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History of geological mapping of the Holocene Rhine-Meuse delta, the Netherlands

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Abstract

A brief overview is given of the history of geological mapping of the Holocene Rhine-Meuse delta. The first accurate map of the delta, based on field observations, was made by Vink (1926). The geological map of the Netherlands, scale 1 : 50,000, made by the 'Geologische Stichting' (1927 - 1938) under the supervision of P. Tesch totally neglected Vink's work, and was a step backwards with regard to the mapping of the Holocene delta. Between 1940 and 1965, the Wageningen group of soil scientists produced detailed regional soil maps, that had a strong 'geogenetic' component. In the 1960's a revolutionary 'profile type legend' was introduced by the Netherlands' Geological Survey. This allowed to map not only the outcropping sediments, but the whole Holocene succession, which gave more insight into the geological history. Over the past 30 years, the Rhine-Meuse delta has been studied extensively by students of physical geography at Utrecht University. More than 250,000 borehole descriptions, 1500 ^{14}C dates and over 36,000 archeological artifacts with associated ages (collected by the National Service for Archaeological Heritage) have accumulated, resulting in the largest database of a delta in the world. The production of detailed maps has been crucial to the solution of many scientific problems. The use of GIS has greatly enhanced geological and geomorphological mapping, and subsequently, understanding of the evolution of the Holocene Rhine-Meuse delta. A new detailed digital elevation map of the Netherlands, based on very accurate laser-altimetry data, will enable us to map larger areas in greater detail, with greater accuracy, and in a much shorter period of time.

Keywords: geological maps, Holocene, Rhine-Meuse delta, fluvial systems, avulsions

Introduction

Geological, geomorphological and soil mapping by individuals or by national organizations has been the basis for understanding the evolution of the Rhine-Meuse delta ever since the first maps were produced. Maps have not only been crucial to scientific work, but also to numerous practical applications, like construction, infrastructure, extraction of minerals and water, environmental planning, reallotment and agriculture. This applies especially to maps that have been produced by the Geological Survey of the Netherlands and the 'Stichting voor Bodemkartering' (Soil Survey of the Netherlands). For overviews of national mapping programs of these institutions, and their aims and products the reader is referred to, e.g., Oele et al. (1983) or Berendsen (2004a, 2005).

In this paper, an overview is given of the history of geological mapping of the Holocene Rhine-Meuse delta, and how mapping has contributed to the scientific understanding of the evolution of the delta. The aim of this paper is to show how progress was made over the years with regard to the understanding of the Holocene delta evolution, using different mapping techniques, better drilling methods, increasing technical facilities, and a gradually growing understanding of processes governing the geological evolution. It is shown that avulsion was a key process in the development of the delta.

Staring's geological map

The first overview of surficial geology of the Netherlands was given by Staring's (1858 - 1867) geological map of the

Netherlands, on a scale of 1 : 200,000. The map included information on agricultural land use. Although this map has been very influential, especially in education, it did not show much detail of the Holocene Rhine-Meuse delta, and only few field observations could be made to produce it.

Vink's work

The first map of part of the delta that was based on detailed field observations, was published in the trail-blazing Ph.D. thesis 'De Lekstreek' by Vink (1926), Fig. 1. His map was the result of purely scientific work. It was the first map that showed coherent 'river systems' (channel belts) which provided a solid basis for beginning to understand the evolution of the Rhine-Meuse delta, even though little was known at that time about river processes. Vink stressed the importance of field observations.

In one of his propositions, he stated: "Staring did not know the river area from his own observations, and only had a fragmented understanding of its literature" (all cited propositions are translated from the Dutch). Although diplomacy was not one of his main assets, his statements generally were correct. Vink was a geography teacher with a profound scientific interest. Only during weekends he was able to map most of the western part of the delta. He produced the first detailed map of a river delta in the world. In the Netherlands, his insights were applied only 20 years later by others (mainly soil scientists). Vink realized, that sand is deposited in the river bed, clay further away from the channel and peat formation occurs far from the river, where little sediment is deposited. These simple assumptions enabled him to accurately map most of the subrecent channel belts, using an iron rod that he could stick into the ditches. If the iron rod met virtually no resistance he knew there was peat, if there was considerable resistance there was clay, and if it was impossible to penetrate the substrate, there was sand. His excellent observations are still valid at the present time, although most of his explanations are now considered obsolete. This reinstates his proposition: "Facts are of lasting value, views are temporary", a proposition that should be well remembered by present-day generations of students, who often seem to think that the explanation is more important than the facts, or worse, tend to adapt the facts so that they fit the current theory. Nevertheless, the master also had his weaknesses, as is now evident from his proposition: "The common opinion, that shifts of river courses and the formation of new channels have occurred in the Holocene Rhine-Meuse delta, as in other deltas in the world, is contradicted by the facts". Here, he seems to have mixed facts and interpretations in an inadmissable way, because we now think that the facts unequivocally seem to tell us that avulsions (shifts of a river course to another location on the floodplain) were quite common.

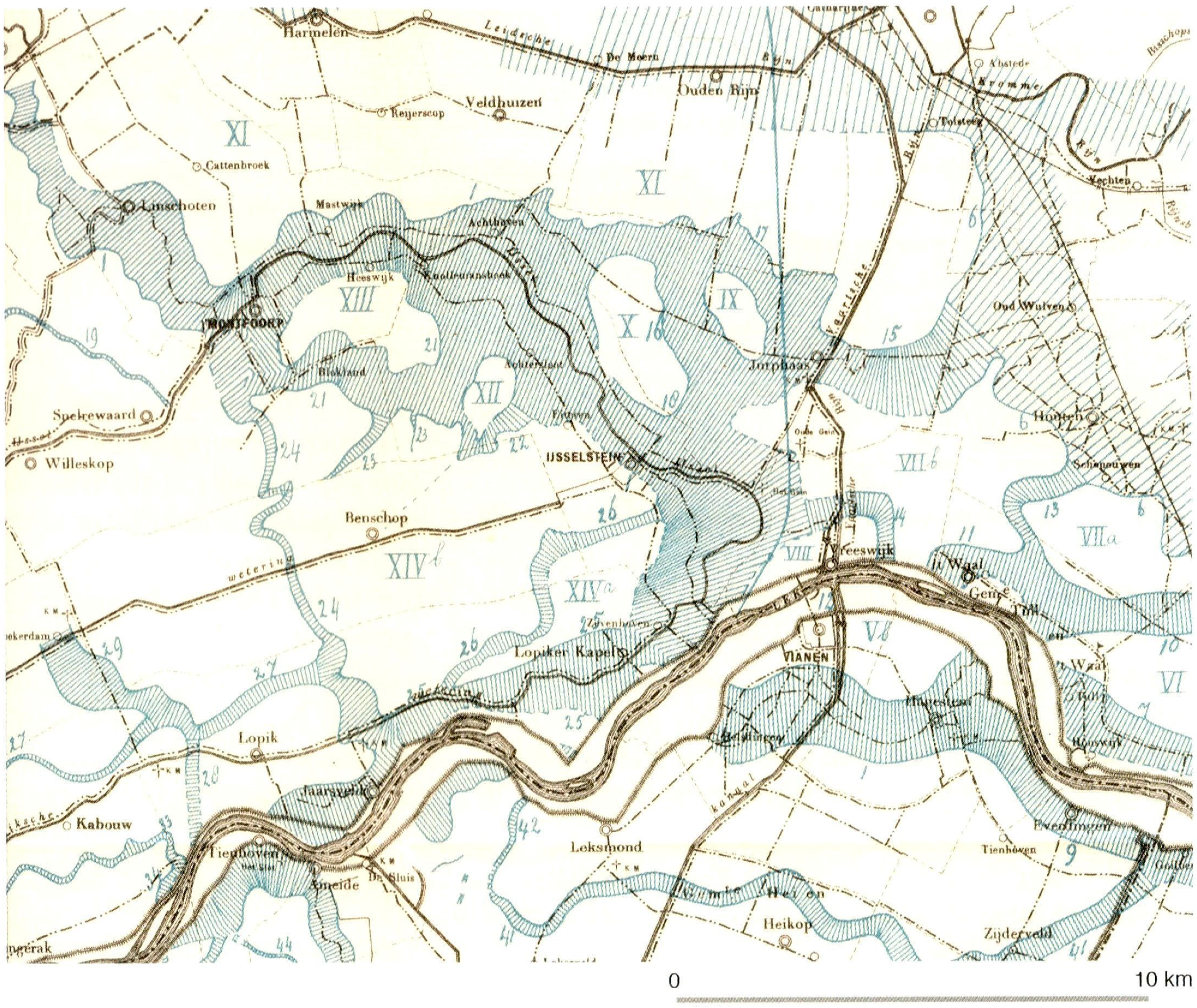

Fig. 1. Fragment of the Holocene channel belt map of Vink (1926). Blue hatch: channel belts, White: floodbasins. Numbers refer to the names of the channel belts and floodbasins. Original scale: 1 : 100,000.

In those days, it was thought that all Holocene rivers were small remnants of gigantic glacial streams, and all Holocene river systems were considered to be coeval. The depth at which sand occurred was just a rough measure for the successive abandonment of the channels. Channels were considered to be equivalent to channel belts, and no knowledge existed about river processes and smaller-scale fluvial landforms like, e.g., point bars, swales, residual channels and crevasse splays. This resulted in some weird explanations, and some rivers actually were considered to flow in the opposite direction. Nevertheless, Vink's contribution was both original and phenomenal. Unfortunately, his thesis was written in Dutch (as was common at that time), and hence it gained no international acclaim. Vink continued to study the Rhine-Meuse delta, and extended his map to the entire western part of the delta. These results were published in 1956, shortly after his death, in a voluminous and at times exhilarating book ('De Rivierstreek', Vink, 1956), in which he described humorous details of encounters in the field. However, by then, modern insights into river processes had arisen, especially by the excellent work of Fisk (1947) in the Mississippi delta. These insights were absent from Vink's second masterpiece, and this severely diminished the scientific value of that work.

First geological map, scale 1 : 50,000

Between 1927 and 1938, the first nationwide geological map at a scale 1 : 50,000 of the Netherlands was published by the Geological Survey (at that time 'Geologische Stichting'; Tesch, 1942). The map aimed to give more detailed information than Staring's (1858 - 1867) geological map, more insight into the origin of Quaternary sediments, and at the same time provide information on the lithology of surface deposits. It was also meant to be used for all kinds of practical problems (Tesch, 1942). The map was produced by a small group of people in a relatively short and economically difficult time. It was quite an accomplishment at the time, but with regard to the mapping of the Holocene Rhine-Meuse delta it was a major step backwards, because it was obvious that Vink's (1926) earlier work was totally neglected. The map showed channel belts as isolated 'islands' of sand (Fig. 2), whereas Vink (1926) had already shown that these sands were connected and formed part of a former river system. It is not clear why this happened. Maybe Tesch was unaware of Vink's work, or maybe he underestimated its significance. Whatever the reason, it resulted in a geological map of the Holocene deltaic area that was obsolete even before it was published. Consequently, the map did not contribute in any way to a better understanding of the evolution of the Holocene delta.

Wageningen soil scientists

The period 1940 - 1965 was the era of the Wageningen school of soil scientists, led by Edelman. The first generation of soil maps had a strong 'geogenetic' component, making them a mixture of a soil map (with a strong lithological component), a geomorphological map and – to a lesser degree – a geological map. Detailed regional mapping started during the Second

Fig. 2. Fragment of the first geological map, scale 1 : 50,000 of the Netherlands (Tesch 1936). Note the 'islands' of sand (code 17k/18z) that are actually parts of channel belts. Green (code 17k) = floodbasins.

World War (Edelman 1943). Shortly thereafter the maps and soil sciences became the basis for a major re-organization of the agricultural landscape in the Netherlands during the post-war period. The maps produced at scales ranging from 1 : 50,000 to 1 : 10,000 were generally excellent and showed much detail on the lithology of the surficial deposits (up to a depth of 1.2 m); examples are Edelman (1950), Edelman et al. (1950), Egberts (1950), Van Diepen (1954), Pons (1957, 1966), Sonneveld (1958), De Boer & Pons (1960), Zonneveld (1960), Van der Voorde (1963). Many publications by the Wageningen group were Ph.D. theses. Some of these publications were among the best in the world at the time, but because they were written in Dutch, they never reached the attention they deserved. Remarkable features are the accurate mapping of residual channels (Figs 3 and 4), even before there was a proper understanding of river processes. The reason for this is, that soil scientists used geomorphology to map soils. To the contrary, geologists were often forced to draw lines between boreholes, because for deposits at greater depth, that have no morphological expression in the field, there was no other way.

Although the maps produced by the Wageningen soil scientists were based on a high boring density and showed much detail, a fundamental understanding of sedimentary processes was still lacking in the beginning. That came only many years after Fisk (1947) completed his phenomenal work in the Mississippi delta.

The tradition of Edelman's work was continued by his scholars in the Soil Survey (Stichting voor Bodemkartering), which published an overview of the entire Netherlands at a 1 : 200,000 scale (Stiboka, 1965). This map also had a 'geogenetic' legend, with geomorphology (physiography) and lithology as important components. Subsequently, the Soil Survey started to produce new soil maps of the Netherlands, scale 1 : 50,000, based on a legend developed by De Bakker & Schelling (1966). The new soil classification was essentially based on soil forming processes, although genetic elements still played a role in the composition of the legend. The new maps (e.g. Stiboka, 1973) were better suited for agricultural demands (especially optimalization of agriculture and land consolidation), and geological information was omitted in the new mapping system. Hence the applicability of the new maps for geological interpretations decreased. However, the accompanying booklets still contained a lot of information on surficial geology and landscapes.

A limitation of the soil maps for geological interpretation in the deltaic area is that the soil maps are based on shallow corings (1.2 m below the surface), and thus older deposits (for example channel belts occurring at greater depth below the surface) are missed.

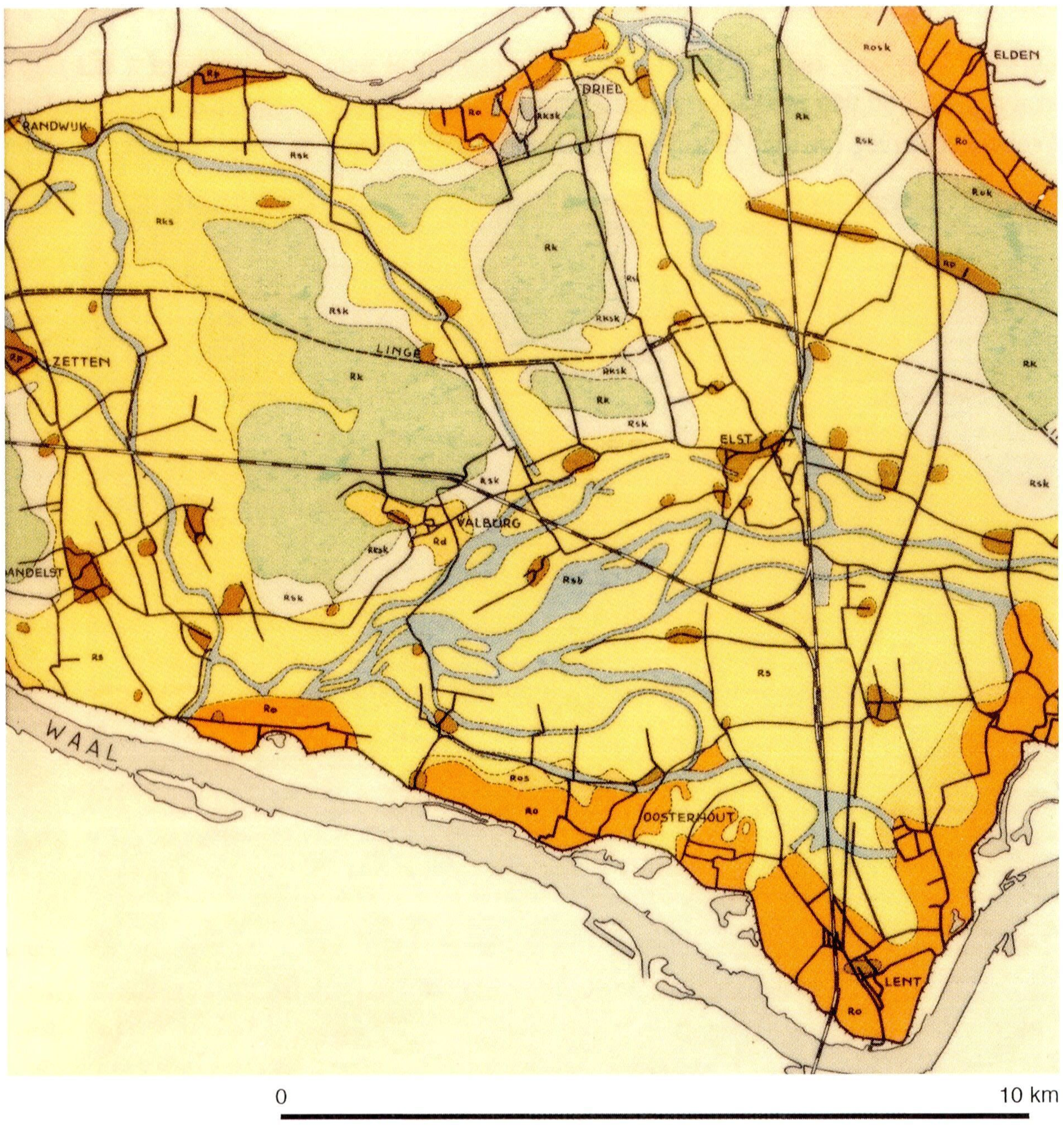

Fig. 3. Example of a soil map of the 'Wageningen soil scientists'; a detail of the soil map of the Betuwe (Egberts 1950). Channel belts are shown in yellow, floodbasins in green, residual channels in blue. Original scale of printed map approximately 1 : 71,400.

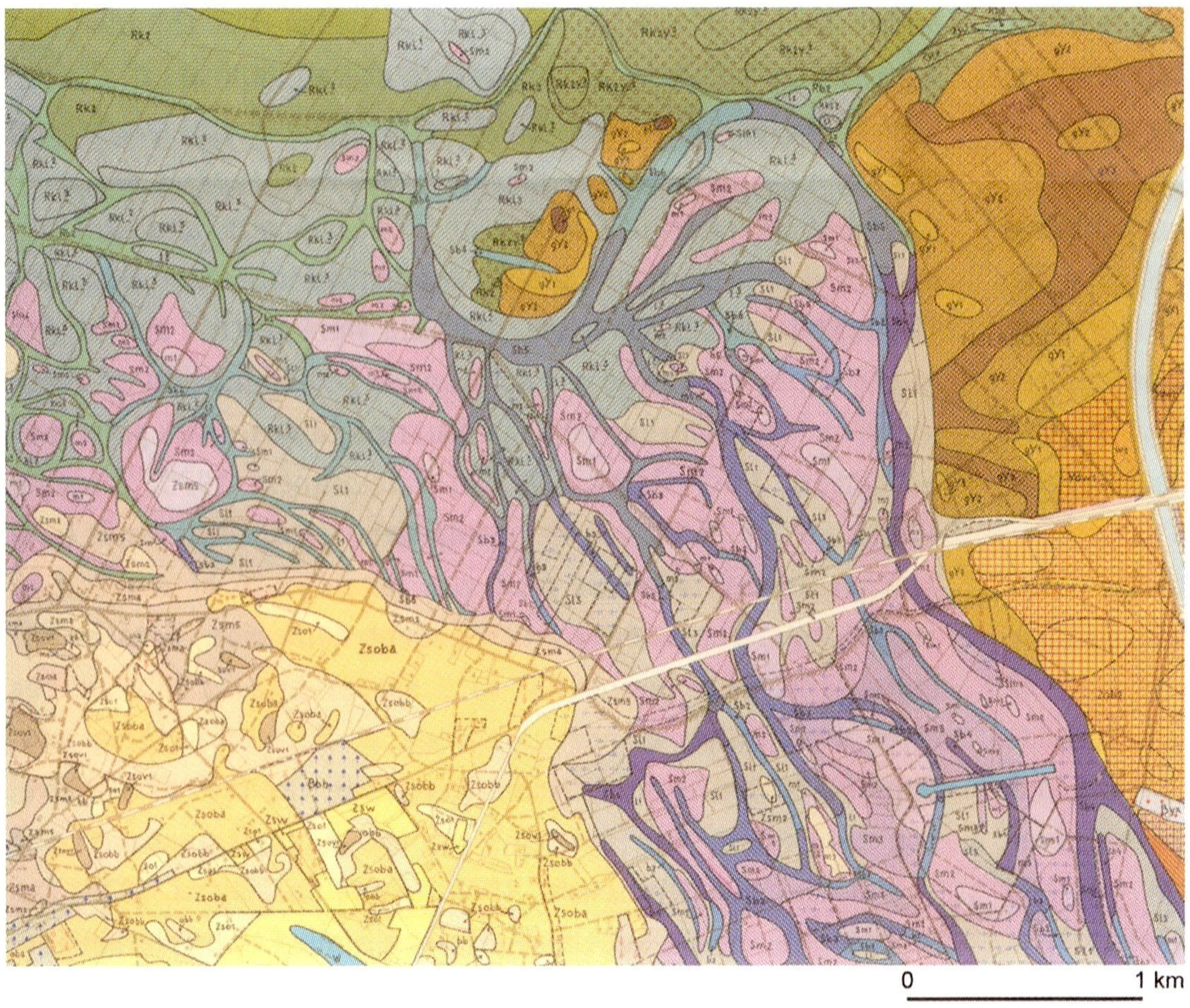

Fig. 4. Example of a soil map of the 'Wageningen soil scientists' (Pons, 1966). Detail of the Late Weichselian braided river pattern in the eastern part of the Netherlands (SW of Nijmegen). Residual channels are shown in blue. The braided channels are of pre-Allerød age; the meandering channel is of Allerød age. Original scale 1 : 25,000.

Geological Survey: introduction of the profile-type legend

Because the old geological map (Tesch, 1942) had become obsolete and many new scientific insights (regarding e.g., the ice ages, the genesis and age of deposits, chrono- and lithostratigraphy, and sedimentology) had developed, a new geological mapping program was started in the 1950's. The new geological map of the Netherlands, scale 1:50,000, to be produced by the Geological Survey, had to include more information on deposits at greater depth (up to 60 m), and should be more distinctive from the soil maps. Because it was felt that the Delta Works could benefit from the 'deeper' and more detailed geological mapping, the mapping program started in Zeeland. A totally new and revolutionary concept for the legend of the new geological map was introduced in the 1960's (Hageman, 1960, 1961, 1963, 1969). The so-called 'profile-type legend' allowed to map not only the outcropping sediments, but the whole Holocene succession or stratigraphy. For the mapping of the Rhine-Meuse delta, this was a great advantage, because it allowed to map deposits in the subsurface that don't have a morphological expression at the surface. The concept for the map was based on the stratigraphy in the Meuse estuary (Westland area), which was subsequently applied to the entire Netherlands. Seven main 'profile types' (A - G) were recognised. Each type was further subdivided into four subtypes, based on the stratigraphic sequence and intercalation of peat layers (Fig. 5). In addition, deposits at the surface were shown with a code. Maps of the fluvial part of the delta using the profile type legend were published by Verbraeck (1970, 1984), Van de Meene et al. (1988) and Bosch & Kok (1994). These maps have significantly contributed to a better understanding of the delta evolution, and greatly stimulated the Utrecht group of physical geographers that started mapping the Rhine-Meuse delta in 1973.

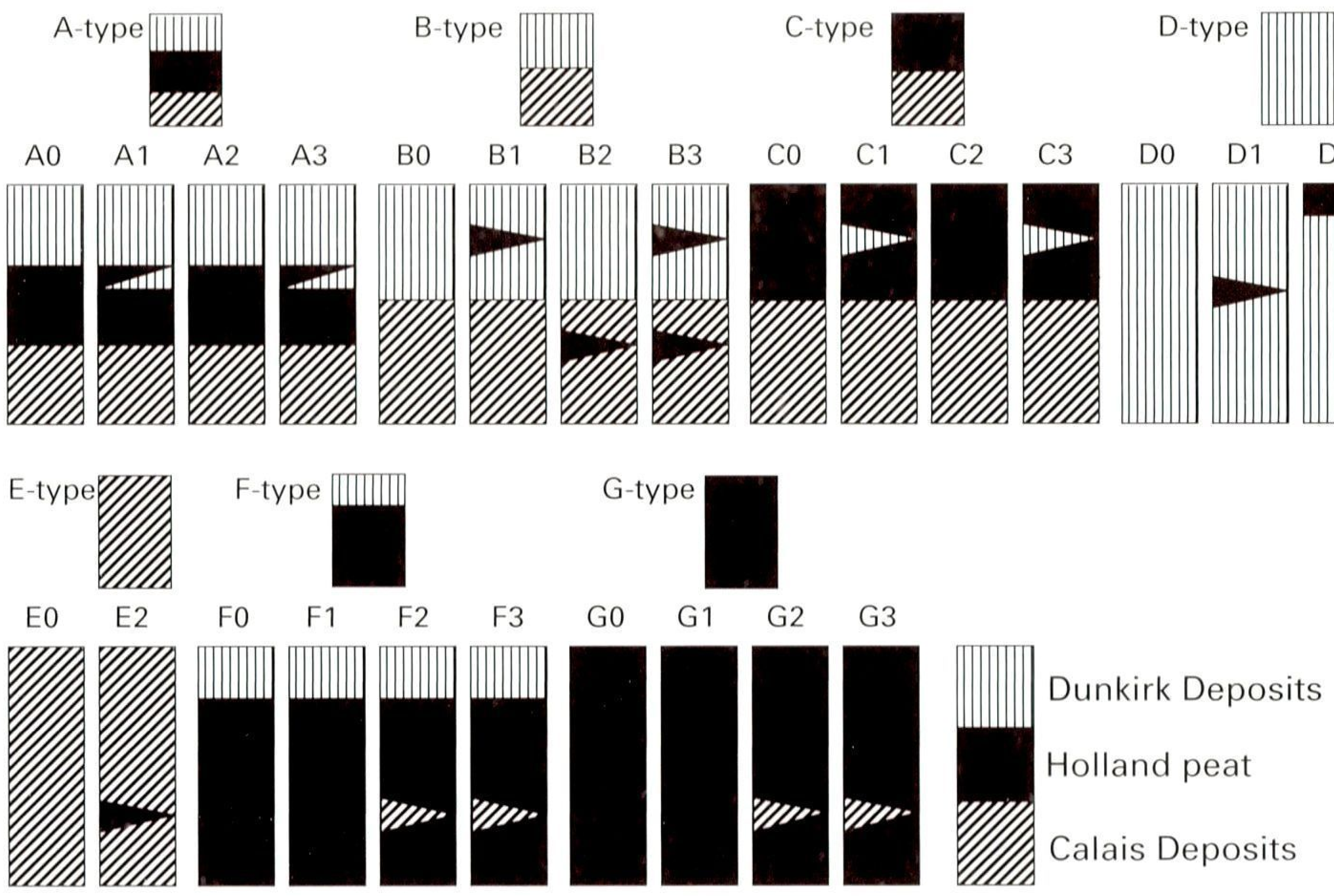

Fig. 5. Profile types and their subdivisions on the geological map of the Netherlands, scale 1:50,000 (Hageman 1963; Verbraeck 1970).

For scientific as well as practical use, however, it was often a problem that the geological map was based on relatively few borings (generally only 6 per km^2; in some areas up to a maximum of 15 per km^2, and one deeper coring per 2 - 3 km^2). This of course was due to the immense and time-consuming task of hand-drilling to a depth of ~10 m over the entire Netherlands. Compared to the soil maps that were produced at the same scale, the geological map was relatively inaccurate, which was mainly due to this low coring density. In the western part of the delta (especially the Alblasserwaard area), where narrow fluvial systems occur at great depth below the surface, the map often proved to be also unreliable with regard to the connections between sand bodies. The 'lung river system' of Hageman (1969), for example, was the result of erroneously connecting locations where sand was found. Because the sand in reality occurred at different depths and was not deposited by one river system, but by several river and tidal systems of different ages, the 'lung river' pattern created an illusion of a river system that never existed.

In addition, it was shown that the stratigraphic concept used in the profile type legend was based on some erroneous presumptions (Berendsen, 1982, 1984a, 1984b). Hageman's (1969) influential paper suggested that the evolution of the lower fluvial and deltaic areas was predominantly governed by sea level rise, and that deposition occurred virtually synchronously all along the coast from northern France to Denmark (see also Berendsen, 2004b, and Weerts et al., 2005). Very few radiocarbon dates were available that actually supported this presumption, but influential authors like Bakker (1954) had stated that this was the case, and it seems that the idea was accepted by virtually all workers. Hence all deposits in the so-called Westland Formation (a lithostratigraphic unit comprising beach and dune deposits, marine Calais and Dunkirk deposits, fluvial or 'perimarine' Gorkum and Tiel deposits, and Holland-peat) had to be stratigraphically subdivided into these Members. The marine and 'perimarine' deposits were further subdivided into 4 units each, and a synchronous sedimentation of these units in the marine and perimarine areas was presumed (Hageman, 1969; Zagwijn & Van Staalduinen, 1975; Zagwijn, 1986), see Fig. 6. Clastic sediments were regarded to result from 'transgressions', whereas peat was regarded to be a result of 'regressions'. These terms created much confusion, because the regressions were connected to a slower rate of relative sea level rise, which is not a regression. Various authors subsequently tried to find slight changes in the rate of sea level rise to explain the existence of these 'transgressions' and 'regressions' (e.g. Roeleveld, 1974; Louwe Kooijmans, 1974; Van de Plassche, 1980), but these efforts all failed to be convincing.

The 'perimarine area' was defined by Hageman (1969) as 'the area where sedimentation or sedentation (peat formation) took place under the direct influence of the relative sea level movements but where marine or brackish sediments themselves are absent'. This areal and genetic definition later caused considerable problems, because it proved to be very difficult to determine from the deposits whether they were 'influenced by the sea' or not. In addition, the formation comprised a large number of members consisting of a wide array of lithological categories. The members were not easily recognisable in the

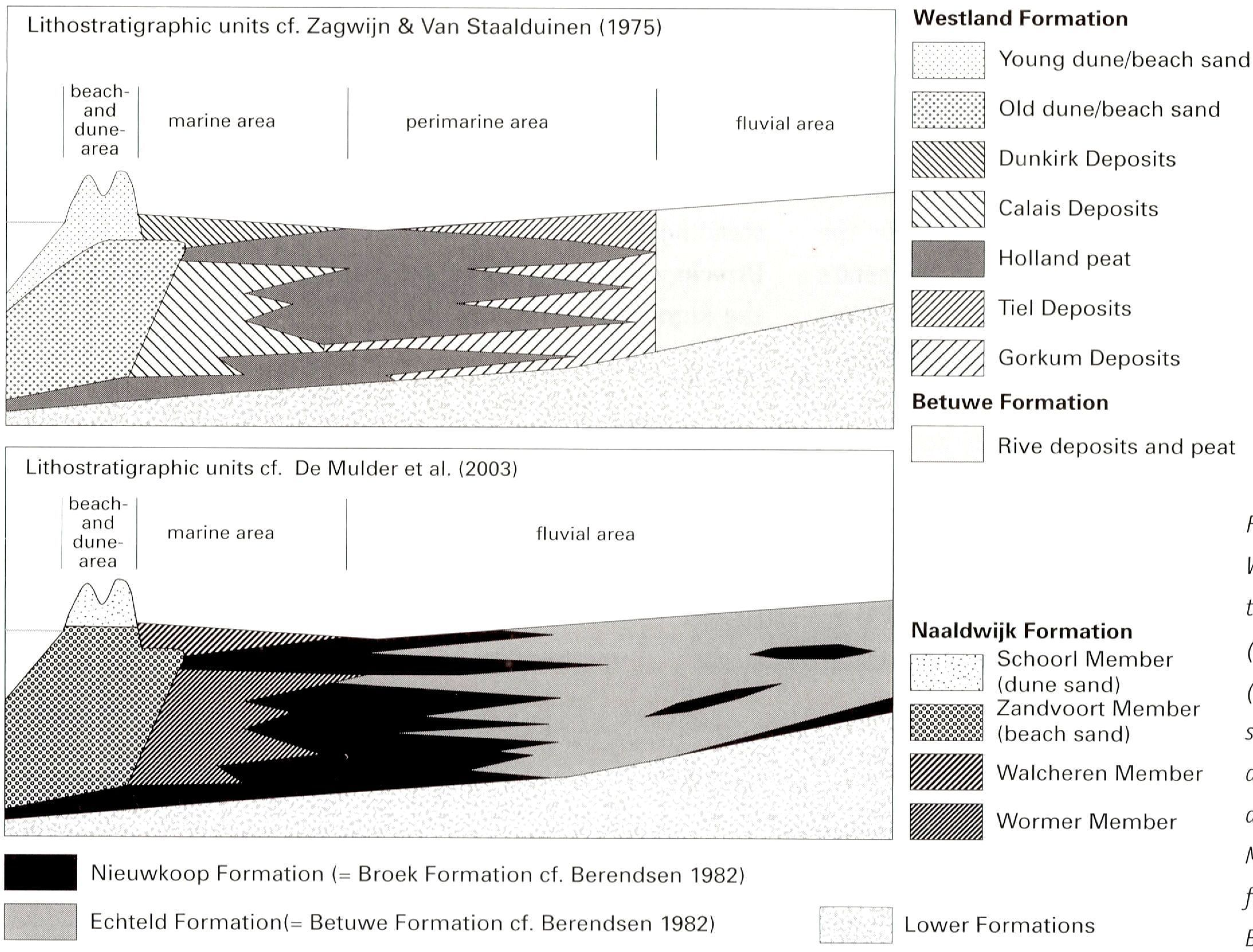

Fig. 6. Subdivision of the Westland Formation according to Zagwijn & Van Staalduinen (1975). The concept of this (originally 'lithostratigraphic') subdivision has now been abandoned, and is replaced by a new lithostratigraphy (De Mulder et al. 2003), essentially following recommendations by Berendsen (1982).

field and lacked macroscopically observable characteristics that could indicate their 'marine', 'perimarine' or 'fluvial' nature. Sometime along the way a fundamental mistake (Salvador, 1994) was made: the original lithostratigraphic subdivision was supposed to be equivalent to a chronostratigraphic subdivision. This soon caused trouble, making the system untenable in the long run. In addition, the subdivision of the members (e.g. Ente et al., 1975) were often beyond the resolving power of ^{14}C dating. Nevertheless, they were by some applied all over the country, and even extended up to the Dutch-German border by Harbers & Mulder (1981). Here the facts were forced to fit the model, which once again illustrates how true Vink's proposition: "Facts are of lasting value, views are temporary" is.

The Geological Survey's concept of synchroneity of sedimentation in the marine and 'perimarine' areas was mainly based on theoretical reasoning, and not on sound quantitative field evidence. Roeleveld (1974) was the first to present a quantitative analysis of radiocarbon dates for the northern part of the Netherlands. His analysis seemed to support Hageman's (1969) ideas, although a more critical look at his data would have shown some inconsistencies: some 'transgressions' and 'regressions' were missing. Griede (1978) found considerable deviations from Hageman's (1969) scheme, but at the time these were regarded as local aberrations. De Mulder & Bosch (1982), in their study of North-Holland found quite substantial deviations from Hageman's (1969) scheme, but these were not explicitly explained. Van der Woude (1979, 1981) found no time correlation at all between sedimentation in the marine and 'perimarine' areas, but his study area was too small to allow regional inferences (he by the way was the first to infer a more or less anastomosing river pattern in the Alblasserwaard, with large lakes in between river systems, although the term 'anastomosing' was not used until later, by Törnqvist, 1993).

Berendsen (1982) finally showed that Hageman's (1969) concept of synchronous sedimentation in the marine and perimarine areas was erroneous. This was based on a quantitative analysis of radiocarbon dates (Berendsen, 1984a, b). Instead, river avulsion (formation of a new river channel and abandonment of the old channel) seemed to dominate sedimentation in the fluvial and 'perimarine' parts of the delta. This was later confirmed by increasing numbers of ^{14}C dates (Törnqvist, 1993; Stouthamer, 2001; Berendsen & Stouthamer, 2001). These findings shifted the attention from the all-determining sea level rise to the fluvial domain. Berendsen (1982) already argued that fluctuations in river water level are far greater than tidal range, and hence the 'perimarine area' had to be much smaller than presumed by Hageman (1969). So, although Hageman's (1969) concept was shown to be incorrect, his ideas certainly stimulated more research on the Rhine-Meuse delta than any other paper over the past 30 years.

These new insights finally resulted in a new lithostratigraphic framework (Fig. 6) being adopted by the Netherlands Geological Survey (now TNO Built Environment and Geosciences, see also Berendsen, 2004b; Weerts et al., 2005). Simultaneously, the lithostratigraphy of the entire Quaternary was revised. The Westland formation and its subdivions are now abolished and the concept of alternations of 'transgressions' and 'regressions' has been abandoned altogether (De Mulder et al., 2003). It is now accepted that the Holocene evolution of both the fluvial and deltaic plain may differ from place to place, depending on the relative proximity of rivers and tidal inlets. The development in different tidal inlets is no longer considered to be synchronous, although a few tidal inlets remained open during much of the Holocene.

The new lithostratigraphic framework allows a more regional differentiation in geological maps. However, it also means that existing geological maps of the deltaic plain need to be revised (although patterns on the maps can in essence be maintained; it is mainly stratigraphy and time-correlation that need to be revised). In the meantime, the Survey has stopped to produce printed geological maps. Instead, 3-D numerical information is now provided, that is easier to update and to apply in practical studies. However, this information is only applicable by a limited group. The general public is still left in a situation, with no detailed geological maps being available for half of the country.

Recently, a new digital elevation model of the Netherlands (AHN, Rijkswaterstaat-AGI, 2005) has become available that allows more rapid and more accurate mapping of the shallow subsurface (Berendsen & Volleberg, 2007). Using this technique should enable the Survey to finish the geological map of the Netherlands, provided that enough funds can be allocated to reach this goal. The geomorphological map of the Netherlands was completed also in this way.

Geomorphological map of the Netherlands

In 1968, Maarleveld initiated the production of a geomorphological map of the Netherlands, scale 1 : 50,000. The first sheets were published as photographic reproductions. Printed sheets were published since 1977 as a joint effort of the Geological Survey and the Stichting voor Bodemkartering (now Alterra). In 1990 almost 70% of the sheets were completed, but then the project had to be suspended as a result of funding problems. Since 1997 Alterra continued to work on the project and finished the (now digital) map in 2003, using the new digital elevation model of the Netherlands.

For the understanding of the evolution of the Rhine-Meuse delta, the map has been insignificant, because all the information was already available from the soil map, the geological map or other sources. This, however, may change in the future, as sheets are revised, based on the AHN.

The Utrecht school of physical geographers

At Utrecht University a 'Rhine-Meuse' field course for undergraduate students started in 1959, under the supervision of Jan van Rossum. In the beginning not much progress was made, partly because the number of students was too low to map substantial areas. The course was initially based on the methods developed by the Wageningen soil scientists. This meant that coring depth was limited to 1.5 m.

From 1973 - 2005 the course was supervised by the author, who transferred it to a geomorphological and geological mapping course. Geomorphological maps, based on borehole descriptions, were made by students of physical geography at a scale of 1 : 10,000. Coring depth increased to a minimum of 2.0 m, with 15% of the corings penetrating the entire Holocene (later this percentage rose to almost 100%). Radiocarbon dating and new coring methods were introduced (like the Van der Staay-corer, invented by Jan van der Staaij, a field geologist at the Geological Survey), and in 1975 the author's Ph.D. study became linked to the field course. Almost simultaneously, the number of students started to rise. The first detailed geomorphological maps (scale 1 : 25,000) of the vicinity of Utrecht were published by Berendsen (1982), and were based on approximately 90,000 corings. The maps had a strong lithological component, and described the lithological succession in the upper 2 m. The emphasis, however, was not on stratigraphy, but on the recognition of architectural facies-units which were defined lithologically. This is an approach that was (independently) also followed by Miall (1985) and many others (see references in Weerts, 1996). Unfortunately, Berendsen's (1982) thesis and regional study of the Bommelerwaard (Berendsen, ed., 1986) were still written in Dutch, and most of his results became widely known only much later, when they were published in English.

A total of approximately 1800 undergraduate students participated in the field course between 1959 and 2006, and more than 250,000 borehole descriptions have accumulated (Berendsen, 2006), resulting in the largest database of a delta in the world. Another 100,000 borehole descriptions of the delta are available in the DINO database from the Geological Survey of the Netherlands (presently incorporated in TNO Built Environment and Geosciences). Other data of relevance for mapping are over 1500 ^{14}C dates and over 36,000 archeological artifacts with associated ages (collected by the National Service for Archaeological Heritage).

In the late-1980's the foundation was laid for the Utrecht school of physical geographers, under the supervision of Ward Koster and the author. This was greatly enhanced by an ever increasing number of students (an all-time high of 120 undergraduate students in physical geography was reached in 1992), the emergence of a generation of excellent Ph.D. students (Törnqvist, Kwadijk, Middelkoop, Asselman, Weerts, Makaske, Stouthamer, Hesselink, Cohen, Schokker, Gouw, Erkens, Bos, Hijma, Van Asselen), and the application of the computer and GIS in data handling (Berendsen et al., 2006). Together, these circumstances created a unique situation: a tremendous working force, that was able to concentrate on purely scientific work in the Rhine-Meuse delta (although teaching remained the main aim of the field course). In recent years, the use of GIS has greatly enhanced geological and geomorphological mapping, and subsequently, understanding of the evolution of the Holocene Rhine-Meuse delta (Berendsen et al., 2007). Results were partly published in numerous international papers and Ph.D. theses, and were summarized by Berendsen & Stouthamer (2001).

In the 1990's more evidence accumulated that supported the importance of avulsions for the evolution of the Dutch river and coastal plain, especially through the theses of Törnqvist (1993), Weerts (1996), and Makaske (1998). This eventually culminated in the publication of Berendsen & Stouthamer (2001), in which a geological-geomorphological map was presented on a scale 1 : 100,000 of the entire Rhine-Meuse delta. The map shows the ages of channel belts (Fig. 7). Although the mapping was done independently from other sources, the location of most early-to-middle Holocene channel belts (especially in the Alblasserwaard area) is still based on the geological map 1 : 50,000, and needs to be revised in the future to bring the accuracy and reliability of this part of the map in line with the rest. This is especially important because this area used to be characterized by anastomosing rivers, and the question whether these rivers did have a low or a high avulsion frequency is still unresolved.

Based on their map, Berendsen & Stouthamer (2000, 2001, 2002) made a detailed reconstruction of the paleogeographic evolution of the Late Weichselian and Holocene delta, that included an analysis of the factors controlling its evolution. It was shown, that the evolution was determined by complex interactions among the following factors: shape of the Late-Weichselian valley, sea-level rise, neotectonic movements, substrate composition, coastal evolution, discharge and sediment load variations, and human interference. The relative importance of these factors varied over time and space. Subsequently, Stouthamer (2001) analyzed the avulsion history. This study has yielded detailed insights of factors influencing avulsions, and up to now, is unique: so far there is no other delta in the world where the avulsion history could be reconstructed over the time scale of the Holocene. The avulsion history was successively determined by sea-level rise, neotectonic movements, discharge and/or sediment load changes, and human interference. The influence of neotectonics in the Holocene Rhine-Meuse delta had not been detected before, but it could be shown that it did influence river pattern as well as avulsion locations. Recently, the influence of avulsions on local groundwater levels at the flanks of eolian dunes was detected (Berendsen et al., 2007, submitted).

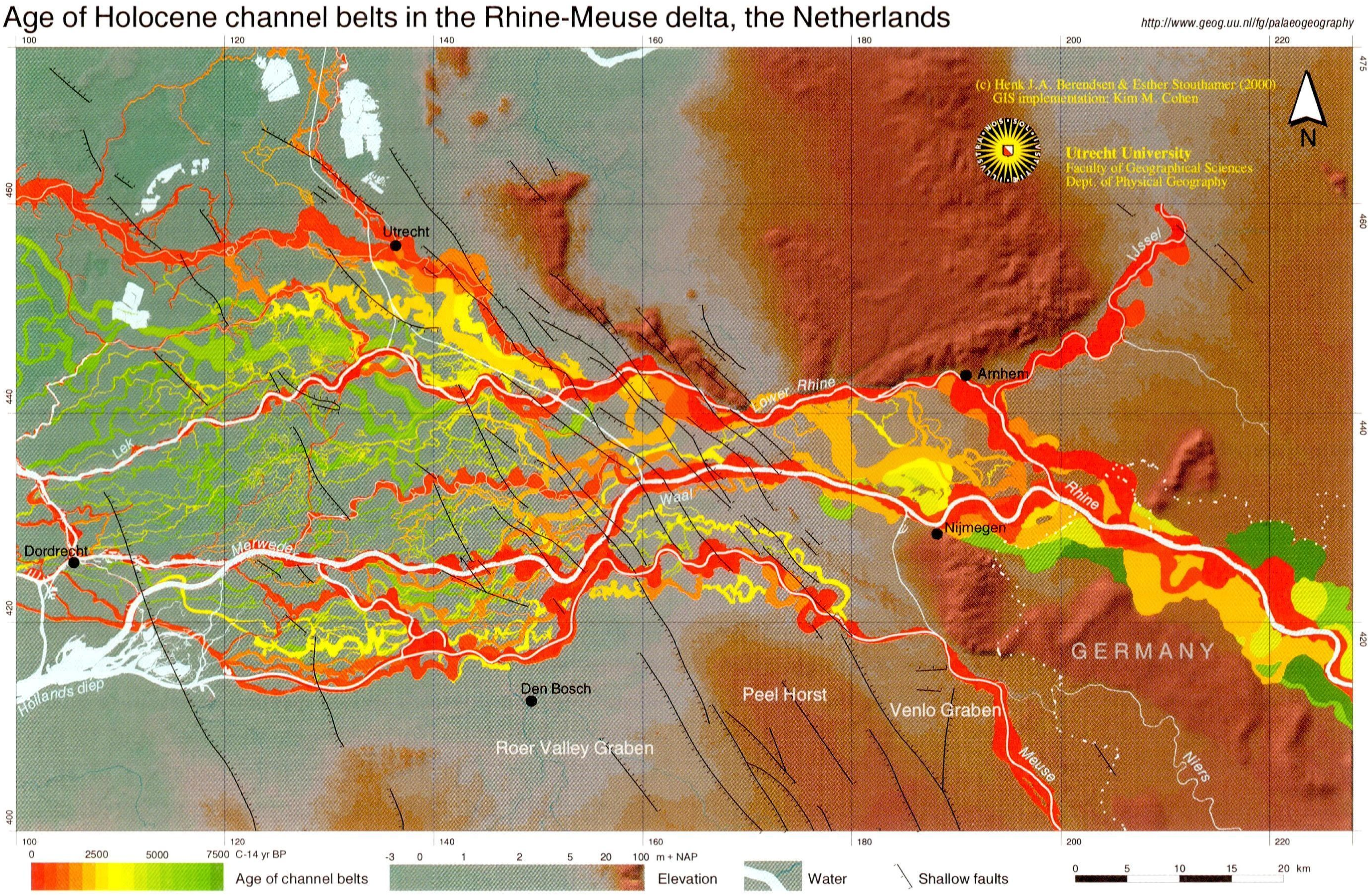

Fig. 7. Geological-geomorphological map of channel belts in the Rhine-Meuse delta (Berendsen & Stouthamer 2001). Channel belt ages are shown in the colors red (=young) to green (=old). Brown to blueish-green colors represent surface elevation. Shallow faults are based on Van Montfrans (1975).

In recent years, the avulsion parameters (avulsion frequency, avulsion duration, and interavulsion period), their mutual relationship, and dependency upon external factors could also be quantified (Stouthamer & Berendsen, 2001, Stouthamer & Berendsen, 2006). In addition, it was found that seven 'avulsion sequences' (as predicted by the Mackey & Bridge (1995) model) may be present in the Holocene Rhine-Meuse delta. During an avulsion sequence, avulsion sites shift progressively upstream with a simultaneous decrease in interavulsion period. This leads to a peak in the avulsion frequency. The sequences can be explained as a result of an autogenic process: continued growth of alluvial ridges and increasing cross-valley slopes upstream of avulsion locations. New channel belt segments down-valley from avulsion locations have low natural levees and a low probability of avulsion, hence avulsion sites tend to shift upstream until the apex of the delta is reached. The next avulsion can then occur far downstream again. The avulsion sequences seem to have a periodicity of ~500 - 600 yr.

Anastomosing river channels (multiple channels with floodbasins in between) were first recognized in the Rhine-Meuse delta by Törnqvist (1993), although similar patterns were described earlier by Hageman (1969) and Van der Woude (1981, 1984). Based on field evidence, Törnqvist (1993) produced a model of changes in fluvial style over time for the Rhine-Meuse delta. The model showed meandering rivers along the northern and southern margins of the delta (Fig. 7), and anastomosing rivers in the central part. The meandering rivers were explained as a result of low bank resistance in areas with coversands near the surface, while the anastomosing rivers were related to the rapid creation of accommodation space as a result of sea level rise, in combination with high bank stability. Makaske (1998) made a comparison of anastomosing river-channel patterns, processes and sediments in the Columbia River (Canada), the Niger inland delta (Mali) and the Rhine-Meuse delta (the Netherlands). He analyzed factors determining channel patterns (gradient, bankfull discharge, grain size) and showed that similar anastomosed river channels occur in different climatic settings. In fact, anastomosis is now regarded on a higher scale than the classic subdivision of channel patterns (straight - meandering - braided). This means that individual distibutaries in an anastomosing channel pattern can either be straight, meandering or braided. In the Mackenzie river delta (Canada) all these channel patterns occur at the same time in the same area. This makes it extremely difficult, if not impossible, to recognize channel patterns from single cores in the fossil record.

The influence of neotectonics on the evolution of the Rhine-Meuse delta has been confirmed in a detailed study by Cohen (2003), based on different approaches. This study allowed to quantify differential neotectonic movements within the delta over the time scale of the Holocene, and thus gave a better insight into regional neotectonic movements. Cohen (2003) also made a 3-D model of Holocene groundwater rise that allows to reconstruct uncompacted peat surfaces over time for any location in the delta (see: *www.geo.uu.nl/fg/palaeogeography*). This has important practical implications, e.g. for (human-induced) compaction studies.

In addition, a detailed 'sand depth atlas' (scale 1 : 25,000) of the eastern part of the Rhine-Meuse delta was produced for practical applications, including hydrological problems like seepage and water extraction, and environmental planning (Berendsen et al., 2002).

The future of mapping

Although the studies by the Utrecht school of geographers were based on an incredible amount of data, and have resulted in more detailed geological maps than were made ever before, considerable improvements of the accuracy of the maps can still be achieved in the near future. This is related to the emergence of the first digital elevation map of the Netherlands based on laser-altimetry. This map (Actueel Hoogtebestand van Nederland (AHN), published by Rijkswaterstaat-AGI, 2005) offers new possibilities to rapidly and more accurately map phenomena that often remained undetected in traditional field campaigns. The AHN has a resolution of 1 measurement per 4 m^2 in the fluvial and deltaic area, and a vertical resolution on the order of 1 cm (vertical accuracy $\sim$ 15 cm). With this digital elevation map minute differences in elevation can be recognized, allowing to map for example channel belts, tidal creeks and crevasse splays, even if they occur at considerable depth below the surface. Figure 8 shows a comparison of the digital elevation map and the map of Berendsen & Stouthamer (2001) of the area near Montfoort, which is probably the most densely drilled area in the world (up to 350 shallow boreholes per square kilometre; plotting the boreholes as a tiny dot in Figure 8 would turn the image completely black). In general, there is an excellent correspondence between the geomorphological/geological map and the digital elevation map. Channel belts, residual channels, crevasse splays and many other features can be interpreted from the digital elevation map. However, in the center-left of the image (indicated by arrows) two meandering channel belts were completely missed. The reason for this is, that in the early years, borings were performed to a depth of 2 m below the surface. Although the coring density was high, the channel belts were missed because they occur slightly deeper than 2 m. Later, drillings were deeper, but the coring density was less, and the spatial pattern could not be established. Now, with the AHN, spatial patterns can be seen that are virtually invisible in the field. The AHN thus makes it easier to find the best coring locations, and often shows details, that are not, or no longer, visible in the terrain. It therefore is a great new tool, that allows to make better maps, in more detail, in a shorter period of time (Berendsen & Volleberg, 2007). An increased accuracy of the maps may to be especially important for geotechnical applications, but it can also be of great scientific value. Past experience has shown that often the solution of large-scale problems lies in the understanding of the details. For example, the reconstruction of the avulsion history by Stouthamer (2001), became only possible after the Berendsen & Stouthamer (2001) map was completed.

Although the AHN offers new and better mapping possibilities, care should be taken not to overestimate its value. Since it is a remote sensing image, field verification remains an absolute necessity.

In the near future, new maps will be made of the IJssel valley and IJssel delta. This is a result of a cooperation with the Province of Gelderland, that involves the production of maps for practical applications. Subsequently, the transitional area between the fluvial dominated and the marine dominated domain (Alblasserwaard) will be mapped in detail, to quantify alluvial architecture parameters in this area, and to try to solve problems regarding the avulsion frequency of anastomosing rivers. This is an area that is so complicated, that it can hardly be mapped without the help of the AHN. This is clearly illustrated when the existing geological map, scale 1 : 50,000 is compared with AHN-images.

In 2001, the Faculty of Geographical Sciences and the Faculty of Earth Sciences started a common first year, and in 2003 they merged into a new Faculty of Geosciences. Over the past 8 years, the number of students in Physical Geography has dropped substantially. This has led to the early retirement of much of the senior staff, including Ward Koster and the author. Hopefully, the young generation (Hans Middelkoop, Esther Stouthamer, Wim Hoek, Derek Karssenberg, Maarten Kleinhans and Kim Cohen) will get the opportunity to lead the delta research into new promising directions.

Conclusions

The understanding of the evolution of the Holocene Rhine-Meuse delta in the Netherlands is intimately tied to the production of detailed geological maps.

The first accurate map of part of the Rhine-Meuse delta was made by Vink (1926). Between 1940 and 1965, the Wageningen group of soil scientists produced detailed regional 'soil' maps with a strong lithological and geomorphological component. In the 1960's a revolutionary 'profile type legend' was introduced by the Netherlands' Geological Survey, that greatly contributed to the mapping of deposits that do not have a morphological expression in the field. Over the past 30 years, the Rhine-Meuse delta has been studied by the author and students of physical geography at Utrecht University. This has resulted in the largest and most detailed database of a delta

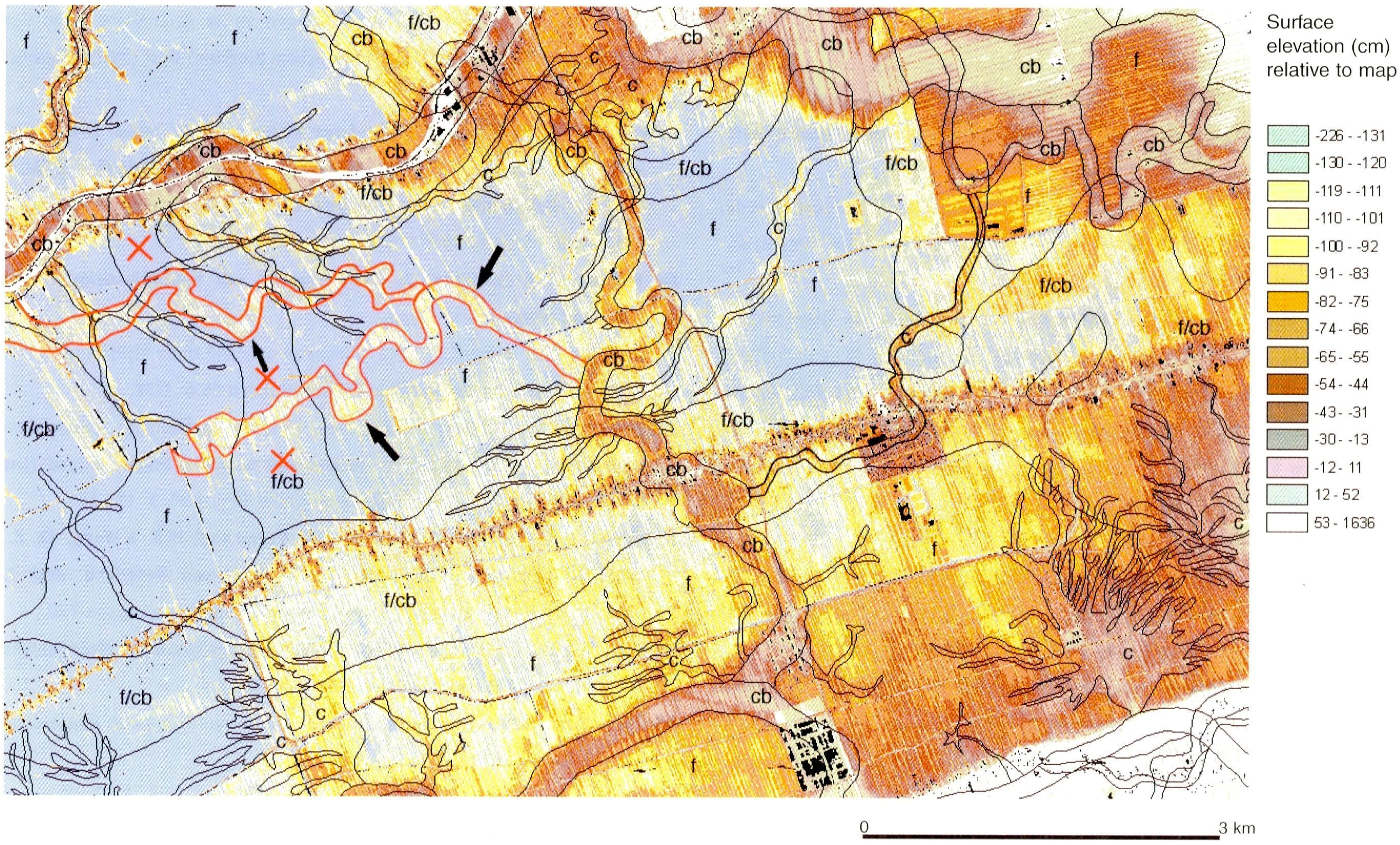

Fig. 8. Digital elevation map of the area near Montfoort, compared to the map of Berendsen & Stouthamer (2001). Black lines are boundaries between map units. Codes represent: cb= channel belts, f/cb= channel belts covered by floodbasin deposits, f = floodbasins, c = crevasse deposits.

The digital elevation map is based on the AHN (Rijkswaterstaat-AGI 2004). Elevation is shown in color: white and red = high, yellow = intermediate, blue = low. Note the generally close correspondence between the elevation and the mapped channel belts. Crevasse splays are clearly recognisable in the elevation image, and can at some places even be extended based on the elevation. Channel belts covered with floodbasin deposits (code f/cb, based on Verbraeck, 1970), are vaguely visible in the eastern and central part of the elevation image. These channel belts, that are 4-6 m below the surface can only be seen in the digital elevation map in areas with considerable differential compaction. In general, their width is too large on the map of Verbraeck (1970). Most important is that in the central part of the image (indicated by arrows) two channel belts (drawn in red) were completely missed in all existing maps. As a result, the avulsion locations were also missed.

The N-S running channel belt with code f/cb (Verbraeck, 1970), indicated by red crosses, does not exist at all. It was probably based on corings that happened to be carried out in the missed channel belts (Berendsen & Volleberg 2007).

Differences in ground water level between polders may cause abrupt elevation changes at the boundary of these polders. This is the reason why the southern channel belt indicated in red seems to stop in the western part of the image. In such cases the colors of the digital elevation model should be exactly tuned to the elevation differences observed in that polder. This will very often make even more details visible in the digital elevation map. The AHN can make selection of drilling locations more effective, but field verification remains a necessity.

in the world. This database, in combination with specific research has enabled Ph.D. students to carry out scientific investigations that up to now, are unique in the world. The use of GIS has greatly enhanced geological and geomorphological mapping, and subsequently, understanding of the geological evolution of the Holocene Rhine-Meuse delta. It could be shown that avulsions play a dominant role in the genesis of the delta. Avulsions determined the paleogeographic evolution, the shifting of areas of clastic sedimentation, the alluvial architecture and local groundwater levels. These studies would have been impossible without detailed mapping. This shows that the key to the solution of large-scale scientific problems often lies in the details.

A detailed digital elevation map of the Netherlands, based on very accurate laser-altimetry data, will in the future enable us to map larger areas in greater detail, with greater accuracy, and in a much shorter period of time.

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