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Major lateral sediment displacement in till-sand-peat associations of the Tjonger Valley fill (the NE Netherlands) – Holocene cryoturbation?

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Abstract

Attention is drawn to an extraordinary type of large-scale cryoturbation in the Tjonger Valley fill (NE Netherlands). A large lateral displacement of sediments, involving sand and till intrusion, is the most conspicuous feature. Sand intrusion has been found especially in gyttja and peat, whereas till and some loam intruded into sand. In the former case elongated ridges, some 10's × 100's metres wide, exhibit dipping layers, partly with extensive folding and some thrustplanes. Till intruded from part of the valley margin into sand layers with an abundance of flow structures and some rare thrusts.

Intrusion of the sand into gyttja and peat presents opportunities to date the event. The first indications point towards an early Holocene age. Major cryoturbation was previously only known from the Pleniglacial of the last ice age in the Netherlands.

Density inversions over thawing permafrost, in a watersaturated environment, are thought to have induced gravity spreading in the vast, but discontinuous layers of various compositions. The type of cryoturbatic structure encountered within deposits not only strongly varies with composition, but also with the dimensions of layers of the same composition.

Introduction

Observation of clastic deposits near the surface of SE Friesland indicates, that deformation structures are widespread and that they are most likely caused by cryoturbation. Age, composition, origin, and setting of the deposits rule out other possibilities such as rapid sedimentation (Owen 1987, Mills 1983), a watersaturated character due to compaction (Morgan et al. 1968, Stel 1976), liquefaction by earthquakes (Leeder 1987) or flooding.

Postsedimentary deformation following freezing of surficial sediments can be due to sediment mobilization by repeated freeze-thaw or by density inversions in super-saturated thawing sediments (e.g. French 1976). The latter process is thought to occur in the vicinity of waterbodies (French 1976, Vesajoki 1982) and on thawing permafrost (VandenBerghe & Van den Broek 1982). Although strong mixing can occur during cryoturbation, vertical displacement is generally the major factor in sediment movement.

A major lateral displacement of sediment in this type of deformation structures was discovered during land management activities in the 500–700 m wide Tjonger Valley, south of the village of Haule (location in Fig. 1). The exposed area measures approximately 75 hectares with nine 1–2 m deep ditches running nearly perpendicular to the valley trend. Sand intrusions lie as linear ridges (some

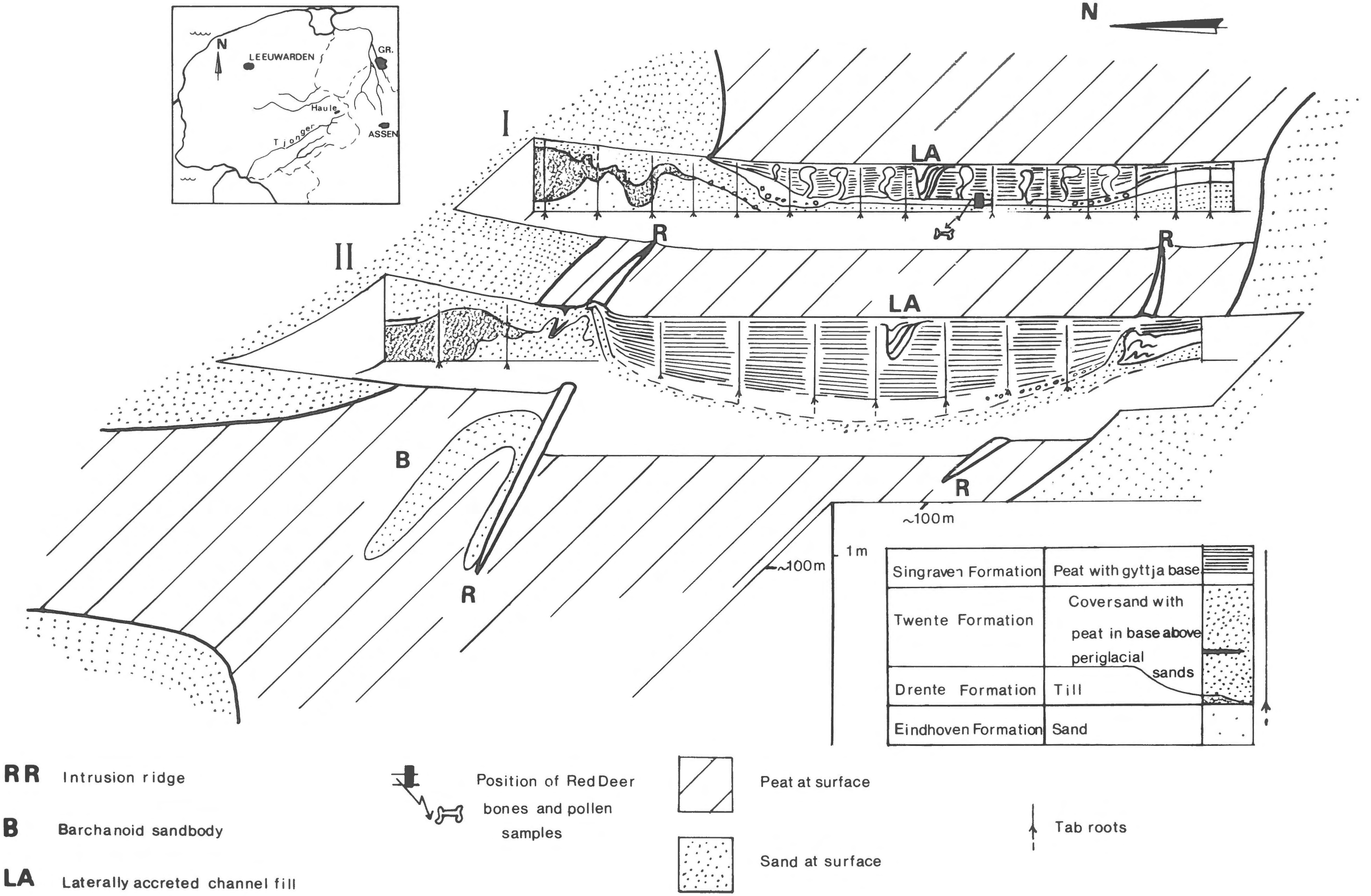

Fig. 1. Locality diagram showing the geometry of the Tjonger Valley structures. The horizontal dimensions are strongly reduced (see scale). The main phenomena are therefore presented schematically only. Inset at the lower right gives stratigraphic position of the deposits. Inset at upper left marks the position of the Tjonger Valley south of the village of Haule, province of Friesland, the Netherlands.

10's × 100's of metres wide) in the peat-gyttja top of the valley fill, and, specifically at the northern flank, the till and locally also loam intrude adjacent sands over distances of up to 100 m.

Geology

The Tjonger Valley fill, which is bordered by Saalian till with a thin coversand top, contains several metre-thick fluvioperiglacial sands with peat on top (De Groot 1987). A thin, marginal peat layer is intercalated between fluvioperiglacial sands below and coversand of the Twente Formation above (Fig. 1). Ochre-coloured gyttja is found at the base of the Singraven Formation (Fig. 1) and consists largely of clastic, silt-sized grains (cf. Van der Meulen 1988). Thin sheets of gravel occur in the gyttja at some locations (Fig. 1, section I). The other, darkbrown deposits of the Singraven Formation are designated peat deposits, despite the presence of some silt (decreasing upwards and away from the margins) and occasionally of algae remains (De Jong 1989, pers. comm.). The laterally-accreted fill of a meandering river (LA in Fig. 1) consists largely of wood debris. Metre-long tab roots are abundantly present in the top of the deposits.

Description

Sand-gyttja ridges in peat

In the studied valley segment, along each margin, a roughly 200 m long sand ridge is found, coincident with a strong reduction in peat thickness (Fig. 1). Eastwards the ridges decrease in height and disappear near to the traverse, where the peat is only 1 m thick (section I in Fig. 1) and where the gyttja and coversand lie at minimum depths. In the ditch exposure of section I, at 5–10 m intervals, small, vertical gyttja intrusions protrude upwards nearly to the top of the peat sequence. During the investigations a largely complete skeleton of a Red Deer and some smaller bone concentrations of the same species were discovered in the gyttja of the traverse (Van der Meulen 1989).

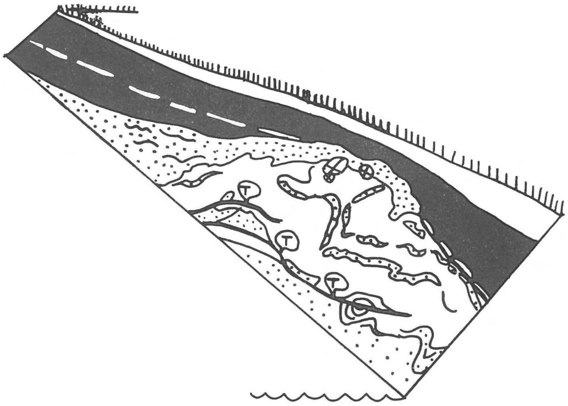

Fig. 2. Cross section of sand intrusion as exposed in wall of drainage ditch. Boulders are situated at the top of the intrusion. In the lower part of the outcrop thrustplanes can be recognized. The vertical height of the exposed face is 1.0 m, the horizontal length is about 15 m. The ditch wall dips 45°. Legend in Fig. 4.

Characteristic sections of the ridge and vertical intrusion structures are presented in Figs 2 and 3, as tracings of two photographs in the latter article. The valleywards-dipping sand layer of the ridge section in Fig. 2 possesses a flat, upper end, associated with up to 30 cm large erratic boulders and pebbles. The peat cover is tilted, but otherwise undisturbed. In the foreground the gyttja underneath the sand layer is folded, together with thin sand layers intruded in the upper parts. There are also two thrustplanes. This ridge could be traced from ditch to ditch and stood out from the dark ploughed peat lands, as a several metres wide, light-coloured sandy band with distinct concentrations of pebbles and boulders.

In general folds and thrustplanes accompany sand intrusion structures. The vergence of the structures is always towards the adjacent margin. The ridges locally merge with the till and sand of the valley margins and then till streaks are incorporated in the sand intrusion. Updoming of the peat layers above the ridges is often manifest, occasionally small supplementary intrusions emerge from the ridge top into the peat cover.

The isolated vertical intrusions in section I of Fig. 1, with exposures occupying only one side of the ditch at a time, consist of ochre-coloured gyttja lumps floating in the peat. The gyttja can still partly

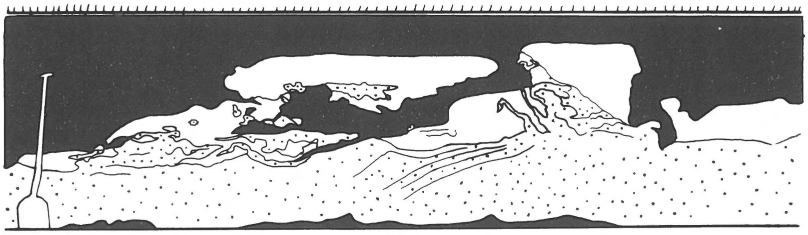

Fig. 3. This exposure of a vertical intrusion, although relatively large, occupies one side of the ditch only. Sand and gyttja are intercalated in the peat. Shovel for scale. Legend in Fig. 4.

be connected to the undisturbed layer underneath, and in the larger structures coversand can be incorporated as in Fig. 3.

Maximal (exposed) size of ridge cross sections

In part of the study area large, barchan-shaped coversand deposits (B in Fig. 1) lie at the mouth of a tributary valley. The injected sand ridge merges with the southernmost flank of the barchan-shaped body, and here the largest cross sections are found (1.8 × 30 m^2 maximum). Figure 4B, C shows a strongly folded sand-gyttja interlamination, overlying a thrustplane (detail in Fig. 5b) in one of these sections. Underneath this plane chaotically deformed gyttja is intermingled with sand. A major injected sandbody deforms the laminated coversand ridge at the base, directly above the sphagnum peat layer, and protrudes at the top as a sand ridge (Figs 4A, 5a). This ridge continues laterally over a distance of more than a hundred meters. Some sand has been intruded in the coversand base through the sphagnum peat layer. The overlying peat is disturbed by a small vertical intrusion in the southern parts (Fig. 4C).

Intrusion of low permeable sediments (till and loam)

In Fig. 4D, E the type of deformation affecting low permeable sediments is summarized. A wedge of light-grey loam (on the left hand side of Fig. 4E) with slightly inclined top and nearly vertical, concave upwards base passes into a (here largely severed) trunk. The thin peat layer underneath is heavily disturbed and the adjacent sand-loam interlamination is tilted. A vertical sanddike crosses the ridge parallel to the ntrusion front.

In the till intrusions flow structures generally dominate with till-sand mixing to a variable degree and till linings in decimetre-scale-layered sand. Fold and thrust structures are almost completely lacking. Only a duplex, which affects both the sands above as underneath the intrusion plane, was occasionally observed.

Outside the valley till-sand mixing occurs in various forms; from simple interfingering on a decimetre-scale to sag features such as canoe structures (cf. Kuenen 1958) on a metre-scale. In shallow depressions flow structures have been observed.

Interpretation

Environmental reconstruction

The till layer along the southern Tjonger Valley bends downward before wedging out; according to De Groot (1987) this often encountered feature implicates valley development during the Saalian glaciation. Intrusion into adjacent sand out of the till top, in places along the northern valley margin, deviates from this general picture. Extension of the till into the valley, locally even crossing major parts of the valley, as discovered in the nearby upper Vledderdiep Valley, is probably also caused by selective glacier action.

In the Late Glacial, after phases of extensive alluvial sedimentation during the Pleniglacial of the Weichselian, windblown coversands dammed the upper Tjonger Valley at several localities. The

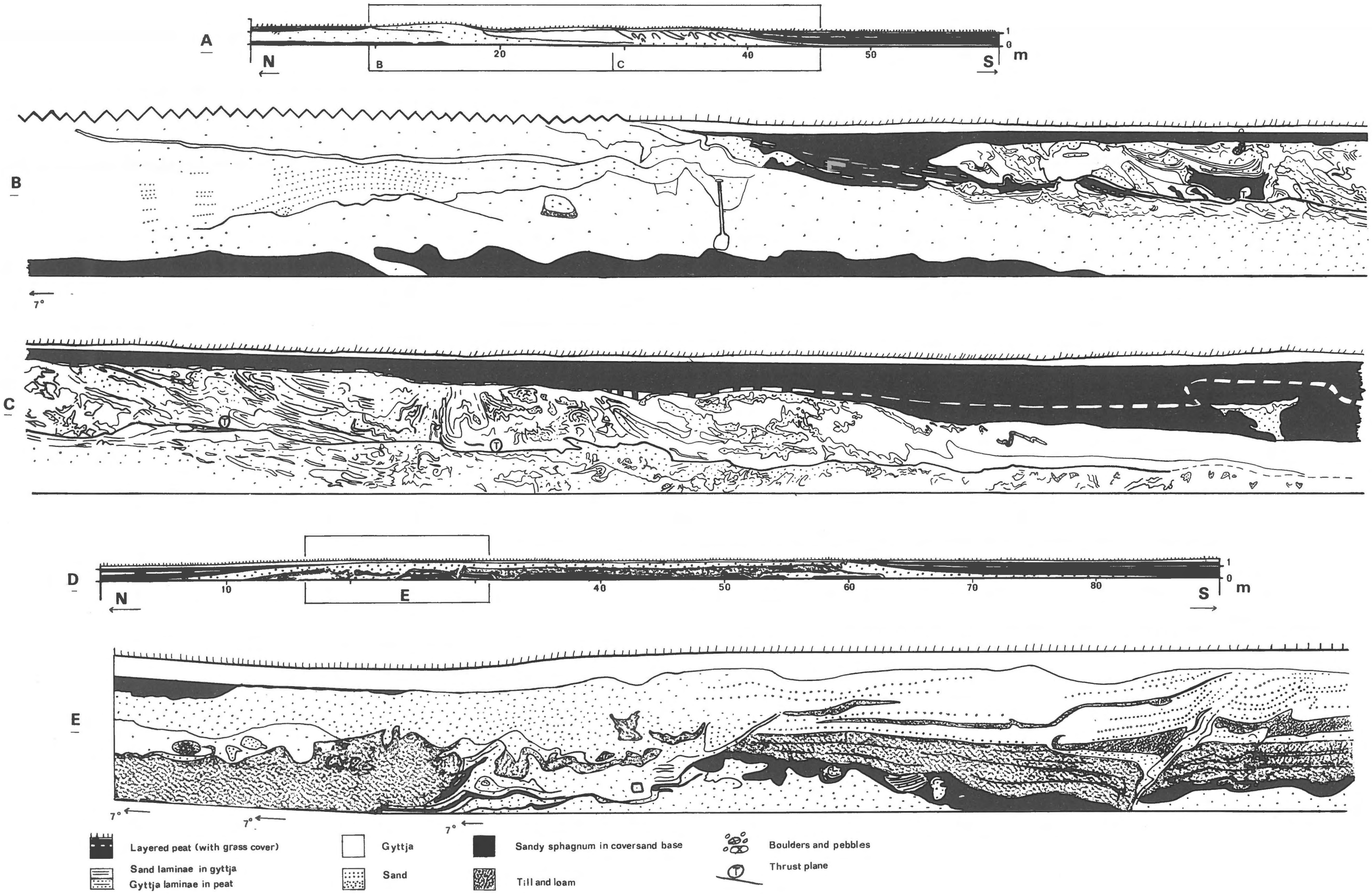

Fig. 4. Figures 4A and 4D give the relief of two sections of coversand ridge B of Fig. 1. The locations of two tracings of colour photographs in Figs 4B, C and 4E are indicated in Figs 4A and 4D respectively. The ditch wall dips 37°. In Fig. 4B the main intrusive sandbody lies on top of a sphagnum peat layer. The top of the intrusion has been levelled (compare Figs 4A and 5a). In Figs 4B, C the strongly folded sand-gyttja body (front in Fig. 4B) overlies a thrustplane. The peat cover is updomed by a small vertical intrusion at the foot of the ridge (Fig. 4B). In Fig. 4E the massive loam passes laterally into a folded trunk. The vertical sand dike continues parallel to the trend of the ridge.

Fig. 5a. In this detail of Figs 4A, B the flank of the coversand ridge has been deformed by an intrusive sandbody (at the location of the shovel).

Fig. 5b. The thrustplane underneath the sand-gyttja interlamination is lined by a 1–2 cm thick sand layer (detail of foreground in Fig. 5a).

till extensions in the valley probably predetermined the dam sites.

In the later part of the Late Glacial windblown silt (loess) and organic detritus formed gyttjas in the shallow lakes in between the dams. Sheet wash off the valley margins and out of the tributary valleys reached into the lakes, which produced thin sheets of gravel and coarse- to fine-grained sand in the gyttja. These blankets cover about 50 × 150 m^2.

During the Holocene climatic amelioration, vegetation stabilized the soils throughout and the clastic sedimentation of both types ceased. The water levels in the shallow lakes dropped and peat growth started. In the final stages a small meandering river cut its course and forests were gradually established.

Origin of the cryoturbatic structures

The direction of intrusion, as expressed by the geometry of the ridges and by internal folds and thrusts, is typically upwards towards the adjacent valley margin. Slumps and fan-deltas would have shown reverse directions and besides this, the minor relief of the area and the outsize measures of the ridges rule out these possibilities.

The ridges are often encountered at steps in the valley profile (Fig. 1), where the peat, but not the gyttja, strongly decreases in thickness. Steepness in slope determined the angle of intrusion and thereby its character; a high relief led to deformation underneath the intrusion (as in Fig. 2), a low relief to deformation above the main intrusion (as in Fig. 4) with small vertical intrusions emerging at the foot of the ridge.

The small, vertical diapirs mostly intrude into a relatively thin peat layer, as in section I of Fig. 1, not in section II of that figure. However as the same peat level overlies (in an updomed fashion) the small vertical as well as the large lateral intrusions (as in Fig. 4C), a contemporaneous origin is evident.

The geometry and sand composition of the ridges show, that the periglacial and coversands of the Twente Formation intruded into the organic Singraven deposits. Liquefaction and consequent liquedization (Owen 1987) of part of the valley fill sands are prerequisites for the intrusive types of deformation. This mobilization of the sediments, which included also the marginal loam and Saalian till, must have taken place in an overall watersaturated environment. The thawing of permafrost is the sole likely cause, as only under such conditions large quantities of water become available in those diverse sediments, diverse both in age and composition. The complete top of the valley fill will have been unstable, as evidenced by the lateral continuity (hundreds of meters) of the ridges. Nevertheless, despite intrusion into the upper parts of the sequence, the topsurface was nowhere breached and this points to a delicate balance of powers. From its present exposed thickness it is clear, that at least 1.8 m of sediments could become deformed.

Upwards intrusion of liquefied sediments must have been due to density inversion, with water accumulation in the lower parts immediately on top of the impervious permafrost. Sand migration was accompanied by forcing of intercalated pebbles and boulders to the top of the large intrusions. The watersaturated gyttja remained rather viscous, and this induced local intrusion of the more mobile, liquedized sand, as well as folding and thrusting. Peat was even more viscous, than gyttja under these conditions, which hampered successful upward intrusion into the relatively thick accumulations. Till and loam became fluidized to a similar degree, and this led to flow structures and to mixing with available mobilized sands.

The exact site of intrusion was clearly determined by lateral discontinuities in the valley fill and periphery. Relatively thin peat layers (as in section I of Fig. 1) could not resist multiple vertical intrusion. Thicker peat accumulations on the other hand could conduct mobilized sand-water mixtures towards the margins, where intrusion could take place in the thinner parts. Ramberg (1981) modeled a situation of mobile rock underneath a solid cover. He showed, that undulations of the boundary plane are produced at regular distances depending on thickness, viscosity and density of the rocks. In time these undulations can evolve into diapirs, but lateral displacement may also occur. These two mechanisms must have been active also in the Tjonger Valley with both multiple vertical intrusions and marginal ridge intrusions into relatively thin and thick peat layers respectively. Lateral till and loam intrusions can also be explained by the lateral intrusion process.

In effect these lateral intrusion types illustrate gravity spreading, i.e. thinning of the sedimentary column by lateral redistribution (cf. Pedersen 1987). In contrast to the Pedersen model, however, the forces do not arise from a moving plate (glacier) above, but from an unstable situation, with mobile low density material in the basal parts. Therefore, it can be considered as a supplementary model to Pedersens large-scale gravity gliding and gravity spreading models from the natural, sedimentary environment.

Discussion of dating

The Red Deer bone finds from the gyttja were dated preliminarily as Late Glacial on the basis of lithostratigraphical features (Van der Meulen 1989). This dating was imposed by the most important type – major cryoturbation – as this type of structure is generally thought to be limited, for these regions, to glacial periods (e.g. French 1976). Subsequent palynological analysis showed that the bones are situated in a Late Dryas gyttja layer, just a few centrimetres underneath the Holocene base, and with even Boreal peat present in the lower decimetre (De Jong 1989, pers. comm.). Pollen data from sediment attached to the bones (Van Leeuwen 1988, pers. comm.) confirm, that the Holocene base is situated near the bone horizon. Although there is a location with Alleröd peat of considerable thickness in the Tjonger Valley (Stapert 1986), the data above are conform to the general Holocene dating (with a very thin Late Dryas base) of the Singraven peat (De Groot 1987). It is then conspicuous, that the top level of cryoturbatic structures near the bone locations lies some 50 cm higher than the established base of the Holocene.

Although Stapert (1986) mentioned some Holocene (Preboreal) peat from frost-fissure fills, especially Late Dryas (Weichselian) deposits from these regions can show (relatively small) frost-related structures (Maarleveld 1976, Stapert 1986). These structures, however, are not necessarily tied to permafrost conditions. De Groot et al. (1987) thought, that there was no permafrost in that period, as in that case the still well-developed fills of early Late Dryas mini-depressions at Scheemda in the NE Netherlands would certainly have been destroyed. Nevertheless, since that publication somewhat deformed mini-depressions were discovered, and these lie at the same stratigraphic level (confirmed by Ter Wee 1988, pers. comm.) underneath coversand with (also major) cryoturbation in the upper Vledderdiep Valley (Van der Meulen 1989). Furthermore, permafrost-related cryoturbation and palsa remnants from the Late Dryas have been described from the Belgian Scheldt Valley (De Moor 1981) and from the Ardennes (Pissart 1983), respectively.

In the Netherlands major cryoturbation has otherwise only been described from some Pleniglacial levels (Maarleveld 1976, 1981, VandenBerghe & Van den Broek 1982). In this respect it should be noted, that the large size of cryoturbatic structures is not directly indicative of severe permafrost-forming conditions. The major cryoturbation in the Netherlands probably originated during climatic amelioration (Maarleveld 1981), as frost fissures are lacking and the thickness of the corresponding active layer must have been measured in metres, rather than in decimetres. Furthermore, VandenBerghe & Van den Broek (1982) indicated, that the large amounts of water necessary for soft sediment deformation, during cryoturbation can only be available above degrading permafrost. The timing of permafrost degradation, and, thereby of cryoturbation, during climatic improvement is adversely influenced by attendent thickening of the vegetation, as this hampers absorption of summer heat, but not of winter cold in the soils (e.g. French 1976). Thus, major cryoturbation on permafrost, inherited from the Late Dryas and degrading in the Holocene, seems to have been possible in the NE Netherlands.

This date is strongly supported by the 5 dm thickness of cryoturbatic peat above the Pleistocene-Holocene boundary at fossil bone locations. As even Boreal peat is already present in the lower parts, at most a similar maximum age of the cryoturbatic event can be assumed.

Conclusions

It has been shown, that large-scale cryoturbation modified the top part of the Tjonger Valley fill and margins, south of the village of Haule (SE Friesland). Sedimentological arguments and palynological information indicate that the associated disappearance of (locally continuous) permafrost – as a clearly defined event – can have occurred in the early Holocene.

Cryoturbation originated during the thawing of the top of permafrost. Part of the thawed, liquefied sediments became laterally displaced due to gravity spreading in a situation with density inversion. In such an environment gravity spreading was induced by the major size of the layers in and along the valley, with sudden facies changes at the valley margins.

Lateral sediment intrusion and accompanying deformation as described here can be considered as an additional type to the examples given by Pedersen (1987) of sediment deformation on a medium scale, in between small-scale laboratorium products and large-scale tectonic structures.

Acknowledgements

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