Patterns and processes in a Pleistocene fluvio-aeolian environment

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Patterns and processes in a Pleistocene fluvio-aeolian environment

Roer Valley Graben, south-eastern Netherlands

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aan Annika

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VOORWOORD

Weinig mensen zullen bij de start van een promotieonderzoek een goed idee hebben van waar ze aan beginnen. Zo ook ik. Als er dan uiteindelijk een boekje ligt, ben je trots dat je het hebt gered. Maar bij het tot stand komen van een proefschrift zijn veel meer mensen betrokken dan de schrijver alleen. Hen wil ik dan ook bedanken in dit voorwoord. Allereerst een dankwoord aan mijn promotor Ward Koster en co-promotor Henk Berendsen. Ward, eindelijk weer eens een onderzoek waar je over kon meepraten! Bedankt voor je kritische vragen en het meedenken over de tekst van Hoofdstuk drie. Jij schiep voor mij de mogelijkheid om af te reizen naar Groenland en stond vierkant achter het uitvoeren van OSL-dateringen. Henk, dit was voor jou een onderwerp dat wat verder van je bed was, maar dat weerhield je er niet van om altijd mee te denken. Bovendien slaagde je er vaak in de lengte van mijn teksten drastisch te reduceren, wat de leesbaarheid ten goede kwam. TNO-NITG wil ik graag bedanken voor het financieren van het grootste deel van dit onderzoek. Van NITG-zijde ben ik vooral terzijde gestaan door Wim Westerhoff en Piet Cleveringa. Wim, mijn boekje is af, nu kun je eindelijk weer verder met je eigen teksten. Bedankt! Piet, je was in het begin maar zijdelings bij mijn onderzoek betrokken, maar dat hebben we later ruimschoots goed gemaakt. Ik hoop dat we in de toekomst nog vaak zullen filosoferen over de dingen des levens. Ook een woord van dank aan je 'vaste vriendin' Meini Blom. Meini, ik zal proberen geen rare attachments meer te versturen of Piet op de meest onmogelijke tijden thuis te bellen. Hij is weer geheel de jouwe. I'd like to thank Andrew Murray and Jakob Wallinga for all the help they provided me with when applying OSL dating. Andrew, now you can safely answer the phone again, without the chance that it's me telling you that you should finish your work by yesterday. I hope that we can work together in the future as well. Jakob, dankzij jouw eerdere werk kon ik zo aan de slag met mijn OSL-kernen. Je leerde me dat een uitkomst altijd interessant is, nooit problematisch. Ik wens je een glansrijke toekomst toe met je eigen lab.

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1 INTRODUCTION

1.1 Background and problem definition

The Roer Valley Graben in the south-eastern Netherlands is an active tectonic subsidence area (Fig. 1.1). It originated in the Early Oligocene as part of the Cenozoic rift system of western and central Europe (Ziegler, 1994) and was filled with alternating marine, coastal and fluvial deposits during the Tertiary and Early Quaternary. The sea withdrew from the Roer Valley Graben in the Early Pleistocene and the area subsequently developed as one of the main depositional centres of the mixed Rhine-Meuse river system. Tectonic movements forced the rivers to a more north-eastern course in the early Middle Pleistocene (Kasse, 1988; Zagwijn, 1989; Van den Berg, 1994). From that moment on, the Roer Valley Graben was left without a large fluvial depositional system. However, tectonic subsidence in the area continued (Houtgast & Van Balen, 2000) and accommodation space was created. Climate changes caused repeated shifts between temperate and cold, periglacial climatic conditions. Fine-grained sand and loam were deposited in a complex sedimentary pattern, associated with aeolian, lacustro-aeolian and small-scale fluvial processes. Locally, thick organic deposits formed as well. The interplay of ongoing tectonic subsidence and climate changes in the absence of large-scale erosion events favoured the development of an up to 35 m-thick terrestrial fluvio-aeolian sedimentary record. The fine-grained sediments are known as Nuenen Group deposits in the Quaternary lithostratigraphic framework of the Netherlands (Bisschops, 1973; Doppert et al., 1975). They form an important archive of terrestrial landscape development in a changing climate during the Middle and Late Quaternary.

Long, continuous continental sequences with an independent chronology are important for correlating climate-related terrestrial environmental changes with the marine and ice-core records. Good possibilities for the preservation of undisturbed continuous records that span at least several glacial-interglacial cycles are offered by lake and loess sequences. In Europe, these are known from the central, southern and eastern part of the continent (e.g. Wijmstra, 1969; Wijmstra & Smit, 1976; Fink & Kukla, 1977; Follieri et al., 1988; De Beaulieu & Reille, 1992, 1995; Tzedakis, 1994; Reille & De Beaulieu, 1995; Boenigk & Frechen, 1998; Reille et al., 2000; De Beaulieu et al., 2001). In north-western Europe, deep lacustrine basins or thick loess sequences are not present, because the landscape repeatedly suffered from glacial remoulding and erosion by periglacial processes (Turner, 1998; Dowling & Coxon, 2001; Thomas, 2001). Still, the region is at the crossroads of the Pleistocene glacial realm in the north, the marine and coastal realm in the west and the terrestrial realm in the south-east. The subsiding Roer Valley Graben

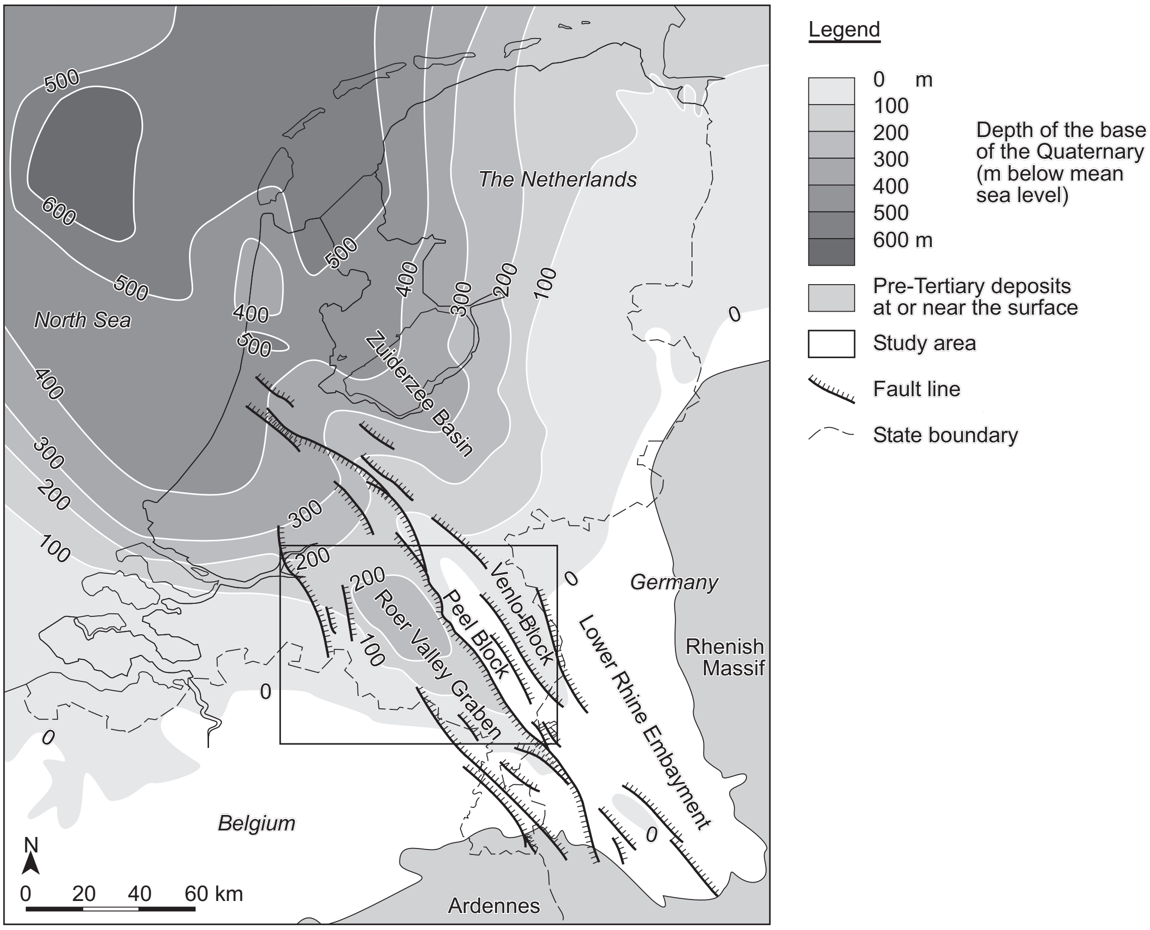

Figure 1.1 Depth contours (below mean sea level) of the base of the Quaternary deposits and location of the study area (modified after: Zagwijn & Doppert, 1978).

has been saved from glacial erosion, because it is situated just south of the maximum extent of the Pleistocene ice sheets. This makes it a key area for correlating the fragmentary glacial record of northern Europe with the lake and loess records in the east and south. In addition, the Roer Valley Graben may contain part of the so-called 'missing' record of upper Middle-Pleistocene sediments (representing Marine Isotope Stages 10 to 7) in continental north-western Europe (Turner, 1998).

Knowledge on the geometry and sedimentary properties of the shallow deposits in the Roer Valley Graben is also of practical and societal relevance. In 1998, the State Geological Survey of the Netherlands (TNO-NITG) initiated the study of these sediments, because a lack of information hampered detailed geological mapping and applied research in the area. Until then, the deposits of the Nuenen Group were schematised in groundwater modelling studies as a single homogeneous layer with a low permeability (aquitard). However, this approach yielded erroneous modelling results when working on a detailed scale. Both geohydrological surveys and studies on soil quality and groundwater quality demanded a better insight into the geometry, lithological variability and geochemical characteristics of the Nuenen Group deposits. Geotechnical surveys and infrastructural planning required detailed information on the sedimentary properties and associated geomechanical characteristics.

1.2 Objectives of this study

The main objectives of this study are:

- To develop a well-defined and applicable lithostratigraphic framework for the fluvio-aeolian deposits in the Roer Valley Graben, based on the following three differentiating criteria: 1. Macroscopically distinguishable lithological characteristics; 2. Stratigraphic position; 3. Practical mappability;
- To reconstruct the prevailing sedimentary processes, local depositional pattern and palaeo-environmental development during the Middle and Late Quaternary;
- To construct a reliable geochronological framework for the Middle- and Upper-Quaternary deposits in the Roer Valley Graben and to assess the influence of regional tectonic movements and climate change on the depositional environment and sedimentation rate in the area.

These goals can be achieved by a characterisation and interpretation of the lithological properties, sedimentary structures, palaeo-ecological data and geochemical and mineralogical properties of the Nuenen Group deposits and comparison of this information to data from other studies in similar depositional settings. Optically Stimulated Luminescence (OSL) dating of quartz grains provides an opportunity to establish a timeframe for the sedimentation of the aeolian deposits in the Roer Valley Graben. When all the above-mentioned objectives are reached, it is possible to assess the significance of the Middle- and Late-Quaternary terrestrial sedimentary sequence in the Roer Valley Graben as an archive of Quaternary landscape development.

1.3 Thesis outline

This PhD thesis contains four papers (Chapter 2 to 5), which have been accepted or submitted for publication in peer-reviewed scientific journals. With the exception of minor typographical corrections and updates of tables and figures, the papers have been reprinted here unaltered. Chapter 6 provides a synthesis of the different chapters. All references used throughout the text have been grouped into one comprehensive reference list at the end of this thesis.

In Chapter 2, a new lithostratigraphy for the Middle- and Upper-Quaternary terrestrial fine-grained deposits in the Netherlands is presented, mainly based on research in the Roer Valley Graben. Chapter 3 focuses on the description and interpretation of the sedimentary facies units that can be recognised in these deposits. The vertical and lateral facies distribution is illustrated and explained. Focus is especially on sedimentation patterns and depositional processes in the Roer Valley Graben in cold (glacial) climatic conditions. In Chapter 4, the palaeo-environmental development during a warm-temperate (interglacial) climate is discussed. The Eemian interglacial (Marine Isotope Stage 5e) thereby serves as an example. Geochronological information is obtained by quartz OSL dating of the Eemian organic deposits. Chapter 5 deals with the provenance of the aeolian and fluvial sediments. The continuity of the sedimentary record is assessed and a comprehensive age model for the timing of deposition is presented. Chapter 6 concludes this thesis by combining the results of the previous chapters, discussing some of the possible applications and exploring paths for future research.

2 INTRODUCTION OF THE BOXTEL FORMATION AND IMPLICATIONS FOR THE QUATERNARY LITHOSTRATIGRAPHY OF THE NETHERLANDS

with Henk J.T. Weerts, Wim E. Westerhoff, Henk J.A. Berendsen & Cees den Otter

submitted to Netherlands Journal of Geosciences / Geologie en Mijnbouw

Abstract

Application of the traditional lithostratigraphic framework to subdivide the Middle- and Upper-Quaternary terrestrial fine-grained deposits in the Netherlands is problematic. Deposits of many formations cannot be distinguished from each other based on lithological characteristics and stratigraphic position alone. To overcome this problem, we present a new, well-defined lithostratigraphy for these deposits, based on detailed research in the central part of the Roer Valley Graben. This area contains an up to 35 m-thick sedimentary record of Middle- and Upper-Quaternary sand, loam and peat deposits. These have mainly been formed by aeolian and fluvial processes and have been preserved as a result of tectonic subsidence. The traditional lithostratigraphic subdivision of these deposits into three formations (Eindhoven Formation, Asten Formation and Twente Formation) was based on a combination of litho-, bio- and chronostratigraphic evidence and the presumed widespread presence of a horizon of organic-rich interglacial sediments of Eemian age. To avoid intermingling of criteria regarding lithological characteristics, genesis and age, we now incorporate all fine-grained sediments into the new Boxtel Formation. The implications for the lithostratigraphic framework in other parts of the country are explored and discussed. Eight lithostratigraphic members are introduced that describe the most characteristic parts of the formation. To fully illustrate the sedimentary sequence in the Roer Valley Graben, two new members are defined here. The Best Member incorporates alternating floodloam deposits and sandy aeolian deposits in the lower part of the Boxtel Formation. The Liempde Member includes reworked aeolian loess and sandy loess deposits ('Brabant loam') that occur in the upper part of the sedimentary sequence.

2.1 Introduction

Ever since the introduction of the Quaternary lithostratigraphic framework of the Netherlands by Doppert et al. (1975), application of this system to the subdivision of terrestrial fine-grained deposits has been problematic. Deposits of many formations cannot be distinguished from each other based on lithological characteristics and stratigraphic position alone. For example, deposits of the Twente Formation (sand, loam and peat deposits, associated to local depositional processes) cannot be uniquely differentiated from deposits of the Kootwijk Formation (aeolian drift sands) or Singraven Formation (sand, loam and peat deposits, associated to small river systems). In the Roer Valley Graben in the south-eastern Netherlands (Fig. 2.1A), problems are particularly large. This active tectonic subsidence area contains the thickest and most complete record of terrestrial fine-grained deposits in the Netherlands. A major lithostratigraphic difficulty in the Roer Valley Graben is the recognition and definition of the Asten Formation (peat and organic-rich clastic deposits). This formation is stratigraphically positioned in-between clastic deposits of the Twente Formation and similar clastic deposits of the Eindhoven Formation. Problems arise, because:

- With the exception of the vicinity of the village of Asten (Fig. 2.1B), deposits of the Asten Formation are absent in the Roer Valley Graben. In that case, a lithologically defined boundary between deposits of the Twente Formation and deposits of the Eindhoven Formation cannot be established;
- Scattered occurrences of silty peat that have been formed in small, isolated basins in the Roer Valley Graben under the influence of a high groundwater table, and even palaeosols, are often erroneously correlated with the Asten Formation, only because of their presumed Eemian or Early-Weichselian age;
- The fine-grained deposits of the Twente Formation and Eindhoven Formation frequently contain more than one thick organic layer in a sandy matrix. On lithostratigraphic grounds, it is impossible to decide, which of these layers should be assigned to the Asten Formation.

The sediments of the Twente Formation and Eindhoven Formation in the Roer Valley Graben are lithologically too similar to permit a subdivision into two lithostratigraphic units, if these units are not separated by a uniquely distinguishable organic layer. As a consequence, the term Nuenen Group was introduced to include all Middle- and Upper-Quaternary fine-grained deposits in the area (Bisschops, 1973; Bisschops et al., 1985). This however was an artificial solution that left the problems of discriminating between Nuenen Group deposits in the Roer Valley Graben and deposits of the Twente Formation, Asten Formation and/or Eindhoven Formation in other parts of the Netherlands.

The objective of this paper is to present a new, well-defined lithostratigraphy of the Middle- and Upper-Quaternary terrestrial fine-grained deposits in the Netherlands, mainly based on detailed research in the central part of the Roer Valley Graben. This includes the introduction of the Boxtel Formation, Best Member and Liempde Member, and the redefinition of six other members. Because the content of the Boxtel Formation is drastically different from that of the previously defined formations, the old lithostratigraphic names cannot be maintained.

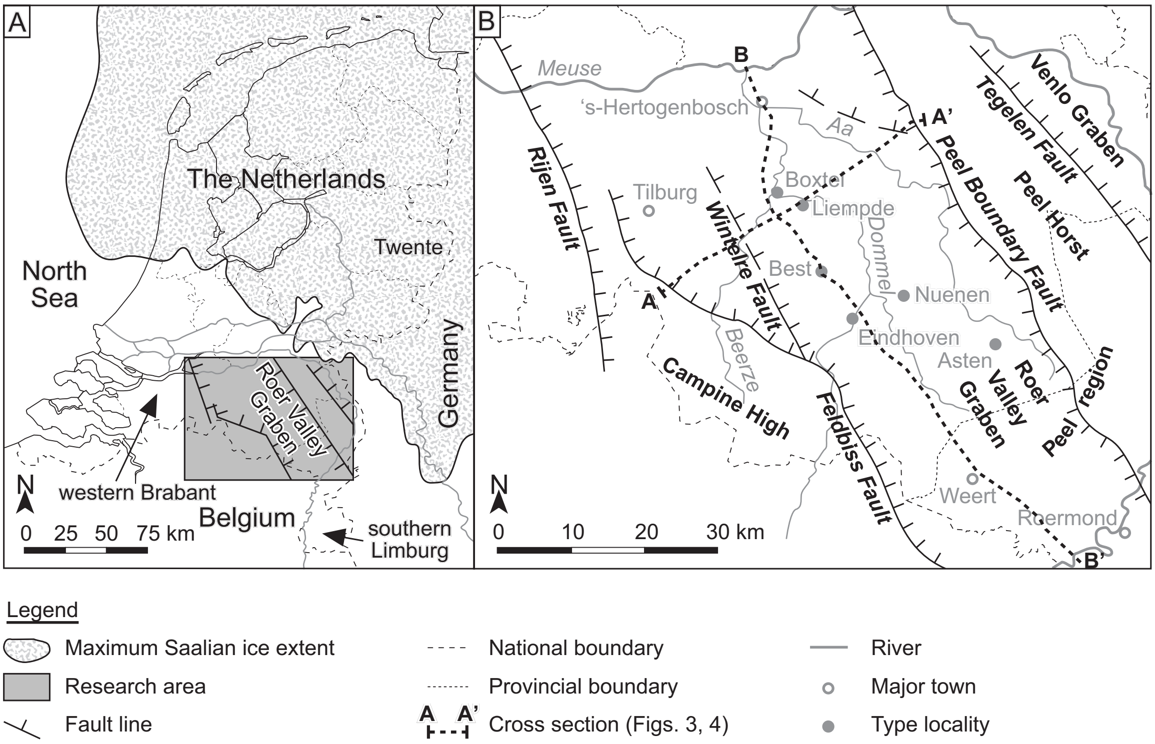

Figure 2.1 (A) Map of the Netherlands with the location of the Roer Valley Graben; (B) Map of the Roer Valley Graben and surrounding areas showing the position of major tectonic blocks and fault systems. Stratotype localities and the position of two geological cross sections (Figs. 2.3, 2.4) are also indicated.

Research is situated in the central part of the Roer Valley Graben. This is a region of active tectonic subsidence, bounded by major fault systems and the river Meuse (Fig. 2.1B). The Roer Valley Graben forms part of the Cenozoic rift system of western and central Europe (Ziegler, 1994). It acted as an important depocentre from the Early Tertiary onward, resulting in an up to 1400 m-thick sedimentary fill (Zagwijn, 1989; Geluk et al., 1994). In the Early Quaternary, the sea withdrew from the area and from that time onward, the Rhine-Meuse fluvial system formed the main sediment source (Van den Berg, 1994). In the course of the Middle Pleistocene, differential tectonic movements forced the rivers Rhine and Meuse to gradually deflect their courses to the east. The central part of the Roer Valley Graben was left without a large fluvial system. However, active tectonic subsidence in the area continued (Van den Berg, 1994; Houtgast & Van Balen, 2000). Rhythmic climate changes caused repeated shifts between warm-temperate and cold-periglacial environmental conditions. In the absence of a large fluvial depositional system, a small-scale depositional pattern developed, associated with aeolian, fluvio-aeolian and lacustro-aeolian processes. Locally, organic deposits formed as well. The interplay of tectonic subsidence and climatic shifts favoured the development and preservation of a heterogeneous, up to 35 m-thick terrestrial sedimentary record in the Roer Valley Graben, testifying to repeated palaeoclimatic and palaeo-environmental change.

2.2 Historical perspective of the stratigraphic problems

Over time, the stratigraphic subdivision of terrestrial fine-grained deposits in the Quaternary sedimentary sequence in the Netherlands has frequently changed. This is a result of evolving scientific ideas, the advent of new laboratory techniques and an increasing regional geological knowledge. In the first comprehensive description of the geology of the Netherlands, Staring (1860) classified the surficial sand deposits in the Netherlands as Sanddiluvium. Later, notion evolved of the Riss (Saalian) glaciation of the northern part of the Netherlands and of a 'zone' with marine influence above the glaciation level (e.g. Lorié, 1907). In the northern Netherlands, the fine-grained sediments above the Glacial diluvium were named Sanddiluvium B (deposits below the marine sediments) or Sanddiluvium A (deposits above the marine sediments). In the south, the Sanddiluvium remained undivided. The stratigraphic framework of the first series of detailed geological maps (1923-1947) was based on a combination of morphostratigraphy, sediment petrology and the presence or absence of biomarkers (Tesch, 1942). In this framework, the terrestrial fine-grained deposits were subdivided in 'Middle Terrace deposits' and 'Lower Terrace deposits', based on their supposed morphological position. Both (supposedly fluvial) units were regarded younger than the Saalian glacial sediments in the northern Netherlands. Research in the Twente region (Fig. 2.1A) later revealed that many of the Middle Terrace deposits and Lower Terrace deposits were in fact not fluvial, but aeolian periglacial in nature (e.g. Van der Hammen, 1951; Van der Vlerk & Florschütz, 1953).

In the 1930's and 1940's, the use of microscopic laboratory techniques to solve geological problems became well established. This also influenced stratigraphy. In 1947, Zonneveld published a stratigraphic subdivision of the Quaternary sediments in the Peel region, based on the heavy-mineral content of sandy deposits. This stratigraphic scheme was later extended to incorporate Quaternary deposits in the entire country (Zonneveld, 1958). The heavy-mineral composition was interpreted in terms of provenance, which was in turn related to the configuration of depositional systems. Sediment petrology proved especially useful to discriminate between fluvial source areas. Zonneveld (1947) re-introduced the term Sanddiluvium for the surficial terrestrial fine-grained deposits in the south-eastern Netherlands (Table 2.1). In the following decades, microscopic sediment-petrological information became an important aspect of lithostratigraphic classification in the Netherlands.

Meanwhile, studies on the sedimentology and microfossil content of Quaternary deposits led to an increasing notion of the complexities of the development of the Pleistocene climate (e.g. Vink, 1949; Van der Hammen, 1951; 1971; Van der Vlerk & Florschütz, 1953; Zagwijn, 1961). This notion was later confirmed by the analysis of deep-sea cores (e.g. Emiliani, 1955; Shackleton & Opdyke, 1973). Contemporaneously, the radiocarbon and K/Ar dating methods for the first time allowed the construction of an 'absolute' timeframe for the Pleistocene. Radiocarbon dating created possibilities to investigate the Late-Pleistocene chronostratigraphic sequence in detail (a.o. Zagwijn, 1961; 1974a; Van der Hammen et al., 1967). In this way, bio- and chronostratigraphic criteria and absolute age were gradually introduced to discriminate between lithostratigraphic units. Notion evolved of the presence of continental Eemian deposits in the Roer Valley Graben and the Peel region (Van der Vlerk & Florschütz, 1953; Florschütz & Anker-Van Someren, 1956; Mente, 1961). Van den Toorn (1967) subsequently used the presence of these deposits to subdivide the Sanddiluvium in three lithostratigraphic formations that were coupled to geologic time periods (Table 2.1). The Eindhoven Formation included the Saalian part of the Sanddiluvium, consisting of sand and loam. The Asten Formation comprised the Eemian organic deposits and the Twente Formation included the Weichselian sand and loam layers. However, palynological analyses were necessary to confirm the Eemian age of the organics, and even if peat was absent, Van den Toorn (1967) tried to differentiate between Saalian and Weichselian sand and loam deposits, a.o. by using subtle lithological differences. Thus, palynology and radiocarbon dating became important tools to subdivide terrestrial deposits.

Table 2.1 Overview of former and present lithostratigraphic classifications of the terrestrial fine-grained deposits in the Roer Valley Graben and Peel region.

Zonneveld (1947)	Van den Toorn (1967), Doppert et al. (1975)	Bisschops (1973), Bisschops et al. (1985)	this paper
Sanddiluvium	Twente Formation Asten Formation Eindhoven Formation	Nuenen Group	Boxtel Formation

Bisschops (1973) could hardly find any Eemian organic deposits in the Roer Valley Graben and did therefore not apply the subdivision into three formations. He introduced the term Nuenen Group to denote all shallow fine-grained deposits in the area. Shortly afterwards, a lithostratigraphic classification of the Upper-Tertiary and Quaternary sediments of the Netherlands was published by Doppert et al. (1975). In this publication, the Eindhoven Formation, Asten Formation and Twente Formation were formally defined. According to Doppert et al. (1975), the term Nuenen Group should be used in areas where the organic deposits of the Asten Formation were lacking and where it was thus impossible to differentiate between the clastic sediments of the Eindhoven Formation and Twente Formation. Bisschops et al. (1985) also used the term Nuenen Group. They showed the presence of interglacial organic deposits in the Roer Valley Graben that were older than Eemian. These organics were considered to be of Holsteinian age. Based on palaeomagnetic work of Zagwijn et al. (1971), Bisschops et al. (1985) placed the onset of deposition of the Nuenen Group sediments in the Middle-Pleistocene Cromerian Stage.

Although not explicitly noted by the above-mentioned authors, the introduction and subsequent use of the stratigraphic term Nuenen Group indicates that the subdivision into three formations was not applicable in the Roer Valley Graben. Similar stratigraphic problems applied to western Brabant and the south-eastern part of the Peel Horst, where up to 15 m-thick sequences of fine-grained deposits occur that were partly assigned to the Eindhoven Formation, and partly to the Twente Formation (cf. Van den Toorn, 1967). Difficulties arose, because not only macroscopically visible lithological characteristics and lithostratigraphic position came to play a role in the subdivision, but also genesis, provenance and age of the deposits (cf. similar discussions by Roeleveld, 1974; Griede, 1978; Berendsen, 1982). The intermingling of litho-, bio- and chronostratigraphic criteria caused a large dependence on laboratory results, such as palynology, sediment petrology and radiometric dating. To overcome this, we introduce the Boxtel Formation and eight lithostratigraphic members, two of which are defined in the Roer Valley Graben (Best Member and Liempde Member). The definition of these units is illustrated with geological cross sections and a general lithological description. Subsequently, the implications for the lithostratigraphy of the Netherlands are explored.

2.3 The Boxtel Formation in the Roer Valley Graben

2.3.1 Thickness, areal distribution and lithological characteristics

Deposits of the Boxtel Formation occur at the surface throughout the Roer Valley Graben. They are underlain by Middle-Pleistocene coarse-grained fluvial deposits of the Sterksel Formation and Beegden Formation (see Appendix). Deposits of the Boxtel Formation are easily discerned from those of the underlying fluvial formations by their smaller median grain size, a higher silt content of the sand and the near absence of clay and gravel. In borehole natural-gamma logs, the sediments of the Boxtel Formation are characterised by low natural-gamma values. In contrast to the deposits of the Sterksel Formation, the sediments of the Boxtel Formation contain only small amounts of mica and feldspar. The thickness of the deposits is strongly influenced by faulting and syn-sedimentary tectonic movements in the area. In the central part of the Roer Valley Graben, with strongest Quaternary subsidence (Kooi, 1997), the Boxtel Formation can reach a thickness of more than 30 m (Fig. 2.2).

Geological cross section A-A' (Fig. 2.3), which runs SW-NE, shows the influence of differential subsidence upon the thickness and areal distribution of the Boxtel Formation. Along the eastern margin of the Roer Valley Graben, the Peel Boundary Fault causes a vertical offset of more than ten meters in the lower boundary of the Boxtel Formation. The cross section also shows that the sedimentary fill of the Roer Valley Graben is asymmetric, with a gentle, stepwise-sloping lower boundary of the Boxtel Formation in the western part and a steep-sloping lower boundary along the eastern margin. The asymmetry is attributed to the presence of a secondary fault (Fig. 2.1B; northward extension of the Wintelre Fault of Bisschops et al., 1985). The same asymmetric subsidence pattern has been observed in the thickness and areal distribution of older deposits (e.g. Geluk et al., 1994; Houtgast & Van Balen, 2000).

A NW-SE geological cross section is shown in Figure 2.4. The thickest sequence of deposits of the Boxtel Formation is present in the north-central part of the Roer Valley Graben (Fig. 2.4: boreholes 51B0082 to 51E0053). The boundary between the Upper-Pleistocene medium-grained fluvial deposits of the Kreftenheye Formation and the fine-grained local deposits of the Boxtel Formation in the north-western part of the cross

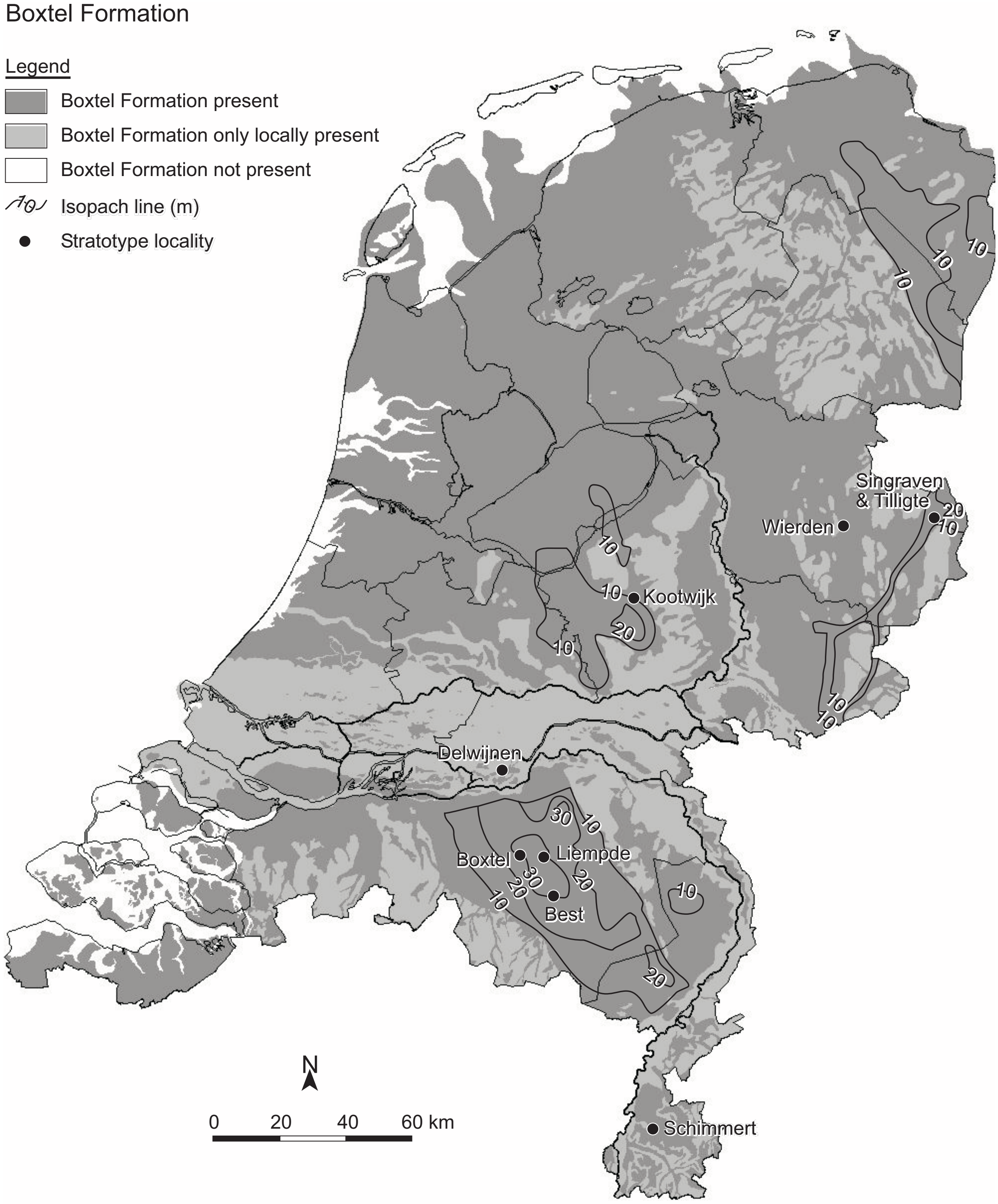

Figure 2.2 Areal extent and thickness of the deposits of the Boxtel Formation. The depth interval is 10 m. Stratotype localities are indicated.

section is erosive. In the southern part of the Roer Valley Graben, the Boxtel Formation overlies Upper-Pleistocene coarse-grained fluvial deposits of the Beegden Formation (Fig. 2.4).

The deposits of the Boxtel Formation in the Roer Valley Graben are characterised by the occurrence of many thin loam and peat layers in an essentially sandy sediment matrix (Figs. 2.3, 2.4). Most of the sand is fine- to medium-grained (105-210 µm), yellowish-grey, non-calcareous and silty. Medium- to coarse-grained (210-420 µm), slightly gravelly sand occurs near major faults or associated with small river valleys. The sand is sometimes parallel or cross-laminated, but in most cases, it is structureless or only vaguely subhorizontally laminated. The sand may be humic and may contain wood fragments or other organic material.

Thin loam layers are present throughout the sedimentary sequence, but thick (>1 m) loam units with a more than local lateral extent only occur in the lower and upper part of the Boxtel Formation. The areal distribution of the lower loam unit (unit BS; Figs. 2.3, 2.4) is restricted to the central part of the Roer Valley Graben (Fig. 2.3). It occurs between 10 and 20 m -NAP (NAP = Dutch Ordnance Datum ≈ mean sea level) and reaches a thickness of 4-10 m. The upper loam unit (unit LM; Figs. 2.3, 2.4) is found at 2-5 m below surface. This unit is characterised by homogeneous, stiff sandy loam. In case the loam is calcareous, small terrestrial and freshwater molluscs may be present. The upper loam unit attains an average thickness of 1.5-2 m and reaches a thickness of more than 3 m in the area between Eindhoven and 's-Hertogenbosch. The lower and upper boundary of this unit are cryoturbated.

Organic-rich deposits frequently occur in the Boxtel Formation in the Roer Valley Graben. Three different types can be distinguished. The first type consists of thin (less than 1 m thick) humic loam and silty peat layers that are often cryoturbated. These organic levels only have a limited areal extent and can generally not be correlated with similar deposits in neighbouring boreholes. The second type consists of 0.5-3 m thick peat levels that show recognisable wood fragments and are associated with a level of rootlets in the deposits below. Although not continuous, these peat levels can sometimes be correlated from core to core. In the Roer Valley Graben, at least two of these extensive organic horizons have been identified so far (Figs. 2.3, 2.4: thick peat levels in borehole 51B0307). As a third type, in the northern part of the Roer Valley Graben, a 5-10 m meter thick unit of horizontally-bedded fine sand and loam occurs, which is characterised by the presence of ample organic fragments and 5-30 cm thick humic loam layers (e.g. borehole 45D0154: 4.42-12.05 m -NAP in Fig. 2.3).

Although some general trends can be deduced from the internal structure of the Boxtel Formation in the Roer Valley Graben, both geological cross sections show large lithological differences between neighbouring boreholes. This is due to the local and discontinuous nature of the aeolian and fluvial depositional processes responsible for the formation of these sediments. The sedimentary sequence has been further disturbed by numerous cryoturbation phases that affected the deposits after their formation. Because cryoturbation does not only depend on low temperatures, but also on the availability of

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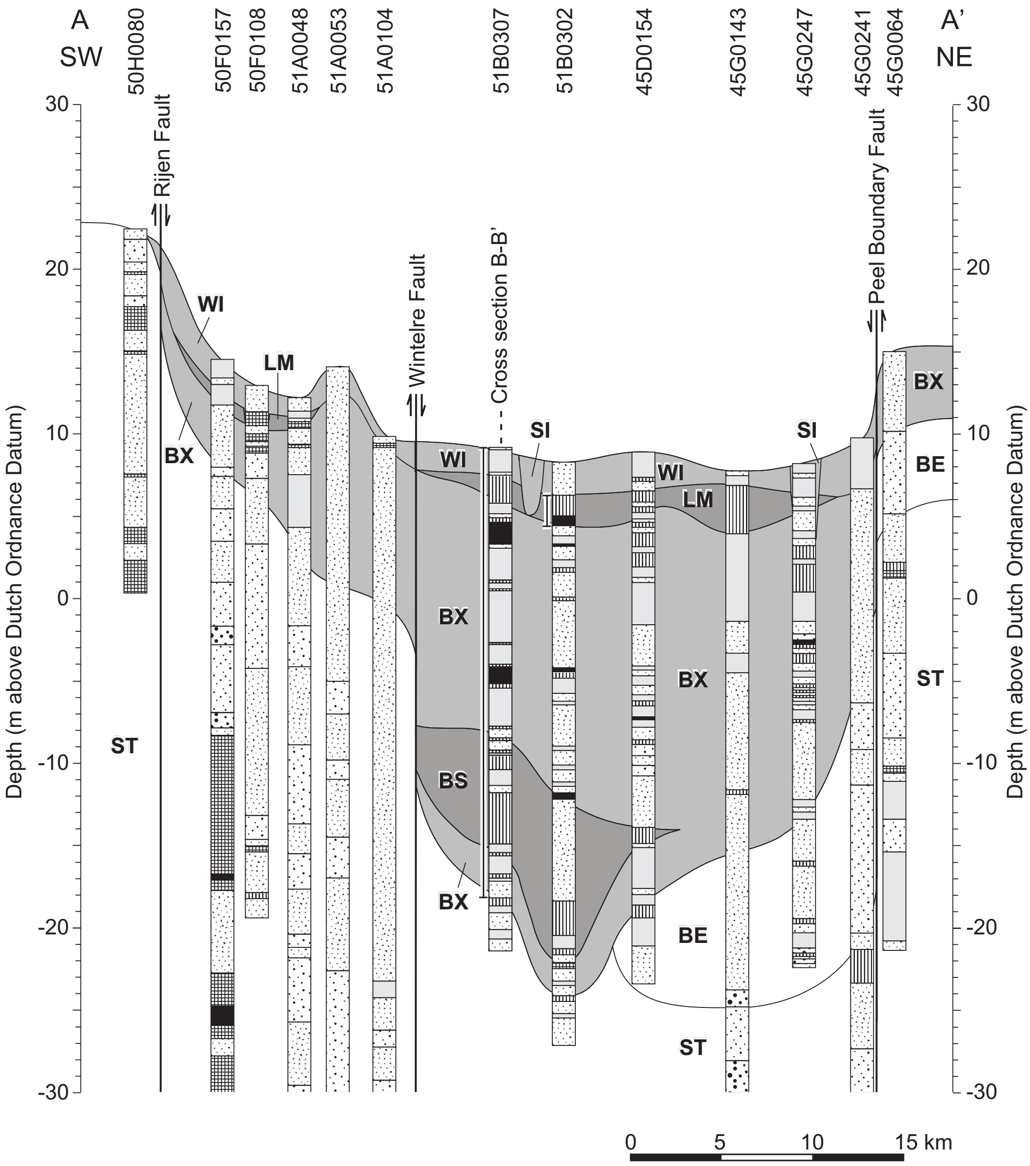
Figure 2.3 (p. 29) Simplified SW-NE geological cross section through the deposits of the Boxtel Formation in the Roer Valley Graben.



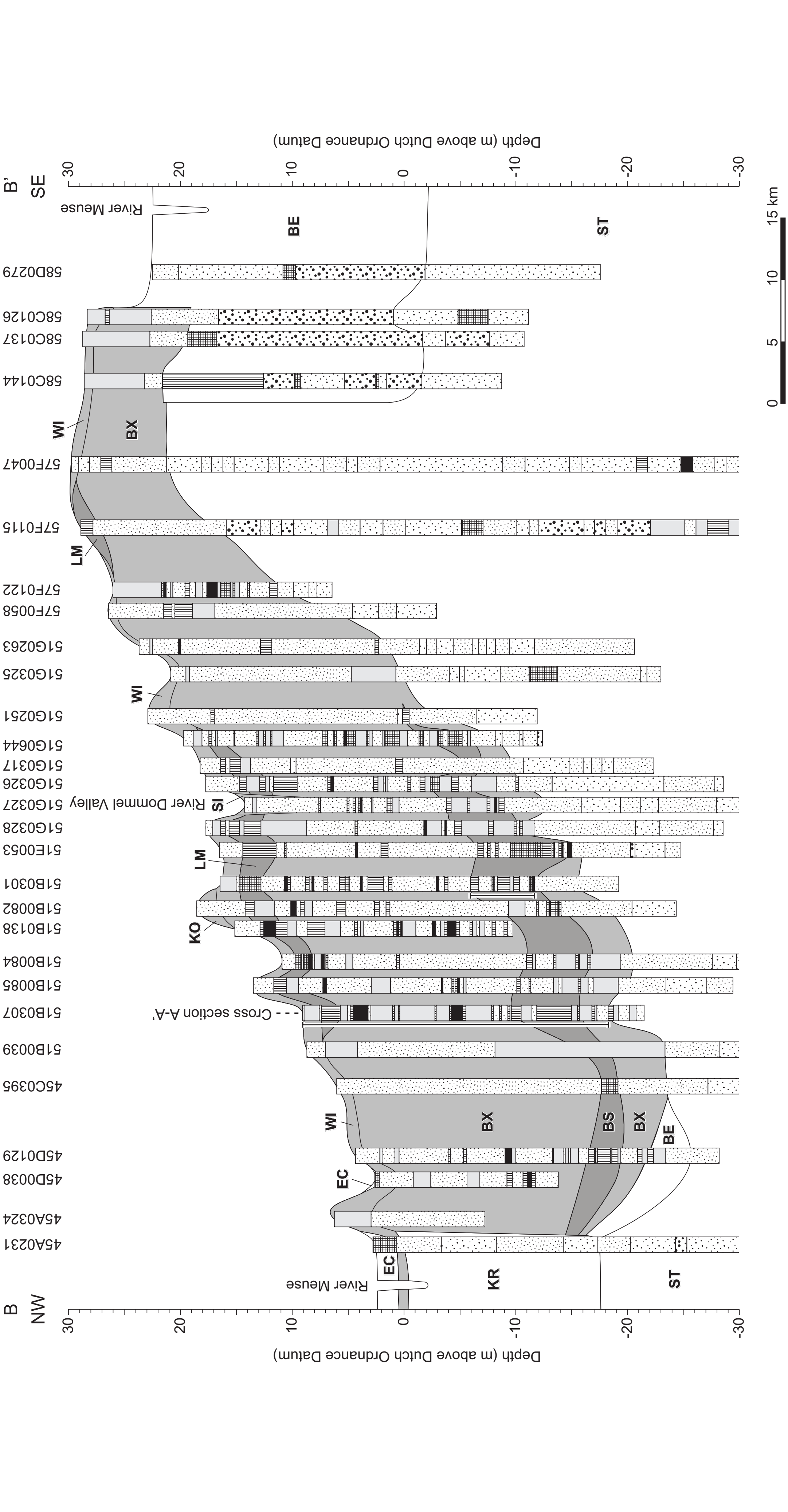
Legend

Lithology

- Peat & gyttja
- Clay
- Loam
- Fine sand (63-150 μm)
- Medium sand (150-300 μm)
- Coarse sand (300-2000 μm)
- Gravel
- Stratotype (Fig. 2.5)
- Fault line

Lithostratigraphy

EC Echteld Formation
KR Kreftenheye Formation
BX Boxtel Formation
KO Boxtel Formation, Kootwijk Member
SI Boxtel Formation, Singraven Member
WI Boxtel Formation, Wierden Member
LM Boxtel Formation, Liempde Member
BS Boxtel Formation, Best Member
BE Beegden Formation
ST Sterksel Formation and older



B
NW
B'
SE
Depth (m above Dutch Ordnance Datum)
30
20
10
0
-10
-20
-30
River Meuse
EC
KR
ST
45A0231
45A0324
45D0038
45D0129
WI
BX
BS
BE
45C0395
51B0039
51B0307
Cross section A-A'
51B0085
51B0084
51B0138
KO
51B0082
51B0301
LM
51E0053
51G0328
51G0327
SI
River Dommel Valley
51G0326
51G0317
51G0644
51G0251
51G0325
51G0263
57F0058
57F0122
57F0115
57F0047
58C0144
58C0137
58C0126
58D0279
0
5
10
15 km

moisture and the grain size of the affected sediment (Vandenberghe & Van den Broek, 1982; Vandenberghe, 1988), the fine-grained deposits in the low-lying Roer Valley Graben have been especially susceptible to cryoturbatic deformation during the cold phases of the Middle and Late Pleistocene.

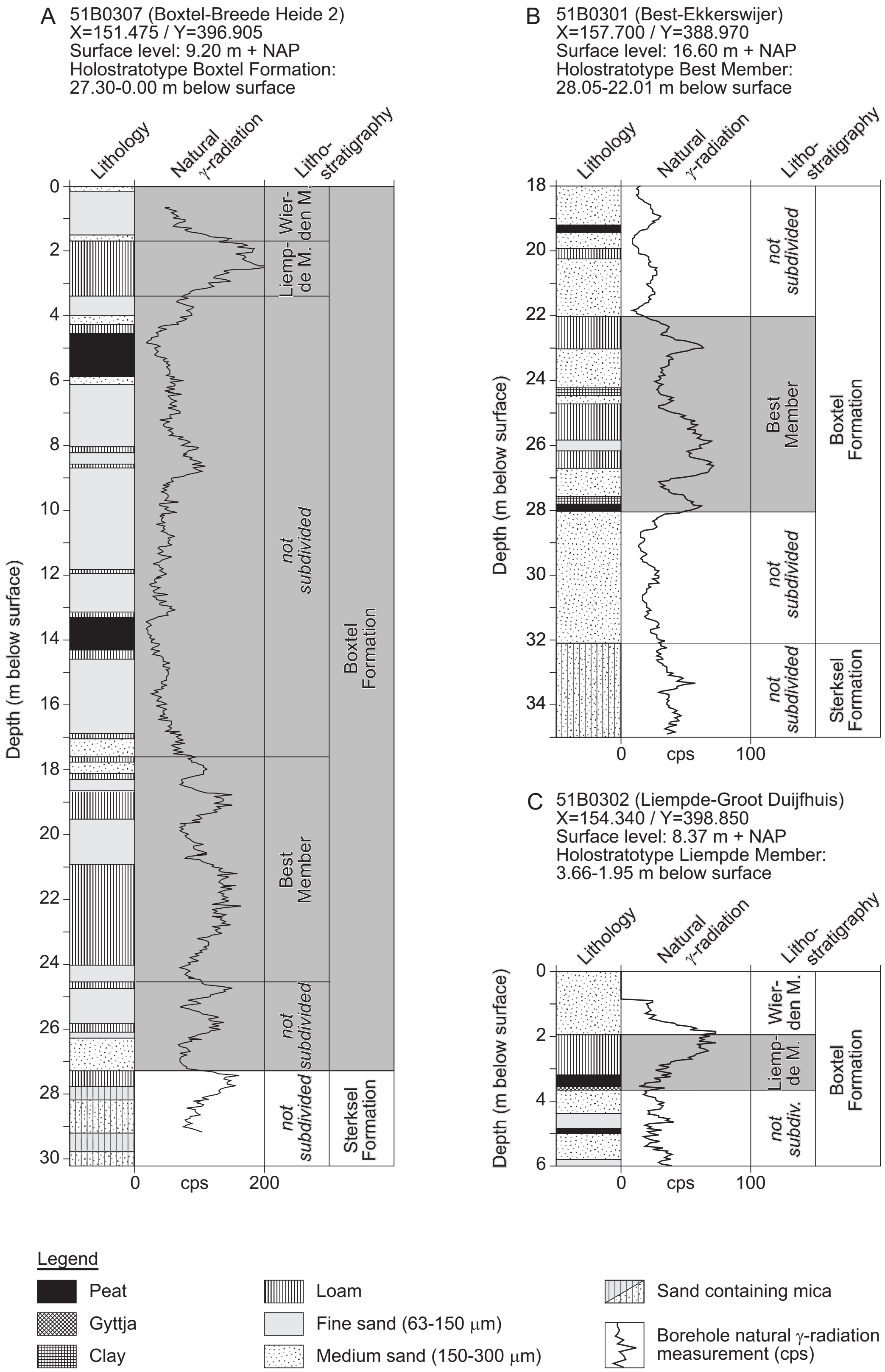
2.3.2 Definition and description of the Boxtel Formation

The holostratotype of the Boxtel Formation is defined in the central part of the Roer Valley Graben, close to the village of Boxtel (Fig. 2.1). It encompasses the sediments of core Boxtel-Breede Heide 2 (51B0307) from a depth of 27.30 m up to the surface (Fig. 2.5A). The core is situated at the intersection of the two geological cross sections shown in Figs. 2.3 and 2.4 and is a good representation of the fine-grained sedimentary sequence in the Roer Valley Graben.

At the stratotype locality, the fine-grained sediments of the Boxtel Formation are underlain by mica-rich, silt-poor, medium-grained fluvial deposits of the Sterksel Formation (Fig. 2.5A). The boundary between the Sterksel Formation and Boxtel Formation appears gradual, because of partial reworking of the deposits of the Sterksel Formation. The lower part of the Boxtel Formation (27.30-24.35 m) shows a dominance of fine to medium sand, silty fine sand and sandy loam. This is interpreted as an alternation of low-energy fluvial deposits and fluvio-aeolian deposits. From 24.35 m upward, bleached fine to medium sand and grey loam alternate. The loam is sandy and stiff and has a characteristic greenish colour. The natural gamma-ray measurement shows relatively high values for both the sand and loam in this unit, because the sediment contains higher contents of potassium feldspar and mica than granulometrically similar sediments in other parts of the Boxtel Formation (Fig. 2.5A). This part of the Boxtel Formation is defined as a separate member (Best Member) and will be described in more detail in the next subsection.

Above 17.56 m, the majority of the sediments in core Boxtel-Breede Heide 2 consists of fine to medium sand, often forming alternating sand and silty sand laminae. Thin (5-50 cm), cryoturbated humic loam to silty peat layers occur at various depths in the sandy sediments (e.g. at 11.90-11.85 m below surface). These organic-rich layers are generally local phenomena that do not occur at the same stratigraphic level in other cores. Two thick organic layers occur at 14.51-13.10 and 5.80-4.27 m below surface, respectively. These consist of peaty sand, peat and humic loam. Most of the peat is amorphic, but plant remains and wood fragments occur at certain levels. Roots penetrate the sand below the peat. A large frost crack extends down from the top of the upper organic layer. The peat layers are characterised by very low natural-gamma values, because of the scarcity of siliciclastic material (Fig. 2.5A).

Figure 2.4 (p. 30) Simplified NW-SE geological cross section through the deposits of the Boxtel Formation in the Roer Valley Graben. For legend, see Figure 2.3.



A 51B0307 (Boxtel-Breede Heide 2)
X=151.475 / Y=396.905
Surface level: 9.20 m + NAP
Holostratotype Boxtel Formation:
27.30-0.00 m below surface
Lithology
Natural γ-radiation
Litho-stratigraphy
Depth (m below surface)
Wier-den M.
Liemp-de M.
not subdivided
Best Member
Boxtel Formation
Sterksel Formation
cps
B 51B0301 (Best-Ekkerswijer)
X=157.700 / Y=388.970
Surface level: 16.60 m + NAP
Holostratotype Best Member:
28.05-22.01 m below surface
C 51B0302 (Liempde-Groot Duijfhuis)
X=154.340 / Y=398.850
Surface level: 8.37 m + NAP
Holostratotype Liempde Member:
3.66-1.95 m below surface
not subdiv.
Legend
Peat
Gyttja
Clay
Loam
Fine sand (63-150 μm)
Medium sand (150-300 μm)
Sand containing mica
Borehole natural γ-radiation measurement (cps)

Between 3.34 and 1.58 m, a thick, greenish-grey sandy loam or humic loam layer occurs, which is characterised by its colour, homogeneous lithology, stiffness and relatively high natural gamma-ray values. The loam unit is widespread in the shallow subsoil of the Roer Valley Graben and because of its characteristic lithology and well-defined stratigraphic position, the sandy loam has been defined as a separate lithostratigraphic member (Liempde Member, see description hereafter). Above the sandy loam unit, horizontally-bedded fine to medium sand occurs (Wierden Member). The sand covers the present land surface and served as parent material for the development of a podsolic soil.

The deposits of the Boxtel Formation have not been formed by a single depositional process, but show gradual vertical and lateral changes from one depositional environment into another. Furthermore, many hiatuses are present in the sedimentary sequence. A distinction can be made between the lower part of the formation (Fig. 2.5A: 27.30-17.56 m below surface), affected by fluvial processes, and the upper part (above 17.56 m), where aeolian processes dominate. In the lower part, the presence of extensive floodloam deposits (Best Member) indicates that the river Meuse affected sedimentation in the area. Above that level, wet-aeolian sand-sheets became the dominant type of deposit and only small streams and standing-water bodies influenced sedimentation. Under predominantly cold climatic conditions, the Roer Valley Graben was filled with aeolian sediments, creating a slightly undulating relief. In shallow, humid depressions, thin humic loam and loamy peat layers developed. The depressions were also the most favourable places for the occurrence of cryoturbatic deformation and frost cracking in very cold periods. During at least two separate warm-temperate periods, peat formation occurred, starting from the humid depressions.

2.3.3 Definition and description of the Best Member

The Best Member is defined in core Best-Ekkerswijer (51B0301: 28.05-22.01 m below surface; Fig. 2.5B). It consists of 1-2 m thick brownish grey to brownish green sandy loam layers, separated by 0.5-1 m thick bleached silty fine to medium sand layers (105-300 µm). The sedimentary contact between sand and loam is usually abrupt. The loam is characterised by its stiffness and green colour. The top of the loam layers may be humic. Locally, medium sand (210-300 µm) and thin silty peat layers occur. The unit contains vertical root fragments and is generally non-calcareous.

The occurrence of the Best Member is restricted to the central part of the Roer Valley Graben. The areal distribution is limited by coarse-grained fluvial sediments of the Kreftenheye Formation in the north, the Wintelre Fault in the south and west and the deposits of the Beegden Formation in the east (Fig. 2.6A). The Best Member occurs between 10 and 20 m -NAP. Its thickness ranges from several meters to ten meters and is related to the number of loam layers present. The average unit thickness is 4-6 m. The

Figure 2.5 (p. 32) (A) Holostratotype of the Boxtel Formation (51B0307); (B) Holostratotype of the Best Member (51B0301); (C) Holostratotype of the Liempde Member (51B0302).

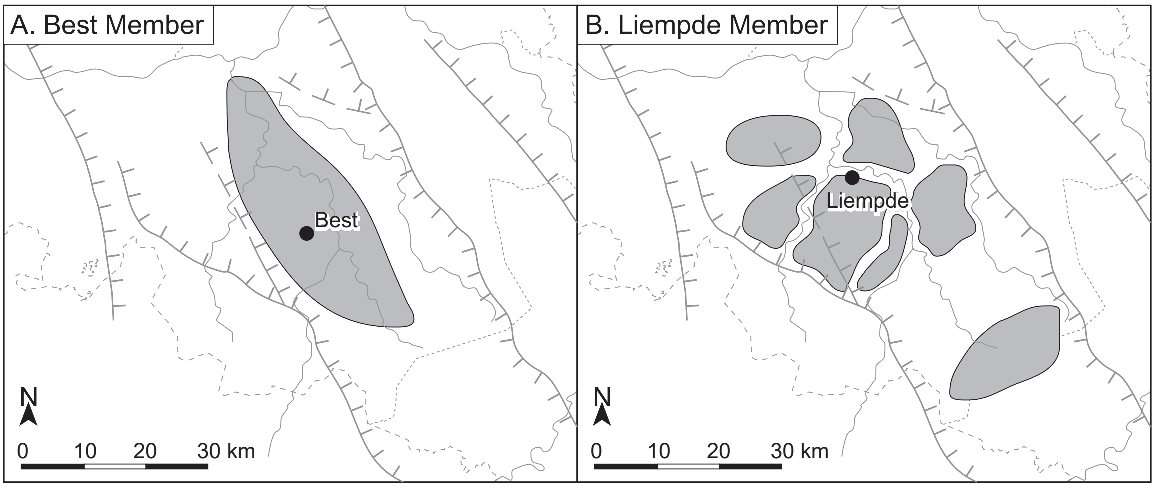


Figure 2.6 Areal distribution of deposits of the Best Member (A) and Liempde Member (B) in the Roer Valley Graben.

Best Member may constitute the lowermost part of the Boxtel Formation, but usually, fine to medium sand and sandy loam of the Boxtel Formation is present below the Best Member (Figs. 2.3, 2.4, 2.5). Cryoturbated sand and loam or horizontally-bedded sand with laminae of reworked organic debris are found on top of the Best Member. The lower and upper boundary of the Best Member are abrupt, the upper boundary may be erosive.

Fig. 2.7 shows a genetic model for the formation of the Best Member. The unit consists of interfingering sandy aeolian deposits, derived from the area west and south of the central part of the Roer Valley Graben, and floodloam deposits, associated with the Meuse fluvial system. Grain-size distributions of the floodloam deposits are typically double-peaked and reveal the presence of an admixture of medium sand (210-300 µm; Fig. 2.8A). The grain-size of the sand is similar to that of aeolian silty sand, which strongly suggests that it is reworked from aeolian sand layers or blown in from adjacent areas during formation of the floodloam. Palynological analyses show that both the sand and loam have been deposited in periglacial climatic conditions. The bleached colour of the sand indicates soil formation (cf. arctic soil of Van der Hammen et al., 1967; Vink & Sevink, 1971). Furthermore, the sediment contains reworked dinoflagellates and reworked pollen grains, including *Classopollis* species. *Classopollis* pollen is derived exclusively from Late-Triassic to Cretaceous sedimentary rocks, which crop out in the upstream part of the catchment of the river Meuse. This points to a genetic link with the coarse-grained fluvial deposits of the Beegden Formation. After a flood event, aeolian deposition and soil formation resumed, until the next flooding took place. Although the floodloam deposits in this unit are genetically related to coarse-grained fluvial deposits of the river Meuse, they interfinger with the sandy aeolian deposits and have incorporated part of these sediments. Therefore, they are regarded as part of the Boxtel Formation.

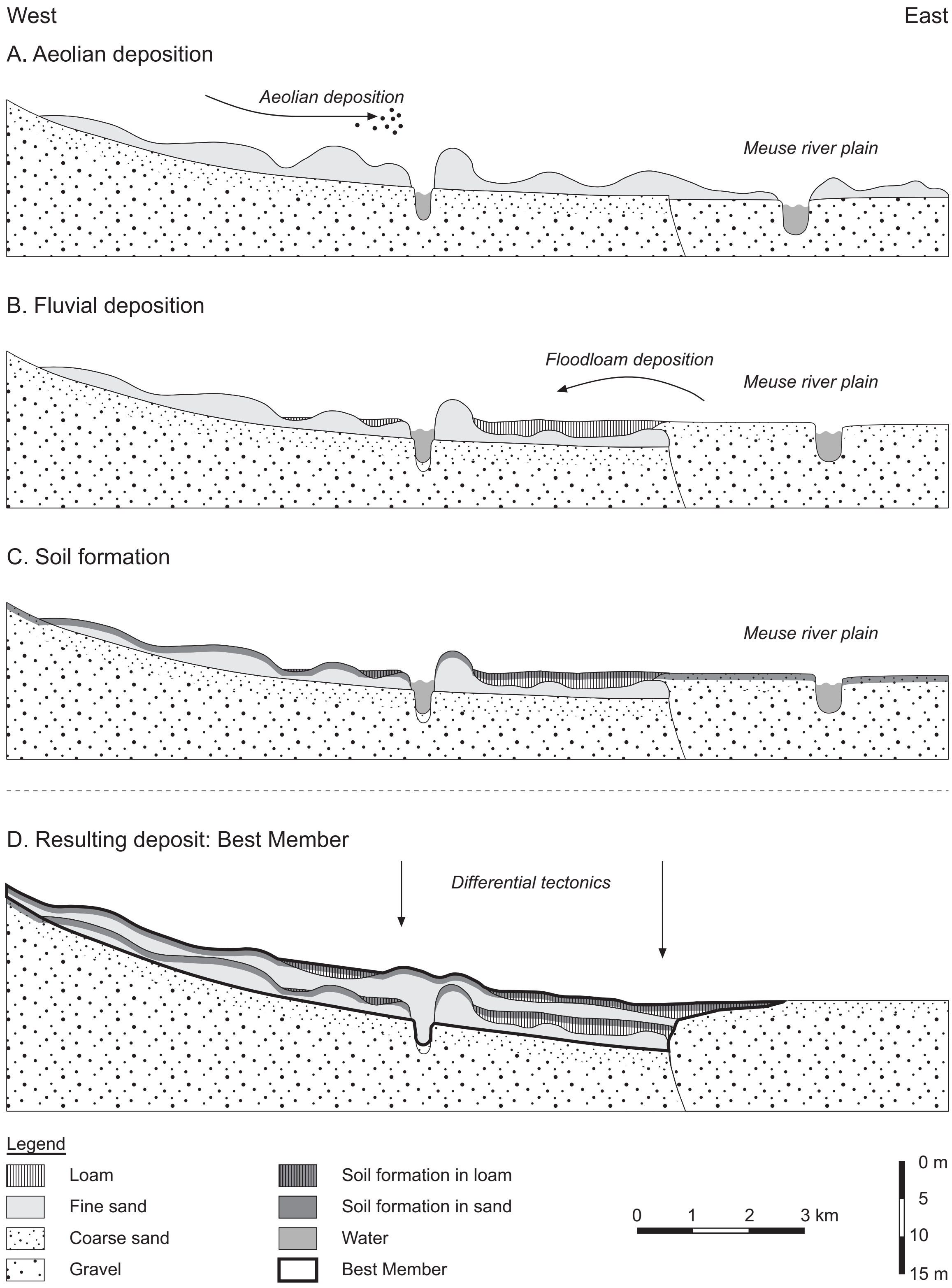


Figure 2.7 Genetic model for the formation of the Best Member. (A-C) Different processes contributing to the formation of the Best member; (D) Resulting sediment body after differential tectonic subsidence: the Best Member.

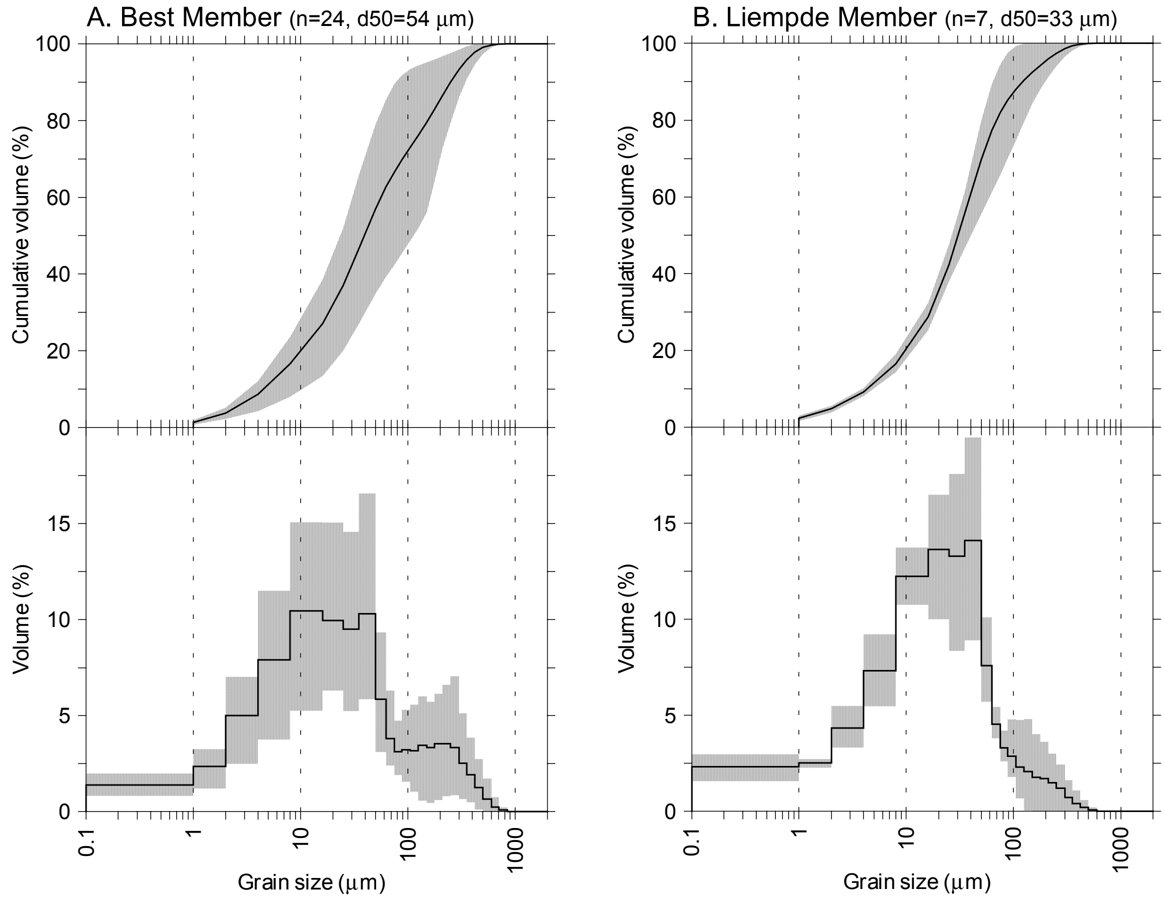


Figure 2.8 Average grain-size distribution (below) and average cumulative grain-size distribution (above) of floodloam deposits of the Best Member (A) and reworked sandy loess deposits of the Liempde Member (B). The grain-size envelopes encompass the 10-90% percentile range for each unit. The number of samples (n) and the median grain size (d50) are indicated above the graphs.

2.3.4 Definition and description of the Liempde Member

The Liempde Member is defined in core Liempde-Groot Duijfhuis (51B0302: 3.66-1.95 m below surface; Fig. 2.5C). It consists of brownish grey to greenish grey sandy loam. The lower part of the loam may be humic or is underlain by silty peat or gyttja. Incidentally, silty fine to medium sand (105-210 µm) is present. The loam is characterised by its grey colour, lithological homogeneity and stiffness. Part of the loam

is calcareous and contains small terrestrial and freshwater molluscs. The lower and upper boundary of the unit are usually cryoturbated. The Liempde Member is present in a large part of the Roer Valley Graben, except in former and present small river valleys and in the elevated area between Eindhoven and Weert (Fig. 2.6B). Throughout the distribution area, the loam has a rather uniform thickness of 1-2 m. Locally, it attains a thickness of more than 3 m. The Liempde Member generally overlies silty medium sand (150-210 µm). Sometimes, the silty sand grades into the loam of the Liempde Member, but more often, the lower boundary is abrupt. On top of the Liempde Member, horizontally-bedded or massive fine to medium sand (105-210 μm) forms a clear lithological contrast. This boundary is often deformed by periglacial loading.

The sediments of the Liempde Member have been first described by Vink (1949) as part of the 'Brabant loam' deposits. This term has subsequently been used in a broad sense by many authors to denote occurrences of loam and sandy loam at shallow depth in the southern Netherlands (e.g. Van Dorsser, 1956; Van den Toorn, 1967; Kuyl & Bisschops, 1969; Bisschops, 1973). Ruegg (1983) included the 'Brabant loam' deposits in his lacustrine subfacies.

The large thickness and areal extent of the loam of the Liempde Member is typical for the shallow subsurface of the Roer Valley Graben. The loam completely covers the interfluvial plateaus between the small river valleys and is rather homogeneous, which makes a fluvial genesis unlikely. The grain-size distribution resembles that of aeolian loess, but with an admixture of fine- to medium-grained sand (Fig. 2.8B; cf. Kuyl & Bisschops, 1969). Palynological and malacological data and the presence of load casts point to deposition in a humid, open landscape under permafrost conditions (Bisschops et al., 1985). The presence of freshwater molluscs and the sparse occurrence of wave ripples indicate that at least part of the sediments has been deposited in very shallow standing water. The unit is therefore considered an aeolian sediment, which has been deposited on a humid surface in a poorly drained area and has been partly reworked by surficial water flow. Deposition in thermokarst lakes, as has been suggested by Bisschops et al. (1985), is unlikely, considering modern-day periglacial environments, where these lakes are shallow and only have a small (less than 2 km) diameter (French, 1996).

2.4 Implications for the lithostratigraphic framework of the Netherlands

2.4.1 Stratigraphic position of the Boxtel Formation

The Boxtel Formation is a newly introduced formation in the lithostratigraphic framework of Upper-Tertiary and Quaternary deposits in the Netherlands. This framework has recently been revised by the National Geological Survey (TNO-NITG). It replaces the old lithostratigraphic scheme by Doppert et al. (1975), which was not exclusively based on lithological characteristics and stratigraphic position, but also used bio- and chronostratigraphy, as well as genesis, as differentiating criteria. The new framework is shown in the Appendix and all formation descriptions can be found at http://www.nitg.tno.nl/ned/. The Boxtel Formation has been greatly extended with respect to the Twente Formation sensu Doppert et al. (1975) (see below). In content, it also differs from the Nuenen Group that was previously used in the Roer Valley Graben. Following Hedberg, ed. (1976) and Salvador, ed. (1994), substantial changes in content should lead to the introduction of a new formation name. Therefore, we introduce the name Boxtel Formation for these deposits.

The Boxtel Formation comprises the deposits of the former Twente Formation, Singraven Formation and Kootwijk Formation (Fig. 2.9) and aeolian dune sands in the Rhine-Meuse floodplain that were formerly considered part of the Kreftenheye Formation (Doppert et al., 1975; see Appendix). Deposits of the former Asten Formation and Eindhoven Formation south of the maximum extent of the Saalian ice sheet (Fig. 2.1A) are also incorporated in the Boxtel Formation. North of the maximum Saalian ice extent, fine-grained deposits underlying glacial and fluvio-glacial deposits of the Drente Formation, are incorporated in the Drachten Formation, because of their clear stratigraphic position. These deposits were formerly incorporated in the Eindhoven Formation, a term that is now abandoned. Coastal peat that formed along the margins of the Saalian glacial basins ("continental Eemian deposits" of Doppert et al., 1975) is now incorporated in the Woudenberg Formation (Fig. 2.9).

In the northern half of the Netherlands, the lower boundary of the Boxtel Formation is formed by the Drente Formation that consists of glacial and fluvio-glacial deposits. In the southern Netherlands the lower boundary of the formation is formed by coarse-grained deposits of the rivers Rhine and Meuse (Waalre Formation, Sterksel Formation, Kreftenheye Formation and Beegden Formation; see Appendix). Locally, fine-grained deposits of the Stramproy Formation underlie the deposits of the Boxtel Formation. In southern Limburg, the lower boundary of the Boxtel Formation is formed by the Beegden Formation, containing coarse-grained deposits of the river Meuse, or by lithified siliciclastic and calcareous deposits of pre-Quaternary age.

In a large part of the country, the Boxtel Formation occurs at the surface. In the coastal plain of the western Netherlands and in the Rhine-Meuse alluvial plain, deposits of the Boxtel Formation have been (partly) eroded (Fig. 2.2) or are covered by clastic fluvial deposits of the Echteld Formation, peat of the Nieuwkoop Formation and clastic coastal or marine deposits of the Naaldwijk Formation (see Appendix). In the eastern and south-eastern Netherlands, the Boxtel Formation is locally covered by peat of the Nieuwkoop Formation.

2.4.2 Subdivision of the Boxtel Formation

The Boxtel Formation contains eight lithostratigraphic members. Table 2.2 shows a short lithological description, general genetic interpretation and the original literature references for each of these members. Fig. 2.10 illustrates their approximate chronostratigraphic position. Part of the Boxtel Formation remains undifferentiated, because members have been defined only if they can be recognised based on their lithological characteristics, stratigraphic position and mappability. If it is possible to identify and define additional members, they can be added to the lithostratigraphic framework in the future. The presented lithostratigraphic subdivision in members is not only applicable in geological mapping, but also in applied geological studies. Because it relates to lithological properties of the sediment, rather than to a combination of lithology, genesis and age, the Boxtel Formation and its internal subdivision can easily be used in for example hydrogeological and geo-engineering studies.

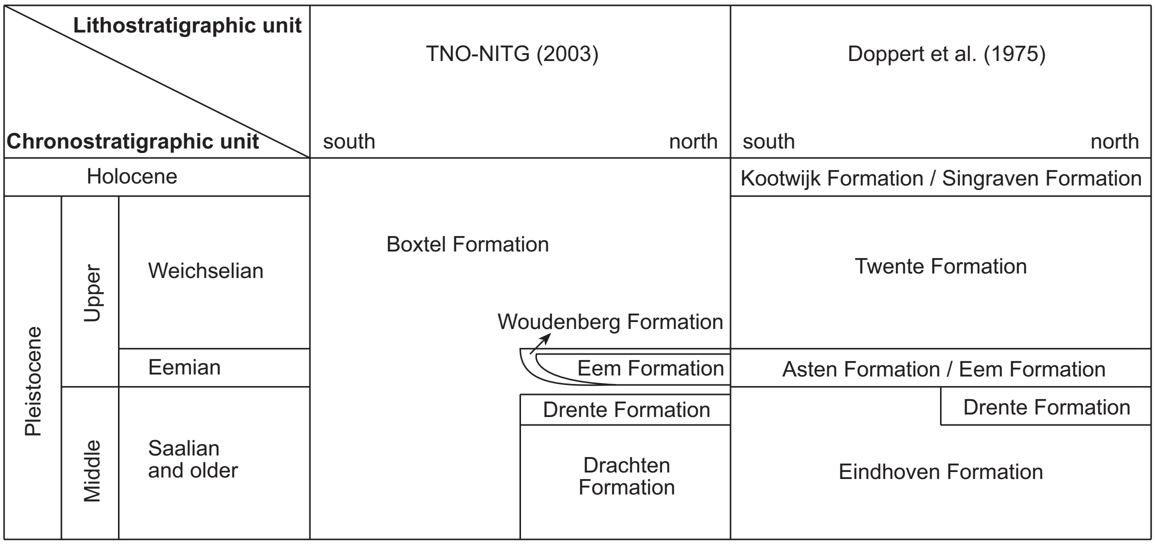


Figure 2.9 The position of the Boxtel Formation in the revised lithostratigraphic framework of the Netherlands (TNO-NITG, 2003) in relation to other formations. The lithostratigraphic framework of Doppert et al. (1975) is shown for comparison.

Within the Boxtel Formation, the Wierden Member generally occurs at the top. It consists of well-sorted aeolian coversand deposits and was originally introduced as a member in the Twente Formation by Van der Hammen (1971). The Kootwijk Member (aeolian drift sand) and Singraven Member (sand, loam and peat formed in small river basins) can locally be distinguished. Their definition is no longer restricted to Holocene deposits, as in the original definition by Doppert et al. (1975), but extends to similar deposits below that level (Fig. 2.10). In the Rhine-Meuse floodplain, the top of the Boxtel Formation may be formed by aeolian inland dune deposits of the Delwijnen Member. These sediments are moderately sorted and slightly coarser than other aeolian deposits of the Boxtel Formation, because they largely consist of reworked fluvial deposits (Koster, 1982; Törnqvist et al., 1994). Sediments belonging to the Schimmert Member (aeolian loess deposits) make up the Boxtel Formation in southern Limburg. These deposits were formerly incorporated in the Twente Formation and Eindhoven Formation (Doppert et al., 1975; Kuyl, 1980). The Tilligte Member contains local loam and peat deposits. It can be discerned in the Twente region and was originally introduced as 'Tilligte beds' in the Twente Formation by Van Huissteden (1990). The Best Member and Liempde Member have been first described and defined in this paper.

2.5 Conclusions

- Application of the traditional Quaternary lithostratigraphic framework of the Netherlands to the subdivision of terrestrial fine-grained deposits has always been problematic. Deposits of many formations could not be distinguished from each other based on lithological characteristics and stratigraphic position alone. Litho-, bio- and chronostratigraphic criteria were intermingled, creating a large dependence on the results of laboratory analyses. Problems were particularly large in the Roer Valley Graben. As a result of tectonic subsidence, this area contains the thickest and most complete sedimentary sequence of Middle- and Upper-Quaternary sand, loam and

Table 2.2 Lithostratigraphic subdivision of the Boxtel Formation into members. * Units described in this paper.

Lithostratigraphic member	Dominant lithology	Depositional environment	Original literature references
Kootwijk Member	Light grey to yellow, non-calcareous fine to medium sand, with coarse sand laminae and organic laminae	Aeolian drift sand deposits	Kootwijk Formation (Doppert et al., 1975)
Singraven Member	Grey to yellow, fine to coarse sand; grey sandy loam; grey, humic sandy clay; peat; gyttja	Channel and floodbasin deposits of small rivers and associated peat and gyttja	Singraven Formation (Doppert et al., 1975)
Delwijnen Member	Grey to brownish grey, non-calcareous medium to coarse sand	Aeolian inland dune deposits	'Riverdune deposits' of the Kreftenheye Formation (Doppert et al., 1975); Delwijnen Member (Törnqvist et al., 1994)
Wierden Member	Light brown to yellowish brown, non-calcareous fine to medium sand	Aeolian coversand deposits	Wierden Member (Van der Hammen, 1971); 'Coversand deposits' of the Twente Formation (Doppert et al., 1975)
Liempde Member *	Grey to greenish grey sandy loam; grey fine to medium silty sand	Aeolian sandy loess deposits, reworked by surficial standing water	Introduced in this paper
Schimmert Member	Dark brown to yellowish brown loam and sandy loam, with calcretes	Aeolian loess and reworked loess deposits	'Loess deposits' of the Eindhoven Formation and Twente Formation (Doppert et al., 1975)
Tilligte Member	Grey, humic sandy loam, with medium to coarse sand laminae; brown, silty to sandy peat; yellowish grey, calcareous gyttja	Floodbasin deposits of small rivers and associated peat and gyttja; lacustrine deposits	'Tilligte beds' (Van Huissteden, 1990)
Best Member *	Green to grey, stiff sandy loam; light brown fine to medium sand	Fluvial floodloam deposits and interfingering aeolian deposits	Introduced in this paper

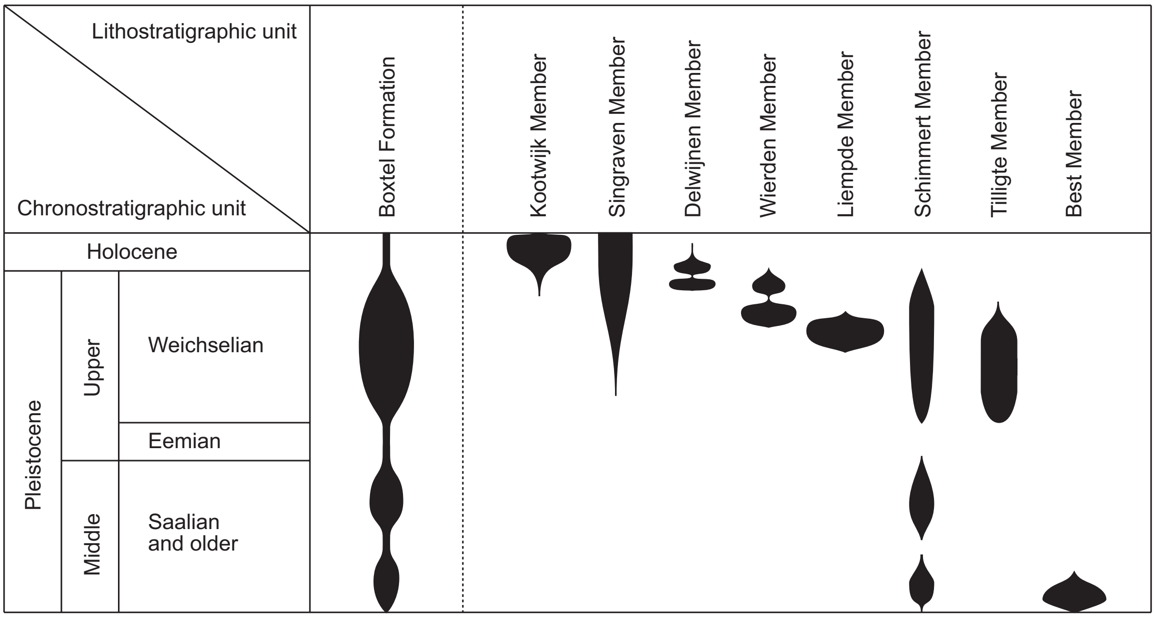


Figure 2.10 Approximate chronostratigraphic position of the Boxtel Formation and the eight lithostratigraphic members in the Boxtel Formation. Line thickness represents the relative amount of sediments deposited during a specific time interval.

peat deposits. These sediments have mainly been formed by aeolian and fluvial processes. The traditional lithostratigraphic subdivision of these deposits into Twente Formation, Asten Formation and Eindhoven Formation was based on the presumed widespread presence of a horizon of organic-rich interglacial sediments of Eemian age. Introduction of the Nuenen Group to describe these deposits was only an artificial solution that left the problem of discriminating between Nuenen Group deposits in the Roer Valley Graben and deposits of the Twente Formation, Asten Formation and/or Eindhoven Formation in other parts of the Netherlands;

- To avoid intermingling of criteria regarding lithological characteristics, genesis and age, the terrestrial fine-grained sediments are now incorporated into the new Boxtel Formation. The Boxtel Formation comprises the deposits of the former Twente Formation, Singraven Formation and Kootwijk Formation and aeolian dune deposits in the Rhine-Meuse floodplain. Deposits of the former Asten Formation and Eindhoven Formation south of the maximum extent of the Saalian ice sheet are also incorporated in the Boxtel Formation. Because the content of the Boxtel Formation is drastically different from that of the former Twente Formation, Asten Formation, Eindhoven Formation or Nuenen Group, these lithostratigraphic names cannot be maintained;

- The Boxtel Formation contains eight lithostratigraphic members that describe the most characteristic parts of the formation. The remaining part of the formation remains undifferentiated. Two members are defined in the Roer Valley Graben. The Best Member incorporates alternating floodloam deposits and sandy aeolian deposits in the lower part of the Boxtel Formation. The Liempde Member includes reworked aeolian loess and sandy loess deposits ('Brabant loam') that occur in the upper part of the sedimentary sequence.

Acknowledgements

We thank Foppe de Lang for attending many critical discussions regarding the Late-Quaternary stratigraphy of the Netherlands. Annika Hesselink and Ward Koster are thanked for critically reading earlier drafts of this manuscript.

3 SEDIMENTOLOGY AND FACIES DISTRIBUTION OF PLEISTOCENE COLD-CLIMATE AEOLIAN AND FLUVIAL DEPOSITS IN THE ROER VALLEY GRABEN (SOUTH-EASTERN NETHERLANDS)

with Eduard A. Koster

Submitted to Permafrost and Periglacial Processes

Abstract

The Roer Valley Graben (south-eastern Netherlands) is a tectonic subsidence area that contains a 35 m-thick record of fine-grained Middle- and Upper-Pleistocene deposits. The sedimentary structures and depositional environment of these sediments were studied using undisturbed sediment cores and cone penetration tests (CPTs). Seven sedimentary facies were distinguished, ranging from sandy fluvial deposits to loamy aeolian deposits and organics. Wet-aeolian sand-sheet and loam deposits are the two most widespread facies. The aeolian sand is characterised by horizontal alternating bedding, attributed to deposition of sand and silty sand on an alternating wet and dry surface. The loam is usually massive and interpreted as a reworked loess deposit. In the sediment sequence, a gradual shift can be observed from a dominance of fluvial deposits to an alternation of fluvial and aeolian deposits and finally, to predominantly aeolian deposits. The majority of the sediments has been deposited during successive Middle- and Late-Pleistocene glacial periods. It is argued that subsidence and humid surface conditions were the main factors determining the local depositional environment and preservation potential of the sediments in the Roer Valley Graben.

3.1 Introduction and geological setting

Pleistocene periglacial aeolian deposits occur at or close to the surface in large parts of north-western Europe. The most widespread are sand-sheet, dune and loess deposits. Sand-sheet deposits (in the Netherlands and Belgium termed coversand deposits, as they often cover the pre-existing morphology) and dune deposits are found in an extensive area just south of the maximum extent of the Weichselian ice sheets (Fig. 3.1). Further to the south, these deposits gradually grade into and intercalate with loamy coversand, sandy loess and loess. Because of their widespread occurrence at or close to the surface, the sediment properties and genesis of sand-sheet, dune and loess deposits are relatively well-known (e.g. Ruegg, 1983; Mücher, 1986; Schwan, 1986, 1988). (Dry-)aeolian deposits are therefore often regarded as characteristic for the Pleistocene glacial landscape in north-western Europe.

In many sedimentary basins, sand-sheet deposits and loess only form the topmost part of a much thicker sequence of Pleistocene fine-grained aeolian, fluvial, shallow marine and organic deposits. Examples are the Saalian glacial basins in the central Netherlands (Fig. 3.2A), such as the Amsterdam Basin (De Gans et al., 2000; Van Leeuwen et al., 2000), Amersfoort Basin (Zagwijn, 1961), Hengelo Basin (Zagwijn, 1974; Van Huissteden, 1990) and Nordhorn Basin (Dinkel Valley fill in e.g. Van der Hammen & Wijmstra, eds., 1971; Van Huissteden, 1990), where 10-25 m-thick Weichselian fine-grained periglacial deposits occur. In the southern Netherlands, south of the maximum extent of the Pleistocene ice sheets, the Roer Valley Graben (Fig. 3.2B) contains up to 35 m-thick fine-grained aeolian, fluvio-aeolian, fluvial and organic deposits of Middle- and Late-Pleistocene age.

The Roer Valley Graben is an active intra-continental subsidence area that forms part of the Cenozoic rift system of western and central Europe (Ziegler, 1994). It originated in the Early Tertiary (Oligocene) and was filled with alternating marine, coastal and fluvial deposits during the Tertiary and Early Quaternary. After the sea withdrew from the area in the course of the Early Pleistocene, sediments from a mixed Rhine-Meuse river system were deposited in the Roer Valley Graben. From the second half of the Middle Pleistocene on, the area does no longer host this large fluvial depositional system (Kasse, 1988; Zagwijn, 1989; Van den Berg, 1994). Since that time, the accommodation space has been filled with fine-grained sand, silt and peat, deposited during several glacial-interglacial cycles. These sediments of diverse character were previously known as Nuenen Group deposits (Bisschops, 1973; Bisschops et al., 1985) and will in this paper be addressed to as Boxtel Formation. They are finer-grained, silty and contain less mica than the underlying fluvial deposits of the Sterksel Formation (medium- to coarse-grained Rhine and Meuse deposits) and Beegden Formation (coarse-grained Meuse deposits). The average relative subsidence rate of the Roer Valley Graben during the Quaternary amounts to 0.06-0.08 mm/a, with possibly a slight increase in the last 600 ka (Geluk et al., 1994; Houtgast & Van Balen, 2000). This equals to an accommodation space of at least 30 m during deposition of the fine-grained sediments of the Boxtel Formation, i.e. the last ~500 ka.

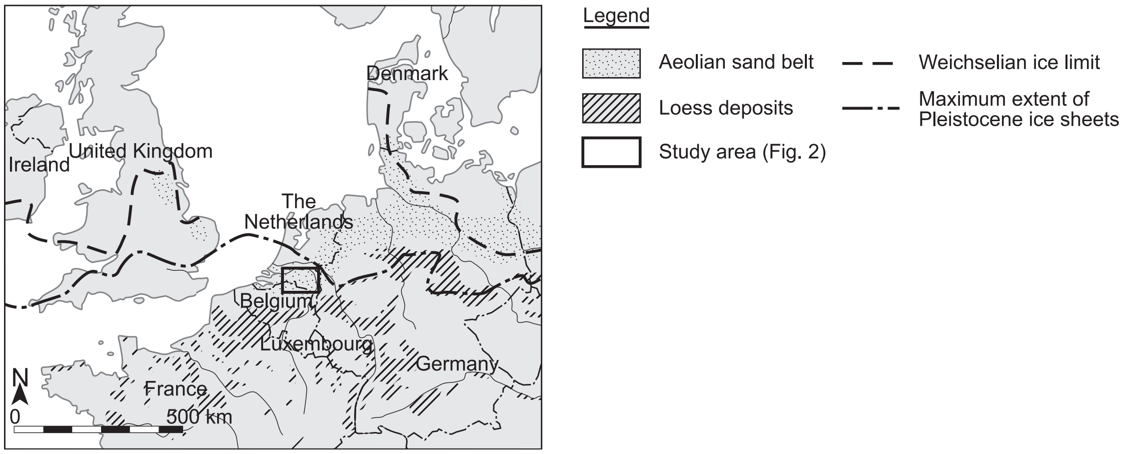


Figure 3.1 Areal distribution of surficial cold-climate sand-sheet, dune and loess deposits in north-western Europe.

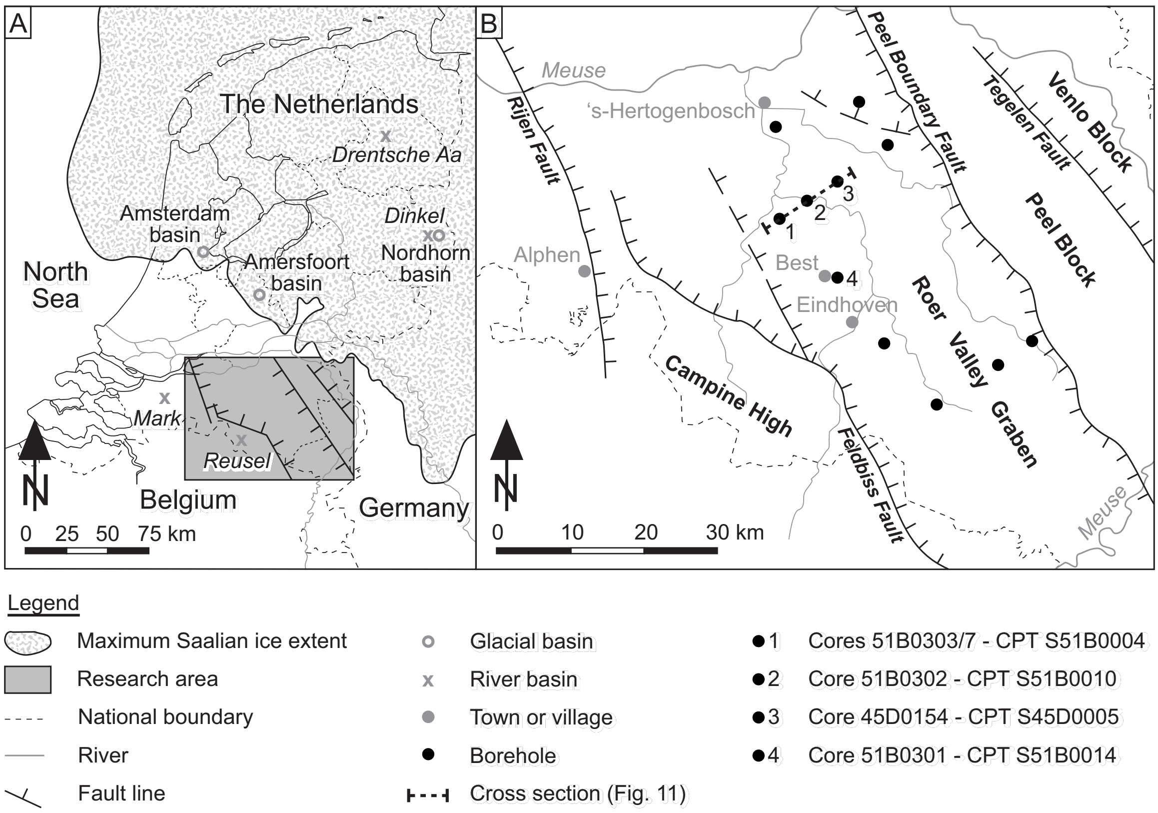


Figure 3.2 (A) Map, showing the position of the Roer Valley Graben relative to the maximum extent of the Pleistocene glaciations; (B) Map of the Roer Valley Graben with major tectonic features and the location of undisturbed sediment cores.

Information on the lithology and sedimentary structures of the Middle- and Upper-Pleistocene fine-grained deposits was mainly gained during geological mapping surveys at a 1/50,000 scale (Van den Toorn, 1967; Bisschops, 1973; Bisschops et al., 1985) and until recently, detailed information on sedimentary structures was largely restricted to the upper few m of the sedimentary record. Only one previous study from the Roer Valley Graben is known, in which undisturbed sediment cores from the deeper part of the Boxtel Formation were studied (Van Alphen, 1984; in: Bisschops et al., 1985). Recently, thirteen new 10 cm-wide, 30-35 m-long, largely undisturbed sediment cores were obtained from the Roer Valley Graben, covering the entire sedimentary sequence from the base of the Boxtel Formation upward. Cone penetration tests (CPTs) were carried out to support the characterisation of sedimentary units and to enable the correlation of data from widely separated boreholes.

The objective of the present paper is to describe and interpret the sedimentary facies that can be recognised in the fine-grained deposits of the Boxtel Formation in the Roer Valley Graben and to explain the vertical and lateral facies distribution. It will be demonstrated that the facies characteristics and architecture are related to a combination of local depositional setting and the generally cold-climate conditions during and after deposition.

3.2 Cold-climate aeolian and small-scale fluvial deposits in the Netherlands

The lithology and sedimentary structures of aeolian deposits in the Netherlands have been studied extensively (e.g. Koster, 1982; 1988; Ruegg, 1983; Mücher, 1986; Schwan, 1986; 1988; Kasse, 1997, and references therein). The majority of the available literature refers to aeolian sediments close to the present land surface. These deposits are usually of Late-Weichselian or Holocene age.

Aeolian dune deposits vary from medium-fine to medium-coarse grained (median grain size 150-300 μm) and are characterised by a combination of subhorizontal lamination and stacked sets of large-scale high-angle cross strata, typical for climbing bedforms (e.g. Koster, 1982). The sediments may form up to 20 m-high longitudinal ridges, transverse ridges and individual parabolic dunes.

Sand-sheet deposits are generally very-fine to medium-fine grained (median grain size 105-210 μm) and may contain silty laminae (16-75 μm) (Schwan, 1986, Kasse, 1997). Basic stratification types include:

- (Sub-)horizontal, even laminated to low-angle (<15°) cross-laminated fine sand (Ruegg, 1983: eolian subfacies A; Schwan, 1986, 1988: facies 2; Koster, 1988: sand sheet facies A; Table 3.1). Granule ripples and adhesion ripples are occasionally present, as are strings of small pebbles and deflation surfaces. This stratification type is attributed to deposition of small wind ripples or deposition in plain beds on a dry surface. Alternatively, it can be explained by sedimentation in the presence of a sparse vegetation cover;
- Horizontal alternating bedding of medium fine sand and silty very fine sand or loam (Ruegg, 1983: eolian subfacies B; Schwan, 1986, 1988: facies 3; Koster, 1988: sand

sheet facies B; Table 3.1). Adhesion ripples are common. This stratification type is attributed to alternating deposition and adhesion of sand (traction load) and loam (adhesion load) on a slightly undulating, alternating dry and moist surface (Ruegg, 1983; Koster et al., 1993). The alternating bedding often has a wavy or crinkly appearance, with irregular contacts between sand and silt. This has been attributed to small-scale water-escape structures or seasonal freezing and thawing (Ruegg, 1983; Schwan, 1986, 1987).

Loess deposits in the Netherlands typically consist of loam or sandy loam, with more than 75% of the grains being silt-sized (Kuyl, 1980). Most of the loess has a rather uniform grain size and lacks clear bedding, but occasionally an alternation of loam and sandy loam is present. This is attributed to solifluction processes in cold, humid conditions (Kuyl, 1980).

Table 3.1 Correlation of sedimentary facies between different authors.

Ruegg (1983)	Schwan (1986, 1988)	Koster (1988)
-	Facies 1	6: Dune sand facies
Eolian subfacies A	Facies 2	5: Sand sheet facies A
Eolian subfacies B	Facies 3	4: Sand sheet facies B
Lacustrine subfacies	-	3: (Aeolian-)lacustrine facies
Flowing-water subfacies	-	1/2: (Local) flowing-water or fluviatile facies A/B

A considerable part of the aeolian sediments has been reworked by fluvial processes or surficial water flow. Other sediments have been deposited in shallow standing-water bodies and lakes, as is indicated by the presence of wave ripples or detrital organic material. Some authors have therefore distinguished a lacustrine subfacies (Ruegg, 1983) or aeolian-lacustrine facies (Koster, 1988; Table 3.1) to denote deposits that consist of evenly- or wave-ripple laminated sand with intercalated silt and gyttja layers. These deposits are regarded as the infilling of shallow pools by aeolian supplied clastic sediments and intercalated organics. Fluvio-aeolian deposits generally consist of moderately sorted silty sand with occasional pebble strings and are interpreted as interbedded or reworked mixtures of fluvial and aeolian sediments. In a wider sense, the product of all reworking of aeolian sediments by surficial water flow and all aeolian redeposition of originally fluvial material can be regarded as fluvio-aeolian deposition. Because grain-size data indicate that both the lacustrine and flowing-water subfacies deposits (Ruegg, 1983; Table 3.1) generally consist of aeolian-derived sediments, the term fluvio-aeolian may be used for all these deposits. Niveo-aeolian sedimentation and associated denivation features have been advocated to have an effect on the internal lamination or sorting of aeolian deposits by various authors (e.g. Schwan, 1986). However, experiments with artificially deposited alternating layers of sand or loess and snow revealed that the original sedimentary structure of sand was not much affected by snowmelt. In contrast to this, the sedimentary lamination of loess was completely destroyed (Dijkmans & Mücher, 1989).

Cold-climate fluvial deposits in small lowland river basins have been the subject of many detailed studies (e.g. Drentsche Aa valley: De Gans, 1981; Dinkel valley: Van der Hammen & Wijmstra, eds., 1971; Van Huissteden, 1990; Mark valley: Vandenberghe et al.; 1987; Bohncke et al., 1987; Reusel valley: Van Huissteden et al., 1986). These studies were mostly restricted to Weichselian deposits, but resulted in detailed knowledge on the reaction of small rivers to various aspects of climate change (Bohncke & Vandenberghe, 1991; Vandenberghe, 1993; 1995; 2002). However, tectonic regime, drainage basin relief and sediment composition are likely to exert a much larger influence on the morphology, discharge regime and sediment load of a river than does regional climate (van Huissteden, 1990, p. 19). As a consequence, cold-climate fluvial deposits of small lowland rivers are as diverse as present-day fluvial deposits and show a wide range of sedimentary facies, ranging from coarse-grained channel deposits to fine-grained overbank deposits and peat. Ruegg (1983) combined all these sediments in a flowing-water subfacies, composed of deposits that show horizontal and climbing-ripple cross-lamination, as well as trough cross-lamination. Locally, loam layers and reworked macroscopic plant remains occur. This sedimentary facies correlates with the local flowing-water / fluvial facies of Koster (1988; Table 3.1).

3.3 Fine-grained deposits in the Roer Valley Graben

The fine-grained sediments of the Boxtel Formation in the Roer Valley Graben have first been studied in more detail in the 1940's and 1950's. This comprised granulometric (Wiggers, 1956), sediment-petrological (Zonneveld, 1947; De Jong, 1956) and palynological (Florschütz & Anker-Van Someren, 1956) research on a restricted number of cores. The lithology and genesis of the deposits were studied systematically during the geological mapping surveys of the area by the Geological Survey of the Netherlands (Van den Toorn, 1967; Bisschops, 1973; Bisschops et al., 1985). On the surficial geological map, four lithogenetical sediment units were distinguished (Bisschops et al., 1985):

- Aeolian periglacial deposits, subdivided in coversand deposits (homogeneous medium fine sand) and loess & coversand deposits (alternation of sand and loam);
- Lacustro-aeolian periglacial deposits or "Brabant Loam" deposits, consisting of laterally extensive layers of loam and sandy loam;
- Fluvial and fluvio-aeolian periglacial deposits, subdivided in fluvial deposits (very fine to very coarse sand with clay and peat fragments) and fluvio-aeolian deposits (alternating very fine to medium fine sand and loam layers, with peaty intercalations);
- Organogenic deposits, comprising a layer of supposedly Eemian to Early-Weichselian organic-rich deposits and an associated palaeosol.

The "Brabant Loam" or "Brabant Silt" deposits have been first described by Vink (1949). The great thickness and large areal extent of these sediments is typical for the shallow subsurface of the Roer Valley Graben. The grain-size distribution of the Brabant Loam is characterised by a peak in the silt fraction and a second peak in the very fine to medium fine sand fraction (105-150 µm). Other characteristics of these deposits are the presence of freshwater molluscs and the sparse occurrence of wave ripples. This indicates that the sediment is of primary aeolian origin, but has been deposited in marshy areas and/or reworked by surficial water flow (Van den Toorn, 1967; Kuyl & Bisschops, 1969; Bisschops, 1973; Bisschops et al., 1985). However, Vandenberghe & Krook (1981) investigated similar deposits at Alphen (Fig. 3.2B), west of the Roer Valley Graben and argued that there is no evidence for water transport after aeolian deposition. They simply regarded the deposits as sandy loess. Ruegg (1983) included the Brabant Loam deposits in his lacustrine subfacies (Table 3.1).

The sedimentary structures of the fine-grained deposits have been studied in detail by Van Alphen (1984; in: Bisschops et al., 1985). Based on research of lacquer peels from twelve 19-30 m deep sediment cores in a small area near the village of Best (Fig. 3.2B), he discerned between aeolian, lacustrine, fluvial and organic deposits. The sediments were subsequently clustered in five climatostratigraphic units, based on the occurrence of cryoturbation levels, the presence of palaeosols and palynological analyses of organic-rich deposits (Fig. 3.3). From this research, it became apparent that the fine-grained sedimentary sequence in the Roer Valley Graben is very complex and contains many depositional hiatuses.

3.4 Methodology

For the present study, we collected data concerning the lithology and sedimentary structures of thirteen 30-35 m deep cores (Fig. 3.2B). The cores were drilled using a mechanised bailer drilling unit with the possibility of retrieving undisturbed 1 m-long cores (Oele et al., 1983). Average sediment recovery ranged from 80% (sand) to 100% (humic loam and peat), with 80-90% of the recovered sediments being undisturbed. The 10-cm wide cores were divided into halves and photographed. One half was used to make a lithological description and to take samples for grain-size analysis, the other half was used to make lacquer peels for the analysis of sedimentary structures. The terminology of primary sedimentary structures follows Lea (1990). The terminology of involution phenomena of supposedly cryogenic nature is derived from the morphological classification of Vandenberghe (1988). He distinguishes between regular, symmetrical forms with an amplitude >0.6 m that require regional degradation of permafrost for their development (type-2 involutions), and regular, symmetrical forms with an amplitude <0.6 m that only require annual freeze-thaw cycles for their formation (type-3 involutions). Wedge-shaped structures are subdivided into frost fissures (cf. Maarleveld, 1976), which are usually only a few cm wide, and ice-wedge casts, which are characterised by the penetration of material into the fissure from above and from the sides, downturned laminae and faulting in adjacent sediments (Vandenberghe, 1983; French, 1996).

Grain size was measured using a Malvern Mastersizer 2000 laser grain-size analyser. This instrument has a measurement range of 0.1-2000 μm. Preparation of the grain-size samples included sieving over a 2 mm sieve and subsequent treatment with hydrogen peroxide (30%) and hydrochloric acid (10%) to remove any organic matter and carbonates. Furthermore, all samples were peptisised using $Na_4P_2O_7 \cdot 10H_20$. 29 grain-size fractions were distinguished, with size classes between 0.25 φ (sand fraction) and 1 φ (clay fraction). The terminology of sand texture classes refers to the Dutch standard for the classification of unconsolidated soil samples (Nederlands Normalisatie Instituut, 1989; Table 3.2).

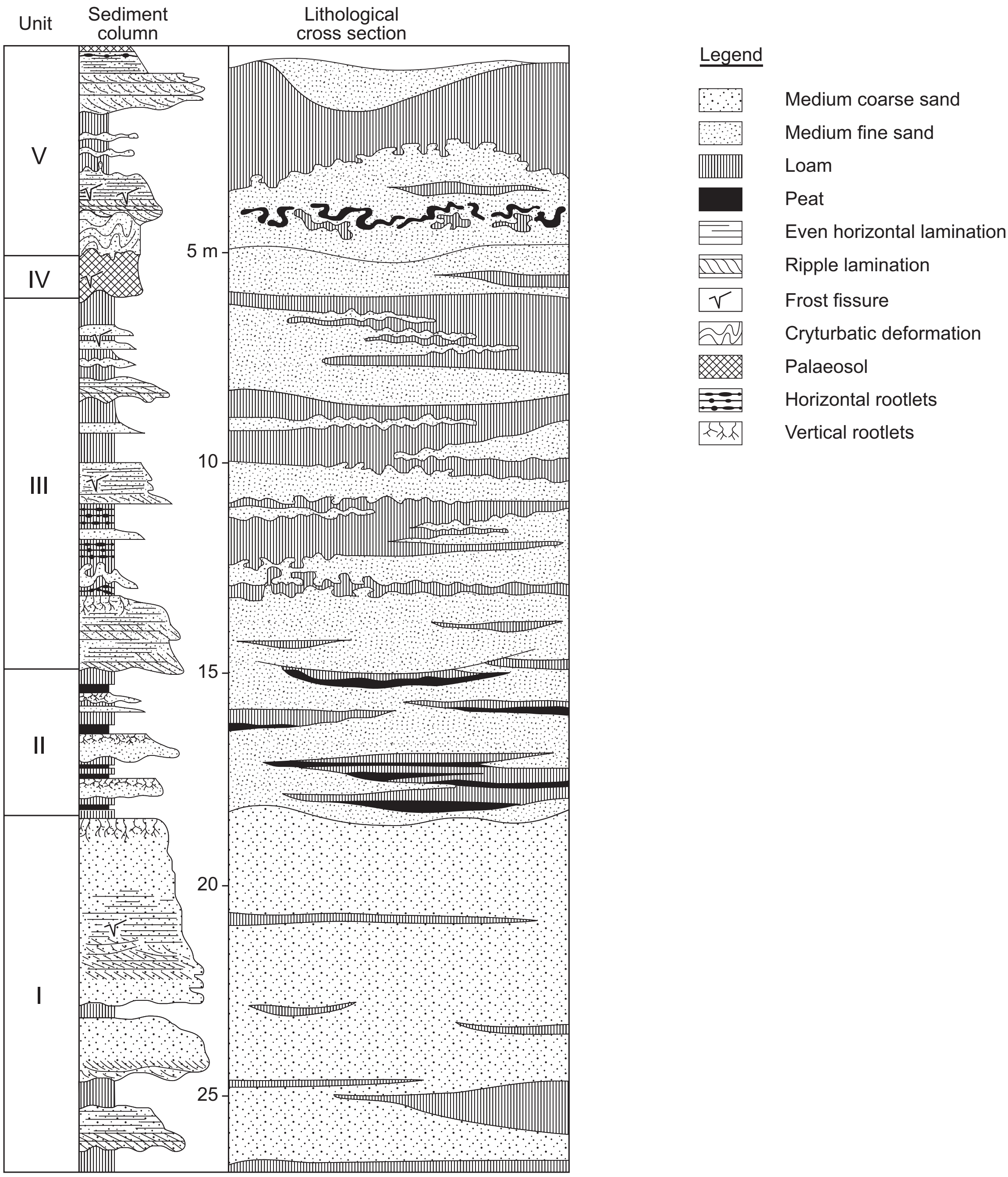


Figure 3.3 Lithology, sedimentary structures and stratigraphic subdivision of the Boxtel Formation near Best (adapted from Bisschops et al., 1985; after: Van Alphen, 1984). According to Van Alphen (1984), units I, III and V represent deposits from cold climatic intervals, whereas units II and IV were formed in warm-temperate stages.

Table 3.2 Sand texture classes (Nederlands Normalisatie Instituut, 1989).

Median grain size (μm)	Texture class name
63-105	extremely fine sand
105-150	very fine sand
150-210	medium fine sand
210-300	medium coarse sand
310-600	very coarse sand
600-2000	extremely coarse sand

Cone penetration tests (CPTs) were used to further characterise the sedimentary units and to enable correlation of data from widely separated boreholes. The CPT is a geotechnical tool that provides information on mechanical properties of unconsolidated sediments in the subsurface. Basic principles of cone penetration testing are given by Lunne et al. (1997). The CPT data used in this study were obtained by using a cylindrical electric penetrometer with a sampling interval of 2 cm. The CPT procedure followed the Dutch

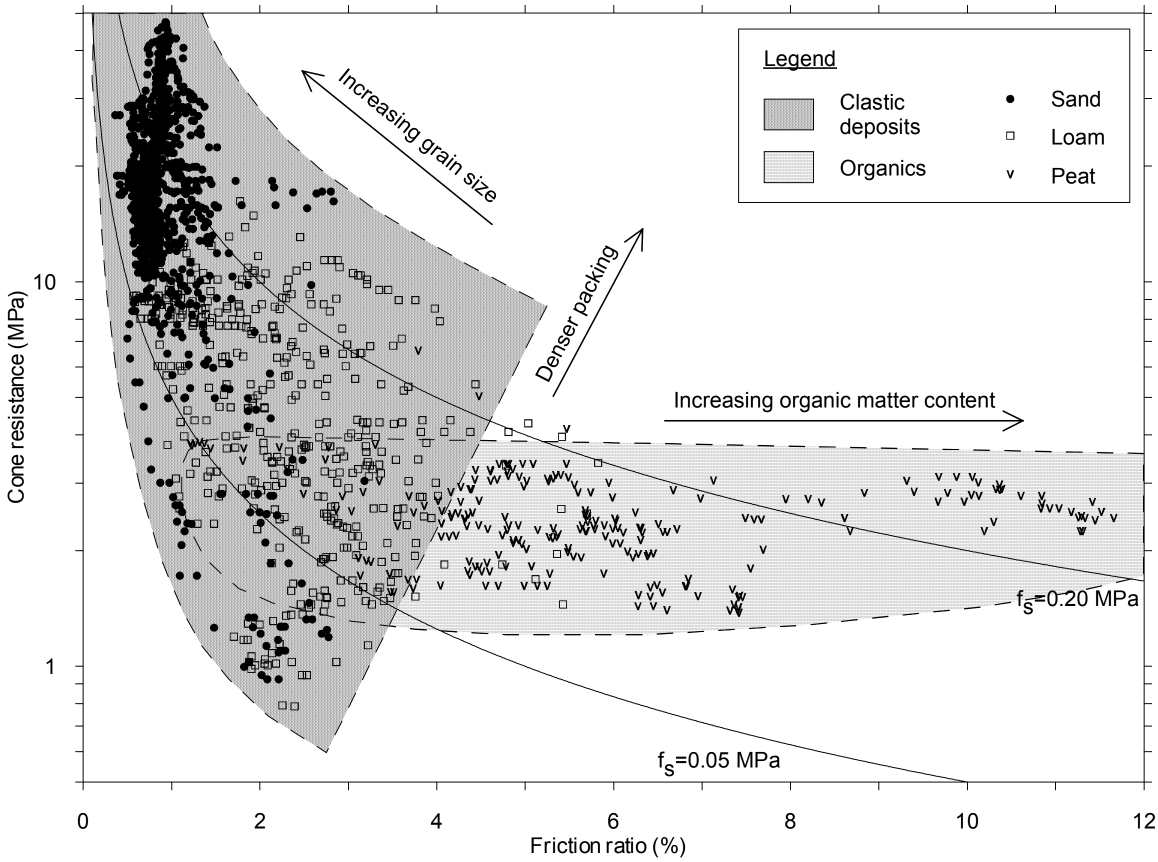


Figure 3.4 Olsen chart, depicting the relationship of the friction ratio (R_f) and cone resistance (c_f) to sediment properties, such as median grain size, for all R_f-c_f data pairs of CPT S51B0004. Lines of equal sleeve friction (f_s) are indicated. The lithology corresponding to each data pair has been deduced from adjacent sediment core 51B0307. The location of both the CPT and sediment core are indicated on Fig. 3.2B.

standard for electric penetration tests (Nederlands Normalisatie Instituut, 1996). Two variables were measured: cone resistance (c_f) and sleeve friction (f_s). The friction ratio (R_f) was computed from these two variables: $R_f = f_s/c_f * 100\%$. A combination of c_f and R_f values can be related most easily to sediment properties, such as median grain size, sediment sorting, packing, organic matter or clay content, fining- or coarsening-up trends and sedimentary lamination (cf. Coerts, 1996). As an example, Figure 3.4 shows a so-called Olsen chart (Douglas & Olsen, 1981) to indicate the relation of data from CPT S51B0004 to lithological properties derived from adjacent sediment core 51B0307. Correlation of neighbouring CPTs in a geological cross section was done manually.

3.5 Sedimentary facies

The fine-grained deposits of the Boxtel Formation in the Roer Valley Graben contain seven distinct sedimentary units (A-G). Each of these units represents a specific depositional environment and is therefore referred to as a facies unit. Facies units A-D primarily consist of sand, units E and F of loam and facies G of organics. Five facies units (B, C, D, F, G) are subdivided into subunits, based on differences in sediment characteristics. Sediment properties and depositional environment of the facies units are summarised in Table 3.3. The different facies are illustrated and discussed with the help of photographs of two sediment cores (Figs. 3.5, 3.6) and their corresponding sedimentary and CPT logs (Figs. 3.7, 3.8). All facies units, with the exception of the organic and organic-rich units (Bo, C, G), have also been characterised by their grain-size distribution. Some of the sedimentary structures in the deposits will be illustrated with modern counterparts from Greenland.

3.5.1 Facies A: Very fine to medium fine sand with even horizontal lamination to low-angle cross lamination (Fig. 3.5: 0.00-1.43 m below surface)

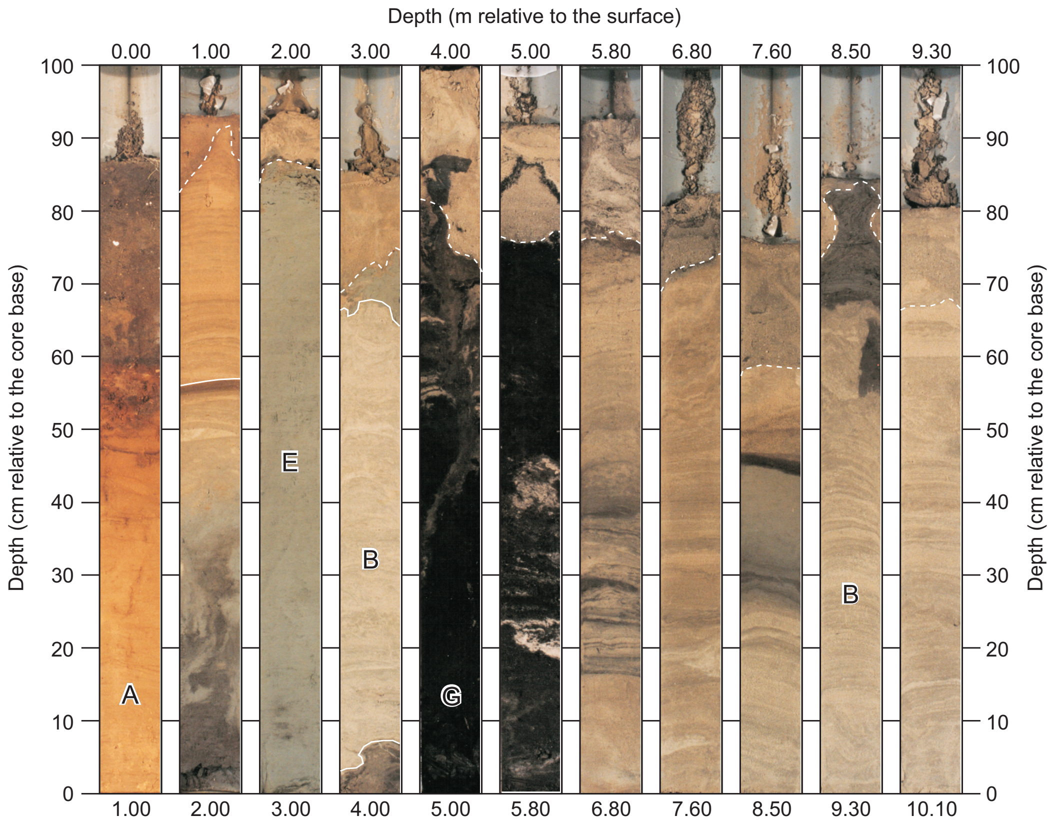
This unit consists of well-rounded, yellow very fine to medium fine sand (median grain size 105-210 μm; Fig. 3.9A) showing even horizontal to slightly inclined parallel lamination. Strings of small pebbles are occasionally present. Incidentally, parallel cm-scale sets of very fine sand (105-150 μm) to medium fine sand (150-210 μm) in mm-thick horizontal laminae occur (Fig. 3.5: 1.00-1.43 m below surface). Low-angle cross-lamination is sparsely visible. In the topmost part of the unit, sedimentary structures are largely obscured by soil-forming processes and rootlets, leading to a structureless or massive appearance. The unit attains a thickness of 1-2 m and is underlain by silty sand of facies B or massive loam deposits of facies E. In the latter case, the lower boundary of the unit may be affected by type-3 involutions (Vandenberghe, 1988). In a CPT, this facies is characterised by very low c_f and R_f values (Fig. 3.7).

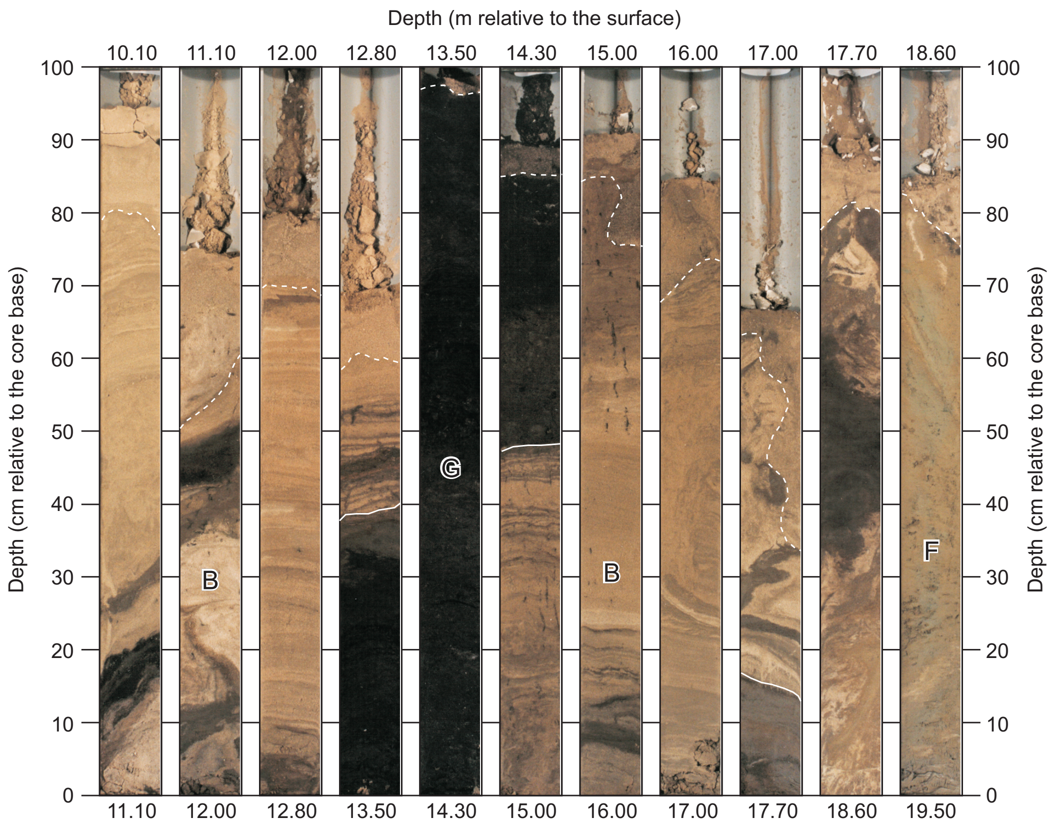
Although facies A only comprises a minor part of the fine-grained deposits, these sediments are well-known due to their stratigraphic position at or near the present land surface and their frequent occurrence in man-made outcrops. They represent planar dry-aeolian sand-sheet deposits and correlate with eolian subfacies A (Ruegg, 1983), facies 2

(Schwan, 1986, 1988) or sand-sheet facies A (Koster, 1988). Sets of parallel laminae represent net migration on a planar surface, pebble strings mark deflation and reactivation (cf. Fig. 3.10A). Low-angle cross-lamination indicates the presence of an undulating surface with wind ripples or low dunes (cf. Fig. 3.10B). Although aeolian dune deposits are known to occur in this area (Heijnens & Tijssen, 1982), high-angle cross stratification (facies 1 of Schwan, 1986, 1988; dune sand facies of Koster, 1988) was not found in any one of the sediment cores. This might be the result of Holocene soil formation and anthropogenic soil levelling, destroying sedimentary structures in the upper part of the unit. Low c_f and R_f values in the CPT indicate a relatively low packing grade, which is consistent with dry deposition of well-sorted sediments.

Table 3.3 Sediment properties and depositional environment of the seven facies units that are distinguished in the fine-grained deposits of the Boxtel Formation in the Roer Valley Graben.

Sedimentary facies	Sediment properties	Depositional environment
Facies A	Very fine to medium fine sand (105-210 µm) with even horizontal lamination to low-angle cross lamination	Dry-aeolian sand-sheet deposits
Facies B	Bs: Silty very fine to medium fine sand (105-210 µm) with wavy or indistinct even horizontal lamination; Bl: Massive sandy loam; Bo: Peaty loam to silty peat	Wet-aeolian sand-sheet deposits, lacustro-aeolian loam deposits and organic-rich deposits on a wet surface
Facies C	Cs: Very fine to medium coarse sand (105-300 µm) with reworked organics, massive to cross-laminated; Cl: Laminated humic loam; Co: Silty peat	Fluvio-lacustrine and lacustrine deposits, with intercalated wet-aeolian sand-sheet deposits
Facies D	Ds: Very fine to medium coarse sand (105-300 µm) with cross lamination; Dl: Even horizontally laminated sandy loam	Low-energy fluvial deposits, overbank deposits and fluvio-aeolian deposits
Facies E	Massive sandy loam and humic loam	Loess-like aeolian deposits, reworked by surficial water flow
Facies F	Fl: Massive sandy loam; Fs: Silty very fine to medium coarse sand (105-300 µm)	Interfingering floodloam deposits and wet-aeolian sand-sheet deposits
Facies G	Go: Peat; Gs: Peaty sand to sandy gyttja; Gl: Humic loam to sandy loam	Peat formation in wet low-lying areas, with clastic sediment input by aeolian and surface runoff processes


Depth (m relative to the surface)
0.00 1.00 2.00 3.00 4.00 5.00 5.80 6.80 7.60 8.50 9.30
1.00 2.00 3.00 4.00 5.00 5.80 6.80 7.60 8.50 9.30 10.10
Depth (cm relative to the core base)
100 90 80 70 60 50 40 30 20 10 0
A E B G B


Depth (m relative to the surface)
10.10 11.10 12.00 12.80 13.50 14.30 15.00 16.00 17.00 17.70 18.60
11.10 12.00 12.80 13.50 14.30 15.00 16.00 17.00 17.70 18.60 19.50
Depth (cm relative to the core base)
100 90 80 70 60 50 40 30 20 10 0
B G B F

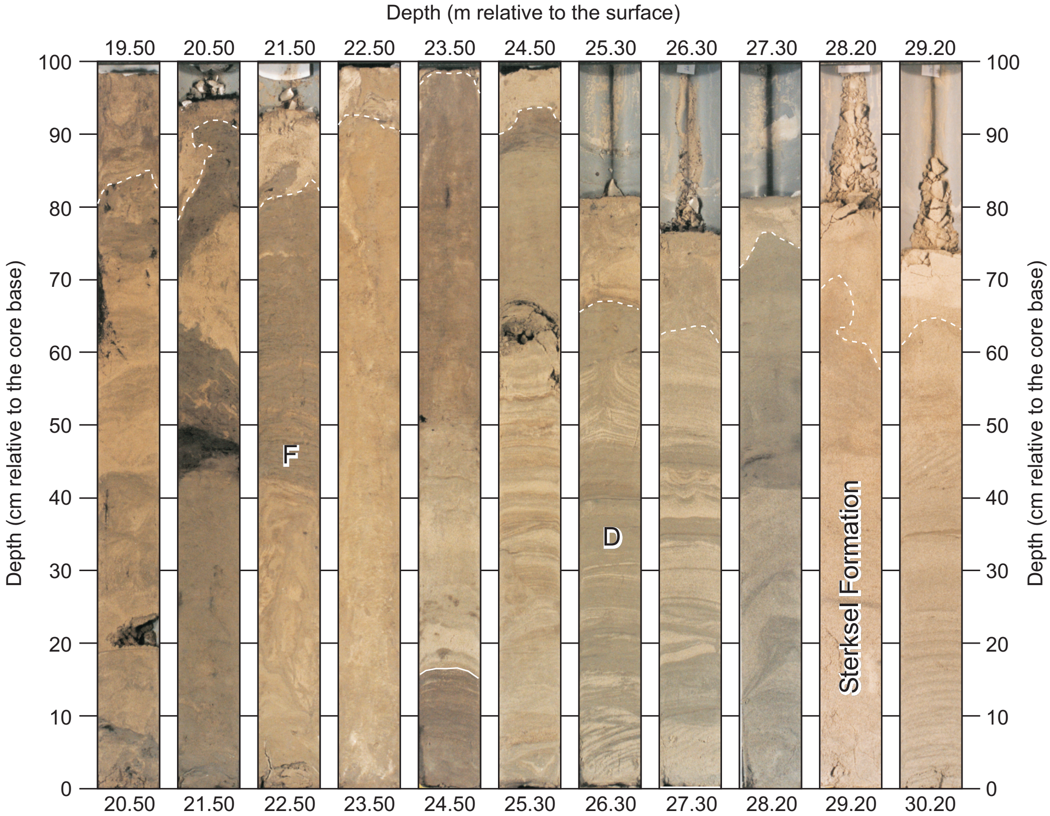


Figure 3.5 (pp. 54-55) Photographs of sediment core 51B0307 (Boxtel-Breede Heide 2) with indication of the facies units. The boundary between disturbed and undisturbed sediments is indicated by a dashed line, facies boundaries are indicated by a solid line. The corresponding sedimentary and CPT log are shown in Fig. 3.7, the location of the core is shown in Fig. 3.2B.

3.5.2 Facies B: Silty very fine to medium fine sand with wavy or indistinct even horizontal lamination (Bs), sandy loam (Bl) and peaty loam (Bo) (Fig. 3.5: 3.34-3.92, 5.80-13.10, 14.51-17.56 m below surface; Fig. 3.6: 12.50-13.50, 21.13-22.10 m below surface)

Facies B is an extensive and complex unit, consisting of three subfacies. 80-90% of the unit consists of yellow to grey, very fine to medium fine sand and silty sand (105-210 µm; Fig. 3.9B; subfacies Bs). Occasionally, thicker loam layers, coarse sand layers and pebble strings are present. Horizontal alternating bedding of silty medium fine sand and silty very fine sand or loam is the most obvious sedimentary structure, but wavy or crinkly lamination and massive to vaguely stratified sand (Fig. 3.5: 6.60-7.24 m below surface) occur frequently also. Locally, shallow scours are present. Scattered in the sandy deposits, 0.1-0.5 m thick sandy loam beds occur (e.g. Fig. 3.5: 8.05-8.23 m below surface; Fig. 3.9E; subfacies Bl). These beds are usually massive and cannot be correlated with similar sediments in neighbouring boreholes. Peaty loam and silty peat beds are also present (subfacies Bo). These may be heavily involuted (e.g. Fig. 3.5: peat beds between 10.80-11.90 m below surface) and can be correlated over distances of more than 1 km.

Sediments of facies B occur throughout the Boxtel Formation and attain a thickness of more than 5 m. Lithological boundaries between the three subunits are often affected by type-2 and type-3 involutions, especially if peat is involved. Small frost fissures are also present. In a CPT, facies B deposits are characterised by a rapid alternation of high c_f-low R_f and low c_f-high R_f values (Fig. 3.7).

Deposits from this unit represent wet-aeolian sediments and intercalated lacustro-aeolian organic depression fills. Horizontal alternating bedding of sand and loam is attributed to deposition and adhesion of sand and loam on an alternating dry and moist surface (Ruegg, 1983: eolian subfacies B; Schwan, 1986, 1988: facies 3; Koster, 1988: sand sheet facies B). Coarse sand layers and pebble strings represent deflation events, scours are associated with the occurrence of shallow ephemeral streams (cf. Fig. 3.10C). Massive to vague subhorizontal or crinkly stratification in fine sediments can be interpreted in terms of adhesion processes (Kocurek & Fielder, 1982; Schwan, 1986; Lea, 1990), related to the presence of a smooth, damp depositional surface (cf. Fig. 3.10D). Thin sandy loam layers represent the infilling of shallow pools (deflation hollows or thermokarst lakes, cf. Bisschops et al., 1985) by aeolian, loess-like sediments. The peaty loam beds have been formed in humid areas, where the local groundwater table was at or near the land surface. Palynological research indicates that their occurrence is usually not associated with warm-climate conditions, but merely reflects wet surface conditions (Bisschops et al., 1985; cf. Van Huissteden et al., 1990). The combination of high c_f and low R_f values is the result of a dense packing of sandy sediments, low c_f and high R_f values indicate the presence of loam or peat.

3.5.3 Facies C: Very fine to medium coarse sand with reworked organics (Cs), humic loam (Cl) and silty peat (Co) (Fig. 3.6: 13.50-21.13 m below surface)

This unit consists of a rapid alternation of 0.1-1 m thick, massive to even horizontally laminated, silty very fine to medium coarse sand layers (105-300 µm) with ample organic fragments (subfacies Cs), and 0.05-0.3 m thick humic loam layers with mm- to cm-scale sand laminae (subfacies Cl). Occasionally, dm-thick coarse sand layers (300-600 µm) and cm-thick layers with detrital plant remains occur. The boundary between sand and loam is usually gradual. In the lower part of the unit, trough cross-laminated and tabular cross-laminated dm-scale sets of medium fine to medium coarse sand (150-300 µm) occur. The stratification is accentuated by the presence of reworked humic loam and peat fragments. Structureless to subhorizontally laminated medium fine sand layers with adhesion lamination may also be intercalated in this unit. In the loam layers, subtle climbing-ripple lamination is highlighted by the presence of organic matter (e.g. Fig. 3.6: 14.00-14.10 m below surface). The top of the unit may be formed by silty peat (subfacies Co; not represented in Fig. 3.6, but present in e.g. core 51B0302). Facies C deposits can attain a thickness of more than 10 m and show a general fining-up trend. Cryoturbatic deformations are usually absent. CPTs reflect the fining-up trend and show intermediate, but highly varying c_f and R_f values for the sand-loam sequence (Fig. 3.8) and very low c_f and very high R_f values for the peat of facies Co.

Facies C largely consists of subaqeous deposits and can be related to the lacustrine facies of Ruegg (1983) or aeolian-lacustrine facies of Koster (1988). Most of the sand layers have been deposited in flowing water, as is evidenced by the presence of reworked loam and peat fragments and the occurrence of cross-lamination. Wet-aeolian deposits, characterised by adhesion lamination, are locally intercalated. Loam layers represent a standing-water environment, with influxes of sediment-laden water (climbing-ripple lamination). Because organic matter is very well preserved and cryoturbatic deformations are absent, the environment must have been permanently wet, also after deposition of the sediments. Facies C is interpreted to have been deposited in and immediately adjacent to lake-like water bodies, with the frequent inflow of sediment-laden water from the sides. The silty peat (subunit Co) that locally occurs at the top of the unit and the general fining-up trend both indicate that the lakes finally filled up and disappeared. Intermediate c_f values for the sand of subunit Cs indicate a loose packing, consistent with fast deposition from sediment-laden water. Generally highly variable c_f and R_f values are the result of rapid changes in lithological composition with depth.

3.5.4 Facies D: Very fine to medium coarse sand with cross lamination (Ds) and even horizontally laminated sandy loam (Dl) (Fig. 3.5: 24.35-27.30 m below surface)

This unit consists of moderately-rounded, grey very fine to medium coarse sand (105-300 µm; Fig. 3.9C; subunit Ds) and sandy loam (Fig. 3.9F; subunit Dl) containing small amounts of mica. The sand is even horizontally laminated to parallel cross-laminated and forms sub-parallel sets that are 0.1 to 2 m in thickness. Set boundaries are usually non-erosive. Channel scours filled with even horizontally laminated sand and trough cross-laminated deposits are less common. Locally, indistinctly laminated very fine to medium fine sand layers (105-210 µm) occur. Loam layers of subunit Dl may be sandy or may contain cm-thick sand laminae, especially in their lower part. The boundary between sand and loam is sometimes affected by water-escape phenomena (e.g. Fig. 3.5: 25.70-25.80 m below surface). Facies D occurs at two distinct positions in the fine-grained sequence. First, it forms one or more 0.2-2 m thick fining-upward sets in the lowermost part of the Boxtel Formation. Second, it may be associated with small river valleys, especially where these cross the bordering faults of the Roer Valley Graben in the south-west and east. Facies D deposits are usually not affected by cryoturbatic deformation and are characterised by intermediate to high c_f and low R_f values.

The sedimentary structures present in this unit originated in a low-energy fluvial environment, dominated by shallow current flow and overbank flow. This indicates formation on a relatively small floodplain or a more distal part of a wider floodplain. Aeolian deposits frequently invaded the fluvial plain and were subsequently reworked by fluvial processes, leading to the formation of fluvio-aeolian sand layers with indistinct lamination (cf. Good & Bryant, 1985). The coarse-grained Middle-Pleistocene deposits of the Sterksel Formation and Beegden Formation provided an important sediment source for these deposits, as evidenced by the occurrence of small amounts of mica. In association with small river valleys close to faults, part of the sediments of facies D may also be interpreted as alluvial fan deposits. Intermediate to high c_f and low R_f values result from the relatively coarse grain size of the sediments.

3.5.5 Facies E: Massive sandy loam (Fig. 3.5: 1.43-3.34 m below surface)

Unit E consists of homogeneous, stiff grey loam and sandy loam (Fig. 3.9G). The lower part of the loam may be humic or underlain by silty peat or gyttja. The loam is massive to even horizontally laminated. Occasionally, wave ripples are present (Bisschops et al., 1985). This facies only occurs in the upper part of the sedimentary sequence, but has a widespread and uniform lateral occurrence. Its thickness ranges from 1 to 3 m. The loam is underlain by subfacies Bs deposits and overlain by facies A or subfacies Bs deposits. The upper and lower boundary are usually affected by type-2 involutions (Vandenberghe,

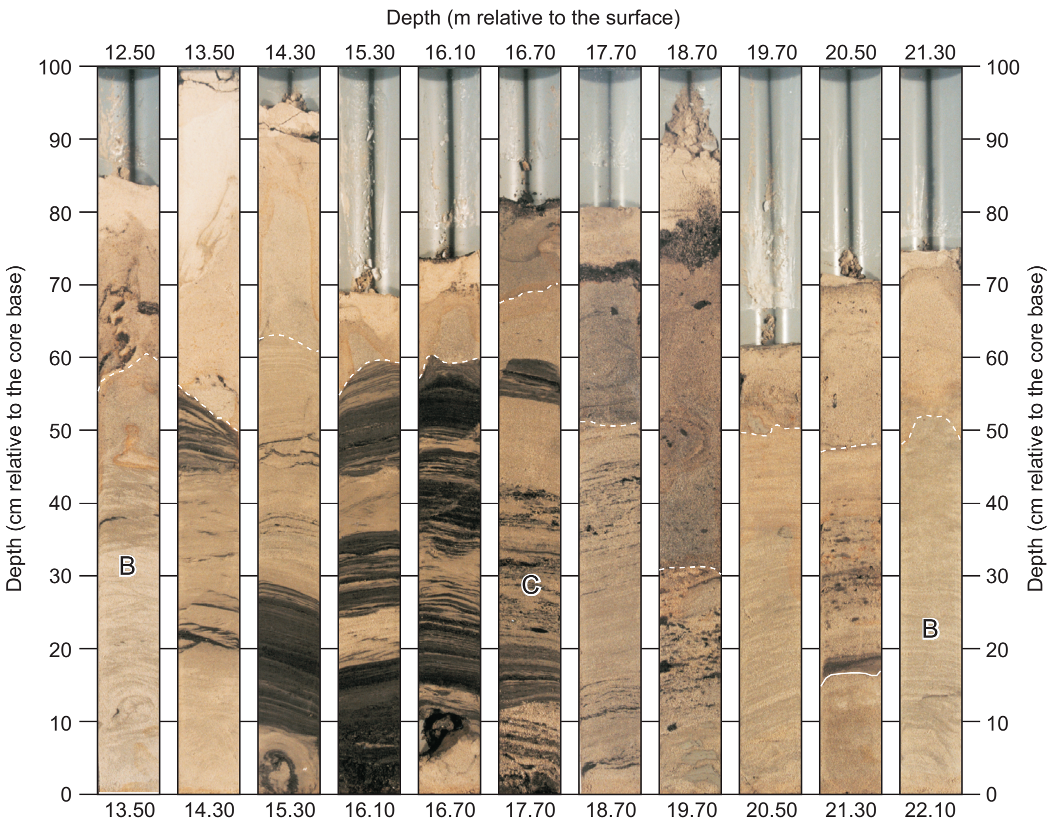
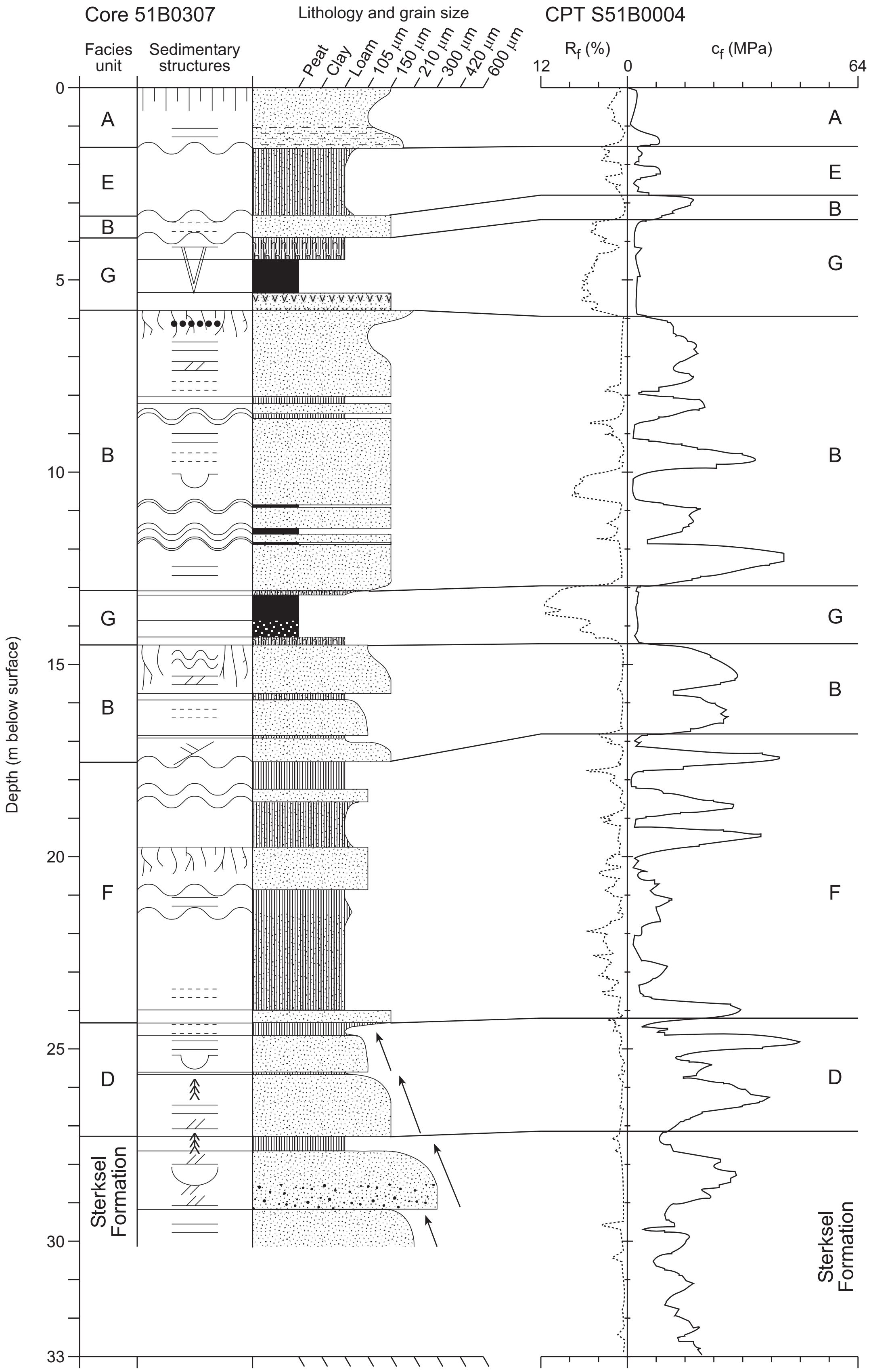


Figure 3.6 Photographs of sediment core 45D0154 (Schijndel-Rooische Heide), showing the deposits between 12.50 and 22.10 m below surface. Facies units are indicated. The boundary between disturbed and undisturbed sediments is indicated by a dashed line, facies boundaries are indicated by a solid line. The corresponding sedimentary and CPT log are shown in Fig. 3.8, the location of the core is shown in Fig. 3.2B.

Figure 3.7 (p. 59) Facies units, lithology and sedimentary structures in core 51B0307 (Boxtel-Breede Heide 2) and correlation with CPT log S51B0004. For legend, see Fig. 3.8.



Core 51B0307
Lithology and grain size
CPT S51B0004
Facies unit
Sedimentary structures
Peat
Clay
Loam
105 µm
150 µm
210 µm
300 µm
420 µm
600 µm
R_f (%)
c_f (MPa)
12
0
64
Depth (m below surface)
0
5
10
15
20
25
30
33
A
E
B
G
B
G
B
F
D
Sterksel Formation
A
E
B
G
B
G
B
F
D
Sterksel Formation

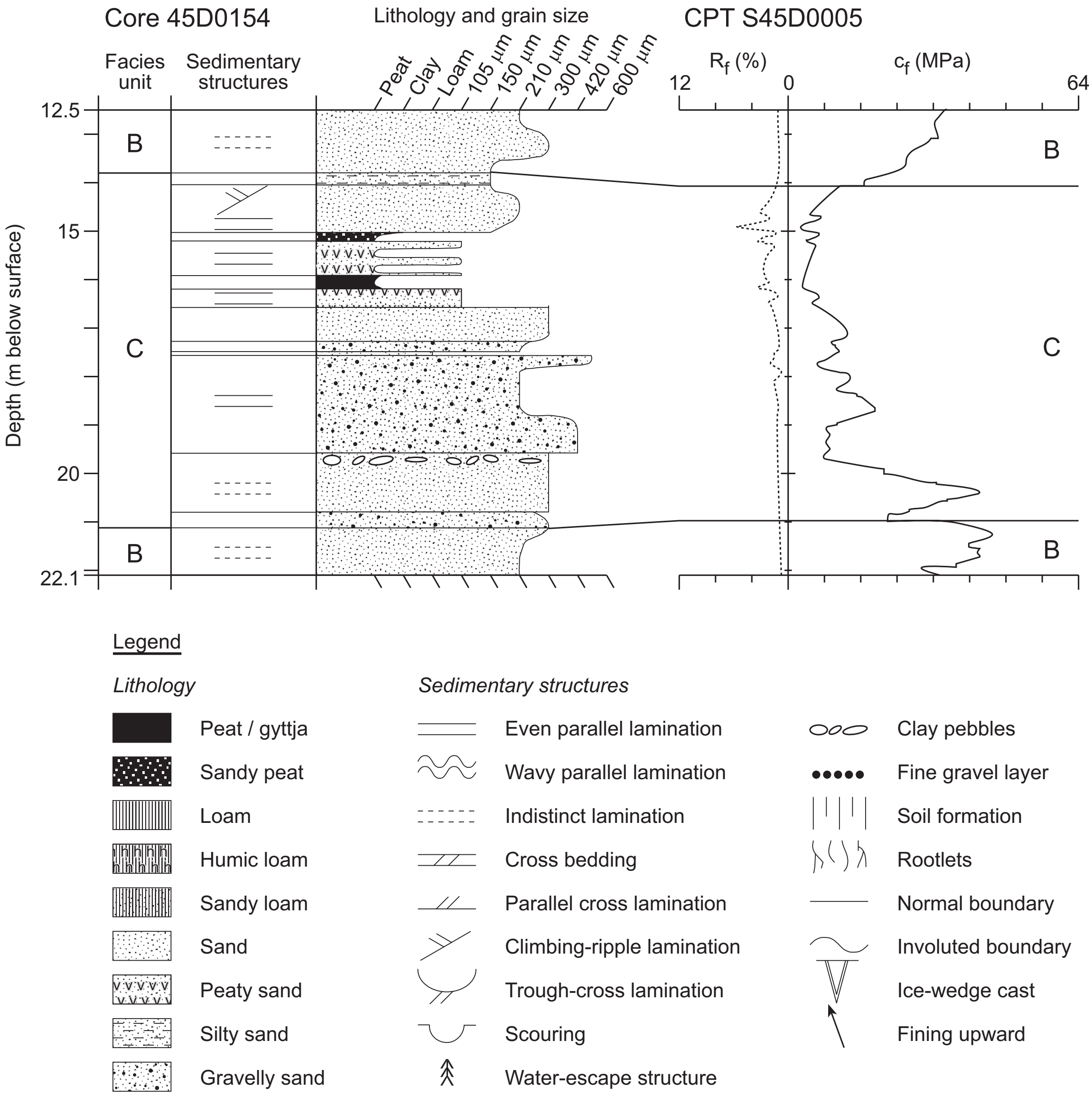
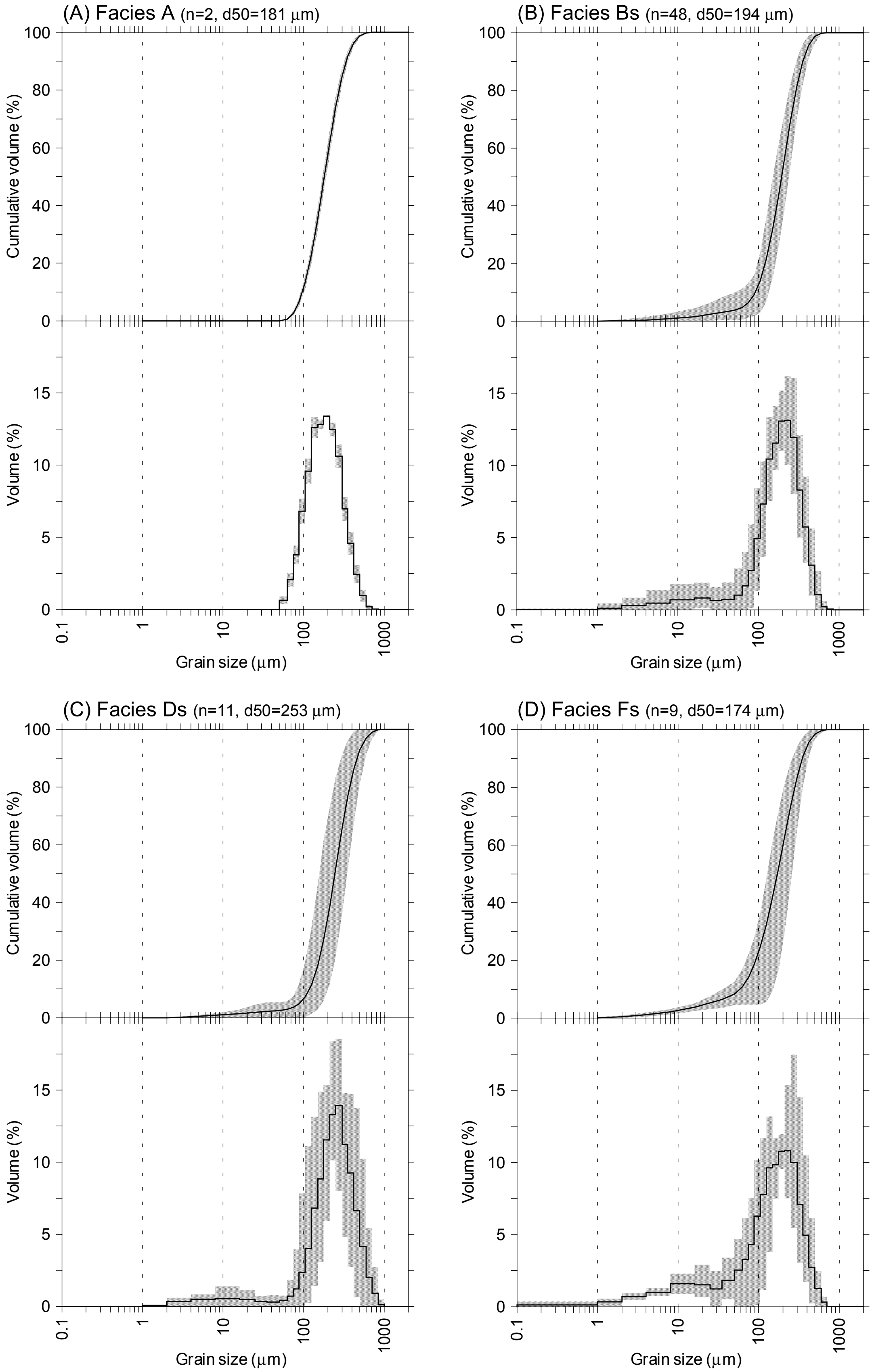
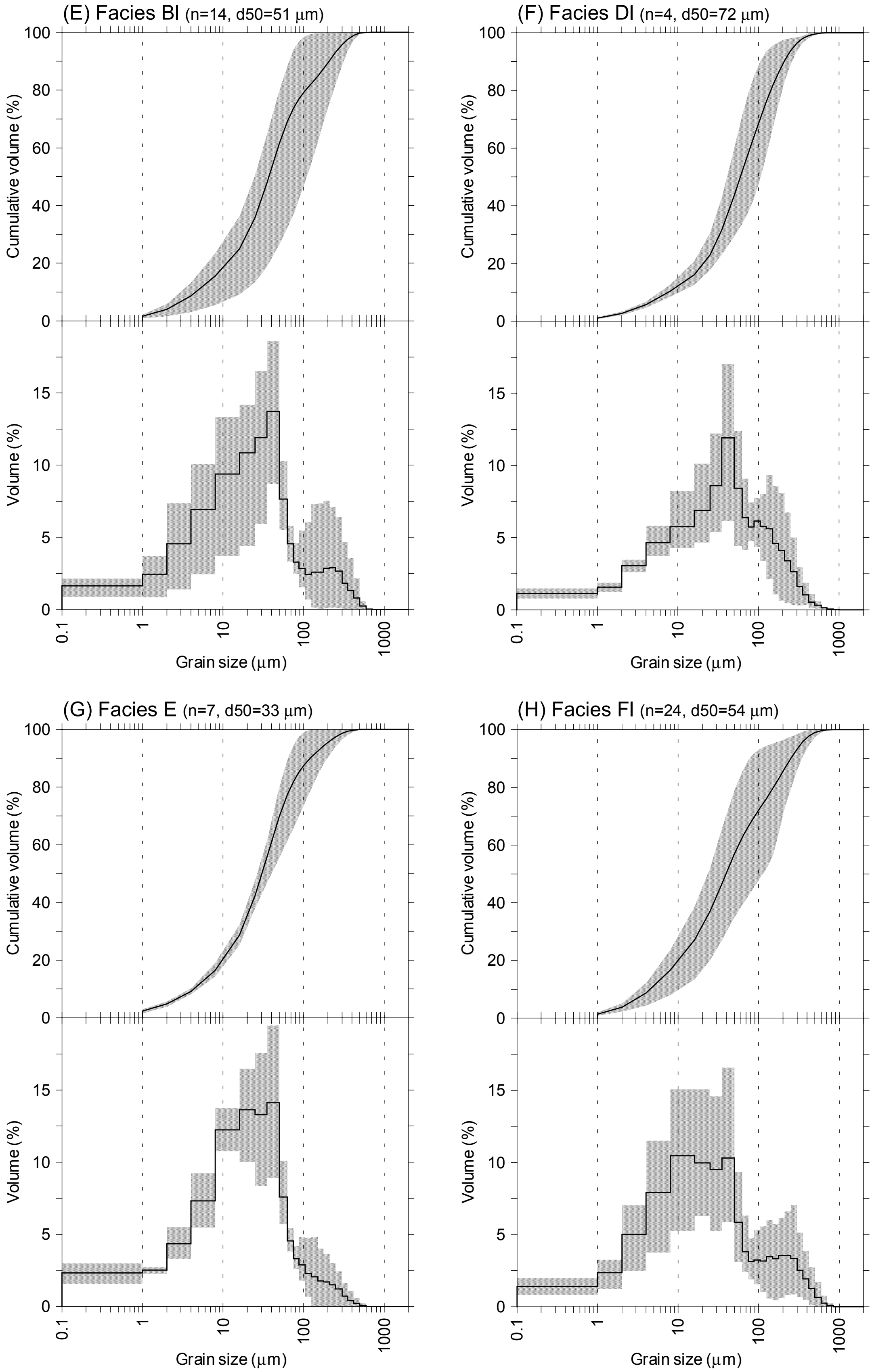


Figure 3.8 Facies units, lithology and sedimentary structures between 12.50 and 22.10 m below surface in core 45D0154 (Schijndel-Rooische Heide) and correlation with CPT log S45D0005.

1988). Based on observations in man-made outcrops, a level of ~2-m deep ice-wedge casts is known to protrude the loam unit from its upper boundary. In a CPT, this unit is characterised by relatively low c_f and high R_f values.

Figure 3.9 (pp. 61-62) (A-H) Average grain-size distribution (below) and average cumulative grain-size distribution (above) of eight sedimentary (sub)facies units, based on grain-size samples from sediment cores 51B0301 and 51B0303. Graphs A-D represent sandy units, graphs E-H represent loamy units. The grain-size envelopes encompass the 10-90% percentile range for each unit. The number of samples (n) and the median grain size (d50) are indicated above the graphs. The location of the sampled sediment cores is indicated in Fig. 3.2B.


(A) Facies A (n=2, d50=181 μm)
(B) Facies Bs (n=48, d50=194 μm)
(C) Facies Ds (n=11, d50=253 μm)
(D) Facies Fs (n=9, d50=174 μm)
Cumulative volume (%)
Volume (%)
Grain size (μm)
0.1
1
10
100
1000
0
20
40
60
80
100
5
15


(E) Facies BI (n=14, d50=51 μm)
(F) Facies DI (n=4, d50=72 μm)
(G) Facies E (n=7, d50=33 μm)
(H) Facies FI (n=24, d50=54 μm)
Cumulative volume (%)
Volume (%)
Grain size (μm)
0
20
40
60
80
100
5
10
15
0.1
1
10
100
1000

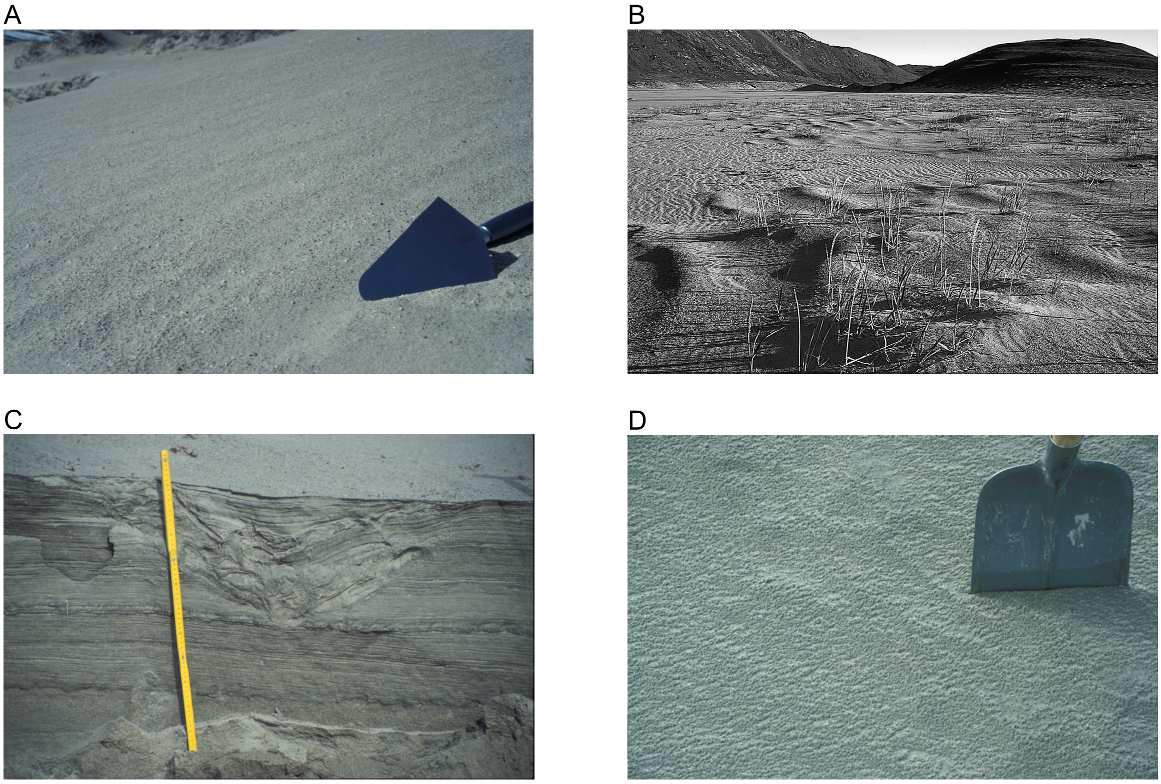


Figure 3.10 Sediments and processes in a present-day cold-climate fluvio-aeolian depositional environment near Kangerlussuaq, West-Greenland. (A) Gravel lag on the Store Sandsø sand sheet. Trowel blade is 15 cm long; (B) Wind ripples and low dunes on the Store Sandsø sand sheet. Photograph: N.W. Willemse; (C) Scour fill in sand-sheet deposits at Store Sandsø. Measure is 60 cm long; (D) Adhesion layer on the upper floodplain of Watson river. Spade blade is 20 cm across.

The grain-size distribution of facies E deposits resembles that of aeolian loess, but with an admixture of very fine to medium fine sand (Fig. 3.9G). However, the sparse occurrence of wave ripples in the sandy loam deposits indicates that at least part of the sediment has been deposited in shallow standing water. The unit is therefore considered a loess-like aeolian sediment that has been deposited on a humid surface and has been subsequently reworked by surficial water flow. This interpretation is confirmed by palynological and malacological analyses, which indicate humid surface conditions in an open landscape under permafrost conditions (cf. Bisschops et al., 1985). The low c_f and high R_f values merely reflect the dominance of loam in this unit.

3.5.6 Facies F: Massive sandy loam (Fl) and silty very fine to medium coarse sand (Fs) (Fig. 3.5: 17.56-24.35 m below surface)

This unit consists of two to four, grey to green, 1-2 m thick sandy loam layers (Fig. 3.9H; subunit Fl), separated by 0.5-1 m thick bleached, silty very fine to medium coarse sand layers (105-300 µm; Fig. 3.9D; subunit Fs). The top of the loam layers may be humic. The sedimentary contact between sand and loam is usually abrupt. The loam is massive to even horizontally laminated, but lamination may be heavily disturbed by both involution processes and penetrating roots. The silty sand is indistinctly laminated. The bleached or mottled aspect of both sand and loam is striking. The unit is widespread in the central part of the Roer Valley Graben at 20-25 m below the surface and attains a thickness of 5-10 m. It is underlain by fluvial sediments of facies D or coarse-grained fluvial sediments of Middle-Pleistocene age (Sterksel Formation). The unit is overlain by facies B or C deposits. In case facies B deposits are present above facies F, the boundary is placed at the top of the uppermost thick sandy loam layer. In a CPT, subfacies Fl deposits are characterised by intermediate c_f and high, but variable R_f values. Subfacies Fs deposits are interbedded layers with high c_f and low R_f values (Fig. 3.7).

Facies F consists of interfingering floodloam deposits and sandy wet-aeolian deposits. The grain size of the sand in the floodloam is similar to that of aeolian silty sand, which strongly suggests that it is reworked from aeolian deposits or blown in from adjacent areas during deposition of the floodloam. Also, bioturbation cannot be excluded. The presence of involutions testifies to deposition in a periglacial climate. The bleached colour of the sand and the mottled aspect of the loam are interpreted as arctic soil formation (cf. arctic soil of Van der Hammen et al., 1967; Vink & Sevink, 1971). The combination of intermediate c_f and high R_f values in CPTs is related to a high packing grade, associated with slow deposition and subsequent soil forming processes. The floodloam deposits (Fl) in this unit interfinger with the aeolian sand of subfacies Fs and have taken up and reworked part of these sediments during transport. Therefore, they are regarded part of the Boxtel Formation.

3.5.7 Facies G: Peat (Go), peaty sand (Gs) and humic loam (Gl) (Fig. 3.5: 3.92-5.80, 13.10-14.51 m below surface)

1-3 m-thick organic deposits occur at various depths in the Boxtel Formation. These deposits show a characteristic sequence, ranging from peaty sand and sandy gyttja (subfacies Gs) and peat (subfacies Go) to humic loam and sandy loam (subfacies Gl). The lowermost part of the unit generally consists of peaty very fine to medium fine sand (105-210 µm) or sandy peat. The latter contains both disperse sand grains and cm-thick clean sand layers. The peat is usually amorphic. Further upwards, the unit consists of pure peat with distinct wood and bark fragments and recognisable plant remains (a.o. *Betula*). Leaves may also be present. This is followed by even horizontally laminated humic loam with peaty intercalations. In the topmost part of the unit, distinct cm-scale fine sand layers (105-210 µm) appear in the humic loam. Facies G deposits conformably overlie sand of subfacies Bs. Roots may penetrate down the sand to a depth of more than 2 m. The top of the unit is usually heavily disturbed by type-2 involutions and is overlain by subfacies Bs deposits. From the top of the upper organic level in core 51B0307, a distinct ice-wedge cast protrudes the facies G deposits (Figs. 3.5, 3.7: 4.00-4.70 m below surface).

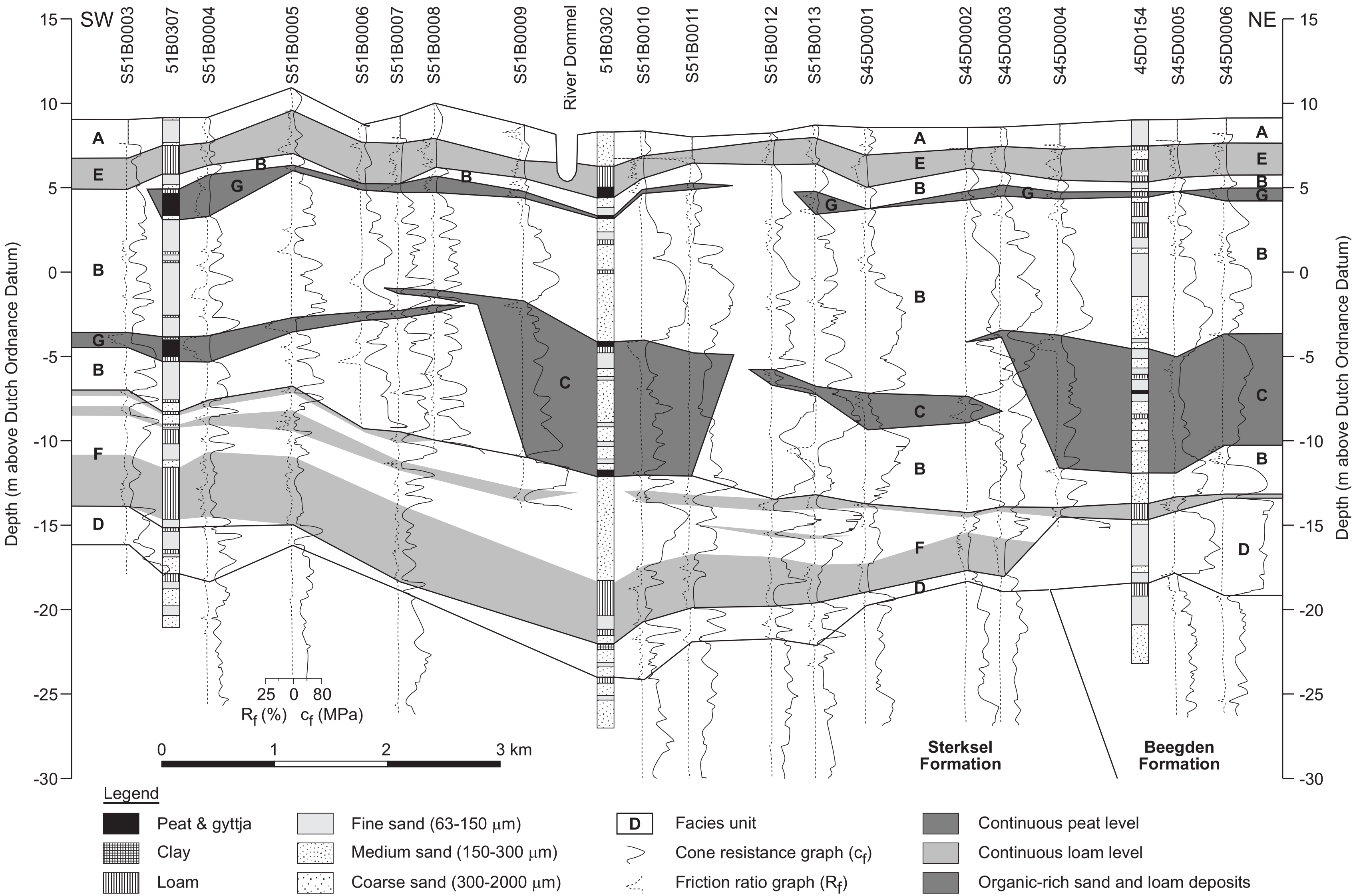
Facies G contains extensive peat deposits that have been formed in wet low-lying areas in the sandy landscape. The input of clastic material in the lower and upper part of the unit testifies to the presence of an unstable, partly open landscape in which wind-driven sediment movement and sediment movement by surface runoff occurred. This is the only facies presented here that is clearly associated with a temperate climate. Both palynological analyses indicating a warm-temperate flora (e.g. Florschütz & Anker-Van Someren, 1956) and the presence of macroscopic wood and bark fragments in the sediment cores point to warm climatic conditions during formation of these organics, with extensive peat formation generally starting in the second half of warm-temperate periods under the influence of a rising groundwater table.

3.6 Facies architecture

To illustrate the spatial relations between the seven sedimentary facies, Fig. 3.11 shows a geological cross section through the central, strongest subsiding part of the Roer Valley Graben. The 9-km long, 40-m deep cross section is based on a combination of data from three undisturbed cores and seventeen CPTs. The CPTs are on average 500 m apart. Some of the CPTs were made in holes that were pre-drilled to a depth of 1-1.5 m. This has led to unrealistic c_f and R_f values in this depth range (often 0 values), but was needed to avoid damage to underground pipelines and wires. Interpretation of the CPT data was accomplished by first correlating three CPTs with immediately adjacent sediment cores: S51B0004 to core 51B0307 (Fig. 3.7), S51B0010 to core 51B0302, and S45D0005 to core 45D0154 (Fig. 3.8). These correlations were subsequently used to interpret the other CPTs, for which no core data was available.

The lowermost part of the cross section shows coarse-grained fluvial deposits of the Sterksel Formation and Beegden Formation. The gravelly deposits of the Beegden Formation have been incised in the mica-rich deposits of the Sterksel Formation and are capped by humic silt or clay (e.g. core 45D0154: 18.33-19.10 m below OD). Both fluvial formations are overlain by fine-grained sediments of facies D and facies F. Facies D deposits are 1-5 m thick and consist of alternating low-energy fluvial deposits and densely packed fluvio-aeolian deposits, characterised by very high c_f values. Facies F contains thick floodloam deposits (subfacies Fl) and interbedded wet-aeolian sand-sheet deposits (subfacies Fs). In this unit, a gradual vertical shift can be observed from a domination of subfacies Fl to alternating subfacies Fl and Fs deposits (Fig. 3.11). Facies D and F are partly of fluvial, partly of aeolian origin and hence form the transition between the fluvially dominated environment of the Sterksel and Beegden Formation and the aeolian environment of the upper part of the Boxtel Formation. The rapidly diminishing fluvial influence is obvious. Hence, facies D and F represent the onset of a marked change in depositional environment in the Roer Valley Graben. This change is related to Middle-Pleistocene tectonic movements, which forced the Rhine-Meuse river system to leave the Roer Valley Graben and take a more eastern course on the Venlo Block (Fig. 3.2A; Kasse, 1988; Zagwijn, 1989; Van den Berg, 1994).

Above the uppermost floodloam level of facies F, cold-climate wet-aeolian sand-sheet deposits (facies B) form the most widespread unit. At -5 and +5 m OD, two widespread


SW
NE
S51B0003
51B0307
S51B0004
S51B0005
S51B0006
S51B0007
S51B0008
S51B0009
River Dommel
51B0302
S51B0010
S51B0011
S51B0012
S51B0013
S45D0001
S45D0002
S45D0003
S45D0004
45D0154
S45D0005
S45D0006
15
10
5
0
-5
-10
-15
-20
-25
-30
Depth (m above Dutch Ordnance Datum)
A
B
C
D
E
F
G
25 0 80
R_f (%) c_f (MPa)
0 1 2 3 km
Sterksel Formation
Beegden Formation
Legend
Peat & gyttja
Clay
Loam
Fine sand (63-150 μm)
Medium sand (150-300 μm)
Coarse sand (300-2000 μm)
Facies unit
Cone resistance graph (c_f)
Friction ratio graph (R_f)
Continuous peat level
Continuous loam level
Organic-rich sand and loam deposits

organic levels (facies G) testify to the presence of deposits from at least two different Middle- or Late-Quaternary warm-temperate periods. Interspersed within facies B and facies G deposits, up to 10-m thick organic-rich fluvio-lacustrine and lacustrine facies C deposits occur, characterised by a fining-up trend and reworked peat fragments (e.g. core 51B0302: 4.01-10.32 m below OD). These deposits are found in a distinct geographic region (the north-central part of the Roer Valley Graben) and at a well-defined stratigraphic position. They represent the infilling of gully-like incisions that were formed just after formation of the lower organic level (Fig. 3.11). Reworked sandy loess deposits (facies E) are found at 2-4 m below the present land surface. Dry-aeolian sand-sheet deposits of facies A only occur above the loess in the topmost part of the fine-grained sediment sequence (Fig. 3.11). In this depth range, CPT values are affected by pre-drilling to a depth of 1-1.5 m, anthropogenic disturbance of the upper sediment layers and boundary effects, caused by the nearby air-sediment interface.

Within the deposits of the Boxtel Formation in the Roer Valley Graben, a clear distinction can be made between the lower part (facies D, F), where fluvial and aeolian sediments are both important, and the upper part (facies A, B, C, E, G), where aeolian processes dominate. In the upper part, above 10-15 m below OD, aeolian sand-sheets are the dominant type of deposit and only small streams and standing-water bodies influenced sedimentation processes. At present, the small river Dommel crosses the cross section ~100 m west of core 51B0302 and CPT S51B0010 (Fig. 3.11). However, corresponding fluvial deposits are not observed in the CPTs, nor in the cores on both sides of the present-day fluvial valley. This is in agreement with detailed research based on hand coring and ^{14}C-dating (Van Leeuwaarden, 1982; Bisschops et al., 1985). Bisschops et al. (1985) argued that the river Dommel has shifted its course in the Roer Valley Graben due to tectonic movements and only follows its present course from approximately the period of maximum cold of the last Glacial (Weichselian) onward. At that moment, the river valley was incised into the loam of facies E and the river was subsequently kept in place by the cohesive loam. As a consequence, the palaeovalley of the river Dommel is relatively narrow and Dommel deposits do not show up in Fig. 3.11.

3.7 Discussion

Unlike many other sites in north-western Europe, the Roer Valley Graben contains a sequence of terrestrial sediments that spans several glacial-interglacial cycles. The formation and preservation of this long terrestrial record is the result of two main factors. First, active subsidence caused the region to be relatively low-lying with respect to neighbouring areas. It thus acted as a sediment sink, where sediments were quickly buried and preserved. Second, the area is situated south of the maximum extent of the

Figure 3.11 (p. 66) SW-NE geological cross section through the central part of the Roer Valley Graben, based on the interpretation of data from sediment cores and CPTs. Sedimentary facies units, continuous peat and loam levels and organic-rich deposits are indicated. For location of the cross section, see Fig. 3.2B.

successive glacial periods (cf. Dowling & Coxon, 2001; Thomas, 2001). However, although sediments were generally well preserved in the area, many hiatuses exist in the fluvio-aeolian sedimentary sequence and sedimentation in time was far from continuous and gradual. It is therefore impossible to correlate individual sediment layers or cone resistance peaks with similar layers or peaks in neighbouring cores or CPTs. Simple 'pancake-layer thinking' without paying attention to the presence of hiatuses may lead to serious misinterpretations in modelling the subsurface in this area.

The fierce climatic swings of the Middle and Late Quaternary caused repeated glaciation of parts of northern Europe, the British Isles and the Alps. Although the Roer Valley Graben has not been glaciated in Quaternary times, repeated freezing and thawing of the sediment are expressed in the sedimentary record as levels of periglacial disturbance. According to Vandenberghe (1988) and Ballantyne & Harris (1994), the combined occurrence of ice-wedge casts and type-2 involutions indicates the presence of at least discontinuous permafrost. Corresponding mean annual air temperatures are –3˚C or lower (Ballantyne & Harris, 1994). These conditions occurred in the Netherlands during considerable parts of the Last Glacial (Weichselian) period (Vandenberghe & Pissart, 1993). Permafrost severely retarded infiltration of (melt)water in spring and summer, leading to standing water bodies and a higher proportion of surface runoff. In the Roer Valley Graben, this effect was enhanced by tectonic subsidence and an associated relatively high groundwater table.

As outlined by Ruegg (1983), Schwan (1986) and Kasse (1997), soil moisture content plays an important role in determining the aeolian sediment stratification type. Together with the ample availability at the surface of sand- and silt-sized material during glacial periods, this resulted in the formation and preservation of even horizontally laminated wet-aeolian deposits (facies B). Dune-like dry-aeolian environments are almost completely absent in the area. Only after melting of the permafrost in the Weichselian Late Glacial (e.g. Kasse, 1997), the ground surface was dry enough for a dune-like aeolian relief to develop. Dry-aeolian sediments have not been preserved at the end of the second-to-last glacial (Saalian) or in earlier phases of the Middle and Late Quaternary. This might indicate that climatic conditions during the Weichselian Late Glacial in this area were rather abnormal and have no counterpart in earlier Quaternary cold phases. Loess sedimentation occasionally took place in the Roer Valley Graben, especially during part of the last glacial cycle (Fig. 3.11: facies E). However, the Roer Valley Graben is situated ~100 km north of the Belgian part of the European belt of surficial loess deposits (Fig. 3.1). This shows that the position and areal extent of loess deposition in north-western Europe constantly changed over time, even within one glacial period, as a result of a changing local depositional environment.

Almost all clastic sediments in the Roer Valley Graben date from glacial periods. Only peat, humic silt and humic sand of Facies G and associated palaeosols testify to repeatedly occurring warm-temperate conditions. Peat formation and preservation requires a groundwater level at or close to the land surface. Local groundwater level and surface humidity are thus the main factors determining the preservation potential of sediments in this area, both during cold (fixation of sand-sheet and loess deposits) and warm (peat formation) climatic conditions.

3.8 Conclusions

- The Roer Valley Graben is an active tectonic subsidence area in the south-eastern Netherlands that contains an up to 35-m thick Middle- and Late-Pleistocene sediment sequence. The sediment record is dominated by fine-grained cold-climate aeolian, fluvio-aeolian and fluvial deposits and intercalated organics;

- In the sediment sequence, a gradual shift can be observed from a dominance of fluvial processes to an alternation of fluvial and aeolian processes and finally, predominantly aeolian sedimentation. This is related to Middle-Pleistocene tectonic movements, which forced the Rhine-Meuse river system to leave the Roer Valley Graben and take a more eastern course on the Venlo Block. The accommodation space was subsequently filled by aeolian sand-sheet and loess deposits, lacustro-aeolian sediments, fluvial deposits of local streams and peat;

- Subsidence, repeated periods of permafrost and associated humid surface conditions exerted a major influence on the depositional environment and preservation potential of the sediments in the Roer Valley Graben, leading to a prevalence of sheet-like, wet-aeolian deposits. These are both sand-sheet deposits and reworked loess deposits. Sediments of this type are characterised by even horizontal lamination or have a massive appearance. Dominant processes include sand-ripple lamination and adhesion lamination;

- Dry-aeolian deposits are only known from the Weichselian Late Glacial. This might indicate that climate and associated depositional conditions in the Roer Valley Graben during this period were rather abnormal and have no counterpart in earlier cold phases;

- The fine-grained sediment sequence in the Roer Valley Graben shows evidence of many hiatuses. It does not represent a continuous and gradually evolved sediment record of the Middle and Late Pleistocene. Nonetheless the sedimentary development in this area greatly contributes to our understanding of processes taking place in the terrestrial realm during this particular period of the Quaternary.

Acknowledgements

Core drilling and collection of CPT data were financed by TNO-NITG. Jorica Baars (TNO-NITG) analysed the grain-size samples. Thanks are due to Annika Hesselink for drawing Fig. 3.3. Henk Berendsen, Annika Hesselink and Wim Westerhoff critically read earlier drafts of this manuscript.

4 PALAEO-ENVIRONMENTAL RECONSTRUCTION AND OSL DATING OF TERRESTRIAL EEMIAN DEPOSITS IN THE SOUTH-EASTERN NETHERLANDS

with Piet Cleveringa & Andrew S. Murray

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Abstract

The Roer Valley Graben in the south-eastern Netherlands is a subsiding area situated just south of the maximum extent of the Pleistocene glaciations. In this area, Eemian (Marine Isotope Stage 5e) clastic and organic deposits have been preserved in a terrestrial sedimentary environment. Deposition took place in the Early Eemian (regional pollen zones E2-E3) and Late Eemian (E5-E6A-E6B). The sedimentary sequence contains a hiatus during the E4A-E4B-E5 regional pollen zones. Sedimentary and palynological data reveal that both the presence and extent of the Eemian deposits are intimately linked to the local groundwater-level history and clastic sediment flux. Changes in these environmental factors are likely to be related to changes in the global climate. Optically Stimulated Luminescence (OSL) dating has been applied to provide an absolute time frame for the Late-Quaternary deposits in the area. This study is thereby the first to present a reliable quartz OSL dating (114 ± 12 ka) for terrestrial Eemian deposits in the Netherlands.

4.1 Introduction

In recent years, detailed information has become available on the palaeo-environmental and palaeoclimatic development of the Eemian interglacial (Marine Isotope Substage 5e) in north-western Europe (e.g. Turner, 2000). Most of the data comes from sites that were glaciated during the preceding Saalian glacial period (Marine Isotope Stage 6). Glaciation resulted in the formation of isolated basins, such as kettle holes and intra-morainic basins. As climate improved and sea level and groundwater level rose, these basins acted as sedimentary sinks. The Eemian type sections in the central-Netherlands (Amersfoort: Zagwijn, 1961; Cleveringa et al., 2000; Amsterdam-Terminal: Van Leeuwen et al., 2000) are both located in Saalian glacial basins (Fig. 4.1A). Both sections consist of lacustrine and shallow marine sediments and therefore give information on sea-level history, as well as on vegetation and landscape development. Dating of the deposits is difficult. A U/Th age of a shallow marine shell bed in the upper part of the Eemian sequence at Amsterdam-Terminal (118.2 ± 6.3 ka; Van Leeuwen et al., 2000) is the only available date so far.

South of the maximum extent of the Saalian glaciation, Eemian deposits are less frequent. They are known from coastal areas in England and Belgium and occur as isolated deposits in fluvial terrace sequences, e.g. along the river Thames (Bridgland, 1994; Gibbard, 1994). In the south-eastern Netherlands, Eemian peat deposits are known from stratigraphic and palynological studies at several sites in the Peel region (Fig. 4.1B; Table 4.1). This is a slightly elevated, low-relief area, which acted as a local water divide. Poor drainage, associated with faulting, caused groundwater exfiltration and extensive peat growth. Correlation of the terrestrial deposits in the Peel region with the lacustrine and shallow marine deposits of the Eemian type sections is hampered by differences in local vegetation development. The general scarcity of dates of Eemian deposits further complicates time correlation.

The aim of this paper is to reconstruct the Eemian palaeo-environmental development in the Roer Valley Graben, just north-west of the Peel region, and to compare it to the classical Eemian biostratigraphy. Chronological information is obtained by Optically Stimulated Luminescence (OSL) dating of sand-sized quartz, which makes this study the first to provide OSL-dating results for terrestrial Eemian deposits in the Netherlands.

The Late-Quaternary sedimentary record in the Roer Valley Graben is very suitable to apply quartz OSL dating, because: (1) The aeolian depositional environment of most of the clastic sediments ensured sufficient exposure to daylight during sediment transport to enable complete resetting of the OSL signal prior to deposition; (2) The clastic deposits consist almost exclusively of quartz grains, which results in a low natural radioactivity. The very low dose rates permit reliable dating far back in time (> 100 ka); (3) The presence of peaty sand deposits enables a direct correlation of the OSL dates with palynological analyses.

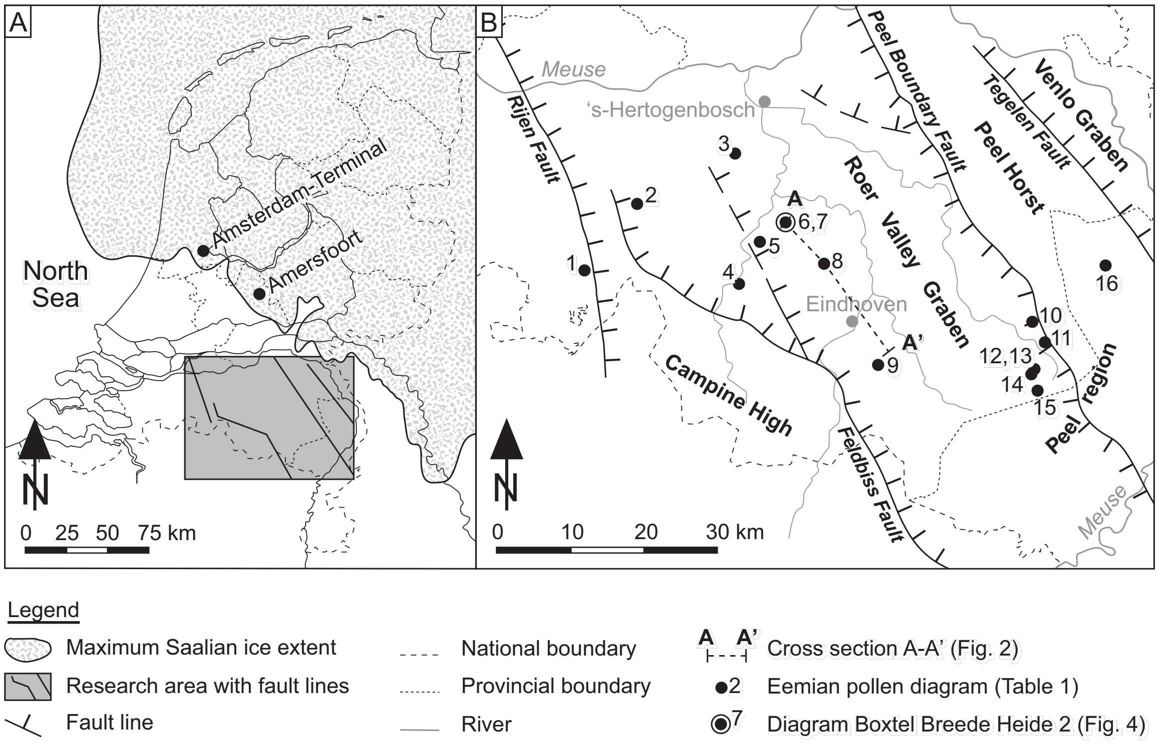


Figure 4.1 (A) Location of the research area with respect to the maximum extent of the Saalian ice sheet; (B) Map of the south-eastern Netherlands showing the position of the Roer Valley Graben and the location of sites that provided an Eemian pollen diagram. The Peel region is also indicated. Numbers refer to Table 4.1.

Table 4.1 Pollen diagrams from the Roer Valley Graben and the Peel region that contain (parts of) the Eemian interglacial.

#	Name	X coord[a]	Y coord[a]	Reference
1	Alphen-'t Zand	125.000	390.000	Vandenberghe & Krook (1981)
2	Tilburg-Podsolen	131.750	397.700	TNO-NITG (unpublished)
3	Helvoirt I	145.300	404.400	Buurman (1970)
4	Middelbeers-Visvijver	144.740	388.070	TNO-NITG (unpublished)
5	Brinksdijk	148.670	395.440	TNO-NITG (unpublished)
6	Boxtel-Breede Heide	151.475	369.910	TNO-NITG (unpublished)
7	Boxtel-Breede Heide 2	151.475	396.905	This paper
8	Best-Core B3	155.650	392.650	Bisschops et al. (1985)
9	Grote Heide	164.290	377.720	TNO-NITG (unpublished)
10	Hoogdonk	184.430	383.010	TNO-NITG (unpublished)
11	Liessel	185.666	380.666	Mente (1961)
12	Asten-Het Gevlocht	184.620	376.390	Van der Vlerk & Florschütz (1953)
13	Asten-Het Gevlocht II	184.620	376.390	Florschütz & Anker-Van Someren (1956)
14	Astensche Peel I	184.300	376.100	Florschütz & Anker-Van Someren (1956)
15	Griendtsveen IX	184.700	373.700	Eshuis (1946)
16	IJsselsteijn	192.500	389.632	Van den Toorn (1967)

[a] Coordinates refer to the Dutch RD coordinate system.

4.2 Geological setting

The Roer Valley Graben (Fig. 4.1B) is an actively subsiding area that continuously provides new accommodation space. It forms part of the Cenozoic rift system of central and western Europe that runs from the Alps to the North Sea and originated in the Early Tertiary (Ziegler, 1994). Until the early Middle Pleistocene, deposits of a mixed Rhine-Meuse river system filled the Roer Valley Graben. In the course of the Cromerian, tectonic movements forced the river Rhine to leave the area and to take its present, more north-eastern course. Later, the Meuse also shifted its course towards the north-east and occupied the Venlo Graben (Fig. 4.1B; Kasse, 1988; Zagwijn, 1989; Van den Berg, 1994). From then on, the central part of the Roer Valley Graben was left without a major fluvial depositional system and small-scale, discontinuous sedimentation processes prevailed. This has led to a complex sedimentary unit (Fig. 4.2). In general, sand- and silt-sized aeolian, lacustro-aeolian and fluvial sediments of small rivers and brooks were deposited during cold periods. In warmer climatic intervals, organic deposits were formed in marshy depressions outside the river valleys, whereas soil formation took place at other localities. In this way, a long terrestrial record has developed in the Roer Valley Graben, testifying to repeated palaeo-environmental and palaeoclimatic changes in the Middle and Late Pleistocene. The record is complicated by cryoturbation levels, which are interpreted in terms of permafrost degradation (cf. Vandenberghe & Van den Broek, 1982; Vandenberghe, 1988).

The lithostratigraphy of the upper part of the geological record is well-known as a result of data collection for detailed surficial geological and soil mapping using hand cores. Outside present-day and former river valleys, on top of aeolian sands, an up to three-meter thick sequence of organic and organoclastic deposits occurs at ~5 m below surface ('Upper organic layer' in Fig. 4.2). These deposits were formed in shallow, wet depressions that were scattered over the sandy, slightly undulating landscape. The organic-rich sequence has traditionally been interpreted as Eemian or Early Weichselian in age, based on its lithostratigraphic position and warm-temperate pollen content (see authors listed in Table 4.1). The top of the sequence is often affected by cryoturbation. Where the organic layer is absent, a reddish-brown soil horizon may be present, testifying to a period of non-deposition under temperate climatic conditions (Kasse & Bohncke, 1992). The formation of these deposits is thus intimately linked to the topographic position of a site and the local groundwater conditions. Above this level, there is an aeolian sand layer, followed by a 1-3 m thick, stiff grey sandy loam layer, locally known as 'Brabant loam' ('Upper loam layer' in Fig. 4.2). Both the pollen and mollusc content of the loam layer point to deposition in a cold, wet and open environment, which is interpreted as loess deposition on a wet surface and subsequent partial reworking by surficial meltwater. Two bulk ^{14}C dates indicate a Middle-Weichselian age of the loam (Bisschops et al., 1985). The top and bottom of the loam layer show intense deformation. The loam layer is covered by Middle- to Late-Weichselian aeolian coversands, in which a Holocene soil has developed.

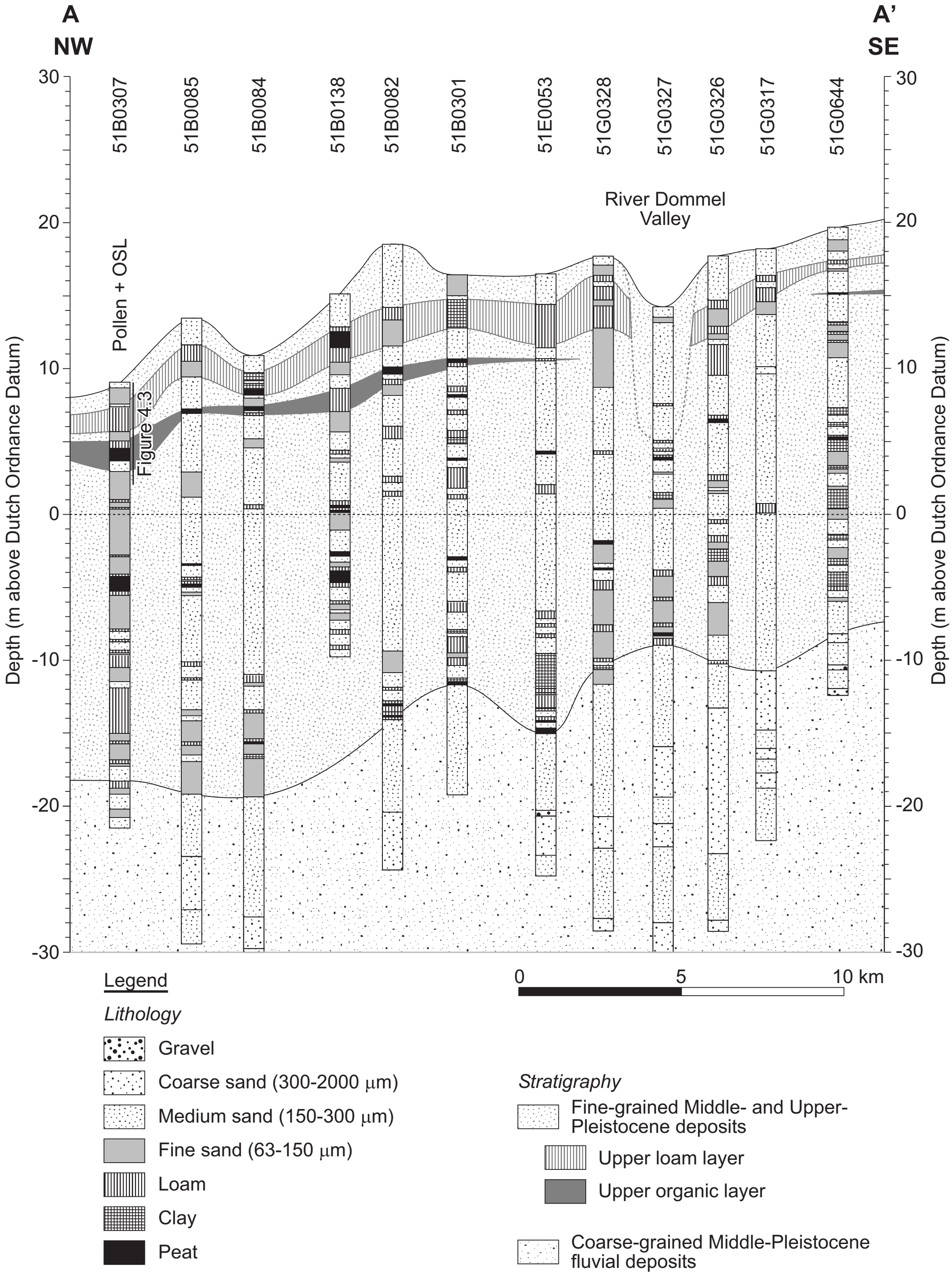


Figure 4.2 Geological NW-SE cross section through the central part of the Roer Valley Graben. The location of the cross section is indicated in Figure 4.1B.

4.3 Methods

We collected data from the upper 7 m of a 30 m deep core 'Boxtel-Breede Heide 2' (for core location, see Fig. 4.1B), which was drilled using a mechanised bailer drilling unit (Oele et al., 1983). Average recovery was more than 90%, with ~90% of the recovered sediments being undisturbed. The 10-cm wide core was split in safe-light conditions. One half was brought into the light, photographed, described and used to make lacquer peels for sedimentological analysis, the other half was kept in the dark to take samples for OSL dating. Later, pollen and loss-on-ignition (LOI) samples were also taken from this half of the core. The combination of sedimentological and palynological data from an undisturbed core provided detailed information on the sedimentary development in the area during the Late Quaternary.

Pollen samples were taken once every 5-20 cm, depending on the lithology of the core and the position of lithological transitions. Sample preparation included peptisation using $Na_4P_2O_7 \cdot 10H_2O$, decalcification with hydrochloric acid (10%) and acetolysis. A sodium polytungstate solution (specific gravity 2.1) was used for heavy-liquid separation of the organic and siliciclastic material. Approximately 300 pollen grains were counted at each level. In presenting the data, aquatics and spores were excluded from the pollen sum. The standard pollen zonation for the Eemian in the Netherlands (Zagwijn, 1961; 1975) was used as a reference.

The chronology of the deposits was investigated by applying quartz OSL dating. This technique provides information on the time of last exposure to light of a sediment sample (Aitken, 1998). Silt- to sand-sized clastic particles are usually sampled. The OSL age is calculated by dividing the estimated amount of ionising radiation the sample has absorbed since burial (equivalent dose) by the amount of energy from ionising radiation the sample has absorbed per year (dose rate). Samples were collected from undisturbed, preferably lithologically homogeneous parts of the sediment cores. All samples were washed and subsequently treated with hydrochloric acid (10%) and hydrogen peroxide (30%) to remove any carbonates and organic matter. After drying, the sediments were sieved to isolate the 180-250 μm grain-size fraction. Treatment with concentrated hydrofluoric acid was applied to obtain a pure quartz sample and to etch away the outer 10 μm of the quartz grains. For equivalent-dose determination, we used the improved single-aliquot regenerative dose (SAR) protocol of Murray & Wintle (2000). Measurements were made on an automated Risø TL/OSL reader using an internal $^{90}Sr/^{90}Y$ beta source and blue light-emitting diodes for stimulation (Bøtter-Jensen et al., 1999; 2000). The dose rate was derived from high-resolution gamma-ray spectrometry measurements in the laboratory (Murray et al., 1987).

4.4 Results

4.4.1 Sedimentology and stratigraphy

The lithology and sedimentology of the upper 7 m of core 'Boxtel-Breede Heide 2' are shown in Figure 4.3A. In this depth range, there is a clastic-organic-clastic sedimentary sequence, which represents the Late Saalian-Eemian-Weichselian time span:

Unit A (>7.00-5.80 m below surface). This clastic sediment unit consists of weakly sub-horizontally bedded, yellowish-brown silty sand (median grain size 140-180 µm). The interval between 6.64 and 6.40 m contains alternating mm-scale loam and sand laminae. Above 6.19 m, the median grain size of the sand increases to 190 µm, in association with the frequent occurrence of coarse sand laminae. Unit A is of aeolian origin. The alternation of loam and sand laminae represents adhesion and deposition processes on an alternating wet and dry land surface (Ruegg, 1983; Schwan, 1986; Koster, 1988; Koster et al., 1993). The coarse sand laminae in the top part of the unit indicate a period of deflation, resulting in the concentration of coarse material at the surface.

Unit B (5.80-3.92 m below surface). This unit is subdivided into three distinct lithological subunits: peaty sand (B1), peat (B2) and peaty loam (B3; Fig. 4.3A). At 5.80 m, peaty sand (Subunit B1) abruptly overlies the yellowish-brown sand of unit A. The peat is uniformly dispersed in the sand, with the exception of some 1-2 cm-thick clean sand layers at ~5.60 and ~5.40 m. Upward from a depth of 5.35 m, clastic sediments are no longer present (Subunit B2). The peat frequently contains small wood fragments and between 5.04 and 4.91 m, distinct bark fragments of *Betula* occur. Above 4.91 m, the peat is amorphous. At 4.48 m, the peat is replaced by horizontally bedded peaty loam (Subunit B3) with intercalated sand layers. An ice-wedge cast extends down from the heavily contorted top of this subunit. The input of clastic material into the core during the formation of subunit B1 and the upper part of subunit B3 testifies to the presence of an unstable, partly open landscape in which sediment movement was driven by wind and possibly also by surface runoff. Palynological analyses of samples from unit B will be presented in the palaeo-ecology section.

Unit C (<3.92 m below surface). Subunit C1 (3.92-3.34 m) consists of weakly bedded, yellowish-grey silty sand (110-150 µm), which is interpreted as aeolian (cf. unit A). The upper boundary of subunit C1 is cryoturbated. Subunit C2 (3.34-1.58 m) consists of a stiff, grey sandy loam layer. It is present over large areas and represents Middle-Weichselian partially reworked, loess-like aeolian deposits (Kuyl & Bisschops, 1969; Bisschops, 1973; Bisschops et al., 1985). The upper 50 cm of subunit C2 are heavily cryoturbated. Subunit C3 (<1.58 m below surface) consists of brown silty sand (100-180 µm), showing horizontal lamination in the lower part. In the homogeneous upper part of the subunit, a Holocene soil occurs. Roots extend downwards into the laminated silty sand. Subunit C3 is interpreted as aeolian coversand, which blanketed the land surface in large parts of the Netherlands in the Middle and Late Weichselian (e.g. Van der Hammen et al., 1967; Van der Hammen, 1971; Koster, 1982; 1988).

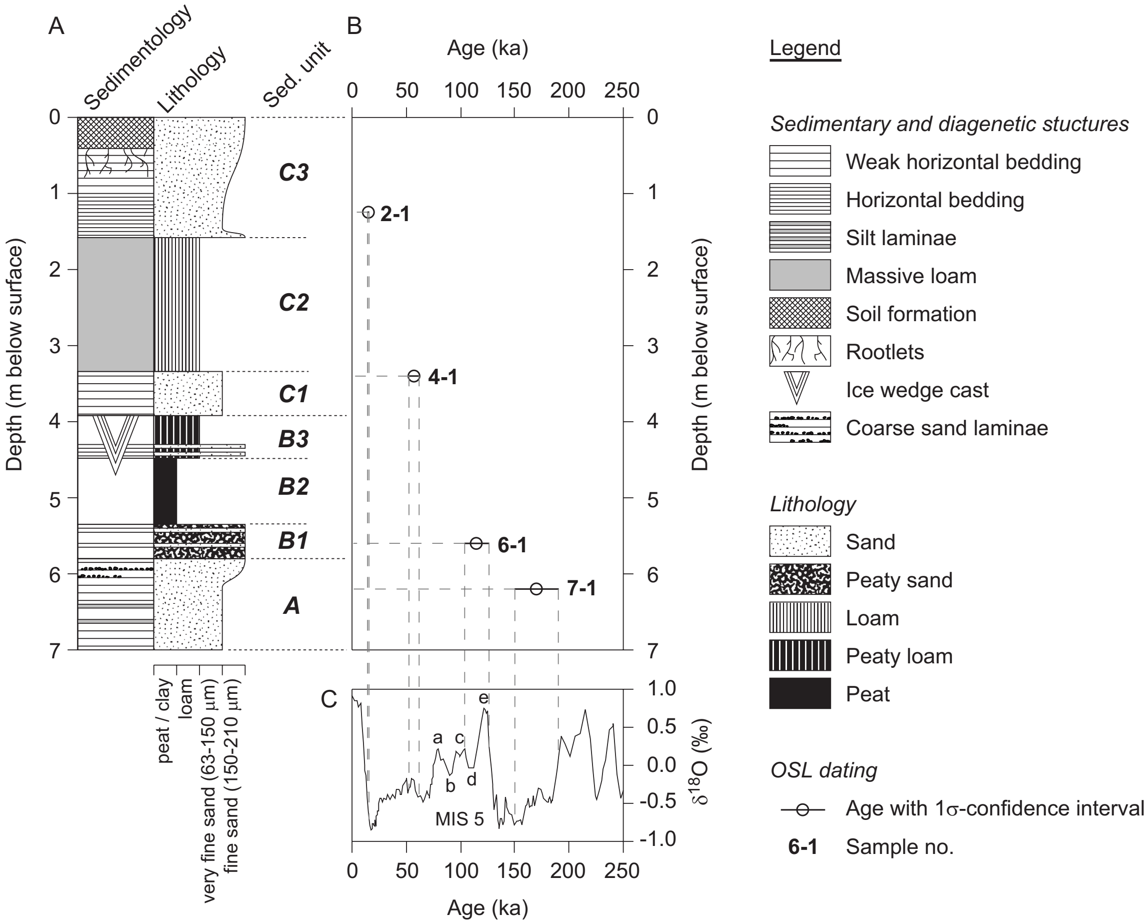


Figure 4.3 (A) Lithology and sedimentology of the upper 7 m of core 'Boxtel-Breede Heide 2'. Sediment units A-C are indicated; (B) Location and age of the OSL samples. See Table 4.2 for sample details; (C) SPECMAP compound $\delta^{18}O$ curve (Martinson et al., 1987).

4.4.2 Palaeo-ecology

Vegetation and landscape development during the Eemian are reflected by pollen and loss-on-ignition data from sediment unit B (Fig. 4.4). Three local pollen zones (LPZs) are distinguished:

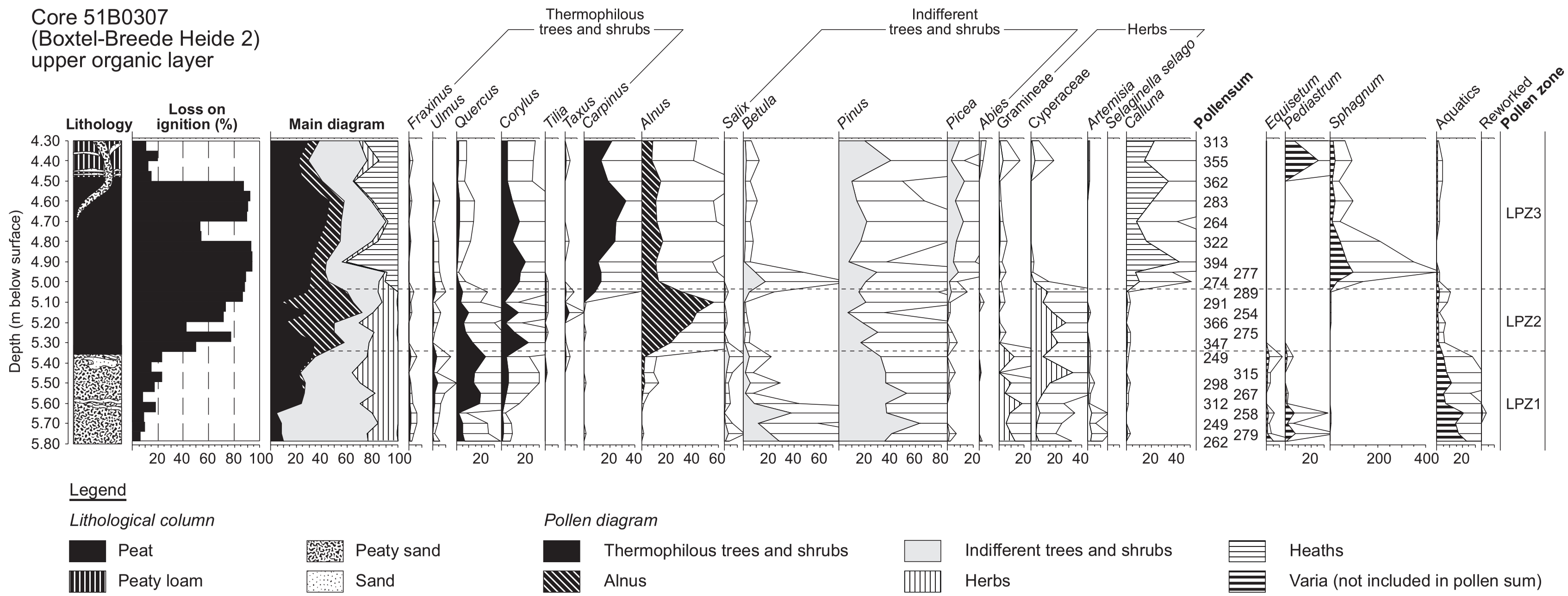
LPZ1 (5.70-5.35 m below surface). This zone encompasses the nine lowermost pollen spectra, which are characterised by an increasing amount of thermophilous tree pollen and the presence of aquatics. *Pinus* is the dominant tree in the lowermost pollen spectra, but *Ulmus*, *Quercus* and *Corylus* are also present from the earliest phase. *Quercus* values peak at 5.55 m. Decreasing amounts of aquatics and a shift from grasses to sedges both indicate shallowing of the originally 1-2 m deep pool that filled the local depression. The presence of the herb *Artemisia* in the lower spectra reflects an open vegetation cover and still immature soils, which matches well with the large influx of sand-sized siliciclastic material into the depression at that time. LPZ1 is correlated with regional pollen zones E2-E3 as defined by Zagwijn (1961, 1975).

LPZ2 (5.35-5.04 m below surface). This pollen zone (spectra 10 to 15) is characterised by a second Cyperaceae peak and increasing *Alnus* values. Aquatics are low, as are thermophilous trees and shrubs. Local vegetation taxa are dominant in the upper spectra. During the formation of LPZ2, the area developed into a mesotrophic marsh, with a groundwater level at or near the surface. The presence of *Helianthemum* (not depicted in Fig. 4.4) indicates that the landscape was not completely stabilised. Fluctuating loss-on-ignition values confirm the presence of a patchy vegetation cover. LPZ2 reflects the onset of renewed peat growth in the later part of regional pollen zone E5 (Zagwijn, 1961; 1975).

LPZ3 (5.04-4.30 m below surface). The nine pollen spectra in this zone are characterised by relatively high, but constant *Carpinus* and *Picea* values. *Corylus* gradually decreases, while *Quercus* remains present in low percentages in all samples. The local vegetation development shows a shift from an *Alnus* vegetation into a *Betula*-dominated vegetation and subsequently into a *Calluna-Sphagnum* cover. Cyperaceae and Gramineae are both virtually absent in the major part of this zone, but show a slight increase in the upper pollen spectra. These spectra also shows the re-appearance of *Artemisia* and a rising *Pediastrum* curve. LPZ3 indicates a high local groundwater level and a shift from mesotrophic to more oligotrophic conditions, as is shown by the formation of an ombrogenic *Sphagnum* peat and simultaneous *Calluna*-growth at dryer localities. *Picea* and *Abies* both point at leached, acidic soils in the area surrounding the depression, which is indicative of the telocratic phase of an interglacial (Iversen, 1958). Above 4.48 m, an increasing input of siliciclastic material into the basin (low LOI values) indicates a degenerating vegetation cover and increasing landscape instability, both of which are also evidenced by rising Gramineae, *Artemisia* and *Pediastrum* values. LPZ3 is correlated with the latest part of the Eemian (regional pollen zones E5-E6 of Zagwijn, 1961, 1975).
Vegetation and landscape development during the Eemian are reflected by pollen and loss-on-ignition data from sediment unit B (Fig. 4.4). Three local pollen zones (LPZs) are distinguished:

4.4.3 OSL Dating

The results of quartz OSL dating on four samples from core 'Boxtel-Breede Heide 2' are given in Table 4.2 and Figure 4.3B. Figure 4.3C shows the orbitally tuned SPECMAP curve of Martinson et al. (1987) for comparison. The OSL age series is both internally consistent and in agreement with other known absolute ages. The uncertainties in the dose rate, equivalent dose and age that are shown in the table all represent the 1σ-confidence interval. We presumed continuous water saturation of the sediments. Because the low natural radionuclide concentrations in the deposits give rise to very low dose rates, the contribution of cosmic rays amounts to ~15% of the total radiation in the uppermost sample. Sample saturation (i.e. the filling of all OSL traps, which leads to a


Core 51B0307
(Boxtel-Breede Heide 2)
upper organic layer
Lithology
Loss on ignition (%)
Main diagram
Thermophilous trees and shrubs
Fraxinus
Ulmus
Quercus
Corylus
Tilia
Taxus
Carpinus
Alnus
Indifferent trees and shrubs
Salix
Betula
Pinus
Picea
Abies
Herbs
Gramineae
Cyperaceae
Artemisia
Selaginella selago
Calluna
Pollensum
Equisetum
Pediastrum
Sphagnum
Aquatics
Reworked
Pollen zone
Depth (m below surface)
4.30
4.40
4.50
4.60
4.70
4.80
4.90
5.00
5.10
5.20
5.30
5.40
5.50
5.60
5.70
5.80
313
355
362
283
264
322
394
277
274
289
291
254
366
275
347
249
315
298
267
312
258
249
279
262
LPZ3
LPZ2
LPZ1
Legend
Lithological column
Peat
Peaty loam
Peaty sand
Sand
Pollen diagram
Thermophilous trees and shrubs
Alnus
Indifferent trees and shrubs
Herbs
Heaths
Varia (not included in pollen sum)

flat dose-response curve) provides an upper limit to the effective OSL dating range. Figure 4.5 shows a representative dose-response curve for an aliquot of sample 7-1. The curve indicates that sample saturation is only approximated at a dose of more than 300 Gy, which is far beyond the equivalent dose of the sample (143 ± 13 Gy). Independent information on the age of the samples is provided by correlation with previously dated sedimentary sequences in the region and by interpretation of the palynological data presented in this paper.

Sample 2-1 (15.0 ± 0.9 ka; subunit C3) is of Late-Weichselian age. It represents the Older Coversand II (Van der Hammen et al., 1967; Van der Hammen, 1971; Koster, 1982; 1988; Kasse, 1997) or the older part of aeolian Phase II (Kasse, 1999). The age agrees well with other OSL dates of similar deposits in the eastern Netherlands, ranging from 13.9 to 17.6 ka (Bateman & Van Huissteden, 1999). Sample 4-1 (58 ± 4 ka; subunit C1) reveals an Early Middle-Weichselian age. Both OSL ages are consistent with two previously published radiocarbon dates on bulk organic matter from the humic loam of the intermediate subunit C2, which gave ages of 31,100 ± 370 (GrN 8171) and 43,300 ± 1,000 (GrN 9426) ^{14}C years BP (Bisschops et al., 1985). The Early Middle-Weichselian age of sample 4-1 is also in agreement with the presence of the ice wedge cast at the boundary between units B and C. A level of these large ice wedge casts is normally associated with cold MIS 4 (Vandenberghe, 1983; 1985).

Sample 6-1 (Subunit B1) gave an age of 114 ± 12 ka, thereby corroborating the Eemian age of unit B, as indicated by pollen analysis. Because the sample is situated in a thin (<20 mm) sand layer within peaty sand (Fig. 4.3A), the effect of water content on the dose rate was considered in detail. The gamma dose rate was assumed to come entirely from the peaty sand surrounding the OSL sample, with a measured water content of 65%.

Table 4.2 Quartz OSL data from core 'Boxtel-Breede Heide 2'.

Risø number	Sample number	Depth (m)	Grain size (μm)	Dose rate (Gy ka^{-1})[a]	Equivalent dose (Gy)	Age (ka)
013116	2-1	1.25	180-250	1.02 ± 0.05[b]	15.3 ± 0.3	15.0 ± 0.9
013117	4-1	3.40	180-250	0.93 ± 0.05[b]	54 ± 2	58 ± 4
013118	6-1	5.60	180-250	0.77 ± 0.06[c]	88 ± 5	114 ± 12
013119	7-1	6.20	180-250	0.83 ± 0.05[b]	143 ± 13	170 ± 20

[a] Spectral data derived from high-resolution gammaspectrometry were converted to activity concentrations and infinite matrix dose rates using the conversion data given by Olley et al. (1996). The dose rate to 180-250 μm quartz grains was calculated from the infinite matrix dose rate using attenuation factors given by Mejdahl (1979), including a contribution from cosmic rays (Prescott & Hutton, 1994).

[b] The dose rate was calculated using a water content of 21 ± 2% (based on an estimated porosity of 35% and a density of 2.65 for the solid fraction) and using attenuation factors given by Zimmerman (1971).

[c] The beta dose rate assumed a water content of 43 ± 7%, the gamma dose rate assumed a water content of 65 ± 7%. Attenuation factors are given by Zimmerman (1971). See text for more details.

Figure 4.4 (p. 80) Percentage pollen diagram (selected taxa) and loss-on-ignition curve of core 'Boxtel-Breede Heide 2'. The depth range shown is 4.30-5.80 m below surface.

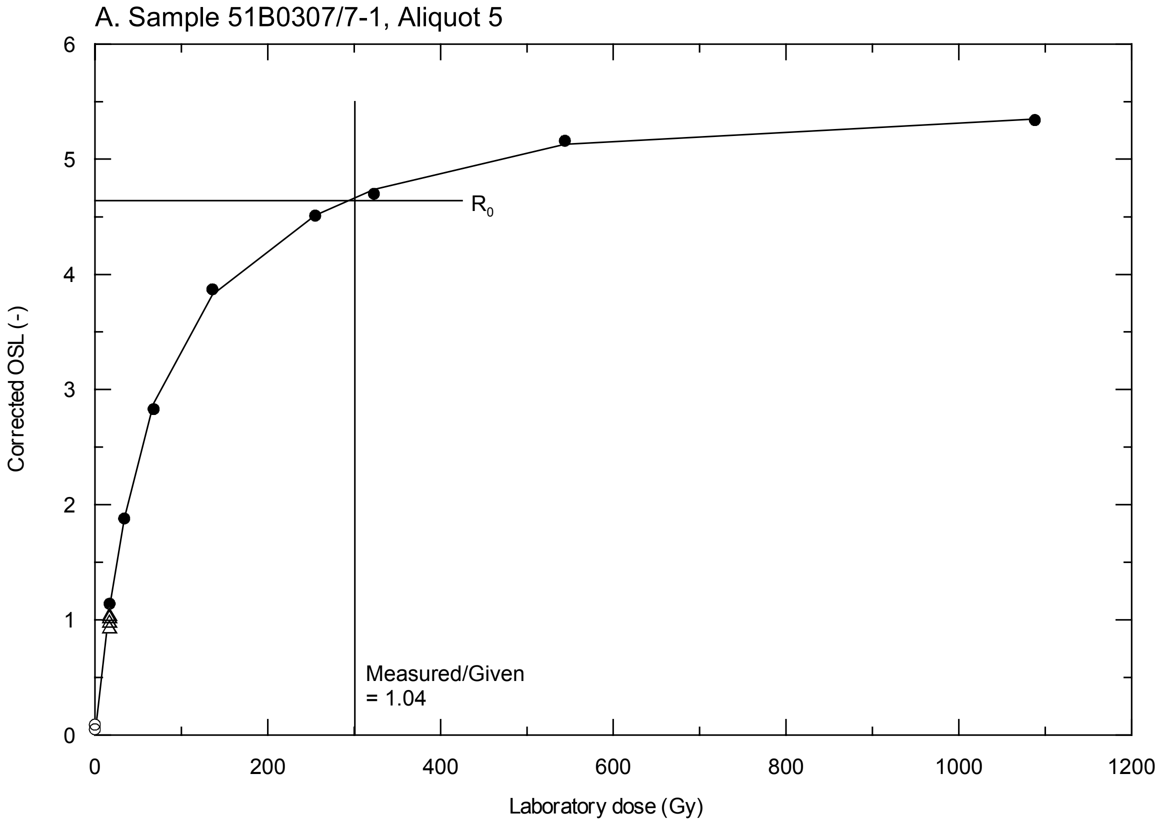


Figure 4.5 Representative dose-response curve for OSL sample 7-1 in core 51B0307. Open dots and open triangles are repeat measurements to test for changes in sensitivity. R_0 = Initial dose.

The beta dose rate comes entirely from within the sand layer. The saturated water content of this layer could not be measured directly, but is assumed to lie between the typical value for the sand deposits elsewhere in the core (21 ± 2%) and the value for the surrounding peaty sand, and so an average value of 43% was chosen. An uncertainty of ±7% was applied to the water contents relevant to both the beta and gamma dosimetry. This is sufficiently large to cover all likely values in a 2σ confidence interval.

Sample 7-1 (170 ± 20 ka; Unit A) is of Saalian age (MIS 6). This suggests that the Saalian maximum cold period is missing from the core, which is also indicated by the absence of cryoturbation phenomena at this level and the occurrence of a deflation lag in the top part of Unit A.

4.5 Interpretation and discussion

4.5.1 Reconstruction of the Eemian palaeo-environment

Regional palaeo-environmental developments have caused the preservation of early- and late-Eemian sediments in core 'Boxtel-Breede Heide 2'. Figure 4.6 shows curves for local groundwater level and local land surface height (A) and clastic sediment influx (B), based on the interpretation of the sedimentological and palaeo-ecological data from this site. Other studied sites in the Roer Valley Graben have revealed similar patterns of preservation and local landscape development (e.g. Asten Het Gevlocht: Van der Vlerk & Florschütz, 1953; Astensche Peel I, Asten Het Gevlocht II: Florschütz & Anker-Van Someren, 1956).

At the beginning of the Eemian, local groundwater level rose quickly (Fig. 4.6A). This resulted in the formation of a shallow pool. The surrounding landscape was not completely covered by vegetation. Deflation processes and erosion from the sides of the pool supplied clastic sediments to the marshy depression (Fig. 4.6B). This resulted in the formation of peaty sand deposits. A rising Cyperaceae curve, associated with a decrease in aquatics, points at shallowing of the pool during the *Quercus* zone (E3; Zagwijn, 1961; 1975). Subsequently, the landscape became completely vegetated and the palaeo-environmental signal was no longer registered.

According to the Eemian varve chronology at Bispingen in Germany (Müller, 1974), *Quercus* values peaked only 500-1000 yrs after the onset of the Eemian. The rapid groundwater rise in the beginning of the Eemian can be interpreted as the result of an increasing precipitation surplus and possibly also the collapse of the Saalian glacial forebulge (cf. Van Leeuwen et al., 2000). After ~1000 years of interglacial warmth, local groundwater level started to decline. Sedimentary or palynological indications of marine influence have not been found, which suggests that the groundwater level in the area was not directly influenced by the Eemian sea-level rise. This conclusion is supported by the asynchroneity of the peak of the groundwater curve presented here and the peak in the Eemian sea-level curve of the Central Netherlands (Zagwijn, 1983; 1996). Tectonic subsidence rates in the Roer Valley Graben (0.06 mm/yr, averaged over the Late

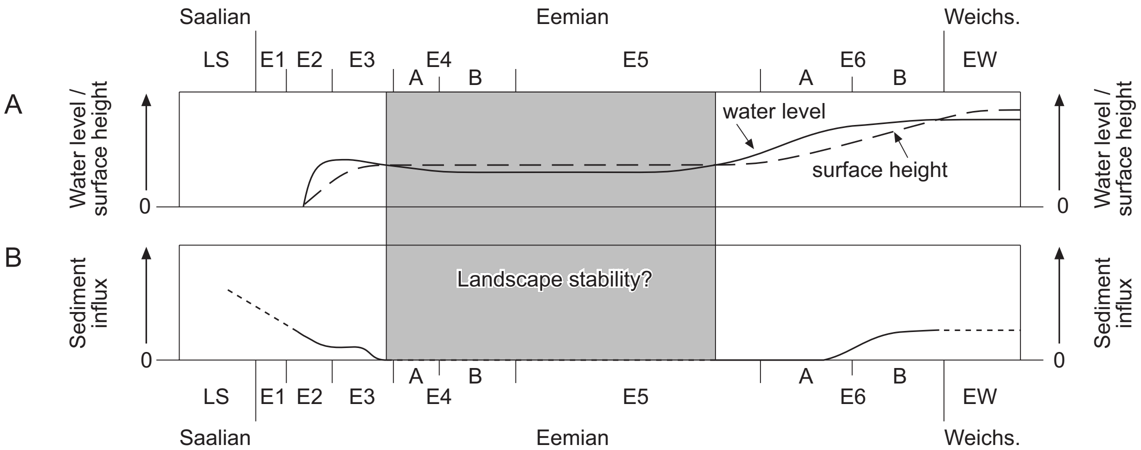


Figure 4.6 Reconstructed Eemian local mean groundwater level, ground surface height (A) and sediment influx (B) at sample site 'Boxtel-Breede Heide 2'. The regional pollen zonation sensu Zagwijn (1961, 1975) is indicated as horizontal scale. See text for more details.

Quaternary; Van den Berg, 1994) are too slow to have had any profound effect on the groundwater curve.

Deposits from regional pollen zone E4 and part of zone E5 are not present in the core, presumably because local groundwater level was too low. This situation equals that at many other sites in the area (listed in Table 4.1), which indicates that it represents a phase of regional non-deposition in a stable landscape, rather than local erosion. The preservation of organic-rich deposits from the beginning of the Eemian however suggests that the local groundwater level cannot have been too far below the surface.

In the late Eemian (E5-E6, Zagwijn, 1961; 1975), mesotrophic *Alnus-Betula* peat (LPZ2) started to grow again due to a rising local groundwater table (Fig. 4.6A). Effective precipitation was higher and air temperature was lower than in the beginning of the Eemian (e.g. Zagwijn, 1996; Aalbersberg & Litt, 1998). The peat gradually changed into an ombrotrophic *Calluna-Sphagnum* peat (LPZ3; Fig. 4.4). In the latest part of the Eemian, a degeneration of the vegetation cover and an increase in sediment reworking by aeolian processes and surficial water flow led to a sharp rise in the input of siliciclastic material into the depression and eventually to the end of peat formation (sediment subunit B3). Both the renewed peat growth and the increasing clastic sediment flux at the end of the Eemian can be linked to regional climate-driven environmental changes. It has however been argued (e.g. Gibbard & West, 2000) and demonstrated for the last interglacial (Sánchez Goñi et al., 1999) that the boundaries between biostratigraphically defined glacial and interglacial stages are not necessarily equal to the boundaries between the marine isotope (sub)stages. The environmental changes that we infer from this terrestrial record and that biostratigraphically fit within the last part of the Eemian may thus correspond to the transition between Substages 5e and 5d in the marine oxygen isotope record.

4.5.2 Implications for OSL dating

Until the last decade, direct dates of Late-Quaternary deposits beyond the age range of radiocarbon were virtually limited to the marine or coastal realm. Van Leeuwen et al. (2000) provided a U/Th date that could be directly linked to the north-west European regional pollen zonation: 118.2 ± 6.3 ka for a shell bed in pollen zone E6A. Törnqvist et al. (2000) applied quartz OSL dating to Late-Quaternary sediments from a core in the west-central Netherlands Rhine-Meuse delta and obtained a dating series, including an age of 120 ± 9 ka for a sample from estuarine deposits with Eemian shell fragments. However, the age of this sample might be overestimated due to poor bleaching in the estuarine environment.

Our sample 6-1 (114 ± 12 ka) does not suffer from the risks of poor bleaching or near-saturation and it can be directly linked to the terrestrial pollen record. The sample is situated in LPZ1, which is correlated with regional pollen zones E2-E3 as defined by Zagwijn (1961, 1975). Sedimentological analysis shows a continuous sedimentation up to 5.35 m below surface, 0.25 m above the sample depth (Fig. 4.3A), followed by a phase of landscape stabilisation of at least 5000 yrs (E4A-E4B-part of E5; cf. Müller, 1974). The OSL sample was subsequently buried to a depth of more than one meter. The preservation of organic deposits from the early Eemian indicates that the sample has been continuously saturated by water, which was one of the presumptions made when calculating the OSL ages. This study is therefore the first to provide a reliable OSL age for terrestrial Eemian deposits in the Netherlands. To improve age control over the time range beyond ^{14}C dating, more detailed OSL dating series should be measured in the future. These ages will then have to be correlated with other absolute datings in the terrestrial realm, such as U/Th ages or tephrochronological results. The Roer Valley Graben might be a perfect locality to do this.

4.6 Conclusions

- In the Late-Quaternary sedimentary record of the Roer Valley Graben, the Eemian is represented by clastic and organic deposits that formed in shallow depressions. Palynological research indicates deposition in the early Eemian (E2-E3) and late Eemian (E5-E6A-E6B). Regional pollen zones E4A, E4B and part of zone E5 are not represented in the record.

- Approximately 1000 years after the onset of the Eemian, the sandy landscape in the southern Netherlands became completely covered by vegetation and local peat growth and clastic sediment movement stopped. At the end of the Eemian, the local landscape destabilised again as a result of climate-related environmental changes. The timing of these environmental changes may correspond to the 5e-5d Substage boundary in the marine oxygen isotope record.

- Local groundwater level rose quickly at the beginning of the Eemian. Very high groundwater levels in the area were already reached in the *Quercus* regional pollen zone (E3). A second groundwater peak occurred at the end of the Eemian.

- The nature of the sedimentary record in the Roer Valley Graben enables reliable OSL dating. The OSL age series presented here is internally consistent and the ages are in agreement with earlier age estimates from similar sediments in this area. The pollen-based Eemian age of the organic complex is clearly corroborated by an OSL age of 114 ± 12 ka for a peaty sand sample.

Acknowledgements

Thanks are due to TNO-NITG for financing the drilling of the core and carrying out the pollen analyses. Hennie Mensink kindfully assisted in taking the OSL samples. We thank Henk Berendsen, Annika Hesselink, Wim Hoek, Kees Kasse, Patrick Kiden, Ward Koster, Jakob Wallinga, Wim Westerhoff and an anonymous reviewer for giving comments on earlier versions of this paper.

5 AN OSL-DATED MIDDLE- AND LATE-QUATERNARY SEDIMENTARY RECORD IN THE ROER VALLEY GRABEN (SOUTH-EASTERN NETHERLANDS)

with Piet Cleveringa, Andrew S. Murray & Wim E. Westerhoff

submitted to Quaternary Science Reviews

Abstract

Well-dated terrestrial sedimentary sequences are important to evaluate the influence of Quaternary climate change on continental landscape evolution. The Roer Valley Graben (south-eastern Netherlands) contains a 35 m-thick sedimentary record of Middle- and Late-Quaternary fluvial, aeolian and organic deposits. Sediment provenance, depositional processes and the continuity and timing of deposition were reconstructed. Sedimentary and geochemical data reveal a change from a fluvial depositional environment to a dominance of aeolian deposits. This change may be related to increased tectonic uplift and the onset of large-scale volcanism in the Ardennes-Eifel region between 800 and 500 ka. The main source of aeolian sediments are Quaternary Rhine deposits that crop out to the north-west of the study area. Sedimentation and preservation in the Roer Valley Graben took place under humid surface conditions. These conditions occurred: 1) in a periglacial climate with permafrost; 2) at the transition from a warm-temperate to a cool climate. Datings from two internally consistent quartz OSL age series in the Roer Valley Graben correspond well with ages derived from the orbitally-tuned Meuse river-terrace flight more to the south. The OSL dates confirm the presence of organic deposits reflecting Marine Isotope Stage (MIS) 9 and MIS 5e. This long terrestrial sequence thus comprises part of the 'missing' Middle-Pleistocene record of north-western Europe and forms a possible link between the glacial history of northern Europe and the long lake and loess records of eastern and southern Europe.

5.1 Introduction

Long terrestrial sedimentary records with an independent chronology are important to evaluate the influence of Quaternary climate change on continental landscape evolution. They also form an important tool for correlating continental environmental changes with variations in the continuous marine and ice-core records. Unfortunately, terrestrial sedimentary records are usually rather discontinuous in time and space. The best possibilities for the preservation of undisturbed continuous records that span at least several glacial-interglacial cycles are offered by lake and loess sequences. In Europe, long lacustrine records are mainly known from the central and southern part of the continent (Fig. 5.1A). However, the resolution of most of these sequences only enables to interpret them in terms of regional climate change and not in terms of local geomorphological processes and landscape development.

North-western Europe does not contain many areas that are suitable for the preservation of long continuous Quaternary sedimentary sequences (Turner, 1998; Dowling & Coxon, 2001; Thomas, 2001). The landscape repeatedly suffered from glacial remoulding and

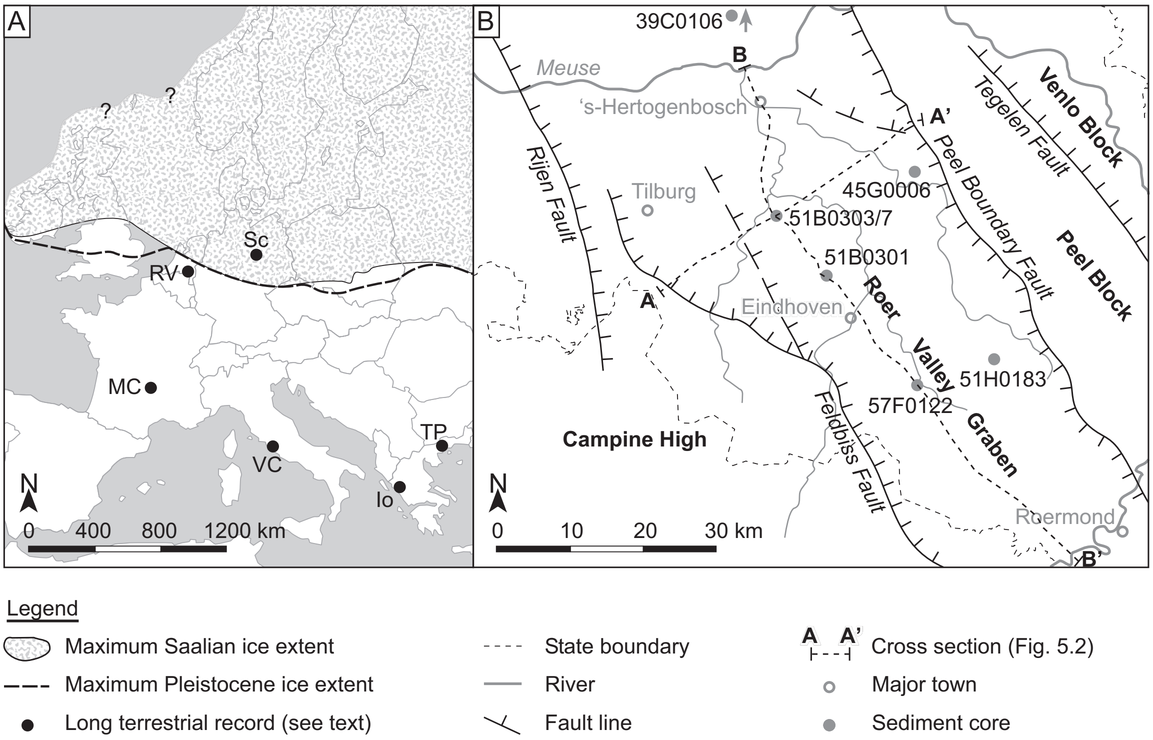


Figure 5.1 (A) Location of the Roer Valley Graben (RV) with respect to the maximum extent of the Pleistocene glaciations in northern Europe, the Middle-Pleistocene sedimentary record from Schöningen and selected long lacustrine records from central and southern Europe. Io = Ioannina (Tzedakis, 1994), MC = Massif Central (e.g. De Beaulieu & Reille, 1992; 1995; Reille & De Beaulieu, 1995; Reille et al., 2000; De Beaulieu et al., 2001), Sc = Schöningen (Urban, 1991; 1995), TP = Tenaghi Phillipon (Wijmstra, 1969; Wijmstra & Smit, 1976), VC = Valle di Castiglione (Follieri et al., 1988); (B) Detailed map of the research area with main fault lines and the location of sediment cores and geological cross sections.

erosion by periglacial processes during the Quaternary. Deep lacustrine basins or thick loess sequences could not develop. Still, the region was at the crossroads of the glacial realm to the north, the marine realm to the west and the terrestrial realm to the east and south. This makes it a key area for correlating the fragmentary glacial record of northern Europe with the lake and loess records in the east and south. Previous authors used borehole data from the Quaternary Rhine-Meuse fluvio-deltaic sequence that formed in the southern North Sea Basin as one, composite record. They applied site-to-site correlation based on palynological and sediment-petrological evidence, combined with sparse absolute datings (Zagwijn, 1974b; 1985; 1989; De Jong, 1988; Gibbard et al., 1991). Still, long-distance correlation within this large, tectonically complex area is very hazardous and there is no evidence that the fluvio-deltaic record is complete.

The subsiding Roer Valley Graben in the south-eastern Netherlands (Fig. 5.1A) is situated at the southern edge of the North Sea Basin. It has remained clear from marine influence from the Early Pleistocene onward (Kasse, 1988; Zagwijn, 1989; Van den Berg, 1994). In the course of the Middle-Pleistocene, tectonic movements forced the mixed Rhine-Meuse river system to abandon the area. This caused a gradual transition from a fluvially-dominated, to a mixed fluvial-aeolian, and finally an aeolian-dominated depositional environment in the area. Although not continuous, the sedimentary record in the Roer Valley Graben contains a wealth of information on the development of the landscape in the non-glaciated part of north-western Europe during the Middle and Late Quaternary. In addition, the widespread presence of aeolian sediments and low natural radiation doses make Optically Stimulated Luminescence (OSL) dating a suitable method to provide an independent chronology for these deposits.

This paper aims to reconstruct the depositional environment, sediment provenance and landscape development in the Roer Valley Graben during the Middle and Late Quaternary by means of sedimentary and palaeo-ecological research. The completeness of the record and the significance of depositional hiatuses for the interpretation of the sedimentary sequence are considered. The age of the deposits is determined by extensive quartz OSL dating at two different sites. Obtained ages are compared to datings derived from the orbitally-tuned Meuse river-terrace flight further south. The multi-disciplinary approach provides detailed knowledge on the geomorphological processes and landscape evolution in north-western Europe under the influence of repeated Quaternary climate change.

5.2 Geological setting

The subsurface of the south-eastern Netherlands is dissected by southeast-northwest trending faults, bounding a number of tectonic blocks that all have their own history of vertical tectonic movements. This zone of active faulting is known as the Roer Valley Rift System. The central, strongest subsiding part is the Roer Valley Graben (Fig. 5.1B; Geluk et al., 1994). The Roer Valley Rift System forms part of the Cenozoic rift system of western and central Europe, a chain of rifted basins that runs from the North Sea to the western Mediterranean. The continental rift originated in the Late Oligocene and is associated with the collision of the Eurasian and African-Arabian plates during the Pyrenean phase of the Alpine orogeny (Ziegler, 1994). The Roer Valley Rift System is confined by the marine North Sea Basin to the north and west, and the Campine High, Ardennes and Rhenish Massif to the east and south.

Due to ongoing subsidence, a more than 200 m-thick Quaternary sedimentary sequence developed in the Roer Valley Graben. Tectonic activity and climate change caused repeated sea-level changes during this period and affected the course and sediment supply of the river systems discharging into the subsiding area from the uplifting hinterland (Zagwijn, 1989). The sea withdrew from the Roer Valley Graben in the Early Pleistocene, leaving the area as one of the main depositional basins for the mixed Rhine-Meuse river system ('Rhine deposits' in Figs. 5.2A, B). In the Middle Pleistocene, accelerated uplift of the Ardennes and Rhenish Massif forced the rivers Rhine and Meuse to incise deep, gorge-like valleys in their middle reaches (Meyer & Stets, 1998; 2002; Van Balen et al., 2000; 2002; Van den Berg & Van Hoof, 2001). At approximately the same time, the lower course of the river Rhine was forced out of the Roer Valley Graben due to north-eastward tectonic tilting (Van Balen et al., 2000). The river Meuse incised a valley in the eastern part of the Roer Valley Graben and deposited the coarse-grained sediments of the Beegden Formation (Veghel-A deposits of Van den Toorn, 1967; 'Meuse deposits' in Figs. 5.2A, B). Later, the river Meuse also took a more north-eastern course. The cause and timing of these fluvial shifts will be discussed later in this paper.

From the second half of the Middle Pleistocene onward, the Roer Valley Graben did no longer host a large fluvial depositional system (Kasse, 1988; Zagwijn, 1989; Van den Berg, 1994). However, active tectonic subsidence of the area continued (Houtgast & Van Balen, 2000). Rhythmic climate changes caused repeated shifts from a warm-temperate to a cold-periglacial climate. A diverse depositional pattern developed, associated with aeolian processes, fluvio-aeolian processes and small-scale fluvial processes. Locally, 1-2 m thick organic deposits formed as well. The interplay of tectonic subsidence and climate change favoured the development and preservation of this heterogeneous, up to 35 m-thick terrestrial sedimentary record in the Roer Valley Graben. The fine-grained sand, loam and peat deposits (previously lithostratigraphically known as Nuenen Group; e.g. Zagwijn, 1989; 1996b) are assigned to the Boxtel Formation (TNO-NITG, 2003; Figs. 5.2A, B). The correlation between lithostratigraphy and dominating depositional environment is shown in Table 5.1.

Because of the heterogeneity of the record and the fact that sedimentation in the fluvio-aeolian environment was far from continuous and gradual, it is likely that hiatuses exist in this sedimentary sequence. A depositional break is sometimes recognised in the sedimentary record as a cryoturbation level or soil horizon, but often it is only indicated by an abrupt lithological change. It is thus impossible to correlate individual sediment layers with similar layers in neighbouring outcrops or cores. Simple 'counting-from-the-top' procedures without paying attention to the presence of hiatuses may lead to serious miscorrelation and misinterpretation when reconstructing the depositional history of the Roer Valley Graben.

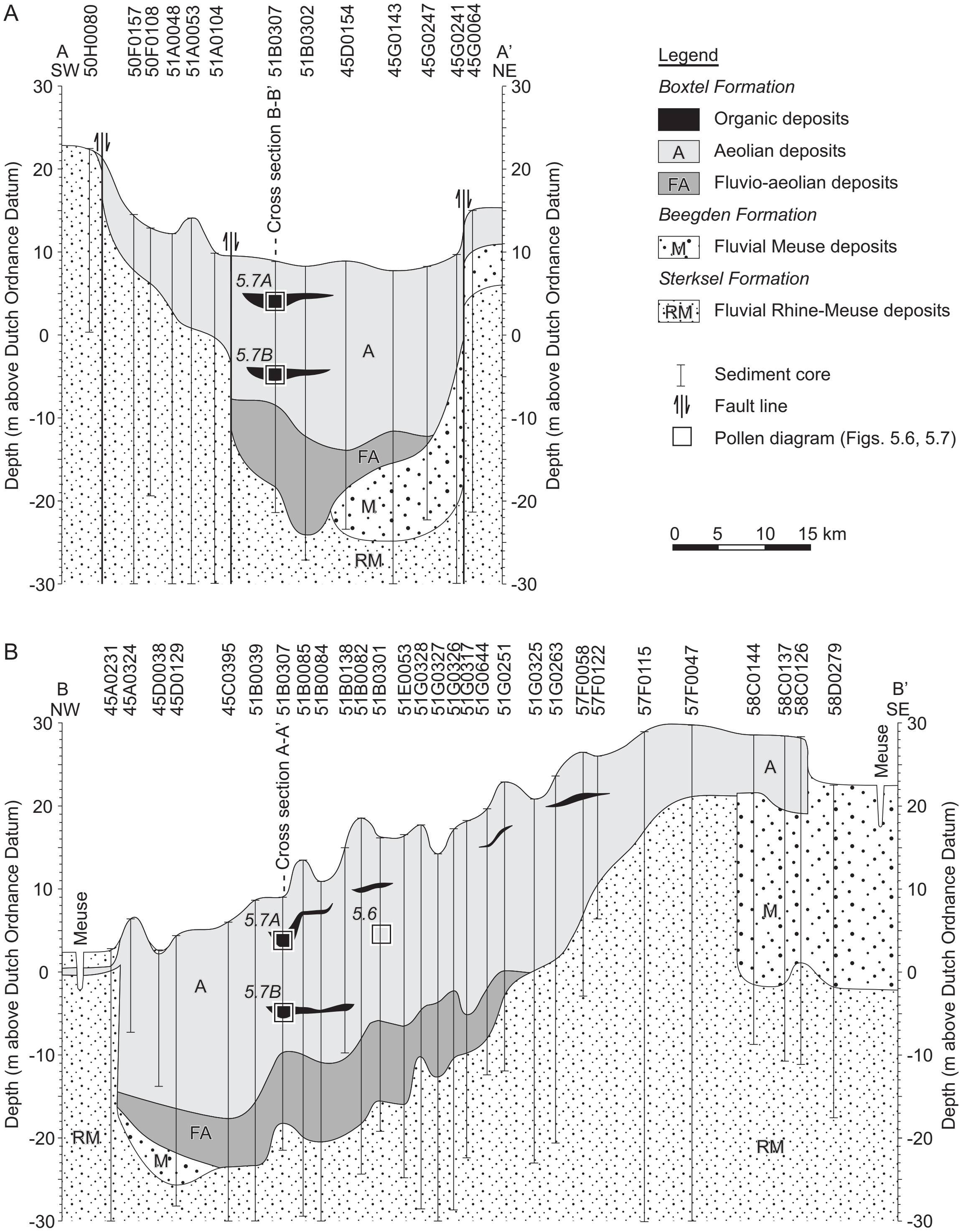


Figure 5.2 (A) SW-NE geological cross section showing the lithostratigraphy of the Middle and Upper-Pleistocene deposits in the Roer Valley Graben. Coarse-grained fluvial deposits are overlain by fine-grained aeolian deposits; (B) NW-SE geological cross section through the Roer Valley Graben. See Fig. 5.1B for the location of both cross sections.

Table 5.1 Lithostratigraphic subdivision in the Roer Valley Graben (TNO-NITG, 2003) and corresponding deposits and depositional environment

Lithostratigraphy (TNO-NITG, 2003)	Dominant type of deposit and depositional environment
Boxtel Formation	Fine-grained aeolian, small-scale fluvial and organic deposits ('aeolian deposits') Fine-grained alternating fluvial and aeolian deposits ('fluvio-aeolian deposits')
Beegden Formation	Coarse-grained fluvial deposits of the river Meuse
Sterksel Formation	Coarse-grained fluvial deposits of the rivers Rhine and Meuse

5.3 Sediment provenance

5.3.1 Method

We collected data concerning the lithology and sedimentary structures of thirteen 30-35 m deep cores (Fig. 5.1B). Cores were drilled using a mechanised bailer drilling unit with the possibility of retrieving undisturbed 1 m-long cores (Oele et al., 1983). Average sediment recovery ranged from 80% (sand) to 100% (humic loam and peat), with 80-90% of the recovered sediments being undisturbed. The 10-cm wide cores were divided into halves and photographed. One half was used to make a lithological description and to take grain-size, geochemistry and pollen samples, the other half was used to make lacquer peels for the analysis of sedimentary structures. Two sediment cores (51B0307 and 51H0183; Fig. 5.1B) were sampled in faint red light for OSL dating before any other processing or sampling was done.

Bulk geochemical analyses (X-ray Fluorescence (XRF) Spectrometry) and heavy-mineral analysis of the sand fraction were applied to get additional information on the provenance of the clastic sediments (cf. Moura & Kroonenberg, 1990; Huisman & Kiden, 1998; Huisman et al., 2000a, b). A major advantage of the XRF method is the rapid analysis of many different elements in a large number of samples. The XRF samples were ground using a Tungsten-carbide mill. Pressed powder tablets were prepared and analysed for major and trace elements, using an ARL8410 spectrometer with a Rh tube, with full matrix correction for major elements and the Compton scatter method for trace elements. To take into account the effects of grain-size differences, part of the samples was taken at the same depths as the grain-size samples. We present Al_2O_3 and Na_2O results from five different sediment cores (Figs. 5.3, 5.4). Na was chosen, because in the shallow subsurface of the Netherlands this element is virtually only derived from Na-bearing feldspars (Van Baren, 1934). Furthermore, Na-feldspar is not very susceptible to chemical weathering in the geochemical environment and time span under consideration. This leaves sorting processes and provenance as the only factors to explain differences in Na content.

Heavy-mineral data were extracted from the TNO-NITG heavy-mineral database, which contains the results of ~40,000 analyses made by the State Geological Survey of the Netherlands since the late 1940's. After treatment with HCl and HNO to remove

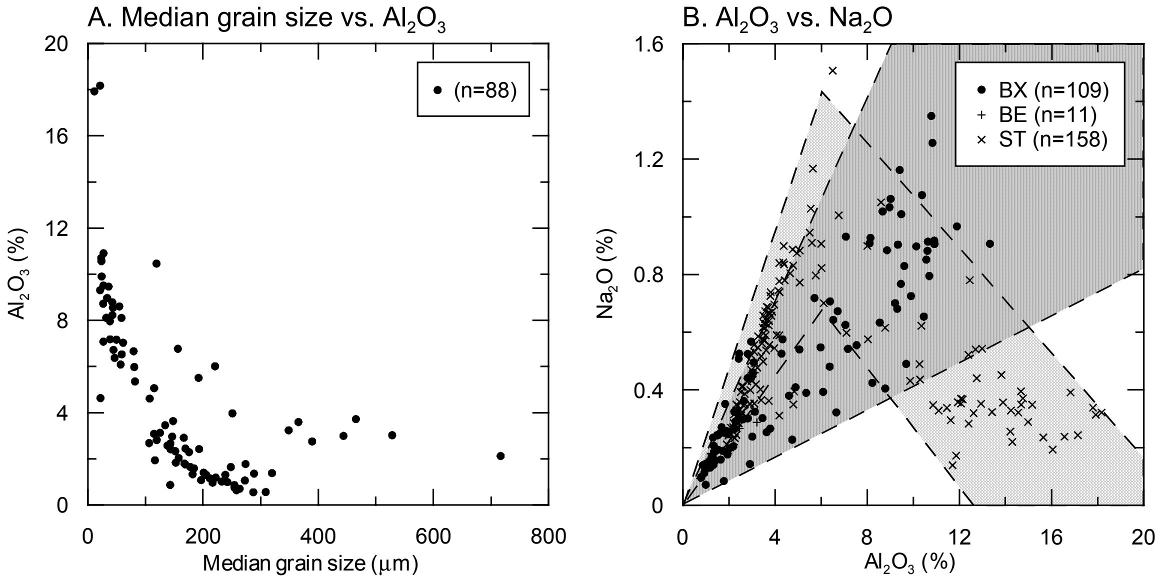


Figure 5.3 (A) Scatterplot of Al_2O_3 versus median grain size for 88 samples from cores 51B0303 and 57F0122; (B) Scatterplot of Na_2O versus Al_2O_3 for samples from cores 39C0106, 45G0006, 51B0301 and 51B0303. BX = Boxtel Formation, BE = Beegden Formation, ST = Sterksel Formation. For the location of the cores, see Fig. 5.1B.

iron(hydr)oxides and humus, 200 transparent grains of the 63-500 µm grain-size fraction with a density >2.87 g/cm^3 were counted by optical determination under a polarising microscope. A major distinction can be made between stable and unstable heavy minerals (e.g. Zonneveld, 1947; Boenigk, 1983). Typical stable minerals are tourmaline, the metamorphic minerals andalusite, kyanite and sillimanite, staurolite and zircon (incorporated in the stable restgroup). These minerals are usually depicted on the right-hand side of a heavy-mineral diagram (cf. Fig. 5.5). Unstable minerals are found on the left-hand side of a diagram and include a.o. garnet, epidote, alterite, saussurite, hornblende and the volcanic mineral augite. To locate the source area of the fluvial and aeolian sediments in the Roer Valley Graben, heavy-mineral analyses from the upper 50 m of eight different sediment cores were plotted on the map (Fig. 5.5).

5.3.2 Results

Bulk geochemical results are strongly related to sample granulometry (Moura & Kroonenberg, 1990; Huisman & Kiden, 1998; Tebbens et al., 2000). The Al_2O_3-concentration can be used to take this effect into account, because Al-bearing phyllosilicates (clay minerals and mica) are concentrated in the clay and fine silt fraction (Tebbens et al., 2000). Based on samples from two different cores, the Al_2O_3-content shows a negative correlation with the median grain size (Fig. 5.3A). Huisman & Kiden (1998) and Tebbens *et al.* (2000) found a similar relation between the Al_2O_3-content and the <16 µm grain-size fraction, based on more extensive geochemical datasets from the

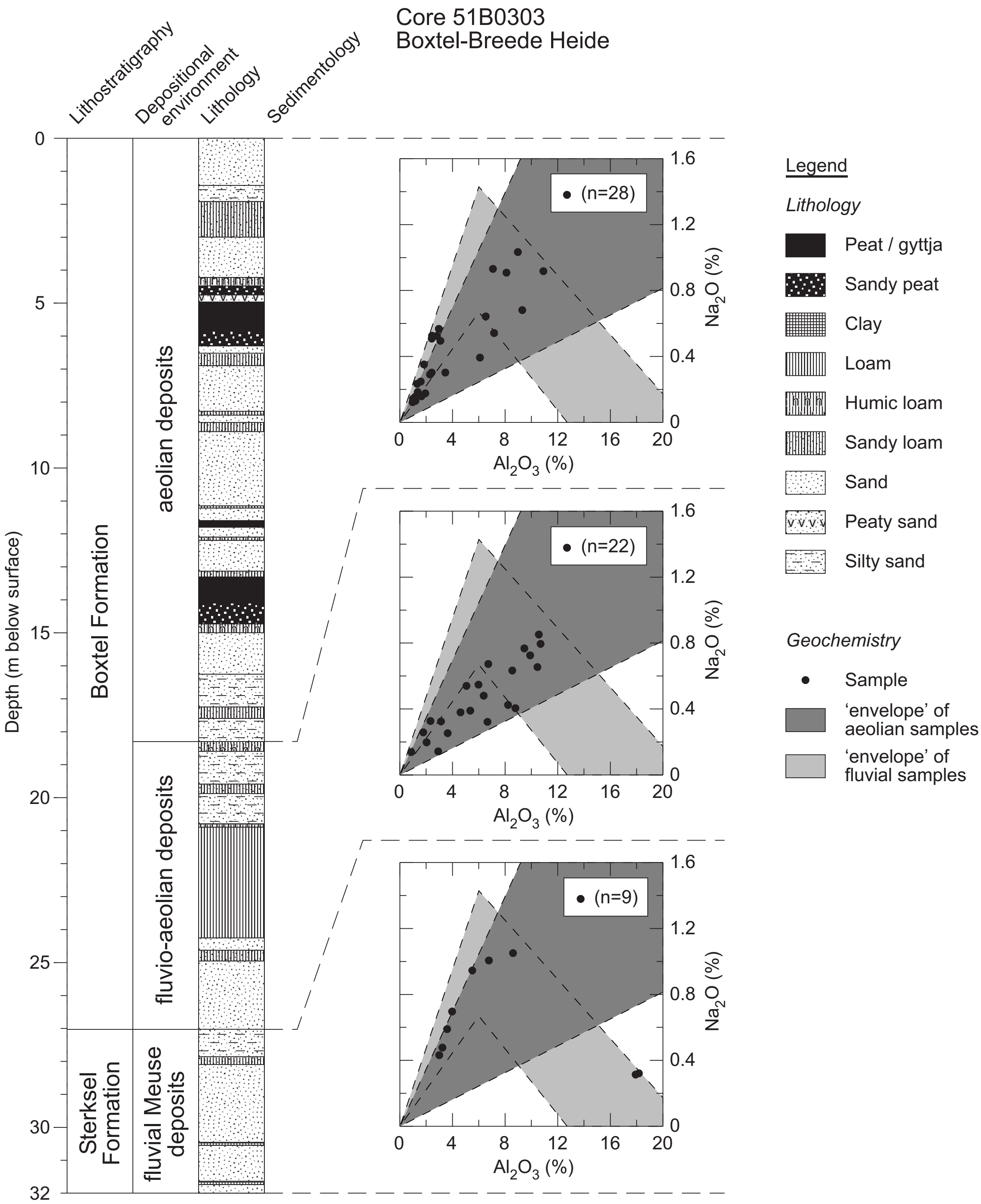
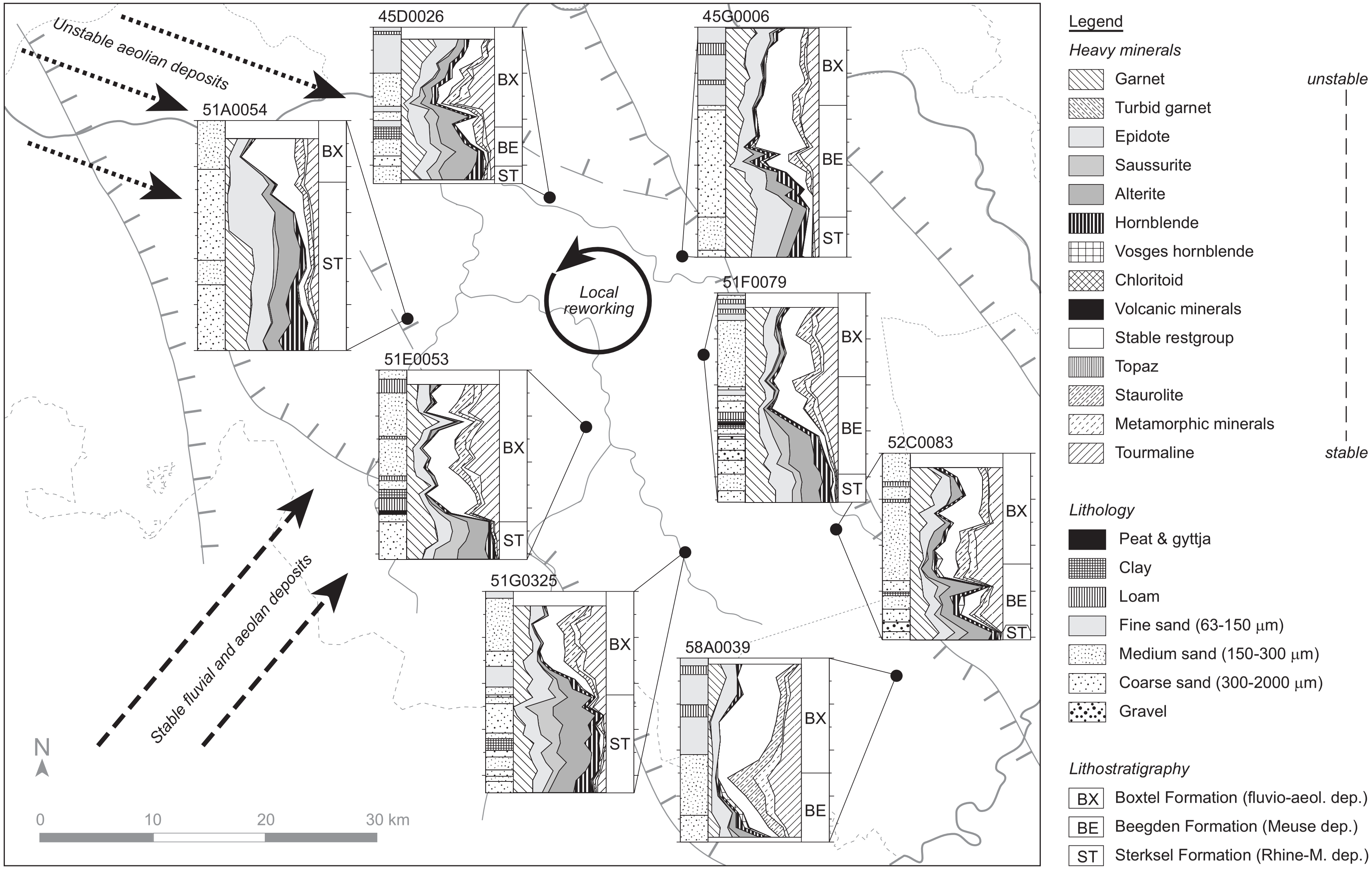


Figure 5.4 Geochemical variation (Na_2O-Al_2O_3) with depth in core 51B0303. Geochemical differences are correlated with differences in depositional environment and sediment provenance (see text). For the location of the core, see Fig. 5.1B.

Figure 5.5 (p. 95) Map showing the heavy-mineral composition with depth for eight sediment cores in the Roer Valley Graben. Only the upper 50 m of each core is shown. Inferred Late-Quaternary sediment fluxes into the region are indicated.


Unstable aeolian deposits
Stable fluvial and aeolan deposits
Local reworking
51A0054
45D0026
45G0006
51E0053
51F0079
52C0083
51G0325
58A0039
BX
BE
ST
N
0
10
20
30 km
Legend
Heavy minerals
Garnet
Turbid garnet
Epidote
Saussurite
Alterite
Hornblende
Vosges hornblende
Chloritoid
Volcanic minerals
Stable restgroup
Topaz
Staurolite
Metamorphic minerals
Tourmaline
unstable
stable
Lithology
Peat & gyttja
Clay
Loam
Fine sand (63-150 μm)
Medium sand (150-300 μm)
Coarse sand (300-2000 μm)
Gravel
Lithostratigraphy
BX Boxtel Formation (fluvio-aeol. dep.)
BE Beegden Formation (Meuse dep.)
ST Sterksel Formation (Rhine-M. dep.)

southern Netherlands. The correlation between Al and median grain-size demonstrates that the Al_2O_3-concentration can be used as a proxy for sample grain size.

Although quartz (SiO_2) is by far the most abundant mineral in Dutch Quaternary deposits, most geochemical variability between sediments is related to varying contents of feldspars, clay minerals and micas. These minerals are characterised by a specific, fixed ratio between Al_2O_3 and the other major oxides (e.g. CaO, K_2O, Na_2O). Figure 5.3B shows a scatterplot of Na_2O versus Al_2O_3 for fluvial and aeolian samples from four different cores. Samples of the fluvial Sterksel Formation show a steady rise in Na_2O with increasing Al_2O_3 content. The highest Na values correlate with ~6% Al_2O_3, corresponding to a median grain size of fine sand. At higher Al_2O_3-values (more silt and clay), Na values drop sharply. The fluvial Beegden Formation could only be sampled in one core (45G0006). These coarse-grained samples show a lower Na_2O-Al_2O_3 ratio than the deposits of the Sterksel Formation. Fluvio-aeolian and aeolian samples of the Boxtel Formation also show a positive correlation between Na and Al, though with a generally lower Na_2O-Al_2O_3 ratio than the deposits of the Sterksel Formation and a large scatter (Fig. 5.3B). The highest Na-values are related to the highest Al-values, corresponding to samples with the smallest median grain size.

To further characterise the relation between Na_2O-Al_2O_3 and sediment provenance, Figure 5.4 shows separate scatterplots of Na_2O versus Al_2O_3 for three depth intervals in sediment core 51B0303. The envelopes of the fluvial and aeolian samples in Fig. 5.3B are shown for comparison. The nine samples of the Sterksel Formation (fluvial deposits of the Rhine and Meuse) clearly fall within the fluvial 'envelope'. Within the Boxtel Formation, a distinction can be made between the fluvio-aeolian samples and aeolian samples: the 22 fluvio-aeolian samples have a distinctly lower Na_2O-Al_2O_3 ratio than the 28 aeolian samples (0.13 ± 0.04 vs. 0.09 ± 0.03).

Provenance variations are also reflected in the heavy-mineral assemblage of the sand fraction of the deposits. Figure 5.5 shows the mineralogical differences with depth for eight sediment cores in the Roer Valley Graben. Seven out of eight cores indicate high values of unstable heavy minerals in their lower part, resulting from the presence of fluvial Rhine-Meuse deposits (Sterksel Formation). The Beegden Formation, which is only present in the eastern part of the region, is characterised by an upward increasing abundance of stable minerals. These Meuse deposits are further distinguished by the presence of small amounts of Vosges hornblende (e.g. cores 52C0083 and 58A0039 in Fig. 5.5). The fluvio-aeolian and aeolian deposits of the Boxtel Formation generally have a stable heavy mineral assemblage. However, cores 45D0026 and 45G0006 in the northern part of the Roer Valley Graben show a gradual shift from a stable association in the lower part to a mixed heavy-mineral association in the upper part of the formation. All deposits are characterised by generally small amounts of volcanic minerals.

5.3.3 *Interpretation*

High Na-values at ~6% Al_2O_3 in the samples of the Sterksel Formation (Fig. 5.3B) indicate that Na-bearing feldspars are primarily found in the fine-sand grain-size fraction (cf. Van Baren, 1934). Coarser grain sizes (low Al_2O_3-values) are dominated by quartz grains, whereas finer grain sizes show increasing amounts of Na-poor, Al-rich clay minerals. These trends are consistent with similar geochemical trends in Early-Pleistocene Rhine deposits (Tegelen Formation; Huisman & Kiden, 1998), except that in the Early-Pleistocene sediments the Na-peak is found at ~10% Al_2O_3 (silt fraction). The high content of Na-bearing feldspars and the unstable heavy-mineral assemblage of the Sterksel Formation are both typical for Rhine sediments from the moment the river had extended its drainage network to southern Germany and the northern Alpine region in the Late Pliocene (Zonneveld, 1947; Boenigk, 1978a, b). The presence of small amounts of volcanic minerals indicates that the Sterksel Formation must be older than the onset of large-scale Middle- and Late-Quaternary volcanism in the Eifel region, which led to very high percentages (up to 40%) of the volcanic mineral augite in Rhine deposits downstream of the Eifel (Zagwijn, 1989).

The fluvial deposits of the Beegden Formation cannot be characterised geochemically, because only a very limited number of samples could be analysed. However, the upward increasing amount of stable heavy minerals indicates a combination of an influx of stable deposits and reworking of the underlying unstable deposits (Zonneveld, 1964). The stable heavy mineral association and the presence of Vosges hornblende clearly point to a Meuse provenance for these deposits. The occurrence of Vosges hornblende indicates that the deposits of the Beegden Formation in the Roer Valley Graben are older than 250 ka. This is the approximate age of the decapitation of the Lorraine Meuse near Toul by the river Moselle, which led to the loss of a considerable part of the upper drainage area of the river Meuse, including the Vosges region in north-eastern France (Krook, 1993; Pissart et al., 1997).

The Na_2O-Al_2O_3 plot of the Boxtel Formation (Fig. 5.3B) shows some resemblance to that of Na-bearing Early-Pleistocene deposits with a south-western (Belgian) provenance (Kedichem Formation; Huisman & Kiden, 1998). However, Na-peak values are much higher. In the Boxtel Formation, the fluvio-aeolian deposits generally have lower Na_2O-Al_2O_3 ratios than the aeolian deposits (Fig. 5.4). This may be related to the input of stable Meuse deposits in the fluvio-aeolian deposits. The very high Na-values in the fine-grained aeolian deposits must be caused by the input of sediments rich in Na-bearing feldspar. The only possible provenance for these sediments are Quaternary Rhine deposits that cropped out to the north and west of the Roer Valley Graben, in the western Netherlands and dry southern North Sea Basin. A north-western provenance for the aeolian deposits is consistent with the heavy-mineral data for the Boxtel Formation. These indicate the highest values of unstable heavy minerals in the northern part of the region (Fig. 5.5). The trend from a stable to a mixed heavy-mineral assemblage in the Boxtel Formation can be explained by assuming a mixed input of: 1) Na-rich, unstable aeolian sediments from the north-west; 2) Na-poor, stable aeolian deposits and deposits of small rivers from the Campine High in the south-west; 3) locally reworked sediments.

It is concluded that after the disappearance of the large river systems from the Roer Valley Graben, Na-rich, unstable aeolian deposits became the dominant clastic sediment source in the region.

5.4 Depositional environment

5.4.1 Method

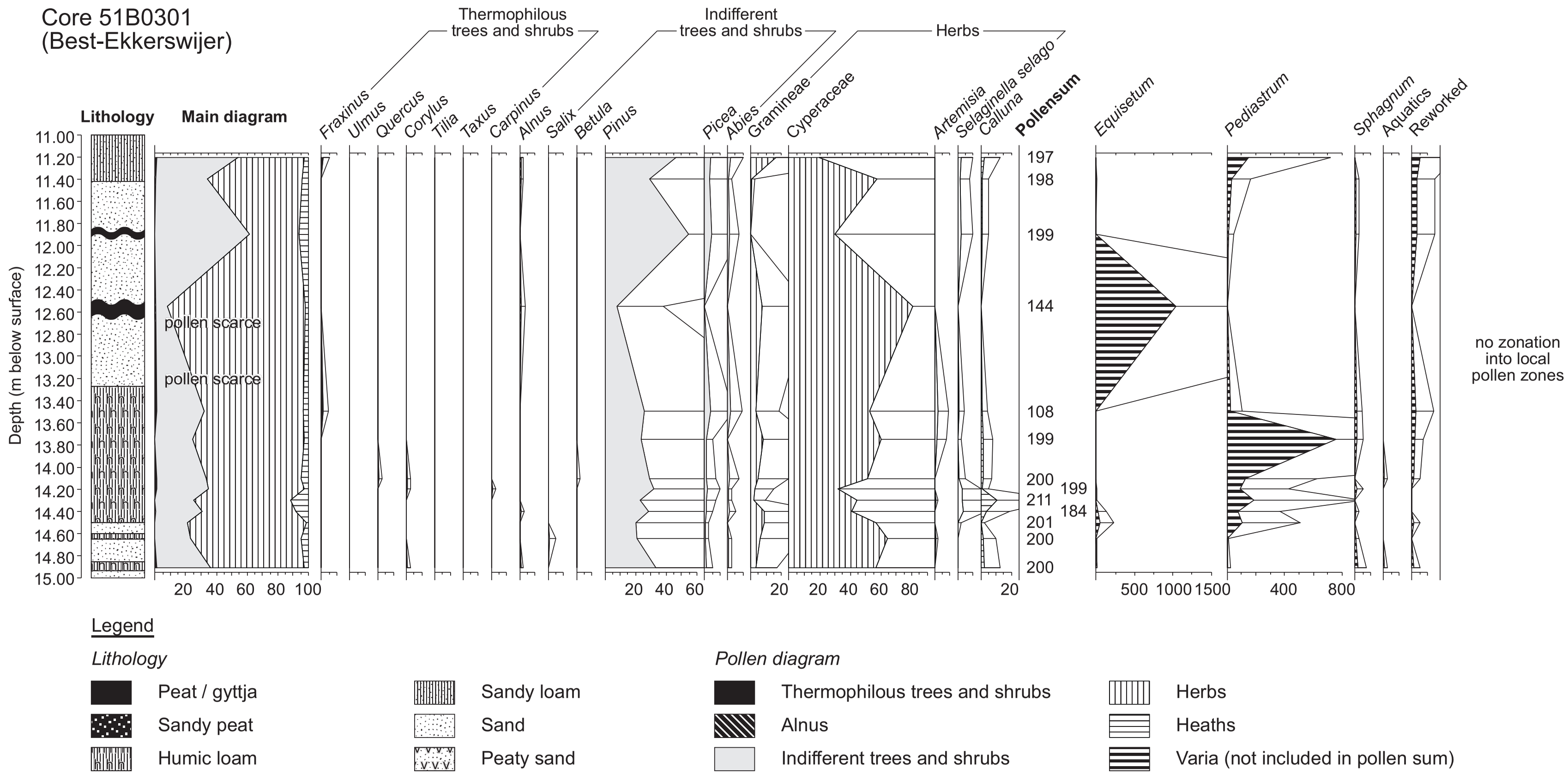
To reconstruct the palaeo-environmental conditions during deposition, pollen samples were taken in selected organic-bearing deposits every 5-20 cm, depending on the lithology of the core and the position of lithological transitions. Sample preparation included peptisation using $Na_4P_2O_7{\cdot}10H_2O$, decalcification with hydrochloric acid (10%) and acetolysis. A sodium polytungstate solution (specific gravity 2.1) was used for heavy-liquid separation of the organic and siliciclastic material. If possible, 200-300 pollen grains were counted at each level. Aquatics and spores were excluded from the pollen sum. In presenting and interpreting the data, the palynological results were combined with sedimentary information (Figs. 5.6, 5.7).

5.4.2 Results

Vegetation and landscape development during deposition of both the clastic and organic deposits of the Boxtel Formation were reconstructed. Sedimentary and palynological data from core 51B0301 (Fig. 5.6) are representative for the depositional conditions during sedimentation of the clastic deposits. The core consists of alternating fine sand and sandy loam. In the core interval between 11.50 and 13.00 m below surface, up to 20 cm-thick cryoturbated loamy peat layers occur. The successive pollen spectra do not show a clear vegetational succession. Herbs and indifferent trees and shrubs dominate the main diagram (Fig. 5.6). Tree pollen is dominated by *Pinus*, with small quantities of *Picea* and *Abies*. Pollen from temperate trees and shrubs, including *Alnus*, is only present in very small quantities. Reworked pollen and spores (Mesozoic and Tertiary species) occur in minor amounts in most pollen spectra, aquatics are virtually absent. Cyperaceae dominate the local flora, with *Artemisia* and *Selaginella selago* both occurring in small numbers. Algae spores *(Pediastrum)* and *Equisetum* occasionally reach percentages of more than 1000%.

Depositional conditions during the formation of two different organic-rich layers are derived from the interpretation of data from core 51B0307 (Figs. 5.7A, B). Both peat levels are embedded in aeolian sand. The diagrams show a clear vegetational succession and are subdivided into local pollen zones (LPZs). In the upper organic layer (5.80-4.30 m below surface; Fig. 5.7A), lithology changes from peaty sand to amorphic peat and

Figure 5.6 (p. 99) Percentage pollen diagram (selected taxa) of core 51B0301. The depth range shown is 15.00-11.00 m below surface. See Fig. 5.1B for the location of the core.


Core 51B0301
(Best-Ekkerswijer)
Lithology
Main diagram
Thermophilous trees and shrubs
Indifferent trees and shrubs
Herbs
Fraxinus
Ulmus
Quercus
Corylus
Tilia
Taxus
Carpinus
Alnus
Salix
Betula
Pinus
Picea
Abies
Gramineae
Cyperaceae
Artemisia
Selaginella selago
Calluna
Pollensum
Equisetum
Pediastrum
Sphagnum
Aquatics
Reworked
Depth (m below surface)
11.00
11.20
11.40
11.60
11.80
12.00
12.20
12.40
12.60
12.80
13.00
13.20
13.40
13.60
13.80
14.00
14.20
14.40
14.60
14.80
15.00
pollen scarce
pollen scarce
197
198
199
144
108
199
200
199
211
184
201
200
200
20 40 60 80 100
20 40 60
20
20 40 60 80
20
500 1000 1500
400 800
no zonation into local pollen zones
Legend
Lithology
Peat / gyttja
Sandy peat
Humic loam
Sandy loam
Sand
Peaty sand
Pollen diagram
Thermophilous trees and shrubs
Alnus
Indifferent trees and shrubs
Herbs
Heaths
Varia (not included in pollen sum)

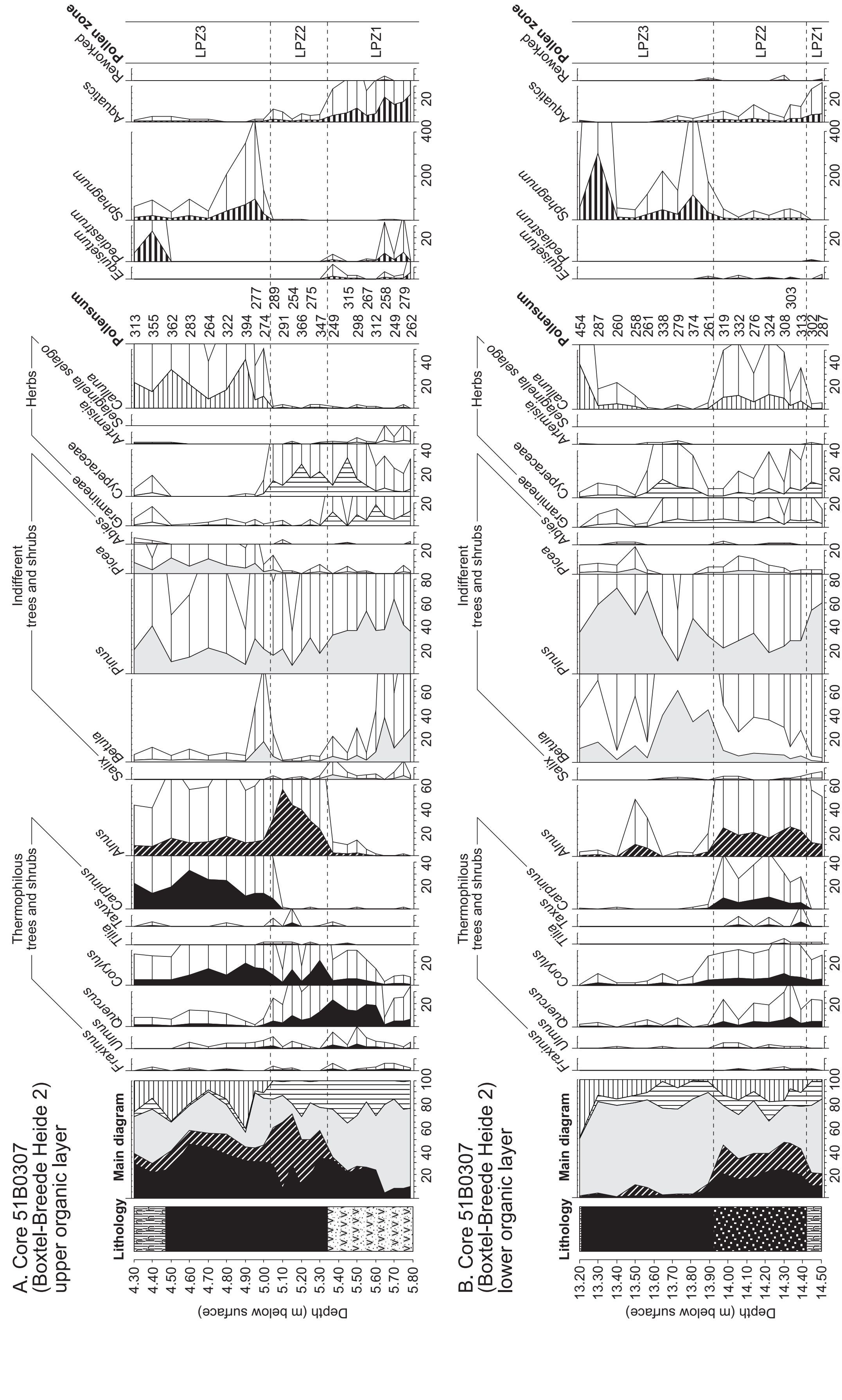
finally peaty loam. These lithological transitions occur partly at the same depths as changes in the pollen association. LPZ1 (5.80-5.35 m below surface) corresponds to the peaty sand interval and is characterised by upward increasing values of thermophilous tree pollen and decreasing aquatics numbers. *Quercus* and *Corylus* are both present throughout this pollen zone. In the local vegetation, a shift from Gramineae to Cyperaceae is observed. *Artemisia* is sparsely present. At 5.35 m, the peaty sand is abruptly overlain by amorphic peat. Pollen spectra in LPZ2 (5.35-5.04 m below surface) are dominated by local taxa, mainly *Alnus* and Cyperaceae. LPZ3 (5.04-4.30 m below surface) is characterised by high values of *Carpinus* and *Picea*. In the local flora, a change is observed from a dominance of *Alnus* and *Betula* to a *Calluna-Sphagnum* vegetation. At 4.48 m, the peat gradually grades into humic loam. This shift occurs at the same depth as the reappearance of *Artemisia* in the pollen diagram.

Pollen assemblages in the lower peat level (14.50-13.20 m below surface; Fig. 5.7B) reflect a partly similar vegetational succession as derived from the pollen in the upper organic layer (Fig. 5.7A). We also see a comparable lithological development from humic sandy loam to amorphic peat to humic loam again. The pollen diagram is subdivided into three LPZs. LPZ1 (14.50-14.42 m below surface) consists of the two lowermost pollen spectra and is characterised by a dominance of *Pinus* and a relatively high percentage of aquatics. LPZ2 (14.42-13.92 m below surface) shows similar depositional conditions as LPZ3 in the upper organic layer, with continuous curves of thermophilous tree pollen, including *Taxus*, and high *Alnus* values. *Calluna* pollen is also present in considerable amounts. LPZ3 (13.92-13.20 m below surface) is characterised by low quantities of thermophilous tree pollen. *Betula* and Cyperaceae pollen show a major increase. In the uppermost pollen spectra, *Betula* is partly replaced by *Pinus*. Throughout this zone, low quantities of *Artemisia* pollen occur.

5.4.3 Interpretation

Figure 5.6 reflects the depositional conditions and associated pollen assemblage of a humid, open landscape in a cold climate. Wet-aeolian sandy sediments alternate with sandy loam layers, representing deposits of small rivers and the lacustro-aeolian infilling of shallow lakes. Loamy sedge peat formed in areas where the local groundwater level was at or near the surface. Sediment reworking is testified by the presence of reworked pollen, including occasional occurrences of temperate tree pollen, and the absence of a clear vegetational succession in these deposits. The combined occurrence of *Artemisia* and *Selaginella selago* is indicative of cold conditions with fresh soils. The local flora was mainly composed of sedges, while heaths and herbs flourished at dryer places. Sporulation peaks of algae and *Equisetum* indicate that these species temporarily suffered from drought stress caused by fluctuating surface water levels throughout the year. This

Figure 5.7 (p. 101) Percentage pollen diagram (selected taxa) of core 51B0307. The depth ranges shown are: (A) 5.80-4.30 m below surface (upper organic layer); (B) 14.50-13.20 m below surface (lower organic layer). See Fig. 5.1B for the location of the core. See Fig. 5.6 for legend.



A. Core 51B0307
(Boxtel-Breede Heide 2)
upper organic layer
B. Core 51B0307
(Boxtel-Breede Heide 2)
lower organic layer
Depth (m below surface)
Lithology
Main diagram
Thermophilous trees and shrubs
Fraxinus
Ulmus
Quercus
Corylus
Tilia
Taxus
Carpinus
Alnus
Indifferent trees and shrubs
Salix
Betula
Pinus
Picea
Abies
Herbs
Gramineae
Cyperaceae
Artemisia
Selaginella selago
Calluna
Pollensum
Equisetum
Pediastrum
Sphagnum
Aquatics
Reworked
Pollen zone
LPZ3
LPZ2
LPZ1

might be the result of permafrost, the presence of which is also indicated by cryoturbatic deformation of the loamy peat beds. The occurrence of permafrost led to a reduced infiltration capacity of the substrate and higher average surface runoff. Furthermore, surface runoff was concentrated in a limited period of the year due to the quick release of water from snow melt and the melting of the active layer in spring and early summer.

Figures 5.7A and B represent depositional conditions and vegetational change during warm-temperate climatic periods. Sediment preservation during these phases was confined to humid depressions in the sandy landscape. In the upper organic layer (Fig. 5.7A), a clear depositional hiatus is present between the formation of LPZ1 and LPZ2. LPZ1 represents the infilling of a shallow depression in an open landscape during an early part of a warm-temperate period, as based on the presence of early-temperate trees and the influx of fine sand into the core. LPZ2 and LPZ3 reflect renewed organic production at the site after a phase of non-deposition. The occurrence of *Carpinus* in this part of the diagram indicates an oceanic climate. The local flora is characterised by the formation of ombrogenic *Sphagnum* peat and the growth of *Calluna* heath at dryer places. *Picea* and *Abies* are both indicative of leached, acidic soils during the last, telocratic stage of an interglacial (Iversen, 1958). Above 4.48 m, a renewed influx of clastic material and rising Gramineae and *Artemisia* values point towards degeneration of the vegetation cover. LPZ2 and LPZ3 are biostratigraphically correlated with the last part of a warm-temperate phase, notably the Eemian (MIS 5e; see also Chapter 4).

A similar late-temperate palaeo-ecological development is deduced from the pollen assemblage in the lower peat layer (Fig. 5.7B). The two *Pinus*-rich pollen spectra in the humic sandy loam of LPZ1 reflect redeposition of soil material under humid surface conditions. LPZ2 is characterised by the presence of *Carpinus* pollen and relatively high *Calluna* values, pointing towards oceanic climatic conditions. High values of *Betula* and Cyperaceae pollen and the decimation of temperate trees and shrubs in LPZ3 reflect partial destruction of the vegetation cover and opening of the landscape at the onset of a cool, periglacial period. Due to the problem of homotaxial vegetation development, it is impossible to correlate the lower organic layer in core 51B0307 with one specific Middle-Pleistocene interglacial-glacial transition.

It seems that sediments in the Roer Valley Graben were preferentially preserved during specific depositional conditions. Preservation of clastic aeolian and fluvial deposits was related to a cool and humid environment, where permafrost may have been present. 1-2 m-thick organic-rich deposits originated under humid conditions at the shift from a warm-temperate (interglacial) to a cool (glacial) climate. These deposits are sometimes underlain by organic-rich sediments from an earlier phase of the interglacial. Both types of environmental conditions are characterised by a humid depositional surface, which is in turn related to a high local groundwater level. Comparison of Figs. 5.7A and B suggests that in reaction to Quaternary climatic shifts, virtually identical palaeo-ecological conditions occurred during subsequent climatic cycles. Both the discontinuity of the sedimentary sequence and cyclic character of the depositional conditions in the Roer Valley Graben pose major problems to uniquely assign part of the record to a specific Middle– or Late-Pleistocene climatic interval.

5.5 Age of the sediments

5.5.1 Method

The chronology of the deposits was investigated by applying quartz OSL dating. This technique provides information on the time of last exposure to light of a sediment sample (Aitken, 1998). The OSL age is calculated by dividing the amount of ionising radiation the sample has received from surrounding deposits since burial (equivalent dose) by the amount of ionising radiation the sample has received per year (dose rate). Samples were collected from undisturbed, preferably lithologically homogeneous parts of the sediment cores. All samples were washed and subsequently treated with hydrochloric acid (10%) and hydrogen peroxide (30%) to remove any carbonates and organic matter. After drying, the sediments were sieved to isolate the 180-250 μm grain-size fraction. Treatment with concentrated hydrofluoric acid was applied to obtain a pure quartz sample and to etch away the outer 10 μm of the quartz grains. For equivalent-dose determination, we used the improved single-aliquot regenerative dose protocol of Murray & Wintle (2000). Measurements were made on an automated Risø TL/OSL reader using an internal $^{90}Sr/^{90}Y$ beta source and blue light emitting diodes for stimulation (Bøtter-Jensen et al., 1999; 2000). The dose rate was derived from high-resolution gamma-ray spectrometry measurements in the laboratory (Murray et al., 1987).

5.5.2 Results

The results of quartz OSL dating on 37 samples from cores 51B0307 ('Boxtel Breede Heide 2') and 51H0183 ('Heusden-Broek 2') are shown in Tables 5.2 and 5.3. Figures 5.8 and 5.9 present the OSL data in relation to the lithology and lithostratigraphy of both cores. For comparison, the figures also depict the orbitally-tuned ODP 677 $\delta^{18}O$ curve (Shackleton et al., 1990). Uncertainties in the equivalent dose, dose rate and age determinations all represent the 1σ-confidence interval. In calculating the dose rates, we presumed continuous water saturation of the sediments. Because the low natural radionuclide concentration in the deposits gave rise to very low dose rates, the contribution of cosmic rays amounts to ~15% of the total natural radiation in the uppermost samples. Sample saturation (i.e. the filling of all OSL traps, which results in a flat dose-response curve) provides an upper limit to the effective OSL dating range. Figure 5.10 shows representative dose-response curves for aliquots of two different OSL samples. Both curves indicate that sample saturation is only approximated at equivalent doses of more than ~300 Gy.

The 16 OSL samples in the aeolian part of core 51B0307 (0.00-17.56 m below surface; Fig. 5.8; Table 5.2) provide an internally consistent dating series and show a steadily increasing age with depth. Also samples 17-1 and 18-1 (14.80 m and 15.60 m below surface, respectively) fit within this dating sequence within two standard deviations. Sample 6-1 at 5.60 m below surface is situated in a less than 2 cm-thick clean sand layer, embedded in peaty sand of the upper organic layer (Fig. 5.8, cf. Fig. 5.7A). This enabled a reliable age estimate of this organic layer. Because of the lithological inhomogeneity around the sample, the effect of water content on sample dose rate had to be considered in detail. The beta dose rate of sample 6-1 was assumed to come entirely from the thin sand layer (water content 43 ± 7%), while the gamma dose rate was assumed to be derived entirely from the peaty sand (water content 65 ± 7%). This resulted in an age estimate of 114 ± 12 ka for the upper organic layer (see also Chapter 4). The samples in the fluvio-aeolian part of the core (17.56-24.35 m below surface) show ages of ~450 ka. The fluvial deposits (27.30-30.20 m below surface) have an average OSL age only just over 300 ka (Table 5.2, Fig. 5.8).

The 14 OSL samples in core 51H0183 reveal the likely presence of a hiatus representing considerable time at ~2.5 m below surface (Table 5.3, Fig. 5.9). Samples 2-1 and 3-1 at 1-2 m below surface have ages of ~30 ka, whereas the underlying sample 5-1 has an age of 300 ± 30 ka. Sample 5-1 is the first of a series of 12 dates that range in age from

Table 5.2 Quartz OSL data from core 51B0307 ('Boxtel-Breede Heide 2'). See Fig. 1B for the location of the core

Risø number	Sample number	Depth (m)	Grain size (μm)	Dose rate (Gy ka^{-1})[a]	Equivalent dose (Gy)	Age (ka)
013115	1-1	0.80	180-250	0.97 ± 0.05[b]	12.8 ± 0.2	13.3 ± 0.8
013116	2-1	1.25	180-250	1.02 ± 0.05[b]	15.3 ± 0.3	15.0 ± 0.9
013117	4-1	3.40	180-250	0.93 ± 0.05[b]	54 ± 2	58 ± 4
013118	6-1	5.60	180-250	0.77 ± 0.06[c]	88 ± 5	114 ± 12
013119	7-1	6.20	180-250	0.83 ± 0.05[b]	143 ± 13	170 ± 20
013120	8-1	7.30	180-250	0.91 ± 0.05[b]	188 ± 7	207 ± 16
013121	10-1	9.00	180-250	0.62 ± 0.03[b]	177 ± 8	280 ± 20
013122	11-1	9.55	180-250	0.63 ± 0.04[b]	201 ± 12	320 ± 30
013123	11-2	9.80	180-250	0.58 ± 0.04[b]	185 ± 5	320 ± 20
013124	12-1	10.55	180-250	0.59 ± 0.04[b]	179 ± 5	300 ± 20
013125	14-1	12.35	180-250	0.44 ± 0.03[b]	143 ± 9	330 ± 30
013126	17-1	14.80	180-250	0.79 ± 0.05[b]	203 ± 8	260 ± 20
013127	18-1	15.40	180-250	0.60 ± 0.05[b]	164 ± 9	270 ± 30
013128	18-2	15.65	180-250	0.44 ± 0.03[b]	183 ± 9	420 ± 30
013129	19-1	16.50	180-250	0.54 ± 0.03[b]	225 ± 14	410 ± 40
013130	20-1	17.33	180-250	0.59 ± 0.03[b]	285 ± 19	480 ± 40
013131	23-1	20.00	180-250	0.60 ± 0.04[b]	274 ± 32	450 ± 60
013132	27-1	24.20	180-250	0.69 ± 0.04[b]	348 ± 36	500 ± 60
013133	28-1	24.85	180-250	0.78 ± 0.05[b]	326 ± 26	420 ± 40
013134	30-1	26.75	180-250	0.86 ± 0.05[b]	368 ± 14	430 ± 30
013135	30-2	27.00	180-250	1.01 ± 0.06[b]	350 ± 27	350 ± 40
013136	31-1	27.95	180-250	1.44 ± 0.07[b]	402 ± 20	280 ± 20
013137	32-1	28.85	180-250	1.09 ± 0.06[b]	334 ± 17	310 ± 20

[a] Spectral data derived from high-resolution gammaspectrometry were converted to activity concentrations and infinite matrix dose rates using the conversion data given by Olley et al. (1996). The dose rate to 180-250 μm quartz grains was calculated from the infinite matrix dose rate using attenuation factors given by Mejdahl (1979), including a contribution from cosmic rays (Prescott & Hutton, 1994).

[b] The dose rate was calculated using a water content of 21 ± 2% (based on an estimated porosity of 35% and a density of 2.65 for the solid fraction) and using attenuation factors given by Zimmerman (1971).

[c] The beta dose rate assumed a water content of 43 ± 7%, the gamma dose rate assumed a water content of 65 ± 7%. Attenuation factors are given by Zimmerman (1971). See text for more details.

Table 5.3 Quartz OSL data from core 51H0183 ('Heusden-Broek 2'). See Fig. 1B for the location of the core

Risø number	Sample number	Depth (m)	Grain size (µm)	Dose rate (Gy ka^{-1})[a,b]	Equivalent dose (Gy)	Age (ka)
013101	2-1	1.35	180-250	1.02 ± 0.06	27 ± 2	27 ± 2
013102	3-1	2.42	180-250	0.69 ± 0.05	21.2 ± 0.7	31 ± 2
013103	5-1	4.35	180-250	0.63 ± 0.04	188 ± 12	300 ± 30
013104	8-1	7.40	180-250	0.76 ± 0.05	181 ± 13	240 ± 20
013105	8-2	7.75	180-250	0.64 ± 0.04	165 ± 4	260 ± 20
013106	12-1	10.98	180-250	0.70 ± 0.04	202 ± 15	290 ± 30
013107	13-1	11.80	180-250	0.57 ± 0.04	146 ± 6	260 ± 20
013108	14-1	12.60	180-250	0.48 ± 0.04	169 ± 3	350 ± 30
013109	15-1	13.60	180-250	0.43 ± 0.06	142 ± 4	330 ± 50
013110	18-1	15.98	180-250	0.33 ± 0.03	119 ± 5	360 ± 40
013111	19-1	16.85	180-250	0.34 ± 0.03	112 ± 8	330 ± 40
013112	20-1	17.70	180-250	0.40 ± 0.03	157 ± 11	400 ± 40
013113	21-1	18.50	180-250	0.41 ± 0.03	160 ± 7	390 ± 30
013114	22-1	19.55	180-250	0.38 ± 0.03	134 ± 5	350 ± 30

[a] Spectral data derived from high-resolution gammaspectrometry were converted to activity concentrations and infinite matrix dose rates using the conversion data given by Olley et al. (1996). The dose rate to 180-250 µm quartz grains was calculated from the infinite matrix dose rate using attenuation factors given by Mejdahl (1979), including a contribution from cosmic rays (Prescott & Hutton, 1994).

[b] The dose rate was calculated using a water content of 21 ± 2% (based on an estimated porosity of 35% and a density of 2.65 for the solid fraction) and using attenuation factors given by Zimmerman (1971).

240 ± 20 ka to 400 ± 40 ka. In this core, no significant age break is observed between the fine-grained aeolian and fluvio-aeolian deposits of the Boxtel Formation and the underlying coarse-grained fluvial deposits of the Beegden Formation.

5.5.3 Interpretation

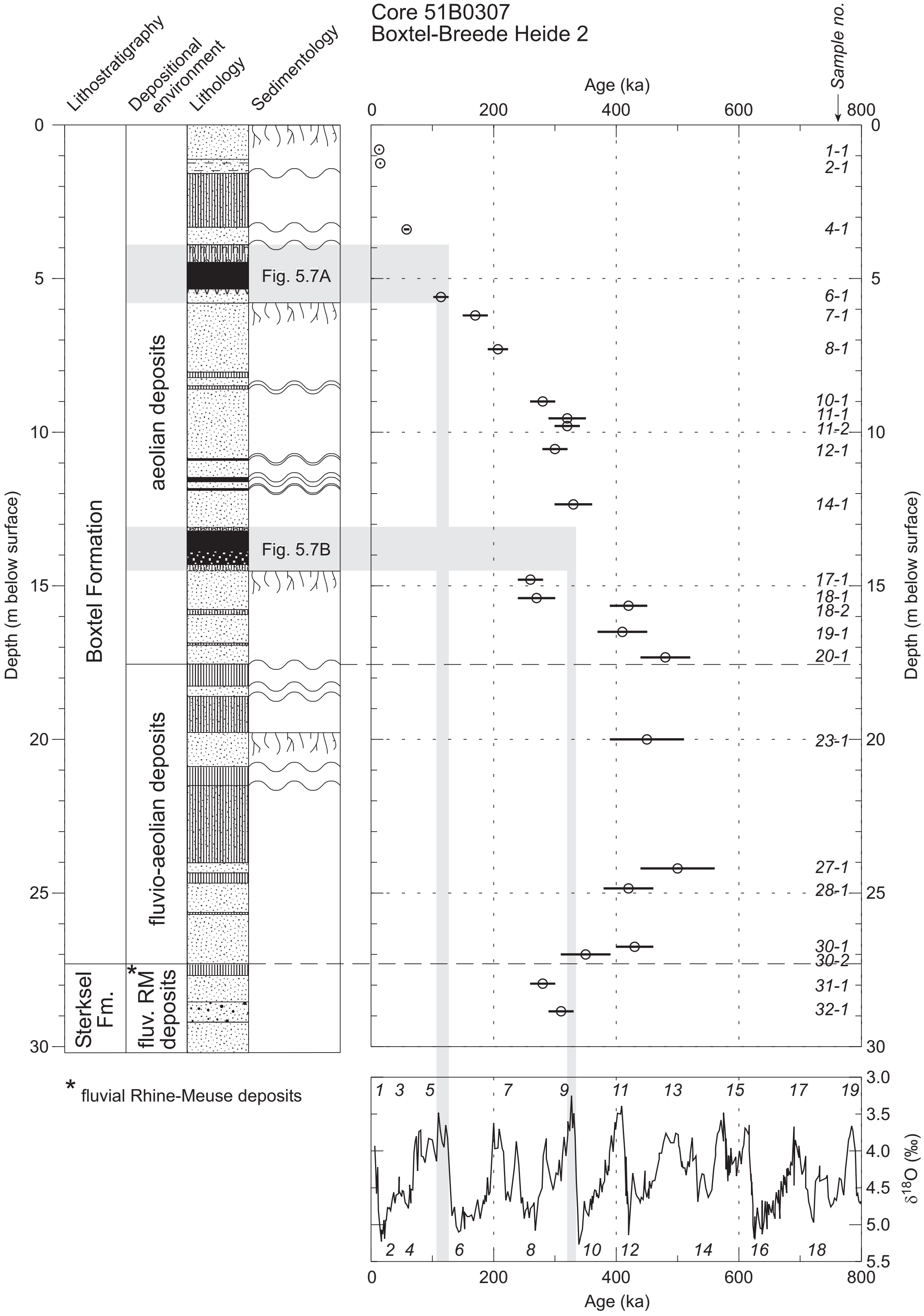
Samples 1-1 (13.3 ± 0.8 ka) and 2-1 (15.0 ± 0.9 ka) in core 51B0307 (Fig. 5.8) represent the Late-Weichselian aeolian coversand (Van der Hammen, 1951). Their ages are comparable to OSL ages of similar deposits in the eastern Netherlands, ranging from 11.7 to 17.6 ka (Bateman & Van Huissteden, 1999). The loam layer between samples 2-1 and 4-1 (Fig. 5.8) has twice been radiocarbon dated (31,100 ± 370 and 43,300 ± 1000 ^{14}C-years BP; Bisschops et al., 1985), which fits in between the OSL ages of samples 2-1 and 4-1 (Table 5.2). The age of sample 6-1 (114 ± 12 ka) suggests an Eemian age (MIS 5e) for the upper organic layer, as was also indicated by pollen analyses (Fig. 5.7A; see also Chapter 4). Deeper in the core, no further independent age control is available. The second organic layer (14.50-13.20 m below surface; Fig. 5.8) is tentatively correlated with MIS 9, because it is situated between samples 14-1 (330 ± 30 ka) and 17-1 (260 ± 20 ka). The slight age reversal at this depth falls within the 2σ-uncertainty range of the dating method. The long-term average sedimentation rate in the aeolian part of the core is calculated at 0.04 mm/a, which is lower than the average Middle- and Late-Quaternary subsidence rate of ~0.06 mm/a calculated for the Roer Valley Graben (Geluk et al., 1994; Van den Berg, 1996; Houtgast & Van Balen, 2000; Houtgast et al., 2002).

Average sedimentation rates were much higher during deposition of the fluvio-aeolian deposits (Fig. 5.8), which can be explained by a larger sediment influx during this period. Apparently, accommodation space was available for the preservation of these deposits. Surprisingly, ages are younger again in the basal, fluvial part of the core. The younger age of these Rhine deposits cannot be explained by incomplete bleaching in the fluvial depositional environment, because this would produce dates that are older than expected. Moreover, Wallinga et al. (2001) effectively demonstrated that Late-Weichselian and Holocene Rhine deposits were well bleached, i.e. that their luminescence signal was completely reset, even in a turbid fluvial environment. Younger ages can be explained by taking into account the effect of inhomogeneous sampling. We took OSL equivalent-dose samples in homogeneous (silty) fine sand, as far away as possible from clay-rich intervals. However, lithological transitions are often gradual in a fluvial environment. Because the dose-rate samples were persistently taken closer to lithological transitions, they might reflect a slightly different lithology, notably sand with a relatively high silt or clay content. For at least one sample (31-1), inhomogeneous sampling was shown to have occurred. As a result, dose-rate estimates may be too high and corresponding age estimates too low. The problem of inhomogeneous sampling is largely restricted to fluvial sediments, because only these deposits contain clay-rich intervals. By performing both the equivalent-dose and dose-rate determination on aliquots of the same sample, this error source could have been avoided.

Age control for core 51H0183 is more restricted. The presence of reworked Eemian pollen in the loamy sediments between samples 2-1 and 3-1 (Fig. 5.9) suggest a post-Eemian age for these samples. This is confirmed by the OSL ages. The hiatus at ~2.5 m below the surface was not detected as an important break in the sediment record, although the location of the core and the thickness of the Boxtel Formation suggested that sedimentation at this site was less continuous than at the site of core 51B0307 (cf. Fig. 5.1B). Sediments from at least two successive glacial-interglacial cycles have not been preserved here. This may be due to either large-scale erosion between the Eemian (MIS 5e) and Middle Weichselian (MIS 3) or a long-period of non-deposition after 250-300 ka. Non-deposition in this region could be related to relative tectonic uplift, causing lowering of the local base level. The age of the Meuse deposits at the base of this core (samples 18-1 to 22-1) ranges from 330 ± 40 ka to 400 ± 40 ka. The sediments are slightly younger than the fluvio-aeolian deposits in core 51B0307 that were presumed to be of the same age. Possibly, the Meuse deposits in core 51H0183 represent a younger fluvial phase, during which the course of the river Meuse had already moved too far to the east to cause sedimentation near core 51B0307 (cf. location of both cores in Fig. 5.1B).

Independent age control of the fluvial deposits in the Roer Valley Graben is provided by correlation with the orbitally-tuned river-terrace flight of the Meuse (Van Balen et al., 2000; Van den Berg & Van Hoof, 2001; Houtgast et al., 2002). Along the middle reaches

Figure 5.8 (p. 107) Lithology, lithostratigraphy and OSL dating results of core 51B0307. The ODP 677 δ^{18}O curve (Shackleton et al., 1990) is shown for comparison. See Fig. 5.9 for legend.



Core 51B0307
Boxtel-Breede Heide 2
Lithostratigraphy
Depositional environment
Lithology
Sedimentology
Age (ka)
Sample no.
Depth (m below surface)
Boxtel Formation
aeolian deposits
fluvio-aeolian deposits
Sterksel Fm.
fluv. RM deposits
Fig. 5.7A
Fig. 5.7B
1-1
2-1
4-1
6-1
7-1
8-1
10-1
11-1
11-2
12-1
14-1
17-1
18-1
18-2
19-1
20-1
23-1
27-1
28-1
30-1
30-2
31-1
32-1
δ18O (‰)
* fluvial Rhine-Meuse deposits

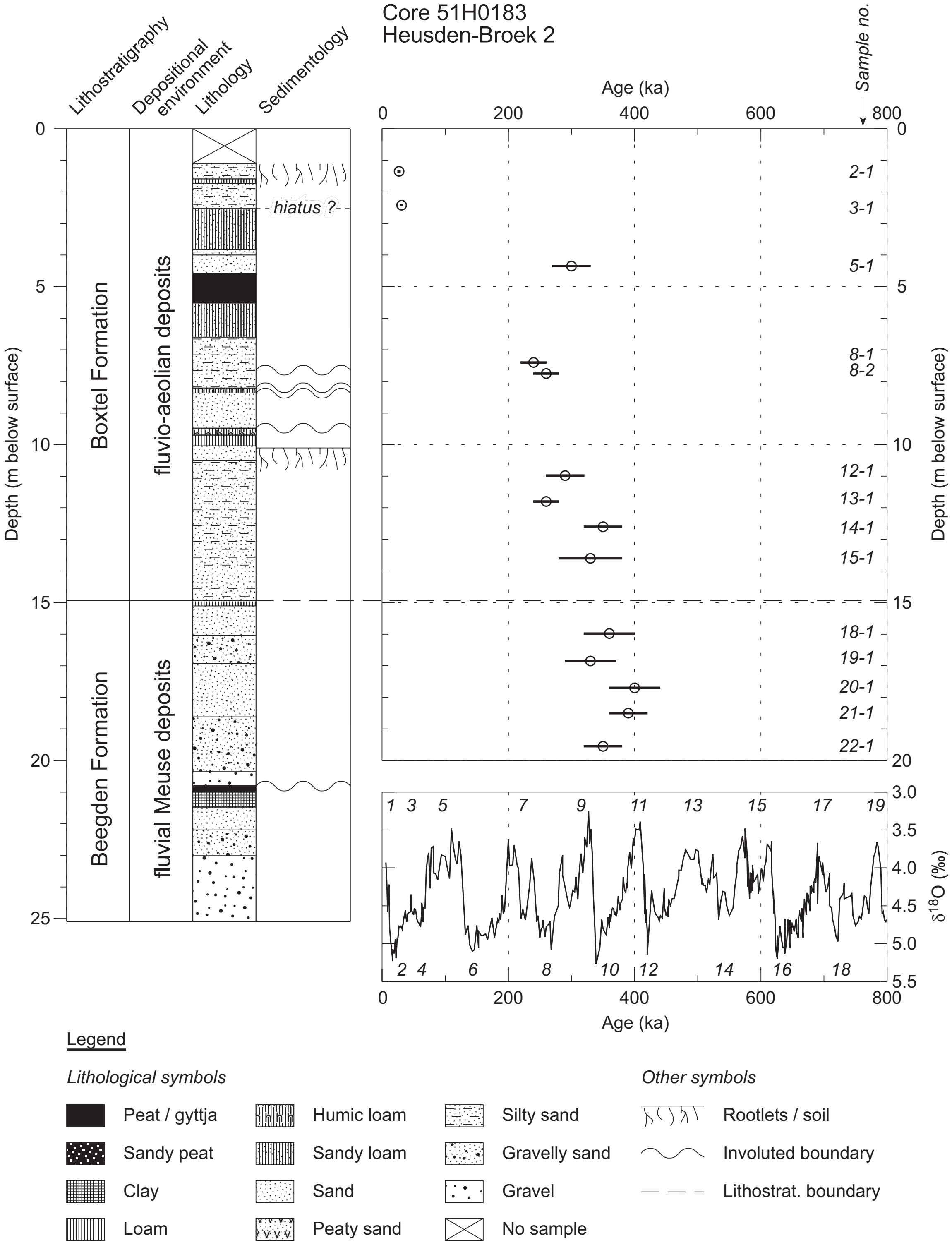


Figure 5.9 Lithology, lithostratigraphy and OSL dating results of core 51H0183. The ODP 677 $\delta^{18}O$ curve (Shackleton et al., 1990) is shown for comparison.

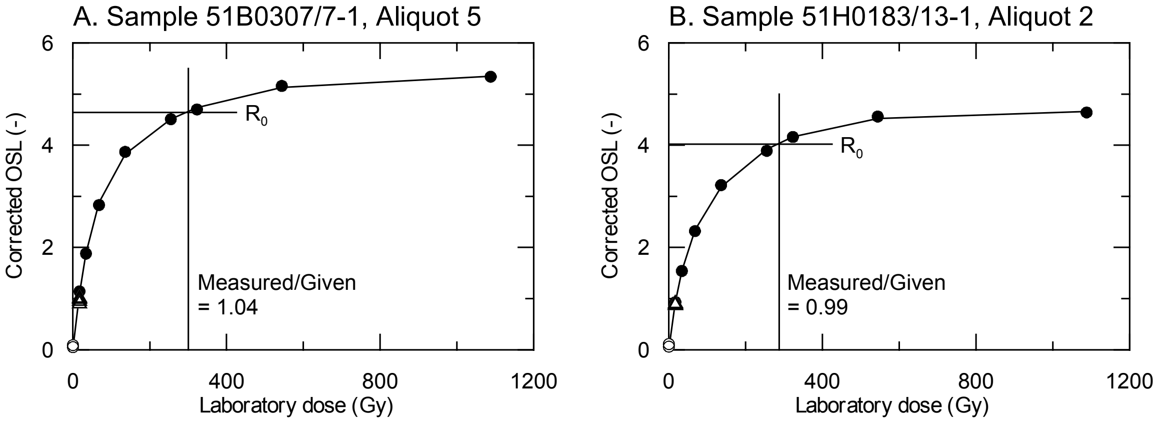


Figure 5.10 Representative dose-response curves for two OSL samples. Open dots and open triangles are repeat measurements to test for changes in sensitivity. R_0 = Initial dose.

of this river, up to 31 different terrace levels were formed, with tectonics and climate as main controlling factors. Within the terrace sequence, a clear morphological break is observed between the plateau-like Main Terraces and very narrow Middle Terraces. This is probably the result of accelerated uplift of the Ardennes from the early Middle Pleistocene onward (Van Balen et al., 2000; Van den Berg & Van Hoof, 2001). The same morphological adjustment is observed along the middle reaches of the river Rhine (Meyer & Stets, 1998; 2002). Here, the change in fluvial morphology is approximately contemporaneous with the onset of large-scale volcanism in the Eifel region and the release of large quantities of volcanic minerals into the catchment of the river Rhine (Zagwijn, 1989). Traditionally, this tectonic event in the Ardennes and Rhenish Massif is also held responsible for a north-eastward shift in the lower course of the river Rhine, as a result of which it no longer flowed through the Roer Valley Graben. Therefore, the top of the Rhine deposits in the Roer Valley Graben (Sterksel Formation) is usually correlated with the youngest of the Main Terraces along the river Rhine (jüngere Hauptterrasse: Meyer & Stets, 1998; 2002) and Meuse (Pietersberg 2 Terrace: Van den Berg & Van Hoof, 2001; Van Balen, pers. comm.). Similarly, the top of the Meuse deposits (Beegden Formation) is correlated with the oldest Middle Terrace levels along both rivers. Evidence of north-eastward tilting of the Roer Valley Graben during this time includes: 1) a phase of deep incision between deposition of Rhine sediments and deposition of Meuse sediments; 2) the restricted occurrence of Meuse deposits along the eastern border of the Roer Valley Graben (cf. Fig. 5.2A). Palaeomagnetic measurements of terrace deposits along the river Meuse near Liège (Pissart et al., 1997) and the middle reaches of the river Rhine (Meyer & Stets, 1998) revealed that the Matuyama-Brunhes palaeomagnetic boundary (780 ± 10 ka; Spell & McDougall, 1992) is situated in the lower part of the youngest Main Terrace deposits. Ar-Ar dating of Eifel volcanic minerals confirmed that the youngest Main Terrace level is indeed younger than the Matuyama-Brunhes boundary (Lippolt et al., 1990). This is in accordance with palaeomagnetic measurements of the youngest deposits of the Sterksel Formation in the Roer Valley Graben, which revealed a normal polarity (Van Montfrans, 1971). Deviating palaeomagnetic measurements of Meuse terrace deposits (Van den Berg, 1996) can be rejected, based on a similar reasoning as performed by Van Balen et al. (2000) and Houtgast et al. (2002): the palaeomagnetic dataset is not consistent, gives many intermediate results and is composed of measurements scattered over a large area. If we then correlate the incision phase between deposition of the Sterksel Formation and deposition of the Beegden Formation in the Roer Valley Graben with the phase of rapid uplift along the river Meuse, the top of the Beegden Formation in the Roer Valley Graben can be linked to the Rothem 2 Terrace, the first widespread Meuse terrace level since the onset of rapid fluvial incision in the early Middle Pleistocene. These correlations result in an age of ~750 ka for the top of the Rhine deposits (Sterksel Formation) and an age of ~530 ka for the top of the Meuse deposits (Beegden Formation) in the Roer Valley Graben.

The age of 530 ka for the top of the Meuse deposits is older than the OSL age of these deposits in core 51H0183 (375 ka) or the age related fluvio-aeolian deposits in core 51B0307 (450 ka). However, we have to keep in mind that using the age model of the Meuse terrace sequence to derive the age of fluvial deposits in the Roer Valley Graben involves uncertain correlations. In fact, there is some mineralogical evidence that the river Rhine did not immediately leave the Roer Valley Graben after the onset of accelerated uplift of the Rhenish Massif. Both in the Roer Valley Graben and in the adjacent part of Germany, Rhine deposits have been found that contain considerable quantities of volcanic minerals (Boenigk, 1995). It is difficult to explain that these deposits are older than the onset of large-scale Eifel volcanism. As a consequence, the top of the Rhine (and Meuse) deposits in the Roer Valley Graben may be younger than 750 ka. This uncertainty in the age of the Middle-Pleistocene fluvial sediments remains to be resolved. Meanwhile, the OSL results presented here provide a first independent absolute dating series for the Middle- and Late-Quaternary aeolian and fluvio-aeolian deposits in the Roer Valley Graben.

5.6 Discussion

Figure 5.11 summarises the changes in depositional environment, sediment composition and tectonic regime that took place in the Roer Valley Graben during the Middle- and Late-Quaternary. Average tectonic subsidence in the area enabled deposition and preservation of sediments, but the subsidence rate was not uniform over time. Increased tectonic activity shortly after the onset of the Brunhes palaeomagnetic chron caused the disappearance of the river Rhine from the Roer Valley Graben and an influx of stable heavy minerals by the river Meuse. Later, tectonic movements also forced the Meuse to shift its course to the north-east, at some time between 375 and 530 ka (Fig. 5.11). Clues on a possible relative uplift event in the southern part of the Roer Valley Graben at ~300 ka (cf. OSL dates in Fig. 5.9) await further confirmation. After the disappearance of the large rivers, aeolian deposition and deposition by small rivers dominated in the area in cold climatic conditions, whereas organic deposits formed in the lower parts of the landscape in a more temperate climate. As is indicated by an upward increasing Na_2O-Al_2O_3 ratio and an increasing percentage of unstable heavy minerals, the main sediment

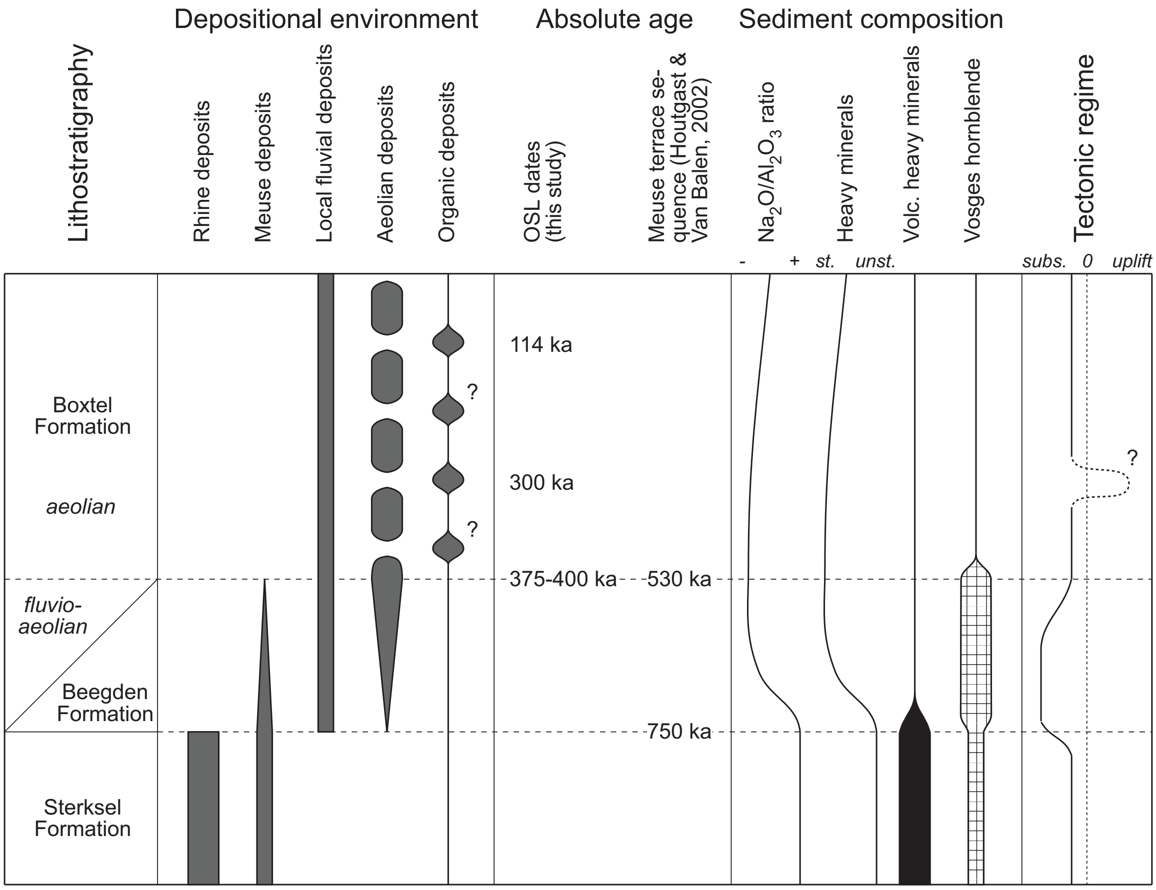


Figure 5.11 Correlation of the depositional environment, sediment composition and tectonic regime in the Roer Valley Graben during the Middle and Late Quaternary.

Marine Isotope Stage	France Massif Central	The Netherlands south	The Netherlands Roer Valley Graben	The Netherlands north	Germany Schöningen
5e	Ribains	Eemian	present	Eemian	Eemian
6				Drenthe till	Warthe till / Drenthe till
7	Le Bouchet I-III		not present	Bantega	Schöningen
8					
9	Landos	Belvédère	present	Hoogeveen	Reinsdorf
10					
11	Praclaux		present ?	Holsteinian	Holsteinian
12				Elster till	Elster till

Figure 5.12 Proposed correlation between the late Middle Pleistocene of France, the Netherlands and north-east Germany (after: Urban, 1995; Turner, 1998; De Beaulieu et al., 2001; T. Meijer, pers. comm.). The stratigraphic position of glacial deposits is also indicated.

source for the aeolian deposits were Quaternary Rhine sediments that cropped out in the western Netherlands and the dry southern North Sea Basin.

Fig. 5.12 shows a correlation scheme between the late Middle-Pleistocene sequences from France, the Netherlands and north-east Germany. In the Roer Valley Graben, organic-rich deposits from at least two different Middle-Pleistocene interglacials have been identified so far. The upper organic layer (Fig. 5.7A) is correlated with MIS 5e (Eemian), based on its stratigraphic position, palynological signature and absolute age (see also Chapter 4). The lower organic layer (Fig. 5.7B) is correlated with MIS 9, based on quartz OSL dating. It proves impossible to uniquely correlate the vegetational succession in this layer with the succession during one specific Middle-Pleistocene interglacial, because similar climatic conditions caused homotaxial vegetational development during different interglacials (cf. De Beaulieu et al., 2001). Organic deposits representing MIS 7 and MIS 11 have not been identified in the Roer Valley Graben so far. This may be related to differences in the global oceanic-atmospheric circulation pattern and the associated climate in north-western Europe (Turner, 1998). During MIS 7, climate was more comparable to interstadial climatic conditions than to interglacial conditions (Kellogg, 1980). In fact, the only deposits hitherto known from MIS 7 in the Netherlands indicate only moderate warming during the Bantega Interstadial (Zagwijn, 1973; Fig. 5.12). Deposits reflecting MIS 11, a period with a full interglacial climate, remain to be discovered in the Roer Valley Graben.

Of course, no single sedimentary record is continuous. Or, as Miall (1996, p. 273) put it: “Although time is continuous, the stratigraphic record of time is not”. This is especially valid for terrestrial records, and even more so for records that largely consist of clastic deposits. Still, the sedimentary sequence in the Roer Valley Graben is one of the very few terrestrial records in north-western Europe that spans several glacial-interglacial cycles and gives a good insight into the influence of Quaternary climate change on continental landscape development. A combination of detailed research into the depositional conditions, quartz OSL dating and correlation with the known uplift history of the Ardennes region allows to place a considerable part of the Middle- and Late-Quaternary terrestrial record in an absolute time frame. The sedimentary and vegetational succession in the Roer Valley Graben thus contains part of the 'missing' late Middle-Pleistocene of north-western Europe (cf. Turner, 1998) and is a possible link between the Quaternary glacial history of northern Europe and the continuous biostratigraphic sequences of central and southern Europe.

5.7 Conclusions

- The Middle- and Late-Quaternary sedimentary record in the Roer Valley Graben enables to reconstruct the influence of Quaternary climate change on continental landscape evolution in north-western Europe. Following increased uplift of the hinterland and a north-eastward shift of the lower courses of the rivers Rhine and Meuse between 800 and 500 ka, sediment deposition and preservation in the Roer Valley Graben was largely restricted to aeolian deposits in cold periods with permafrost and organic deposits during transitions from warm-temperate to cool climatic conditions. Both environments are associated with a humid depositional surface, which is caused by a high local groundwater level;

- Two quartz OSL dating series have been presented that indicate a Middle- to Late-Quaternary age of the fluvio-aeolian and aeolian deposits in the Roer Valley Graben. The north-eastward shift of the lower course of the river Meuse is OSL-dated at 375 to 450 ka. These dates are somewhat younger than a date of 530 ka, which was derived from correlation with the orbitally-tuned Meuse river-terrace flight further south;

- Two widespread organic layers have been dated at 114 ± 12 ka (MIS 5e, Eemian) and ~300 ka (MIS 9), respectively. The age of the upper organic layer is confirmed by its stratigraphic position and palynological signature. The age of the lower organic layer corroborates that this sequence contains part of the 'missing' record of the Middle Pleistocene in north-western Europe;

- Reworked Na-rich deposits with an unstable heavy mineral assemblage form the main source material for the aeolian deposits in the Roer Valley Graben. The most likely provenance is the area north and west of the Roer Valley Graben, where Quaternary Rhine deposits are present near the surface. Na-poor, stable sediments from the Campine High in the south-west may have acted as a secondary, less important sediment source.

Acknowledgements

Thanks are due to TNO-NITG for financing this project. Hennie Mensink kindly assisted in taking the OSL samples. We thank Hans Huisman for assistance in the interpretation of the bulk geochemical results and Jakob Wallinga for stimulating discussions regarding the use and interpretation of quartz OSL dates. Henk Berendsen, Ward Koster and Ronald van Balen critically read earlier drafts of this manuscript.

6 SYNTHESIS, APPLICATION OF THE RESULTS AND IMPLICATIONS FOR FUTURE RESEARCH

6.1 Results

The Roer Valley Graben contains a well-preserved Middle- and Late-Quaternary sedimentary record, reflecting changing depositional patterns and sedimentary processes in a fluvio-aeolian environment. In this thesis, the following results were obtained:

- A well-defined lithostratigraphic subdivision of the deposits, involving the definition of the Boxtel Formation and two new lithostratigraphic members;
- A reconstruction of the provenance of the fluvial and aeolian sediments, prevailing sedimentary processes and the development of the local depositional environment;
- A chronological framework of the deposits, based on quartz Optically Stimulated Luminescence (OSL) dates and correlated with regional tectonic events and cyclic climate change.

These results are summarised and discussed in the following sections.

6.1.1 Lithostratigraphy

A new lithostratigraphic framework has been defined for the Middle- and Upper-Quaternary sand, loam and peat deposits in the Roer Valley Graben and similar deposits in other parts of the Netherlands (Chapter 2). The new Boxtel Formation incorporates all terrestrial fine-grained sediments that overlie the topmost (Saalian) glacial deposits in the northern Netherlands and the topmost coarse-grained fluvial deposits of the rivers Rhine and Meuse in the southern part of the country. Eight lithostratigraphic members are recognised in the Boxtel Formation (Table 2.2). Two of these members have been defined in the Roer Valley Graben. The Best Member incorporates alternating floodloam deposits and sandy aeolian deposits in the lowermost part of the Boxtel Formation. The Liempde Member includes reworked aeolian loess and sandy loess deposits ('Brabant loam' deposits of Vink, 1949) that occur in the upper part of the Boxtel Formation. The Boxtel Formation and its subdivision into members are an integral part of the lithostratigraphy of the Upper-Tertiary and Quaternary deposits in the Netherlands (TNO-NITG, 2003). The new units replace the informal stratigraphic term Nuenen Group (Bisschops, 1973) and the formal lithostratigraphic units Twente Formation, Asten Formation and Eindhoven Formation (Doppert et al., 1975). Lithostratigraphic, biostratigraphic and chronostratigraphic criteria are no longer intermingled. Definition of this new lithostratigraphic framework forms a sound basis for further description, mapping and use of the terrestrial fine-grained deposits in the Roer Valley Graben and beyond.

6.1.2 Sediment provenance, sedimentary processes and depositional environment

In the sedimentary record of the Roer Valley Graben, a gradual vertical shift is observed from coarse-grained fluvial sediments of the rivers Rhine and Meuse (Sterksel Formation and Beegden Formation; see Appendix) to an alternation of fluvial and aeolian sediments (Best Member of the Boxtel Formation), and finally to alternating fine-grained aeolian deposits, lacustro-aeolian deposits, sediments from small rivers and peat (Boxtel Formation). Sheet-like, wet-aeolian sand and loam deposits are the dominant sediment types that were formed and preserved in a cold climate (Chapter 3). These sediments are characterised by even horizontal lamination or have a massive appearance. Prevailing depositional processes include sand-ripple lamination and adhesion lamination. At the end of warm-temperate climatic phases, 1-2 m thick peat layers locally formed (Chapters 4, 5). Palaeo-ecological data indicate that deposition and preservation of sediments in both cold and more temperate climatic conditions in the Roer Valley Graben was favoured by a rising regional ground-water table and the local occurrence of humid surface conditions. In a periglacial climate, this was related to the presence of permafrost. In temperate, interglacial conditions, a more oceanic climate, as initiated by changes in the coupled global oceanic-atmospheric circulation, may have played an important role (Chapters 4, 5). Changing environmental conditions, such as an increasing surface humidity, are rapidly reflected in the palynological record of this fluvio-aeolian environment. The temporal resolution of e.g. organic deposits that reflect an interglacial-glacial shift is significantly higher in the Roer Valley Graben than in a slowly accumulating lacustrine or loess record. The sedimentary sequence in the Roer Valley Graben thus yields knowledge on the small-scale environmental processes that take place during periods of rapid climate change.

Bulk geochemical and heavy-mineral data (Chapter 5) confirm the abrupt change within the coarse-grained sediments from deposition by a Rhine-dominated fluvial system to deposition by the river Meuse solely. These data also reveal the presence of multiple sediment source areas for the fine-grained deposits of the Boxtel Formation. The coarse-grained fluvial deposits consist of Na-rich sediments with an unstable heavy mineral association that are derived from the catchment of the river Rhine (Sterksel Formation) and Na-poor sediments with a stable heavy mineral association that are derived from the Meuse catchment (Beegden Formation). The mineralogical composition of the Beegden Formation is further characterised by the occurrence of Vosges hornblende, a mineral that was typical for Meuse deposits before the decapitation of the Lorraine Meuse near Toul by the river Moselle (Krook, 1993; Pissart et al., 1997). Within the Boxtel Formation, an upward trend occurs from Na-poor, stable sediments to Na-bearing sediments with a mixed heavy-mineral assemblage (Fig. 5.7). This trend is strongest in the northern part of the Roer Valley Graben and can be explained by a mixed sediment input of:

- Na-rich aeolian deposits with an unstable heavy mineral association and a north-western provenance. Pleistocene Rhine sediments in the western Netherlands and the southern North Sea Basin acted as sediment source area for these deposits;
- Na-poor aeolian and fluvial deposits with a stable heavy mineral association and a south-western source area. Tertiary coastal and marine deposits that crop out in northern Belgium are the main sediment source for these deposits;

- Local reworking of underlying sediments in the Roer Valley Graben.

6.1.3 Chronology and correlation

Quartz OSL dating was applied to construct a geochronological framework for the fine-grained deposits in the Roer Valley Graben (Chapters 4, 5). This method is very suitable to date these deposits, because:

- The aeolian depositional environment of most of the clastic sediments ensured sufficient exposure to daylight during sediment transport to enable complete bleaching of the grains;
- The clastic sediments consist almost exclusively of quartz grains, which causes very low natural radiation doses and permits reliable OSL dating far back in time;
- The OSL dates can be compared to geomorphological and palynological age indications and can be correlated with the orbitally-tuned Meuse river-terrace flight (Van Balen et al., 2000; Van den Berg & Van Hoof, 2001; Houtgast et al., 2002). They can also be compared to earlier OSL and ^{14}C dates on similar deposits in other areas (e.g. coversand OSL dates of Bateman & Van Huissteden, 1999).

Growth curves (Fig. 5.10) show that saturation of the OSL signal in these samples does not occur below equivalent dose values of 300 Gy. This indicates that the dating results of the aeolian samples and the majority of the fluvio-aeolian and fluvial samples are reliable (Tables 5.2, 5.3). The aeolian samples show gradually increasing ages with depth, to ages of more than 350 ka. The OSL age of the fluvio-aeolian samples and contemporaneous coarse-grained fluvial samples of the Beegden Formation ranges from 330 ± 40 ka to 500 ± 60 ka. These dates indicate a much higher sedimentation rate during this period than during the last 350 ka. Fluvial Rhine deposits of the Sterksel Formation could not be dated accurately, probably due to sample inhomogeneity. The preservation of organic deposits from the ultimate part of at least two different interglacial periods has been confirmed. Organic-rich aeolian sand deposits that were attributed to the Eemian (MIS 5e) on palynological and stratigraphic grounds have been directly dated at 114 ± 12 ka (Table 4.2, Fig. 4.3). A second organic-rich interval at a lower stratigraphic level has been attributed to MIS 9. This study shows the value of the quartz OSL dating technique for the absolute dating of aeolian and fluvio-aeolian deposits of Middle- and Late-Quaternary age. The OSL dating technique also for the first time allowed a direct dating of terrestrial Eemian deposits in the Netherlands.

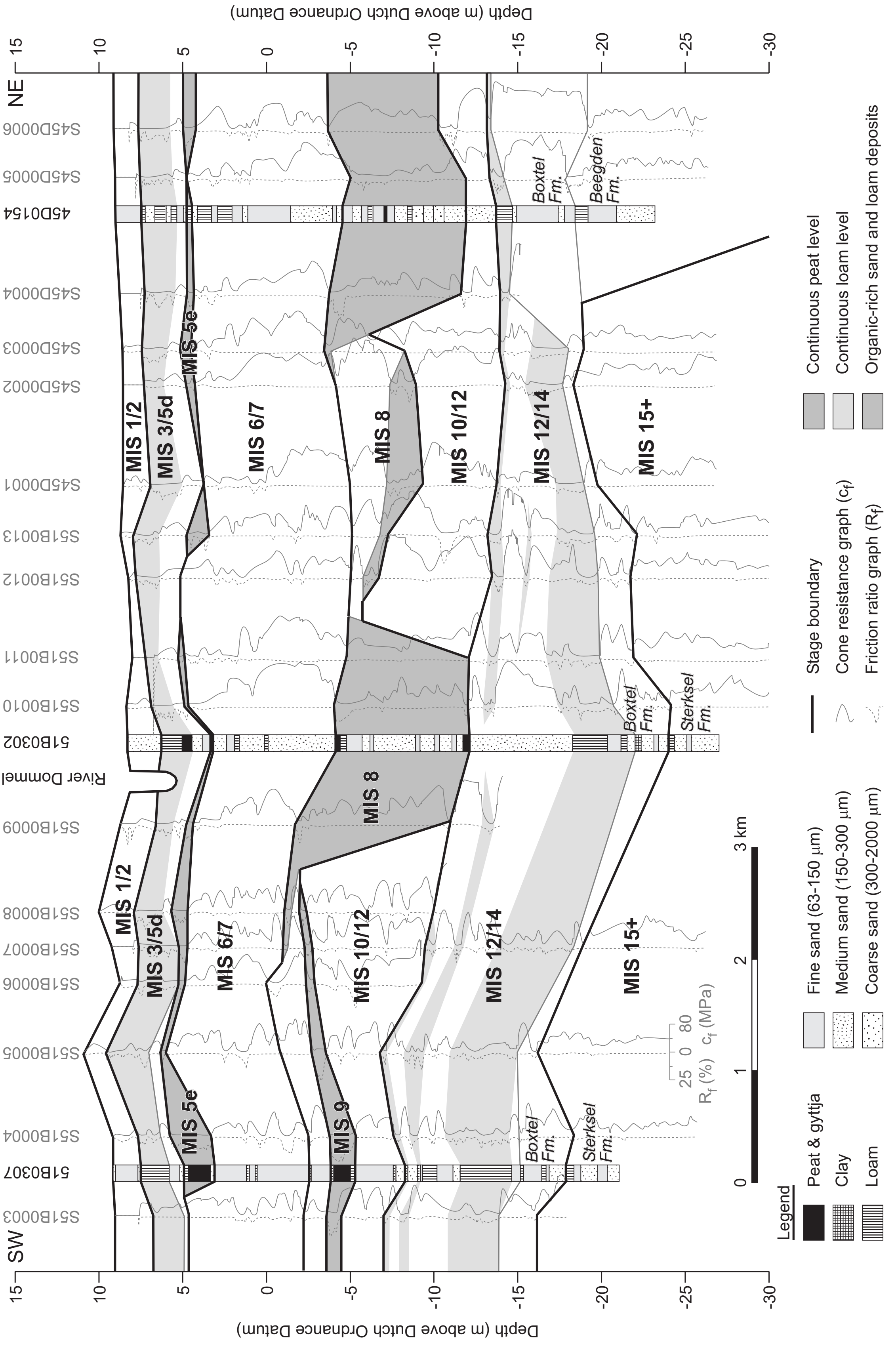
6.1.4 The value of the record

The sedimentary sequence in the Roer Valley Graben represents an excellent record of changing depositional patterns and geomorphological processes during the Middle- and Late-Quaternary. Active tectonic subsidence resulted in the creation of accommodation space, which favoured the preservation of fluvial, aeolian and organic deposits. The strength of the research approach has been the integration of lithological and sedimentary information with palaeo-ecological data and reliable geochronological information. By getting grip on the repeated character of phases of deposition and non-deposition, this fragmentary terrestrial record could be interpreted. Fluvio-aeolian sequences allow the use of chronometric dating such as quartz OSL to date sediments with ages well beyond 100 ka. These records are thus a valuable addition to existing long terrestrial records (e.g. lacustrine sequences) that usually only provide biostratigraphical information.

Figure 6.1 presents a tentative chronology of the deposits in the Roer Valley Graben in a SW-NE geological cross section. The chronological interpretation is based on a combination of sedimentary analysis (Chapter 3), palaeo-ecology (Chapters 4, 5) and quartz OSL dates from core 51B0307 (Fig. 5.8; Table 5.2). The principal markers in the cross section are two in-situ organic horizons that are correlated with MIS 5e and MIS 9, respectively (Fig. 6.1). The whole sequence of fine-grained deposits of the Boxtel Formation is correlated with Marine Isotope Stages 14 to 1 (570 ka to present). The fluvio-aeolian deposits in the lower part of the Boxtel Formation (Best Member) have been formed contemporaneously with the coarse-grained Meuse deposits of the Beegden Formation and date from MIS 14 to MIS 12 (570-420 ka). As a consequence, fluvial Rhine deposits (Sterksel Formation) in the Roer Valley Graben must date from MIS 15 (570 ka) and older. This relatively young age is consistent with the presence of Rhine deposits that are rich in volcanic heavy minerals in the Roer Valley Graben and the adjacent part of Germany (Boenigk, 1995; W. Westerhoff, oral comm.). Because of the ample occurrence of volcanic minerals, these deposits must be younger than the onset of large-scale Eifel volcanism at ~750 ka (Lippolt et al., 1990). Correlation of the morphological boundary between the Main and Middle Terraces along the rivers Rhine and Meuse (dated at ~750 ka; Houtgast et al., 2002) with the lithostratigraphic boundary between the Sterksel and Beegden Formation in the Roer Valley Graben (dated at ~570 ka) is therefore erroneous (Chapter 5).

The question arises why only organic deposits representing MIS 5e and MIS 9 have been found in the Roer Valley Graben and no deposits representing MIS 7 or MIS 11. As for organic deposits from MIS 11, these have not been identified in the cross section of Fig. 6.1, but are probably present in core 51B0301 near the town of Best (Fig. 2.4, at ~5 m below Dutch Ordnance Datum). The palynological signature of these deposits has been described by Bisschops et al. (1985), but their age remains to be confirmed by absolute dating. The lack of organic deposits representing MIS 7 could be explained by simply assuming that these have yet to be discovered. However, given the density of corings in the area, that is unlikely. Following the reasoning that sedimentation and preservation of sediments in the Roer Valley Graben only took place on a humid sediment surface (Section 6.1.2), local groundwater level during MIS 7 may have been too low to allow the formation and preservation of organics. This may have been caused by a lower subsidence rate or a higher precipitation-evaporation ratio in the region. The OSL dates do not show any evidence of a lower subsidence rate during this time (Figs, 5.8, 5.11).

Figure 6.1 (p. 119) SW-NE geological cross section through the central part of the Roer Valley Graben, based on data from sediment cores and cone penetration tests. Chronological units, continuous peat and loam levels and organic-rich deposits are indicated. For location of the cross section, see Fig. 3.2B.


SW
NE
Depth (m above Dutch Ordnance Datum)
S51B0003
51B0307
S51B0004
S51B0005
S51B0006
S51B0007
S51B0008
S51B0009
River Dommel
51B0302
S51B0010
S51B0011
S51B0012
S51B0013
S45D0001
S45D0002
S45D0003
S45D0004
45D0154
S45D0005
S45D0006
MIS 1/2
MIS 3/5d
MIS 5e
MIS 6/7
MIS 8
MIS 9
MIS 10/12
MIS 12/14
MIS 15+
Boxtel Fm.
Sterksel Fm.
Beegden Fm.
25 0 80
Rf (%) cf (MPa)
0 1 2 3 km
Legend
Peat & gyttja
Clay
Loam
Fine sand (63-150 µm)
Medium sand (150-300 µm)
Coarse sand (300-2000 µm)
Stage boundary
Cone resistance graph (cf)
Friction ratio graph (Rf)
Continuous peat level
Continuous loam level
Organic-rich sand and loam deposits

However, there are indications from the marine record that during MIS 7 sea-surface temperatures in the Norwegian Sea (Northern Atlantic Ocean) only approximated those during the interstadial MIS 5a (Kellogg, 1980). This suggests that climate in north-western Europe was less oceanic during the second part of MIS 7 than during e.g. the second part of the Eemian (MIS 5e). Hence, the precipitation-evaporation ratio in the region and the local groundwater level may have been considerably lower.

Because of its geographical position in a subsidence area just south of the region severely affected by glacial remoulding by the Pleistocene ice sheets, the Roer Valley Graben contains important parts of the 'missing' late-Middle Pleistocene record in continental north-western Europe (sediments from MIS 7 to MIS 10; Turner, 1998). The sedimentary sequence in the Roer Valley Graben thus forms a possible link between the glacial record of northern Europe, the $\delta^{18}O$ climate records of the deep sea and the continuous lacustrine and loess sequences in the eastern and southern part of the continent (Fig. 5.12).

6.2 Research applications

Rather than putting all effort into detailed palynological research, simultaneous lithostratigraphic, biostratigraphic and chronostratigraphic research is much more beneficial when investigating long terrestrial sequences. It is the integration of results from various geoscientific disciplines that enabled the interpretation of the sedimentary record in the Roer Valley Graben. In north-western Europe, a similar approach could be adopted when investigating the sedimentary record of the deep Elsterian glacial tunnel valleys or the infilling of the Saalian and Weichselian glacial basins. A good example is provided by the detailed study of the Amsterdam Basin (Van Leeuwen et al., 2000).

The well-defined lithostratigraphy and detailed sedimentary description of the fine-grained deposits in the Roer Valley Graben can be easily used in other areas that are outside the depositional realm of the sea, large river systems and ice sheets. A similar research approach is also applicable to comparable deposits at other stratigraphic levels (e.g. the Lower-Pleistocene deposits of the Stramproy Formation; see Appendix). Because the lithostratigraphic subdivision strongly relates to lithological properties of the sediment, the results can be used in applied geological studies as well. Future hydrogeological models for the Roer Valley Graben can take into account the large differences in vertical and lateral permeability of the sediments of the Boxtel Formation that result from the small-scale depositional pattern and lateral discontinuity of most loam layers. Similarly, geotechnical studies can incorporate the laterally inhomogeneous soil-strength parameters of these deposits. Both applications benefit from the facies model described in Chapter 3.

6.3 Future research

Now that this study has proven the possibilities for retrieving detailed palaeo-environmental and palaeoclimatic data from the sedimentary sequence in the Roer Valley Graben, future studies of terrestrial sequences should aim at:

- Completing the terrestrial sedimentary record and improving correlation with other long records. For example in the Roer Valley Graben, it is supposed that apart from organic deposits representing MIS 5e and MIS 9, organics from the Holsteinian Interglacial (MIS 11) have also been preserved. MIS 11 is probably the best analogue for our present-day interglacial and its future (Droxler & Farrell, 2000; Berger & Loutre, 2002) and therefore deserves intensive study. Furthermore, improved correlation of the deposits in the Roer Valley Graben with the orbitally-tuned fluvial terrace record of the river Meuse in the southern Netherlands and Belgium is needed (cf. Section 6.1.4). Also, correlation with the fluvial record in the Rhine-Meuse delta plain to the north-west of the study area needs to be established. Ultimately, terrestrial records of Quaternary landscape change should be correlated with the long continuous ice-core and marine records by means of common proxies.
- Improved dating control, especially for the Middle-Pleistocene. Beyond the Eemian (MIS 5e), time control is currently very limited. Although quartz OSL dating yields promising results, these dates cannot be checked against other absolute dating methods. The additional use of tephrochronological dating, U-series dating of peat or K-Ar dating may reduce dating uncertainties in this time frame considerably. Tephrochronology might be especially suitable in the Roer Valley Graben, because of: 1) recent improvements in the recognition and analysis of microtephra horizons (Turney et al., 1997; Turney, 1998; Wastegård & Rasmussen, 2001); 2) the geographical position of the Netherlands at the boundary of the influence of the active Icelandic volcanoes and the Quaternary Eifel volcanics (Davies et al., 2002).
- Detailed research on the transition between interglacial and glacial periods. The Late Weichselian to Holocene transition (Last Termination) serves as a good example of a well-investigated glacial-interglacial shift (Lowe et al., 2001). However, natural climate does not head towards a glacial-interglacial transition, but towards an interglacial-glacial shift. Repeatedly, deposits with a high temporal resolution have been preserved in the Roer Valley Graben that represent transition periods from temperate to cool, periglacial climatic conditions. Detailed palaeo-environmental research in this region and similar areas elsewhere might give us clues on the character and timing of changes in landscape and vegetation that take place at the onset of phases of prolonged glacial cooling.

SUMMARY

Patterns and processes in a Pleistocene fluvio-aeolian environment (Roer Valley Graben, south-eastern Netherlands)

Introduction

The Roer Valley Graben in the south-eastern Netherlands is an area of active tectonic subsidence. In this region, an up to 35-m thick terrestrial fluvio-aeolian sedimentary record of Middle and Late-Quaternary age recorded the interplay of tectonic subsidence and climate changes. The fine-grained sediments were previously known as Nuenen Group deposits in the Quaternary lithostratigraphic framework of the Netherlands. They form an important archive of terrestrial landscape development in a changing climate. The subsiding Roer Valley Graben has been saved from glacial erosion, because it is situated south of the maximum extent of the Pleistocene ice sheets. This makes it a key area for correlating the fragmentary glacial record of northern Europe with the lake and loess records in the eastern and southern part of the continent. In addition, the Roer Valley Graben may contain part of the so-called 'missing' record of upper Middle-Pleistocene sediments (representing Marine Isotope Stages 10 to 7) in continental north-western Europe. In 1998, the State Geological Survey of the Netherlands (TNO-NITG) initiated this study, because a lack of sedimentary information hampered detailed geological mapping and applied research in the area.

The main objectives of this study were:

- To develop a well-defined and applicable lithostratigraphic framework for the fluvio-aeolian deposits in the Roer Valley Graben (Chapter 2);
- To reconstruct the prevailing sedimentary processes, local depositional pattern and palaeo-environmental development in the Roer Valley Graben during the Middle and Late Quaternary (Chapters 3, 4, 5);
- To construct a geochronological framework for the Middle- and Upper-Quaternary deposits in the Roer Valley Graben and to assess the influence of regional tectonic movements and climate changes on the depositional environment and sedimentation rate in the area (Chapters 4, 5).

These goals were achieved by a characterisation and interpretation of the lithological properties, sedimentary structures, palaeo-ecological data and geochemical and mineralogical properties of the Nuenen Group deposits and comparison of this information to data from other studies in similar depositional settings. Optically Stimulated Luminescence (OSL) dating of quartz grains provided an opportunity to establish a reliable timeframe for the sedimentation of the terrestrial fluvio-aeolian deposits in the Roer Valley Graben.

Lithostratigraphy

Application of the traditional lithostratigraphic framework to subdivide the Middle- and Upper-Quaternary terrestrial fine-grained deposits in the Netherlands is problematic. Deposits of many formations cannot be distinguished from each other, based on lithological characteristics and stratigraphic position alone. To overcome this problem, Chapter 2 presents a new, well-defined lithostratigraphy for these deposits, based on detailed research in the central part of the Roer Valley Graben. The traditional lithostratigraphic subdivision of the fine-grained deposits in this area into three formations (Eindhoven Formation, Asten Formation and Twente Formation) was based on a combination of litho-, bio- and chronostratigraphic evidence and the presumed widespread presence of a horizon of organic-rich interglacial sediments of Eemian age. To avoid intermingling of criteria regarding lithological characteristics, genesis and age, all fine-grained sediments are now incorporated into the new Boxtel Formation. The implications for the lithostratigraphic framework in other parts of the country are explored and discussed. Eight lithostratigraphic members are introduced that describe the most characteristic parts of the formation. To fully illustrate the sedimentary sequence in the Roer Valley Graben, two new members are defined there. The Best Member incorporates floodloam deposits alternating with sandy aeolian deposits in the lower part of the Boxtel Formation. The Liempde Member includes reworked aeolian loess and sandy loess deposits ('Brabant loam') that occur in the upper part of the sedimentary sequence.

Sedimentary processes and depositional pattern

Chapter 3 details the sedimentary structures and depositional environment of the sediments, using undisturbed sediment cores and cone penetration tests (CPTs). Seven sedimentary facies are distinguished, ranging from sandy fluvial deposits to loamy aeolian deposits and organics. Wet-aeolian sand-sheet and loam deposits are the two most widespread facies. The aeolian sand is characterised by horizontal alternating bedding, attributed to deposition of sand and silty sand on an alternating wet and dry surface. Dominant processes include sand-ripple lamination and adhesion lamination. The loam is usually massive and interpreted as a reworked loess deposit. Not only sedimentary data (Chapter 3), but also mineralogical and geochemical data (Chapter 5) reveal an upward change from a fluvial depositional environment to a dominance of aeolian deposits. This change may be related to increased tectonic uplift and the onset of large-scale volcanism in the Ardennes-Eifel region and a north-eastward shift of the lower courses of the rivers Rhine and Meuse between 800 and 500 ka. Reworked Na-rich deposits with an unstable heavy mineral assemblage form the main source material for the aeolian deposits in the Roer Valley Graben. The most likely provenance is the area north and west of the Roer Valley Graben, where Quaternary Rhine deposits were present near the surface. Na-poor sediments with a stable heavy mineral assemblage from the Campine High in the south-west may have acted as a secondary sediment source. Sedimentation and preservation in the Roer Valley Graben predominantly took place under humid surface conditions. These conditions occurred: 1) in a periglacial climate with permafrost; 2) at the transition from a warm-temperate to a cool climate.

Organic deposits from at least two different interglacial periods (Marine Isotope Stage (MIS) 5e and MIS 9) have been preserved in the central part of the Roer Valley Graben. During the Eemian (MIS 5e) clastic and organic deposition took place in the early part (E2-E3) and last part of the interglacial (E5-E6A-E6B). The sedimentary sequence contains a widespread hiatus during the E4A-E4B-E5 regional pollen zones (Chapters 4, 5). During MIS 9, clastic and organic deposition was restricted to the last part of the interglacial period (Chapter 5). Sedimentological and palynological data reveal that both the presence and extent of deposits from interglacial periods are related to the local groundwater level history and clastic sediment flux. Regional changes in these environmental factors are probably related to changes in the global oceanic-atmospheric circulation pattern.

Optically Stimulated Luminescence dating

Optically Stimulated Luminescence (OSL) dating has been applied to provide an absolute time frame for the Middle- and Late-Quaternary deposits in the area (Chapters 4, 5). This method is very suitable to date these deposits, because:

- The aeolian depositional environment of most of the clastic sediments ensured sufficient exposure to daylight during sediment transport to enable complete bleaching of the grains;
- The clastic sediments consist almost exclusively of quartz grains, which causes very low natural radiation doses and permits reliable OSL dating far back in time.

Two quartz OSL dating series are presented (Chapter 5) that indicate a Middle- to Late-Quaternary age of the fluvio-aeolian and aeolian deposits in the Roer Valley Graben. The whole sequence of fine-grained deposits of the Boxtel Formation is correlated with Marine Isotope Stages 14 to 1 (570 ka to present; Chapter 6). The fluvio-aeolian deposits in the lower part of the Boxtel Formation (Best Member) have been formed contemporaneously with the coarse-grained Meuse deposits of the Beegden Formation and date from MIS 14 to MIS 12 (570-420 ka). As a consequence, fluvial Rhine-Meuse deposits (Sterksel Formation) in the Roer Valley Graben must date from MIS 15 (570 ka) and older. Correlation of the morphological boundary between the Main and Middle Terraces along the rivers Rhine and Meuse (previously dated at ~750 ka) with the lithostratigraphic boundary between the Sterksel and Beegden Formation in the Roer Valley Graben (dated at ~570 ka) is therefore erroneous (Chapter 5). The two widespread organic layers in the Boxtel Formation are dated at 114 ± 12 ka (MIS 5e, Eemian) and ~300 ka (MIS 9), respectively. The age of the upper organic layer is supported by its stratigraphic position and palynological signature, which makes this study the first to present a reliable OSL dating result for terrestrial Eemian deposits in the Netherlands (Chapter 4).

Conclusions

The Roer Valley Graben contains a well-preserved Middle- and Late-Quaternary sedimentary record, reflecting changing depositional patterns and sedimentary processes in a fluvio-aeolian environment. The following results were obtained:

- A well-defined lithostratigraphic subdivision of the deposits, involving the definition of the Boxtel Formation and two new lithostratigraphic members: the Best Member and Liempde Member;
- A reconstruction of the provenance of the fluvial and aeolian sediments, prevailing sedimentary processes and the development of the local depositional environment;
- A chronological framework of the deposits, based on quartz OSL dates and correlated with regional tectonic events and cyclic climate change.

The strength of the research approach has been the integration of lithological and sedimentary information with palaeo-ecological data and reliable geochronological information. This permitted to interpret this fragmentary terrestrial record in terms of repeated phases of deposition and non-deposition. Fluvio-aeolian sequences allow the use of chronometric dating such as quartz OSL to date sediments with ages well beyond 100 ka. These records are therefore a valuable addition to existing long terrestrial records (e.g. lacustrine sequences) that usually only provide biostratigraphical information. Because of its geographical position in a subsidence area, just south of the region that was severely affected by glacial remoulding by the Pleistocene ice sheets, the Roer Valley Graben contains important parts of the 'missing' late-Middle Pleistocene record in continental north-western Europe (sediments from MIS 10 to MIS 7). The sedimentary sequence in the Roer Valley Graben thus forms a possible link between the glacial record of northern Europe, the $\delta^{18}O$ climate records of the deep sea and the continuous lacustrine and loess sequences in the eastern and southern part of the continent.

SAMENVATTING

Patronen en processen in een Pleistoceen fluvio-eolisch afzettingsmilieu (Roerdalslenk, zuid-oost Nederland)

Inleiding

De Roerdalslenk in het zuid-oosten van Nederland is een gebied waar bodemdaling plaatsvindt. Ten gevolge van deze tectonische daling en Kwartaire klimaatveranderingen is in dit gebied in de afgelopen 500.000 jaar een tot 35 meter dik pakket fijnkorrelige beek- en windafzettingen (fluvio-eolische afzettingen) en veen gevormd. Deze afzettingen werden lithostratigrafisch gerekend tot de Nuenen Groep en vormen een belangrijk archief van terrestrische landschapsontwikkeling onder invloed van veranderende klimaatsomstandigheden. Omdat de Roerdalslenk zich ten zuiden van de maximale uitbreiding van de Pleistocene landijskappen bevond, zijn de sedimenten gespaard gebleven voor glaciale erosie. Hierdoor vormen de afzettingen in dit gebied een belangrijke schakel tussen de fragmentarische glaciale sedimentaire sequenties in noord-Europa en de completere meer- en lösssequenties die aanwezig zijn in het zuiden en oosten van Europa. Bovendien is het mogelijk dat in de Roerdalslenk een deel van de 'ontbrekende' boven Midden-Pleistocene afzettingen, gevormd tijdens Mariene Isotopen Etage 10 t/m 7, aanwezig is. Omdat een geologische karakterisatie van de sedimenten grotendeels ontbrak en daarmee toegepast onderzoek in het gebied bijna niet mogelijk was, is in opdracht van TNO-NITG in 1998 het onderzoek van deze afzettingen gestart.

De belangrijkste doelstellingen van deze studie waren:
- Het ontwikkelen van een toepasbare lithostratigrafische indeling voor de Midden- en Boven-Kwartaire wind- en rivierafzettingen in de Roerdalslenk (Hoofdstuk 2);
- Het reconstrueren van de overheersende sedimentaire processen, het locale afzettingspatroon en de ontwikkeling van het afzettingsmilieu in de Roerdalslenk tijdens het Midden- en Laat-Kwartair (Hoofdstukken 3, 4, 5);
- Het bepalen van de ouderdom van de Midden- en Boven-Kwartaire afzettingen in de Roerdalslenk en het inschatten van het belang van grootschalige bodembewegingen en klimaatveranderingen voor het afzettingsmilieu en de sedimentatiesnelheid in het gebied (Hoofdstukken 4, 5).

Deze doelen zijn nagestreefd door het maken van een gedetailleerde beschrijving en interpretatie van de gesteente-eigenschappen, sedimentaire structuren, paleo-ecologische data en geochemische en mineralogische eigenschappen van de afzettingen van de Nuenen Groep. Optisch Gestimuleerde Luminescentie (OSL) datering van kwartskorrels heeft ouderdomsbepaling van deze sedimenten mogelijk gemaakt.

Lithostratigrafie

Toepassing van de traditionele lithostratigrafische indeling op de Midden- en Boven-Kwartaire terrestrische fijnkorrelige afzettingen in Nederland levert problemen op. Vaak kunnen de afzettingen van verschillende formaties op grond van hun gesteentekenmerken en stratigrafische positie alleen niet van elkaar onderscheiden worden. Daarom wordt in Hoofdstuk 2 een nieuw, goed gedefinieerd lithostratigrafisch raamwerk gepresenteerd voor deze afzettingen, dat vooral gebaseerd is op onderzoek in het centrale deel van de Roerdalslenk. Dit neemt de plaats in van de traditionele indeling in drie formaties (Formatie van Twente, Formatie van Asten en Formatie van Eindhoven) die gebaseerd was op een combinatie van litho-, bio- en chronostratigrafische criteria en op de veronderstelde wijdverspreide aanwezigheid van een niveau met organisch-rijke sedimenten uit het voorlaatste interglaciaal (Eemien). Om vermenging van gesteentekenmerken, ontstaanswijze en ouderdom als criteria die een rol spelen in de lithostratigrafische indeling te vermijden, is de Formatie van Boxtel ingevoerd. Deze formatie omvat alle fijnkorrelige wind- en beekafzettingen, alsmede ingeschakelde veenvoorkomens, die aanwezig zijn boven de bovenste glaciale afzettingen in het noorden van Nederland en boven de grofkorrelige rivierafzettingen in het zuiden van Nederland. De gevolgen van het invoeren van deze nieuwe eenheid worden onderzocht en bediscussieerd. Binnen de Formatie van Boxtel worden acht laagpakketten gedefinieerd. Deze omvatten de meest karakteristieke gedeelten van de formatie. Twee van deze laagpakketten zijn gedefinieerd in de Roerdalslenk. Het Laagpakket van Best omvat een afwisseling van overstromingslemen en zandige windafzettingen in het onderste gedeelte van de Formatie van Boxtel. Het Laagpakket van Liempde omvat geremanieerde löss- en zandige lössafzettingen (de zgn. 'Brabantse leem') in het bovenste deel van de sedimentaire sequentie.

Sedimentaire processen en afzettingsmilieu

De sedimentaire structuren en het afzettingsmilieu van de afzettingen worden gedetailleerd beschreven in Hoofdstuk 3. Hierbij wordt gebruik gemaakt van zowel ongestoorde sedimentkernen als elektrische sonderingen (CPT’s). Er worden zeven verschillende sedimentaire facieseenheden onderscheiden, variërend van zandige en lemige beek- en windafzettingen tot veen. Zandige en lemige windafzettingen, gevormd op een nat oppervlak, komen het meeste voor. De zandpakketten worden gekenmerkt door een afwisseling van dunne zandlaagjes en lemige zandlaagjes, ontstaan door afzetting op een afwisselend droog en nat oppervlak. Belangrijke processen zijn zandribbellaminatie en adhesielaminatie. De leem is meestal ongelaagd en wordt geïnterpreteerd als een geremanieerde lössafzetting. Sedimentaire, mineralogische en geochemische gegevens tonen aan dat het fluviatiele afzettingsmilieu dat onderin de afzettingen overheerst naar boven toe geleidelijk overgaat in een eolisch afzettingsmilieu. Dit hangt mogelijk samen met een toenemende opheffing van het Ardennen-Eifel gebied en een daarmee samenhangende noord-oostwaartse verplaatsing van de benedenlopen van de rivieren Maas en Rijn, ruwweg tussen 750.000 en 450.000 jaar geleden (Hoofdstuk 5). Het belangrijkste bronmateriaal voor de windafzettingen in de

Roerdalslenk wordt gevormd door natriumrijke afzettingen met een instabiele zware mineralenassociatie. Het meest waarschijnlijke herkomstgebied van dit materiaal is het westen van Nederland en het drooggevallen zuidelijke Noordzeebekken, waar op dat moment Rijnafzettingen aan het oppervlak lagen. Een tweede sedimentbron wordt gevormd door natriumarme sedimenten met een stabiele zware mineralenassociatie, die afkomstig zijn van het Kempisch Plateau (noord-België). Sedimentatie en preservatie van sedimenten in de Roerdalslenk vond plaats wanneer het landoppervlak vochtig was. Deze omstandigheden traden vooral op: 1) in een koud, periglaciaal klimaat met permafrost; 2) op de overgang van een warm naar een koeler klimaat.

Op verschillende plaatsen in de Roerdalslenk is veen bewaard gebleven (Hoofdstukken 4, 5). Dit veen is, behalve in de huidige warme tijd, gevormd gedurende tenminste twee verschillende oudere interglaciale perioden, te weten MIS 5e (Eemien) en MIS 9. Gedurende het Eemien werden organisch-rijke afzettingen gevormd in het vroege deel van het interglaciaal (pollenzones E2-E3) en het laatste deel van het interglaciaal (pollenzones E5-E6A-E6B). Er zijn geen afzettingen bewaard gebleven uit de tussenliggende periode. Gedurende MIS 9 was de vorming van organisch-rijke afzettingen beperkt tot het laatste deel van het interglaciaal. Sedimentaire en pollenanalytische gegevens tonen aan dat zowel de aanwezigheid als de uitgestrektheid van interglaciale afzettingen bepaald wordt door de locale grondwaterstand op het moment van vorming. Variaties in het wereldwijde gekoppelde oceanisch-atmosferische circulatiepatroon zijn waarschijnlijk verantwoordelijk voor de veranderingen in de locale afzettingsomstandigheden in de Roerdalslenk.

Optisch Gestimuleerde Luminescentie datering

De ouderdom van de wind- en rivierafzettingen in de Roerdalslenk is bepaald met behulp van Optisch Gestimuleerde Luminescentie (OSL) datering van kwarts (Hoofdstukken 4, 5). Deze dateringsmethode kon hier met succes worden toegepast, omdat:

- Met name windafzettingen tijdens transport voldoende worden blootgesteld aan licht, waardoor volledige bleking plaatsvindt (het OSL-signaal wordt 'op nul gezet');
- Het zandige sediment in de Roerdalslenk bijna volledig bestaat uit kwartskorrels. Dit veroorzaakt een lage natuurlijke stralingsdosis, wat ertoe leidt dat relatief oude sedimenten gedateerd kunnen worden.

De resultaten van in totaal 37 OSL-dateringen van kwarts laten zien dat de wind- en rivierafzettingen in de Formatie van Boxtel inderdaad van Midden- en Laat-Kwartaire ouderdom zijn (Hoofdstuk 5). De Formatie van Boxtel is afgezet gedurende MIS 14 t/m 1 (570.000 jaar voor heden tot nu; Hoofdstuk 6). De fluvio-eolische afzettingen in het onderste deel van de Formatie van Boxtel (Laagpakket van Best) zijn gelijktijdig gevormd met de grofkorrelige Maasafzettingen van de Formatie van Beegden in de Roerdalslenk en dateren van MIS 14 t/m 12 (570.000 tot 420.000 jaar voor heden). Dit betekent dat de Rijn- en Maasafzettingen van de Formatie van Sterksel in de Roerdalslenk ouder moeten zijn dan 570.000 jaar. Het koppelen van de morfologische grens tussen de Hoog- en Middenterrassen langs de Rijn en Maas (eerder door middel van paleomagnetisme gedateerd op ongeveer 750.000 jaar) aan de lithostratigrafische grens tussen de afzettingen van de Formatie van Beegden en Sterksel is dus niet correct (Hoofdstuk 5). De twee veenlagen in de Formatie van Boxtel konden gedateerd worden op respectievelijk 114.000 ± 12.000 jaar (MIS 5e, Eemien) en ongeveer 300.000 jaar voor heden (MIS 9). De Eemien-ouderdom van de bovenste veenlaag wordt ondersteund door zijn stratigrafische positie en polleninhoud. Deze studie is daarmee de eerste die een betrouwbare OSL datering levert van terrestrische afzettingen uit het Eemien in Nederland (Hoofdstuk 4).

Conclusies

In de Roerdalslenk is een pakket Midden- en Laat-Kwartaire fijnkorrelige sedimenten aanwezig. Deze afzettingen zijn gevormd door sedimentaire processen in een fluvio-eolisch afzettingsmilieu. De studie van deze sedimenten heeft de volgende resultaten opgeleverd:

- Een goed gedefinieerde lithostratigrafische indeling van deze afzettingen, waarbij als nieuwe eenheden de Formatie van Boxtel, het Laagpakket van Best en het Laagpakket van Liempde zijn gedefinieerd;
- Een reconstructie van de herkomst van de rivier- en windafzettingen, van de overheersende sedimentaire processen en de ontwikkeling van het locale afzettingsmilieu;
- Een bepaling van de ouderdom van de afzettingen, gebaseerd op kwarts OSL-dateringen en gekoppeld aan regionale tectonische gebeurtenissen en Kwartaire klimaatveranderingen.

Een sterk punt van dit onderzoek is de integratie van sedimentaire gegevens met paleo-ecologische informatie en betrouwbare dateringen. Deze fragmentarische sequentie kon ontrafeld worden door rekening te houden met het cyclische karakter van fases van depositie en non-depositie. Omdat fluvio-eolische afzettingen gedateerd kunnen worden met kwarts OSL, waarbij betrouwbare dateringen tot ver boven de 100.000 jaar mogelijk zijn, zijn dit soort records een waardevolle aanvulling op reeds bestaande lange terrestrische records, zoals meersequenties, waaruit vooral biostratigrafische informatie verkregen wordt. Vanwege de ligging in een dalingsgebied net ten zuiden van de maximale Pleistocene landijsuitbreiding, bevat de Roerdalslenk belangrijke gedeelten van de zgn. 'ontbrekende' laat Midden-Pleistocene sedimentaire record in continentaal noord-west Europa (sedimenten uit MIS 10 t/m MIS 7). De sedimentare sequentie in de Roerdalslenk vormt dus een mogelijke verbinding tussen de glaciale record in het noorden van Europa, de zuurstofisotopenrecords van de diepzee en de continue meer- en lösssequenties in oost- en zuid-Europa.

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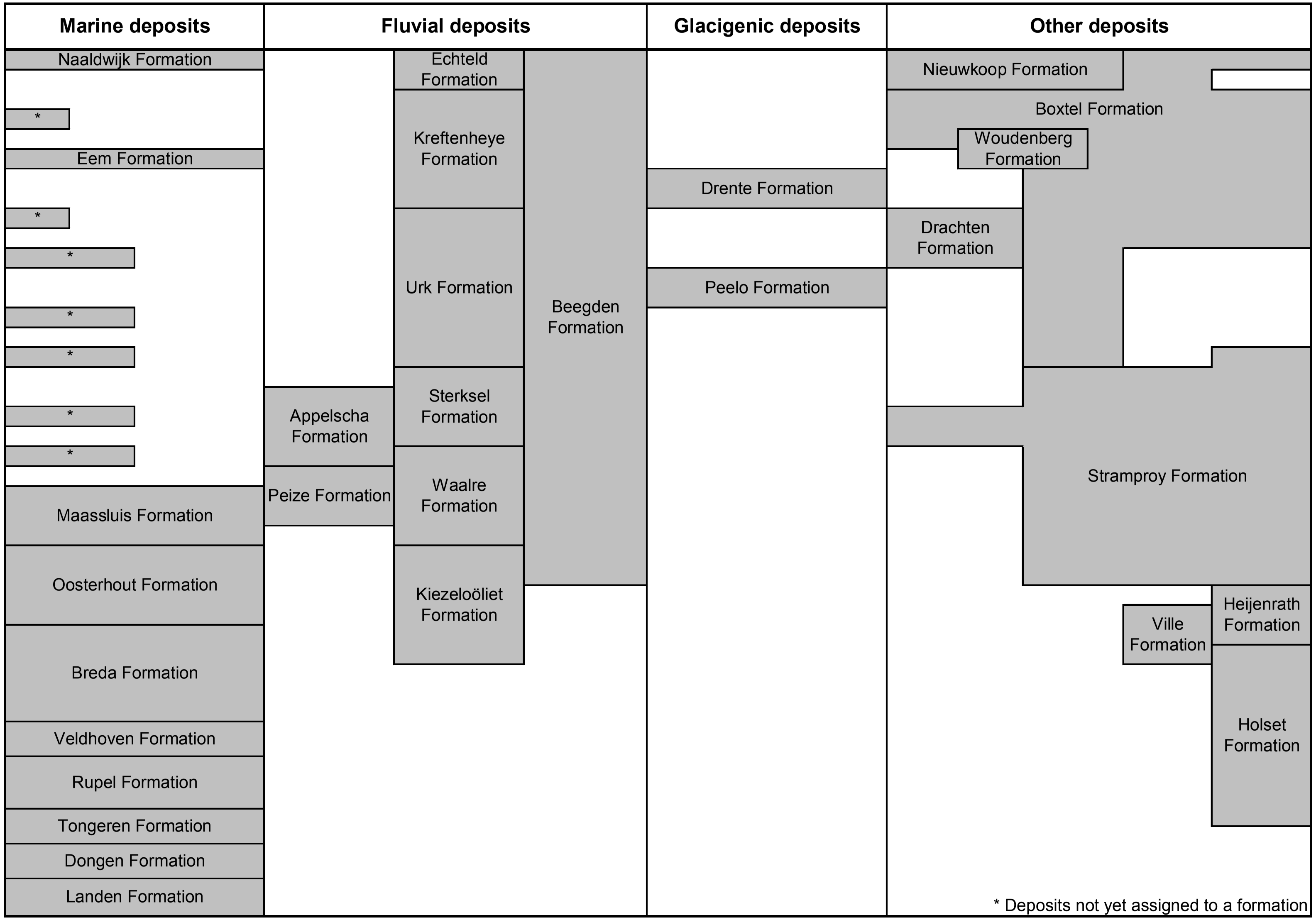
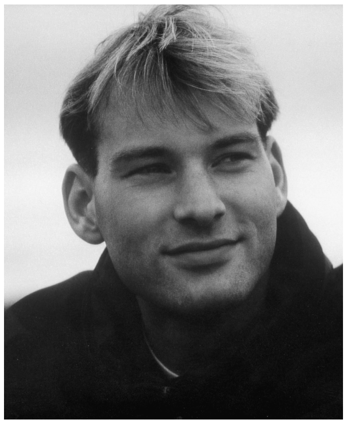
APPENDIX

Table A.1 Lithostratigraphic framework of Upper-Tertiary and Quaternary deposits in the Netherlands (TNO-NITG, 2003).



CURRICULUM VITAE



Jeroen Schokker werd geboren op 4 april 1975 in Raalte. Het sneeuwde. Zijn jeugd bracht hij grotendeels door in De Rijp en Alkmaar. In 1993 behaalde hij zijn VWO-diploma aan het Murmellius Gymnasium in Alkmaar. Van 1993 tot 1998 studeerde hij Fysische Geografie aan de Vrije Universiteit Amsterdam met als afstudeerrichting Toegepaste Fysische Geografie / Kwartairgeologie. Van augustus tot december 1996 verbleef hij aan de Universitet i Bergen, Noorwegen, alwaar hij zich verder bekwaamde in de paleoklimatologie en kwartairstratigrafie. Ook deed hij veldwerk in zuid-west Noorwegen en op de Hardangervidda. Zijn afstudeerstage over de geologische en hydrologische opbouw van de stuwwal van Enschede vond plaats bij TNO-NITG in Zwolle, onder leiding van Meindert van den Berg. Na zijn afstuderen werkte hij twee maanden bij TNO-NITG in Haarlem. Op 1 oktober 1998 begon hij aan zijn promotieonderzoek bij de Vakgroep Fysische Geografie van de Universiteit Utrecht. Gedurende zijn promotie werkte hij afwisselend in Utrecht en bij District Zuid van de Afdeling Geo-Kartering van TNO-NITG in Nuenen. Ook nam hij deel aan veldonderzoek op West-Groenland. Per 1 maart 2003 is hij begonnen als geoloog bij de Afdeling Geo-Infrastructuur van TNO-NITG in Utrecht. In zijn vrije tijd gaat Jeroen graag fotograferen, bergwandelen en kanoën en houdt hij zich bezig met meteorologie.

Jeroen Schokker was born on April 4, 1975 in Raalte (The Netherlands), while it was snowing. He largely spent his youth in the north-western part of the country (De Rijp and Alkmaar). In 1993, he graduated from secondary school at the Murmellius Gymnasium in Alkmaar. Between 1993 and 1998, he studied Physical Geography at the Free University of Amsterdam. He specialised in Applied Physical Geography / Quaternary Geology. From August to December 1996, Jeroen was a student at Bergen University, Norway, where he took courses in Palaeoclimatology and Quaternary Stratigraphy and attended field trips in the south-western part of Norway and on the Hardangervidda. His graduation work was carried out at the Netherlands Institute of Applied Geoscience TNO – *National Geological Survey* (TNO-NITG) in Zwolle, where he investigated the geological and hydrological structure of the Saalian ice-pushed ridge near Enschede. After his graduation, he worked for two months at TNO-NITG in Haarlem. On October 1, 1998, he started his PhD-research at the Department of Physical Geography of Utrecht University. During his doctoral research, he worked alternately in Utrecht and in Nuenen at the local branch of TNO-NITG. He also conducted fieldwork on West-Greenland. From March 1, 2003 onward, he is appointed as geologist at the Department of Geo-Infrastructure of TNO-NITG in Utrecht. In his spare time, Jeroen likes taking photographs, rambling and canoeing and he practises his interest in meteorology.

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