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The spatial facies of a group of pingo remnants on the southeast Frisian till plateau (the Netherlands)

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Abstract

A group of Weichselian pingo remnants on the southeast Frisian till plateau has been investigated in 2 m deep ditch exposures and in borings. Pingo geometry comprises a more or less continuous outer till rim, an inner till terrace, and a central depression, which runs down through the 3.5–5 m thick till. The rim developed in a peripheral stressfield, the inner terrace consists of sagged pingo skin, and the central depression approximately represents the former pingo crater. Sand, gyttja, and peat cover the inner terrace and fill the central depression, which possibly contains some till interlayers in the basal parts.

The pingos originated at the flanks of a winding erosion valley (80 m wide), a tributary to one of the main valleys of the till plateau. This setting and the minor relief of the area indicate a closed-system pingo origin. However, the interpreted positions of the former pingo ice lenses at the base of the till layer, for pingos which are strongly different in size, may indicate some artesian influence (open-system processes).

The pingos and sand wedges (2 m long, several decimetres wide) originated under an arid, arctic climate which succeeded a wet, Pleniglacial phase. Pingo degradation with some climatic amelioration was accompanied by minor lateral transport of the pingo skin, which explains the low relief of the rampart. Aeolian sand accumulated in the remnants, where furthermore loess became mixed with organic material (gyttja). Under Holocene climates aeolian transport ceased and peat growth started, together with the formation of podzolic soil profiles.

Introduction

The southeastern parts of the province of Friesland, the Netherlands, show many metre-deep closed depressions with diameters up to hundreds of metres. The depressions are mostly peat- and gyttja-filled, although peat digging has removed part or all of the fill in several localities. The depressions, which are called dobbes in these regions, are prominent on the higher parts of the till plateau, in between the parallel, shallow river valleys. They are fewer in number on the slopes and close to the valley centres.

Maarleveld & Van der Toorn (1955) were the first to explain that the closed depressions are the result of pingo development in permafrost. Dating of the organic infill on the basis of pollen and ^{14}C established a Late Weichselian age, which excludes origins as kettle holes (Saalien), as proposed by Veenenbos (1954). Several other pingo remnants were identified since in these parts (Casparie & Van Zeist, 1960; Nossin, 1961; Paris et al., 1979; Ploeger & Groenman-Van Wateringe, 1964), as well as on the adjacent Drente plateau (Cleveringa et al., 1977; De Gans, 1976, 1982; De Gans et al., 1984; De Gans & Sohl, 1981; Ter Wee, 1966, 1979). Bijlsma & De Lange (1983) described a pingo remnant from the eastern parts of the Netherlands, and remnants were furthermore discovered in most of the northwestern European countries (Flemal, 1976).

Research on the Dutch examples has been concentrated on drill cores of the organic infill of the pingo remnants. Because of soil and ground conditions only artificial exposure is possible. Up until now only a trench section of 2 × 20 m^2 of a rampart, the characteristic rim around the depressions, has been described (De Gans et al., 1984). The study presented here describes temporary exposures existing in an 18 hectare large area with closed depressions near Donkerbroek (location in Fig. 1) during land consolidation activities. Ditches, 1–2 m deep and with a total length of 2 km, provided sloping sections. Ploughing revealed the facies distribution at 0.5 m below the grass-covered surface.

The purpose of this study is to record the facies of the remnants and the surrounding area in the ditches and ploughed area. The geometry of the closed depressions as a whole was reconstructed using additional information from hand auger drillings. Most conspicuous are the compressional structures of the outer rim.

Topography and geology

The study area is situated on a till plateau that covers part of the provinces of Friesland and Groningen (Fig. 1) and major parts of Drente. In southeast Friesland southwest-heading erosion valleys traverse the plateau. These valleys contain no till, but are filled with alluvial and aeolian sediments and peat (Cnossen, 1961; De Gans, 1980, 1981, 1983; De Gans & Cleveringa, 1981; Nossin, 1961; and Ter Wee, 1966, 1979). At present channelized rivulets discharge through the major valleys. Upstream there are several major divides of the valleys. The study area (P in Fig. 1) lies in between two such divides (Fig. 2). Only the southern one contains a rivulet, the Tjonger or Kuinder River. Presumed minor branches to the main erosion valleys are indicated as negative relief elements in Fig. 2.

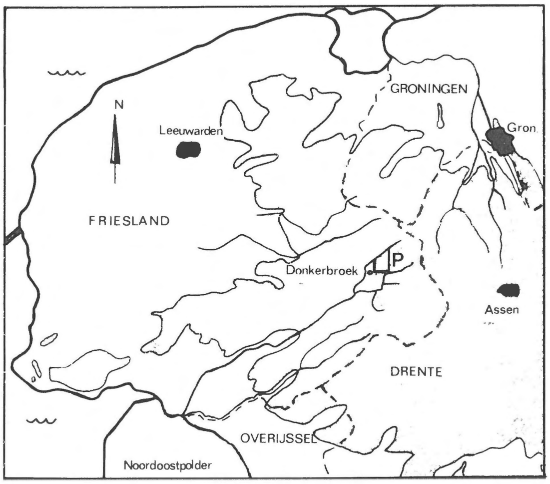

Fig. 1. The extent of the till plateau in the province of Friesland and bordering provinces is marked in grey (after Edelman & Maarleveld, 1958). Major erosion valleys are also indicated. The relief of area P is given in Fig. 2. Compare Figs 2 and 4 for scale.

Positive relief elements are mainly formed by cover sand ridges on top of the till. Five major closed depressions (A, B, C, X, and Y) are indicated in the tributary valley running towards the area of detailed study (DS) and in the adjacent areas. The

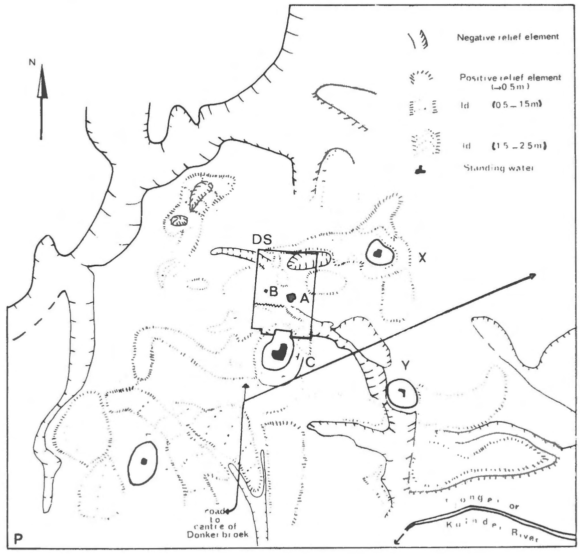

Fig. 2. The relief of region P in Fig. 1. It surrounds the area with closed depressions A, B, and C, that was studied in detail (area DS). Closed depressions X and Y are considered to be similar features. The depression in the northeastern part of area DS is more shallow and has no organic fill.

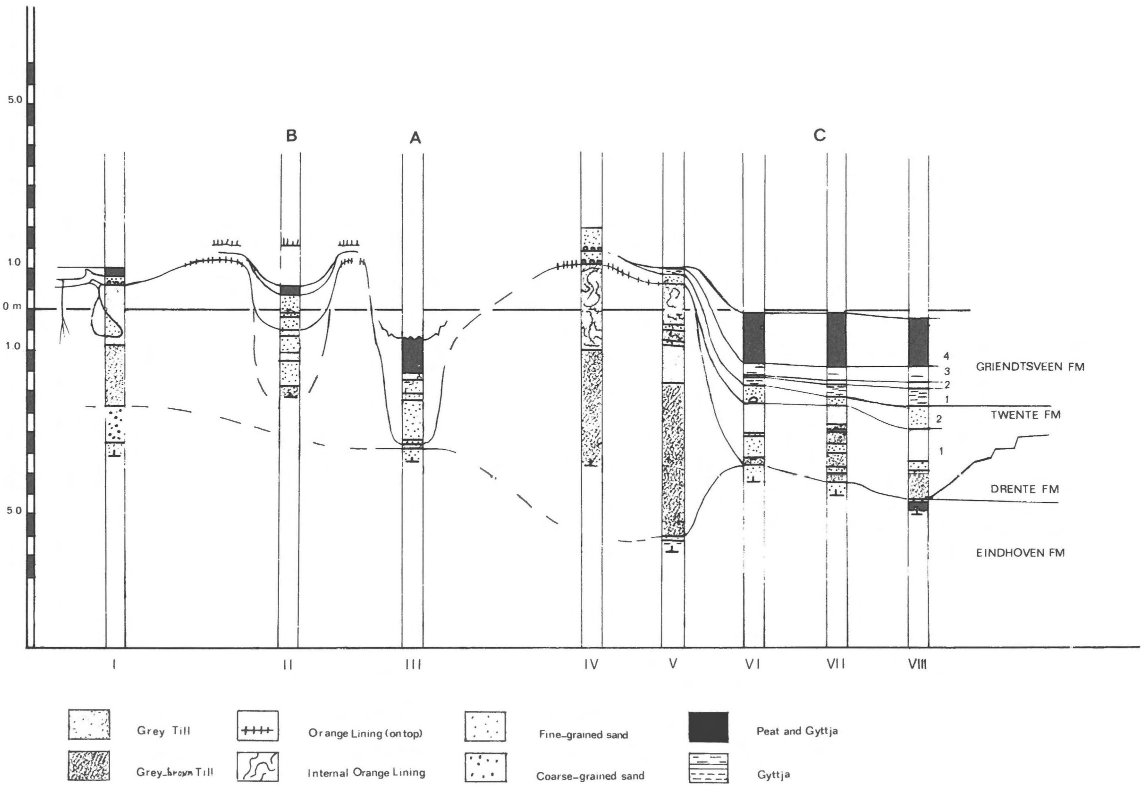

Fig. 3. The stratigraphic subdivision of the deposits in the study area is indicated for eight drill cores. The main ditch water level is taken as the datum level (see Fig. 4). The drill cores are located in Fig. 4 (cores I–III) and Fig. 5 (IV–VIII).

setting of the only two major sand ridges in the area, to the west of depressions C and X with an east-west trend, forms a conspicious combination of the two relief types.

The studied deposits can be subdivided according to the stratigraphy of De Gans & Sohl (1981). Hand auger drilling of the deposits is possible down to the top of the closely-packed sands of the Eindhoven Formation (Fig. 3) underneath the till of the Drente Formation. Locally also some compact peat is present (cores V and VIII) here. In the borings till only lacks in the centre of depression A; depressions B and C have only a basal sand-till interlayering above densely-compacted sands. This interlayering and a decimetre-thick sand cover in depression C are assigned to the Twente Formation (respectively subdivisions 1 and 2 in cores VI–VIII, Fig. 3). The surrounding cover sands and some channelized deposits on top of the till belong also to the Twente Formation. Depression A has a basal infill of organic sands, topped by a detrital gyttja, which belong to the Griendtsveen Formation. In depression C this Formation consists of a black gyttja with some peat (Layer 4) on top of light-coloured, silt-rich gyttja (Layers 1–3).

Sedimentary petrology

The garnet content of the sands in the study area can be used for subdivision, as is done for the Eindhoven Formation 10–35 km to the south (Ter Wee, 1966). With 100 grains counted 7 samples of the Eindhoven top show 17–28% garnet, intermediate between 1 alluvial (14%) and 2 aeolian (both 38%) Twente sand samples. Sands interlayered with till in depression C yield garnet contents of Eindhoven (2 samples) and aeolian Twente sands (1 sample in between the other two).

Description of the study area

Although the three-dimensionally exposed area (Fig. 4, DS in Fig. 2) lies at the water divide between two major valleys (Fig. 2), it comprises an up to 80 m wide valley, hidden by a sandy fill. The till top geometry (Fig. 4) shows that the clearly outlined valley containing depression Y in Fig. 2 can be traced through area DS. In the valley a relatively narrow channel fill continues upstream from close to N2 in Fig. 4, along the western margin of depression A (compare Fig. 5), towards the northeast in the direction of depression X. The sandy channel fill is loam-capped, except for the area to the west of depression A (see section W3E3, Fig. 4). The flat sand and loam wings at part of the channel fill sides are tilted to the north of depression C (in section W1-W2-N4, Fig. 5). A shallow valley without fill joins the relatively deep incision from the northwest of the study area.

Geometry of the closed depressions and sedimentary characteristics

Sand ridges determine the geometry of the shallow northeastern depression in area DS (Figs 2 and 4). The depression lies in the centre of the valley, on top of the loam-capped alluvial fill, and contains only a thin peat layer. The major depressions A, B and C at the bases of the valley sides are composed of four morphological elements: 1) a deep central depression running through the massive till; 2) an inner terrace, which gradually slopes towards the central depression; 3) an outer rim mainly consisting of till (0.5–1.0 m thick) with local sand bodies; in exposures major compressional features have been recognized. The top of the till has a pronounced orange colour (see also Nossin, 1961). The rim is not necessarily continuous along the depression (e.g. the east side of depression A); 4) a flat-topped fill of sands and organic matter in the central area.

Detailed cross sections are presented of the largest depression (C) in Fig. 5. The outer till rim can be distinguished in most, but not in all sections. The wide inner terrace passes into the central depression with a sharp break in slope. At the break vertical, 2 m deep sand wedges are locally present (e.g. in between E6 and E8, Fig. 5).

Sand bodies lie against the deformed rim (e.g. section W4E4 in between 250 and 400 m and the N2S2 section, Fig. 4). The rim sands are commonly white in colour, turning to light grey-topped, brown towards the inner terrace (Fig. 6). The sands of the inner terrace are connected either to the basal cover in the central depression or to a sand wedge in the gyttja. This subdivision could be made in depression C, but not in A because of the overall sandy character of the fill.

The organic content of the gyttjas of depression C varies vertically as well as laterally. The yellow- to ochre-coloured basal layer (Griendtsveen 1 in Fig. 3) comprises 24% organic material in a central area sample, but only 15% in a sample from the eastern margin. The light brown-grey-coloured Griendtsveen Layer 3 contains 7 and 8% organic matter in two central samples. All four samples furthermore consists predominantly of silt (loess). The Griendtsveen Layer 2 (not shown in Fig. 5) consists mainly of fine-grained sand and macerated plant debris laminae (0.5–2 cm thick). Combinations of these laminae types also occur scattered in the otherwise massive Layers 1 and 3.

Gyttja-fine-grained sand lamination lies against the eastern sand wedge in the gyttja. Consequently, coarsening-upwards sequences (with a fining-up top to the southeast) can be distinguished in a tens of metres-wide, distal zone. In the other parts the gyttja Layers 1 and 3 gradually thin and wedge out at the inner terrace, where the layer division is obliterated by vertical rootlets and some oxidation. The black gyttja (with some peat) of Griendtsveen Layer 4 passes with a major thinning into peat at the inner terrace. A thin layer of black, massive peat reaches up to the southeastern rim (sections N4S4 and W7E7 in Fig. 5).

Description of rim sections

Deformation structures in the exposed rim zone are of a type, which has been described neither from fossil, nor from recent examples. In the E4E5 section (Fig. 5) folded sand layers of the rim pass outwards into a series of fault blocks (Fig. 7). At the transition (432–435 m, Fig. 7) folds as well as a deformed block are found (Fig. 8a). The fault

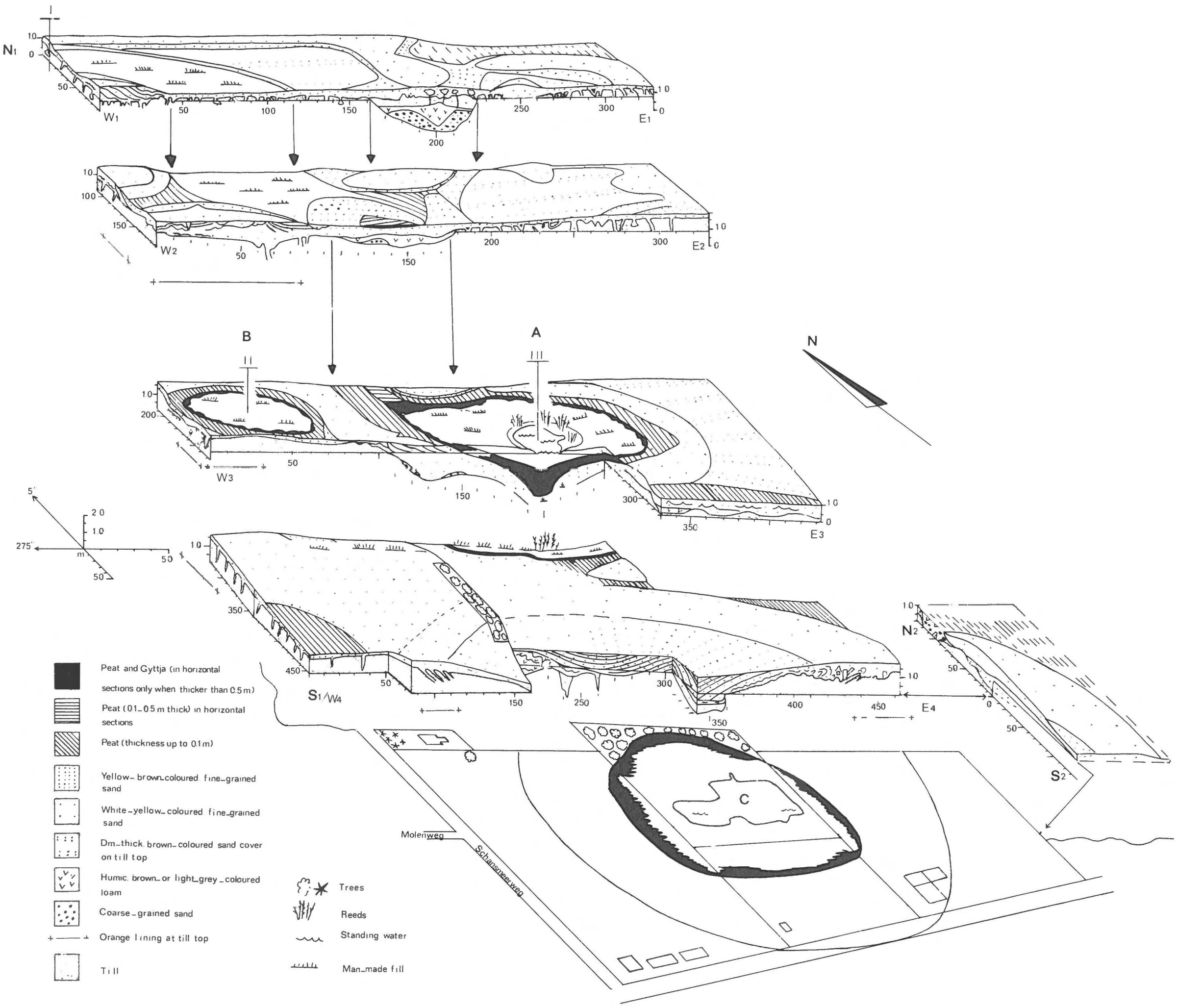

Fig. 4. The three-dimensional representation of the ditch exposures is locally supplemented with drill data down to the till top. The water level in the main and (more shallow) tributary ditches is taken as the datum levels. The actual long axis/short axis ratios and the long axis directions of the depressions are: A, 1.4, E-W direction: B, 1.2, E-W direction: C, 1.7, approximately N-S direction.

blocks of varying sizes are rotated in a clock- or anticlockwise direction. The top of the till underneath is irregular with a flat updoming at the western margin and with several low to high angle upthrusts. The vergence of the folds and the tilt of the fault blocks are directly related to the directions of the till upthrusts. There also seem to be larger units in the sands that possess a thrust front (marked F in Fig. 7). The thrust planes could not be traced down through the till, except, in a minor way, at 438 m where there are sand block inclusions in the till. The vergence of the deformation has a direction of 80° (eastwards), slightly oblique to the radius from this location to the centre of the depression.

Tension cracks, as minor features at 430 and 431 m, are associated with sag faulting of the adjacent sand blocks. The fissure at 430 m has been filled in phases by successive sand laminae. These sands belong to a larger unit, which covers and smoothens the rim relief. Both this unit and the deformed sands consist of fine-grained sand with scattered medium and coarse grains and some thin lags of small pebbles (0.2–2 cm size).

A tilted sand-till interbedding (dip 45°–70° to the

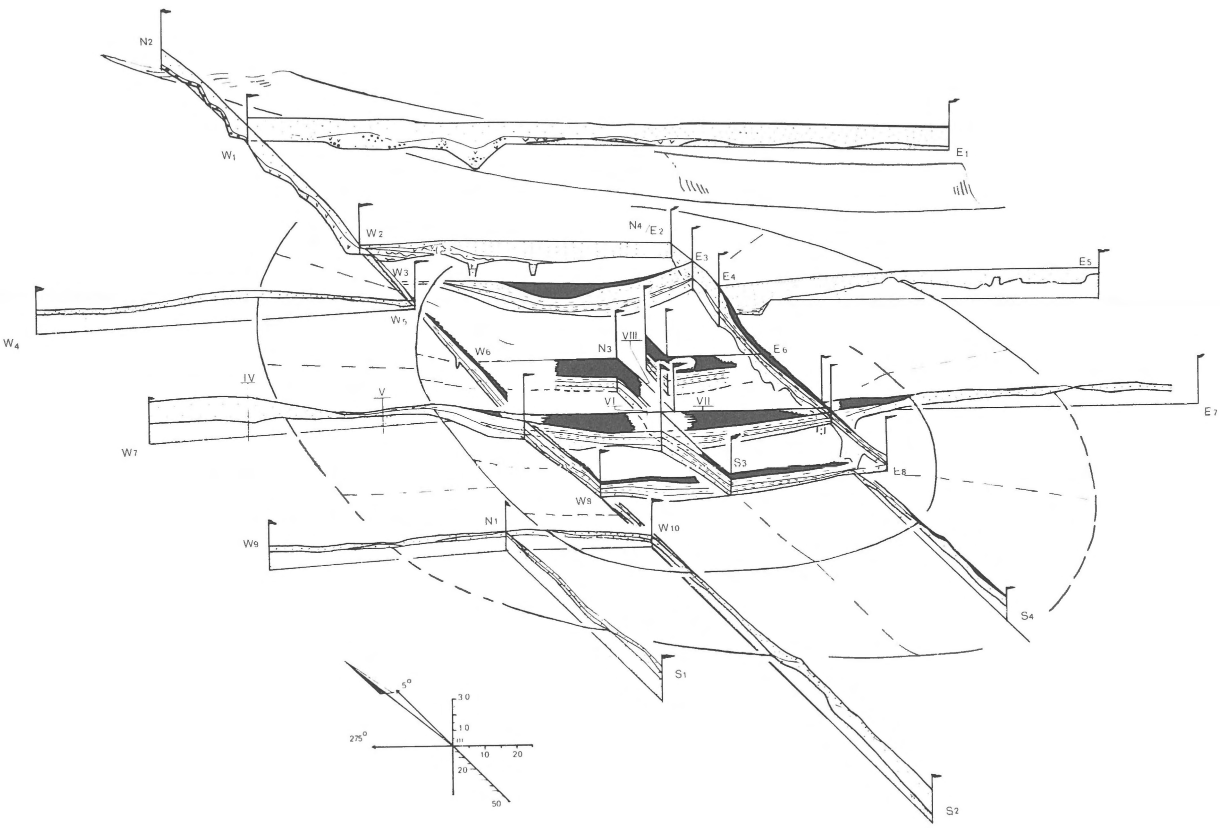

Fig. 5. The constructed geometry of depression C is based on drill data and a ditch exposure along W4W5W2E4E5. The water level of this continuation of the main ditch in Fig. 4 is taken as datum level (at 3.9 m above N.A.P.). In between the sections the contours of the outer rim and outer boundary of gyttja distribution are indicated, together with the channel bend to the northeast.

northeast, at an angle of 72.5° with the radius from this location to the depression centre) in section W4W5 (Fig. 4) is pictured in Fig. 8b. Sand veins in the till are somewhat folded. The sand bed to the left incorporates an irregular till block. A succession of undulating sand and loam layers is observed in the northern rim (section W1W2, Fig. 5) and dips inward at the inner terrace (section W2E2, Fig. 5).

At the southwestern rim of depression B there is a decimetre-thick sand layer with steeply-inclined lamination in between the till and the coversand. At 220 m of section N1S1 (Fig. 4) the till contains an inclined sand layer (dip 40°–45°, at an angle of 10° with the radius from this location to the depression centre).

Sedimentary facies

1. Till: the massive till is light to brownish grey in exposures. In borings the lower part is brown-grey (Fig. 3), which is due to the constant presence of groundwater (Ter Wee 1966). The till consists of a mixture of sand, silt and clay in varying proportions. Minor amounts of pebble and very scattered boulders are intercalated.
2. Sand wedges: up to 2 m long, 0.2 m wide vertical wedges extend downwards from the till top in the W3S1 section in Fig. 4. The wedges are filled with fine-grained sand. Minor veins continue beyond the basal parts. This wedge type alternates with Y-shaped wedges at the somewhat convex till slopes of the valley in the study area (section W1E1, 260–330 m and W2E2, 180–330 m, Fig. 4). Sand wedges in relatively low areas show bulges

Fig. 6. In this view from 70 m in the W3E3 section in Fig. 4, the inner terrace and the central depression of depression B can be distinguished from each other on the basis of different colours of the ploughed land. The inner terrace is covered by brown sands with some peat. The central depression became filled with white rim sands during land reclamation around 1950.

that are associated with sand intrusions in the cover sand (as indicated to the left of core I in Fig. 3).

3. Channel fill facies: the sediments consist of coarse-, medium- and fine-grained sands in individual layers with moderate sorting, and in mixed layers. Pebbles can be dispersed or concentrated in basal lags. There is always a basal lag to the whole sequence. Light grey loam is present as a 0.1–0.5 m thick cap (Fig. 4, sections W1E1, W2E2 and near N2). Brown, humic loam is intercalated as thin beds in the lower parts of the fill and predominantly in the channel wing to the north of depression C (Fig. 5).

4. Ridge and cover sand facies: the fine-grained convex sand bodies are connected with 1–3 dm thick layers and together they cover the whole area. Flat lamination and bedding is the main structure. Sand bodies over 1.5 m thick also exhibit crossbedding and -lamination.

Podzolic soil profiles are developed in the sands. Brown colours increase in intensity with decreasing elevation of the top of the deposits. The decimetre-thick, light-grey sand top first becomes discontinuous in the low areas, and then disappears in the lows under a thickening peat layer.

Interpretation

Closed depressions on the Drente till plateau have been interpreted to be pingo remnants because of four characteristics (De Gans & Sohl, 1981): 1. The depression is rooted in the Eindhoven sands underneath the much less permeable till; 2. a non-aeolian rampart is present; 3. the depression is situated in the upstream, tributary part of the drainage system of the plateau; 4. the basal infill has a Late Glacial or Pleniglacial age.

The closed depressions A, B and C fulfil these conditions as follows:

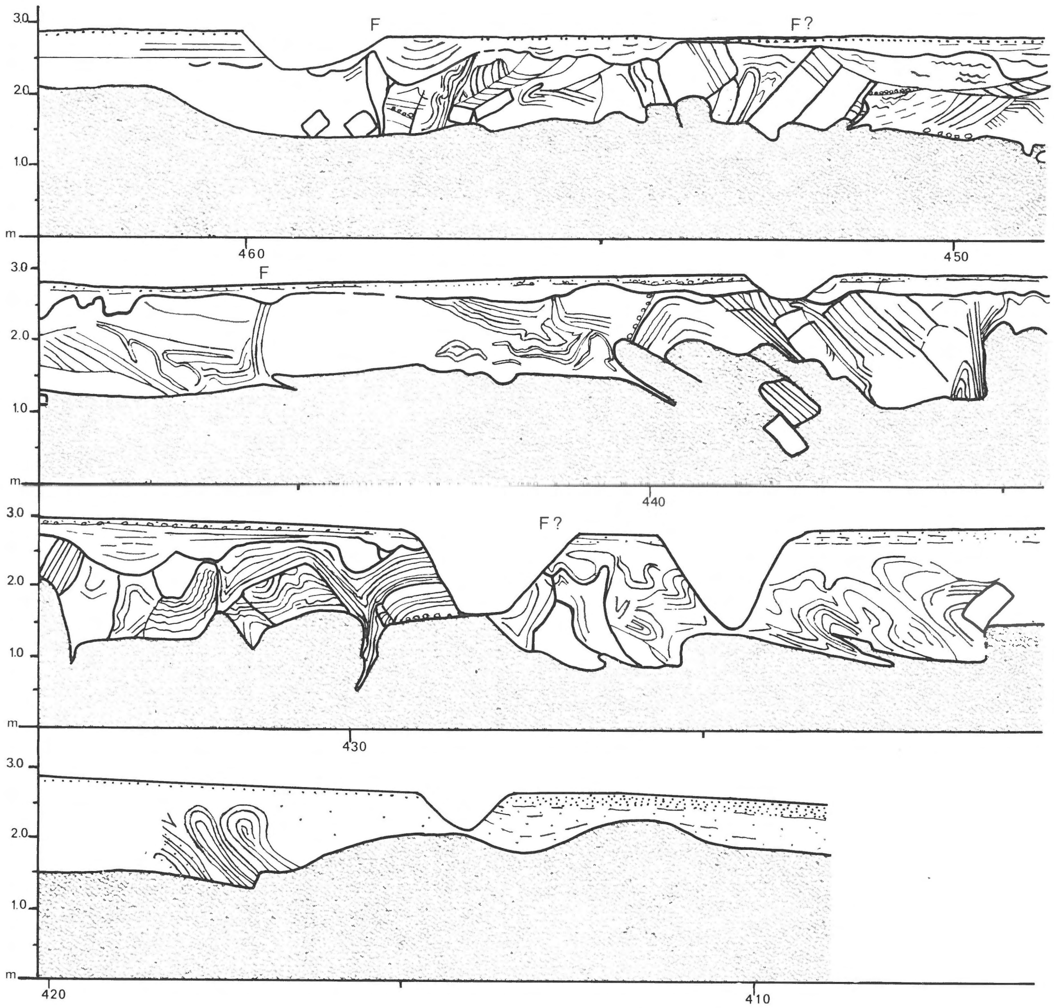

Fig. 7. The major compressional structures of the eastern half of section E4E5 (Fig. 5) are represented in this drawing of the northward-facing ditch wall. The exposed surface dips 40°. The metre scale is according to section W4E4 in Fig. 4.

1. The depressions run through the till to the Eindhoven sands. The base of the depression can contain till layers in sand, the sands, however, belong to the Twente and possibly to the Eindhoven Formation, indicating reworking of the till layers.
2. There are distinct till rims along major parts of the depressions. The till rims in outcrop contain inclined sand layers or a compressed sand body is found on top. According to the setting and most directional features the compression is related to the rim development along the depression. Because of the setting the rim as a whole can be considered as a rampart in the conception of De Gans & Sohl (1981). An aeolian sand cover has only locally accentuated the rampart relief.
3. Since the study of Maarleveld & Van den Toorn (1955) the setting of pingo remnants along former alluvial valleys has been shown in the Netherlands by Nossin (1961), Ploeger & Groenman-Van Wateringe (1964), Paris et al. (1979), De Gans & Sohl (1981), De Gans (1982) and De Gans et al. (1984). Even in cases of no surficial relief expression, alluvially-incised valleys in the till have been shown to exist in the vicinity of pingoremnants (De Gans, 1982) and the same applies here.
4. All basal gyttjas in Dutch pingo remnants, which are comparable to the studied examples, were dated in the range of Upper Pleniglacial to Late Gla-

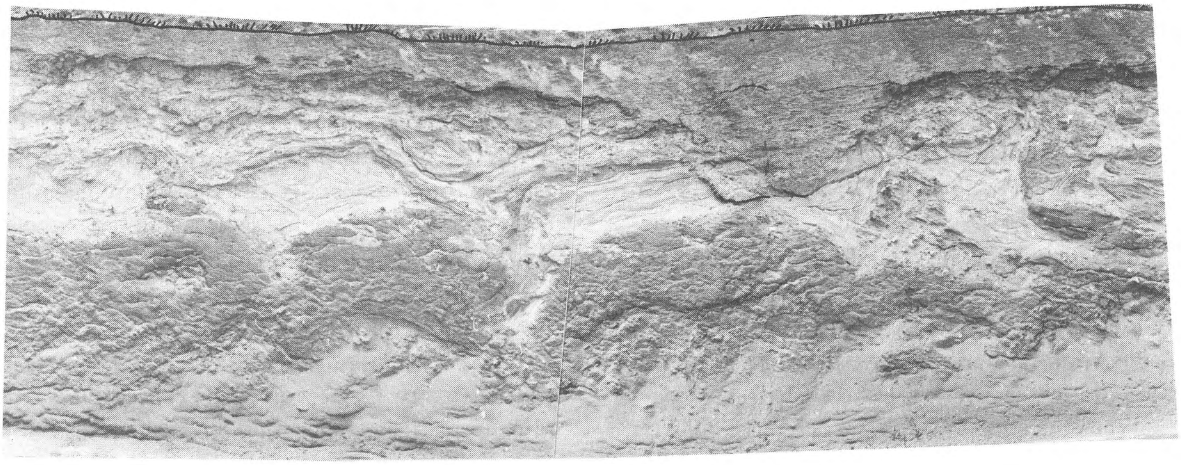

Fig. 8a. In this detail of Fig. 7 (in between 433 and 426 m) strongly deformed sand blocks and layers pass laterally in well-preserved, rotated blocks. The fissures in between the central blocks have been filled in several phases.

cial (De Gans & Sohl, 1981). Loamy alluvial deposits in a corresponding setting as the valley fill loam were dated at Middle Pleniglacial (De Gans, 1982; De Gans et al., 1984; Paris et al., 1979), and this narrows down the period of pingo evolution with removal (to the west of A) and tilting (to the north of C) of the alluvial deposits to the period in between the two dates.

The shallow northeastern depression in the DS area originated because aeolian sand ridges dammed the alluvial valley at this location. Such a type of depression is called an aeolian depression (e.g. De Gans, 1976, 1982).

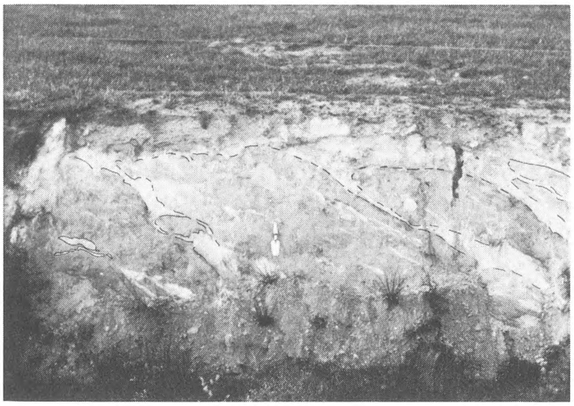

Fig. 8b. A tilted sand-till interlayering (till in grey) in the rim of depression C (section W4E4 of Fig. 4 in between 90 and 115 m).

Hydrologic and permafrost conditions during pingo development

Pingo remnants (= former ice-cored hills) are indisputable evidence of former permafrost (Flemal, 1976). Unfrozen material (talik) in permafrost is a prerequisite for pingo development. In general pingos are subdivided in open- and closed-system types, in which artesian and cryostatic pressures build the ice-cored hills respectively. Open-system pingos develop in discontinuous and closed-system pingos in continuous permafrost.

Formerly the pingo remnants of the till plateau were thought to be the results of open-system processes. De Gans (1982), however, decided for a closed-system origin because of the low relief of the surrounding area, with till at the water divides, which both exclude considerable build up of artesian pressures, sufficient for pingo development. Furthermore, the assumed presence of continuous permafrost and of thaw lake environments are indicating closed-system pingo development (De Gans, 1982).

Recent closed-system pingos are mostly known from drained, shallow lakes. Frost hill formation is due to permafrost aggradation in the talik after lake drainage has removed the protective water cover. Progressive enclosure of the talik by permafrost causes upward expulsion of pore water (Mackay, 1973; Müller, 1959). Heave of the lake bottom centre takes place at the level where upwards pressure first exceeds the overburden pressure. Therefore, drained lake size, pingo volume and overburden thickness are directly related in case of regular lake geometry (Müller, 1959).

Mackay (1963) and Pissart & French (1976) described closed-system pingos from the alluvial environment. Pissart & French (1976) considered these pingos as a specific subtype, because pingo development is closely related to pecularities of the alluvial environment. In our case the talik necessary for pingo growth is interpreted also to have been preserved, because of the presence of the alluvial valley (analogous to Pissart & French, 1976). For two reasons the presence of a thaw lake which induces pingo growth is rejected. Firstly, sand wedges accompany the pingos, and not relics of ice wedges, which are thought to play a major role in thaw lake development (e.g. Washburn, 1979). Secondly, the relief is not reversed as can be expected after permafrost disappearance from the environment (Flemal, 1976).

The vertical sand wedges, whose description agrees with the ones by Black (1975) and Kolstrup (1986), originated in winters that were at least partly snow-free (Black, 1975). Drift sand accumulated in vertical contraction cracks, which could become Y-shaped at convex-up valley walls. Soft sediment deformation of part of the wedges was a much younger process, that took place simultaneously with the cover sand sedimentation after pingo decay.

The sand wedges are only associated with aeolian, fine-grained sand sedimentation; there are no signs of either alluvial sedimentation or erosion at the wedges, not even in the shallow, till-floored valley branch. Therefore, although the valley fill could not be examined for sand wedge presence, most likely the wedges originated after the transition of a wet, cold to an arid, even colder climate, as has been reconstructed by Van der Hammen (1952), Ter Wee (1966) and De Gans (1982) for the Middle to Upper Pleniglacial boundary. The transition would then be marked by the light grey loam cap of the alluvial deposits.

In the next, Upper Pleniglacial period sand wedge formation started, (soon) accompanied by pingo development (analogous to Paris et al., 1979). In this respect it is notable that Black (1975) mentioned the dependence of both sand wedge and pingo formation on permafrost presence, especially of the continuous type for the sand wedges. Despite the sand wedge presence as indication of (partly) snow-free winters the aeolian sedimentation will have been limited to the wedge sites and to some locations in the lee of the pingos. Such sand bodies could become deformed during pingo evolution. The tilted sand-till interbedding (Fig. 8b) of the depression C rim most likely represents a group of sand wedges as deduced from the irregular interfaces, sand veinlets in the till, and fragments of the till host in the wedges.

Winter discharge in between ice and river bed and through the sediments allows initial talik preservation in permafrosted alluvial valleys (Pissart & French, 1976). Because of the reconstructed aridity of the Upper Pleniglacial climate and the upstream setting in the drainage system, high moisture content of the valley floor is thought to have been the major decelerating factor in permafrost aggradation. The calculation by Müller (1959) of the minimum standing water measures required for open talik at the base learns that in this case permafrost aggradation from the sides could only be retarded. The local situation with several confluent tributaries will have increased the retardation effect. Several tributaries join just in front of a nearly perpendicular bend with a downstream narrowing. Pissart & French (1976) mentioned stagnation of alluvial discharge as a factor promoting pingo development. Therefore, although closely-spaced pingos are mainly known from the open-system environment, closed system processes are completely in line with the described setting. The lack of pingo rejuvenation and the regular remnant geometry support such an interpretation (c.f. Müller, 1959).

Nevertheless, there are some striking deviations from the closed-system model in other respects. In the first place the pingos originated close to but not at the confluences and not even in the centres of the valleys, which is a regular feature of the till plateau examples (De Gans, 1982). Central pingo setting has generally been found in lakes and Pissart & French (1976) also described a direct relation of pingo setting and channel position. In the second place the ice lens base must have been situated at the transition of the Eindhoven sands and the till. Thus the overburdens of the pingos A and C have been equally thick, despite the major size difference. Especially the latter deviation, together with the low permeability of the till layer, point to some influence of open-system processes. The Eindhoven sands may have acted as an aquifer (as is the situation today (Ter Wee, 1979) – however, the result of the interference of permafrost with this aquifer situation is not known). Nevertheless, the difference in elevation along the base of the till plateau (some tens of metres) is far too small to allow for pingo skin heave by hydraulic pressure.

Reconstruction of pingo build-up and degradation

Free water, segregated water, and pore water freeze during permafrost aggradation in talik (Mackay, 1973) and the consequent forces build a pingo, when the overburden pressure is exceeded. Growth rates decline during the process and pingos can remain intact for hundreds and possibly thousands of years (Müller, 1959). Depending on talik geometries round or elongate (as in our case) pingos will develop.

With continued overburden upheaval the pingo top cracks, and consequently, with a transition from a starlike opening (Pihlainen et al., 1956) to a round crater, the pingo ice lens becomes exposed and melting can commence. Upon ice core decay considerable outwards displacement of pingo skin by artesian flow can result in open-system-pingos (Müller, 1959). In contrast, inward slumping of pingo skin in the central melting zone is the displacement process in this stage of closed-system pingos (Mackay, 1973).

In permafrost areas a doughnut type geometry with a broad rampart and a narrow, but deep central depression results after central ice melt in the closed-system pingo; the ultimate geometry after permafrost disappearance cannot be induced (Mackay, 1973). The inner terrace of remnant C most likely originated during regular sagging of the till and of the local alluvial layers of this rampart with the complete disappearance of the pingo ice from underneath. The deep central depression of C then represents the central melt-out zone with some slumped till in the basal sand fill. The similarity in garnet content of these sand layers either with aeolian Twente or with Eindhoven sands indicates reworking of the till in the Twente stage. The major sand-filled cracks at the boundary of the central depression in C most likely originated during slumping.

There is a problem with the interpretation of the compressional character of the outer rim. From recent pingos only deformation through pingo skin heave is known (Mackay, 1973; Müller, 1959; Pissart & French, 1976). However, lack of frost creep and of continuous slumps (the till protrusions in Fig. 7 are discontinuous) indicates a setting at the former pingo base in stead of at the heaved slope (c.f. Pissart & French, 1976). In fact slumping of a thick active layer incorporating both pingo skin sands and till is unlikely, because the blocky character of the rim sandbody points to deformation in a frozen state. Furthermore, as there is no sign of till on top of the deformed sands, mass flow of skin during pingo decay can also be excluded. The arid climate will have been the reason for this; under wet conditions the till is highly susceptible to plastic flow.

Rim formation during lateral pingo growth is not likely, as pingos especially grow vertically (Mackay, 1973), but a peripheral, hinge-type strainfield is associated with overburden uplift by the hydrolaccolith of a pingo (Mackay, 1987). In recent examples the strainfield is only shown by peripheral faulting (with possible springflow); these faults propagated upward from the lower tension area through the upper stressfield. Nevertheless compression in this stressfield of the pingo periphery is the best explanation for the observed rim deformation. A phased low-angle thrusting, which prograded outwards, can be in line with pingo growth cycles due to alternating gradual build-up and abrupt release of pressure at the ice lens (Müller, 1959). Local tension resulting from thrusting at different angles can explain the structure at 430–431 m in Fig. 7. Aeolian sediments covered the relief during the several phases of deformation.

The rim deformation was largely radial. Deviation of this trend at the tilted sand wedge group can be linked with a pronounced till thickening to the west of remnant C (Fig. 3). As a consequence rim curvature is also less well developed.

The rim compression will have increased the area over which the pingo skin became distributed after complete degradation. This can explain the material shortage at the (depressed) inner terrace (together with aeolian deflation of the former pingo) and enlargement of the central depression (together with slumping of the crater wall). Basal tension effects at the periphery and/or differential sagging can be held responsible for partial rim disappearance.

Sedimentary evolution after pingo decay

Aeolian sand sheets were the first deposits in the remnants. The sand top of the rim was levelled, before further sedimentation took place, locally on top of a lag. Silty gyttjas (in depression C) and sands with organic matter (in depression A) were formed, after the pingo ice had completely disappeared and the remnant was filled with water. The major sand incursion in the gyttja, from the northeast, is probably of a Late Dryas age (analoguous to the build up of the remnant fill near Wateren, (Ter Wee, 1966)). The gyttja extends at least halfway over the inner terrace of remnant C (Fig. 5), therefore in the Late Glacial standing water must have largely filled the remnant; in winters with ice on top. Consequently (compare Ter Wee, 1979), summer sedimentation will have prevailed, with dominance of loess deposition supplemented with organic detritus. Occasional storms will have introduced the macerated plant debris and fine-grained sand, which were deposited in very thin sheets. The sand probably originated from the ridges, which were build in the vicinity of the remnants and possibly partly earlier during pingo build-up.

Conclusions

1. A detailed facies and geometrical representation has been given of a formerly pingoed area. Fig. 4 (based on exposures) is a more detailed example of the sketch model by De Gans (1982) of such an environment.
2. a. The pingo remnants consist of a low rim along major parts of a gradually sloping inner terrace and a deep, but small central depression.
   b. The outer rim is a compressional structure.
   c. The rim was partly enlarged by Late Glacial, aeolian sedimentation.
   d. The inner terrace is made up of the till layer which constitutes the former, now sagged pingo skin.
   e. The central deep depression largely represents the former pingo crater. Overall there was minor lateral displacement of material by pingo action, compared to examples from elsewhere.
3. Most characteristics point to a closed-system origin in a Pleniglacial alluvial valley. The overburden only comprises the till layer in both large and small former pingos, which may indicate some artesian supply during ice lens growth.
4. Late Glacial aeolian sands accumulated in the area and also in the decayed pingos, soon accompanied by organic detritus and especially loess.
5. Holocene peat growth in the lows, together with soil formation of the podzolic type, were the most recent natural processes in the area.

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References

Black, R.F. 1976. Periglacial features indicative of permafrost: Ice and soil wedges – Quat. Res. 6: 3–26

Bijlsma, S. & G.W. De Lange. 1983. Geology, palynology and age of a pingo remnant near Daarle, province of Overijssel, The Netherlands – Geol. Mijnbouw 62: 563–568

Casparie, W.A. & W. Van Zeist. 1960. A Late-Glacial lake deposit near Waskemeer (Prov. of Friesland) – Acta Botan. Neerl. 9: 191–196

Cleveringa, P., W. De Gans, E. Kolstrup & F.P. Paris. 1977. Vegetational and climatic developments during the Late Glacial and the early Holocene and aeolian sedimentation as recorded in the Uteringsveen (Drente, The Netherlands) – Geol. Mijnbouw 56: 234–243

Cnossen, J. 1961. De bodem van het Boven-Boornegebied – Fryske Akademy 178, Wâldrige 9, Laverman, Drachten: 95–116

De Gans, W. 1976. Dobben op het Drents plateau – K.N.A.G. Geogr. Tijdschr. 5: 354–364

De Gans, W. 1980. Outlines of the Late Quaternary history of the Drentsche Aa valley, Drente, The Netherlands – Geol. Mijnbouw 59: 353–362

De Gans, W. 1981. Stratigraphy, palynology and radiocarbon data of Eemian and early Weichselian fluvial deposits in the Drentsche Aa valley system, Drente, The Netherlands – Geol. Mijnbouw 60: 193–202

De Gans, W. 1982. Location, age and origin of pingo remnants in the Drentsche Aa valley area, The Netherlands – Geol. Mijnbouw 61: 147–158

De Gans, W. 1983. Lithology, stratigraphy and palynology of Holocene deposits in the Drentsche Aa valley system – Geol. Mijnbouw 62: 285–296

De Gans, W. & P. Cleveringa. 1981. Stratigraphy, palynology and radiocarbon dating of Middle and Late Weichselian deposits in the Drentsche Aa valley system, Drente, The Netherlands – Geol. Mijnbouw 60: 373–384

De Gans, W. & P. Cleveringa. 1986. Het Ballooërveld – Grondboor en Hamer 40: 137–150

De Gans, W., P. Cleveringa & W. Gonggrijp. 1984. Een ontsluiting in de wal van een pingo ruïne nabij Papenvoort – RIN-rapport 84/6, Rijksinst. Natuurbeheer, Leersum

De Gans, W. & H. Sohl. 1981. Weichselian pingo remnants and permafrost on the Drente Plateau, The Netherlands – In: A.J. Van Loon (ed): Quaternary Geology: a farewell to A.J. Wiggers – Geol. Mijnbouw 60: 447–452

Edelman, C.H. & G.C. Maarleveld. 1958. Pleistozän-geologische Ergebnisse der Bodenkartierung in den Niederlanden – Geol. Jahrb. 37: 639–684

Flemal, R.C. 1976. Pingos and pingo scars: their characteristics, distribution and utility in reconstructing former permafrost environments – Quat. Res. 6: 37–53

Kolstrup, E. 1986. Reappraisal of the upper Weichselian periglacial environment from Danish frost wedge casts – Palaeogeogr. Palacoclimatol. Palaeoecol. 56: 237–249

Maarleveld, G.C. & Van den Toorn. 1955. Pseudo-sölle in Noord-Nederland – T.K.N.A.G. tweede reeks, deel LXXII 4: 344–360

Mackay, J.R. 1963. The Mackenzie Delta area, N.W.T. – Geogr. Branch, Can. Dept. Mines Tech. Surv., Mem. 8: 202 pp

Mackay, J.R. 1973. The growth of pingos, western arctic coast, Canada – Can. J. Earth Sci. 10: 979–1004

Mackay, J.R. 1987. Some mechanical aspects of pingo growth and failure, western Arctic coast, Canada – Can. J. Earth Sci. 24: 1108–1119

Müller, F. 1959. Beobachtungen über pingos – Detailuntersuchungen in Ost Grönland und in der Kanadischen Arktis – Medd. Grønland 153: 127 pp

Nossin, J.J. 1961. De reliëf ontwikkeling in Zuidoosterlijk Friesland – Fryske Akademy 178, Wâldrige 9, Laverman, Drachten: 48–70

Paris, F.P., P. Cleveringa & W. De Gans. 1979. The Stokers Dobbe: geology and palynology of a deep pingo remnant in Friesland (The Netherlands) – Geol. Mijnbouw 58: 33–38

Pihlainen, J.A., R.J.E. Brown & R.F. Legget. 1956. Pingo in the Mackenzie Delta, Northwest Territories, Canada – Bull. Geol. Soc. Am. 67: 1119–1122

Pissart, A. & H.M. French. 1976. Pingo investigations, north-central Banks Island, Canadian Arctic – Can. J. Earth Sci. 13: 937–946

Ploeger, P.L. & W. Groenman-Van Wateringe. 1964. Late Glacial pingo and valley development in the Boorne region near Wijnjeterp, province of Friesland, The Netherlands – Biul. Peryglacj. 13: 199–223

Ter Wee, M.W. 1966. Toelichtingen bij de geologische kaart van Nederland 1:50.000 Kaartblad Steenwijk Oost (16O) Rijks Geol. Dienst (Haarlem)

Ter Wee, M.W. 1979. Toelichtingen bij de geologische kaart van Nederland 1:50.000 Kaartblad Emmen West (17 W) – Emmen Oost (17 O) Rijks Geol. Dienst (Haarlem)

Van der Hammen, Th. 1952. Late-glacial flora and periglacial phenomena in the Netherlands – Leidse Geol. Meded. 17: 71–184

Veenenbos, J.S. 1954. Het landschap van Zuidoostelijk Friesland en zijn ontstaan – Boor en Spade 7: 111–136

Washburn, A.L. 1979. Geocryology: A survey of periglacial processes and environments – Edward Arnold (London): 460 pp