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Periglacial environments during the Weichselian Late Glacial in the Maas valley, the Netherlands

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Abstract

The sandpit at Bosscherheide, on the east bank of the Maas (= Meuse), provides a detailed record of Late Weichselian palaeoenvironmental changes. The periglacial fluvial, and aeolian processes recorded in its sediments have been studied by means of pollen, macrobotanical and thin section analyses, sedimentological observations and radiocarbon datings. The data reveal a series of processes involving rapid environmental changes, which determined the termination of the Bølling-Allerød interstadial complex. At the transition from Allerød to Late Dryas, ca 10 800 BP, large-scale floodings and deposition of suspension load took place. Prior to these floodings, a short period with (incipient) permafrost occurred. The aeolian sedimentation, leading to the formation of parabolic dunes, took place mainly between 10 500 and 10 150 BP.

Introduction

Bosscherheide is located in the southern Netherlands on the east bank of the Maas (= Meuse) in an extensive fossil dune area. These dunes are characterized by a general parabolic outline (Fig. 1). As a result of intensive exploitation of gravel and sand in this area, numerous profiles became available that showed the transition from a fluvial to an aeolian environment, dating from the termination of the Weichselian Late Glacial (Fig. 2). The organic infill of an abandoned gully and the lateral extension of this infill over the adjacent terrace, form the top of the fluvial sequence and have been sampled for pollen analyses and dating purposes. Well-developed cryoturbation structures that originated at the fluvial-aeolian transition, demonstrate cold conditions. These cryoturbation structures have been studied both macroscopically and in thin sections. Moreover, the grainsize characteristics of the aeolian sediments have been analyzed.

In the Dutch and German lowland region a palaeosol of Allerød age, the so-called Usselo soil (Van der Hammen 1951), frequently occurs, buried under parabolic dunes of Late Dryas age. This is also the case at Bosscherheide where Late Glacial organic sediments and peat are present at the base of the dune sands. This lithological sequence reveals a series of processes, which had previously been observed at Notsel, in the Mark valley, some 90 km to the west (Vandenberghe et al. 1987, Bohncke et al. 1987), but which could not be dated accurately due to the absence of organic material. Two important features, related to the early Late Dryas climatic deterioration, were described at Notsel: 1) a reactivation of the fluvial regime indicated by the deposition of fluvial loams and sands and 2) the establishment of deep seasonal frost or discontinuous permafrost, witnessed by the occurrence of a structure,

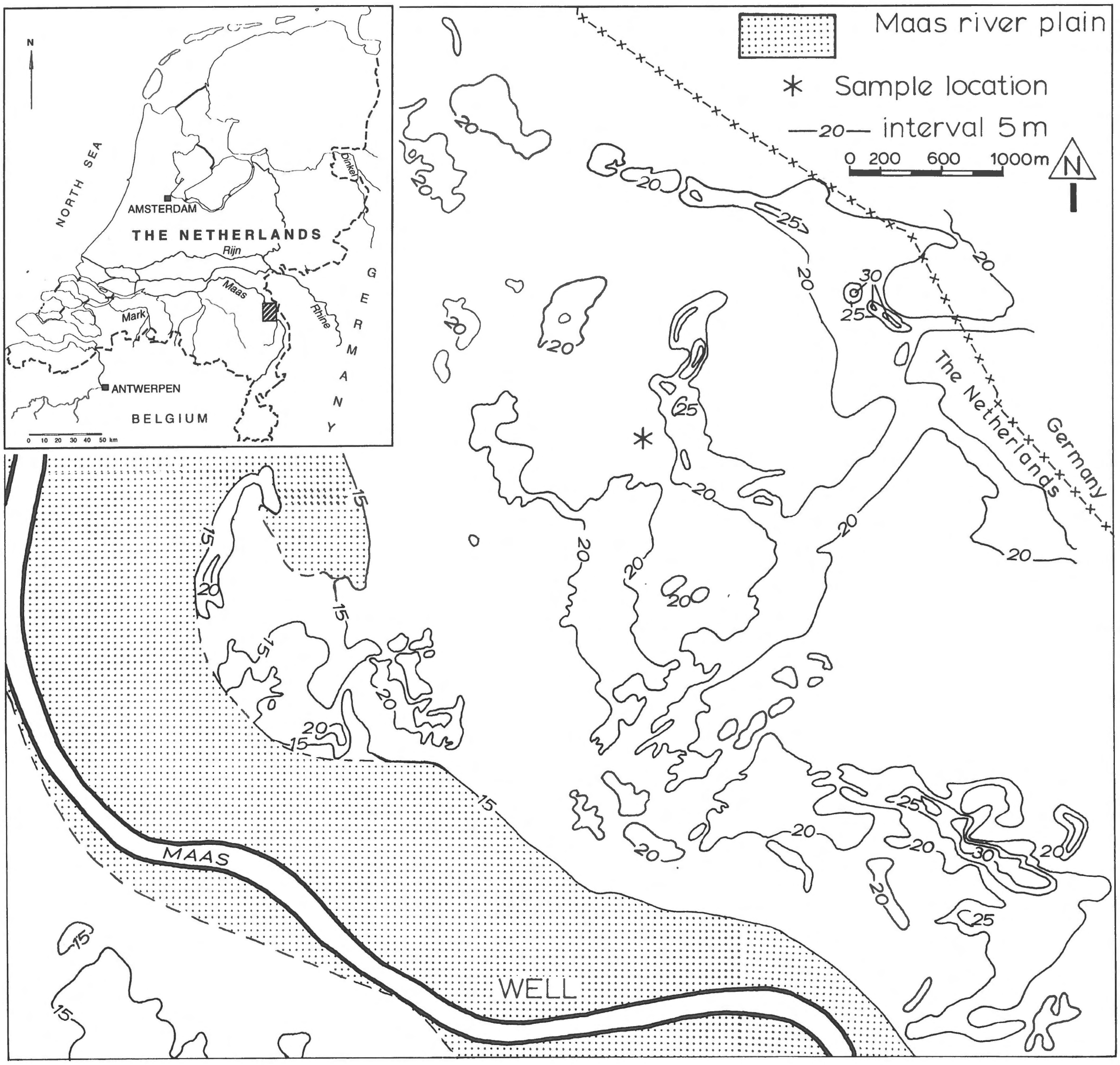


Fig. 1. Location map of the investigation site Bosscherheide showing the Late Dryas parabolic dune complex on the east bank of the Maas. Contours in metres above sealevel.

transitional between an ice-wedge cast and a frost fissure.

Dating of the terrace at Bosscherheide

In the area between Arcen, 8 km south of Bosscherheide, and Bergen, 5 km north of Bosscherheide, the terraces are partly of Rijn (= Rhine) and partly of Maas origin (Zonneveld 1956). At Bosscherheide the substratum of the Late Weichselian fluvial and organic sediments is formed by the Well Sands, which have a Rhine heavy-mineral assemblage. According to Zonneveld (1956, 1958) these coarse and gravelly sands were deposited when the expanding Saalian inland ice forced the Rhine to divert its course in westerly directions; the depression between the terraces of Walbeck and Twisteden (due south of Bosscherheide) would have functioned as the southernmost escape route of the

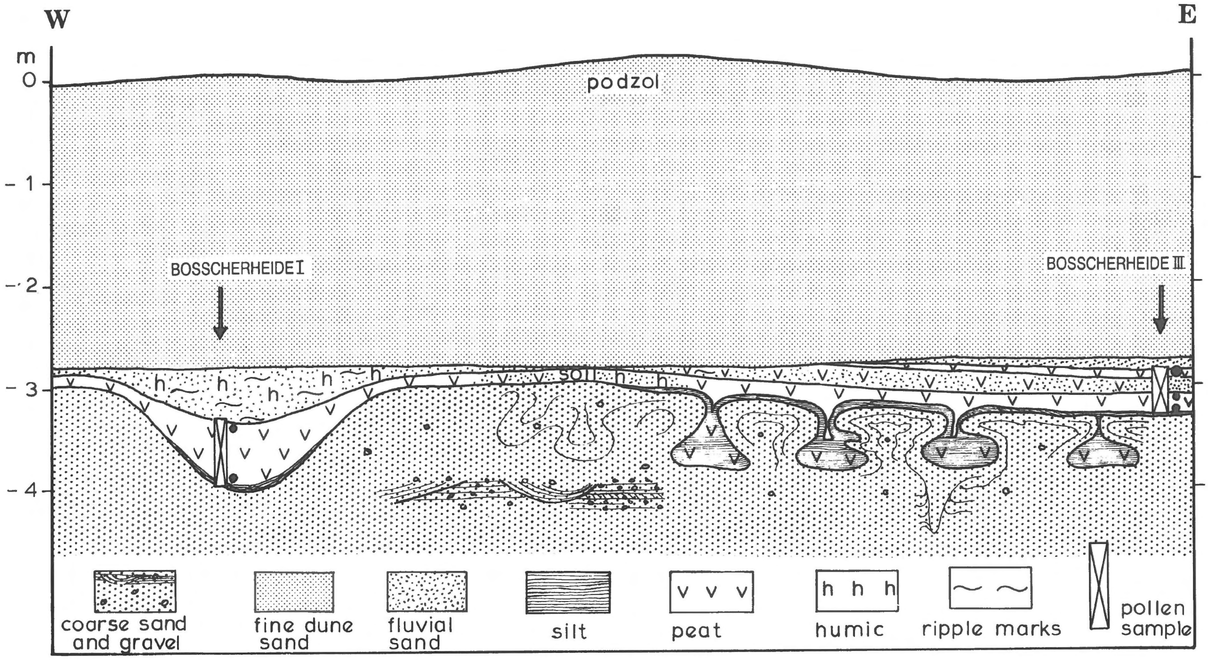


Fig. 2. Schematic profile of the exposures at Bosscherheide showing the location of the pollen samples. The black dots refer to the radiocarbon-dated levels: Bosscherheide I, top GrN 13379, 10 940 ± 60, bottom GrN 13382, 12 110 ± 70; Bosscherheide III: from top to bottom GrN 11568, 10 500 ± 60; GrN 11569, 10 880 ± 50 and GrN 12165, 11 500 ± 50 BP.

Rhine waters. During the Weichselian Middle and Late Pleniglacial, these Rhine deposits have been reworked by a braided river system into the Kreftenheye Formation (Pons 1957, Teunissen 1983).

A dominant feature of this fluvial unit is the rapid alternation of shallow gullies (2–5 m-wide). Many gullies contain horizontal, sharply-bounded sets of sand and gravel. These relatively thin sets often show an internal oblique lamination and may be interpreted as channel bars. Other gullies are filled completely with obliquely laminated sands, caused by lateral accretion. The sedimentary structures point to a high accumulation rate in a multi-channel river system.

This fluvial unit was capped by a grey sandy loam at the time the gullies merged into a single incising channel, transforming in this way the earlier fluvial deposits into a terrace. This terrace forms part of the Lower Maas terrace (cf. Teunissen 1983). In the abandoned gullies, organic sediments started to accumulate. Virtually no time seems to have elapsed between gully abandonment and the first accumulation of organic matter, since aquatic species are abundantly present in the lowermost samples of the infill (Fig. 3).

Stratigraphy, chronology and palaeoenvironment of the fluvial sediments

Four C-14 dates are available from the organic gully fill, and three from the lateral extension of this fill (Table 1). Biostratigraphical information is provided by pollen records, both from the gully (section Bosscherheide I) and the adjacent river plain (section Bosscherheide III). The palaeoenvironmental data are supplemented with a macrofossil diagram of the gully sequence (Fig. 5).

The pollen record of the abandoned gully fill starts with an open heliophilous shrub assemblage, in which *Juniperus* forms the dominant shrub (zone BOH-1). This is followed by a gradual spread of birch wood (zones BOH-2 and BOH-3) as demonstrated by high *Betula* values and a distinct *Betula* peak in the concentration diagram (Figs 3, 4). Subsequently, a herb-rich zone occurs (zone BOH-4),

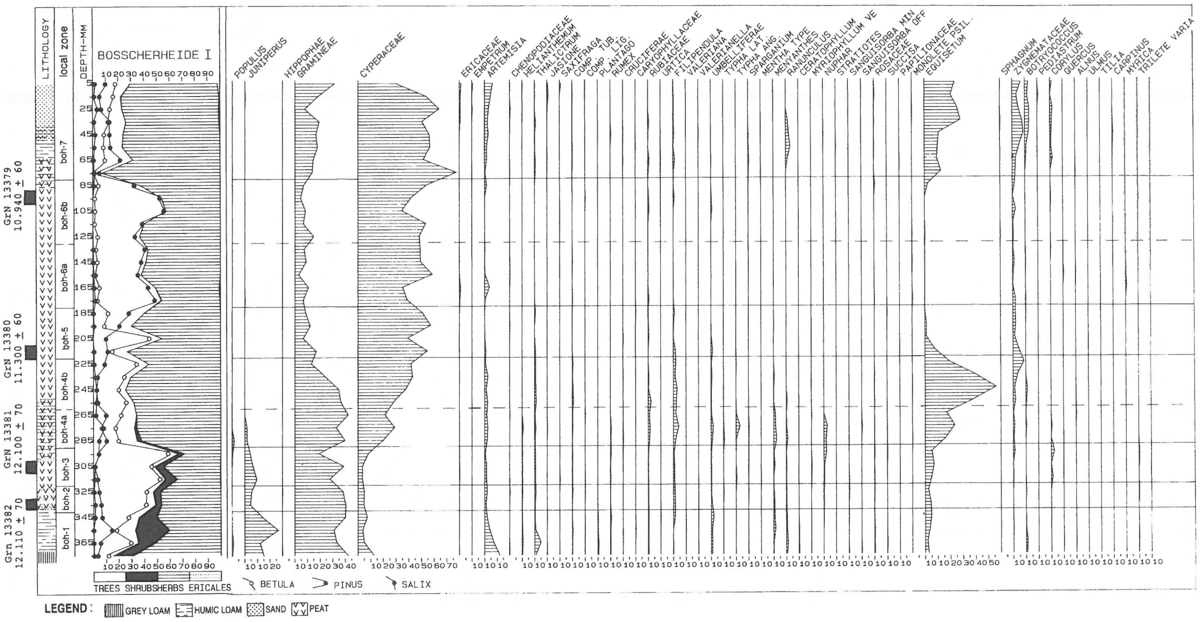


Fig. 3. Relative pollendiagram and radiocarbon ages of section Bosscherheide I representing the organic infill of the abandoned gully as depicted at the left in Fig. 2.

after which a second *Betula* maximum is reached, both in relative and in absolute terms. The vegetational succession finally culminates in a pine forest of the boreal type (zone BOH-6) before a herbaceous-rich vegetation, reflecting a retrogressive vegetational development, returns to the site (zone BOH-7).

On the base of biostratigraphical data and radiocarbon ages, the described succession is assigned to the Late Glacial. The start of the gully infill correlates with the beginning of the Bølling-Allerød interstadial complex.

It is problematic to recognize a biozone which can be attributed to the Early Dryas, as is also the case for the pollen record at Notsel (cf. Bohncke et al. 1987: 80). In agreement with the sequence at Notsel, the Early Dryas is thought to represent a period of minimum humidity. At Bosscherheide such a minimum occurs between 29 and 30 cm depth below the top of section Bosscherheide I (Fig. 3). The subsequent decline in *Betula* values and the concomitant relative increase in herbaceous species (zone BOH-4) is clearly related to local changes in the hydrology, e.g. an expansion of open water and wet habitats. The pollen assemblage of zone BOH-4 resembles biozones identified with the Early Dryas in lake sediments (Iversen 1942, 1954, Van der Hammen 1951), but the palaeohydrological evidence is in conflict with the frequently recorded view that the Early Dryas represents a dry phase in the vegetational development (Ralska-Jasiewiczoa 1966, Cleveringa et al. 1977, Kolstrup 1982, Berglund et al. 1984, Bohncke & Wijmstra 1988). The response of the vegetation to the dry conditions that prevailed during the Early Dryas depends strongly on the geomorphological position of the site under

Table 1. C-14 dates from sections Bosscherheide I (gully infill) and Bosscherheide III (lateral extension of infill over adjacent river plain).

Sample GrN no.	Section	Depth below top of section	C-14 years BP
13379	Bosscherheide I	9–10 cm	10 940 ± 60
13380	Bosscherheide I	21–22 cm	11 300 ± 60
13381	Bosscherheide I	30–31 cm	12 100 ± 70
13382	Bosscherheide I	33–34 cm	12 110 ± 70
11568	Bosscherheide III	2–3 cm	10 500 ± 60
11569	Bosscherheide III	11–12 cm	10 880 ± 50
12165	Bosscherheide III	13–14 cm	11 500 ± 50

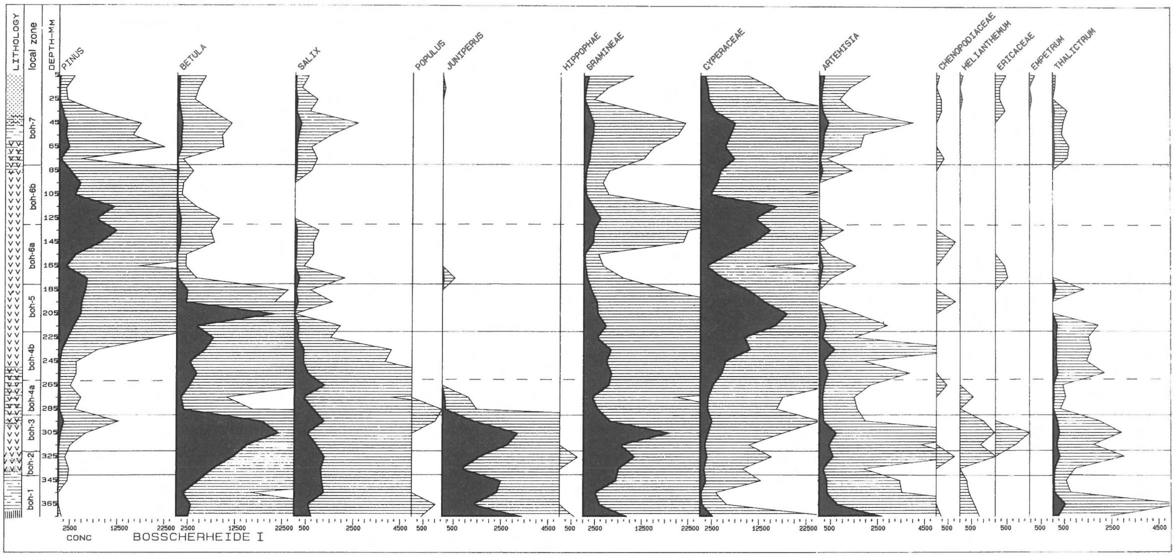


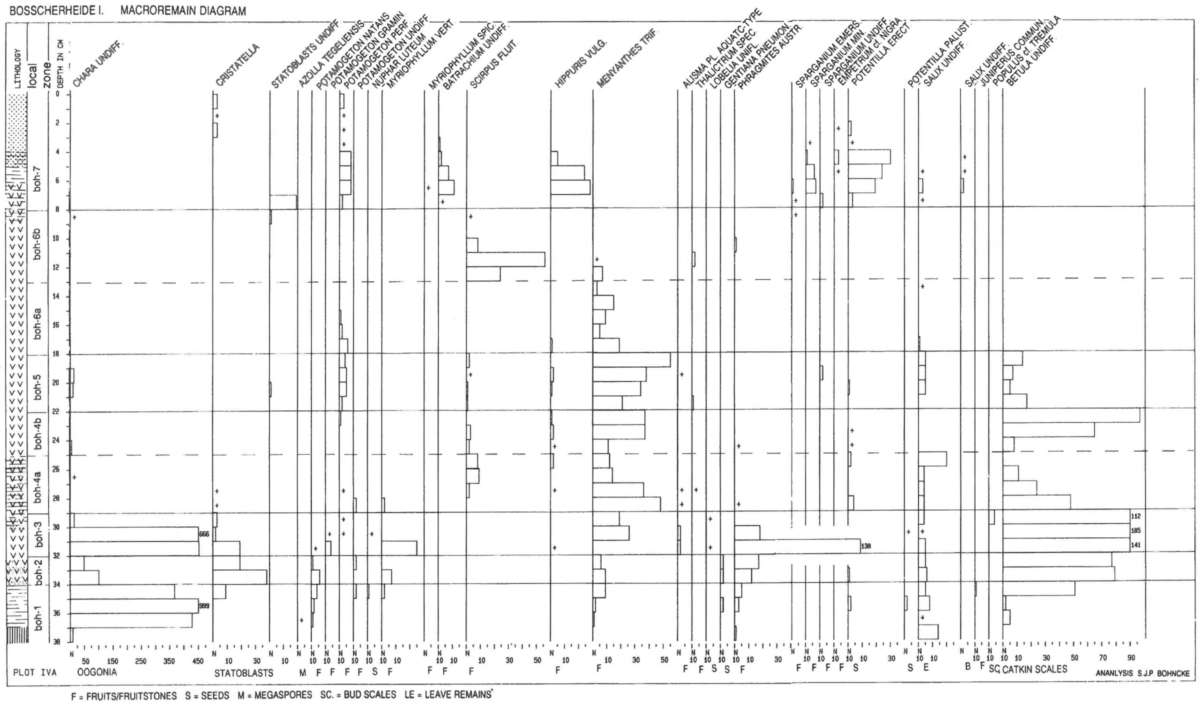
Fig. 4. Pollen concentration diagram of selected taxa from section Bosscherheide I. Black curves indicate ten-times-reduced values.

study. During the Early Dryas, a decline in the lake levels enables a better registration of the marshy fringe zone of a lake, whereas a mire during a dry phase becomes suitable for the establishment of shrubs and trees (Vandenberghe & Bohncke 1985, Bohncke et al. 1987, 1988).

The botanical succession at Bosscherheide has to be evaluated against this background and the first maximum in the *Betula* pollen (29.5 cm) reflects the local establishment of birches close to the gully (cf. Fig. 5). Zone BOH-4 reflects the first wet phase of the Allerød chronozone, which continues into the zones BOH-5 and BOH-6. The sudden decline in the *Pinus* pollen at the transition to zone BOH-7, which coincides with increased wet conditions, occurs also in the backswamps of the Mark valley (Bohncke et al. 1987) and marks the transition to the Late Dryas. Moreover these wet conditions at the Allerød-Late Dryas transition are also met elsewhere in the Netherlands, e.g. section Usselo (Van Geel et al. 1989), section 'de Hamert' (Teunissen 1983) and in the pingo remnants on the Drente plateau and the Veluwe (Bohncke & Wijmstra 1988).

Both radiocarbon dates at the base of section Bosscherheide I, GrN 13381 and GrN 13382, are within one overlapping standard deviation. They derive from within the first *Betula* expansion and should, biostratigraphically, refer to the Bølling zone. The macrobotanical content gives further information concerning the reliability of the provided age determinations. Sample GrN 13381 (12 100 ± 70 BP), at 30–31 cm, derives from a level, where *Betula* remains form the bulk of the macrobotanical assemblage (Fig. 5). The abundant presence of Characeae oogonia indicates water rich in calcium carbonate at the time of deposition. This $CaCO_3$ may have influenced the carbon isotope ratio and possibly caused an aging of the sample. On the other hand, in shallow depressions like the abandoned gully, we may assume that the CO_2 in the water maintained an equilibrium with atmospheric CO_2. The macrofossil assemblage of sample GrN 13382 (12 110 ± 70 BP), at 33–34 cm, contains aquatic species (Characeae, *Myriophyllum verticillatum, Potamogeton natans* and *Menyanthes trifoliata*), while the contribution of terrestrial taxa is considerably lower than in sample GrN 13381. In view of its biostratigraphical position, an aging effect is nevertheless absent or compensated by contamination with younger material from the overlying well-developed *Phragmites* peat (Fig. 5).

The oldest radiocarbon date for a stratigraphically comparable transition from underlying thin sandy loam to organic infill within the region, was established at 12 760 ± 150 BP, in section 'de Hamert' (GrN 4478; Teunissen 1983), due south of Bosscher-



heide on the east bank of the Maas. A similar date has been obtained from the organic infill of an abandoned braided channel at Notsel: 12 600 ± 60 BP (Bohncke et al. 1987). Hence we conclude that sample GrN 13381 provides a more reliable radiocarbon age than the bottom one, GrN 13382. Alternatively, a rapid sedimentation has made it impossible to discriminate between these ages.

Inferred vegetational history of section Bosscherheide I (Figs 3–5)

Zone BOH-1 (38–34 cm)

Lithology: grey loam grading upwards into humus-rich laminated loam

The pollen record of the gully fill starts with an open shrub vegetation dominated by *Betula nana, Salix* spp. *Juniperus* and some *Hippophaë,* while the herbaceous constituent is dominated by Gramineae, *Artemisia, Thalictrum* and some *Helianthemum.* Locally, the abundant Characeae oogonia indicate standing, carbonate-rich, open water. Besides Characeae, *Potamogeton natans* and *Ceratophyllum* cf. *demersum* were present.

Megaspores of *Azolla tegeliensis,* of which the time-stratigraphical occurrence is limited to the Early Pleistocene, stress the fact that reworked material was occasionally deposited during fluvial inundations, which left standing water in the gully. This process led to the deposition of a laminated, humus-rich loam. Moreover, periodical inundations maintained a pioneer vegetation during which *Chara* spp., light-requiring bottom dwellers, thrived.

Zone BOH-2 (34–32 cm)

Lithology: sandy peat

In comparison to zone BOH-1, the deposition of loam is hampered. The pollen assemblage indicates a succession towards an open birch forest. *Juniperus* is gradually shaded out by the spreading of this forest over the Lower Maas terrace.

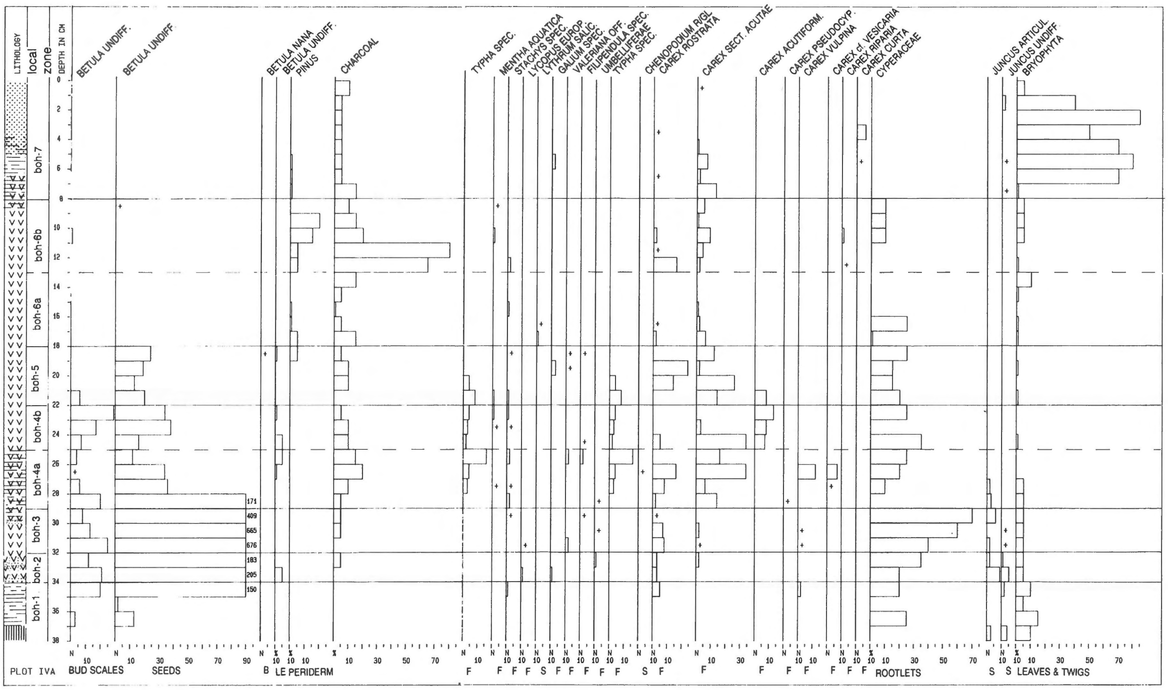


Fig. 5. Macrobotanical diagram of section Bosscherheide I. N = number of individuals; % = percentual contribution to the organic fraction of the analysed sample.

Locally, in the absence of inundations, a hydroseral succession took place. The Characeae are shaded out by aquatic species like *Potamogeton natans, Nuphar luteum, Menyanthes trifoliata* and *Myriophyllum verticillatum.* The succession culminates in a phase dominated by Bryozoa (statoblasts of *Cistatella*) indicating rather shallow water at the site. The declining water budget favoured the spread of *Phragmites australis.* The presence of *Lycopus europaeus* and *Galium* sp. fruits is indicative for a Phragmition phytocoenose.

The change in lithology, from laminated loam to a sandy peat, agrees well with the palaeobotanical changes even though the origin of the sand remains unexplained.

Zone BOH-3 (32–29 cm)

Lithology: loamy peat grading into peat

In this zone the lithology changes back to loamy peat and grades into a peat (30–29 cm). Characeae oogonia increase abruptly, indicating that the water level rose and the initial pioneer situation was restored by fluvial inundations. Other aquatic taxa occurring in this zone are *Myriophyllum verticillatum, Nuphar luteum, Potamogeton gramineus, Potamogeton perfoliatus, Hippuris vulgaris, Menyanthes trifoliata* and *Alisma plantago aquatica.* Fruits of *Phragmites* are abundant and *Phragmites* seems to have been favoured by the increased wetness.

In the topmost centimetre of the zone (30–29 cm), a rapid hydroseral succession with sedges forming the local climax vegetation took place. Unlike in zone BOH-2, a gradual hydroseral succession did not develop, as may be deduced from the absence of aquatic species (29.5 cm). Hence a decline in the groundwater level may be assumed. In the vicinity of the gully *Betula* increased during this episode.

Zone BOH-4 (29–22 cm)

Based on the frequencies of aquatic taxa, and on lithological changes, this zone has been subdivided into two subzones.

Subzone BOH-4a (29–26 cm)

Lithology: slightly loamy peat
Inundations resumed when the deposition of this subzone began and loam became trapped in the peat-forming vegetation. The return to wetter conditions (28.5 cm) favoured the spread of *Salix* in the vicinity of the gully, at the expense of *Betula*. Regionally *Betula* maintained itself.

The contribution of *Betula* remains to the macrobotanical assemblage declines significantly. Instead, both in the macro and in the microfossil record, aquatic species increase (*Myriophyllum verticillatum, Nuphar luteum, Potamogeton perfoliatus, Menyanthes trifoliata, Alisma plantago aquatica, Sparganium* and *Typha* spp.). The increase in *Filipendula* pollen is possibly also related to the spread in wet, water-logged, habitats near the gully.

At the top of this zone an autogenous succession is registered as appears from the increase in sedges (macrofossils) and *Equisetum* (microfossils), and the concomitant decline in obligate aquatics. *Scirpus fluitans, Carex rostrata, Carex* section *Acutae* and *Typha* spp. become the dominant species in and surrounding the gully. The absence of *Phragmites australis* is remarkable.

Subzone BOH-4b (26–22 cm)

Lithology: strongly compressed crumbly peat
Macrobotanically this zone is dominated by Cyperaceae fruits and rootlets and fruits of *Menyanthes*. Fruits of *Hippuris* indicate a continuous supply of carbonate-rich seepage water. These conditions are also favoured by *Menyanthes*. *Typha* probably thrived along the borders of the gully and in waterlogged sites on the interfluvia. It is intermingled with Rubiaceae (probably *Galium* spp.), *Valeriana* and *Filipendula*. Gradually, under steady hydrological conditions, *Betula* started to regain habitats close to the gully. This resulted in relatively higher *Betula* values in the palynological and macrobotanical record. The absence of fluvial inundations is, besides by the lack of loam in the lithology, further illustrated by the decline in *Salix*, both as macro and as microfossil.

Zone BOH-5 (22–18 cm)

Lithology: strongly compressed crumbly peat
A spread of wet habitats and a return to open water conditions in the upper part of this zone is demonstrated by fruitstones of *Potamogeton perfoliatus*, Characeae oogonia and Bryozoa (Fig. 5). *Salix* also reappears in this assemblage and is probably favoured by the return of fluvial inundations. An increase in loam in the peat, as was observed in a comparable horizon at Notsel (Bohncke et al. 1987), could not be observed with the bare eye. Moreover, fruits of *Sparganium* sp. and *Alisma plantago aquatica* are present. *Typha* (according to the pollen record *T. angustifolia*), on the other hand, disappears although its environmental requirements were probably fulfilled. Its disappearance may point to deteriorating climatic conditions. These conditions cannot be found in the interpreted mean July temperature (*T. angustifolia* requires a mean July temperature above 14° C (Kolstrup 1980)), since the mean July temperature, as derived from the Coleoptera assemblage at Notsel (Bohncke et al. 1987), was between 15 and 18° C throughout the Allerød. Hence it is assumed that declining winter temperatures expelled rhizomatose perennials from participating in the vegetational succession (Du Rietz 1965, Bohncke & Wijmstra 1988, Paus 1989). In such conditions a more intensive freeze-thaw cycle, involving the yearly penetration of segregation ice into the sediments, is supposed to break up the rhizomes and thus to prevent reproduction.

Remarkably, the disappearance of *Typha* coincides with the regional spread of *Pinus*, which is regarded as a continental species. Increased continentality possibly implies lower winter temperatures and the subsequent disappearance of rhizomatose perennials such as *Typha angustifolia*. Instead, *Carex* species (*Carex rostrata, Carex* section *Acutae*) seem to expand, but in the upper levels of this subzone indications for drier and more ruderal conditions are found in the presence of *Stachys, Galium* cf. *palustre, Valeriana, Filipendula* and *Lythrum salicaria* near the base of the overlying zone (17 cm).

Zone BOH-6 (18–8 cm)

Lithology: strongly compressed crumbly peat
Although rather uniform in lithology and microfossil content, the macrobotanical composition of this zone requires a subdivision into two subzones.

Subzone BOH-6a (18–13 cm)

With the onset of drier conditions, *Pinus* spread over the Maas terrace. *Betula* pollen values diminish, indicating that stands with *Betula* were replaced by this spreading *Pinus* forest. The dry conditions resulted in poor preservation in the gully and very few taxa are present among the macroremains. Besides peridermal fragments of *Pinus,* fruits of *Lythrum salicaria. Stachys* sp. and *Menyanthes trifoliata* are present. The bulk of the macroremains is formed by rootlets of Cyperaceae.

Subzone BOH-6b (13–8 cm)

Most pronounced in this subzone is the prominent increase in charcoal at its base, which coincides with a decline in the *Pinus* pollen percentage. Probably the *Pinus* forest was damaged by fire incidences so that pollen production or even the entire *Pinus* forest was reduced. Fire also affected the vegetation in the gully as is demonstrated by the numerous charred fruits of *Scirpus (fluitans).* Evidently *Scirpus fluitans* was present before the fire incidences but the charred fruits at this level had a higher preservation possibility. Subsequently the environmental conditions were restored and *Pinus* peridermal remains, sedges and some pleurocarpe mosses again formed the bulk of the macroremain assemblage.

Zone BOH-7 (8–0 cm)

Lithology: loamy peat grading into a sandy humic loam with moss laminae
A sudden drop in the *Pinus* pollen values and a sudden change in lithology mark the base of this zone. The pine forest was replaced by an open shrub vegetation with *Betula (nana)* and *Salix* spp. Heliophilic herbs became relatively frequent (*Artemisia, Thalictrum,* Chenopodiaceae and *Helianthemum*). Reworked pollen (*Corylus, Carpinus, Alnus*) appear in the pollen assemblage and indicate renewed fluvial inundations. Lithologically, this corresponds to the abrupt change from pure to loamy sandy peat.

The return to open water is also indicated by fruits of *Potamogeton perfoliatus, Batrachium* spp. *Hippuris vulgaris, Myriophyllum spicatum, Sparganium emersum* and *Sparganium minimum* and by spores of *Equisetum* and Zygnemataceae algae. Moreover *Salix* cf. *reticulata* bracts and epidermal remains occur. Pleurocarpe mosses form the bulk of the macroremains. The aquatics show high values in the lower samples of this zone in which there is an upward tendency to drier conditions with less open water. Concurrently the loam content diminishes in favour of sand.

The final phase of fluvial activity (Fig. 6).

The lateral extension of the described gully fill over the adjacent terrace has been studied in section Bosscherheide III, 20 m east of Bosscherheide I (Fig. 2). Here the peat deposit with the *Pinus*-phase of the Allerød (zone BOH-6) is overlain by fluvial loam with a herbaceous-rich vegetation (zone BOH-7). More distal from the alluvial plain of the Maas, this Allerød peat changes into a sandy, charcoal-rich, palaeosol, or into remains of this soil, which are traceable in the loam that caps the underlying fluvial series. The fluvial loam overlying the interstadial organic deposits or soil, is a laterally consistent feature. Macrobotanically this loam contains seeds and fruits of aquatic taxa, indicating the return of shallow open water conditions to the site. Moreover the fluvial loam contains pollen of *Clas-*

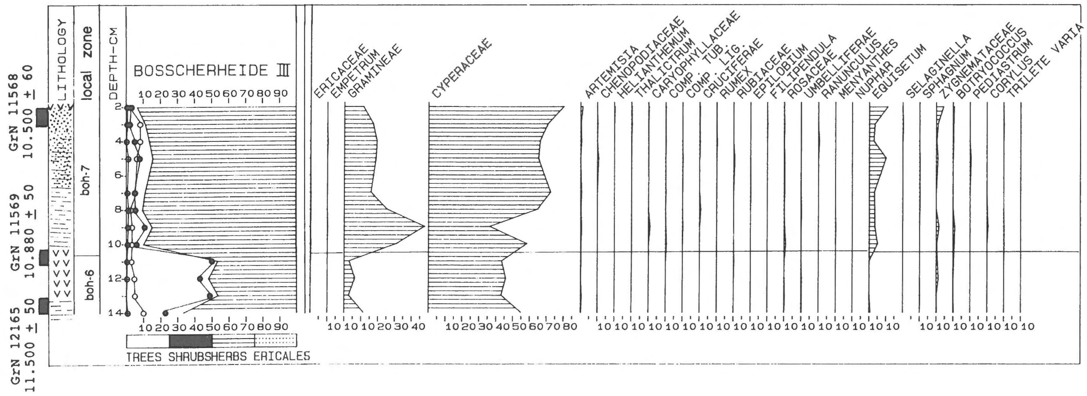


Fig. 6. Relative pollen diagram of selected taxa of section Bosscherheide (BH) III representing the lateral extension of the organic deposit over the river plain as depicted at the right in Fig. 2.

sopollis, derived from the Lower Cretaceous in the former upper course of the Maas. This demonstrates a reactivation of the fluvial system. Similarly, megaspores of *Azolla tegeliensis,* reworked from the underlying Lower Pleistocene, were encountered in the fluvial loams that cap the interstadial Bølling-Allerød peat at Notsel (Bohncke et al. 1987), emphasizing that the reactivation of the fluvial regime had a regional character.

The phase with fluvial inundations is intercalated between the interstadial organic deposits of which the top has been dated in the gully and on the adjacent terrace at 10 940 ± 60 BP and 10 880 ± 50 BP, respectively, and an overlying moss layer dated at 10 500 ± 60 BP. At Notsel the termination of the interstadial peat was dated at 10 970 ± 50 BP and due south of Bosscherheide, Teunissen (1983) obtained a date of 10 870 ± 100 BP for this event. These dates unambiguously put the fluvial loam in the early Late Dryas.

The Bosscherheide profiles show that, towards the very end of the Bølling-Allerød interstadial and prior to the deposition of the fluvial loam, a brief period of (incipient) permafrost followed (see text 'Periglacial features'). During the subsequent large-scale fluvial inundations (see below), the topsoil thawed and well-developed loading structures were formed (Figs 2, 8).

The lateral extension of the loam reflects large-scale floodings and deposition of suspension load in large shallow lakes (Pons & Schelling 1951). Proximal to the alluvial plain of the Maas the sediment series grade into heterogenous, medium-sized sand with small current ripples (Fig. 2), followed by sandy-gyttja and silty clay. The flood sediments show a very distinct bimodal and poorly sorted character (Fig. 7, curve 4) and a high content of very fine sediment (≤ 16 μm). The coarse-grained part shows a similar grain size as the fluvial sediments, while the fine-grained part has a modal value around 30 μm which points to a loessic provenance. The relatively high clay content indicates setting of the suspension load in standing water. Swampy conditions between the subsequent floodings are also confirmed by the high organic content of these samples.

Distally, these fluvial sands were frequently intercalated by thin moss layers and clayey gyttjas and

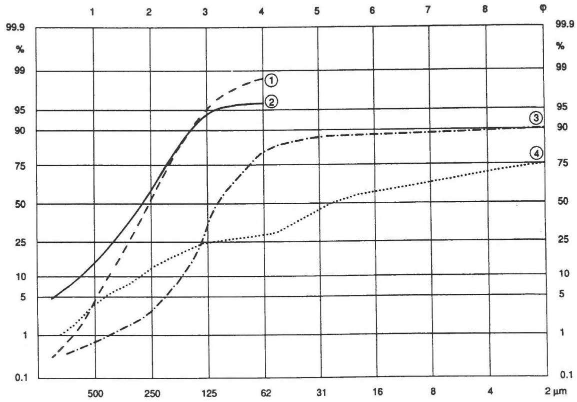


Fig. 7. Cumulative grain-size curves for dune sand at Bosscherheide (1), underlying fluvial sand (2), Pleniglacial coversand (for comparison) (3), and flood sediment (4).

peat. This sedimentological unit represents the end of the fluvial activity at this location. On top of it an aeolian layer of varying thickness and consisting of fine, horizontally and low-angle laminated sands has been deposited.

The start of the aeolian activity at this location could be dated at 10 500 ± 60 BP in the moss layer directly underlying the aeolian deposits (Fig. 2).

Aeolian activity

The Late Dryas dune complex of Bosscherheide is part of a 4 km-wide inland dune area extending ca. 30 km along the east side of the Maas alluvial plain. This area comprises about eight dune complexes characterized by a general parabolic outline with SW-NE orientation. Each of these complexes consists of numerous small, sometimes parabolic ridges (Fig. 1), particularly so on the outer parabolic edges. The steeper outer slope of the parabolic ridges is facing to the northeast, corresponding with a SW-wind.

In order to find out the provenance and transport distance of the dune sands, the underlying fluvial sands have been investigated as a supposed source material. Granulometric comparison shows that the mean grain size of the dune sands and the fluvial sands is very similar; both sands have modal values of 250–300 μm (Fig. 7). This remarkable similarity strongly suggests that the floodplain sediments of the former Maas represent the source material for these dunes. The preservation of the main granulometric properties also points to a very short transport distance. This is confirmed by the fact that the maximum westward extent of the terrace from the site does not exceed 2 km. Nevertheless, slight modifications due to wind transport are observed: better sorting of the aeolian deposits caused by a decreased capacity to transport large grains (above 500 μm) and by the blowing out of very fine sand and silt (below 100 μm). The dunes at Bosscherheide thus may be considered as river dunes in accordance with Pons (1957) and Verbraeck (1974).

As explained above, the maximum age of the Bosscherheide dunes may be fixed at 10 500 BP. A terminus ante quem for the maximum of the aeolian deposition phase can be obtained from a site in the Dinkel valley, in the eastern Netherlands (Van Geel et al. 1981), where in a depression within the inland dunes of Late Dryas age, organic accumulation started shortly before 10 150 ± 90 BP. A radiocarbon-dated peat overlying a similar dune some 200 km to the west of Bosscherheide provided a minimum age for these dunes of 9050 BP (Schwan 1991). Consequently, the dunes date from the later part of the Late Dryas.

Periglacial features

The upper part of the coarse sand and gravel and the lower part of the overlying fine-grained loam and interstadial peat are deformed by a regular pattern of pronounced involutions. The mean amplitude is ca. 60 cm. The updoming parts have a diapir-like form and the sinking parts reach a remarkably constant depth (Fig. 2, Photo 1). Comparison with similar structures allows to interpret the involutions as periglacial load casts (Vandenberghe & Van den Broek 1982; Vandenberghe 1983). The horizontal boundary between the flat-bottomed involutions and the underlying, actually very permeable sediments may be interpreted as the permafrost table at the time of involution. Although the amplitude of the involutions is relatively small in comparison to other cryoturbations in the region (Vandenberghe & Krook 1981, 1985), the regular development of the involutions testifies to their single development and excludes a multiple formation, such as a recurring yearly thawing of soils (French 1986).

The generation of the involutions on top of a degrading frozen subsoil agrees with the presence of two wedge forms just below the involution zone (Fig. 8; Photo 2). These reach a depth of 45 cm and a maximum width of 15 cm. Distinct, but weak upturning of the edges has been observed, but downturning occurs as well. The fill of completely homogenized sand contrasts with the surrounding, distinctly layered sediment structure. The limited depth of these wedges (ca. 1 m from the former surface, i.e. the top of the cryoturbated horizon) and the absence of subsidence features (such as faults and slump structures) raise questions on their in-

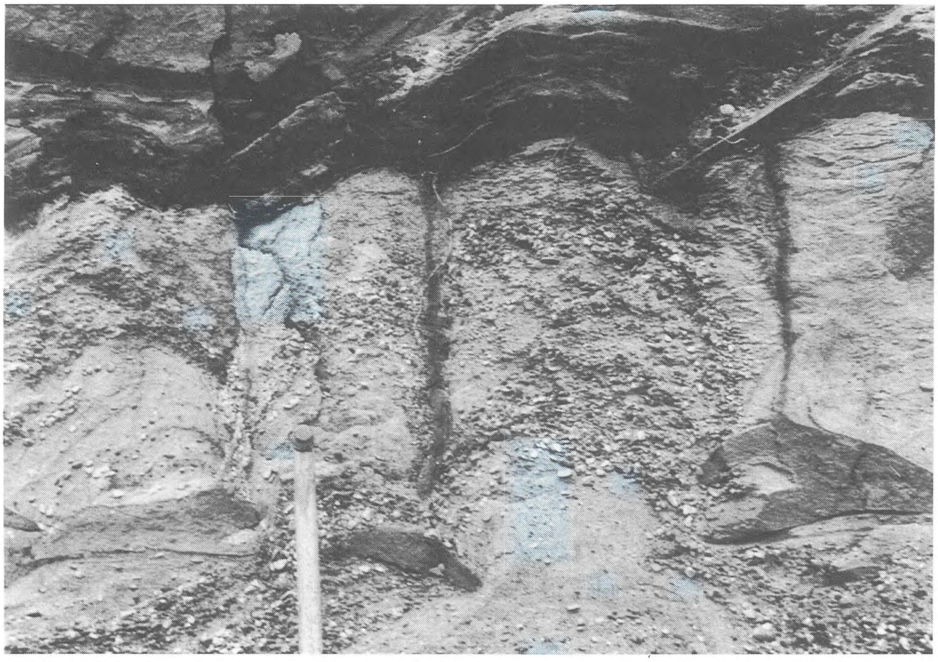


Photo 1. Example of flat-bottomed involutions caused by periglacial loading, early in the Late Dryas, at Bosscherheide (amplitude of structures is 60 cm).

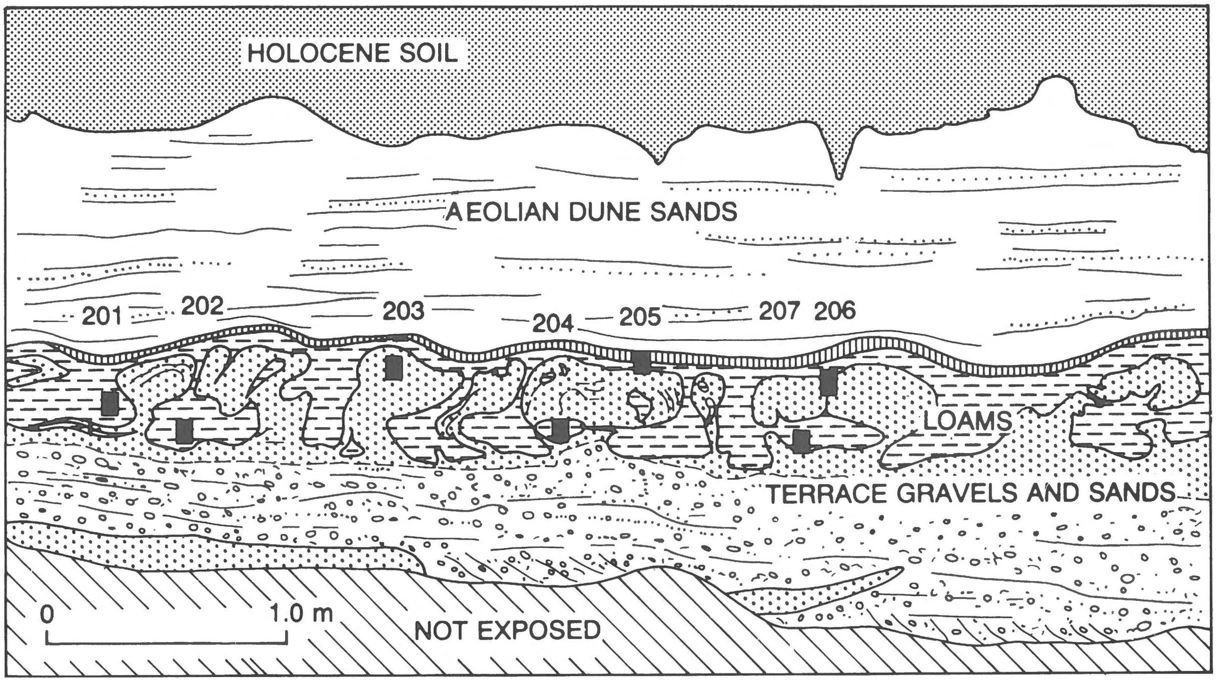


Fig. 8. Detailed section of the cryoturbation level characterized by loams (horizontally hatched) involuted in the Pleniglacial/early Late Glacial coarse fluviatile deposits at Bosscherheide (cf. Fig. 2); Vertically hatched is the Late Dryas fluvial loam. Traces of the Allerød interstadial soil at this location are present in the cryoturbated loam. The micromorphologically analysed thin sections are indicated by ■. Vertical scale equals horizontal scale.

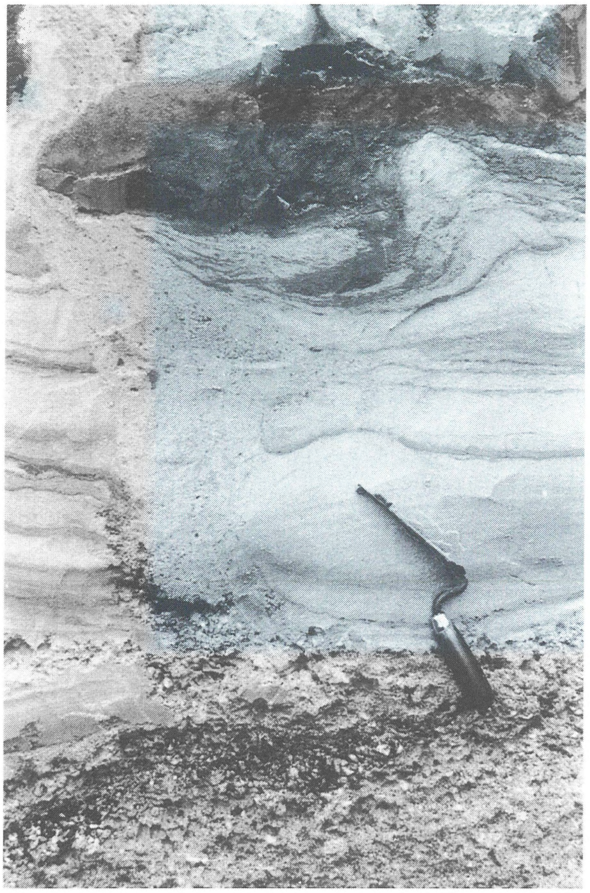


Photo 2. Indistinct wedge form just below the level of strong cryoturbations at Bosscherheide.

terpretation as ice-wedge casts. The absence of vertical lamination and the only weakly upturned edges reject an interpretation as sand-wedge casts. A similar wedge form, of which however the upper part was only slightly disturbed by cryoturbation, has been described by Vandenberghe et al. (1987) from the Mark valley, ca. 90 km to the west. This form could be interpreted either as an intensely developed frost fissure formed during numerous successive winters in a deeply (min. 1 m) seasonally frozen ground, or as an initial ice-wedge cast. In the light of the overlying cryoturbations, the latter interpretation now seems more probable. It is concluded that in this region local permafrost was present for a short time only.

Shortly after the cryoturbation, the soil underwent again an involution process, but the resulting deformations – although regularly developed – have a very small amplitude (max. 30 cm) and a large wavelength (ca. 120 cm; Photo 3). Small slump structures occur on the steeper parts of the undulations. These undulations resemble 'earth hummocks' (cf. Tarnocai & Zoltai 1978) and 'thufurs' (cf. Schunke 1977) which, like the undulations at Bosscherheide, also comprise a peat and a peaty loam layer near their top. It is, however, not clear at present whether the same processes are involved.

In any case, the tops of these hummocks appear to coincide with the centres of the updomed parts of the underlying load-cast, while the depressions are generally situated above the downsinking part of these involutions. The formation of the large involutions had led to a lateral inhomogeneity with a regular lateral alternation of updomed gravel and downward bent loam. Due to the different surface lithologies frost penetration was unequal. The loams in particular were more frost-susceptible than the gravels. Consequently, the gravels gave rise to updoming, while simultaneously the loams moved downward. These movements are in accordance with the results of the experiments by Pissart (1982). Thus this generation of the undulations (hummocks) may be considered as an example of weak cryoturbation by cryostatic pressure (as opposed to the periglacial loading of the underlying cryoturbations).

Radiocarbon analyses of over and underlying peat layers permitted a detailed age determination of the periglacial phenomena. The rate of peat growth in section BH III (see Fig. 2) was calculated and it follows that the peat formation ended at 10 750 ± 50 BP. The cryoturbation took place just after this. An overlying peat layer of 1 to 1.5 cm thickness which is not affected by the cryoturbation is dated at 10 500 ± 50 BP. Assuming the same growth rate, the formation of the latter peat started at ca. 10 550 ± 50 BP. Thus, the degradation of the frozen layer, manifested by the load casting, took place between 10 750 and 10 550 ± 50 BP. Also the later hummocks formed before 10 550 ± 50 BP. The permafrost has to be dated shortly before the cryoturbation. It has to be stressed that all these periglacial phenomena may be formed in a short time.

The thawing of the frozen subsoil is not necessarily the expression of a climatic amelioration. Espe-

Photo 3. Regular pattern of low-amplitude (ca. 35 cm) undulations at Bosscherheide which might be interpreted as earth hummocks (see text 'Periglacial features'). These hummocks developed subsequent to the early Late Dryas cryoturbation phase and prior to 10 500 ± 60 BP, the start of the dune accumulation.

cially in valleys, the talik underneath the river is confined to the lateral migration of the river (Bryant 1983). This process seems likely to have occurred at Bosscherheide since the Maas was nearby.

In the Mark valley, 90 km to the west, a similar thermal contraction wedge has developed and degraded in the same time-interval before the formation of large dunes at the end of the Late Dryas and after deposition of an organic deposit of Bølling-Allerød age (Vandenberghe et al. 1987). The age determinations at Bosscherheide suggest that the coldest phase of the Late Dryas in the Netherlands, expressed by a (discontinuous) permafrost, occurred between 10 800 and 10 500 BP. This is in agreement with the interpretations of frost-mound scars from that period by De Groot et al. (1987) and the observations on a so-called 'Tropfenboden' made by Van der Hammen & Maarleveld (1952). Similarly, the first half of the Late Dryas, between 11 000 and 10 500 BP, appears to have been the period of maximum cold in Britain (Pennington 1975). Its mean annual temperature may be estimated between – 2 and – 5° C at least (cf. Huijzer 1993). Around 10 500 BP, the permafrost disappeared completely and in the later part of the Late Dryas (up to 10 250 BP) the mean annual temperatures increased to about – 1° C.

Cryogenic microfabrics

The cryogenic macrostructures viz. an initial ice-wedge cast and flat-bottomed, regularly developed load-cast involutions, point to permafrost conditions (Fig. 2; Photos 1, 2). The cryoturbation process involved is called here 'periglacial loading', even though this process has been much discussed recently (cf. Vandenberghe 1988; Van Vliet-Lanoë 1991). Preliminary results of a microstructure analysis of the cryoturbations by means of thin sections seem to provide more evidence for the operative process (Huijzer 1993). The section depicted in Fig. 8 was chosen deliberately since the organic interstadial layer, that could have disturbed micromorphological features, was absent.

Micromorphological samples (5 × 8 cm) were selected from the (lower) cryoturbation level where the 'drop soil' (cf. Gullentops & Paulissen 1978) is best developed (Fig. 8). Observed microfabrics include lenticular platy microstructures (thickness 1–2 mm; thin sections 201, 202, 204, 206, 207) and silt cappings (thickness ≤ 550 µm; 203) on coarse (≤ 1800 µm) matrix grains. Lenticular platy microstructures are common in loamy sediments, whereas silt cappings are occasionally found in the fluviatile sands. Primarily, the lenticular platy microstructures are related to ice-segregation processes (Van Vliet-Lanoë 1976, 1985, 1988a, Harris 1985). Silt cappings on platy aggregates or coarser grains are generally related to the vertical translocation of fine material induced by thawing of the (top)soil, and therefore associated with freezing and thawing. Furthermore, physical stress exerted by ice-lens growth (freeze-thaw) presumably led to small-scale (≤ 35 µm) plasma-orientation *in situ* (of fine material) around coarse matrix components, which may be defined as a 'granostriated birefringence fabric' according to Bullock et al. (1985). Such a 'b-fabric' is common in the loamy fluviatile facies (Fig. 6; thin sections 201, 202, 204, 206 and 207). Granostriated b-fabrics, which might be associated with alternating freeze-thaw cycles, have originally been described by Morozova (1965). Optically oriented clay microstructures related to cryogenic processes are also reported by Koniščec et al. (1973), Fox (1983), Miedema (1987) and Pécsi & Morozova (1987). However, (grano)striated b-fabrics are far from diagnostic for periglacial environments, as emphasized by Morozova (1965) and Brewer & Pawluk (1975). Physical pressure and tension, for instance, might also originate from alternating wetting and drying (Green-Kelly & Mackney 1970, Jamagne 1972, Brewer 1976, p. 339). Nevertheless, the association of microfabrics clearly illustrates periglacial conditions, though it does not imply a specific palaeoclimate, as it might develop both in active layers and in seasonally frozen soils.

The analysis of cryogenic macrostructures and microfabrics enables to reconstruct the cryoturbation mechanism. Most relevant is the downward deflection of a lenticular platy microstructure into the neck of a descending loam drop (Fig. 6, 206; Photo 4). This feature is supplemented by the presence of inclined silt cappings in the sandy deposits (Fig. 6, 203). In general, ice segregation is parallel to the ground isotherms and results in lenticular platy microstructures parallel to the soil surface. However, contrasting sediment types such as sand and loam may generate anomalous ground isotherms (Van Vliet-Lanoë 1988a, 1988b). Nevertheless, excessively inclined (30 to 50°) lenticular platy microstructures do not correspond to ice segregation under natural ground isothermal conditions. Consequently, it is concluded that these platy microstructures were already developed prior to the cryoturbation. During the cryoturbation the platy microstructure was apparently (plastically) deformed downwards into the neck, whereas silt cappings were slightly rotated and tilted. Since the observed cryogenic microfabrics are not directly associated with the cryo-

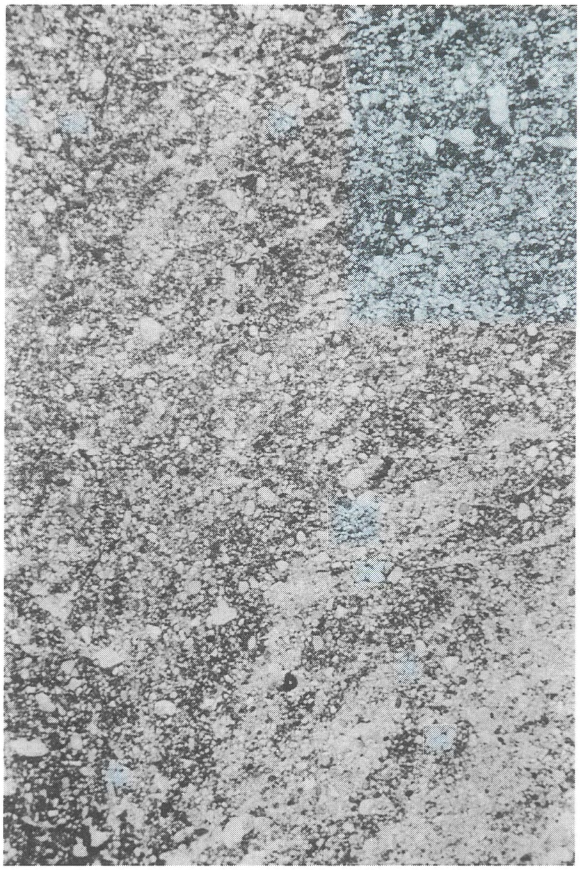


Photo 4. Microphotograph of the upper part of a descending loam drop (cf. Fig. 6, thin section 206) with an inclined lenticular platy microstructure at the right-hand side due to plastic deformation during periglacial load casting (plane polarized light; horizontal frame length is 17 mm). For further explanation see text 'Cryogenic microfabrics'.

turbation process, it may be concluded that periglacial conditions already prevailed prior to the early Late Dryas cryoturbation. Cryogenic microstructures primarily related to the cryoturbation process were not observed and it is concluded that the load casting of the loamy sediment deformed and tilted the internal cryogenic microfabrics. The microfabric analysis confirms that periglacial load casting is the most likely mechanism causing the cryoturbations.

Conclusions

The study of the periglacial, fluvial, limnic and aeolian sediments of the Late Glacial at Bosscherheide leads to the following conclusions:

1) The palaeochannel at Bosscherheide became inactive in the course of the Bølling period, but the terrace on which it is located remained subjected to occasional floodings up to 12 100 ± 70 BP.
2) During the Early Dryas, these floodings ceased and a rapid hydroseral succession, culminating in the establishment of tree birches in the vicinity of the abandoned gully, took place.
3) During the initial phase of the Allerød (ca. 11 800 BP), the fluvial inundations resumed.
4) At ca. 11 300 ± 60 BP, temporary wet conditions are registered at the site. A simultaneous decline in winter temperature seems evident from the palaeobotanical record. This decline presumably involved more intense freeze-thaw incidences.
5) At ca. 10 750 ± 50 BP, large-scale floodings of the terrace and deposition from suspension loads took place, indicating renewed fluvial activity.
6) A maximum in cold conditions, with mean annual temperatures between – 2 and – 5° C, was reached between 10 800 and 10 500 ± 60 BP. The sudden decline in both summer and winter temperatures at the transition to the Late Dryas, resulted in a (discontinuous) permafrost, that degraded subsequently during a phase of overbank deposition. Both macro and microstructure analyses suggest that the associated involutions have been shaped by periglacial load casting.
7) Dry conditions prevailed after 10 500 ± 60 BP and aeolian deposition started to predominate, leading to the formation of parabolic dunes. It is postulated that the bulk of the aeolian sediments were deposited before 10 150 ± 90 BP.

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