) also indicates that after deposition of the lowermost overbank clay sedimentation was restricted and peat growth became dominant on the river banks and locally even extended over the river channel deposits. However, the presence of clay in this peat layer as recorded in section CC′ (Fig. 6) indicates that some clay continued to be deposited. The decrease in sedimentation of clay may be the result of the shift in discharge to the Vecht, which is dated from 2440 BP (Bos et al., 2009), and the sediment fill of lakes, which originated along the Amstel course (Bos, 2010; de Gans & Bunnik, 2011, 2012). The sedimentation of Amstel clay in the overbank deposits in section AA′ ended probably at or short after 1000 AD (de Gans & Bunnik, 2011). However, in theory the discharge of Rhine water by the Amstel river and sedimentation in its bed and adjacent intercalated peat layer continued until the construction of the Kromme Rijn dam near Wijk bij Duurstede in 1122 AD, as fluvial sedimentation in the Beursplein core

(Fig. 7) continued until the 12th/13th centuries (de Gans & Bunnik, 2011).

The top layer of overbank deposits in section CC′ (Dam) is suggested to have been deposited during storm surges in 1164 AD and 1170 AD (Veerkamp, 1998), which is about half a century after the supply of Rhine water was stopped due to the construction of a dam upstream in 1122 AD. The source of the storm surge sediments must have been the expanding Zuiderzee. These storm surges penetrated deep inland following the Amstel floodplain (Veerkamp, 1998). High water levels at the seaward side of the Dam were documented from the 16th century onwards regularly. Floods with heights to over 2 m +NAP were recorded several times in each century, often flooding the Amstel Dam (van Malde, 2002). On the basis of these data, it is suggested that before 1164 AD floods would also have penetrated the Amstel flood plain. de Gans & Bunnik (2011) recorded influxes of brackish water in the Amstel channel deposits in the Beursplein core dating from about 800 AD onwards. This is the same period the connection with the North Sea became wide enough to introduce tide and brackish water into the Zuiderzee (Vos et al., 2011). It is suggested that the Zuiderzee deposits along the Amstel as far south as Ouderkerk aan de Amstel (Fig. 2) can be related to the major 12th century influxes. The presumed age of younger than 1000 AD for the uppermost overbank sediments related with these Zuiderzee deposits in section AA′ (Fig. 3; de Gans & Bunnik, 2011) is in agreement with these data of storm surges. The age of 250–500 AD presented on the Soil Map (Bodemkaart van Nederland, 1965) is too old. It is assumed that the highest overbank clay deposits in section BB′ (Fig. 4) can also be related to these 12th century influxes. All these data indicate that brackish water influxes penetrated deep inland following the Amstel floodplain.

The date of the initial growth of the intercalated peat layer in between the two overbank clay layers north of section AA′ is uncertain. The transition from clay sedimentation to peat growth in the overbank area is hypothetically related with the presumed termination of overbank clay sedimentation by the Amstel between about 1000 AD and 1122 AD, as recorded in section AA′ (Fig. 3). The cause of the peat growth is thought to have been higher water levels in the downstream part of the Amstel. The latter may be due to penetrations of Zuiderzee water in the Amstel floodplain during storms, thus damming up the Amstel waters and inundating the adjacent overbanks. It is presumed that the introduction of tide in the Zuiderzee may also have influenced the raising of the water level in the downstream part of the Amstel. The introduction of tide in the Zuiderzee due to the increasing width of the connection between the Zuiderzee and the Waddenzee/North Sea is dated at about 800 AD (Vos et al., 2011). Finally, subsidence of the peat surface due to cultivation may have been of influence too. The influence of sea level rise can almost be excluded given the curves of sea level rise in the Netherlands (de Mulder et al., 2003). The development of the intercalated peat layer ended with the deposition of brackish overbank clay from the Zuiderzee in the 12th century or possibly earlier. The brackish overbank clay or Zuiderzee clay deposits along the Amstel reach further south than the intercalated peat layer, suggesting increasing water levels over time due to damming up of water in the downstream Amstel. Minor intrusions of Zuiderzee water into the Amstel channel may have started as early as the 9th century as brackish water influxes are recorded in the Amstel channel fill in the Beursplein core from about this time (de Gans & Bunnik, 2011). It is possible also that part of the intercalated peat layer was eroded during the storm surges.

Based on the discovery of a 12th century stone jar in the Amstel (6 m –NAP; Veerkamp, 1998), the depth of the floor of the Medieval Dam lock (5–6 m –NAP) and the lowermost Medieval material found in the Amstel channel deposits in the Rokin metro pit (6 m –NAP) and the Damrak Metro pit (at 6.5 m –NAP) it is concluded that the 12th century water depth of the Amstel in Amsterdam was about 6 m –NAP (Fig. 7). In Roman times the Amstel was presumably deeper. The Amstel directly south of Toronto brug was probably shallower in Medieval and Roman times. However, the position of these finds may be too deep as in the whole study area compaction and subsidence has occurred, due to the thick fill, especially over the channel fill underneath the artificial island of Amsterdam's Central Railway Station (Fig. 7). Before the construction of this man-made island the Zuiderzee deposits were dredged to a depth of 5 m –NAP (Veerkamp, 1997). The depth of this surface is now at 7, 9 and 13 m –NAP below 10, 12 and 16 m of sand, respectively. This gives compaction values of 2, 4 and 8 m (Fig. 7). It is estimated that compaction of the top of the Amstel deposits in section DD′ (Fig. 7), positioned below 5–6 m raised soil, must have been about 1 m.

The estuarine channel west of section DD′ (Figs 1, 5 and 7) was completely filled by 1000 AD (de Gans & Bunnik, 2012). The data from the Omegam borehole at Stations eiland (Fig. 7) suggest that the former estuary was still deep here until the 17th century. Since then, the silting up has amounted to about 15 m, given the position of 17th century pottery fragments. However, this datum may be several metres too large because of compaction. Nevertheless this means that from the 17th/18th centuries the harbour at Amsterdam became gradually inaccessible for seagoing vessels because of the high sedimentation rate. Palynological data from a core in the estuarine channel several kilometres to the east, opposite Schellingwoude (Fig. 1), are in accordance with these data (Cleveringa, 1992; Bunnik, 2008).

Soil scientists, historians and historical geographers have presented the theory that part of the Amstel, the segment between Stopera and Watergraafsmeer, originated as a man-made connection, dug between the end of the 11th and the middle of the 13th centuries (Pons, 1973; de Bont, 2008). This theory is not valid from a geological point of view based on the

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following arguments. With respect to the presumed southern Amstel course the presence of an extensive overbank clay layer directly south of its presumed source in the Watergraafsmeer (Figs 2 and 3) is incompatible with the fact that the initial Amstel could not erode into the underlying lagoonal deposits (Fig. 3), thus it could not erode, transport and provide clay for the overbank deposits. Also the presence of *Abies* and *Picea* pollen suggests a Rhine provenance of the overbank clay. Moreover, the presence of eutrophic peat along the river does not fit with the idea that the southern Amstel was a minor river in a peatland area. Concerning the presumed man-made stretch, section BB′ (Fig. 4) shows a depth of the Amstel channel exceeding 7 m –NAP and a river width of 70–100 m. These dimensions do not fit with a man-made hypotheses of this river stretch. Furthermore, the presence of the lowermost 1 m thick overbank clay layer and the presence of the intercalated 80 cm thick peat layer east of the present river does not support the young man-made age. With respect to the presumed northern Amstel course, the presence of *Picea* and *Abies* pollen in the Amstel deposits in the Beursplein borehole (which suggests a Rhine provenance of the sediments) also contradicts the man-made character. If the Amstel stretch between Watergaafsmeer and Stopera was man-made, these pollen would only be present in the top level of the core. The renewed peat growth along the Amstel river after the deposition of the lowermost overbank clay layer indicates that sedimentation on the Amstel banks decreased but still continued since deposition in the Amstel channel continued as recorded in the Beursplein core (de Gans & Bunnik, 2011). It is possible that the river was straightened by human activities between the 11th and 13th centuries to facilitate discharge and navigation. However, in essence the discussed stretch of the Amstel river has a natural origin.

A definitive answer to these contradictory hypotheses and conflicting views of historical and geological sciences may be found by undertaking research focused on the overbank clay and peat layer along the disputed stretch of the Amstel.

Conclusions

On the basis of cross-sections it is concluded that in its downstream part the Amstel overbank deposits are composed of two overbank clay layers, separated by a peat layer about 1 m thick. The lowermost overbank clay layer is related to sedimentary processes in the Amstel, which started around 3000 years BP and ended about 1000 AD. The peat layer in between the overbank deposits indicates a decrease in fluvial overbank sedimentation in the Amstel. The termination of the deposition of the lowermost overbank clay layer may be caused by a shift in discharge to the Vecht and subsequent decreased sediment supply of the Amstel, the infilling of former lakes along the Amstel such as the Watergraafsmeer, which acted as a sediment sink, and finally the construction of a dam near Wijk bij Duurstede in 1122 AD. The renewed peat growth on top of the lowermost overbank clay layer may have taken place between about 1000 AD and the 12th century. The initiation of the growth of the intercalated peat layer may be caused by storms forcing intrusion of water from the Zuiderzee into the downstream Amstel, thus damming up the water level. The introduction of tide in the Zuiderzee, which possibly occurred at about 800 AD, and subsidence of the peat surface due to cultivation may also have had an influence. The uppermost overbank clay layer was deposited during storm surges from the Zuiderzee in 1170 AD, 1164 AD and perhaps earlier. This layer is related to the Zuiderzee deposits described on the Soil Map as far south as Ouderkerk aan de Amstel. Based on these data it is concluded that in the discussed downstream part of the Amstel between the 11th and 12th centuries the deposition of Amstel clay was impeded and was replaced by deposition of Zuiderzee deposits after a short period of peat growth on top of the lowermost overbank deposits. The presumption that the Amstel only followed its recent course after the digging of a canal between the Watergraafsmeer and Stopera, thus connecting two separate rivers with opposite stream-flow directions, is disproved on the basis of geological arguments. It might be possible, however, that the above mentioned river stretch was straightened by human activities after renewed peat growth on the overbank clay and riverbanks, but discharge of the Amstel was not impeded. In essence the discussed stretch of the Amstel has a natural origin. On the basis of the cross-sections it is also concluded that the bottom of the Amstel channel was deepened towards its confluence in the Oer-IJ estuary as a result of tidal processes. The water depth of the Amstel in Amsterdam in the 13th century was about 5–6 m. The water depth of the estuarine channel in front of the Amstel confluence in the Late Roman Period (200–400 AD) was about 25 m. Compaction values up to 8 m are recorded below the artificial Stations eiland. Because of the high sedimentation rate in the former estuarine channel, in front of and east of the Amstel mouth, the entrance to Amsterdam harbour became gradually impeded from the 17th/18th centuries onwards. By studying recent geological processes which are influenced by anthropogenic actions, cooperation between historical geographers, historians, soil scientists and geologists is highly recommended given the complex character of the resulting sedimentation patterns.

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References

Berendsen, H.J.A., 1982. De genese van het landschap in het zuiden van de provincie Utrecht. Thesis Utrecht University: 256 pp.

Berendsen, H.J.A. & ***Stouthamer, E.***, 2001. Palaeogeographic development of the Rhine-Meuse delta, The Netherlands. Van Gorkum (Assen).

Bodemkaart van Nederland, 1965. Schaal 1:50.000. Blad 25 Oost, Amsterdam. Stichting voor Bodemkartering (Wageningen).

Bos, I.J., 2010. Distal delta-plain successions. Architecture and lithofacies of organics and lake fills in the Holocene Rhine-Meuse Delta. Thesis Utrecht University: 208 pp.

Bos, I.J., ***Feiken, H.***, ***Bunnik, F.*** & ***Schokker, J.***, 2009. Influence of organics and clastic lake fills in distributary channel processes in the distal Rhine-Meuse delta (The Netherlands). Palaeogeography, Palaeoclimatology, Palaeoecology 284: 353–374.

Bunnik, F., 2008. Pollenscans van de Boring Zeeburgereiland (B25G0922). TNO rapport.

Cleveringa, P., 1992. Paleobotanisch onerzoek aan boring Zeeburgereiland 25G0922. RGD rapport 1169.

Cleveringa, P., 1998. Paleobotanisch onderzoek aan de boring Beursplein 25G0943. NITG-TNO rapport 1273.

Cohen, K.M., ***Stouthamer, E.***, ***Pieriks, H.J.*** & ***Geurts, A.H.***, 2012. Digitaal Basis bestand. Paleogeografie van de Rijn-Maas Delta. Department Fysische Geografie. Universiteit Utrecht. Digitale Dataset.

de Bont, Chr., 2008. Vergeten land: ontginning, bewoning en waterbeheer in de westnederlandse veengebieden (800–1350). Thesis Wageningen University: 652 pp.

de Gans, W., 2011. De Bodem onder Amsterdam. TNO: 69 pp.

de Gans, W. & ***Bunnik, F.***, 2011. De loop van de Amstel in Amsterdam. Grondboor en Hamer 65/2: 42–49.

de Gans, W. & ***Bunnik, F.***, 2012. Ruigoord en het Oer IJ. Grondboor en Hamer 66/6: 462–468.

de Gans, W. & ***Wassing, B.B.T.***, 2000. Geology and related geotechnical aspects of the underground of Amsterdam. Zeitschrift Deutschen Geologischen Gesellschaft 151/1–2: 9–20.

de Jong, J., 1968. Pollenanalytisch onderzoek van een boring te Uitermeer. Report 508. Paleobotanische Afdeling, Rijks Geologische Dienst (Haarlem).

de Mulder, E.F.J., ***Geluk, M.***, ***Ritsema, I.L.***, ***Westerhoff, W.E.*** & ***Wong, Th.E.***, 2003. De ondergrond van Nederland. Wolters-Noordhoff: 479 pp.

Güray, A.R., 1952. De bodemgesteldheid van de IJpolderts. Boor en Spade V: 1–28.

Makaske, B., 2001. Anastomosing rivers: a review of their classification, origin and sedimentary products. Earth Science Reviews 53: 149–196.

Pons, L.J., 1973. De Amstel is een kanaal. Het Vrije Volk, 20 Januari.

van Malde, J., 2002. Historische Stormvloedstanden. Aqua Systems International. Rijkswaterstaat. Rapport 2002.07.1: 136 pp.

van Regteren Altena, H.H., 1966. Opgravingen aan de Oude Zijds (1954–1962). *In*: van Regteren Altena, H.H. (ed.), Stadskernonderzoek in Amsterdam (1954–1962). Wolters (Groningen): 10–54.

Veerkamp, J., 1997. Mammoeten in Amsterdam? Archeologie Amsterdam: 87 pp.

Veerkamp, J., 1998. Mammoeten in Amsterdam. Directie Noord/Zuidlijn Amsterdam: 88 pp.

Vos, P.C., ***Bazelmans, J.***, ***Weerts, H.J.T.*** & ***van der Meulen, M.J.*** (eds), 2011. Atlas van Nederland in het Holoceen (Amsterdam): 94 pp.

Weerts, H.P., ***Cleveringa, P.*** & ***Gouw, M.***, 2002. De Vecht/Angstel, een rivier systeem in het veen. Grondboor en Hamer 56/3/4: 66–71.

Zagwijn, W.H., 1986. Nederland in het Holoceen. Rijks Geologische Dienst/Staatsuitgeverij: 46 pp.

https://doi.org/10.1017/njg.2014.41 Published online by Cambridge University Press