

Frost-mound scars and the evolution of a Late Dryas environment (northern Netherlands)

Th. de Groot¹, P. Cleveringa² & B. Klijnstra³

¹*Rijks Geologische Dienst, District West, P.O. Box 5007, 1802 TA Alkmaar, The Netherlands;* ²*Rijks Geologische Dienst, Afdeling Wetenschappelijk Laboratorium, P.O. Box 157, 2000 AD Haarlem, The Netherlands;* ³*Rijks Geologische Dienst, District Noord, Molenweg 21, 8431 HP Oosterwolde, The Netherlands*

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Abstract

Small, oval to round depressions in Weichselian deposits near Scheemda in the northern Netherlands were formed in Late Dryas time. Lithology, sedimentology, and stratigraphic position indicate that these depressions were produced by seasonal frost action followed by thermokarst solution. Comparison with the results of earlier studies on similar features in the northern part of the Netherlands shows that climatic change during the Late Glacial was strongly influenced by local environmental factors.

Introduction

In 1981, during excavations for the construction of the Midwolderbos recreation park near Nieuw Scheemda, the Netherlands (Fig. 1), a number of regular, oval to round depressions were found in a sandy substrate (Figs. 2 and 3).

Both the stratigraphic position of the depressions and the conditions under which they were formed were established by an analysis of the sedimentary structures, the physical properties of the sediments, and the results of palynological and diatom analyses. This paper presents a model of the development stages in relation to the regional geology and the evolution of the local environment.

Geological setting

In the area investigated, the fluvatile deposits from the Tertiary Scheemda Formation (Zagwijn

& Van Staaldunin, 1975) are overlain by Middle-Pleistocene Rhine sediments from the Urk Formation (Fig. 4). During the Elsterian, large parts of both these formations were eroded and covered by deposits from the Peelo Formation. In the area two lithological units can be distinguished: pottery clay (a compact, dark-brown to black meltwater clay) and fine-grained micaceous sands, alternating with clay layers (also considered to be meltwater deposits).

During the last phase of the Saalian glaciation (Ter Wee, 1962), the geomorphology of the region changed drastically by the formation of an ice-pushed ridge involving the older deposits (Fig. 1).

The Weichselian sediments (Twente Formation) are predominantly fine-grained, well-sorted fluvatile and aeolian deposits that accumulated under periglacial conditions. The investigated bowl-to-funnel-shaped depressions (Fig. 5) are situated in the fine sands and silts of this formation, they vary in diameter between 15 cm and about 15 m, are round to slightly oval at the surface (Fig.

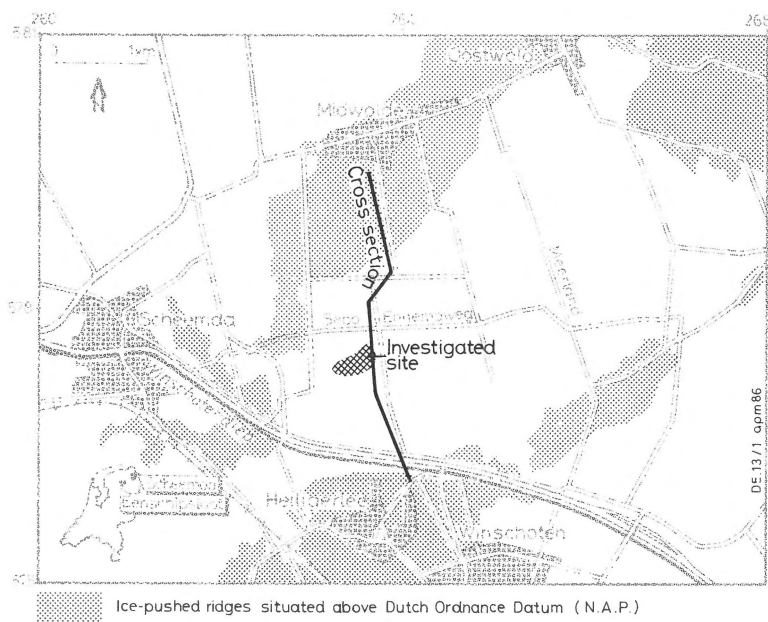


Fig. 1. Locality diagram.

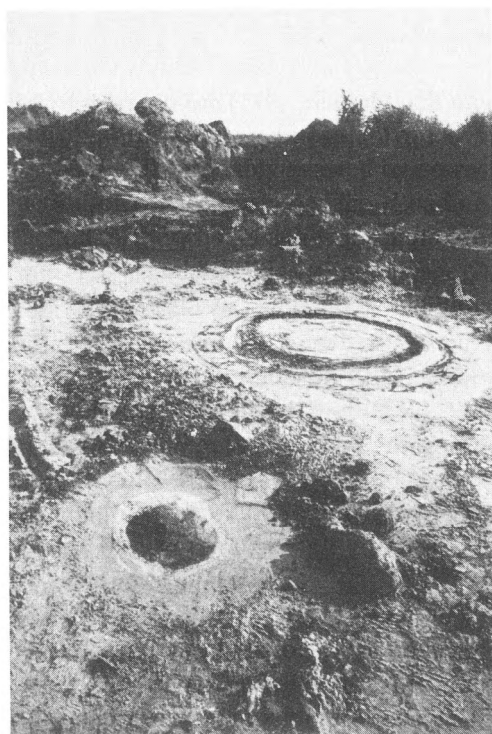


Fig. 2. Plane view of some of the depressions. Diameter of depression in background approximately 1.5 m.

2), and may attain depths of more than 1.50 m.

The investigated site is covered with a thick layer of peat of the Holocene Griendtsveen Formation.

A geological cross-section, based on auger coring is given in Fig. 6.

Lithology and sedimentary structures

The deposits of the area investigated, and especially the material filling the depressions, can be subdivided into the following lithological units (Figs. 5 and 6):

Unit 1

This unit consists of slightly loamy fine- to very fine-grained sand with disseminated coarser components. Mechanical penetration values are high, 4.7 MN/m² (Van der Louw, pers. comm.). Sedimentary structures are poorly defined, mainly even-lamination is exhibited with locally small sets of small scale cross-lamination. Between 10 and

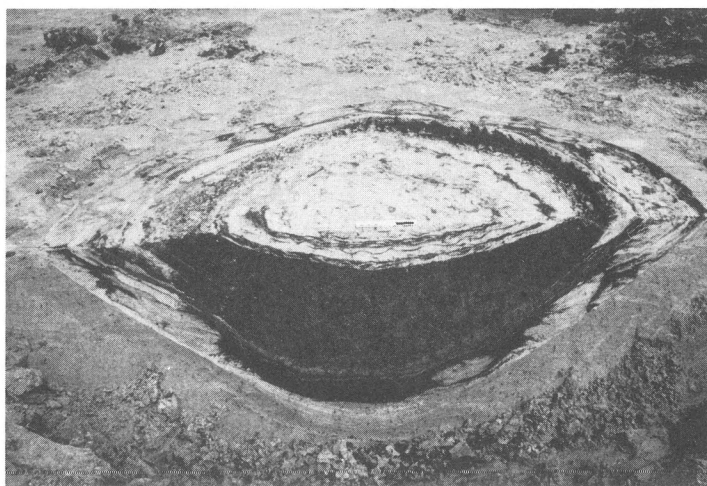


Fig. 3. Photograph of the infilling of a depression. Scale bar in middle of photograph is 15 cm.

100 cm below the top of the unit, the sediments are sometimes deformed by cryoturbation. At the very top, just below unit 2, there are a few microdepressions (diameter <10 cm) that are filled with the same sediments. Lithology, sedimentary structures, and regional geology of the unit indicate a mainly aeolian sedimentation with temporary influxes of streaming water under low-energy conditions.

Unit 2

Unit 2 is a gyttja, with numerous lenses a few centimetres thick and with strings of fine-grained, structureless sand. The lower boundary of the unit as a rule is rather sharp, but there are indications of a gradual increase of organic components and a decrease of the clastic fraction in the lowermost centimetres of the unit. The upper boundary is locally contorted by the load of the overlying units. The unit is restricted to topographical lows and is absent or only developed as a loamy sand layer with organic material on the highs. The sand lenses and strings represent aeolian influxes in the system, whereas the loadcasts indicate that the unit was waterlogged during deposition of the overlying units.

Unit 3

This unit can be subdivided into two subunits of which 3a is restricted to the depressions.

Subunit 3a consists of coarse-grained sand and gravel with sometimes chaotically distributed gyttja lumps in a fining-upward sequence. Even-lamination is the dominant internal structure. Slump structures are common on the slopes of the larger depressions. The subunit does not occur in the smaller depressions (diameter <50 cm).

Subunit 3b is a gyttja, that is well-developed inside the depressions, but is at most 10 cm thick outside. In some depressions the subunit is markedly two-fold with a lower, darker gyttja resembling that of unit 2, and a lighter gyttja on top. Inside the depressions, and only in the higher gyttja, there are evenly laminated, well-sorted, fine-grained sand bodies, that wedge-out toward the centre, and interfinger with the gyttja. Secondary slumping is locally developed as a wavy pattern or it produced separate slump bodies. The lithology of the sand wedges indicates an aeolian origin, whereas later slumps developed in a water-saturated environment.

Chronostratigraphy				Lithostratigraphy		
QUATERNARY	HOLOCENE				SINGRAVEN & WESTL.F.	GRIENDTSV. F.
	PLEISTOCENE	Upper	WEICHSELIAN	LATE	LATE GLACIAL	TWENTE FORMATION
				MIDDLE	PLENI GLACIAL	
				EARLY	EARLY GLACIAL	
			EEMIAN			
		Middle	SAALIAN			DRENTE FORMATION
			HOLSTEINIAN			EINDHOVEN FORMATION
	ELSTERIAN			PEELO FORMATION		
	CROMERIAN			URK I FORMATION		
	Lower	BAVELIAN				
		MENAPIAN				
		WAALIAN				
		EBURONIAN				
		TIGLIAN				
		PRAETIGLIAN				
TERTIARY	PLIOCENE	UPPER (REUVERIAN)			SCHEEMDA FORMATION	
		LOWER (BRUNSSUMIAN)				

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Fig. 4. Chrono- and lithostratigraphy of the northern Netherlands after Zagwijn & Van Staaldin, 1975.

Unit 4

This unit can also be subdivided into two subunits.

Subunit 4a is a fine-grained sand with an increasing clay and a decreasing organic-matter content toward the top. It exhibits moderate mechanical penetration values 2 MN/m² (Van der Louw, pers. comm.). In places the subunit shows a marked cyclic sedimentation pattern built up by asymmetrical wave-ripple trains.

Each cycle begins predominantly clastic, with little clay and organic material draping the ripple

trains. Upwards, the organic-matter and clay contents increase gradually, culminating in a thin (a few centimetres thick) dark clay layer. The wave-ripple trains have an average wave length of 10 cm, and ripple height of 1 cm. Locally, the subunit is only developed as an evenly laminated sand layer a few decimetres thick. Outside the depressions the subunit can be load-cast into the underlying deposits. Lithology and regional geology indicate an aeolian origin of the sandy component of the subunit, later reworked in shallow water-bodies, probably under seasonal influence.

Subunit 4b is a heavy, micaceous clay, with an average thickness of a few decimetres, that is locally absent or developed as a clayey-sand layer. The lithology is very similar to that of the Elsterian pottery clay. The subunit must therefore represent a local erosion product derived from the nearby ice-pushed ridge.

Unit 5

This unit consists of fine-grained, moderately sorted sand with poorly developed sedimentary structures, probably even-lamination. This unit is well-known in the Netherlands as an aeolian cover-sand.

Unit 6

This thick peat layer covers the entire investigated area, but will not be further discussed.

In short, the following sedimentary evolution can be observed:

- increased aeolian activity from unit 2 to 5;
- water-dominated processes under low-energy conditions (units 1 and 4);
- increasing loam/clay contents from unit 3 to unit 4 coupled to decreasing organic-matter contents.

When considering the conditions of depression development the following points, within and without the depressions, are of particular interest:

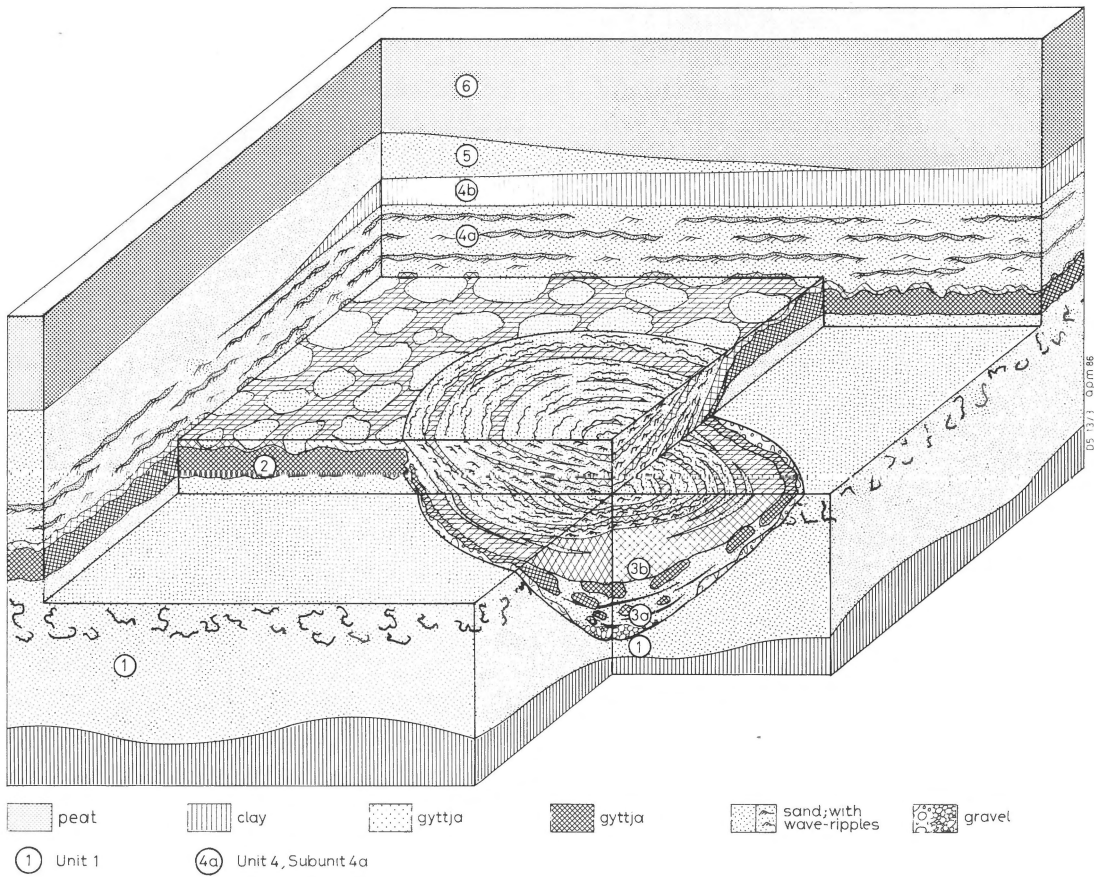


Fig. 5. Synthetic blockdiagram of a depression and the surrounding deposits. Numbers refer to the (sub-) units (see description in text) (not to scale; approximate diameter of depression is 1.5 m).

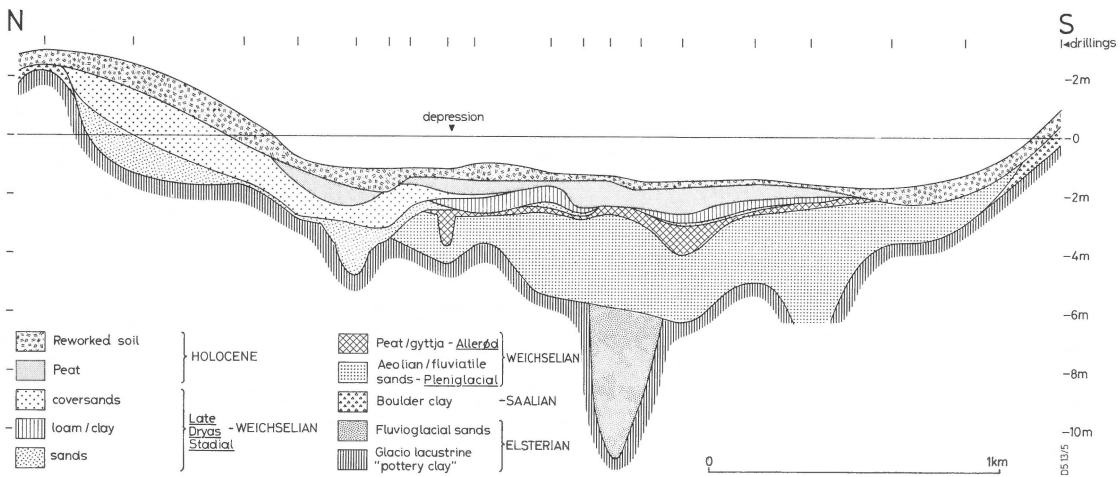


Fig. 6. Cross-section through the investigated area. For location, see Fig. 1 (depicted depression not to scale).

- The presence of sorted coarse detrital sediments, chaotically distributed gyttja-lumps, and slump structures (subunit 3a). The absence of these elements in the surrounding strata indicates a kind of sorting that must be related to the genesis of the depressions.
- Loadcasting (unit 4), indicating water-saturated environmental conditions.
- Fine-grained sand-fingers in subunit 3b, which are indicative of aeolian transport but also expressions of the morphological changes that shaped the depressions.

Laboratory analysis

Palynology and dating

Three sites were investigated: location A inside a representative depression; location B in an undisturbed sequence outside the depressions (unit 2 to unit 4); location C in the peat layer that covers the whole area (unit 6). The samples were treated according to Erdtman (1933) and Faegri et al. (1975). Both tree and non-tree pollen (as indicated on the diagrams in Fig. 7a, b and c) were used for percentage calculations.

The diagram of the depression fill (subunit 3b) at location A (Fig. 7a) shows a continuous *Empetrum* curve, the presence of *Juniperus*, and relatively high percentages of herbs. Striking also are the absence of a distinct succession of *Betula* and *Pinus* (contrary to location B), the little mutual variation in the values of *Betula*, *Pinus* and *Salix*, and the presence on a large scale of algae (*Botryococcus*, *Pediastrum*, *Scenedesmus*, and *Tetraedron*). The pollen spectra below the depression fill (subunit 3a) did not permit a division into subzones. These spectra are influenced by reworked Tertiary palynomorphs which also contributed to the values of *Pinus* and *Betula*. However, the presence and percentages of *Artemisia* indicate a Late Glacial age (LW). For all these reasons, the filling of the depressions is dated as Late Dryas Stadial (LW III) (De Jong, 1982).

Location B (Fig. 7b) shows, after high *Betula* values (pollen zone LW IIa), an increase in *Pinus*

(pollen zone LW IIb). It must therefore be concluded that the gyttja development (unit 2) started and continued during the Allerød Interstadial. Increasing percentages of *Empetrum*, the presence of *Juniperus*, and the (high) values of the herbs (Cyperaceae, Gramineae, and *Artemisia*) in subunit 4a indicate a Late Dryas age. In the upper part of the diagram (pollen zone LW III), especially in subunit 4b, an increase of Tertiary pollen is observed.

In the diagram for location C (Fig. 7c), the values for *Pinus* and *Betula* indicate a Preboreal age for the beginning of the accumulation of organic material at the top of unit 5 or, in its absence, unit 4. The spectra from the basal part of unit 6 and from the top of the underlying unit 5 indicate open eutrophic water conditions during the first part of the Holocene (algae, *Myriophyllum* spp., *Nymphaea*, Typhaceae, *Batrachium*). In the spectra of pollen zone H II (Boreal), the percentage of open-water plants decreases strongly and the environment becomes oligotrophic (*Sphagnum* and Ericaceae). The dating of the base of the peat (pollen zone H I, Preboreal) suggests a pre-Holocene age for the majority of the underlying deposits. This is confirmed by the pollen content of the lowermost spectra of the peat. Although there is some infiltration of Holocene pollen from above, a Late Glacial age of these spectra seems acceptable.

Diatom analysis

The analysed samples were taken from the same locations as those used for the pollen diagrams (locations A and B). For location B only one sample from unit 1 shows a distinct diatom flora (*Fragilaria brevistriata*, *F. pinnata*, and *F. construens* var. *venter*) indicating a food-rich and alkaline, shallow fresh-water environment (De Wolf, pers. comm.). Samples around it show a poor *Fragilaria* flora. In all other samples, including those from location A, diatoms are absent or occur sporadically. It should be mentioned that purely terrestrial environments are generally poor in diatoms.

Chronostratigraphy		Conv. radiocarbon years B.P.	Pollen zones	Pollen-analytical features
		Lithostratigraphy		
Late Glacial	Late Dryas Stadial	Younger Coversand II	10.200 LW III	Herbs, <u>Betula</u> , <u>Pinus</u> , <u>Salix</u> (subarctic park landscape)
	Allerød Interstadial	Organic material/ Loamy sand	11.000 LW II	<u>Pinus</u> forests <u>Betula</u> forests
	Earlier Dryas Stadial	Younger Coversand I	11.800 LW Ic	Herbs (open subarctic landscape)
	Bølling Interstadial s.l.	Organic material/ Loamy sand	12.000 LW I ^b 13.000 LW I ^a	Herbs, <u>Betula</u> , <u>Salix</u> (park landscape with Birch and Willow)

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Fig. 8. Chronostratigraphy and pollenanalytical features in the northern Netherlands.

Origin of the depressions

On the basis of the stratigraphic position and the results of palynological investigations, the development of the bowl- to funnel-shaped depressions must be situated approximately in the period of the Allerød Interstadial/Late Dryas Stadial, after the decline of *Pinus* reflected by the pollen diagrams (Fig. 8).

Depressions similar to those near Scheemda were first described by Casparie & Ter Wee (1981) at Een-Schipsloot (Fig. 1) which is also in the northern part of The Netherlands. They dated a peat layer (comparable to our subunit 3b) from the base of one such depression-fill as 10495 ± 60 BP (GrN-6341), which indicates that the depression was filled after that time. The depressions dealt with here are filled with gravel at the base (comparable in position to the artefacts in the depression of Een-Schipsloot) followed by well-sorted sands (fining-upward) and gyttja lumps, and finally with alternating layers of gyttja and of sand. In both localities the sequence points to selective surface processes prior to the development of the depression. The origin of the depressions from Scheemda and Een-Schipsloot must therefore be closely related.

Casparie & Ter Wee (1981) thought that the origin of the depressions was associated with permafrost at the beginning of the Late Dryas. At Scheemda the cryogenic structures and the high mechanical penetration value of the substrate (unit 1) indicate frost action and permafrost conditions during the Pleniglacial and probably the first half of the Late Glacial. Both the preservation of micro-

depressions just below the organic Allerød layer and the sedimentary structures observed in the fill of the depressions exclude permafrost conditions during the second half of the Late Glacial. These structures would have been destroyed by cryogenic processes associated with the presence of a fossil, shallow permafrost, or by renewed growth during the Late Dryas followed by melting.

On these grounds we developed a model for the evolution of the depressions that is here presented. It is framed within the context of changing local environmental conditions (summarized at the end of the section on Lithology and sedimentary structures), the stratigraphic position of the depressions, and the course of the climate during the Late Glacial in the northern part of The Netherlands as documented by e.g. Van der Hammen, 1951; Van der Hammen & Wijmstra, 1971; Casparie & Van Zeist, 1960; Casparie, 1972; Cleveringa et al., 1977; De Gans, 1981 (Fig. 8).

We start our model with the formation of the lower part of unit 2 (Fig. 9, stage 0), when wet conditions prevailed for a time, as reflected by the aquatic flora. The local wet conditions in this area were probably strongly influenced by the presence of the impermeable pottery clay at relatively shallow depth and by the surrounding ice-pushed ridges, but also by the mechanical properties of the substrate (unit 1).

An increase in temperature during the Allerød resulted in the formation of frost-related microdepressions – which started as soon as the permafrost table was sufficiently low not to influence the superficial sediments directly – and in locally

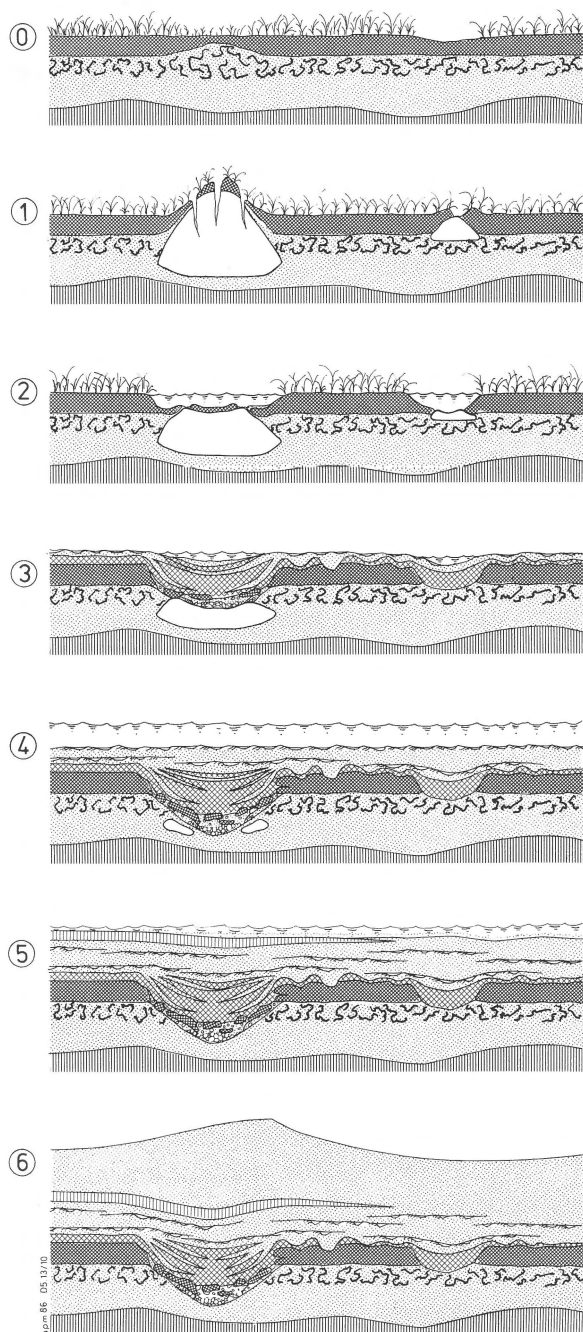


Fig. 9. Evolutionary model of the depression formation. For the legend, see Fig. 5 (not to scale).

drier conditions, as reflected by the reduced percentages of algae and aquatic flora (Fig. 7b). Sand eroded from the higher parts of the ice-pushed ridge was deposited on the site under study as thin lenses in the gyttja layer.

As a result of cooling during the second half of the Allerød (Coope, 1970, 1975; Kolstrup, 1979), the change in micro-topography that is determined by differences in vegetation, by the local presence of small sand bodies over the vegetation, and possibly by differences in snow-cover thickness during winter, led to changes in the local albedo and thermal conductivity of the ground (Rydén, 1983; Rydén & Kostov, 1980). 'During freeze-up, moisture from the adjacent area migrates, causing differential frost-heave and the segregation of local ice bodies' (French, 1976). The local geohydrological conditions, determined predominantly by the presence of the impermeable pottery clay, probably caused growth of the ice bodies by injection of ground-water, that is seasonally – i.e. during the winter – under pressure. At the surface, these ice bodies formed seasonal frost mounds (Brown et al., 1983; Chen et al., 1983; Van Everdingen, 1978; Froehlich & Supik, 1978; Pollard & French, 1983, 1984, 1985). Erosion of material from the core of the mounds could probably occur via cracks at the summits and on the flanks (Fig. 9: stage 1).

Higher thermal conductivity favoured by the vegetational differences on the drier frost mounds, trapping of aeolian sand against the flanks of the mounds, and possibly variations in snow cover during the winter, induced thermokarst, and therefore melting of the ice bodies and the collapse of the frost mounds. Lateral and mechanical sorting (Corte, 1966; Hallet & Prestud, 1986) gradually formed concentrations of coarse material and lumps from the destroyed gyttja layer in the larger depressions, while in the smaller ones the organic material was lost through erosion. The modelling of the depressions indicates that during this stage too, anorganic material was lost by repeated freeze-and-thaw processes (Fig. 9: stage 2). It must be kept in mind that frost-mound aggradation is part of a dynamic system terminating in a natural degradation process. In the recent subarctic environment, frost effects are followed by thermo-

karst phenomena. During the thermokarst stage, local wet environmental conditions are dominant (Czudek & Demek, 1970; French, 1976; Hopkins, 1949; Sigafos, 1951; Washburn, 1979).

During the collapse of the frost mounds, the environment was characterized by very wet conditions during the summer and by increasing aeolian sand transport and deposition during the winter. The flanks of the gradually deepening depressions slumped down (Fig. 9: stage 3).

The summer landscape was dominated by numerous ponds and mires, where wind-blown sand left from the winter was extensively reworked by wave action. In the course of a year, locally more and more organic and clayey material was brought into the environment and draped over the wave-ripple trains. Winter was characterized by sedimentation of the suspension load under the protective ice-cover and by aeolian-sand transport from the higher parts of the surrounding landscape (Fig. 9: stage 4).

As conditions for the spread of the vegetation worsened due to frost activity in the surface layer, less and less organic material was brought into the system, while more and more clay material was being derived from the denuded areas. This culminated in the erosion and deposition of clays and sand (subunit 4b), probably assisted by downslope gelifluction of the ice-pushed ridge. Loading and compaction further changed the morphology of the former frost-mound localities (Fig. 9: stage 5).

Finally, the aeolian action culminated in the deposition of a cover-sand sheet due to further worsening of vegetation growth conditions, primarily induced by better hydrological conditions in the investigated area (Fig. 9: stage 6).

Study of the successive development stages of the depressions and the related phenomena showed that besides the Allerød/Late Dryas deterioration (cooling) of the climate (Atkinson et al., 1987; Coope, 1975; Van der Hammen, 1951), local factors including the lithology, geomorphology, and hydrology, determined the time when, the rate at which, and the way in which the environment changed. This makes it difficult to reconstruct or to generalize the temperature change during this period. In Fig. 10 an attempt is made to visualize

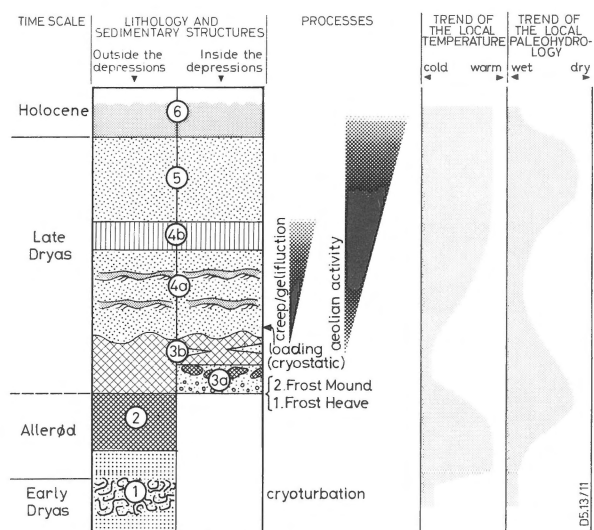


Fig. 10. Trends of the local paleo-temperature and paleo-geohydrology in the investigated area as deduced from the lithology, sedimentary structures and the local environmental processes (legend: see Fig. 5).

the local climatic and geohydrologic variations.

Conclusions

From this study the following conclusions can be drawn:

1. The cryogenic structures and the high penetration values in the substrate (unit 1) were formed under permafrost conditions during the Pleniglacial and probably the first half of the Late Glacial. The micro-depressions just below the organic layer indicate that just before the Allerød the permafrost table and related active layer already lay sufficiently low to preserve them.
2. Preservation of the Late Dryas seasonal frost-mound scars and of their fill is impossible if they had been exposed to the influence of an active layer. This supports our first conclusion that the permafrost table had dropped or had disappeared during the Late Glacial as already mentioned by Stapert (1986). Therefore, the origin of the depressions must have had a strongly seasonal and local character.

3. The expression of seasonal climatic variation during the Late Glacial was predominantly influenced by local factors (lithology, hydrology, morphology). These factors determine the formation, the evolution, and the preservation of the frost-related phenomena.
4. From the relative amount of aeolian sand in the depressions of the investigated area and the local hydrological conditions during the Late Dryas Stadial, a thin to virtually absent snow cover can be inferred (as was postulated on theoretical grounds by Van Geel & Kolstrup, 1978). This too underlines the importance of local environmental factors in the expression of frost action in a low-lying area between ice-pushed ridges.
5. Comparison of our results with those of earlier studies on the Late Glacial (e.g. Veenenbosch, 1954; Wiggers, 1955: *An increasing wetness of the environment at the transition Allerød/Late Dryas*; Van der Hammen & Wijmstra, 1971; Maarleveld, 1976; Stapert, 1982, 1986; Van der Tak-Schneider, 1968: *Frost wedges dated somewhere in the Late Dryas*; Casparie & Ter Wee, 1981: *Frost wedges dated earlier than the formations of seasonal frost mounds*), shows that the expression of the cooling of the climate during the Late Glacial was marked by time shifts. We assume that the observed variations and shifts are the expression of global fluctuations, locally enhanced by environmental factors. This underlines the difficulty of reconstructing the temperature curve for the Late Glacial, as much as giving it more than local significance.

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