Permafrost and Periglacial Processes, Vol 3: 327–342 (1992)

Weichselian Upper Pleniglacial Aeolian and Ice-cored Morphology in the Southern Netherlands (Noord-Brabant, Groote Peel)

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ABSTRACT

The morphology of the Weichselian Late Pleniglacial land surface in the Groote Peel nature reserve (southern Netherlands) is characterized by numerous circular to oval depressions. The depressions are up to 90 m wide and 3 m deep. Some are surrounded by low (50–100 cm) ridges. Two depressions were selected for detailed study. One, of aeolian origin, is shallow (less than 1 m), the underlying sedimentary units are undisturbed and the ridge surrounding it consists of horizontally bedded aeolian sand. The second, formed by the melting of an ice core, is deeper (3 m) and dissects older units. The ice lens probably formed during the Weichselian Late Pleniglacial. Ice segregation was favoured by a low topographic gradient, impermeable beds in the subsoil and poor drainage. After partial decay of the ice core, a remnant survived during the cold, arid conditions of the Beuningen deflation phase. Final melting of the ice core occurred after deposition of Late Pleniglacial aeolian coversand, at the onset of the Late Glacial climatic amelioration. Palynological analysis indicates that infilling of the ice-core depression started in the Late Glacial Older Dryas and possibly even during Oldest Dryas.

RÉSUMÉ

Dans la réserve naturelle 'Groote Peel' dans le sud des Pays-Bas, la surface pléniglaciaire de la dernière glaciation est caractérisée par de nombreuses dépressions circulaires ou ovales. Les dépressions ont le plus souvent une longueur de 90 m et une profondeur de 3 m au maximum.

Quelques-unes sont entourées par un rampart peu élevé atteignant 50 cm à 100 cm d'élévation. Deux de ces dépressions soigneusement choisies ont été étudiées.

La première, due à la déflation éolienne est peu profonde (moins de 1 m) et les unités sédimentaires sous-jacentes à la cuvette n'ont pas été déformées; la ride qui l'entoure consiste de sables éoliens horizontalement stratifiés. La seconde, formée à la suite de la fusion d'une masse de glace dans le sol, est plus profonde (3 m) et affecte des unités plus anciennes. La lentille de glace a probablement été formée pendant le pléniglaciaire de la fin du Weichselien. La ségrégation de glace a été favorisée par une faible pente, des lits imperméables dans le sous-sol et un mauvais drainage. Après la fusion partielle du noyau de glace, un reste a persisté pendant les périodes froides et arides de la phase de déflation de Beuningen. La fonte totale du noyau de glace s'est produite après le dépôt des sables de couverture de la fin du pléniglaciaire soit au début de l'amélioration climatique tardiglaciaire. Les analyses palynologiques indiquent que le colmatage de la dépression a commencé lors du Dryas ancien et peut-être même pendant le Dryas le plus ancien.

KEY WORDS: Weichselian Pleniglacial   Frost mounds   Ground ice   Aeolian coversands

1045-6740/92/040327-16$13.00

Received 28 August 1991
Accepted 10 December 1991

INTRODUCTION

Frost mound scars from the Weichselian period have frequently been reported from the Netherlands (Maarleveld and Van den Toorn, 1955; Paris *et al.*, 1979; De Gans, 1981; De Gans and Sohl, 1981; Bijlsma and De Lange, 1983; Bohncke *et al.*, 1988; Van der Meulen, 1988). Mostly they are interpreted as pingo scars (De Gans, 1988), but some are attributed to seasonal frost (De Groot *et al.*, 1987). The presence of pingo scars is important, since they allow palaeoclimatic reconstruction. Their formation is restricted to permafrost areas. The closed-system pingos in the present-day periglacial areas of Alaska and northern Canada occur where the mean annual ground surface temperature is about −5 °C or colder, and the mean annual air temperature about −8 °C or colder (Mackay, 1987).

The Groote Peel nature reserve is located in the southern Netherlands. It is situated due west of the Peel Horst in the Central Graben, approximately 27 m above sea level (Figure 1). The Quaternary sequence is about 160 m thick and the upper 25 m consist of fine sands with silty beds of aeolian and local fluvial origin (Twente and Eindhoven Formations). Deeper than 25 m an alternation of coarser-grained aquifers and finer-grained aquicludes is present, formed by the Rhine, Meuse and local rivers (Joosten and Bakker, 1987). The landscape is characterized by a nearly flat to weakly undulating aeolian morphology. This Weichselian morphology was subsequently covered by peat during the Holocene, especially since the Atlantic (Joosten and Bakker, 1987). From the late Middle Ages onward (*c.* A.D. 1400) until 1984 this peat was exploited for fuel and soil improvement (Joosten, 1990) and the fossilized and undisturbed Pleniglacial morphology was exposed to the surface again. Aerial photographs of the region revealed several closed, circular and oval depressions marked by differences in vegetation (Figure 2). According to Joosten and Bakker (1987), Van den Munckhof (1988) and Joosten (1988), these depressions are possibly pingo remnants.

In contrast to the northern and central Nether-

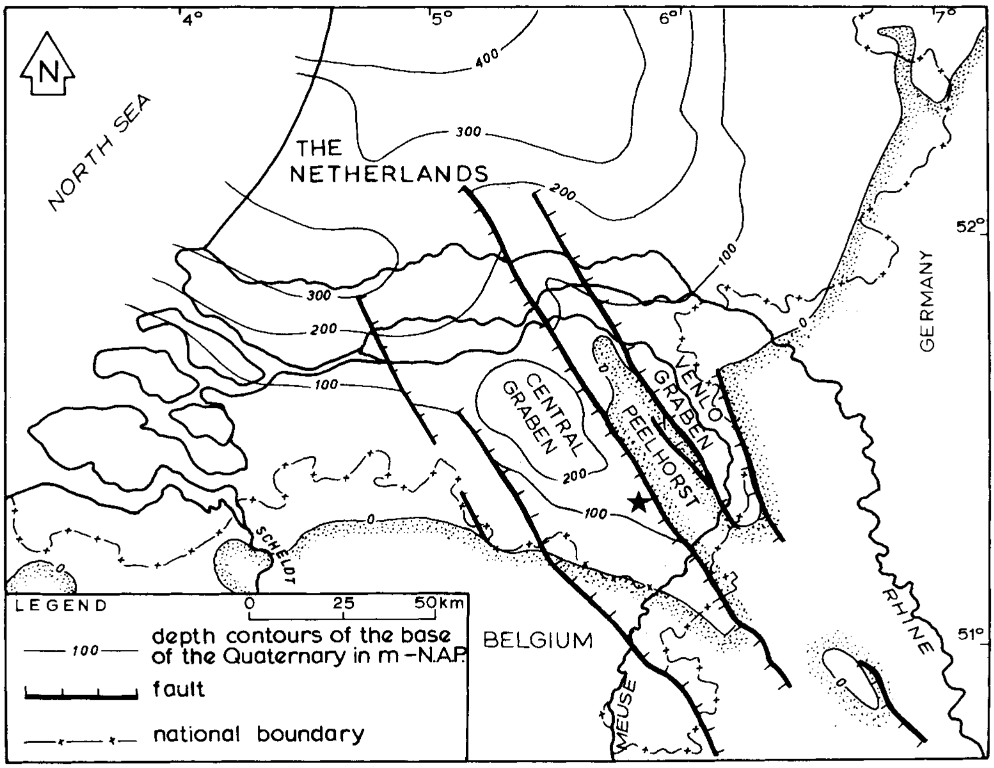

Figure 1 Depth contours of the base of the Quaternary sediments and major tectonic units of the southern North Sea basin (after Zagwijn and Doppert, 1978). Groote Peel indicated by an asterisk.

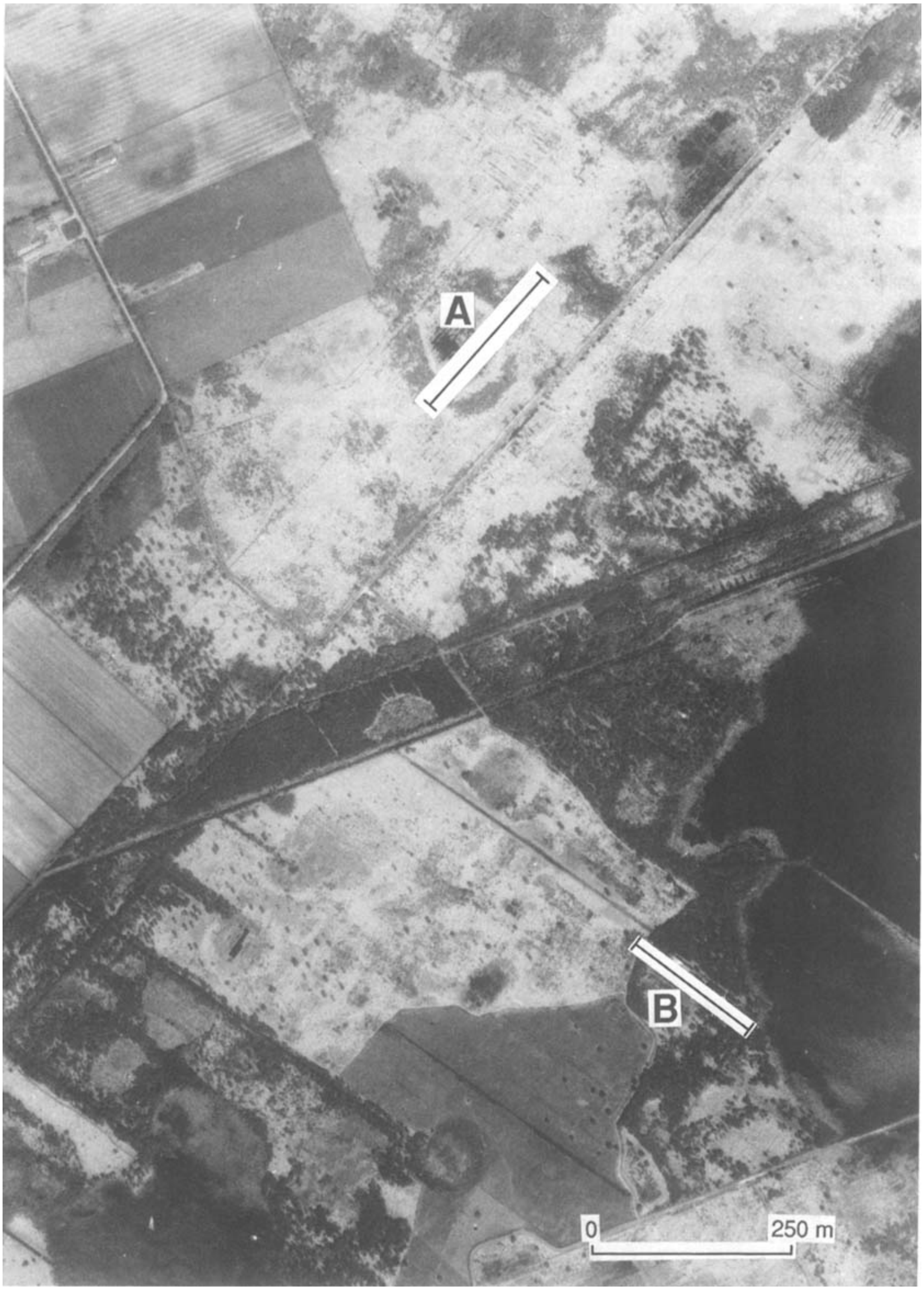

Figure 2 Aerial photograph of the Groote Peel, showing several circular depressions and the investigated sites A and B. Depression B is situated on the western flank of a shallow valley, now filled by a lake. The top of the photo is to the north. Copyright Topografische Dienst, Emmen.

lands (De Gans, 1981; Bohncke *et al.*, 1988), the presence of pingo scars in the southern Netherlands is debatable, since they are scarce and often shallow (Bisschops *et al.*, 1985). Therefore, it was decided to investigate the circular depressions in the Groote Peel. Since the presence of a rampart and the depth of the depression (larger than 1.5–2 m) are used as criteria for pingo recognition (De Gans, 1981, 1988), two depressions were selected for detailed lithological, sedimentological and palynological study (Figure 2). Depression A is surrounded by a low ridge, but appeared to be shallow; depression B does not have a ridge, but contained a rather thick (*c*. 3 m) organic fill.

LITHOSTRATIGRAPHY

The lithostratigraphy of the Groote Peel region is illustrated by two characteristic cross-sections over the depressions A and B (Figure 3). The results are summarized in Figure 4.

Unit 1 consists of moderately sorted, fine to medium sand (150–300 μm; mean, 183 μm), with intercalated greenish grey, sandy silt beds (up to 25 cm thick). Small fining-upward sequences are regularly found. The unit is interpreted as a fluvial deposit, formed by shallow streams and surface runoff. The silt beds developed in stagnant pools or abandoned channels. The stratigraphical position below unit 2 (Asten Formation of Eemian age) places unit 1 within the Eindhoven Formation of Saalian age (Zagwijn and Van Staalduinen, 1975) (Figure 4).

Unit 2 is a humic sand or amorphous peat layer, which is developed in or on top of unit 1. This unit is interpreted as a palaeosol, because of its characteristic soil horizons. The humic to peaty Ah horizon overlies a grey-brown eluviation horizon (E) and a black to bright brown humus illuviation horizon (Bh2 and Bh3). The complete soil profile is 0.95–1.35 m thick. The horizonation indicates that podzolization was the dominant soil-forming process. The thickness of the illuviation horizon

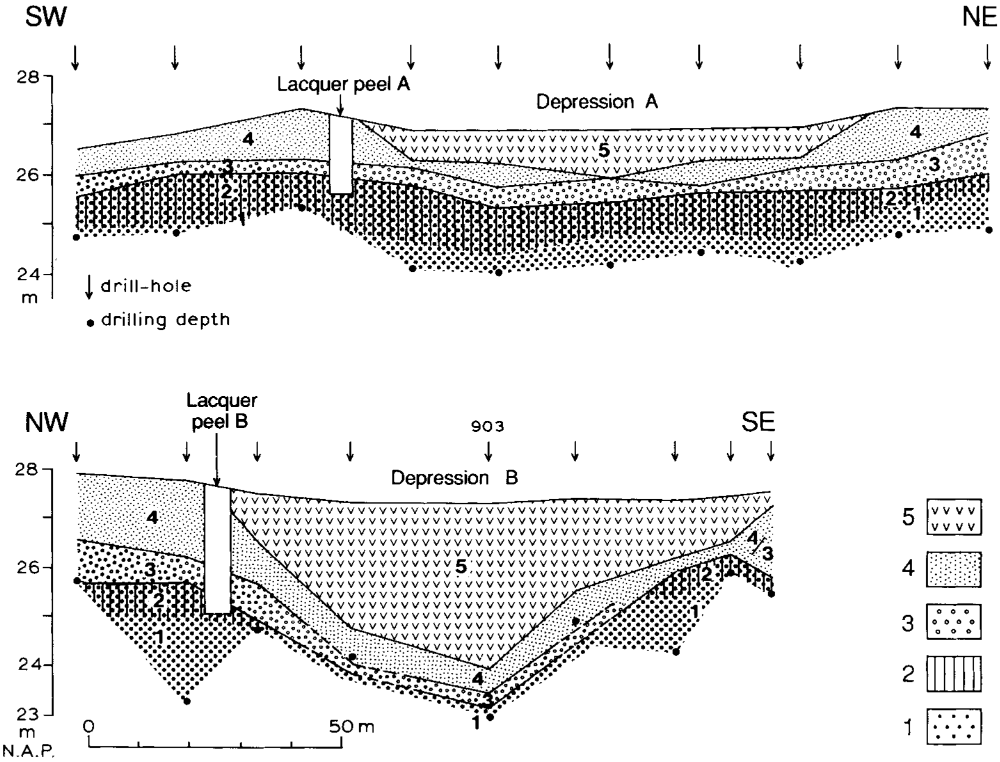

Figure 3 Cross sections over depressions A and B in the Groote Peel (see Figure 2 for location). Core 903 has been taken for pollen analysis. 1 = fine to medium sand; 2 = Eemian palaeosol; 3 = fine sand with Beuningen gravel bed at the top; 4 = fine sand; 5 = peat and gyttja.

Local units	Regional Lithostratigraphy	Chronostratigraphy	Sedimentary and Periglacial processes
5	Griendtsveen Fm.	Holocene Weichselian: Late - Glacial	Peat and soil formation Gyttja deposition Final ice-core decay and lake formation
4	Twente Fm.: Older Coversand II Beuningen Bed	Weichselian: Upper Pleni-Glacial	Coversand deposition on ice-core remnant Cryoplanation of rampart
3	Twente Fm.	Weichselian	Initial ice-core decay and cryoturbation Ice-core growth Superficial runoff
2	Asten Fm.	Eemian	Soil formation
1	Eindhoven Fm.	Saalian	Superficial runoff

Figure 4 Lithostratigraphy, chronostratigraphy and genesis of the Groote Peel region and its depressions.

(40–60 cm) and the local peaty character of the A horizon point to a hydromorphic podzol with periodic water saturation of the soil (FAO: Gleyic Podzol).

The pollen assemblage of the peaty soil is characterized by *Pinus*, *Alnus*, *Corylus*, *Carpinus* and *Quercus*, which is probably equivalent with pollen zone E5 of the Eemian (Zagwijn, 1983). Because of its lithostratigraphic position and age, unit 2 is correlated with the Asten Formation, of which the type locality is defined only 4 km northwest of the investigated site (Zagwijn and Van Staalduinen, 1975).

Unit 3 consists of moderately sorted, fine sand (150–210 μm; mean, 165 μm). Thin silt beds and fining-upward sequences were found locally. Towards the top fine gravel is present and the boundary to unit 4 is often developed as a thin, fine gravel bed. Like unit 1, this unit was probably formed by shallow fluvial systems and surface runoff from the Peel Horst in the east. The more homogeneous beds of fine sand may be of aeolian origin. The widespread gravel bed on top of unit 3, which overlies the cryoturbated sediments of units 1, 2 and 3 (see Figures 7 and 8), is equivalent with the Beuningen gravel bed; a deflation lag of Weichselian Late Pleniglacial age (Van der Hammen and Wijmstra, 1971). Therefore, unit 3 must be formed between the Eemian and the Late Pleniglacial.

Unit 4 is exposed at the surface, except where it is overlain by unit 5. The unit is characterized by moderately sorted, silty fine sand (105–210 μm; mean, 144 μm) with fine-grained laminae of sandy silt. Fine gravel laminae are present in the lower part. The sedimentary structures in the upper part have been destroyed by Holocene soil formation. Because of its stratigraphic position, its vertical homogeneity and lateral continuity and its alternating fine sand–silt lamination, this unit is interpreted as an aeolian deposit (so-called coversands) of Late Pleniglacial age (Vandenberghe, 1985).

Unit 5 is an organic layer up to 3 m thick which is a remnant of the thick peat layer which covered the landscape before excavation. The lower part consists of fine and coarse detrital gyttja, locally with moss beds. Higher up in the sequence occur coarse detrital gyttja and peat. The ecology of the deepest organic fill is described below.

BIOSTRATIGRAPHY OF DEPRESSION B

The palynological study of core 903 provides a minimum age for the formation of depression B (Figures 5 and 6). Moreover, chronostratigraphical time control is provided by a ^{14}C date of a sample taken from a depth of 272–276 cm. The radiocarbon age came to 11 500 $\pm$ 50 years B.P. (GrN-17139). The cross-section (Figure 3) over the depression demonstrates that the base of the depres-

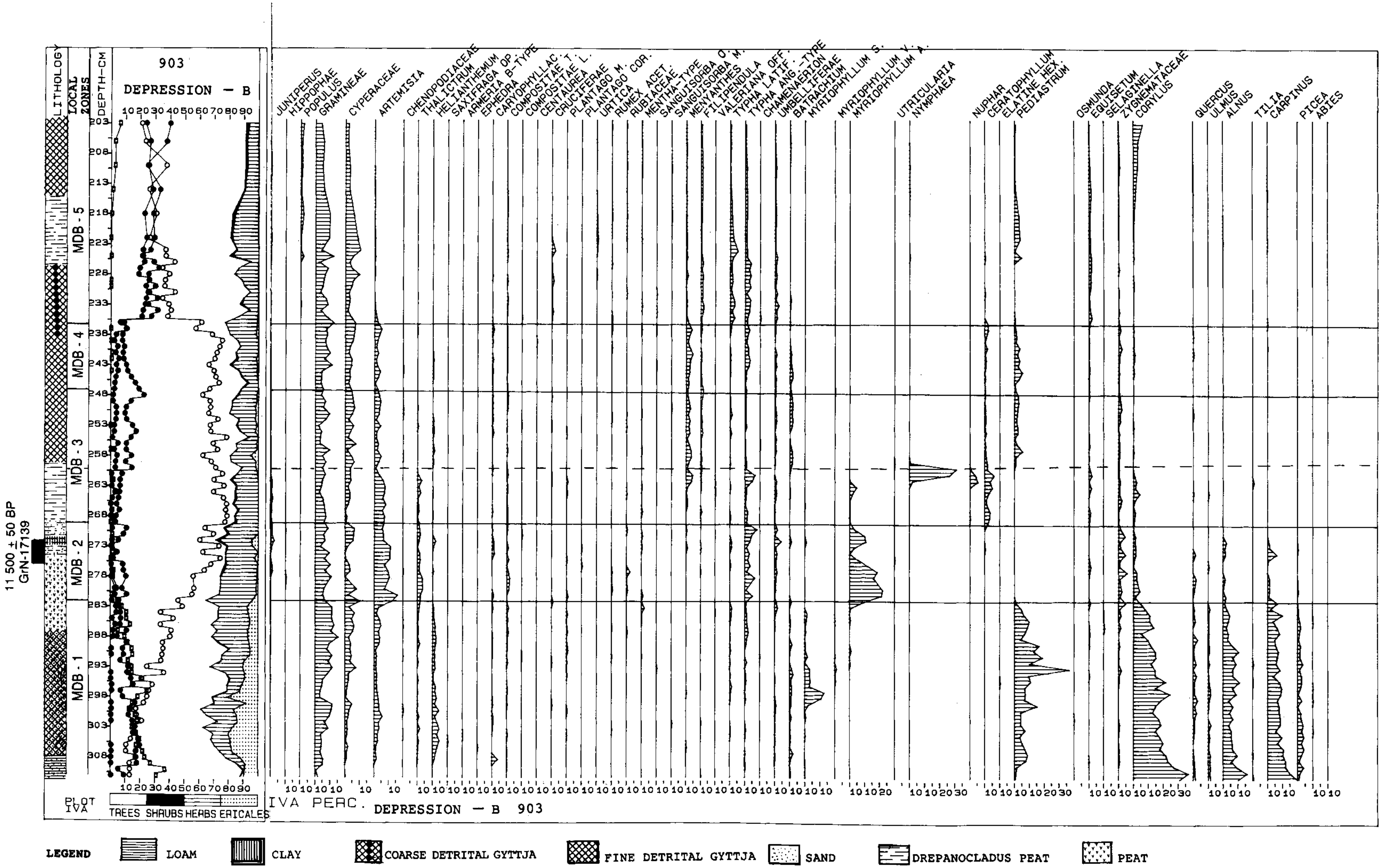

Figure 5 Relative pollen diagram (selected curves) from the organic fill of depression B, core 903.

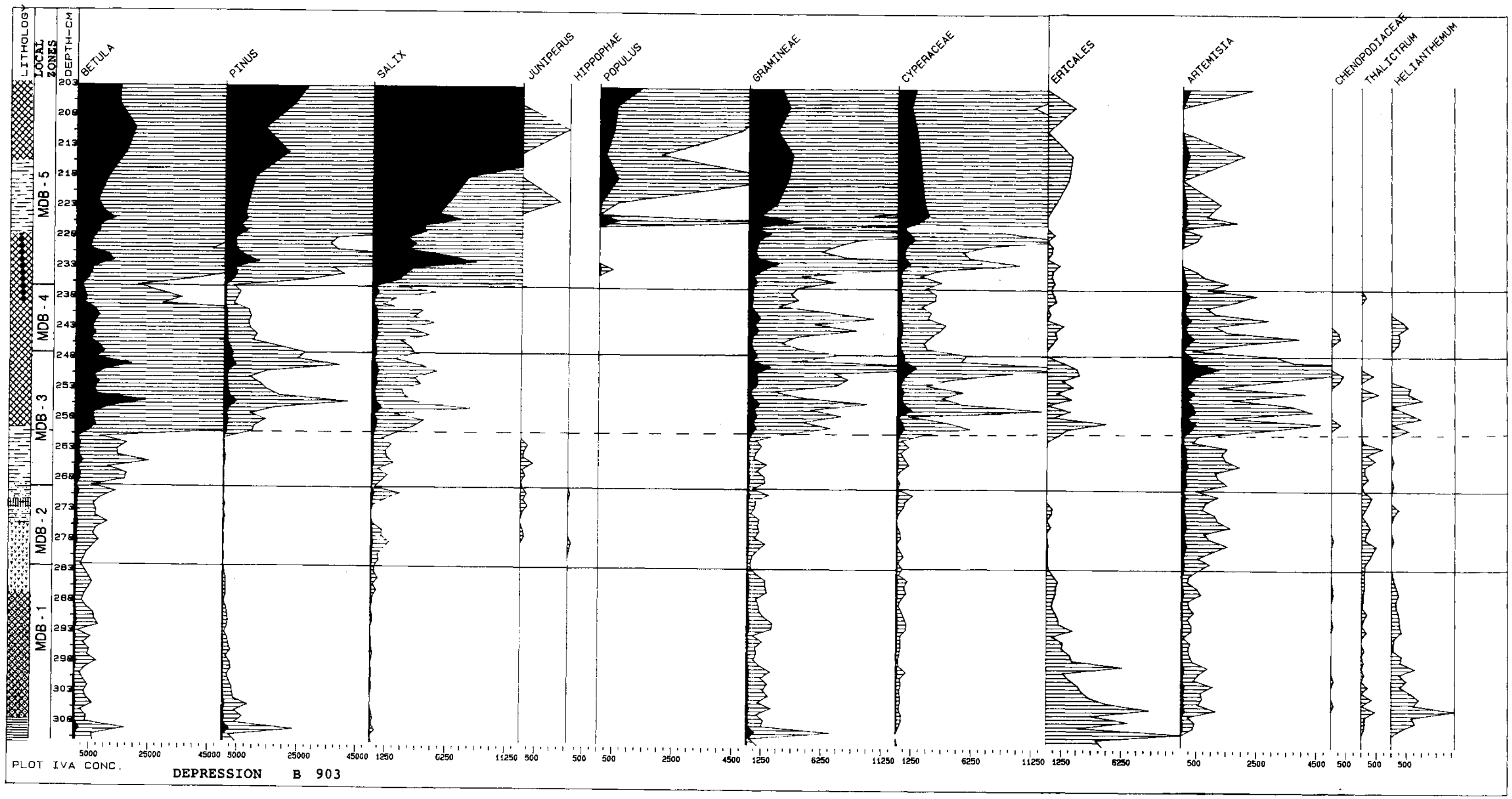

Figure 6 Concentration diagram of a selection of taxa from the organic fill of depression B, core 903.

sion cuts through the palaeosol (Figure 3: unit 2) which, on palynological grounds, has been dated to the Eemian.

Pollen samples were extracted from the core at 1 cm intervals except for the interval 225–203 cm, where a 3 cm interval was chosen. Preparation followed standard techniques (Faegri and Iversen, 1975). Where necessary, a heavy liquid separation was applied. A minimum pollen sum of 300 was used throughout the section and included all tree pollen, Gramineae, Cyperaceae, Ericales, *Artemisia*, *Thalictrum*, Chenopodiaceae and *Helianthemum*.

Local Pollen Zone MDB-1 (312–282 cm)

The basal layers of the infill contain a large amount of reworked pollen, derived from the Eemian palaeosol. *Picea*, *Alnus*, *Corylus*, *Carpinus*, *Quercus*, *Ulmus* and Ericaceae in the bottom samples are all interpreted as reworked taxa. Their relatively high values are thought to be an effect of the very low pollen production of the vegetation surrounding the basin at the time of deposition. This vegetation can be characterized as a rather open heliophilous herb cover with Gramineae, *Artemisia*, *Helianthemum*, *Plantago* spp. intermingled with Cyperaceae on the wetter locations.

The upper boundary of this zone is formed by the abrupt decline in all the reworked taxa. Slightly below this zone boundary a change in the lithology from a sandy peat into a slightly sandy *Drepanocladus* peat has occurred.

Local Pollen Zone MDB-2 (282–269 cm)

In the absence of large quantities of reworked pollen, *Betula* shows a relative increase and subsequently fluctuates. Simultaneously *Artemisia* and *Thalictrum* increase strongly. Shrubs such as *Salix*, *Juniperus* and *Hippophaë* start to spread. *Helianthemum*, which characterized the preceding zone, is almost absent in this zone.

The pollen assemblage of this zone shows marked similarities with the *Salix*, *Betula*, *Artemisia* PAZ (pollen assemblage zone) as defined by Bohncke *et al.* (1988) on the basis of lake sediments from pingo remains in the central and northeastern part of The Netherlands. This PAZ is correlated with the Older Dryas biozone. The increase in *Artemisia*, both relatively and in its concentrations, is thought to indicate the presence of unstable ground conditions. Moreover, *Hippophaë* is a common constituent of the Older Dryas flora.

In the lithology a thin clay layer is present between 272 cm and 273 cm depth, where pollen-analytically a slight increase in reworked taxa is registered (e.g. *Carpinus*, *Alnus*). This phenomenon underlines the prevailing unstable soil conditions during the period involved and probably reflects an inwash of material from the borders of the depression.

Local Pollen Zone MDB-3 (269–247 cm)

At the transition to zone MDB-3 a further spread of *Betula* in the vegetation is registered, accompanied, in the initial phase, by *Juniperus* and *Salix*. Elements of the herbaceous rich vegetation of the preceding zone decline, although *Artemisia* stays firmly present, indicating that the regional vegetation remained rather open. With the spread of the vegetation the slopes of the depression became stabilized and the inwash of sand diminished, as is demonstrated in the lithological column. From 260 cm a gradual rise of *Pinus* is registered but it never reaches dominance over *Betula*. All the aquatic taxa show minimum values during this interval (260–248 cm) except for *Menyanthes* and *Batrachium*. Here, as well, concentration values for all taxa increase firmly, reflecting a considerable decline in the accumulation rate, although the effect of a more dense vegetation cover cannot be excluded. The latter effect can also be concluded from the decline in the *Artemisia* and the nearby absence of *Thalictrum*.

Local Pollen Zone MDB-4 (247–236 cm)

Both *Betula* and *Pinus* show a drop in their concentration curves, although *Betula* remains fairly stable in its relative values. The relative values of the non-arboreal pollen increase somewhat, indicating the presence of a more open herbaceous-rich vegetation during this zone.

Marked changes occur in the top of this zone, where *Pinus* and *Salix* show a sudden increase and *Betula* shows a concomitant drop in its relative values. It is concluded that these sudden changes in the pollen record reflect a period of non-deposition. The lithology at this level changes from a fine detrital gyttja into a coarse detrital gyttja. This lithological change reflects more shallow water conditions at the site, during which periods of non-registration are able to occur.

Local Pollen Zone MDB-5 (236–203 cm)

At the base of this zone a marked increase in the tree pollen at the expense of the herbaceous pollen is registered. *Betula* and *Pinus* are present in almost equally high values, while *Salix* shrubs become increasingly more important in the local vegetation development. *Artemisia* is virtually absent and *Filipendula* becomes an important constituent of the herb layer. A more dense regional vegetation cover is concluded for this zone. *Salix* becomes a dominant species in and surrounding the basin together with *Typha latifolia.*

Interpretation

The first recognizable biozone in the infill of this depression, local zone MDB-2, can be correlated with the Older Dryas. This biostratigraphical evidence conflicts with the radiocarbon age determination. The interval 272–276 cm is dated to 11 500 $\pm$ 50 B.P. and therefore indicates an Allerød age for this level. Nevertheless, the biostratigraphical evidence is so convincing that an Older Dryas age for this zone is concluded. The age determination, some 300 years too young, can possibly be ascribed to younger root penetration during the accumulation of the overlying gyttja and peat. Especially, the local presence of *Salix* and *Typha latifolia* during zone MDB-5 may have contributed to this process.

Local zone MDB-1 cannot be attributed with any accuracy to the known biostratigraphical picture of the Late Glacial, owing to contamination with reworked pollen from the Eemian soil. Nevertheless, the relatively high *Helianthemum* pollen curve in the basal part of this zone simultaneously with a first rise in the *Artemisia* curve may provisionally be correlated with the Oldest Dryas sensu Van der Hammen (1951).

Zone MDB-3 reflects the *Betula* and *Pinus* phase of the Allerød, although *Pinus* does not reach the high values as registered in other sites in the southern Netherlands (Van Leeuwaarden, 1982; Bohncke *et al.*, 1987). Probably the substratum in the Peel area, with a relatively high local groundwater table, makes *Pinus* a weak competitor with *Betula* and *Salix*. Both the latter species prefer a damp, water-saturated, substratum.

The retrogressive development towards a more open herbaceous vegetation during zone MDB-4 is supposed to represent the Younger Dryas period. Between 235 cm and 236 cm a period of non-registration occurs covering the last part of the Younger Dryas and the beginning of the Holocene.

Zone MDB-5 represents the last part of the Preboreal, where *Pinus* gradually rises and *Betula* diminishes. *Corylus* gradually increases in the top part of the section and preludes the Boreal.

With respect to the genesis of depression B, it is concluded that it was formed before 12 000 B.P., being the start of the Older Dryas, local zone MDB-2. It is difficult to assess how much time is involved in the basal zone MDB-1. Pollen-analytically there are some indications for a pre-Bølling start for the accumulation of sediment in the depression. This is some 800 years earlier than in most of the Dutch pingo remnants (Casparie and Van Zeist, 1960; Cleveringa *et al.*, 1977; Paris *et al.*, 1979; Bohncke *et al.*, 1988).

SEDIMENTARY ENVIRONMENTS

The presence of a rampart and the depth of the depression (more than 1.5–2 m) have been used as diagnostic criteria to differentiate pingo scars from depressions with an aeolian genesis (De Gans, 1981, 1988). Ramparts form by mass wasting during pingo decay. The depth criterion is based on the assumption that pingo growth could only occur below the active layer. Because of the large (2 m) cryoturbation structures in the Pleniglacial deposits in the Netherlands, Maarleveld (1976) supposed there to be an active layer thickness of 2 m. However, Vandenberghe (1985) stated that these deep cryoturbations formed during degradation of the top of the permafrost and the active layer therefore may have been less than 2 m. Since depression A only meets the first requirement (presence of a ridge) and depression B only the second one (depth more than 2 m), two pits were dug and lacquer peels were made from the sides, in order to study the sedimentary structures in the ridge and close to the depressions (Figures 7 and 8).

Lacquer peel A (Figure 7) was made in the ridge around depression A, parallel to the ridge crest. Three units are distinguished and the assigned unit numbers are in agreement with the geological cross-sections (Figure 3). The deformed humose sand of unit 2 belongs to the top of the Eemian soil. Fine sand with fine gravel laminae is the dominant sediment in unit 3. The deformed, horizontal lamination in the sand beds is interpreted either as aeolian planebed lamination formed by tractional deposition at wind velocities too high for the existence of ripples (Schwan, 1988) or as low-angle

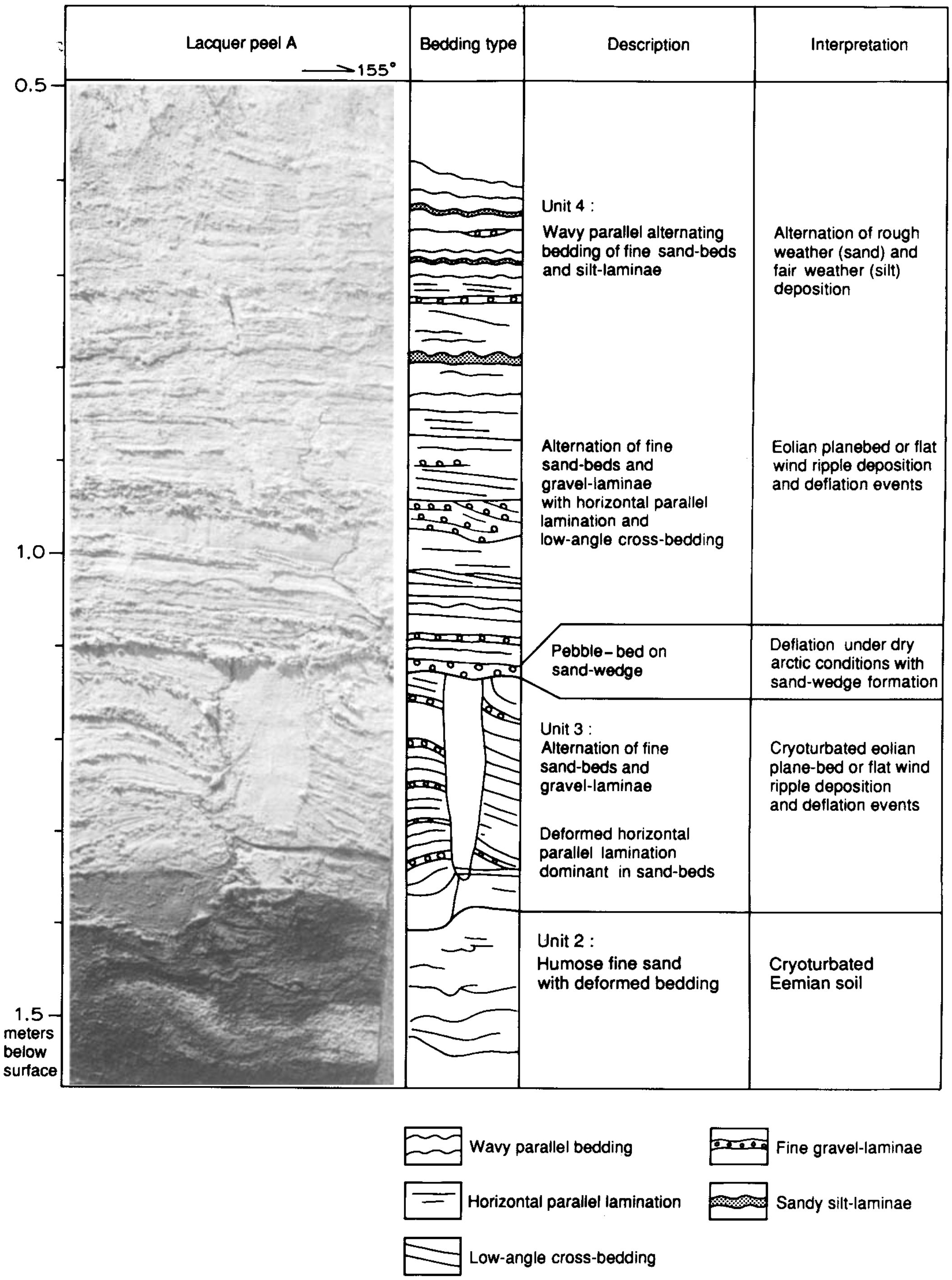

Figure 7 Lacquer peel A from the ridge surrounding depression A (see Figure 3 for location). The ridge (0–1.1 m below the surface) consists of aeolian coversand.

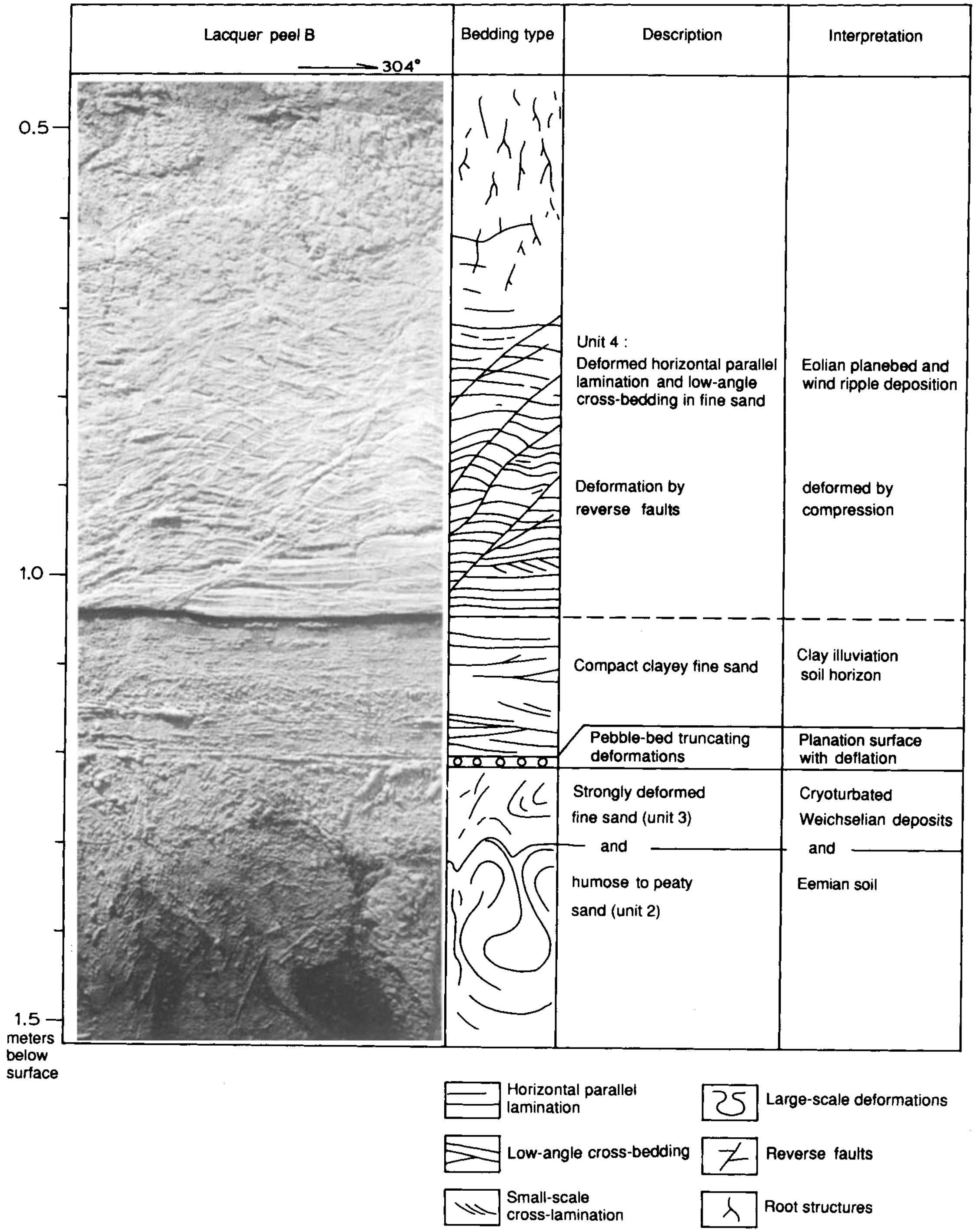

Figure 8 Lacquer peel B close to the deeper depression B (see Figure 3 for location). Faulting of the aeolian coversands (unit 4: 0–1.2 m below the surface) was caused by final melting of the ice core.

climbing ripple cross-lamination by flat wind ripples (subcritically climbing translatent stratification of Hunter, 1977). The gravel laminae represent deflation phases in which gravel was concentrated on the surface as a lag deposit.

The well-developed gravel bed separating units 3 and 4 is interpreted as a deflation lag deposit (Beuningen gravel bed; Van der Hammen and Wijmstra, 1971). It discordantly overlies the deformations in units 2 and 3. The wedge-like structure (Figure 7: 1.1 m below the surface), which is younger than the deformed strata of unit 3, is overlain by the Beuningen gravel bed. The wedge is probably a sand wedge, which formed by annual thermal contraction of the surface in winter and infilling of the crack by wind-blown sand. The sand wedge developed during or shortly before the Beuningen deflation period under the dry and cold conditions that characterize the termination of the Late Pleniglacial (Vandenberghe, 1983). Although sand wedges are found normally in polar permafrost regions (Romanovskij, 1973; Karte, 1979), there are no indications here that permafrost was present during the formation of the Beuningen gravel bed and the associated sand-wedge-like structure.

Horizontal and wavy parallel bedding are the dominant bedding types of unit 4. At the base fine sand beds with horizontal laminations alternate with fine gravel laminae. As in unit 3, this alternation is interpreted as aeolian planebed deposition alternated with deflation. Higher up in unit 4 gravel laminae decrease in number and wavy parallel alternating bedding of fine sand and silt becomes more important. The alternation of fine sandy beds and fine-grained silty laminae in aeolian coversands (unit 4) is explained by cyclic sedimentation (Schwan, 1988). Under conditions with low wind velocities (summer) silt settled from suspension and adhered to the moist, seasonally thawed, surface. In rough weather periods with high wind velocities (winter) sand was transported by stronger winds and deposited in thin sheets with planebed lamination or low-angle climbing ripple cross-lamination.

Lacquer peel B (Figure 8) was made on the western flank of depression B (see Figures 2 and 3 for location). Depression B lacks a ridge, but the locally thick organic fill (3 m) may indicate that it is a pingo scar (De Gans, 1981, 1988).

As in peel A, three units are present and the sedimentary sequence is almost comparable with that of peel A. The top of the Eemian soil (unit 2) and the overlying unit 3 are more intensively cryoturbated than in peel A. These deformations were probably generated during the degradation of the permafrost after the maximum cold of the Late Pleniglacial (Vandenberghe, 1983). The cryoturbation structures are truncated by the Beuningen gravel bed.

Deformed horizontal lamination and low-angle cross-bedding in fine sand are the dominant bedding types in unit 4. These bedding types are formed by aeolian planebed deposition. The local presence of small-scale cross-lamination indicates that deposition of wind ripples occurred as well. The lower silt content in comparison with peel A points to a dry depositional surface. The compact clayey sand bed at the base of unit 4 is a postdepositional phenomenon. A thin section shows the presence of oriented clay in the pores between the sand grains, which is attributed to clay illuviation on top of the lithological contact between units 3 and 4. The clay illuviation process occurred after the Late Pleniglacial deposition of the aeolian sands (unit 4); this is during the Late Glacial and Early Holocene, but before the start of the regional peat formation in the Atlanticum.

GENESIS

Depression A

The sedimentary structures in unit 4 clearly show that the ridge-enclosed depression A (Figures 3 and 7) is an aeolian depositional form. The ridge does not reveal any signs of mass movement which can be associated with pingo decay (see, e.g., Pissart, 1983). Because of the aeolian nature of the ridge, the shallow depth and the near absence of aeolian sand in the depression and the undisturbed presence of the Eemian palaeosol underneath, it is likely that depression A is a blowout structure from which the deflated sand accumulated in the surrounding ridge (De Gans and Cleveringa, 1986). Maarleveld and Van den Toorn (1955) argued that it is difficult to understand how an almost closed ridge surrounding a depression could develop by aeolian activity. Furthermore, a more prominent accumulation at the downwind side and elongation of the deflation hollow would be expected. According to De Gans and Cleveringa (1986), aeolian deposition in the low vegetation surrounding wet places can explain the formation of such circular to oval ridges. Therefore, an aeolian genesis for depression A and its ridge is favoured, especially since positive arguments for the formation of this depression by the degradation of ground ice are lacking. The possibility of the presence of a periglacial frost mound and simultaneous deposition of aeolian sand around it is rejected, because perennial periglacial structures are unknown in the Late Pleniglacial aeolian sands of the Netherlands (Vandenberghe, 1983).

Depression B

Origin

The presence of aeolian sands in and around depression B may give the impression that the depression was formed by deflation during or shortly after the deposition of unit 4. This explanation is rejected for several reasons. First, the depression depth of more than 3 m and the slope angles of the depression margins of up to 13 % are contradictory to the generally weakly undulating morphology of the top of unit 4. Second, it is unlikely that during a period of widespread aeolian accretion locally deep erosion occurred into the Eemian soil and underlying Eindhoven Formation. It might also be argued that depression B resulted from the damming of a small tributary by aeolian deposition. Depression B is indeed situated upstream in a Weichselian valley system, now occupied by an artificial lake (see Figure 2, right of B). However, an additional cross-section, perpendicular to the cross-section in Figure 3, did not reveal a subsurface valley morphology, or a thicker accumulation of aeolian sand.

In contrast to peel A, unit 4 in peel B contains a dense pattern of reverse faults, dipping towards the centre of the depression. The genesis of this faulting is puzzling. Normal faulting would be expected, when the faults were caused by the decay of an underlying ice lens. If the reverse faulting were caused by ice lens growth, then the ice lens developed after the deposition of the Late Pleniglacial aeolian sand (unit 4); this is during the Late Glacial. In that case, ground ice formation during the Younger Dryas, being the coldest phase of the Late Glacial, would be the most likely (cf. Pissart, 1983). This hypothesis is untenable because the infilling of depression B started already during the Older Dryas or even earlier, indicating that the depression already existed during the Younger Dryas. This is in agreement with the fill of most pingo scars in the Netherlands (Casparie and Van Zeist, 1960; Cleveringa *et al.*, 1977; Paris *et al.*, 1979; Bohncke *et al.*, 1988). Therefore, the deformation structures are most likely to be associated with decay of a pre Bølling-age ice lens, after deposition of aeolian sand (unit 4). Possibly the final melting of the ice lens resulted not only in a downward movement with normal faulting, but also in a weak sideward displacement of the sands, leading to reverse faulting.

As stated above, an aeolian genesis for depression B is unlikely. It is suggested, therefore, that depression B was formed by the degradation of an ice core. Ice-cored terrain includes 'not only morphologically distinctive ice-cored features such as pingos, palsas and seasonal frost mounds, but also flat or undulating terrain which is underlain by bodies of massive ice' (Harry, 1988, p. 124). This general term is favoured here, since the source of moisture prior to freezing, the transport mechanism of the water and the ice type are unknown. According to Mackay (1979), pore water expulsion during closed system freezing can give a continuum of ground ice landforms, such as sheets of intrusive ice, conical pingos and bodies of massive segregated ice. On the other hand, a range of ice types may be found within one distinct form such as a pingo. This wide range of forms and formative processes hampers the interpretation of previously ice-cored terrain.

The depression cannot be explained by degradation of a seasonal frost mound (terminology according to Pollard, 1988). Not only is the preservation of seasonal frost mound scars likely to be low, but also a seasonal frost mound scar would have been filled by aeolian sedimentation if a scar formed before or during the deposition of unit 4. If, on the other hand, a seasonal frost mound developed shortly after deposition of unit 4, then the sediments removed from the scar should be found in a surrounding rampart, which is not the case (see Figure 8).

The general topographic slope (0.1–0.3 %) to the northwest and the resulting hydraulic gradient are too small for the development of a classical open-system pingo. This pingo type is normally found in discontinuous permafrost regions with sufficient relief (2–26° in Yukon: Hughes, 1969) to generate the hydraulic gradient for open-system pingo growth by subpermafrost groundwater flow (Mackay, 1987; Pissart, 1988). Likewise, a closed-system pingo genesis requires aggrading permafrost, pore water expulsion and high hydrostatic pressure in an unfrozen former thermokarst lake bottom or alluvial plain. Depression B is indeed situated on the flank of a shallow Weichselian valley, now occupied by an artificial lake (Joosten, 1990; see Figure 2), but lacustrine or substantial fluvial sediments of Weichselian age have not been found around the depression. Therefore, a closed-system pingo origin is not likely.

The general absence of well-established pingo scars in the southern Netherlands may be caused by the smaller thickness of the permafrost in this region in comparison with the northern Netherlands. The melting of thin permafrost below a lake or river floodplain possibly led to the complete disappearance of permafrost and the formation of a so-called through talik (Mackay, 1979). As a consequence, during refreezing of a former lake bottom, an intrapermafrost talik, with associated high pore water pressure needed for closed-system pingo growth, would not develop.

A more general and perhaps less satisfying explanation is that depression B was formed by the decay of an ice lens. The Groote Peel region is characterized by poor drainage. In the Eemian and Holocene extensive peat growth occurred in the area (Asten Formation and Griendtsveen Formation, respectively). The high water table in this poorly drained, nearly flat landscape and the presence of impermeable silt beds in between more permeable sand beds (unit 1) may have stimulated the formation of a large segregation ice lens during the Weichselian Late Pleniglacial permafrost phase.

Degradation

The formation of ground ice and pingos in the Netherlands probably occurred during the maximum cold of the Late Pleniglacial between 25 000 and 18 000 B.P. (Vandenberghe, 1983, 1985; De Gans, 1988) (Figure 4). According to De Gans (1988), the youngest ^{14}C date, obtained from below a rampart, suggests initial pingo collapse after 18 000 B.P. The cryoturbation in the top of unit 3 (see Figure 8) testifies to the melting of the ice-rich top of permafrost, which would have caused inverse density gradients and loading of the soil. At the same time the melting of the upper part of the ice core, which was situated in unit 1, would have led to rampart formation by mass wasting on the flanks of the ice core.

According to Mackay (1988), the ridges of recent, large pingo remnants may exceed 10 m in height. However, from the cross-section (Figure 3) and lacquer peel B (Figure 8) it is clear that part of units 1 and 2 have been removed from depression B, but no rampart is present around the depression. The cryoturbated level is overlain everywhere by the Beuningen gravel bed, which represents an aeolian lag deposit, formed between 18 000 and 14 000 B.P. in an arctic desert environment (Kolstrup, 1980; Vandenberghe, 1985). The discordant truncation of the underlying sediments by the gravel bed indicates erosion of the surface. In our opinion this erosional phase contributed to the destruction and removal of the rampart around depression B. De Gans (1988) also suggested that erosion occurred after the formation of the ramparts, since the ramparts are too small in comparison with the volume of the depressions. This erosion, forming the Beuningen gravel bed, would thus account for the near-absence of ramparts round Pleniglacial pingo scars. This idea is supported by the fact that the Late Glacial frost mound scars of Younger Dryas age, which were not subjected to severe periglacial erosion because of the rapid climatic amelioration at the start of the Holocene, often possess well-developed ramparts (e.g. around the Younger Dryas palsa scars in Belgium—Pissart, 1983; and the Late-Glacial pingo scars in Wales—Watson, 1971).

Because the scar of the Pleniglacial ice core is still visible today, we must assume that a remnant of the ice core persisted during the Beuningen deflation phase. If the ice core had wasted completely around 18 000 B.P., then the scar would have been infilled during the Beuningen deflation phase and afterwards by aeolian deposition. Since this is not the case, final melt of the buried remnant of the ice core took place after the last Pleniglacial aeolian deposition (unit 4), probably due to the rapid temperature rise in the beginning of the Bølling. The Beuningen gravel bed and the aeolian sands, which were deposited on the buried ice core, subsided in the final melting, and formed the bottom of the pond (see Figure 3: core 903). The presence of a buried ice core, which remained unaltered between the initial and final melting, was previously postulated also by Bijlsma and De Lange (1983), who studied a pingo scar in the eastern Netherlands.

This supposed process of partial melting of the ground ice is supported by present-day observations in Alaska (Péwé, 1965) and along the western arctic coast of Canada (Mackay, 1987, 1988). Péwé reported inactive ice wedges of which the tops have melted during post-Wisconsinan time, probably during the climatic optimum of the Holocene between 8 000 and 4 000 years ago, while the lower parts of the ice wedges are still preserved. Mackay states that below a recently collapsed pingo any ice below the maximum thaw depth reached during pingo collapse will still be preserved. Drilling shows that at least 8 m of pingo ice still underlies a pingo ridge. In our opinion it seems possible that a remnant of the ice core persisted below the ice-core scar during the Late Pleniglacial. Final melting at the start of the Bølling led to pond formation and/or deepening, followed by organic infilling.

CONCLUSIONS

The circular depressions in the Groote Peel nature reserve (southern Netherlands) have different origins, in spite of their morphological similarity.

The shallow depression A is an aeolian blow-out structure, which formed during the widespread aeolian sedimentation of the Late Pleniglacial. The low ridge surrounding depression A consists of horizontally bedded aeolian sands of the same period and no evidence is found of mass wasting, such as is seen in ramparts formed by ice-core degradation.

The deeper depression B is interpreted as an ice-cored scar. The low topographic gradient, the presence of silt beds and the Eemian palaeosol result in poor drainage which would have favoured the development of segregation ice in the soil. This formation of ground ice is correlated with the Late Pleniglacial permafrost phase (25 000–18 000 B.P.) in the Netherlands.

Initial degradation of the permafrost and the ice core probably occurred after 18 000 B.P. The sediments were deformed by periglacial loading and a rampart possibly developed around the ice core. A remnant of the ice core persisted in the subsoil during the Beuningen erosional phase (18 000–14 000 B.P.) and during the succeeding deposition, between 14 000 and 12 500 B.P., of the final Late Pleniglacial aeolian coversands.

Final melting of the residual ice core occurred during the climatic amelioration at the start of the Late Glacial and resulted in pond formation. The infilling of the pond started during the Older Dryas or possibly even the Oldest Dryas.

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