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Introduction of the Boxtel Formation and implications for the Quaternary lithostratigraphy of the Netherlands

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Abstract

Application of the traditional lithostratigraphic framework to subdivide the Middle- and Upper-Quaternary locally-derived 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 small-scale 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.

Keywords: aeolian deposits, Boxtel Formation, fluvial deposits, lithostratigraphy, periglacial deposits, Quaternary, Roer Valley Graben

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 locally-derived 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. 1a), problems are particularly large. This active tectonic subsidence area contains the thickest and most complete record of locally-derived 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 overlying clastic deposits of the Twente Formation and underlying similar clastic deposits of the Eindhoven Formation (Fig. 2). Problems arise, because:

– with the exception of the vicinity of the village of Asten

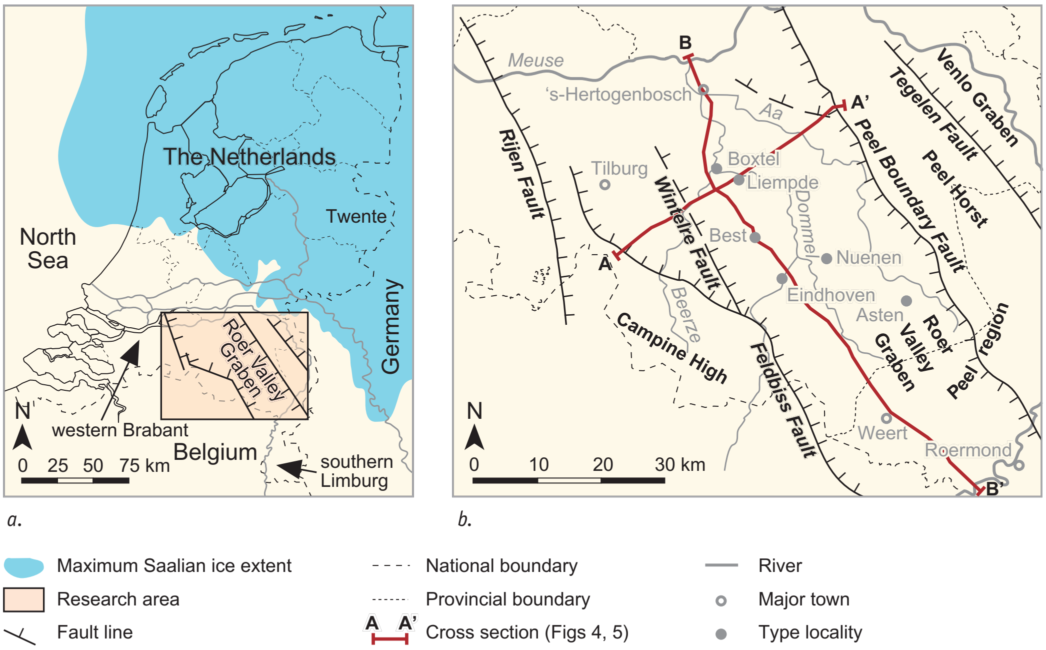


Fig. 1. a. Map of the Netherlands with the location of the Roer Valley Graben; b. Map of the Roer Valley Graben and surrounding areas showing the position of major tectonic blocks and fault systems. Stratotype localities and the position of two geological cross sections (Figs 4, 5) are also indicated.

(Fig. 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-Quaternary 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 locally-derived 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.

Chronostratigraphic unit \ Lithostratigraphic unit			Doppert et al. (1975) South	Doppert et al. (1975) North	TNO (2007) South	TNO (2007) North
Holocene			Kootwijk Formation / Singraven Formation		Boxtel Formation	
Pleistocene	Upper	Weichselian	Twente Formation		Boxtel Formation	Woudenberg Formation
Pleistocene	Upper	Eemian	Asten Formation / Eem Formation		Boxtel Formation	Eem Formation
Pleistocene	Middle	Saalian and older	Eindhoven Formation	Drente Formation	Boxtel Formation	Drente Formation
Pleistocene	Middle	Saalian and older	Eindhoven Formation	Eindhoven Formation	Boxtel Formation	Drachten Formation

Fig. 2. The original lithostratigraphic framework of Doppert et al. (1975) compared with the revised lithostratigraphic framework (De Mulder et al., 2003; TNO, 2007). Only part of both stratigraphic columns is shown.

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. 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 acted as 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.

Historical perspective of the stratigraphic problems

Over time, the stratigraphic subdivision of locally-derived 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. 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 southeastern Netherlands (Table 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 (e.g. Zagwijn, 1961, 1974; 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

Table 1. Overview of former and present lithostratigraphic classifications of the locally-derived 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
	Twente Formation		
Sanddiluvium	Asten Formation	Nuenen Group	Boxtel Formation
	Eindhoven Formation		

the presence of these deposits to subdivide the Sanddiluvium in three lithostratigraphic formations that were coupled to geologic time periods (Table 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 by using subtle lithological differences. Thus, palynology and radiocarbon dating became important tools to subdivide locally-derived deposits.

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 in this paper 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.

The Boxtel Formation in the Roer Valley Graben

Lithological characteristics, thickness and areal distribution

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 (Schokker & Koster, 2004; TNO, 2007). They occur at the surface throughout the area and are underlain by Middle-Pleistocene coarse-grained fluvial deposits of the Sterksel Formation and Beegden Formation (De Mulder et al., 2003; TNO, 2007). 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. 3).

Geological cross section A-A' (Fig. 4), 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 metres 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. 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 5. The thickest sequence of deposits of the Boxtel Formation is present in the north-central part of the Roer Valley Graben (Fig. 5: 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

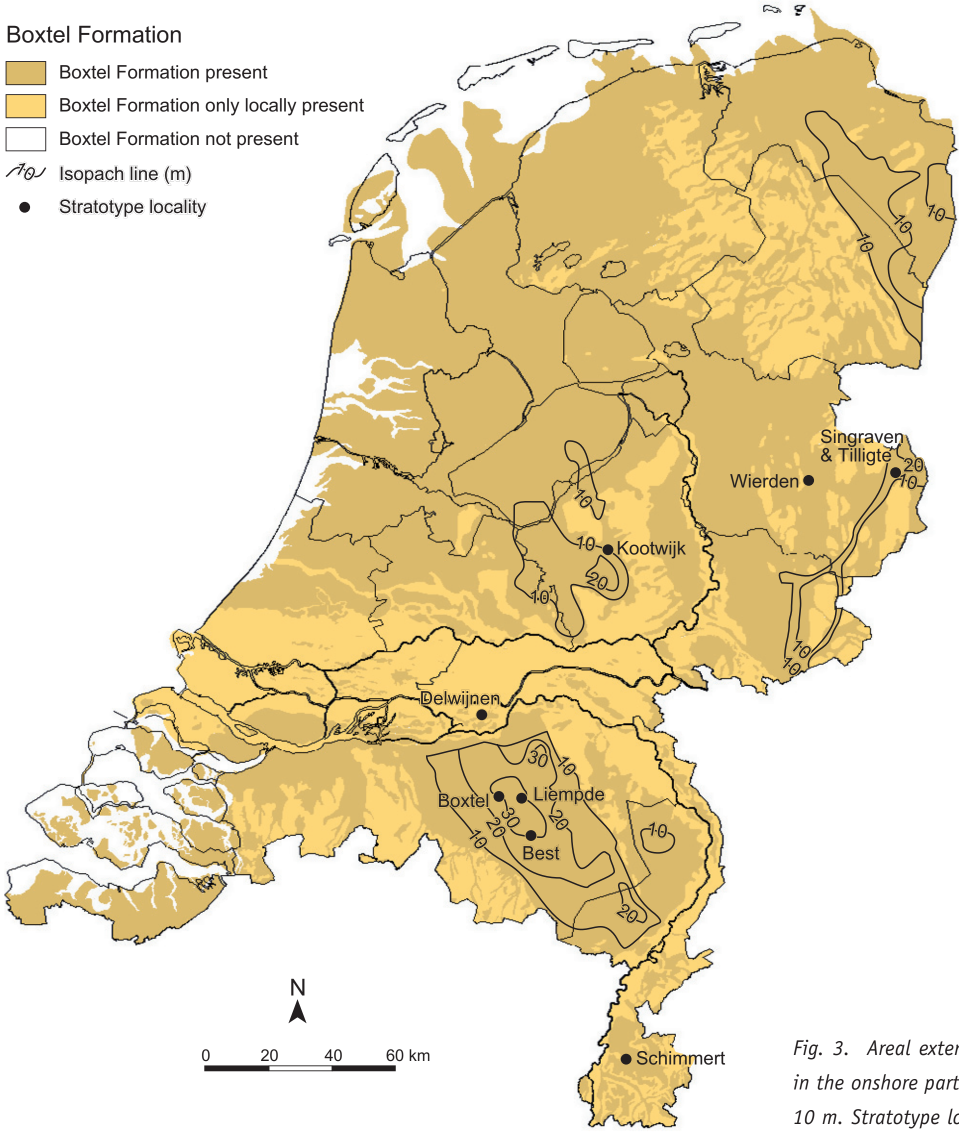


Fig. 3. Areal extent and thickness of the Boxtel Formation in the onshore part of the Netherlands. The depth interval is 10 m. Stratotype localities are indicated.

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. 5).

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 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 cryogenic deformation during the cold phases of the Middle and Late Pleistocene.

Definition and description of the Boxtel Formation at the stratotype locality

The holostratotype of the Boxtel Formation is defined in the central part of the Roer Valley Graben, close to the village of Boxtel (Fig. 1). It encompasses the sediments of core Boxtel-Breede Heide 2 (51B0307) from a depth of 27.30 m up to the surface (Fig. 6a). The core is situated at the intersection of the two geological cross sections shown in Figs 4 and 5 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. 6a). 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

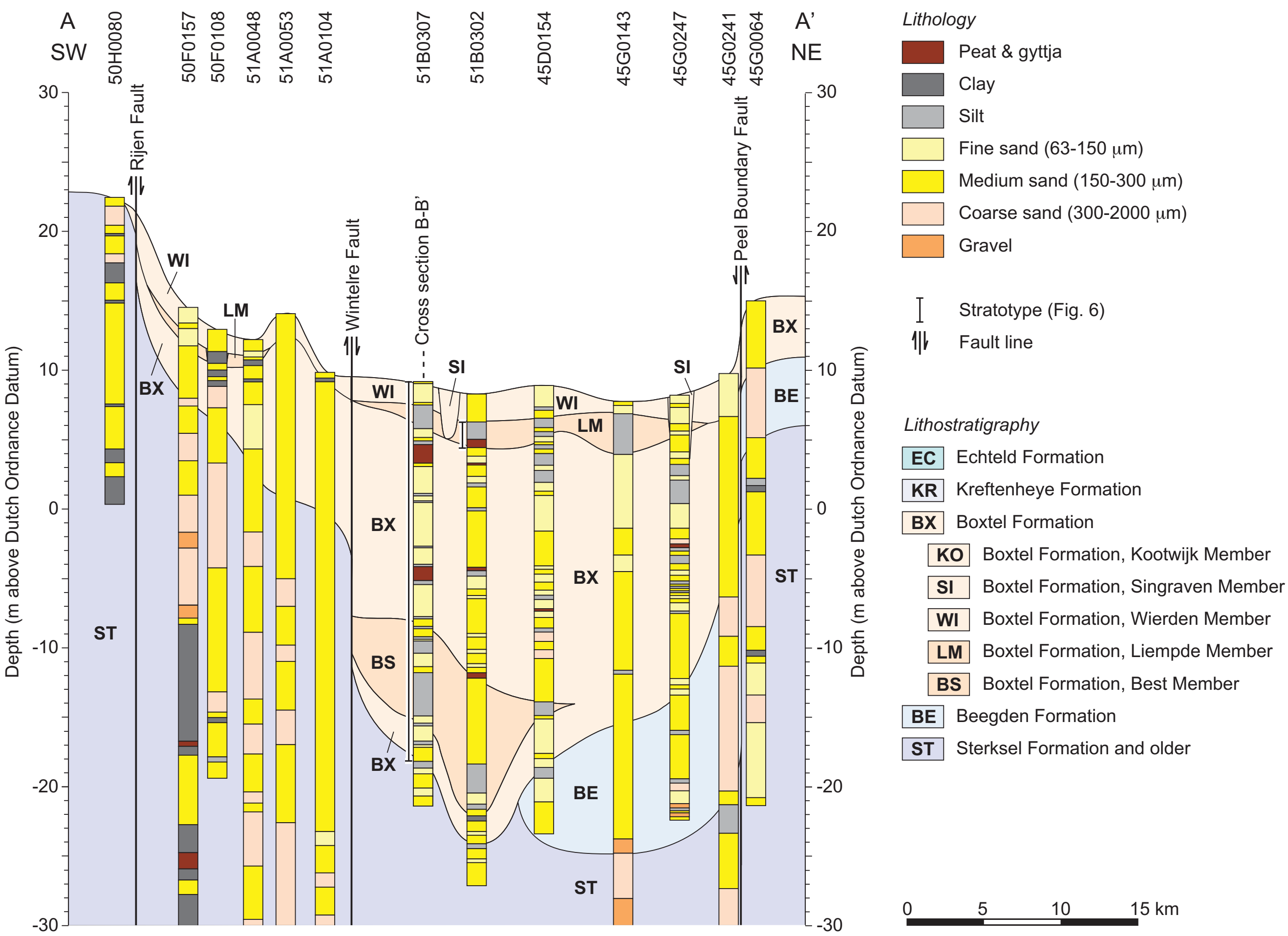


Fig. 4. Simplified SW-NE geological cross section through the deposits of the Boxtel Formation in the Roer Valley Graben. For location, see Fig. 1.

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 percentages of potassium feldspar and mica than granulometrically similar sediments in other parts of the Boxtel Formation (Fig. 6a). 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 (See also Schokker et al., 2004; 2005). 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. 6a).

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 presently occurs at the 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. 6a: 27.30 - 17.56 m below surface), affected by fluvial processes, and the upper part (above 17.56 m),

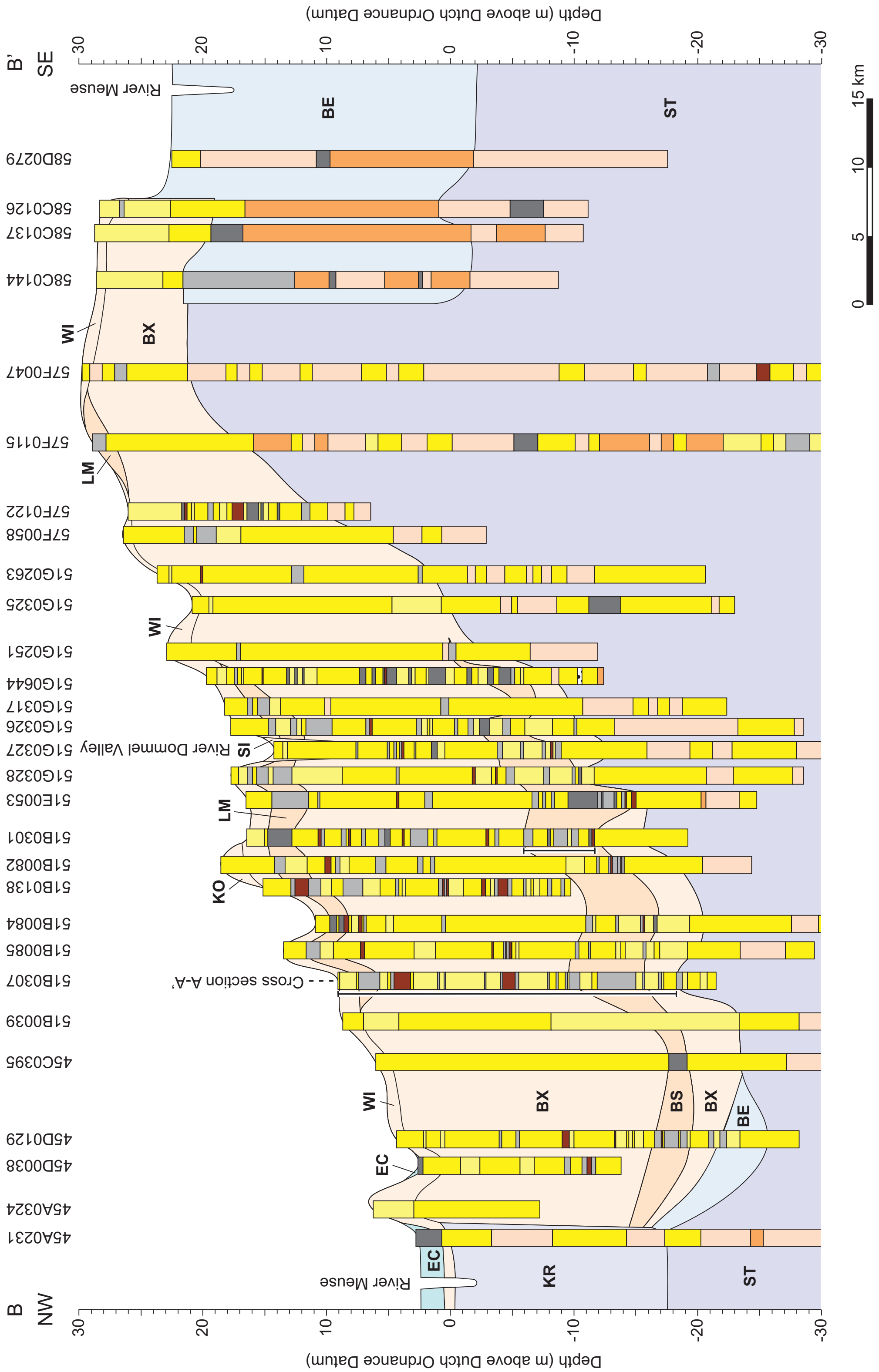


Fig. 5. Simplified NW-SE geological cross section through the deposits of the Boxtel Formation in the Roer Valley Graben. For location, see Fig. 1. For legend, see Fig. 4.

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.

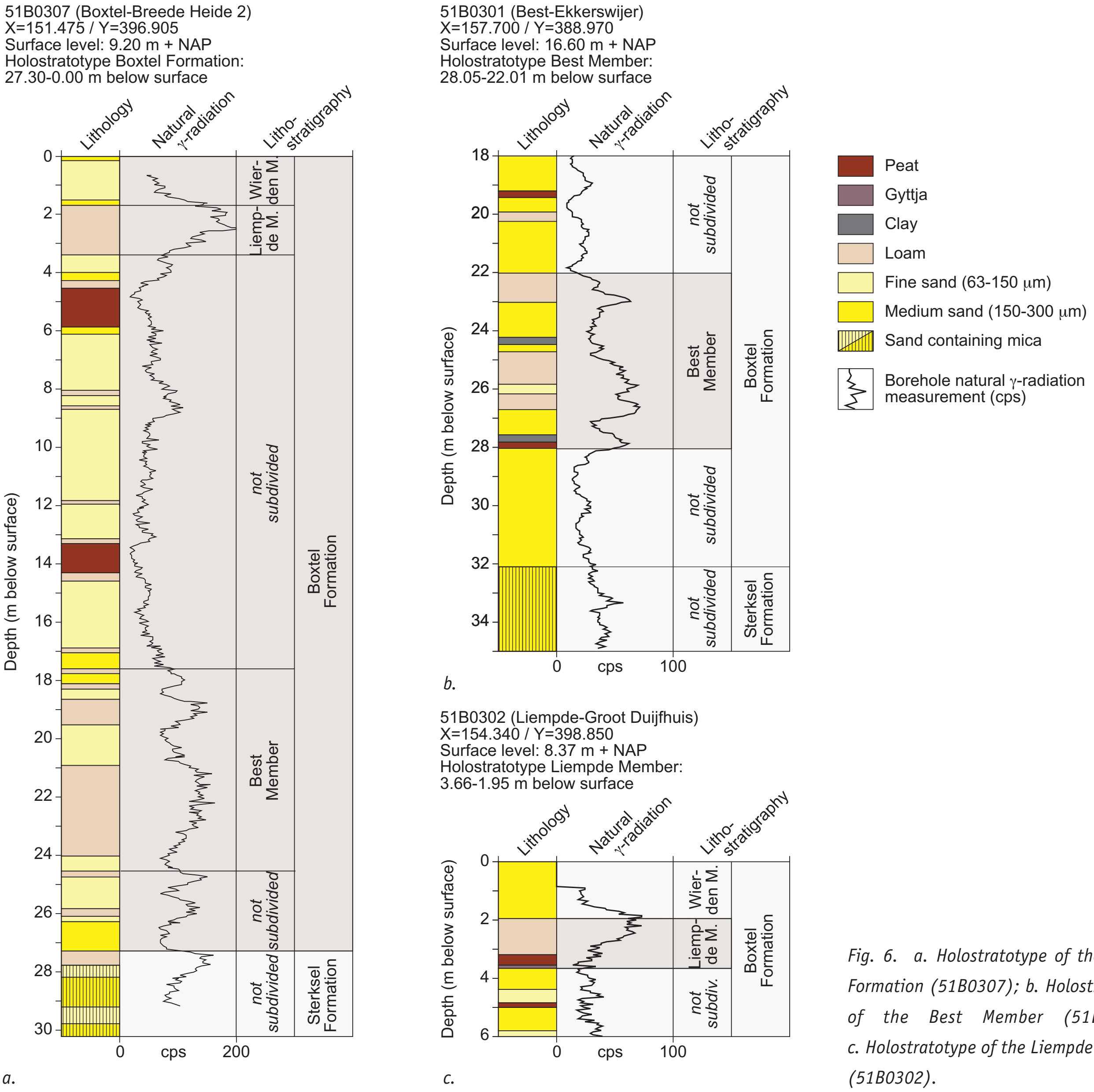


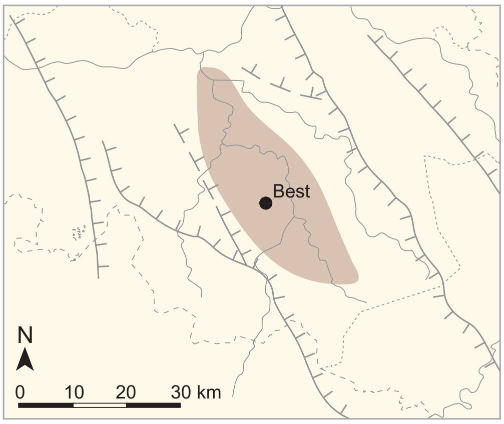
Fig. 6. a. Holostratotype of the Boxtel Formation (51B0307); b. Holostratotype of the Best Member (51B0301); c. Holostratotype of the Liempde Member (51B0302).

Definition and description of the Best Member at the stratotype locality

The Best Member is defined in core Best-Ekkerswijer (51B0301: 28.05 - 22.01 m below surface; Fig. 6b). 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. 7a). The Best Member occurs between 10 and 20 m –NAP. Its thickness ranges from several metres to ten metres and is related to the number of loam layers present. The average unit thickness is 4 - 6 m. The 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 4, 5, 6). Cryoturbated sand and loam or horizontally-bedded sand with laminae of reworked organic debris overlay the Best Member. The lower and upper boundary of the Best Member are abrupt, the upper boundary may be erosive.

Figure 8 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



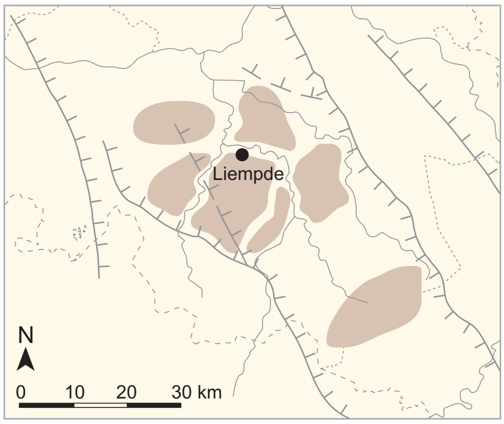


Fig. 7. Areal distribution of deposits of the a. Best Member; and b. Liempde Member in the Roer Valley Graben. *a.* *b.*

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. 9a). 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.

Definition and description of the Liempde Member at the stratotype locality

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 Liempde Member is defined in core Liempde-Groot Duijfhuis (51B0302: 3.66 - 1.95 m below surface; Fig. 6c). 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. 7b). 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 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-grained to medium-grained sand (Fig. 9b; cf. Kuyl & Bisschops, 1969). Palynological and malacological data and the presence of involutions 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 less likely, considering modern-day periglacial environments, where these lakes are shallow and only have a small (less than 2 km) diameter (French, 1996).

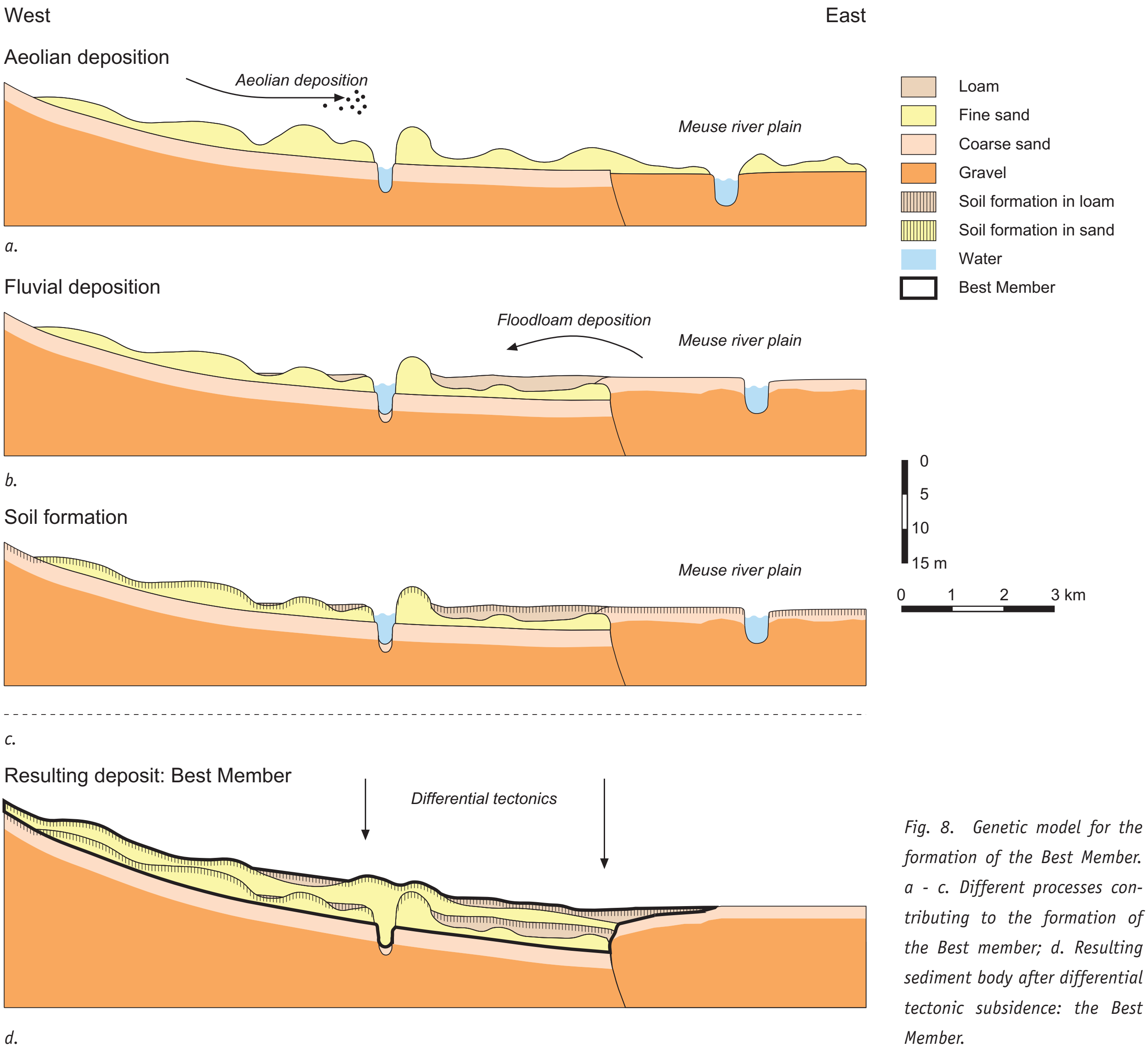


Fig. 8. Genetic model for the formation of the Best Member. a - c. Different processes contributing to the formation of the Best member; d. Resulting sediment body after differential tectonic subsidence: the Best Member.

Implications for the lithostratigraphic framework of the Netherlands

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 Geological Survey of the Netherlands (TNO). It replaces the old lithostratigraphic scheme by Doppert et al. (1975), which was not exclusively based on lithological characteristics and stratigraphic position, but also on bio- and chronostratigraphic criteria, as well as genesis. The new framework and detailed formation descriptions can be found at *www.nitg.tno.nl/nomenclatorShallow/start/start/introduction/index.html*. An overview of the formations is also available in De Mulder et al. (2003). 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) and aeolian dune sands in the Rhine-Meuse floodplain that were formerly considered part of the Kreftenheye Formation (Doppert et al., 1975). Deposits of the former Asten Formation and Eindhoven Formation south of the maximum extent of the Saalian ice sheet (Fig. 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 incor-

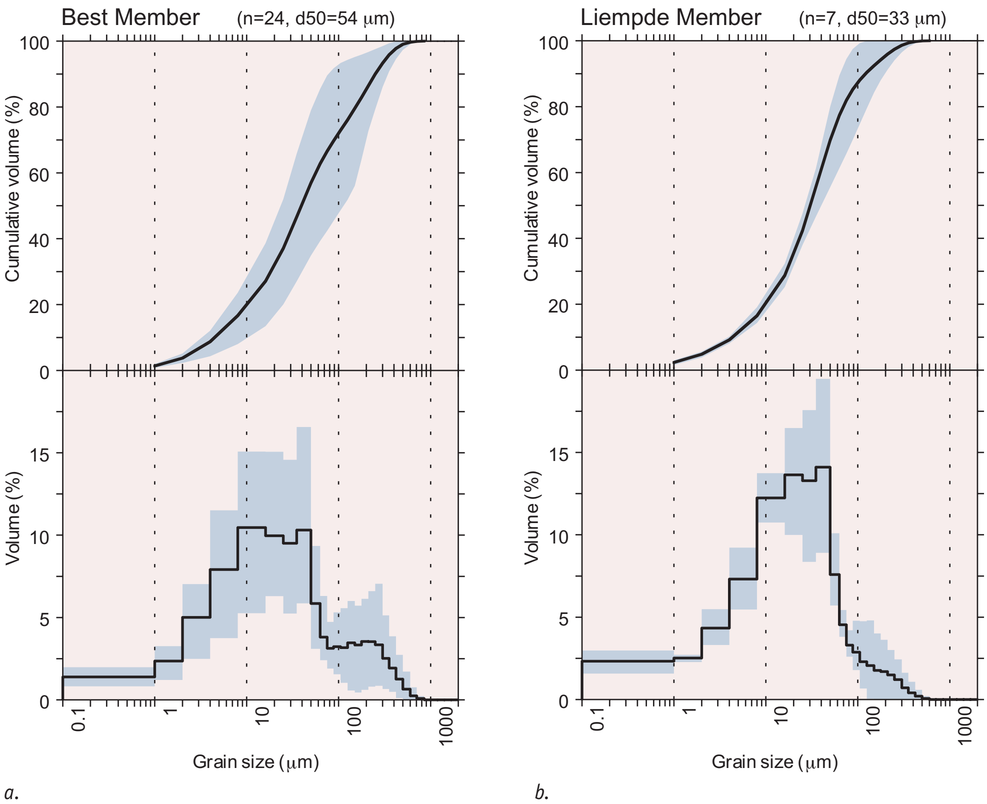


Fig. 9. Average grain-size distribution (below) and average cumulative grain-size distribution (above) of floodloam deposits of a. the Best Member and reworked sandy loess deposits of b. the Liempde Member. The grain-size envelopes encompass the 10 - 90% percentile range for each unit. The number of samples (n) and the median grain size (d50) are indicated above the graphs.

porated in the Drachten Formation, because of their clear stratigraphic position[1]. 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).

In the northern half of the Netherlands, the lower boundary of the Boxtel Formation is generally formed by the Drente Formation that consists of glacial and fluvio-glacial deposits. In the north-eastern part of the Netherlands, the Boxtel Formation may directly overlie fine-grained glacial and lacustroglacial deposits of the Peelo Formation. In the southern Netherlands the lower boundary of the formation is generally formed by coarse-grained deposits of the rivers Rhine and Meuse (Waalre Formation, Sterksel Formation, Kreftenheye Formation and Beegden Formation (De Mulder et al., 2003; TNO, 2007). In western Brabant, the Boxtel Formation overlies fine-grained deposits of the Stramproy Formation. In southern Limburg and the easternmost part of the Netherlands, the lower boundary of the Boxtel Formation is formed by 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. 3) 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 (De Mulder et al., 2003; TNO, 2007). In the eastern and south-eastern Netherlands, the Boxtel Formation is locally covered by peat of the Nieuwkoop Formation.

Subdivision of the Boxtel Formation

The Boxtel Formation contains eight lithostratigraphic members. Table 2 shows a short lithological description, general genetic interpretation and the original literature references for each of these members. Figure 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.

1 It is important to note here that De Mulder et al. (2003) considered the sediments of the Drachten Formation part of the Boxtel Formation, Drachten Member. This viewpoint has in the meantime been abandoned (cf. TNO, 2007).

*Table 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

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. 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

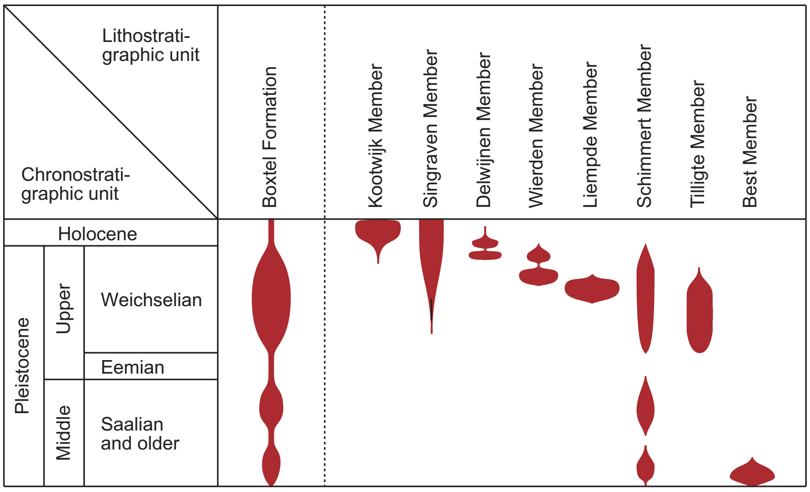


Fig. 10. Approximate chronostratigraphic position of the Boxtel Formation and the eight lithostratigraphic members in the Boxtel Formation. Line thickness represents the relative amount of sediments deposited during a specific time interval.

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.

Conclusions

- Application of the traditional Quaternary lithostratigraphic framework of the Netherlands to the subdivision of locally-derived 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-Quaternary and Upper-Quaternary sand, loam and 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 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 locally-derived 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.

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