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.

<table>
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<th>Y coord</th>
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<td>145.300</td>
<td>404.400</td>
<td>Buurman (1970)</td>
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<td>4</td>
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<tr>
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<td>TNO-NITG (unpublished)</td>
</tr>
<tr>
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<tr>
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<td>373.700</td>
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<td>Van den Toorn (1967)</td>
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* 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-easterly 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, lacustrine-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 palaeoenvironmental 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 Na₄P₂O₇·10H₂O, 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 ⁹⁰Sr/⁹⁰Y 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, elastic 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).
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
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) 14C 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 (Vandenbergh, 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'.

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<th>Sample number</th>
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<th>Equivalent dose (Gy)</th>
<th>Age (ka)</th>
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<td>2-1</td>
<td>1.25</td>
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<td>15.3 ± 0.3</td>
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<td>3.40</td>
<td>180-250</td>
<td>0.93 ± 0.05ᵇ</td>
<td>54 ± 2</td>
<td>58 ± 4</td>
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<td>013118</td>
<td>6-1</td>
<td>5.60</td>
<td>180-250</td>
<td>0.77 ± 0.06ᶜ</td>
<td>88 ± 5</td>
<td>114 ± 12</td>
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<td>013119</td>
<td>7-1</td>
<td>6.20</td>
<td>180-250</td>
<td>0.83 ± 0.05ᵇ</td>
<td>143 ± 13</td>
<td>170 ± 20</td>
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</table>

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.
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 asynchronicity 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.
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.

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