Netherlands Journal of Geosciences — Geologie en Mijnbouw | 86 - 1 | 23 - 54 | 2007

Architecture of the Holocene Rhine-Meuse delta (the Netherlands) – A result of changing external controls

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Manuscript received: October 2006; accepted: March 2007

Abstract

The Holocene Rhine-Meuse delta is formed under the influence of sea-level rise, tectonics, and variations in discharge and sediment supply. This paper aims to determine the relative importance of these external controls to improve our understanding of the evolution of the Rhine-Meuse fluvio-deltaic system. To do this, the geological and lithological composition of the fluvio-deltaic wedge has to be known in detail, both in space and time. This study presents five cross-valley sections in the Holocene Rhine-Meuse delta, based on almost 2000 shallow borings. Over 130 ^{14}C dates provide detailed time control and are used to draw time lines in the sections. Distinct spatio-temporal trends in the composition of the Holocene fluvio-deltaic wedge were found. In the upstream delta, the Holocene succession is characterised by stacked channel belts encased in clastic flood basin deposits through which several palaeo-A-horizon levels are traceable. In a downstream direction, the fluvio-deltaic wedge thickens from 3 to 7 m. The Holocene succession in the downstream cross sections formed from *~8000 cal yr BP* onwards and is characterised by single channel belts encased in organic flood basin deposits. The main part of the organic beds accumulated between *6000* and *3000 cal yr BP*. After *3000 cal yr BP*, clastic deposition dominated throughout the delta, indicating an increase in the area of clastic sedimentation. The Holocene fluvio-deltaic wedge is subdivided into three segments based on the relative importance of eustatic sea-level rise, subsidence, and upstream controls (discharge and sediment supply). Before *5000 cal yr BP*, eustatic sea-level rise controlled the build-up of the wedge. After eustatic sea-level rise ceased, subsidence was dominant from *5000* to *3000 cal yr BP*. From *3000 cal yr BP* onwards, increased sediment supply and discharge from the hinterland controlled the formation of the fluvio-deltaic wedge. A significant part of the present-day Rhine-Meuse fluvio-deltaic wedge aggraded *after* eustatic sea-level rise ceased. We therefore conclude that external controls other than eustatic sea-level rise were also of major importance for the formation of the fluvio-deltaic wedge. Because this is probably true for other aggrading fluvial systems at continental margins as well, all external controls should be addressed to when interpreting (ancient) fluvio-deltaic successions.

Keywords: Rhine-Meuse delta, fluvial stratigraphy, sea-level rise, subsidence, time lines, upstream controls

Introduction

Holocene fluvio-deltaic wedges ('coastal prisms'; cf. Posamentier et al., 1992) accommodate a virtually continuous record of Holocene delta formation, which initiated in response to deceleration of sea-level rise after the Early Holocene (Stanley & Warne, 1994). Despite the fact that (sub)recent river deltas have been subject of many studies, e.g. the Mississippi delta, USA (Saucier, 1994), the Rhine-Meuse delta, the Netherlands (Berendsen & Stouthamer, 2001), and the Po delta, Italy (Amorosi et al., 1999), a detailed geological-lithological characterisation of a fluvio-deltaic wedge as a whole is presently lacking. The main reason for this is that field data is limited for most deltas (see, for example, Amorosi et al., 1999; Tanabe et al., 2003), whereas large datasets are needed to characterise fluvial successions in detail (Bridge, 2003). The large amount of subsurface data available for the Holocene Rhine-Meuse delta (Fig. 1) (Berendsen & Stouthamer, 2001; Berendsen, 2005) offers the opportunity to characterise its architecture to gain a better understanding of the relative importance of the controls involved in the evolution of the delta. High-resolution field data can be used to validate numerical models simulating

https://doi.org/10.1017/S0016774600021302 Published online by Cambridge University Press

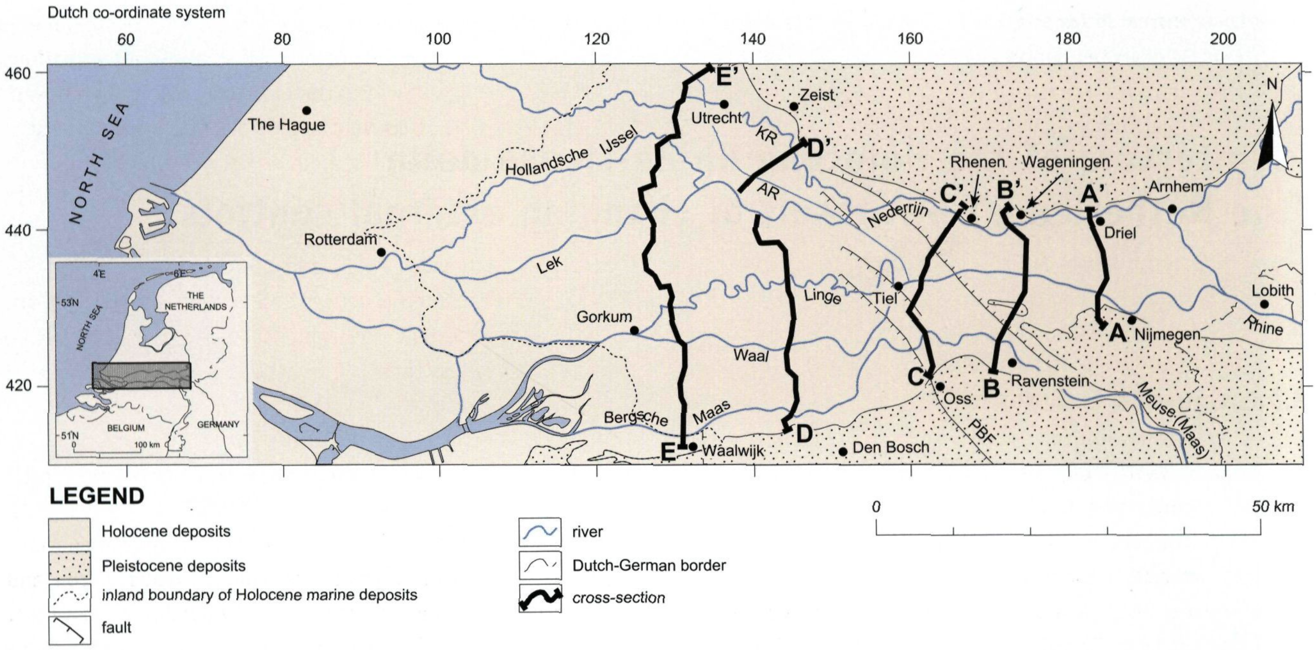

Fig. 1. The Rhine-Meuse delta, the Netherlands, with locations of the cross sections discussed in the text. AR = Amsterdam-Rhine Canal, KR = Kromme Rijn River, PBF = Peel Boundary Fault zone.

delta evolution. Furthermore, the Holocene fluvio-deltaic wedge of the Rhine-Meuse delta can be regarded as an analogue to ancient fluvio-deltaic successions, which commonly form hydrocarbon reservoirs (e.g. Tye et al., 1999; Ryseth, 2000).

The cross sections of Törnqvist (1993a) and Cohen (2003) provide a starting point for our study. Törnqvist (1993a) published a transect covering a large part of the lower Holocene Rhine-Meuse delta. The cross section of Cohen (2003) is located further upstream. However, additional cross sections and time control are needed in the central and upper parts of the delta to obtain a complete delta-scale overview of the architecture of the Holocene Rhine-Meuse delta. We present new cross sections and ^{14}C data, and propose a method for constructing time lines. This paper aims to discuss the relative importance of the several different external controls involved in the formation of the Holocene fluvio-deltaic wedge, based on the presented cross sections and ^{14}C dates.

Geological setting and lithostratigraphy

The Rhine in the Netherlands has followed its current E-W course since the Middle-Weichselian (Zagwijn, 1974). During the Late Pleniglacial (Table 1), the Rhine-Meuse system predominantly consisted of braided channels that deposited mainly (coarse) sand and gravel. These deposits belong to the Kreftenheye Formation (lithostratigraphy cf. Westerhoff et al., 2003; Table 1) and are overlain by a stiff clay layer in large parts of the Rhine-Meuse delta. This distinct clay layer (the Wijchen Member of the Kreftenheye Formation; Törnqvist et al., 1994; Westerhoff et al., 2003) was deposited by incised meandering channels that developed in response to the climatic warming during the Bølling/Allerød interstadial (Berendsen et al., 1995). River channels re-adopted a braided pattern during the following Younger Dryas stadial. The Younger Dryas braid plain surface is at a lower level than the Pleniglacial braid plain surface and, consequently, two Late-Pleistocene 'terrace' levels can be recognised in the subsurface of the Rhine-Meuse delta (Pons, 1957). Differences in height between these two terrace levels of up to 2 m are reported for the upper Rhine-Meuse delta (Berendsen et al., 1995). Both terraces dip in a westerly direction and converge near Rotterdam (Törnqvist,

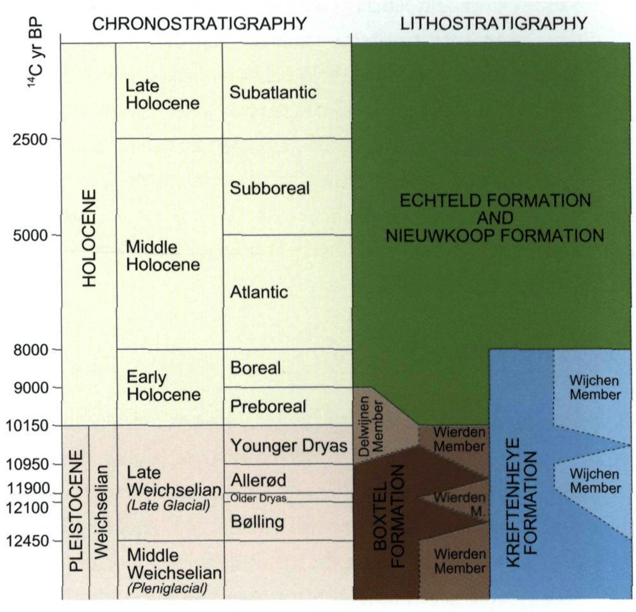

Table 1. Chronostratigraphy (cf. Mangerud et al., 1974 and Hoek, 1997) and lithostratigraphy (cf. Westerhoff et al., 2003) of the Holocene Rhine-Meuse delta (Weerts, 1996, modified).

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1998). The Younger Dryas terrace is also capped by the Wijchen Member. These sediments originate from incised Early-Holocene meandering channels (Berendsen et al., 1995). Locally, eolian dunes of Younger Dryas age overlie the Wijchen Member. These eolian dunes usually occur on top of the Pleniglacial terrace (Berendsen et al., 1995). The deposits of the eolian dunes belong to the Delwijnen Member of the Boxtel Formation. The Late-Weichselian Rhine-Meuse palaeo-valley is laterally bordered by eolian deposits (Wierden Member of the Boxtel Formation) and ice-pushed ridges, both of Pleistocene age.

The formation of the Holocene fluvio-deltaic wedge started approximately 8200 ^{14}C yr BP / *~9250 cal yr BP* (all calendar *years in this paper are in italics*) in the western part of the present delta (NITG-TNO, 1998). The boundary between net Holocene aggradation and incision progressively shifted upstream during the Holocene (Fig. 2). Downstream from the aggradation-incision boundary between the Holocene and Pleistocene deposits, a stacked succession of fluvio-deltaic deposits was formed. The Holocene fluvio-deltaic wedge of the Rhine-Meuse delta thickens in a downstream (western) direction to about 20 m near the North Sea coast. It comprises numerous channel belts with associated natural levee, crevasse-splay, and flood basin deposits. All clastic fluvial deposits of Holocene age in the Rhine-Meuse delta belong to the Echteld Formation. The Echteld Formation is informally subdivided into six units based on lithology and genesis (cf. Berendsen, 1982): channel-belt deposits, natural levee deposits, crevasse-splay deposits, channel-fill deposits, flood basin deposits, and dike-breach deposits. The channel-belt deposits mainly consist of fine to coarse sand (150 - 850 µm), sometimes mixed with gravel (Berendsen, 1982; Weerts, 1996). Natural levee deposits are characterised by silty and sandy clay (in this paper, the nomenclature of the texture classes is after Nederlands Normalisatie Instituut, 1989). Crevasse-splay deposits consist of very fine to coarse sand, silty and sandy clay, and clay. Flood basin as well as channel-fill deposits typically are (silty) clays that may be slightly to strongly humic. The flood basin deposits are intercalated with peat layers and beds of organic mud ('gyttja'), the latter indicating lacustrine conditions. The Holocene organic deposits in the fluvio-deltaic wedge of the Rhine-Meuse delta belong to the Nieuwkoop Formation.

Methods

Borings and cross sections

In order to characterise the Rhine-Meuse fluvio-deltaic wedge, we used palaeogeographic maps (Berendsen & Stouthamer, 2001) and five detailed valley-wide cross sections. The spacing between the cross sections is ~15 km. Parts of the cross sections have previously been published by Berendsen (1982), Törnqvist (1993a), and Cohen (2003). The location of the cross sections (Fig. 1) was chosen in order to: 1) obtain a series of evenly-spaced cross sections oriented perpendicular to the general flow direction; 2) cross all major fluvial landforms in various parts of the delta; and 3) use the existing dataset (Berendsen, 2005; see below) as effectively as possible. We therefore located the cross sections where borehole density was highest.

To compile the five cross sections, we used a total of 1928 borings of which 1556 were retrieved from the archives at Utrecht University (Berendsen, 2005) and 105 from the database of TNO - Geological Survey of the Netherlands. We carried out 267 additional borings. The average borehole spacing in the cross sections is less than 100 m, which is sufficient to obtain a general overview of the lithostratigraphy (Weerts & Bierkens, 1993). Sediment cores were retrieved with hand-operated drilling material (Edelman auger, gouge, and Van der Staay suction corer; Oele et al., 1983) and logged in the field at 10 cm intervals. This involved a description of texture, organic matter content, gravel content, median grain size, colour, oxidised iron and calcium carbonate content, occurrence of groundwater, and other characteristics, such as occurrence of shells and plant remains (cf. Berendsen & Stouthamer, 2001). Almost all borings reach either the Pleistocene substrate or sandy channel-belt deposits of Holocene age. Some Holocene channel belts were penetrated to determine channel-belt thickness and/or to establish if they scoured into to the Pleistocene substrate. Coordinates of the boring locations were determined using a handheld GPS-device (accuracy: 4 to 6 m) and topographic maps (1 : 10,000 scale). Surface elevation of the boring locations was obtained with digital elevation maps (AHN: Actueel Hoogtebestand Nederland, accuracy: 15 cm) or surface elevation maps (1 : 10,000 scale). Levelling (1 cm accuracy) was performed only in case the boring was carried out for dating purposes.

The borings obviously are not in a perfectly straight line perpendicular to the general flow direction. This could result in an overestimation of the width of the fluvio-deltaic wedge and the architectural elements therein. Therefore, we remodelled the line connecting the boring locations to obtain a cross section, which is approximately perpendicular to the general flow direction. First, a 50 m buffer was drawn around the line connecting the boring locations. Within this buffer, the cross sectional line was drawn and all borings were projected on this line. Using this method, the cross sections became ~10% shorter than the initial line connecting the boring locations.

We used the principles described by, e.g., Berendsen (1982), Törnqvist (1993a) and Weerts (1996) to determine lithogenetic units from the obtained lithological information. The most fundamental principle applied was that the fluvial deposits in the Rhine-Meuse delta correspond to the facies-model for a meandering river (Fig. 3). For example, every channel belt has adjacent natural levee deposits and flood basin deposits that correlate to the channel belt. In this study, the occurrence of silty deposits is used as a criterion for the extent of the natural levees. The silty natural levee deposits laterally grade into clayey flood basin deposits.

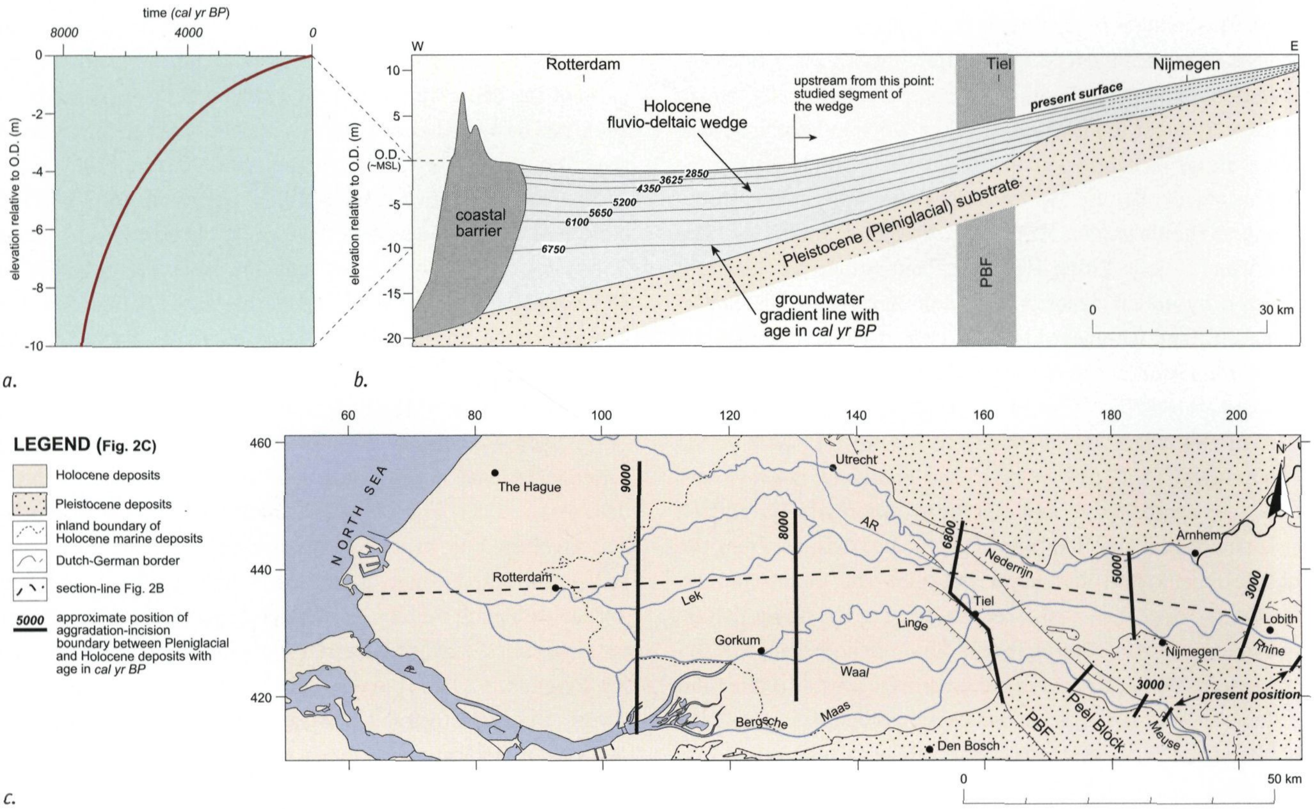

Fig. 2. a. Relative sea-level rise (Jelgersma, 1979; Van de Plassche, 1982); b. longitudinal section through the fluvio-deltaic wedge of the Holocene Rhine-Meuse delta with paleo-groundwater gradient lines (after Van Dijk et al., 1991; Cohen et al., 2002); and c. upstream migration of the aggradation-incision boundary during the Holocene (after Stouthamer & Berendsen, 2000; 2001 and Cohen et al., 2002). The aggradation-incision boundary marks the updip limit of the Holocene fluvio-deltaic wedge and is represented in (b) by the intersection between the groundwater gradient lines and the Pleistocene substrate. Between 8000 *and* 6800 cal yr BP, *the upstream shift of the aggradation-incision boundary decreased due to the upthrown Peel Block (Stouthamer and Berendsen, 2000). All ages in* cal yr BP. *The studied part of the fluvio-deltaic wedge is indicated in (b). PBF = Peel Boundary Fault zone.*

In the cross sections, the channel belts are represented by relatively large sand bodies. The associated overbank deposits are subdivided into natural levee deposits, crevasse-splay deposits and flood basin deposits. Natural levee deposits and crevasse-splay deposits are lithologically similar. Therefore, they are merged into a single unit. The lithogenetic unit 'flood basin deposits' only comprises the clayey flood basin deposits. Peat and organic mud, commonly found in the flood basins, are incorporated in the unit 'organics'. Locally, residual channels were encountered. At the southern end of the westernmost cross section, tidal deposits occur. These are lithologically similar to natural levee deposits, but contain marine shells.

^{14}C and OSL-dating

Precise time control is essential to determine temporal changes in the architecture of the Rhine-Meuse fluvio-deltaic wedge. We used two dating methods: ^{14}C dating for organic beds and optically stimulated luminescence (OSL) dating for sandy deposits.

All available ^{14}C dates within 500 m of the cross sections were evaluated, yielding 88 ^{14}C dates from previous studies. We took an additional 45 ^{14}C samples (Table 2) to improve time control. Loss-on-ignition analyses (cf. Heiri et al., 2001) were performed on the samples to determine the organic matter content. The samples were treated with a 5% KOH-solution and washed. Subsequently, terrestrial macrofossils were selected for AMS dating. We used OxCal 3.10 software (Bronk Ramsey, 1995; 2001) to calibrate the radiocarbon dates. In most cases, several ^{14}C samples were taken from the same core at various stratigraphic levels. This resulted in a vertical sequence of ^{14}C dates, which provided time control throughout the Holocene succession.

Wallinga (2001) showed that quartz OSL-dating is a useful tool for dating Late Glacial and Holocene Rhine-Meuse deposits. For a detailed description of the principles of OSL-dating and its application to fluvial stratigraphy, we refer to Wallinga (2001) and references therein. OSL-dating for the present study was carried out at the Netherlands Centre for Luminescence Dating at Delft University of Technology. Eight a.

b.

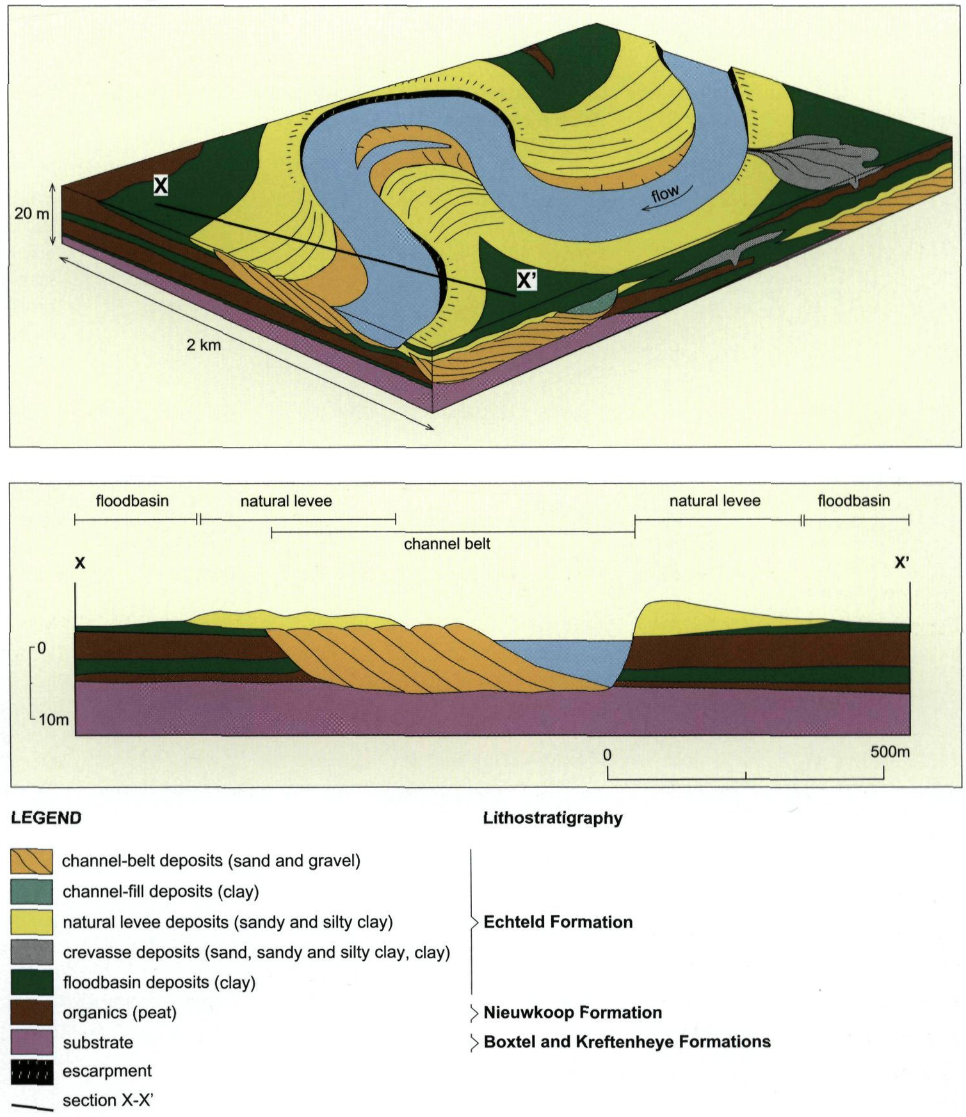

Fig. 3. Block diagram (a) and cross section (b) of a meandering river in the Rhine-Meuse delta, showing the depositional environments as recorded in the Holocene fluvio-deltaic succession (adapted from Weerts, 1996).

OSL-samples (Table 3) were selected from two different cores. To determine the equivalent dose, the quartz single-aliquot regenerative-dose (SAR) protocol (Murray & Wintle, 2000) was used. All OSL-ages are presented in kyr with 1σ-confidence intervals to account for uncertainty.

Time lines

Time lines are defined as lines that bound the time frame in which a given part of the fluvial succession is formed. We constructed time lines in the vicinity of dated cores on the basis of the dates in the cross sections. We then extended the time lines into areas with little or no dates using stratigraphic relationships between channel belts and associated overbank deposits (Fig. 4).

The period of activity of the channel belts is based on Berendsen & Stouthamer (2001) and Cohen (2003). We presumed that the beginning of activity of a channel belt is marked by the base of the associated overbank deposits. The top of the overbank deposits marks the end of activity of the channel belt. This concept was used to constrain the time lines (Fig. 4). In the flood basins, peat and dark-coloured palaeo-A-horizons (e.g. Berendsen & Stouthamer, 2001) represent periods of less or no sedimentation. These marker horizons can be used to draw time lines in the flood basins. When the above-described techniques were ineffective to construct reliable time lines, we used a 3-D groundwater model (Cohen, 2005) to reconstruct the groundwater level at a certain moment in time. These levels were considered to represent a minimum surface elevation at that time.

The construction of reliable time lines in cross sections is only possible if solid stratigraphic relationships can be established and if good age control exists. Given the well-known stratigraphic relationships and the excellent age control in the Holocene Rhine-Meuse delta, we estimate the accuracy of the time line elevations to be better than ~0.5 m for the cross sections in the upper delta, and ~1.0 m for the downstream cross sections.

Table 2. New ^{14}C dates resulting from this study.

UtC nr[a]	^{14}C age ± 1σ (yr BP)	Calendar age[b] (*cal yr BP*)	Co-ordinates[c] (km)/ surface elevation (m ± O.D.)	Depth below surface (cm)	Sample name	Dated material and source material	Reference in this article
14213	1567 ± 44	*1411-1517*	172.180-441.100/+6.98	118-119	Wageningen 1	Terrestrial botanical macrofossils (slightly clayey peat)	Fig. 7 (15)
14214	2873 ± 48	*2925-3075*	174.348-439.194/+6.72	205-209	Opheusden 1	Terrestrial botanical macrofossils (humic clay)	Fig. 7 (11)
14215	4454 ± 49	*4975-5019,* 5028-5070, 5108-5127, 5167-5276	174.348-439.194/+6.72	295-296	Opheusden 2	Terrestrial botanical macrofossils (humic clay)	Fig. 7 (12)
14216	5210 ± 49	*5910-6001*	174.348-439.194/+6.72	368-369	Opheusden 3	Terrestrial botanical macrofossils (strongly clayey peat)	Fig. 7 (13)
14217	5820 ± 70	*6535-6719*	174.348-439.194/+6.72	481-482	Opheusden 5	Terrestrial botanical macrofossils (humic clay to strongly clayey peat)	Fig. 7 (14)
14218	3131 ± 46	*3269-3287, 3325-3402*	174.482-433.588/+7.60	332-333	Deest 2	Terrestrial botanical macrofossils (humic clay)	Fig. 7 (6)
14219	4050 ± 60	*4427-4585, 4596-4612, 4767-4783*	174.482-433.588/+7.60	384-386	Deest 3	Terrestrial botanical macrofossils (strongly clayey peat)	Fig. 7 (7)
14220	3033 ± 45	*3166-3182, 3207-3335*	174.060-422.695/+5.96	205-207	Ravenstein	Terrestrial botanical macrofossils (humic clay)	Fig. 7 (1)
14271	5077 ± 41	*5752-5827, 5860-5899*	140.317-439.896/+0.64	240-242	Zoowijk 2B	Terrestrial botanical macrofossils (slightly clayey peat)	Fig. 9 (46)
14272	4099 ± 47	*4526-4645, 4675-4693, 4761-4801*	140.421-439.111/+0.88	204-207	Zoowijk 1A	Terrestrial botanical macrofossils (humic clay)	Fig. 9 (37)
14273	4383 ± 50	*4866-4979, 5008-5036*	140.421-439.111/+0.88	334-336	Zoowijk 1C	Terrestrial botanical macrofossils (slightly clayey peat)	Fig. 9 (39)
14274	7120 ± 90	*7844-8019*	140.421-439.111/+0.88	640-642	Zoowijk 1E	Terrestrial botanical macrofossils (humic clay to strongly clayey peat)	Fig. 9 (41)
14275	4047 ± 47	*4436-4578, 4771-4779*	141.807-438.329/+0.34	194-196	Lange Avontuur II	Terrestrial botanical macrofossils (peat)	Fig. 9 (33)
14276	5022 ± 50	*5663-5674, 5680-5690, 5709-5761, 5810-5887*	141.807-438.329/+0.34	305-306	Lange Avontuur III	Terrestrial botanical macrofossils (peat)	Fig. 9 (34)
14277	5830 ± 60	*6561-6726*	143.792-437.415/+0.53	307-308	Zeedijk IV	Terrestrial botanical macrofossils (slightly clayey peat)	Fig. 9 (29)
14278	6010 ± 60	*6785-6935*	143.792-437.415/+0.53	451-452	Zeedijk V	Terrestrial botanical macrofossils (humic clay; 'gyttja')	Fig. 9 (30)
14279	5340 ± 50	*6007-6082, 6102-6159, 6171-6205*	144.750-430.729/+1.18	341-342	Voetakkers IV	Terrestrial botanical macrofossils (slightly clayey peat)	Fig. 9 (14)
14280	5540 ± 60	*6291-6355, 6362-6398*	144.750-430.729/+1.18	450-451	Voetakkers V	Terrestrial botanical macrofossils (humic clay)	Fig. 9 (15)
14281	6100 ± 50	*6890-7020, 7122-7152*	144.750-430.729/+1.18	523-524	Voetakkers VI	Terrestrial botanical macrofossils (humic clay)	Fig. 9 (16)
14282	3057 ± 45	*3219-3230, 3239-3342*	145.071-428.877/+1.66	210-211	Waardenburg I	Terrestrial botanical macrofossils (slightly clayey peat)	Fig. 9 (9)
14283	4790 ± 60	*5469-5595*	145.071-428.877/+1.66	262-263	Waardenburg II	Terrestrial botanical macrofossils (strongly clayey peat)	Fig. 9 (10)
14284	5270 ± 50	*5945-5969, 5986-6028, 6043-6069, 6076-6118, 6150-6177*	144.941-427.649/+2.25	453-455	Regterweide I	Terrestrial botanical macrofossils (strongly clayey peat)	Fig. 9 (6)
14285	5224 ± 49	*5916-6004, 6083-6100, 6160-6170*	144.941-427.649/+2.25	470-471	Regterweide II	Terrestrial botanical macrofossils (strongly clayey peat)	Fig. 9 (7)
14286	5820 ± 60	*6544-6693, 6702-6718*	144.941-427.649/+2.25	591-592	Regterweide III	Terrestrial botanical macrofossils (humic clay to strongly clayey peat)	Fig. 9 (8)
14287	3137 ± 43	*3365-3443*	145.033-420.190/+2.01	173-174	Hedel I	Terrestrial botanical macrofossils (slightly clayey peat)	Fig. 9 (3)

UtC nr[a]	^{14}C age ± 1σ (yr BP)	Calendar age[b] (*cal yr BP*)	Co-ordinates[c] (km)/ surface elevation (m ± O.D.)	Depth below surface (cm)	Sample name	Dated material and source material	Reference in this article
14288	4750 ± 50	*5334-5346, 5465-5584*	145.033-420.190/+2.01	324-325	Hedel II	Terrestrial botanical macrofossils (strongly clayey peat)	Fig. 9 (4)
14289	4860 ± 60	*5485-5514, 5523-5526, 5580-5657*	145.033-420.190/+2.01	475-476	Hedel III	Terrestrial botanical macrofossils (humic clay)	Fig. 9 (5)
14290	2189 ± 40	*2145-2184, 2192-2207, 2230-2307*	144.094-415.795/+3.20	171-172	Bokhoven III	Terrestrial botanical macrofossils (humic clay to strongly clayey peat)	Fig. 9 (1)
14291	4362 ± 47	*4860-4972*	183.698-438.770/+7.54	159-160	Driel	Terrestrial botanical macrofossils (slightly clayey peat)	Fig. 6 (1)
14343	4525 ± 47	*5060-5113, 5118-5186, 5215-5222, 5266-5302*	140.317-439.896/+0.64	145-146	Zoowijk 2A	Terrestrial botanical macrofossils (slightly clayey peat)	Fig. 9 (45)
14344	4350 ± 70	*4844-4979, 5009-5036*	140.421-439.111/+0.88	290-294	Zoowijk 1B	Terrestrial botanical macrofossils (slightly clayey peat)	Fig. 9 (38)
14345	4760 ± 80	*5331-5375, 5459-5588*	140.421-439.111/+0.88	438-440	Zoowijk 1D	Terrestrial botanical macrofossils (humic clay)	Fig. 9 (40)
14346	7810 ± 60	*8479-8494, 8515-8648, 8675-8684*	140.421-439.111/+0.88	658-660	Zoowijk 1F	Terrestrial botanical macrofossils (humic clay)	Fig. 9 (42)
14347	8110 ± 70	*8981-9139, 9175-9205, 9220-9242*	140.421-439.111/+0.88	722-727	Zoowijk 1G	Terrestrial botanical macrofossils (humic clay; palaeo-A-horizon)	Fig. 9 (43)
14348	8310 ± 90	*9140-9175, 9205-9220, 9241-9443*	140.421-439.111/+0.88	743-753	Zoowijk 1H	Terrestrial botanical macrofossils (humic clay; palaeo-A-horizon)	Fig. 9 (44)
14349	2584 ± 46	*2545-2560, 2616-2635, 2702-2763*	141.807-438.329/+0.34	100-101	Lange Avontuur I	Terrestrial botanical macrofossils (strongly clayey peat)	Fig. 9 (32)
14350	6980 ± 50	*7750-7862, 7902-7921*	141.807-438.329/+0.34	514-516	Lange Avontuur V	Terrestrial botanical macrofossils (peat)	Fig. 9 (35)
14351	4240 ± 60	*4647-4673, 4697-4760, 4805-4865*	143.792-437.415/+0.53	77-79	Zeedijk I	Terrestrial botanical macrofossils (strongly clayey peat to slightly clayey peat)	Fig. 9 (26)
14352	5210 ± 60	5906-6011, 6082-6104, 6158-6172	143.792-437.415/+0.53	195-196	Zeedijk II	Terrestrial botanical macrofossils (strongly clayey peat)	Fig. 9 (27)
14353	5220 ± 90	*5906-6030, 6039-6119, 6149-6177*	143.792-437.415/+0.53	260-262	Zeedijk III	Terrestrial botanical macrofossils (slightly clayey peat)	Fig. 9 (28)
14354	7620 ± 70	*8369-8479, 8495-8515*	143.792-437.415/+0.53	562-563	Zeedijk VI	Terrestrial botanical macrofossils (slightly clayey peat)	Fig. 9 (31)
14355	3100 ± 50	*3262-3378*	144.750-430.729/+1.18	120-122	Voetakkers I	Terrestrial botanical macrofossils (slightly clayey peat)	Fig. 9 (12)
14356	3230 ± 70	*3380-3487, 3499-3507, 3522-3555*	144.750-430.729/+1.18	183-185	Voetakkers VIII	Terrestrial botanical macrofossils (peat)	Fig. 9 (13)
14357	5710 ± 70	*6410-6565, 6590-6601*	145.071-428.877/+1.66	532-533	Waardenburg III	Terrestrial botanical macrofossils (humic clay)	Fig. 9 (11)
14358	3170 ± 70	*3274-3280, 3334-3470*	144.094-415.795/+3.20	204-209	Bokhoven IV	Terrestrial botanical macrofossils (strongly clayey peat)	Fig. 9 (2)

a laboratory number R.J. van de Graaff laboratory, Utrecht University

b ^{14}C dates calibrated using OxCal 3.10 software (Bronk Ramsey, 1995; 2001), 1σ intervals

c in Dutch co-ordinate grid (Rijksdriehoekstelsel)

Results

Description of cross sections

The main characteristics of the fluvial stratigraphy depicted in the cross sections are described below (Fig. 1). The key to the cross sections is shown in Fig. 5. Nomenclature of the Holocene channel belts is according to Berendsen & Stouthamer (2001), unless stated otherwise. For details of ^{14}C dates established by other studies, we refer to Törnqvist (1993a), Berendsen & Stouthamer (2001), Cohen (2003) and the website of Rhine-Meuse delta studies at Utrecht University (*www.geo.uu.nl/fg/palaeogeography/*).

Cross section Nijmegen - Driel (A-A')

Cross section A-A' (Fig. 6) is 15.5 km long and is based on 152 boreholes. It crosses several Rhine distributaries and their associated deposits. A Weichselian fluvial terrace remnant underlies the Boxtel Formation and bounds the Holocene deposits on the south edge of the section. The ice-pushed ridge of Arnhem forms the northern edge of the cross section. North of the Waal, deposits of the Kreftenheye Formation occur at approximately 5 m +O.D. (= Dutch Ordnance Datum) and underlie the Holocene succession. In a boring at km 12.7, we found pumice within the deposits of the Kreftenheye Formation. The pumice originates from the Laacher See eruption, Germany, and is dated at 11,063 ± 12 ^{14}C yr BP (Friedrich et al., 1999). The deposits of the Kreftenheye Formation, in which the pumice was found, must therefore be younger. This is confirmed by a series of OSL-dates at km 9.6, which yielded ages ranging from 10.41 ± 0.56 kyr (NCL-4505088) to 11.73 ± 0.83 kyr (NCL-4505090). The Pleniglacial terrace seems to be absent in the cross section.

The Holocene channel-belt deposits (Echteld Formation) are concentrated in three complexes: near the river Waal, in the area between km 5.2 and 9.7, and near the river Nederrijn. The Waal channel belt is connected to the channel belt of an

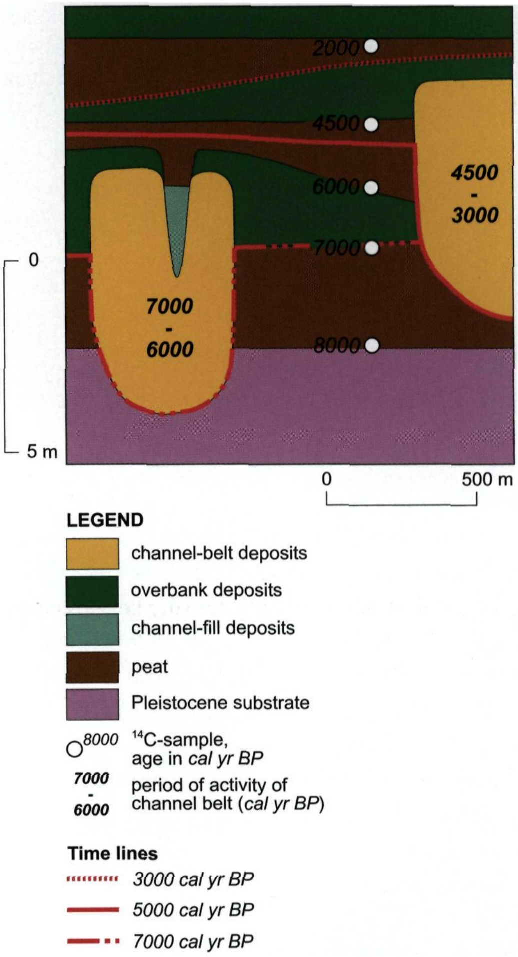

Fig. 4. Construction of time lines is mainly based on (1) stratigraphic relationships of overbank deposits and the associated channel belts and (2) ^{14}C dating of flood basin deposits.

Table 3. OSL ages in cross section A-A' (Fig. 6).

Sample number[a]	NCL nr[b]	Co-ordinates[c] (km)/ surface elevation (m ± O.D.)	Depth below surface (m)	Dose rate (Gy/kyr)	Equivalent dose (Gy)	OSL-age[d] ± 1σ (kyr)
I	4605091	187.634-436.647/+8.87	6.78	1.89 ± 0.07	5.2 ± 0.2	2.77 ± 0.15
II	4605092	187.634-436.647/+8.87	7.68	1.87 ± 0.07	6.0 ± 0.3	3.21 ± 0.19
III	4605093	187.634-436.647/+8.87	8.58	1.64 ± 0.06	4.4 ± 0.1	2.69 ± 0.13
IV	4605094	187.634-436.647/+8.87	10.55	1.30 ± 0.05	3.9 ± 0.1	2.96 ± 0.15
V	4505087	184.600-437.138/+8.74	3.47	1.73 ± 0.06	18.9 ± 0.8	10.89 ± 0.60
VI	4505088	184.600-437.138/+8.74	5.49	1.65 ± 0.06	17.1 ± 0.6	10.41 ± 0.56
VII	4505089	184.600-437.138/+8.74	6.39	1.60 ± 0.06	18.2 ± 0.7	11.34 ± 0.61
VIII	4505090	184.600-437.138/+8.74	7.70	1.08 ± 0.05	12.7 ± 0.7	11.73 ± 0.83

a In Fig. 6

b Laboratory number Netherlands Centre for Luminescence Dating (NCL), Delft University of Technology

c In Dutch co-ordinate grid (*Rijksdriehoekstelsel*)

d Groundwater and geological burial history are incorporated in calculations

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older Rhine distributary. The top of the channel-belt complex between km 5.2 and 9.7 is present at 7 - 8 m +O.D. This complex comprises at least four phases of channel-belt development (Weerts, 1996, p. 144; Berendsen & Stouthamer, 2001, p. 231). Four OSL-dates in the northern and youngest part of the channel-belt complex indicate that Holocene channel-belt deposits occur up to 10.5 m below the surface. The modern Nederrijn seems to be incised into an older channel belt, whose deposits are located below 6.5 m +O.D.

Between km 9.6 and 13.8, a 3 m thick succession of clastic flood basin deposits (Echteld Formation) is underlain by a basal peat layer (Nieuwkoop Formation). The base of this peat layer was dated at its contact with the Kreftenheye Formation, yielding an age of 4362 ± 47 ^{14}C yr BP (UtC-14291) / *4875 cal yr BP*. We believe that regional Holocene aggradation in the area began somewhat earlier, because the sample is located above a slightly elevated part of the Pleistocene substrate. Furthermore, a date of basal peat should actually be considered as a minimum age for the beginning of net Holocene aggradation. A palaeo-A-horizon at 7 m +O.D. can be traced throughout the entire flood basin; the small elevation differences are attributed to differential compaction. This palaeo-A-horizon predates the Nederrijn and Waal channel belts as it is overlain by natural levee deposits of the Waal and Nederrijn. In the flood basin north of the Waal, the basal peat is absent and two additional palaeo-A-horizons are encountered.

Cross section Ravenstein - Wageningen (B-B')

The 26 km long cross section B-B' (Fig. 7) runs from the village of Ravenstein in the south to Wageningen in the north (Fig. 1) and incorporates 292 boreholes. Weichselian eolian deposits (Boxtel Formation, Wierden Member) form the southern and northern rim of the cross section. The Kreftenheye Formation is present at two distinct levels. The highest level ranges from 3 to 5 m +O.D and is covered by an eolian dune complex (Boxtel Formation, Delwijnen Member) of Younger Dryas age (km 8.7 - 11.7). We therefore interpreted this level of the Kreftenheye Formation as being a Pleniglacial terrace remnant, following the model of Berendsen et al. (1995). The lowest level of the Kreftenheye Formation (e.g. between km 17.5 and 21; at 1 - 3 m +O.D.) is mainly formed during the Younger Dryas.

The Holocene channel-belt deposits of the Rhine are present in two wide channel-belt complexes, located near the rivers Waal and Nederrijn. The channel belt of the modern Maas and some older Maas distributaries occur south of the large eolian dune complex. The channel-belt complex near the Waal (km 14.7 - 17.5) seems to consist of four separate channel belts that occur at 3.8 m +O.D., 5 m +O.D., 6 m +O.D. and 7.3 m +O.D. Just north of the Nederrijn, the cross section reveals at least two channel-belt levels (at 4.5 m +O.D. and 5.5 m +O.D.) besides the channel belt of the modern river. Several narrow channel belts are present in the flood basins bounding these

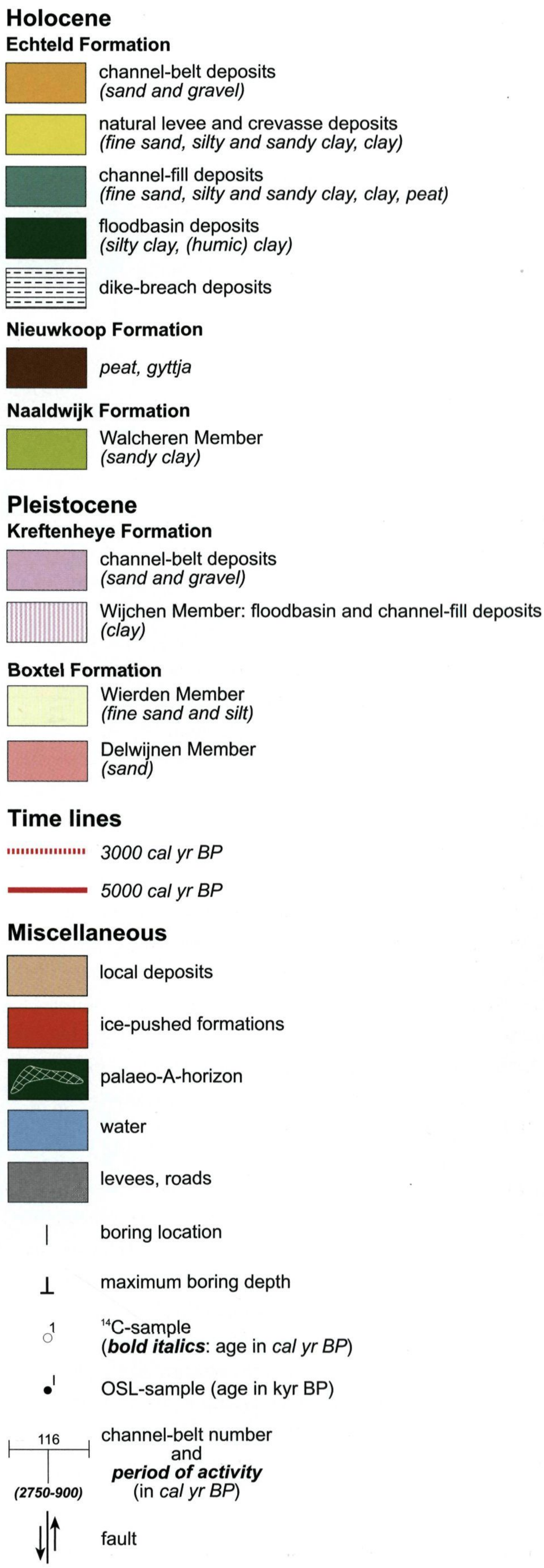

Fig. 5. Key to the cross sections (Figs. 6 - 10). Channel-belt numbers are cf. Berendsen & Stouthamer (2001).

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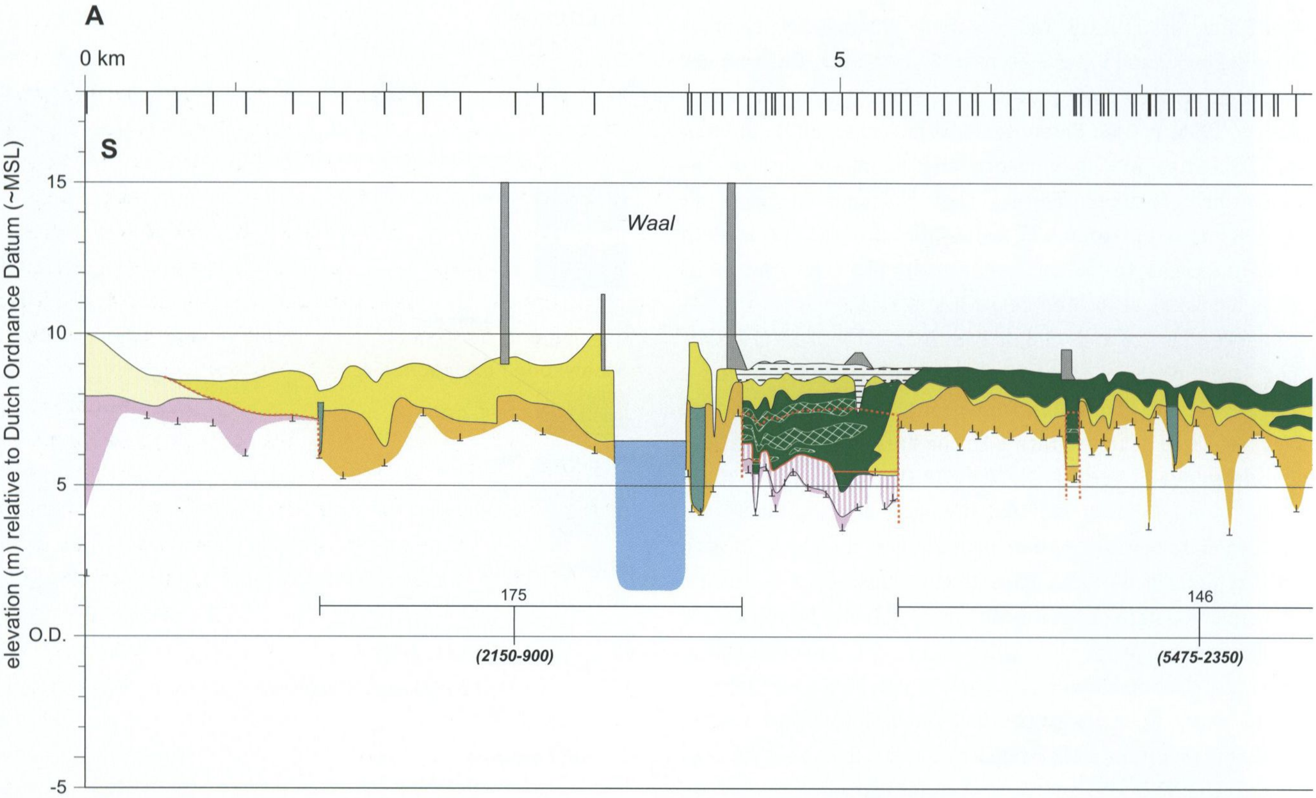


Fig. 6. Cross section A-A' (Nijmegen - Driel). Note that the OSL-ages are in kyr BP. For legend, see Fig. 5.

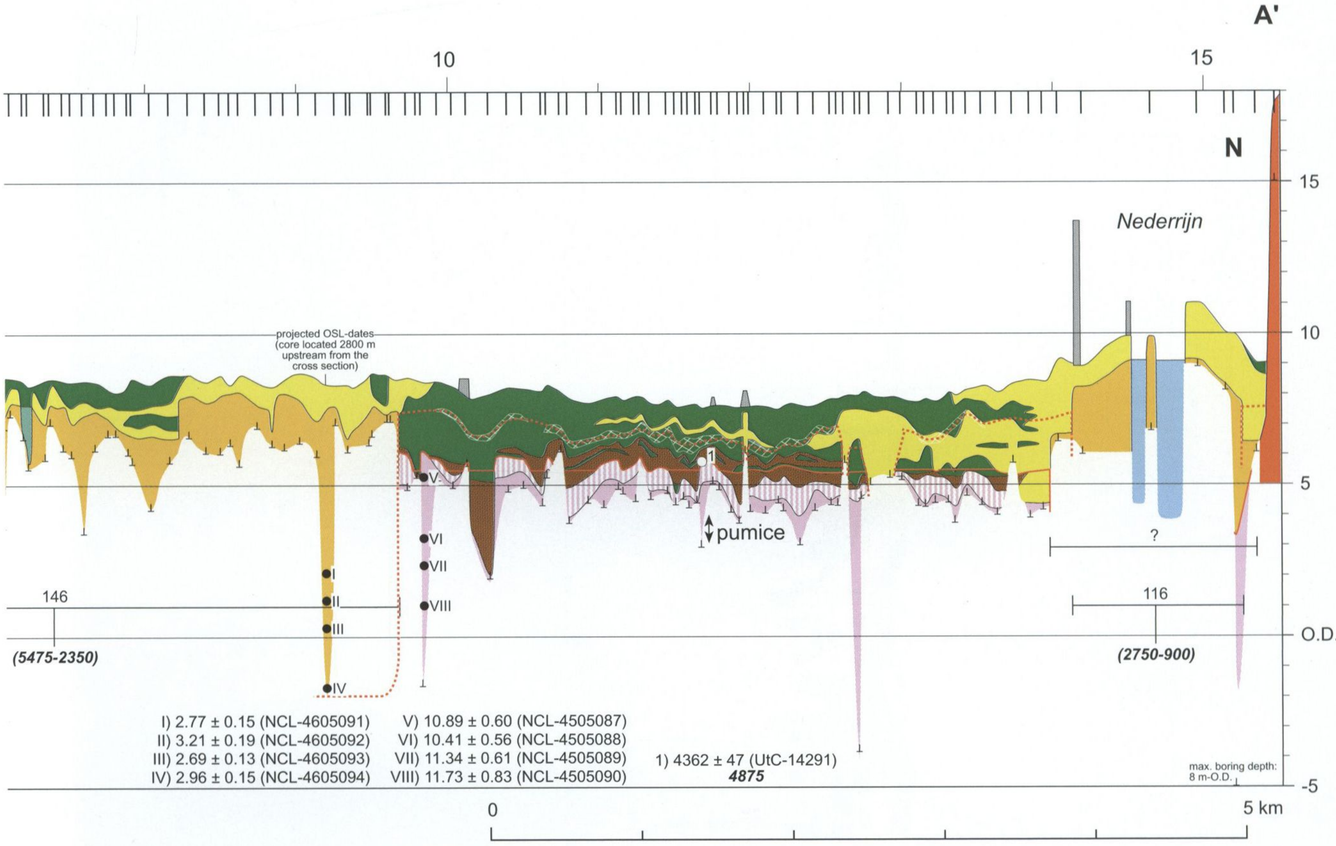
channel-belt complexes. Some Holocene channel belts occur at a lower level than the Weichselian fluvial terraces, e.g. between km 6 - 6.8 (just north of the Maas) and in the flood basin between the Waal and Nederrijn rivers (km 18.5 and 19.5). These channel belts are interpreted to represent channel belts that formed before net Holocene aggradation took place in the area. Based on the dating result of a basal peat on top of a Younger Dryas terrace (km 20.6), these incised Holocene channel belts must have been active before 5820 ± 70 ^{14}C yr BP (UtC-14217) / *6650 cal yr BP*. Holocene aggradation on top of the Pleniglacial terrace started before 4050 ± 60 ^{14}C yr BP (UtC-14219) / *4450 cal yr BP*. This implies that it took at least ~1800 ^{14}C years of Holocene aggradation to overcome the 2 m difference in elevation between the two terrace levels.

Small channel belts and isolated crevasse-splay deposits encased in clayey flood basin deposits characterise the up to 6 m thick flood basin succession between the Waal and Nederrijn channel belts. Several palaeo-A-horizons occur within the succession and organic layers are present south of the Nederrijn. The flood basins surrounding the Maas and Waal channel belts are composed of clays that encase channel-belt, natural levee, and crevasse-splay deposits.

Cross section Oss - Rhenen (C-C')

A total of 286 boreholes was used to construct cross section C-C' (25.5 km; Fig. 8), which is based on a cross section initially developed by Cohen (2003). An ice-pushed ridge near the village of Rhenen bounds the cross section in the north. Deposits of the Boxtel Formation (Wierden Member) underlie the Holocene deposits at the southern end of the cross section. The top of the Kreftenheye Formation generally occurs between 0 and 1 m +O.D. in the entire cross section. The presence of Younger Dryas eolian dunes on top of these Kreftenheye Formation deposits points to a Middle Weichselian (Pleniglacial) age of this level. The Younger Dryas terrace seems to be absent in the cross section: it is most-likely eroded by Early-Holocene channel belts (see below). South of the Maas, two levels of Kreftenheye Formation deposits are recognized: at 2 m +O.D. (km 2.7 - 5.8) and 3 m +O.D. (km 0.5 - 2.7). The latter is considered to be a fluvial terrace remnant of pre-Weichselian age (Cohen, 2003).

The architecture of the Holocene succession in cross section C-C' resembles cross section B-B'. Two complexes of channel-belt deposits are present near the rivers Waal and Nederrijn (nomenclature and age of the channel belts are cf. Cohen, 2003). The complex of channel-belt deposits near the river Waal consists of at least three channel belts at 3 m +O.D., 5 m +O.D., and 6 m +O.D., respectively. According to Cohen (2003), six stacked channel belts form the second complex located near the Nederrijn. Apart from these two channel-belt complexes, the cross section shows several single, mainly narrow, channel belts at varying stratigraphic levels, including below the level of the top of the Kreftenheye Formation deposits (e.g. channel belts HM-1 and HM-2 between km 8.7 and 10.1). Thus, the



incised Early-Holocene channel belts are encountered in this cross section, too.

The flood basin south of the river Maas contains a former Maas distributary (km 3.2 - 3.9) encased in clastic flood basin deposits. Some crevasse channels dissected the Pleistocene subsurface. Two palaeo-A-horizons (at 3 and 4 m +O.D.) can be traced in the flood basin between the Nederrijn and Waal rivers. Below the lower palaeo-A-horizon, two ~0.5 m thick peat layers are present. Relatively thick, laterally extensive natural levee and crevasse-splay deposits characterise the flood basin succession south of the Nederrijn. These natural levee and crevasse-splay deposits are related to the complex of stacked channel belts around the Nederrijn. Large-scale Holocene aggradation in the flood basins started approximately 6000 ^{14}C yr BP / *6800 cal yr BP* (see UtC-1235 and GrN-1196), although earlier aggradation occurred in down-thrown areas along the Peel Boundary Fault zone (Fig. 8).

Cross section Den Bosch - Zeist (D-D')

Cross section D-D' (Fig. 9) is 44.4 km long, significantly longer than the three cross sections described above. It is located downstream from where the Rhine-Meuse delta widens (Fig. 1). The cross section incorporates 547 borings. At the southern end of the cross section (south of km 5.8), a 0.5 m thick Holocene clay layer overlies deposits of the Boxtel Formation (Wierden Member). Between km 5.8 and 35.8, the Pleistocene subsurface consists of fluvial deposits (Kreftenheye Formation). Three levels can be recognised in the top of the Kreftenheye Formation: ~4 m -O.D. (south of km 24), ~5 m -O.D. (km 24 - 29), and ~7 m -O.D (km 31 - 35). The occurrence of an eolian dune on top of the 4 m -O.D. level suggests a Pleniglacial age for the deposits at this level. Deposits of the Boxtel Formation (Wierden Member) are exposed at the northern end of the cross section.

In contrast with the previously described cross sections, channel-belt deposits in cross section D-D' are more scattered throughout the Holocene succession. Most Holocene channel belts occur near the northern and southern fringes of the cross section. The southernmost channel belt in the cross section is associated with the present-day Maas. The beginning of Maas sedimentation has previously been dated at 1760 ± 50 ^{14}C yr BP (UtC-1604), but this is an indirect date from a residual channel cut through by the Maas (Weerts & Berendsen, 1995; Berendsen & Stouthamer, 2001). In our cross section, a new date directly at the base of Maas overbank deposits yielded an age of 2189 ± 40 ^{14}C yr BP (UtC-14290) / *2150 cal yr BP*. Because this ^{14}C age is a direct date, it probably is better associated to the onset of sedimentation of the Maas channel belt than the indirect date aforementioned. In the area between the Maas and Waal rivers, the proportion of channel-belt deposits is relatively high. The area between the Waal and Linge is characterised by several narrow channel belts encased in flood basin deposits, as is the area between the Lek and Linge channel belts. The majority of the up to 300 m wide channel belts occurs below 2 m -O.D. Directly south of the Lek (km 29 - 31), the deposits of at least four stacked channel belts can be

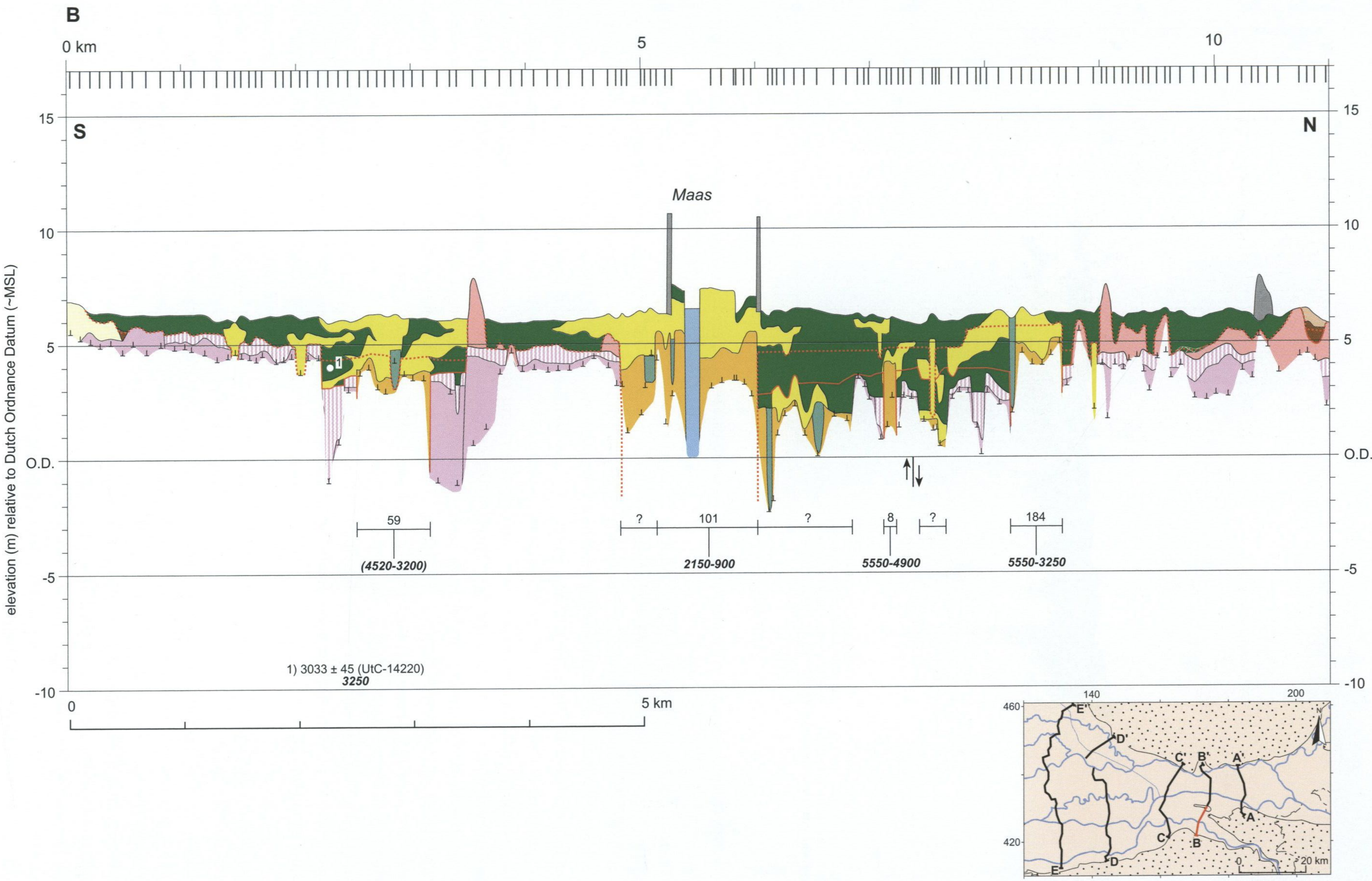


Fig. 7. Cross section B-B' (Ravenstein - Wageningen), part 1. For legend, see Fig. 5.

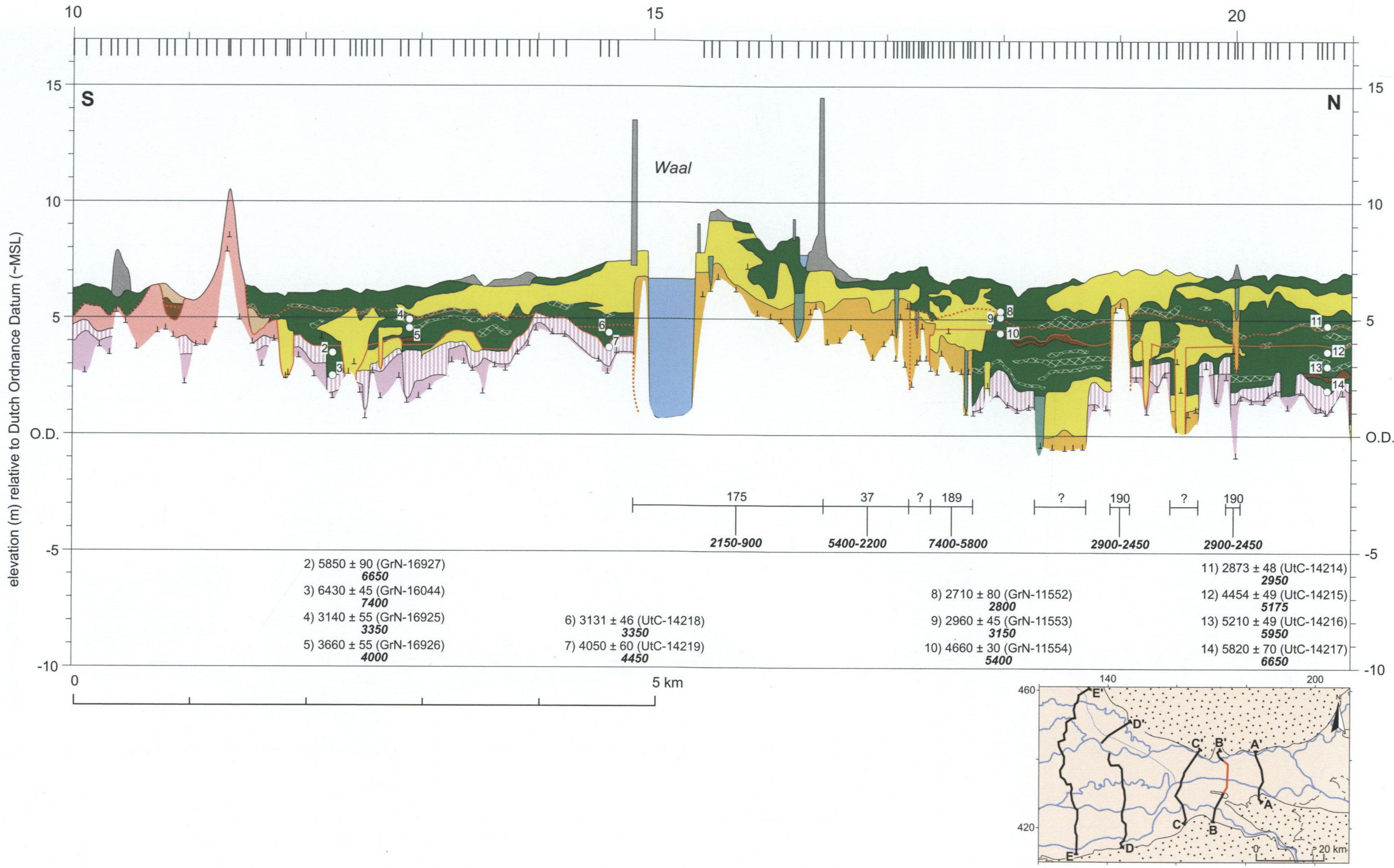

10
15
20
S
N
Waal
elevation (m) relative to Dutch Ordnance Datum (~MSL)
O.D.
-5
-10
175
37
?
189
190
2150-900
5400-2200
7400-5800
2900-2450
2) 5850 ± 90 (GrN-16927)
6650
3) 6430 ± 45 (GrN-16044)
7400
4) 3140 ± 55 (GrN-16925)
3350
5) 3660 ± 55 (GrN-16926)
4000
6) 3131 ± 46 (UtC-14218)
3350
7) 4050 ± 60 (UtC-14219)
4450
8) 2710 ± 80 (GrN-11552)
2800
9) 2960 ± 45 (GrN-11553)
3150
10) 4660 ± 30 (GrN-11554)
5400
11) 2873 ± 48 (UtC-14214)
2950
12) 4454 ± 49 (UtC-14215)
5175
13) 5210 ± 49 (UtC-14216)
5950
14) 5820 ± 70 (UtC-14217)
6650
0
5 km
140
200
460
420
A
A'
B
B'
C
C'
D
D'
E
E'
20 km

Fig. 7. Part 2.

recognised (at 5 m -O.D., 3 m -O.D., 1.5 m -O.D., and 0 m +O.D.). Several distributaries of the Utrecht river system (Berendsen, 1982) are encountered in the area north of the Lek channel belt.

The thickness of the Holocene deposits in the flood basins typically is ~6 m, and more than 9 m at a maximum. North of the Linge channel belt, a palaeo-A-horizon at 0 m +O.D. can be traced in the cross section. The proportion of organics is relatively high in the flood basin north of the Linge, especially between km 22.1 and 25. The basal peat in this flood basin was dated at 6980 ± 50 ^{14}C yr BP (UtC-14350) / *7800 cal yr BP*. The flood basin deposits between the Linge and the Waal are clastic dominated (clays), although several 0.5 m thick peat layers are encountered. The basal peat was dated at three locations resulting in ages of 6100 ± 50 ^{14}C yr BP (UtC-14281) / *6950 cal yr BP*, 5710 ± 50 ^{14}C yr BP (UtC-14357) / *6450 cal yr BP*, and 5820 ± 60 ^{14}C yr BP (UtC-14286) / *6650 cal yr BP*. These ages mark the onset of Holocene sedimentation on top of the Pleniglacial surface. Between km 14.7 and 16.5, a palaeo-A-horizon is present at 1 m -O.D. Its formation ended before 3057 ± 45 ^{14}C yr BP (UtC-14282) / *3300 cal yr BP*. The flood basin succession south of the river Waal mainly consists of natural levee and crevasse-splay deposits.

Cross section Waalwijk - Utrecht (E-E')

Cross section E-E' (Fig. 10) is a modified version of the transect of Törnqvist (1993a) north of the river Waal, which has been extended to the south. The cross section is 59 km long and incorporates 645 borings. North of km 41.8, the substrate consists of Weichselian eolian deposits (Boxtel Formation) that occur between 1 m -O.D. and 7 m -O.D. Between km 9.5 and 41.8, the Pleistocene substratum belongs to the Kreftenheye Formation, which is found at an elevation of 7 - 8 m -O.D. South of the Afgedamde Maas, the Pleistocene subsurface rises from 7 m -O.D. to 1 m -O.D. at the southern end of the cross section. Deposits of the Boxtel Formation (Wierden Member) form the top of the Pleistocene substrate south of km 5.8. South of the Bergsche Maas, a thin basal peat layer underlies Late-Holocene tidal deposits (Naaldwijk Formation, Walcheren Member).

The Holocene channel belts are scattered throughout the Holocene succession and only one complex of stacked channel belts is recognised near the Hollandsche IJssel. North of this channel-belt complex, a few channel belts are present, encased in an up to 5 m thick peaty flood basin succession. Several narrow channel belts are found in the area between the Waal

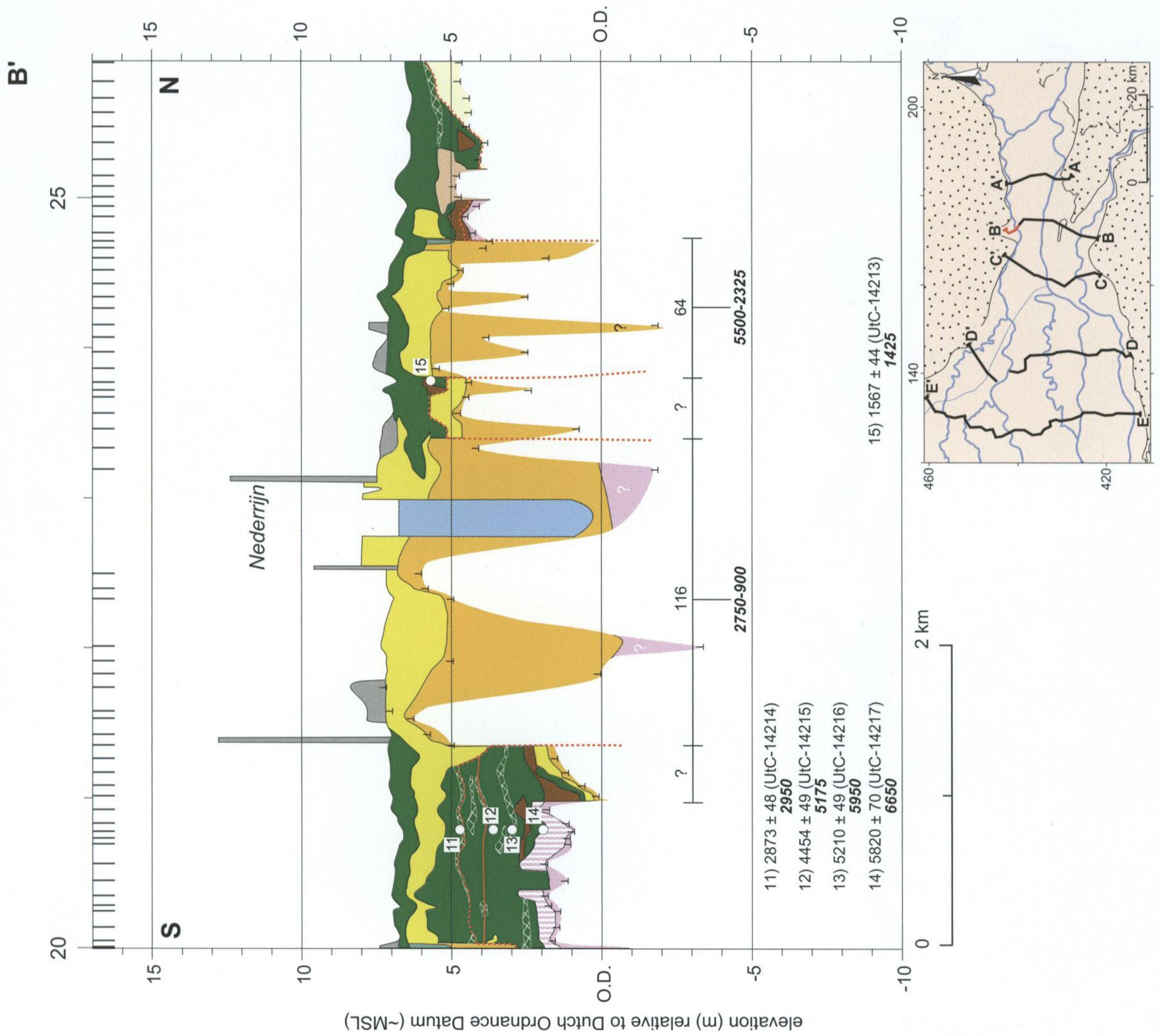


Fig. 7. Part 3.

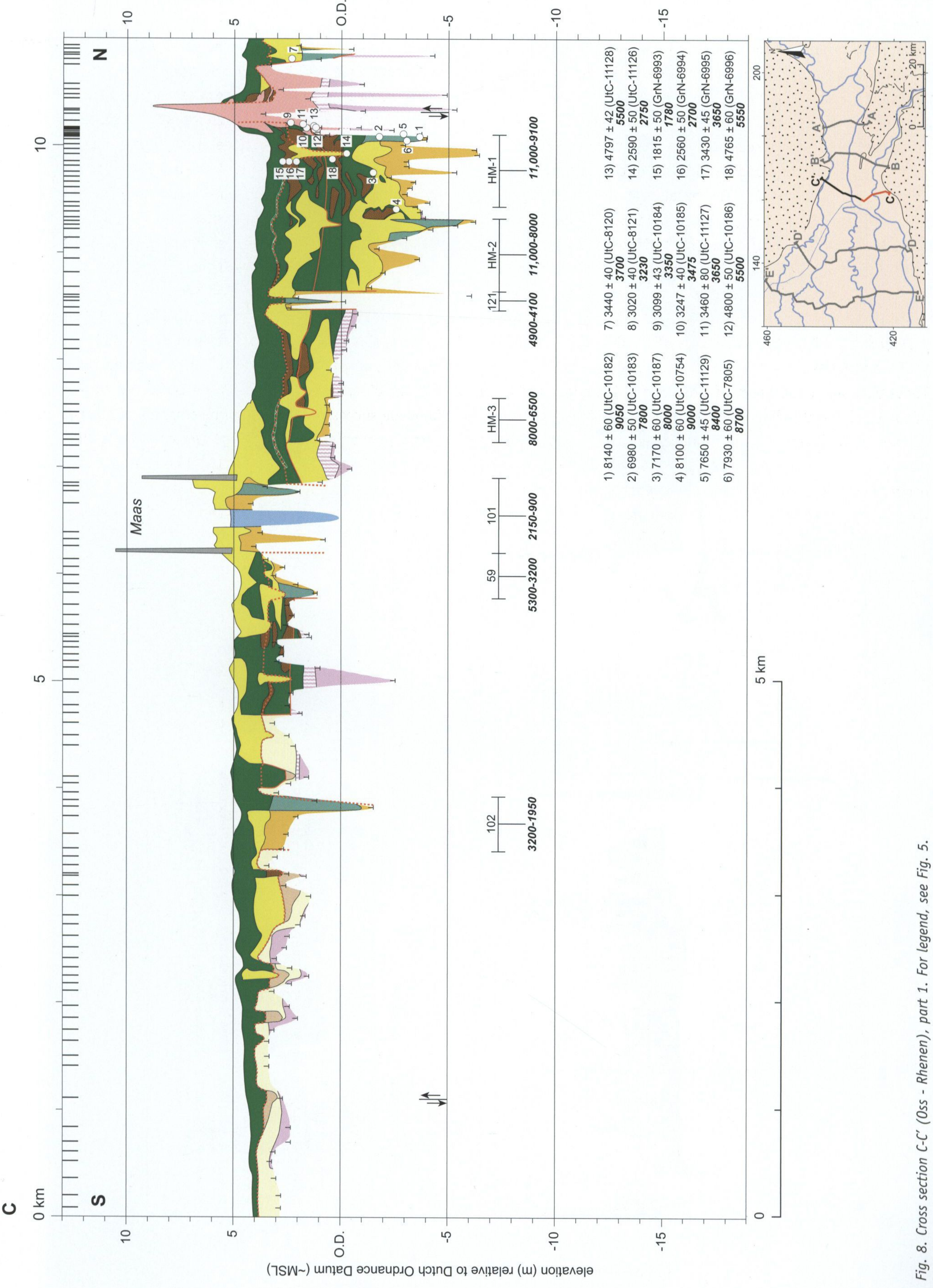


Fig. 8. Cross section C-C' (Oss - Rhenen), part 1. For legend, see Fig. 5.

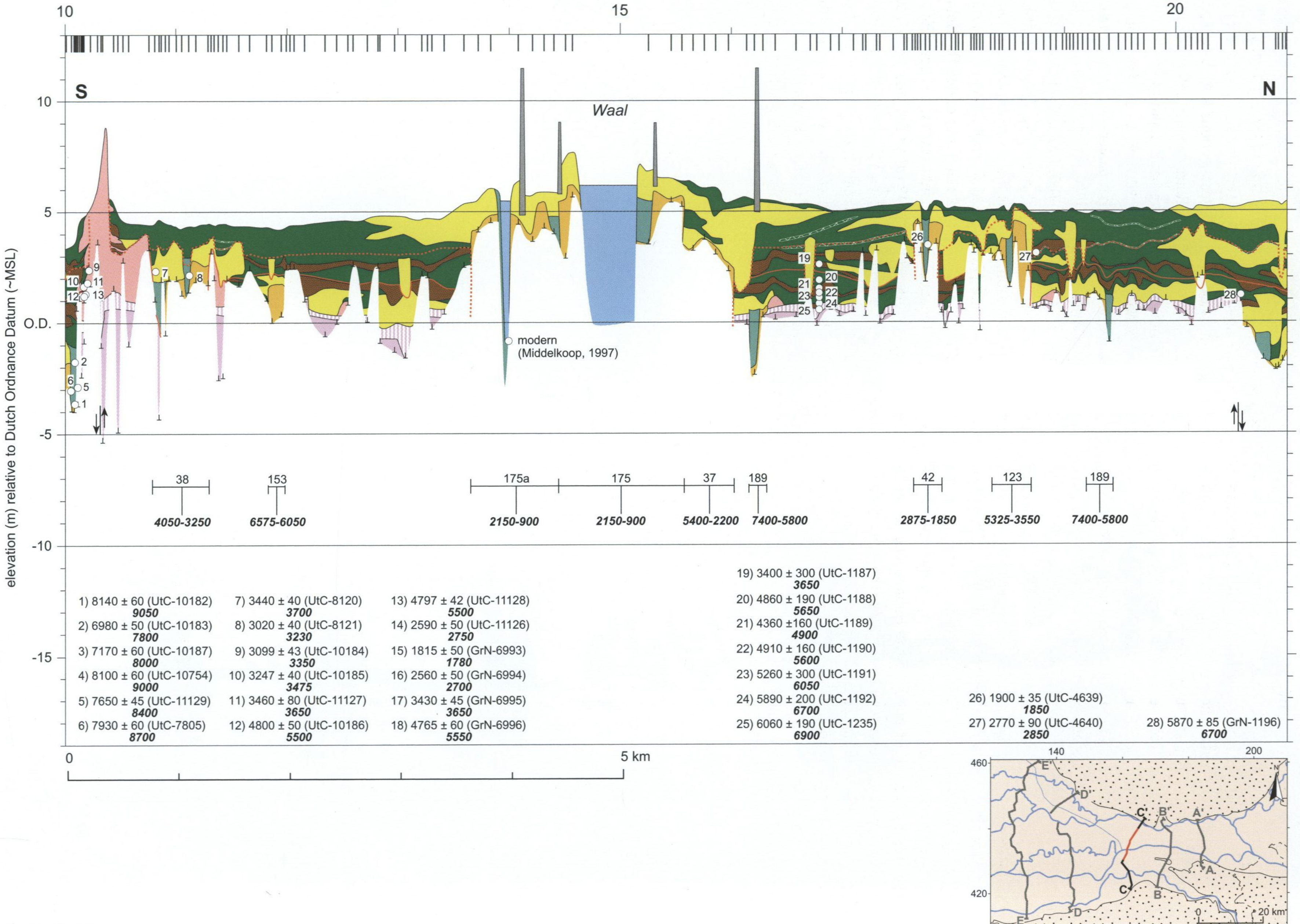

S
N
Waal
10
15
20
10
5
O.D.
-5
-10
-15
elevation (m) relative to Dutch Ordnance Datum (~MSL)
modern
(Middelkoop, 1997)
38
4050-3250
153
6575-6050
175a
2150-900
175
2150-900
37
5400-2200
189
7400-5800
42
2875-1850
123
5325-3550
189
7400-5800
1) 8140 ± 60 (UtC-10182)
9050
2) 6980 ± 50 (UtC-10183)
7800
3) 7170 ± 60 (UtC-10187)
8000
4) 8100 ± 60 (UtC-10754)
9000
5) 7650 ± 45 (UtC-11129)
8400
6) 7930 ± 60 (UtC-7805)
8700
7) 3440 ± 40 (UtC-8120)
3700
8) 3020 ± 40 (UtC-8121)
3230
9) 3099 ± 43 (UtC-10184)
3350
10) 3247 ± 40 (UtC-10185)
3475
11) 3460 ± 80 (UtC-11127)
3650
12) 4800 ± 50 (UtC-10186)
5500
13) 4797 ± 42 (UtC-11128)
5500
14) 2590 ± 50 (UtC-11126)
2750
15) 1815 ± 50 (GrN-6993)
1780
16) 2560 ± 50 (GrN-6994)
2700
17) 3430 ± 45 (GrN-6995)
3650
18) 4765 ± 60 (GrN-6996)
5550
19) 3400 ± 300 (UtC-1187)
3650
20) 4860 ± 190 (UtC-1188)
5650
21) 4360 ±160 (UtC-1189)
4900
22) 4910 ± 160 (UtC-1190)
5600
23) 5260 ± 300 (UtC-1191)
6050
24) 5890 ± 200 (UtC-1192)
6700
25) 6060 ± 190 (UtC-1235)
6900
26) 1900 ± 35 (UtC-4639)
1850
27) 2770 ± 90 (UtC-4640)
2850
28) 5870 ± 85 (GrN-1196)
6700
0
5 km
140
200
460
420
20 km

Fig. 8. Part 2.

and the Hollandsche IJssel. The Afgedamde Maas seems to be incised into two older channel belts. Between the Afgedamde Maas and the Bergsche Maas, five channel belts occur at levels between 3 m –O.D. and 0 m +O.D. The Bergsche Maas is an artificial channel, which was dug in 1904 AD (Berendsen & Stouthamer, 2001). Directly north of this canal, the channel-belt deposits of a Maas distributary are found. Clayey deposits intercalated with 0.5 m thick peat layers dominate the Holocene flood basin succession south of the Afgedamde Maas.

The Holocene deposits in the flood basins are 7 to 10 m thick. The flood basin succession can be subdivided in an organic dominated upper part (between 4 m –O.D. and 1 m –O.D.) and a clastic dominated lower part (below 4 m –O.D.). The base of the organic dominated part of the succession was dated at ~5400 ^{14}C yr BP / *~6200 cal yr BP* (see GrN-18925, UtC-1894, and UtC-1897). Between km 23 and 28.5, the entire Holocene succession is clastic-dominated. Well-traceable palaeo-A-horizons exclusively occur north of the Hollandsche IJssel. A basal peat layer is present in practically the entire cross section. This peat layer was dated at several locations (Fig. 10), resulting in ages ranging from 6680 ± 50 ^{14}C yr BP (GrN-18933) / *7525 cal yr BP* to 7350 ± 70 ^{14}C yr BP (GrN-18919) / *8175 cal yr BP* (Törnqvist, 1993a).

Time lines

The *3000* and *5000 cal yr BP* time lines are drawn in the cross sections (Figs 6 - 10). The elevation of the *5000 cal yr BP* time line is ~5.5 m+O.D. in cross section A-A' and decreases to ~4 m –O.D. in section E-E'. In cross sections A-A', B-B', and C-C', the *3000 cal yr BP* time line follows distinct palaeo-A-horizons that are present below the overbank deposits of the modern Nederrijn and Waal rivers. The *3000 cal yr BP* time line in the other cross sections follows either palaeo-A-horizons or organic layers. The elevation of the *3000 cal yr BP* time line ranges from ~7 m +O.D (A-A') to ~2 m –O.D. (E-E'). The vertical distance between the *3000* and *5000 cal yr BP* time lines increases in a downstream direction, which is due to a downstream increase in aggradation rate (Van Dijk et al., 1991; Cohen, 2005).

The *3000* and *5000 cal yr BP* time lines divide the Holocene succession in the cross sections into three time slices: Holocene *pre-5000 cal yr BP*, *5000 - 3000 cal yr BP*, and *post-3000 cal yr BP*. Each time slice comprises the fluvio-deltaic deposits that accumulated within that particular period. Two distinct architectural trends over time can be recognised within the Holocene succession: 1) the proportion of organics in the *5000 - 3000 cal yr BP* time slice of cross sections D-D' and E-E' is

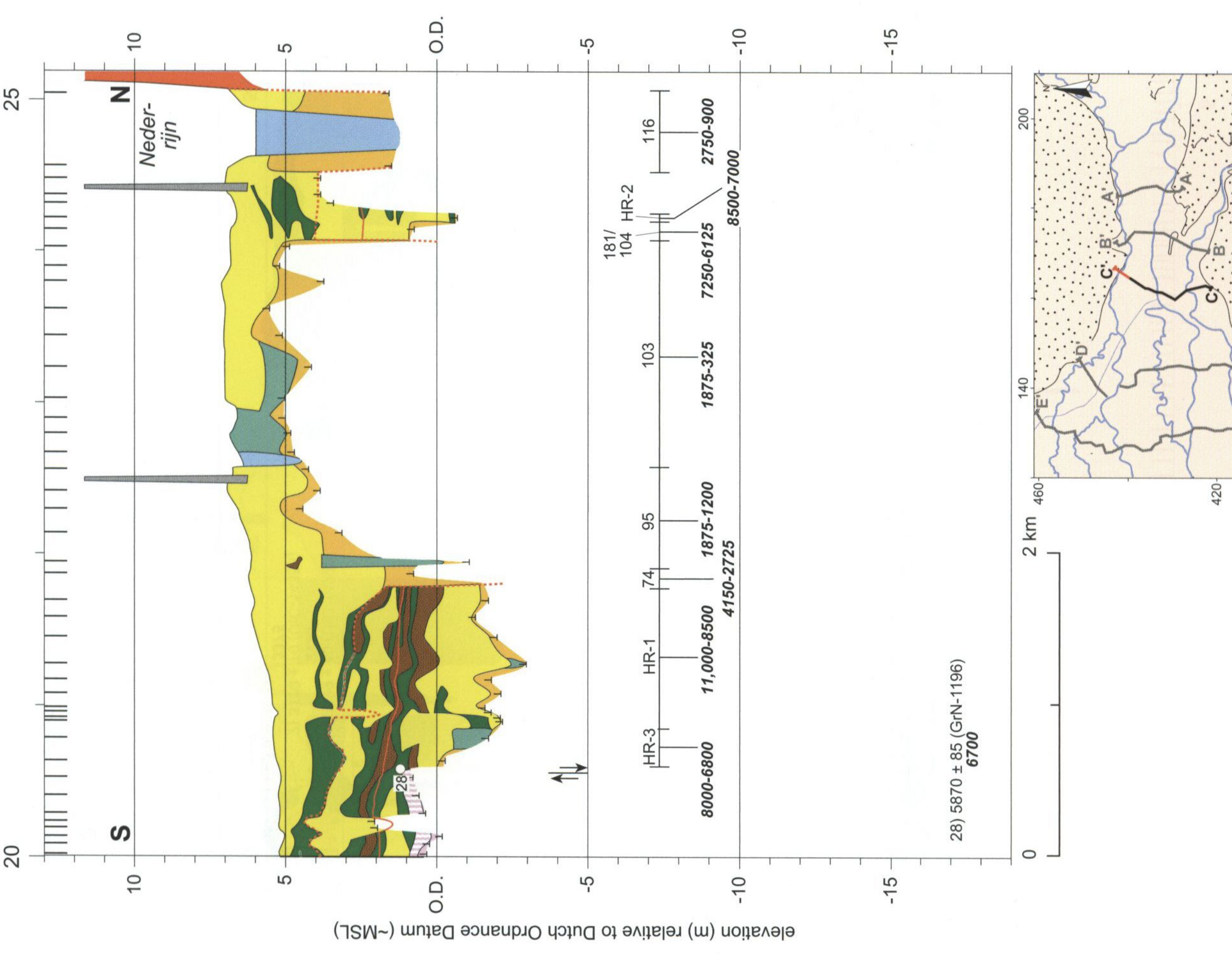


Fig. 8. Part 3.

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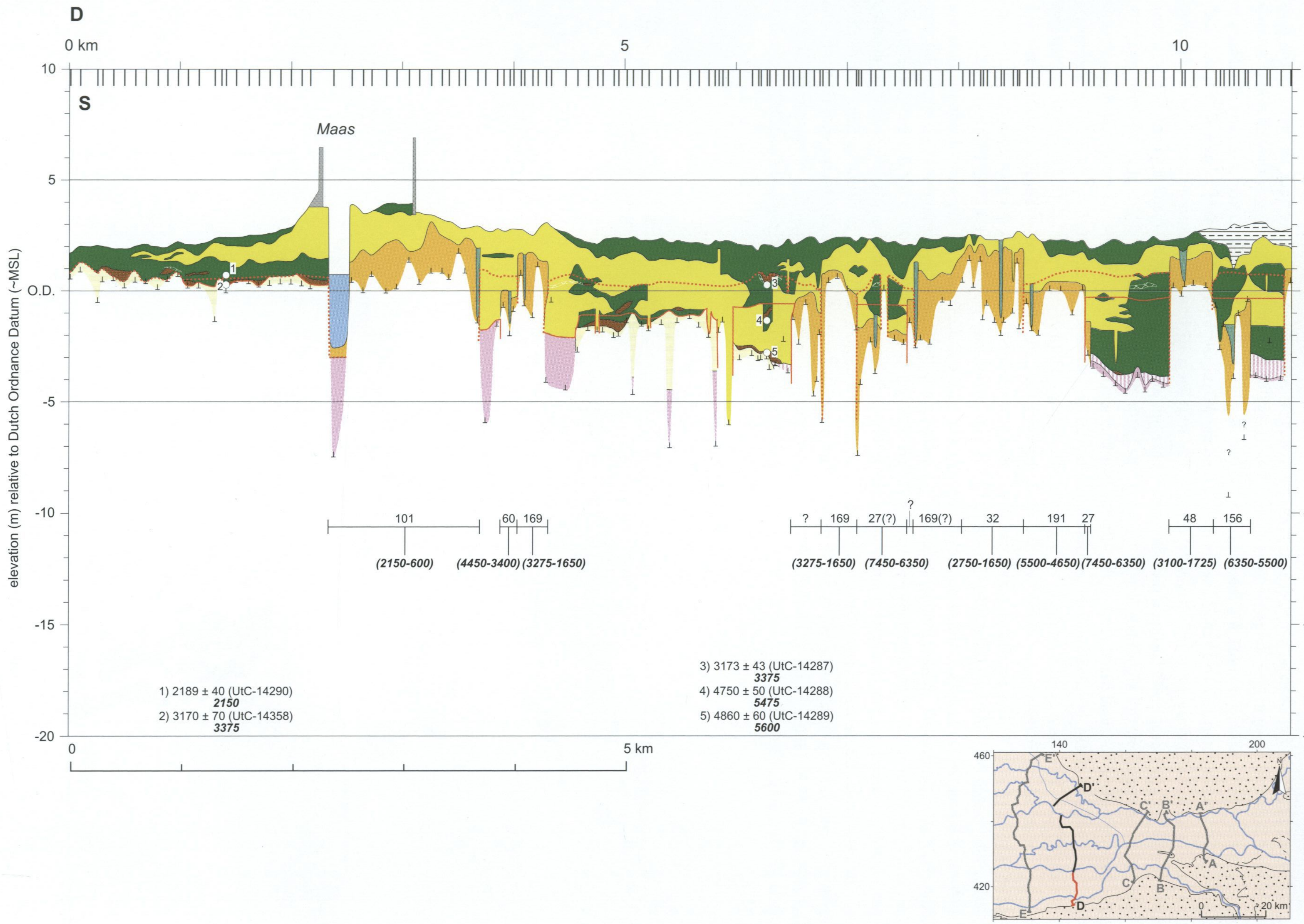

Fig. 9. Cross section D-D′ (Den Bosch - Zeist), part 1. The section north of the Lek is based on Berendsen (1982). For legend, see Fig. 5.

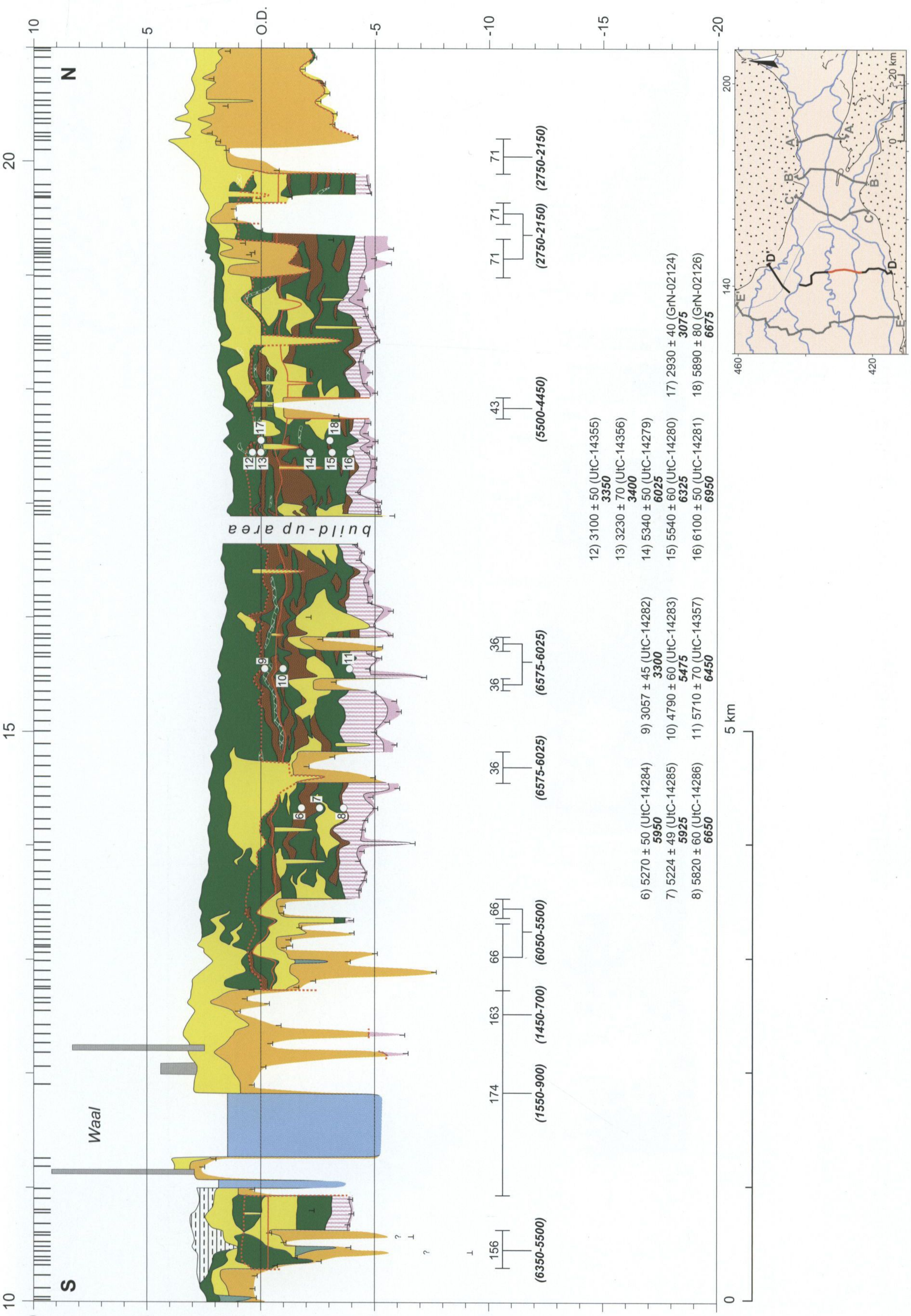
S
N
Waal
build-up area
elevation (m) relative to Dutch Ordnance Datum (~MSL)
10
5
O.D.
-5
-10
-15
-20
156
(6350-5500)
174
(1550-900)
163
(1450-700)
66
66
(6050-5500)
36
(6575-6025)
36
36
(6575-6025)
43
(5500-4450)
71
71
71
(2750-2150)
(2750-2150)
6) 5270 ± 50 (UtC-14284)
5950
7) 5224 ± 49 (UtC-14285)
5925
8) 5820 ± 60 (UtC-14286)
6650
9) 3057 ± 45 (UtC-14282)
3300
10) 4790 ± 60 (UtC-14283)
5475
11) 5710 ± 70 (UtC-14357)
6450
12) 3100 ± 50 (UtC-14355)
3350
13) 3230 ± 70 (UtC-14356)
3400
14) 5340 ± 50 (UtC-14279)
6025
15) 5540 ± 60 (UtC-14280)
6325
16) 6100 ± 50 (UtC-14281)
6950
17) 2930 ± 40 (GrN-02124)
3075
18) 5890 ± 80 (GrN-02126)
6675
0
5 km
10
15
20
140
200
460
420
20 km

Fig. 9. Part 2.

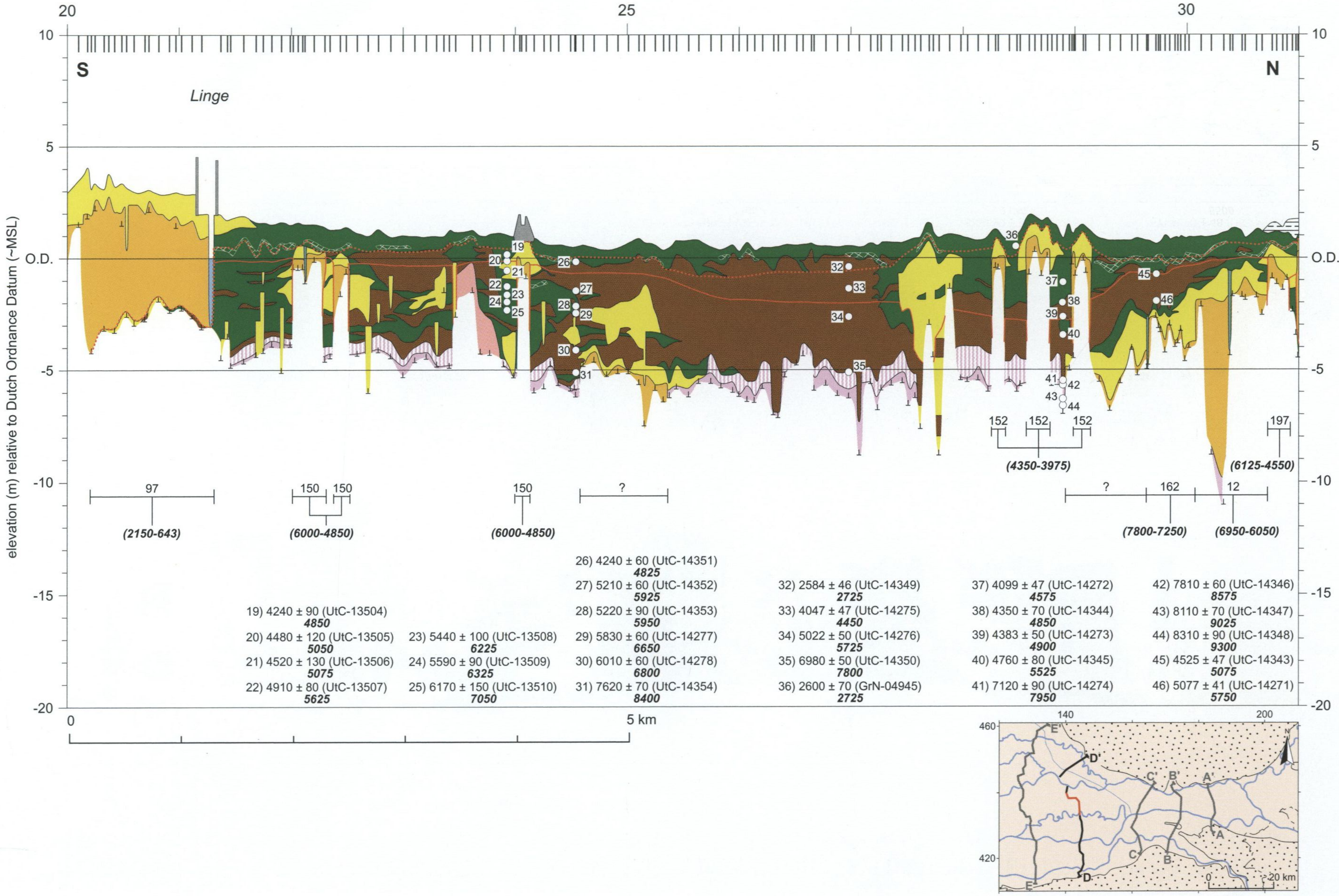
S
N
Linge
elevation (m) relative to Dutch Ordnance Datum (~MSL)
O.D.
97
(2150-643)
150
150
(6000-4850)
150
(6000-4850)
?
152
152
152
(4350-3975)
197
(6125-4550)
?
162
12
(7800-7250)
(6950-6050)
0
5 km
19) 4240 ± 90 (UtC-13504) 4850
20) 4480 ± 120 (UtC-13505) 5050
21) 4520 ± 130 (UtC-13506) 5075
22) 4910 ± 80 (UtC-13507) 5625
23) 5440 ± 100 (UtC-13508) 6225
24) 5590 ± 90 (UtC-13509) 6325
25) 6170 ± 150 (UtC-13510) 7050
26) 4240 ± 60 (UtC-14351) 4825
27) 5210 ± 60 (UtC-14352) 5925
28) 5220 ± 90 (UtC-14353) 5950
29) 5830 ± 60 (UtC-14277) 6650
30) 6010 ± 60 (UtC-14278) 6800
31) 7620 ± 70 (UtC-14354) 8400
32) 2584 ± 46 (UtC-14349) 2725
33) 4047 ± 47 (UtC-14275) 4450
34) 5022 ± 50 (UtC-14276) 5725
35) 6980 ± 50 (UtC-14350) 7800
36) 2600 ± 70 (GrN-04945) 2725
37) 4099 ± 47 (UtC-14272) 4575
38) 4350 ± 70 (UtC-14344) 4850
39) 4383 ± 50 (UtC-14273) 4900
40) 4760 ± 80 (UtC-14345) 5525
41) 7120 ± 90 (UtC-14274) 7950
42) 7810 ± 60 (UtC-14346) 8575
43) 8110 ± 70 (UtC-14347) 9025
44) 8310 ± 90 (UtC-14348) 9300
45) 4525 ± 47 (UtC-14343) 5075
46) 5077 ± 41 (UtC-14271) 5750
20 km

Fig. 9. Part 3.

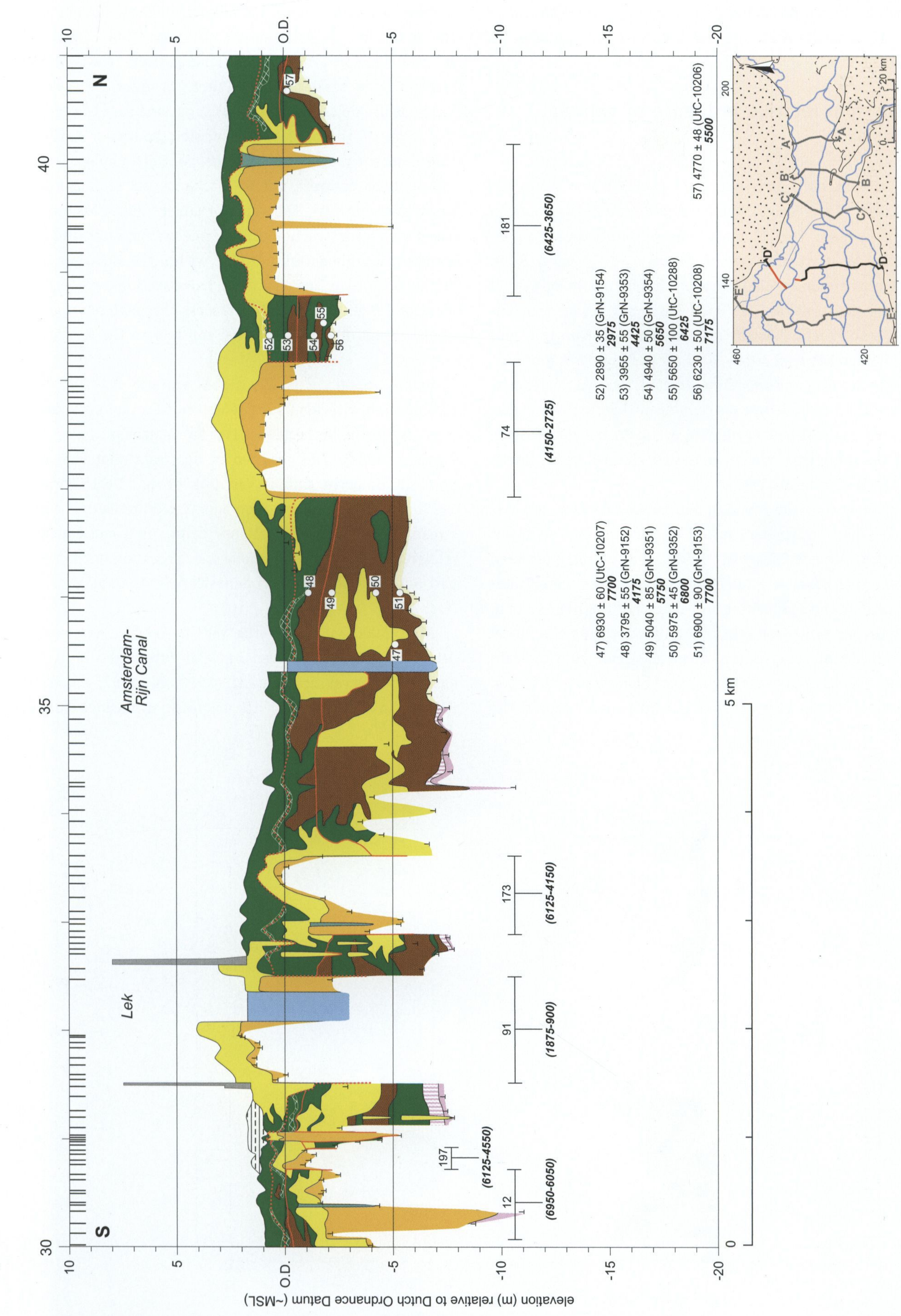

Fig. 9. Part 4.

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higher than in the preceding period; and 2) after *3000 cal yr BP*, clastic deposits dominate the Holocene succession in all cross sections.

Discussion: relative influence of external controls

The cross sections (Figs 6 - 10) show distinct changes in the architecture of the Rhine-Meuse fluvio-deltaic wedge, both in time and in space. The ^{14}C dates indicate that Holocene aggradation in the study area started between *~8000 cal yr BP* in the downstream and *~5000 cal yr BP* in the upstream part of the Rhine-Meuse delta. The flood basin succession thickens from ~3 m to ~7 m in a downstream direction. The organic beds mainly formed between *6000 - 3000 cal yr BP* and are abundant in the downstream cross sections. In contrast, clastic deposits dominate the fluvio-deltaic succession in the upstream delta. Here, wide channel-belt complexes occur. In the downstream part of the study area, numerous narrow channel belts characterise the Holocene succession.

All river systems are prone to downstream controls of base-level rise, and to upstream controls of discharge and sediment supply (e.g. Blum & Törnqvist, 2000). The interplay between these external controls, plus effects of tectonics, determines the behaviour and sedimentation patterns of the river system. The effects of downstream controls on the formation of a fluvial succession diminish up-valley, where upstream controls gain dominance (e.g. Bridge, 2003, p. 364; Cohen, 2005; Holbrook et al., 2006). In the case of rivers at continental margins, the present position of the aggradation-incision boundary (i.e. the updip limit of Holocene onlap) seems to be controlled by sediment supply and river discharge from the hinterland rather than by sea-level rise (Blum & Törnqvist, 2000). For the Rhine-Meuse delta, Cohen (2005) suggested that the upstream migration of the aggradation-incision boundary during the Late Holocene indeed was no longer controlled by sea-level rise (downstream control), but by discharge and sediment supply (upstream controls). The study of Cohen (2005) essentially is based on a reconstruction of Holocene groundwater rise. Below, we use the sedimentary patterns within the Holocene fluvio-deltaic wedge, as shown in our cross sections, to verify the ideas of Cohen (2005) and to discuss the relative importance of the several different external controls on the formation of the wedge.

Before *~5000 cal yr BP*, global eustatic sea-level rise in combination with land subsidence led to a rapid relative sea-level rise in the Netherlands (Fig. 2a; Jelgersma, 1979; Van de Plassche, 1982). This resulted in upstream migration of the point of Holocene onlap (Van Dijk et al., 1991; Törnqvist, 1993b; Cohen, 2005) and high aggradation rates in the downstream part of the Rhine-Meuse delta. As a consequence, a relatively large part of the Holocene succession in the western part of the delta consists of deposits older than *5000 cal yr BP* (Fig. 11).

After *5000 cal yr BP*, the rate of relative sea-level rise decreased as it was driven by land subsidence only. When eustatic sea-level rise ceased (*~5000 cal yr BP*; e.g. Peltier, 2002; Milne et al., 2004), the aggradation-incision boundary

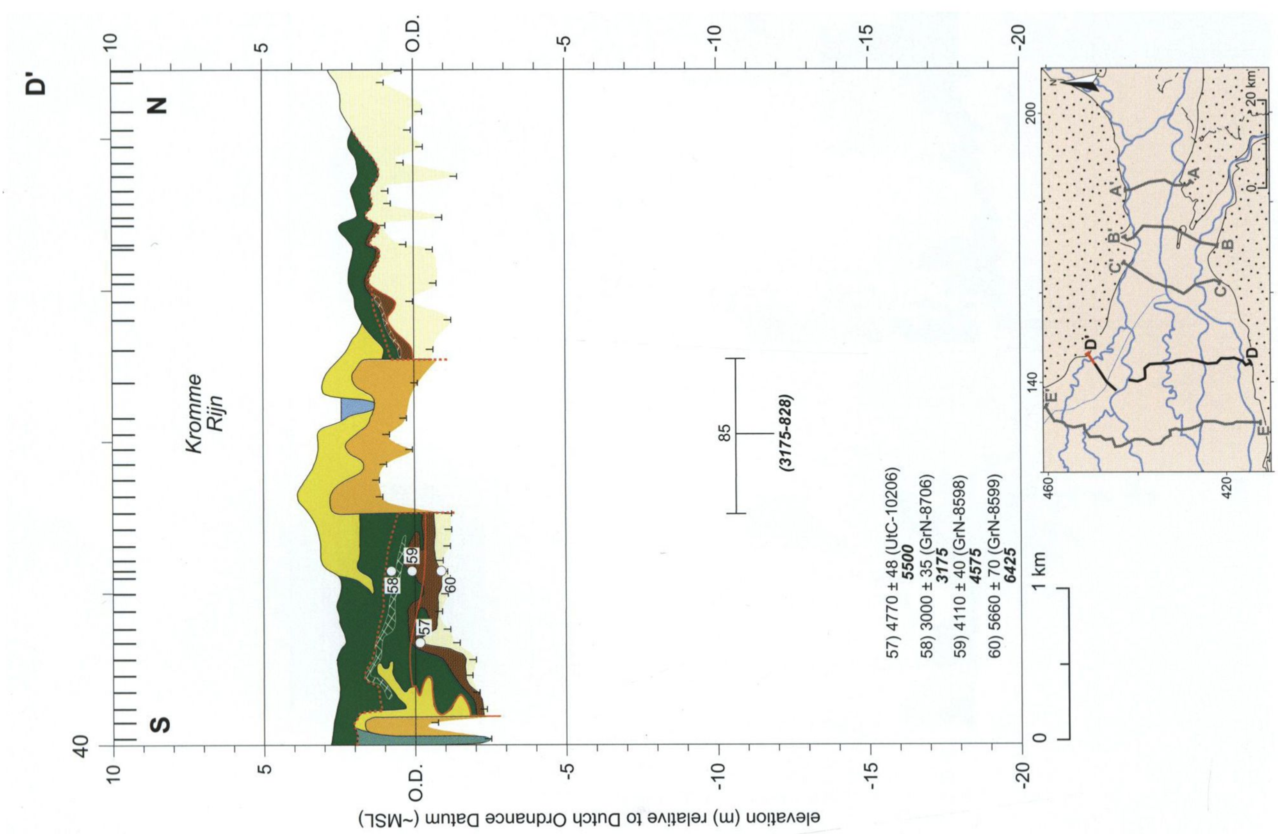

Fig. 9. Part 5.

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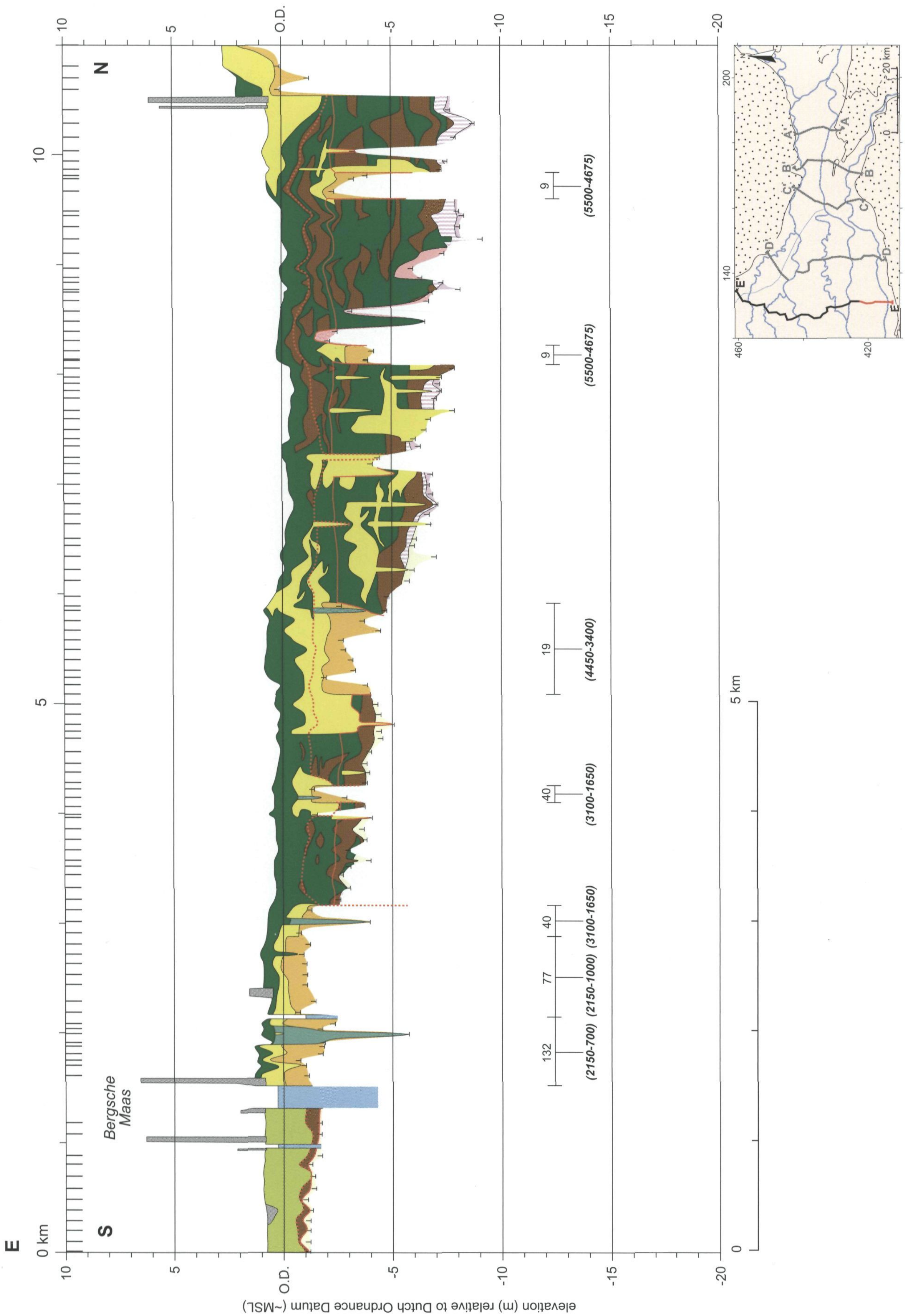

Fig. 10. Cross section E-E' (Waalwijk - Utrecht), part 1. For legend, see Fig. 5.

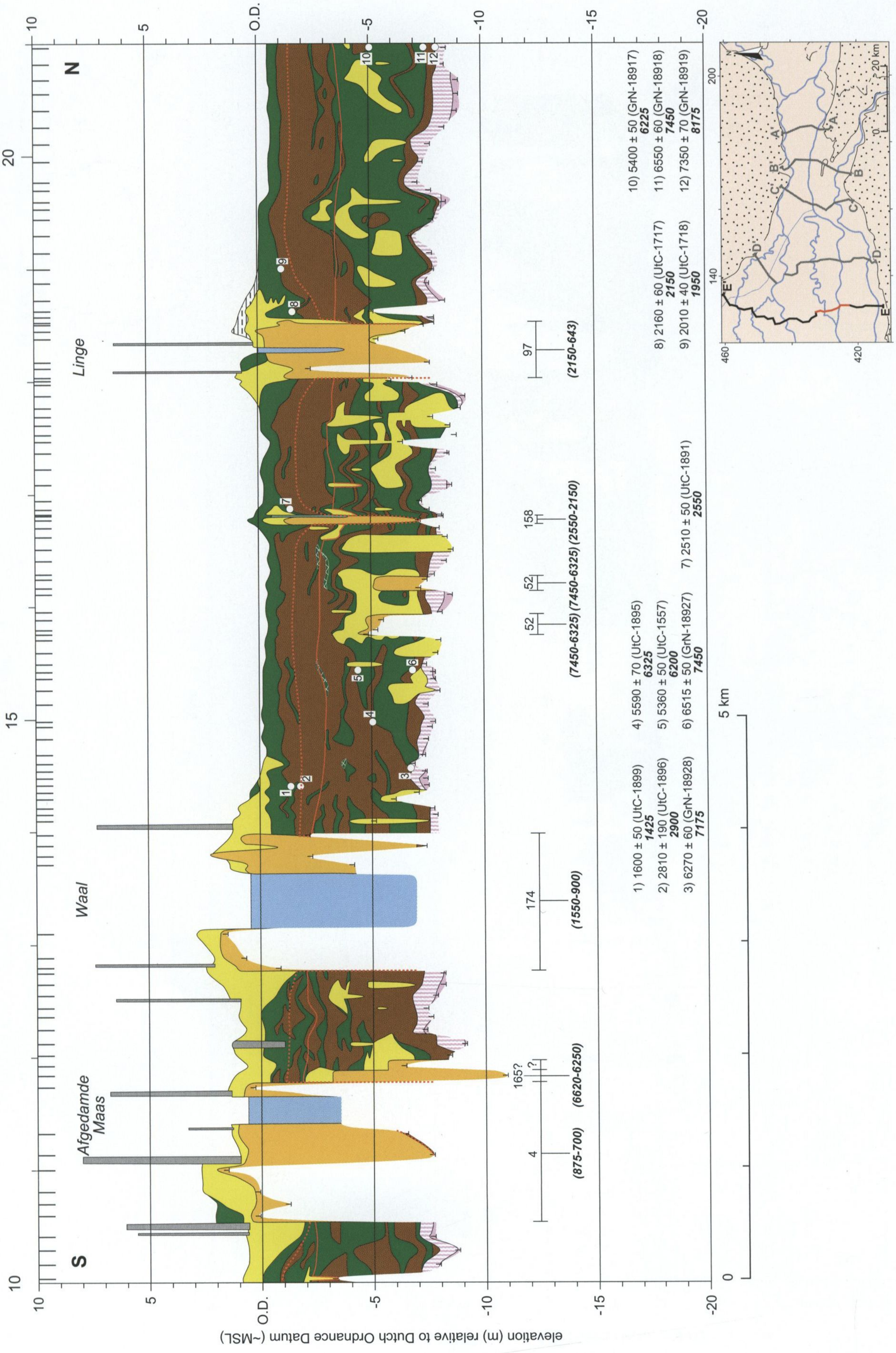
S
N
Afgedamde Maas
Waal
Linge
elevation (m) relative to Dutch Ordnance Datum (~MSL)
O.D.
4
(875-700)
165?
(6620-6250)
174
(1550-900)
52
(7450-6325)
52
(7450-6325)
158
(2550-2150)
97
(2150-643)
1) 1600 ± 50 (UtC-1899) 1425
2) 2810 ± 190 (UtC-1896) 2900
3) 6270 ± 60 (GrN-18928) 7175
4) 5590 ± 70 (UtC-1895) 6325
5) 5360 ± 50 (UtC-1557) 6200
6) 6515 ± 50 (GrN-18927) 7450
7) 2510 ± 50 (UtC-1891) 2550
8) 2160 ± 60 (UtC-1717) 2150
9) 2010 ± 40 (UtC-1718) 1950
10) 5400 ± 50 (GrN-18917) 6225
11) 6550 ± 60 (GrN-18918) 7450
12) 7350 ± 70 (GrN-18919) 8175
0
5 km
20 km

Fig. 10. Part 2.

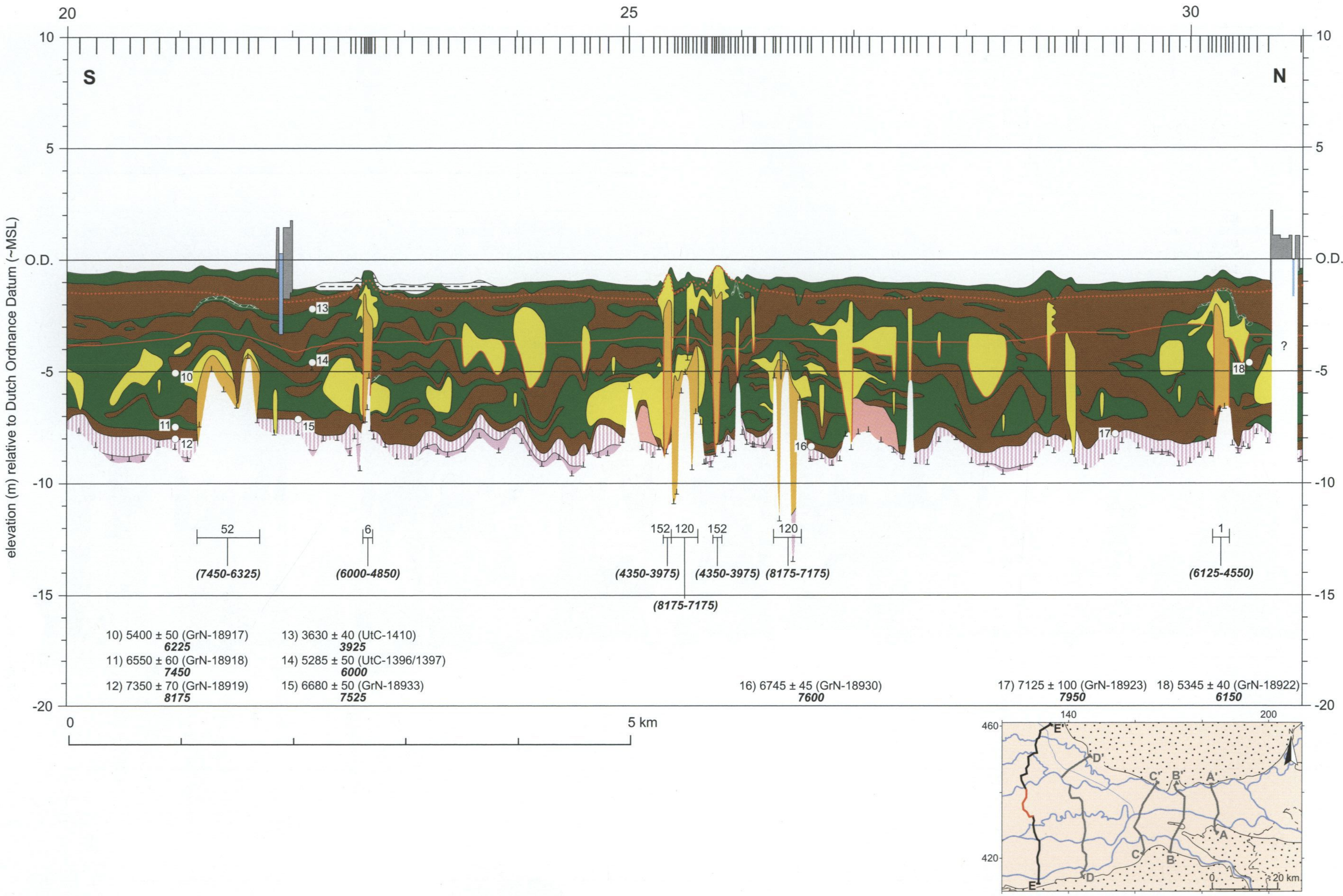

Fig. 10. Part 3.

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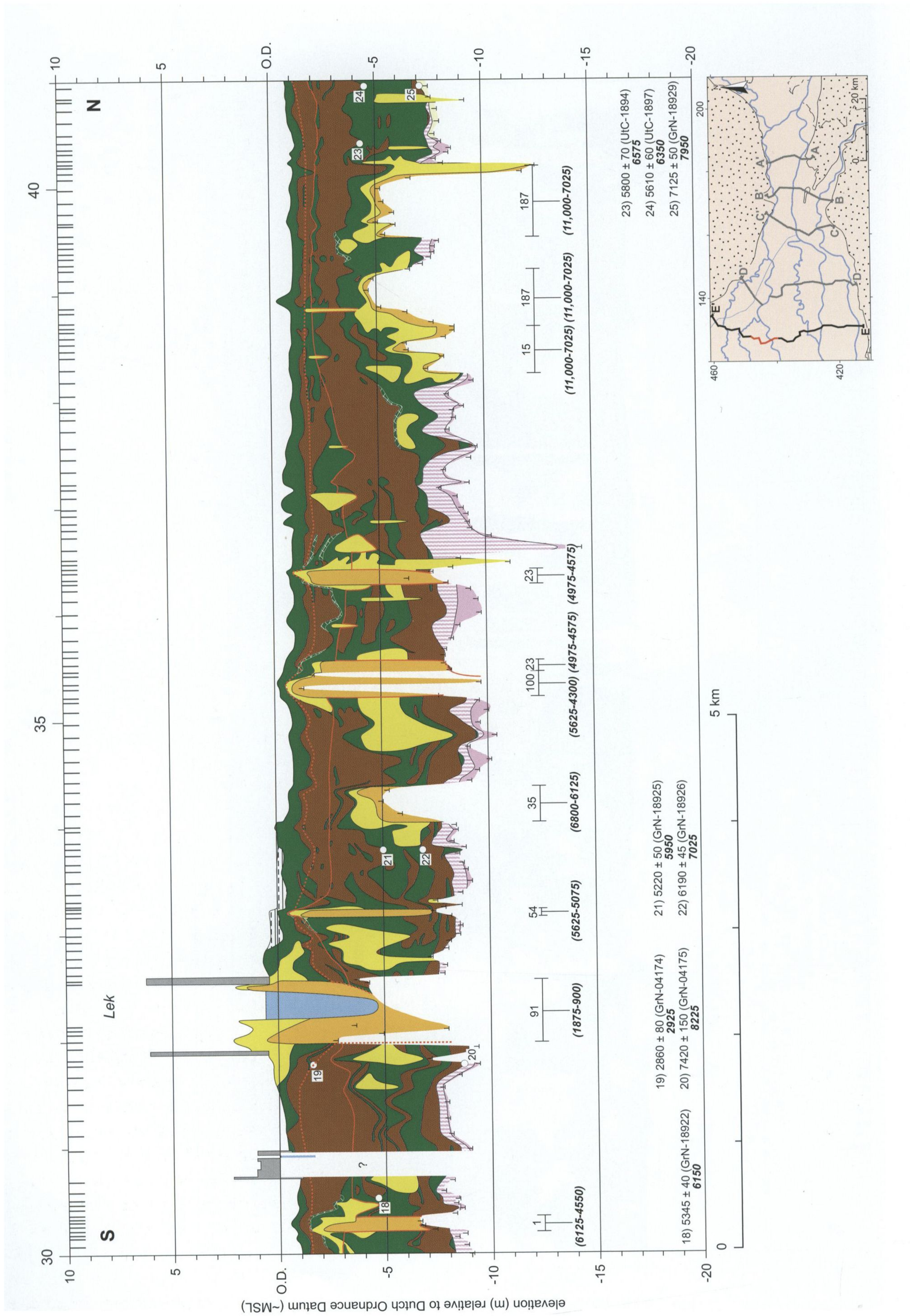

S
N
Lek
elevation (m) relative to Dutch Ordnance Datum (~MSL)
O.D.
5 km
(6125-4550)
(1875-900)
(5625-5075)
(6800-6125)
(5625-4300) (4975-4575)
(4975-4575)
(11,000-7025) (11,000-7025)
(11,000-7025)
18) 5345 ± 40 (GrN-18922)
6150
19) 2860 ± 80 (GrN-04174)
2925
20) 7420 ± 150 (GrN-04175)
8225
21) 5220 ± 50 (GrN-18925)
5950
22) 6190 ± 45 (GrN-18926)
7025
23) 5800 ± 70 (UtC-1894)
6575
24) 5610 ± 60 (UtC-1897)
6350
25) 7125 ± 50 (GrN-18929)
7950
20 km

Fig. 10. Part 4.

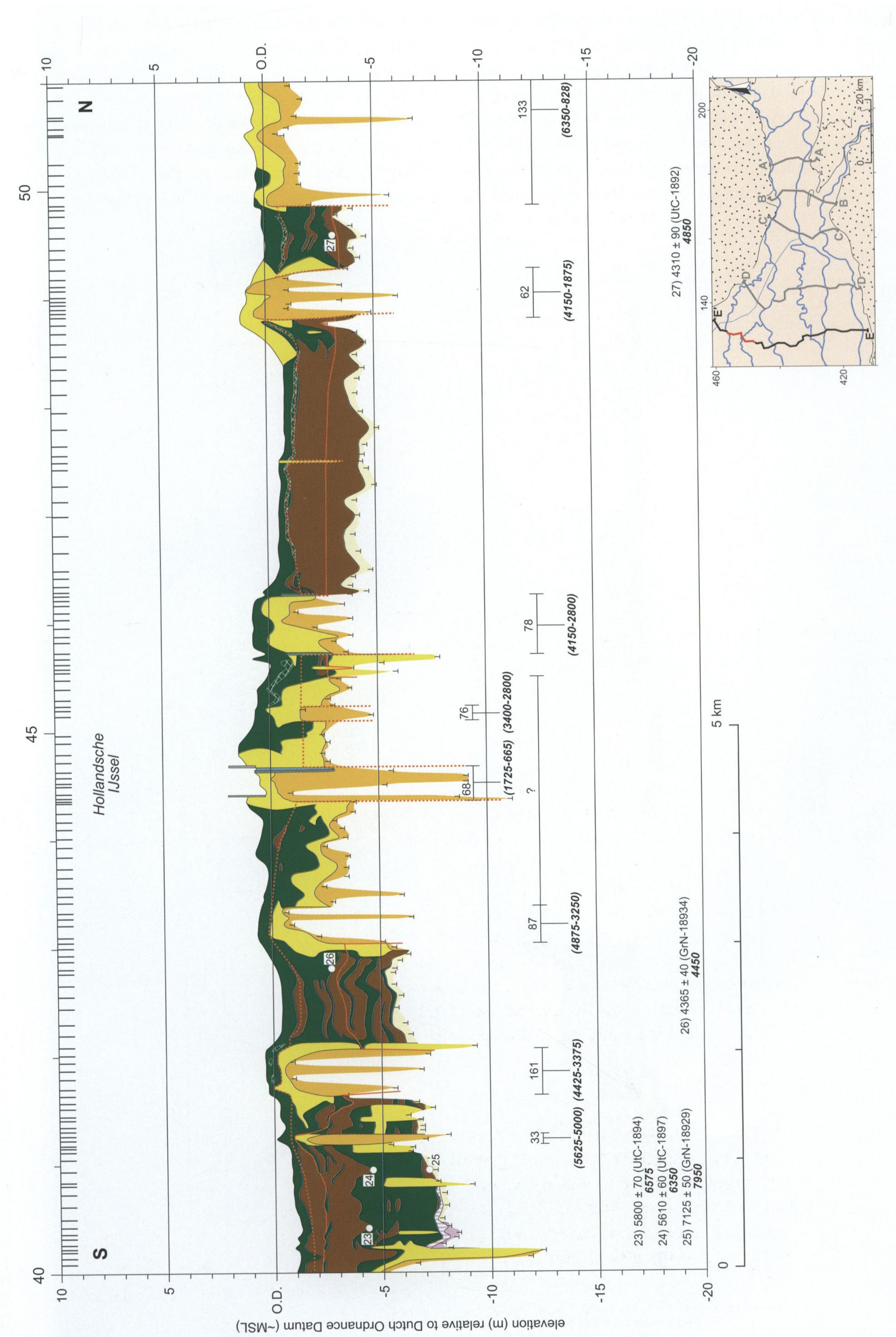

Fig. 10. Part 5.

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was located well inland, approximately at the position of cross section A-A' (i.e. ~120 km inland from the present-day North Sea coast; see Figs 1 and 2). All Holocene sediments older than *5000 cal yr BP* located downstream from cross section A-A' (Fig. 1) were deposited while eustatic sea-level rise was in progress. This implies that the influence of eustatic sea-level rise on delta formation extended less than ~120 km inland from the present-day shoreline, because other factors such as subsidence and upstream discharge and sediment supply also influenced the position of the aggradation-incision boundary. Thus, the present position of Holocene onlap (about 150 km inland, see Fig. 2) is not a good measure for the inland distance to which eustatic sea-level rise influenced aggradation and incision in the delta (see also Cohen, 2005, p. 357).

The upstream extension of the fluvio-deltaic wedge continued after the cessation of eustatic sea-level rise (see

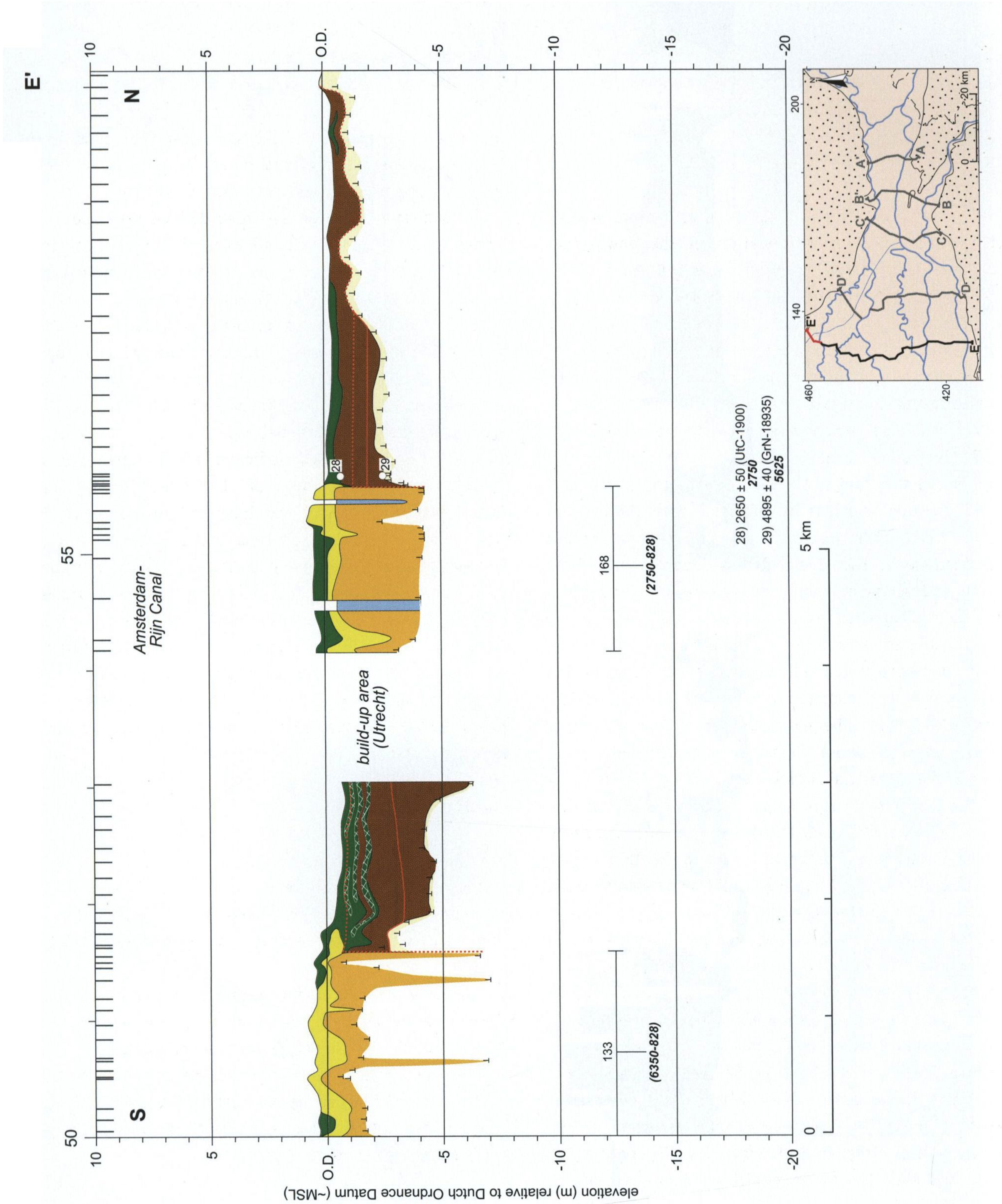

Fig. 10. Part 6.

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Figs 2b; 2c). The larger part of the 3-m-thick Holocene flood basin succession in cross section A-A' postdates *5000 cal yr BP*. Therefore, other factors than eustatic sea-level rise controlled aggradation during the second half of the Holocene. In the *post-5000 cal yr BP* succession, two distinct changes in the sedimentary pattern occur:

1. A widespread lithological change (organics to clastic deposits) at *~3000 cal yr BP* is present in the westernmost cross sections (Figs 9 - 10).
2. After *3000 cal yr BP*, clastic sedimentation occurred in the entire delta (Figs 6 - 10). This implies that the area of clastic sedimentation increased, which led to a downstream extension ('progradation') of the fluvio-deltaic wedge besides extension in an upstream direction ('backfilling') (Cohen, 2005).

These observations are in accordance with other studies, which indicated that peat formation in the downstream Rhine-Meuse delta practically ceased after *3000 cal yr BP* as clastic overbank sedimentation increased (Berendsen & Stouthamer, 2000; 2001; Cohen, 2003, p. 129). In addition, Weerts & Berendsen (1995) and Stouthamer & Berendsen (2000) reported indications for an increase in river discharge, sediment load and/or within-channel sedimentation after 2800 ^{14}C yr BP / *~2900 cal yr BP*, i.e. an increase in importance of upstream controls. Hence, we conclude that discharge and sediment supply became dominant in the Rhine-Meuse delta from *3000 cal yr BP* onwards, which is in agreement with the ideas of Cohen (2005). However, we cannot pinpoint the exact reasons for the increase in discharge and/or sediment supply. Both discharge and sediment supply are the result of upstream external factors, e.g. climate and land use, as well as of intrinsic fluvial processes acting within the river catchment. Therefore, variations in discharge and sediment supply may result from a complex response to changes in upstream external factors (Schumm, 1973; Vandenberghe, 1995; Houben, 2003) and/or autogenic river behaviour in the catchment. Only those changes in the hinterland, which were large enough to overwhelm the recognisable signatures of the other factors and processes involved (Schumm, 1973), were capable of causing changes in discharge and sediment supply to the Rhine-Meuse delta. Because a widespread change in the sedimentary record of the delta is present at *~3000 cal yr BP*, indicating an increase in discharge and sediment supply, this implies there was a major change in the hinterland. Studies in the upstream part of the Rhine-catchment suggest that this may be related to changes in land use due to increased human cultivation (e.g. Lang & Nolte, 1999; Mäckel et al., 2003).

Between *5000* and *3000 cal yr BP*, peat formation was at a maximum in the central delta (Figs 9 - 10; Berendsen & Stouthamer, 2001). The palaeogeographic evolution of the Rhine-Meuse delta offers an explanation for this observation. Between *5000* and *3000 cal yr*, clastic sedimentation *BP* was concentrated at the fringes of the delta (see Fig. 10). This is related to a shift of the main Rhine distributaries towards a more northerly course at approximately *6500 cal yr BP*, while the Maas stayed near the southern rim of the delta. In addition, the closure of the North Sea barrier coast disconnected the central delta from any marine influence and favoured conditions for peat growth (Berendsen & Stouthamer, 2000, and references therein). The extensive peat formation points to a shortage of sediment relative to the available accumulation space (cf. Blum & Törnqvist, 2000). It is therefore likely that sediment supply did not control aggradation in the downstream Rhine-Meuse delta between *5000* and *3000 cal yr BP*. Because eustatic sea-level rise had already ceased at that time, subsidence, enhanced by compaction of the underlying peat, most likely was the most important control on aggradation until *3000 cal yr BP*, at least in the downstream part of the delta.

In conclusion, each of the three defined time slices was formed under the dominant influence of a different external control, which is reflected in the sedimentary architecture of the fluvio-deltaic wedge (Fig. 11). Before *5000 cal yr BP*, eustatic sea-level rise was dominant, followed by subsidence (*5000 - 3000 cal yr BP*), and increased discharge and sediment supply from the hinterland (*3000 cal yr BP*-present). Eustatic sea-level rise caused initial upstream migration of Holocene onlap, subsidence created additional space to accommodate the sediments, and increased sediment supply and discharge resulted in areal expansion of clastic sedimentation and downstream extension of the fluvio-deltaic wedge. Similar interactions of external controls probably occur in other fluvio-deltaic settings as well, because the controls involved are common to many aggrading fluvial systems at continental margins. This could have implications for the interpretation of fluvio-deltaic successions elsewhere and challenges views in sequence stratigraphic studies (e.g. Posamentier et al., 1988; Shanley & McCabe, 1991), in which relative sea-level rise is emphasised as the main control on the creation of fluvio-deltaic successions.

Conclusions

Five cross-valley sections in the Rhine-Meuse delta show distinct spatio-temporal trends in the architecture of the Holocene fluvio-deltaic wedge. These trends are related to the interplay between eustatic sea-level rise, subsidence, discharge, and sediment supply:

1. The upper delta is characterised by a clastic-dominated Holocene succession in which several palaeo-A-horizons are present. The channel-belt deposits are concentrated in wide complexes. Channel belts in the downstream cross sections are scattered throughout the fluvio-deltaic wedge. A large part of the Holocene succession in the downstream part of the study area consists of organics.

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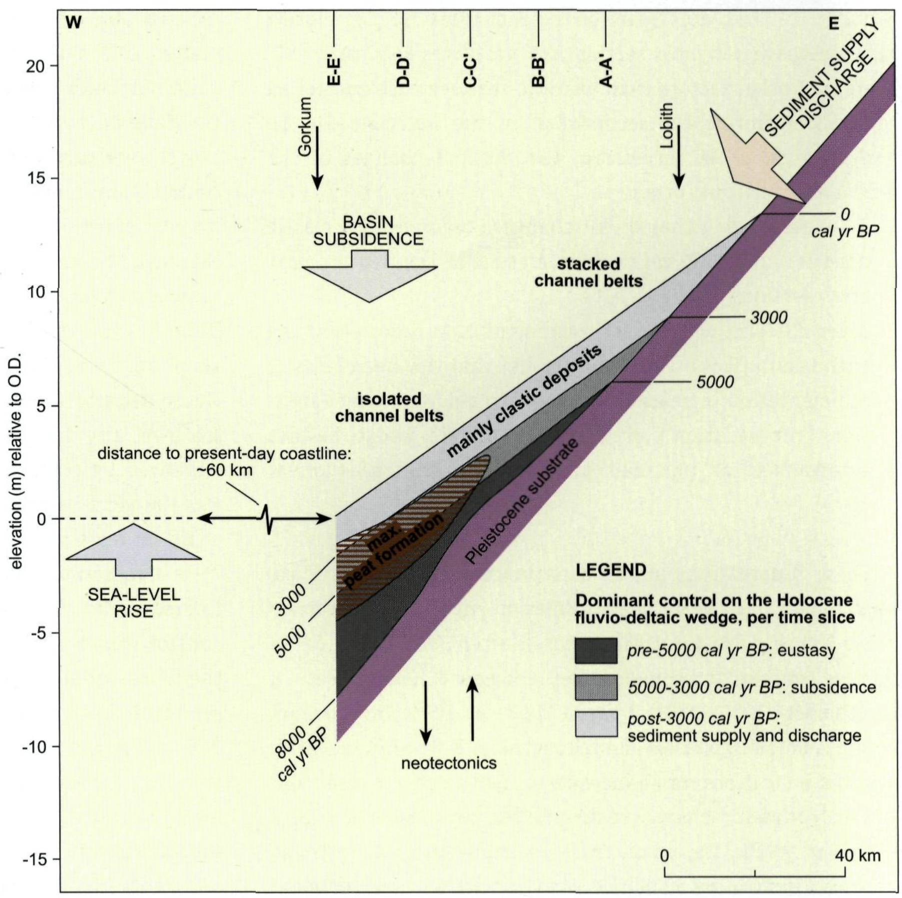

Figure 11. The Rhine-Meuse fluvio-deltaic wedge and the dominant external control for each of the three defined time intervals. Maximum peat formation is based on Berendsen & Stouthamer (2000) and the ^{14}C dates in the cross sections. See text for discussion.

2. Two temporal trends are recognised within the Holocene succession. Firstly, the proportion of organics is highest within the *5000 - 3000 cal yr BP* time slice, which is related to a shortage of sediment relative to the available accumulation space. Secondly, the segment of the fluvio-deltaic wedge formed after *3000 cal yr BP* consists mostly of clastic deposits, i.e. the area of clastic sedimentation increased. This is associated to increasing sediment supply and discharge.
3. Deposits older than *5000 cal yr BP* form a relatively large part of the Holocene flood basins in the downstream part of the Rhine-Meuse delta. This can be explained by the high aggradation rate during the first part of the Holocene as a result of eustatic sea-level rise. From *5000 - 3000 cal yr BP*, subsidence controlled aggradation, and discharge and sediment supply from the hinterland after *3000 cal yr BP*. Hence, other external controls besides sea-level rise considerably influenced the formation of the Rhine-Meuse fluvio-deltaic wedge. This is probably common to many fluvio-deltaic systems and should always be considered when interpreting (ancient) fluvio-deltaic successions.

Acknowledgements

We are very grateful to the landowners who kindly gave us permission to drill on their property. Many thanks to all the people who participated in the fieldwork, especially Pieter Doornenbal, Matthijs Verschuren, and Koen Volleberg. We thank Henk Weerts for the permission to use the database of TNO – Geological Survey of the Netherlands and Jeroen Schokker for letting us sample the Bemmel and Elst cores. Hanneke Bos selected the macrofossils for the AMS-samples. Radiocarbon dating was performed at the R.J. van de Graaff laboratory, Utrecht University (*www.phys.uu.nl/ams/*). Jakob Wallinga of the Netherlands Centre for Luminescence Dating (*www.ncl-lumdat.nl* and *www.lumid.nl*) is thanked for preparing and dating the OSL-samples. Henk Berendsen, Kim Cohen, Wim Hoek, and Ward Koster commented on an earlier draft of the paper. The paper greatly benefited from the constructive reviews of Whitney Autin and Kees Kasse. The five cross sections presented in this paper can be downloaded from the website of Rhine-Meuse delta studies at Utrecht University (*www.geo.uu.nl/fg/palaeogeography/*).

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