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Dune dynamics and cryoturbation features controlled by Holocene water level change, Hietatievat, Finnish Lapland

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Abstract

The inland dune field at Hietatievat (Finnish Lapland) is derived from an esker and accumulated during the early Holocene. A spodosol developed in a humid climate at least until the end of the Atlantic. A generalized phase of cryoturbation occurred at that time, in the absence of permafrost and in response to a higher standing water level in autumn. As a consequence of forest fires and a lowering of the water level during the Subboreal, dunes were reactivated during the Subatlantic and are still active today. The frost susceptibility of the clean sand is related to amorphous clays and organic matter accumulated by podsolisation. Cryoturbations resulting from a negative gradient of frost susceptibility (the surface horizon is less susceptible to frost heave than the subsurface) and a high standing water table evolve into hummocks during periods with a low-standing autumn water table. These hummocks develop into pseudo-convective forms (mounds with a central injection). Features observed at Hietatievat are similar to those observed in aeolian sands at the Gåsebu site (Svalbard, continuous permafrost) and are governed by the same laws of mechanical deformation. Permafrost is not a prerequisite for the development of cryoturbation. These deformations can be used as analogs for the understanding of the Late Glacial phenomena of western Europe. Holocene changes in the hydraulic regime observed through the cryopedological approach seem consistent with the results obtained by other methods.

Introduction

In the literature (reviewed in Washburn 1979), cryoturbations are commonly attributed to a permafrost environment, especially when used for palaeoclimatic purposes. Field work performed on active cryoturbation in Svalbard (Van Vliet-Lanoë 1985, 1988, 1991) and experiments performed in Liège (Pissart 1982) and Caen (Coutard & Mücher 1985, Van Vliet-Lanoë 1988) have demonstrated that permafrost is not a prerequisite for the occurrence of cryoturbations. The aim of the present study, performed in June 1989, is to discuss active cryoturbations related to differential frost heave, and to understand their dynamics in a non-permafrost area. Frost susceptibility is the basic concept of this paper: it corresponds with the capability of a sediment to develop ice lenses and related heave. Heave and ice accumulation in soil are accentuated by high water retention, particularly in the form of water adsorbed on colloid surfaces, remaining unfrozen below 0° C (as low as – 40° C for pure clays).

Observations were carried out in the Hietatievat dune field (68°26′N, 24°40′E; Fig. 1A, B) which is associated with a large esker some 12 km NE of Nunnanen, Enontekiö, NW Finland, at an altitude

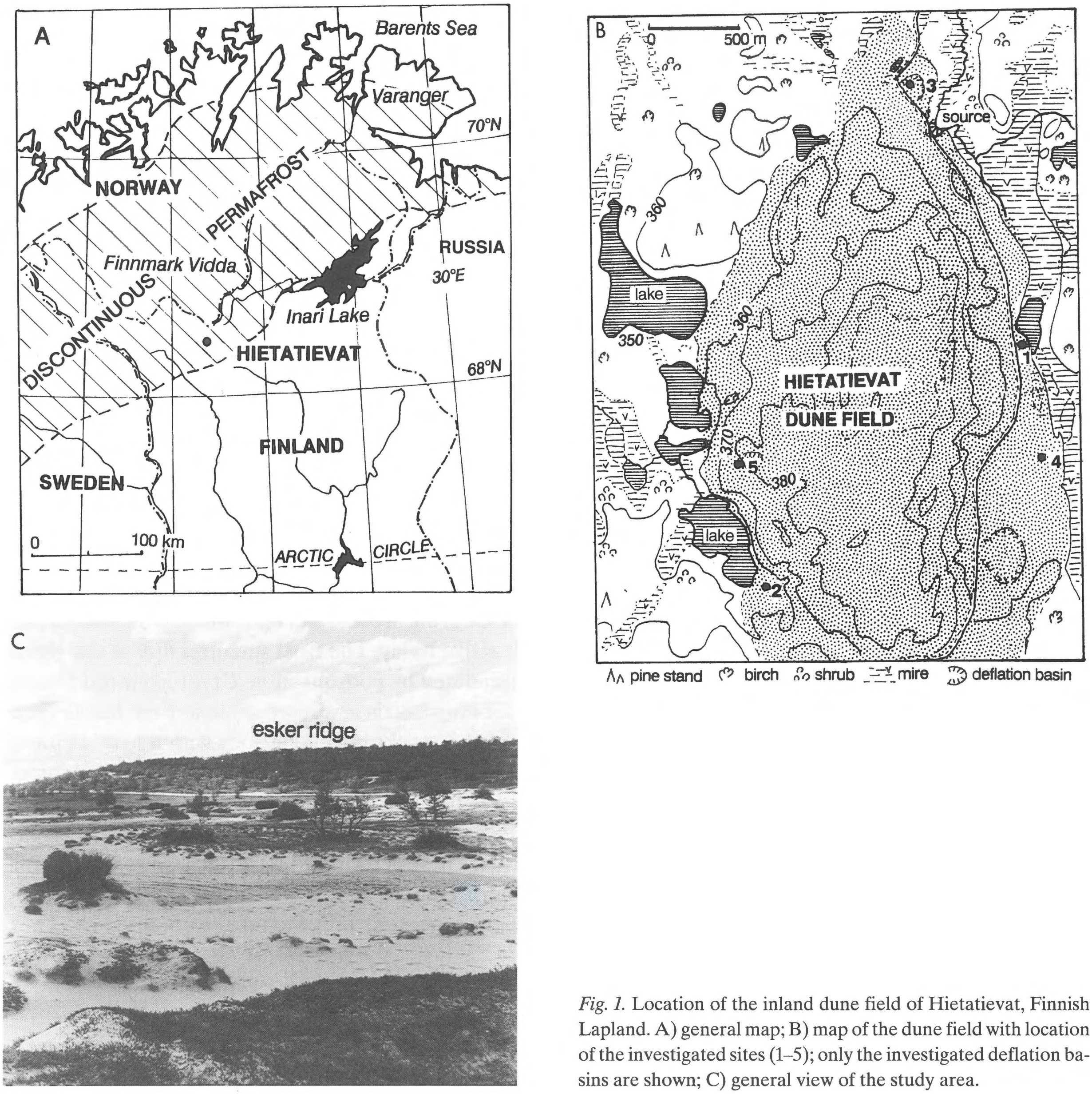

Fig. 1. Location of the inland dune field of Hietatievat, Finnish Lapland. A) general map; B) map of the dune field with location of the investigated sites (1–5); only the investigated deflation basins are shown; C) general view of the study area.

of 350 to 385 m above sea level (a.s.l.). The tree line is slightly above 400 m. This region was deglaciated around 9500 BP (Kujansuu 1967).

On both faces and on the top of the approximately 30 m-high esker (Fig. 1C) running towards the Norwegian border, aeolian and periglacial processes took place (Seppälä 1966, 1982, 1984, 1987). The vegetation succession has been studied by Tobolski (1975). Present-day deflation is related to forest fires and limited by the level of the water table (e.g. Seppälä 1981). The present soil is podsolic but its development is often limited to Arctic brown because of dryness (Ohlson 1957, Jauhiainen 1970). Buried soils associated with charcoal layers are frequently observed in dune fields in Lapland (Seppälä 1971, 1981). The cryoturbations at Hietatievat are observed in depressions only, reworking the surface and buried podsols.

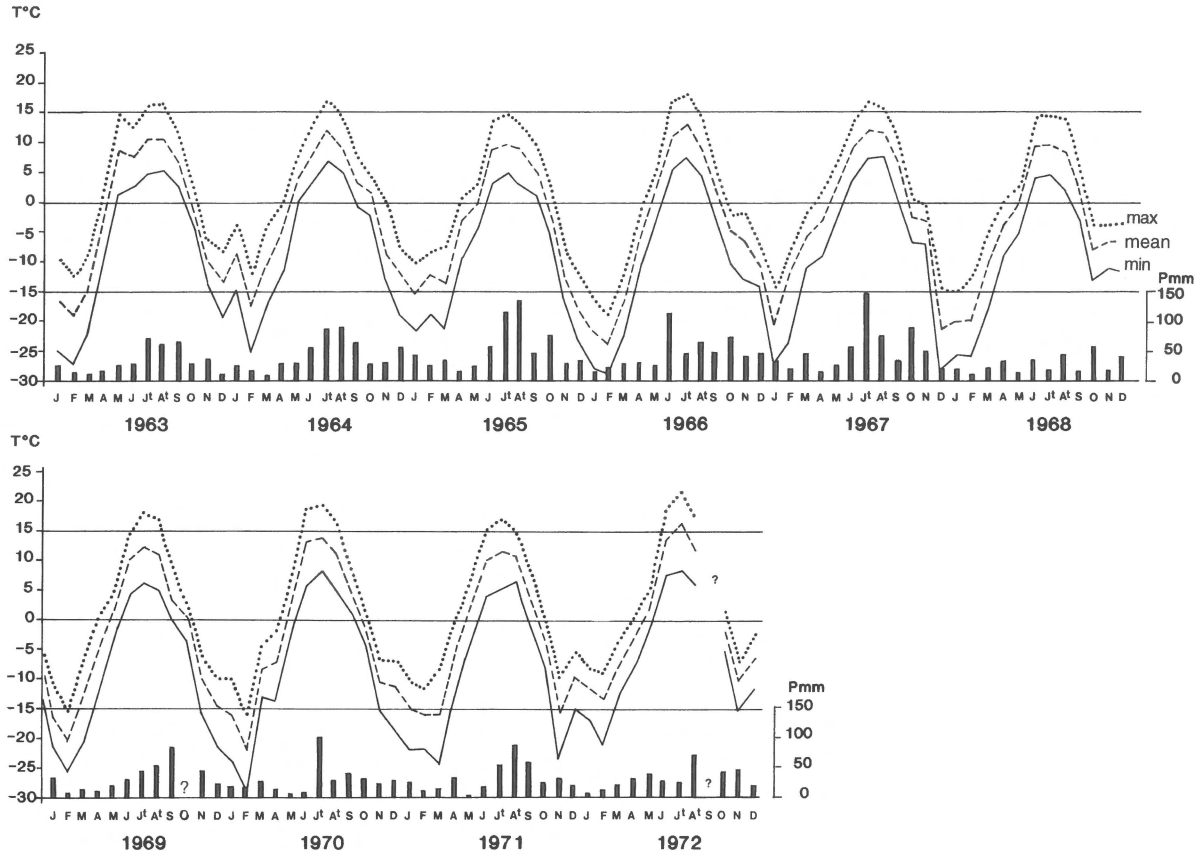

Fig. 2. Climate data at Kalman Kaltio border station, some 5 km of Hietatievat, site 3 (adapted from Kaÿhkö 1991). Monthly precipitation: black bars; mean monthly temperature: broken line, max. monthly temperature: dashed line; min. monthly temperature: solid line.

Environmental conditions

Climate

The mean annual air temperature reaches about – 2° C with a minimum of – 40° C (Kolkki 1966, Ohlson 1964, Käyhkö 1991). Annual precipitation is about 400 mm of which about 50% occurs between June and September (Helimäki 1967) (Fig. 2). The average annual frost penetration is 2 to 3.5 m in drained sites and about 50 cm in peatlands. Geoelectric soundings did not detect the presence of permafrost in the dune field (King & Seppälä 1987). Sporadic permafrost in the area is restricted to poorly drained plains covered by mires forming palsas (Seppälä 1979), with discontinuous permafrost developing above of the tree line (Fig. 1A).

Drainage

The dune field is immediately south of the water divide between the Baltic Sea and the Barents Sea. East of the dune field, a reticulated mire without palsas drains to the north into the Keähkkil River; a permanent spring has caused a small amphitheatre-like basin with a diameter of 60 m, east of the edge of the dune field (Ohlson 1957). The western side drains into a chain of lakes also flowing to the Keähkkil River, and draining into the Gulf of Bothnia. The ground water table in the dune field seems to be related mainly to the regional climate rather than to the external drainage (peatland and lakes). Peatlands surrounding the lakes commonly present thufurs or pounus and locally large palsas (south of the Hietatievat dune field). The highest lake surfaces around the dune field reach 356 m a.s.l. on the west side and 349 m on the east side. Geomorphological and lithological conditions are favourable to analyse climate-induced modifications of the drainage. In general, the ground water table in the deflation basins in the middle of June 1989 was between 35 and 200 cm below the surface. In most of the sites investigated for cryoturbation dynamics, a high water level was restricted to the bottom of depressions in an otherwise flat microtopography; the water level lowered (30 to 50 cm deep) towards the end of the soil thaw. Hummocky soils were moist (pF = 2.5) but had a water table deeper than 60 cm. Dune sands were already nearly dry (pF > 3) in mid June.

Methods

Profiles were excavated and described in detail (microstratigraphy and pedological development) in different basins with the aim of determining the history of the dune field. Four profiles were excavated, two in the dune field itself and two close to lake shores, to try to understand the relationships between general water level and dune mobility. Additional sites with varying microtopography were excavated to observe present soil dynamics and deformations related to frost, with the aim of understanding the meaning of the cryoturbated buried soils recorded within the dune. Micromorphological sampling was performed in order to check the soil genesis, the action of fire and the intensity of cryogenic diagenesis in soils in relation to cryoturbation. Macroscopic charcoal fragments from pine trees, *Juniperus* and birch are commonly associated with buried podsols and were used for ^{14}C datings. The ground water level was surveyed with piezometers.

Stratigraphy

On both sides of the esker a glacio-lacustrine, greyish sandy silt (unit A) exists which is generally subhorizontal and well-stratified, but locally shows thin cross laminations. It is highly frost-susceptible and responsible for many patterned-ground features developed at the bottom of deflation basins (Seppälä 1966, 1987) (see Fig. 3). It is mainly preserved on the northwestern face of the esker and at its foot, below the aeolian sand cover. Locally, coarser facies exist which are seemingly related to former fluvio-glacial channels.

Above this glacio-lacustrine unit, which is found at the base of most of the profiles and on the sides and the top of the esker, an aeolian sequence occurs. The more complete sequences are those recorded in the eastern deflation basins: the aeolian units seem to be correlated with basin formation.

East lake bank, site 1

The following sequence of sediments and processes has been described from the bottom to the top (Fig. 3-1):

- coarse sand of fluvio-glacial origin (unit A).
- fine sand, greyish (Fe^{2+}), of aeolian origin (unit B).
- surface stabilization characterized by peaty to sandy podsolic hummock development (unit D), associated with some charcoal, incised by a trace of shore ice: lake level 50 cm above its present-day position.
- massive cover sand, of aeolian origin (non-ashy) (units E and F).
- surface stabilization and podsolization (unit G).
- deformation by soil creep and cryoturbation (unit G).
- gullying (snowmelt, incising the topographical surface and associated with a lowering of the water table).

Close to this profile, in a shallow depression or palaeolake, the buried podsol (D) is developed in the form of a peaty hydromorphic podsol, which was cryoturbated afterwards.

Eastern deflation basins, sites 3 and 4 (Figs 3-3 and 3-4)

- coarse till with superposed silty sand of glacio-lacustrine origin (unit A).

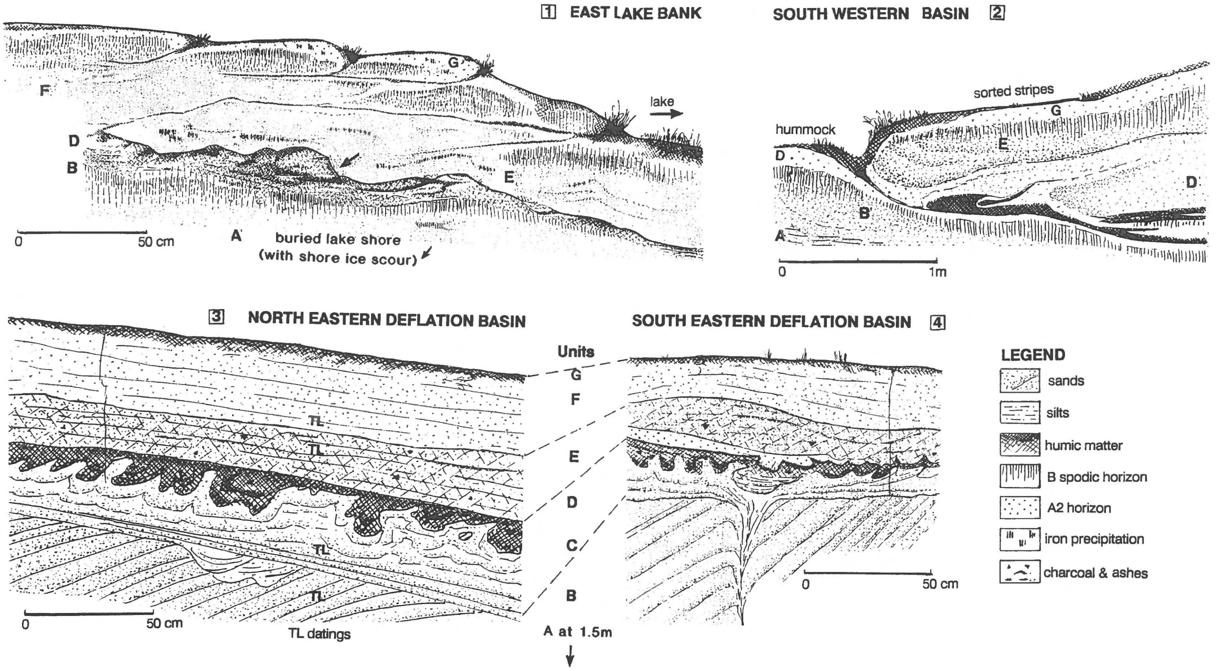

Fig. 3. Profile showing microstratigraphical record in Hietatievat. Site numbers refer to Fig. 1B. For description of units see text 'Stratigraphy'.

- first generation of greyish sand (unit B) of aeolian origin, with large-scale cross laminations.
- truncation by an erosional surface (rill).
- second generation of greyish sand (unit C) of aeolian origin, with oblique cross-bedding (change in direction, compared to B) and some traces of gullying. Syngenetic thermal cracking, in the form of a sand wedge (Fig. 3-4).
- buried soil development: podsol type (unit D), associated with pine charcoal.
- cryoturbation or solifluction after soil development.
- soil burned *in situ,* after cryoturbation or locally reworked after fire, sometimes in association with fallen trees (Fig. 4).
- greyish, ashy sand, coarsely stratified (unit E), with reworked burned humus, deposited in conformity with the podsol surface; aeolian origin.
- whitish, clean sand, often stratified (unit F), in conformity with the ashy sand.
- subactive to active aeolian activity.
- weak podsol development in moist sites only; weak arctic brown soil elsewhere (unit G). Rare thermal cracks, 60 to 100 cm long.

Southwestern basin, site 2 (Fig. 3-2)

- coarse sand, fluvioglacial (unit A).
- silty sand, lacustrine (unit A).
- fine sand (unit B).
- peaty layer with hydromorphic podsolization (unit D).
- cryoturbation phase (injection).
- hummock growth.
- surface stabilization and podsolization.

In large depressions, never degraded by present-day deflation, e.g. close to site 4 (Figs 1B and 3-4), the buried soil is preserved close to the surface (under a thin sheet, < 5 cm, of undifferentiated cover sand E or F) and also shows traces of fire, viz. ashes and charcoal. At other locations, on the eastern, leeward side of the esker, cryogenic activity was totally prevented by desiccation and not related to the occurrence of the present-day water table.

Pedogenesis and frost susceptibility of sands

We must understand why cryoturbations develop in

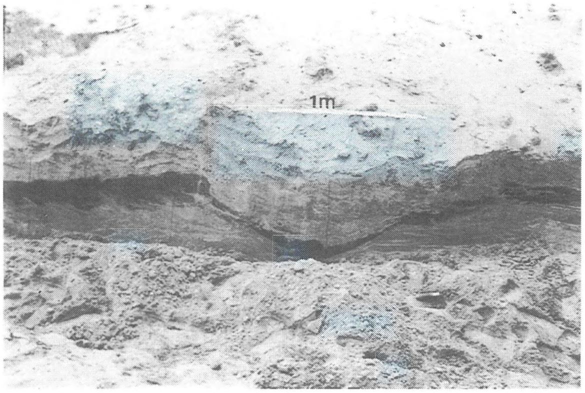

Fig. 4. Scar of a fallen tree, associated with fire, disrupting the palaeosurface characterized by the cryoturbated podsol (site 3). Same legend as Fig. 3.

originally clean sands. Since the cryoturbations in Hietatievat developed in relation to the podsolic buried soil, we first have to understand how pedogenesis is able to modify the frost susceptibility of the sands.

The sands and silts, derived from the esker, are rich in fragile minerals (susceptible to frost shattering, hydration and biochemical weathering) such as micas (10% in sands to 25% in silts), plagioclases (10%) and amphiboles (5% in sands to 15% in silts). Recent sands (units E, F) are much poorer in micas (2–5%) and amphiboles (2%). The median grain size of the aeolian sands is generally over 0.14 mm, and skewness is close to 1. Grain roundness is poor as described by Seppälä (1971) from the Kaamasjoki basin, Finnish Lapland, but somewhat better in the recent sands (unit F). The older, esker and dune deposits are more susceptible to pedological weathering, due to their mineralogical composition.

The soil record in this dune field is characterized by its rather constant type throughout the Holocene. In relation to the climatic conditions during the vegetative season, podsolization is mainly active in spring as described from Alaska by Ugolini (1986). Soil differentiation is mainly related to the local moisture regime and is most intense on the edges of depressions (humid but drained). Litter and humus are generally thin and weakly humified in the dry dunes. On young sands, the surface is commonly covered by a cryptogamic crust (algae, lichens and mosses) progressively invaded, with ageing, by grasses and Ericales. The dominant humification agent is mycelium with a weak contribution of acarids and diptera larvae (determined by the droppings in thin sections); this association is confirmed by the observations of Remmert (1980). Under the original pine tree stand, the litter of needles is rather thick, depending upon the fire frequency, and less humified than in more humid forests (Olsson 1983). In moist but not waterlogged sites, the grassy vegetation is associated with lichens, mosses, Ericales and shrubs of willow and *Betula nana.* During summer, when the soil is drained but not dry and rather susceptible to fire, humification is intense because of the high activity of mycelium and soil fauna (abundant droppings of collembola, acarids and oribatid mites in thin sections, Fig. 5B). The role of soil fauna is important because the organic fragments and/or droppings are intermixed with the mineral matter; well-digested or decomposed organic fragments have a high retention surface for adsorbed water. Water retention of organic matter is about ten times higher than in mineral soils (at field capacity: pF 1 instead of 2.5).

During the optimum soil development (unit D), the main water level was rather high and a distinct Bs horizon occurred with amorphous clay accumulation (imogolite; Farmer 1986), clearly visible in blue-light epifluorescence microscopy (Van Vliet-Lanoë 1980; Fig. 5D). Bacterial iron precipitates developed along root tracks in the banks of depressions (Fig. 5C). This iron precipitate, now disrupted by frost shattering, formed when frost penetration in the wet depression was shallower and summer temperatures were probably higher than today. Imogolite is characterized by a microtubular fabric, enhancing water retention and frost susceptibility.

In several drained sites (NE of the dune field), the buried humus and Bs horizon are degraded by fire (dehydration and carbonization of the organic matter and amorphous clays) in association with leaching of ash particles and/or by mycelium activity (degradation of humus by hyphae in the form of bleached spots in the Bhs horizon). In hydromorphic sites, like in the eastern lake banks, buried organic remains are perfectly preserved and unweath-

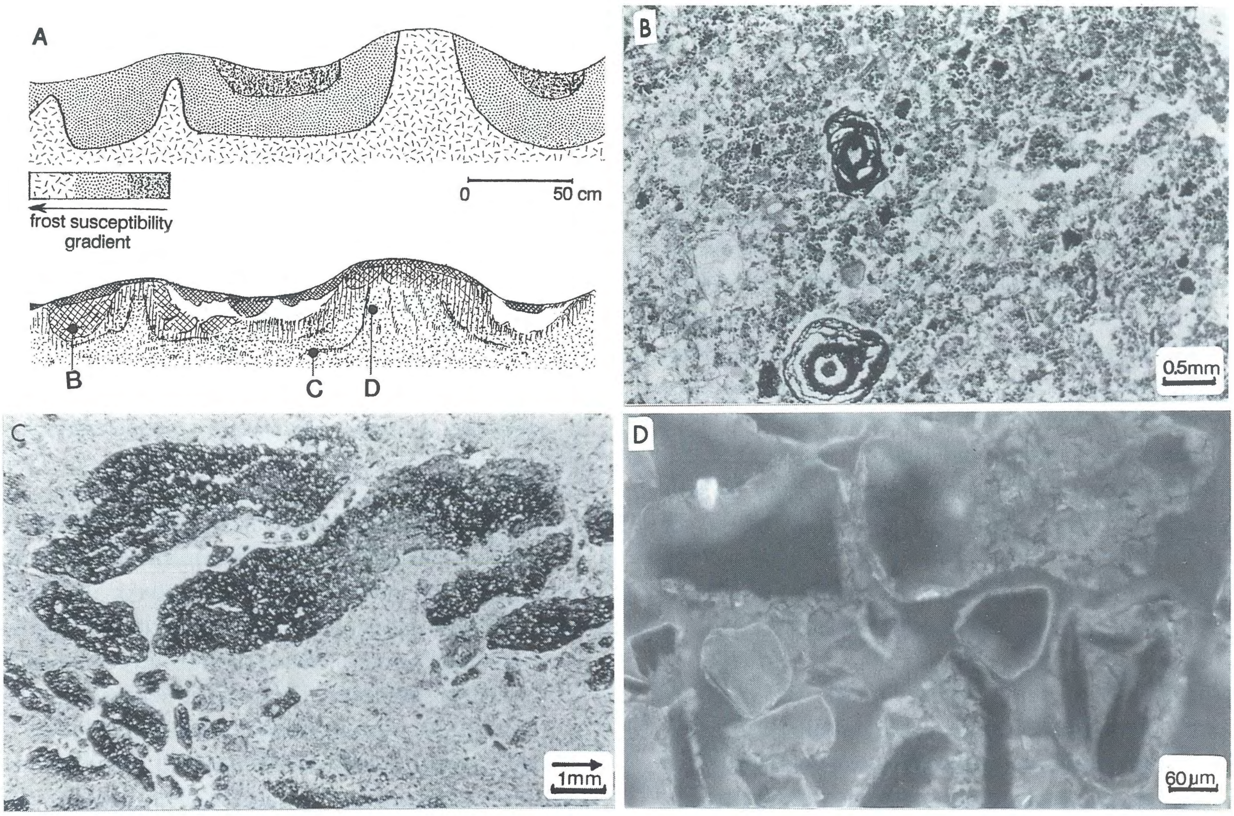

Fig. 5. Hietatievat, site 1. A) Shallow depression 20 m from the shore of the eastern lake. Letters indicate the location of the micromorphological samples of Figs 5B, C, D; same legend as in Fig. 3. B) Micrograph of the Bh horizon, rich in acarid droppings and burned grass remains (black); notice the faint oblique lamination inherited from ice lensing. C) bacterial iron hydroxyde nodules following root tracks; churned by cryoturbation. D) Microcracked imogolite coating on sand grains (micas and quartz), natural epifluorescence (blue light).

ered though the deeper horizons are commonly disrupted by intense cryoturbation.

To conclude, the accumulation of organic matter and amorphous compounds resulting from faunal activity and podsolization induces frost susceptibility in the previously non-susceptible sands (Van Vliet-Lanoë 1986). These compounds form a microporous coating on sand grains and microaggregates (droppings of fauna) accumulated between them. Pedogenic modifications lead to an increased water retention and also to an important hydraulic conductivity due to amorphous compounds, at temperatures below 0° C (Figs 5B, D). These coatings are burned away but can be restored by further pedogenesis under stable topography and vegetation cover. Moreover, the incorporation of organic or mineral, amorphous compounds in the sands drastically lowers the dry bulk density (from 1.7 to 1.2 (A1 horizon) or 1.5 (Bs)). In drained situations as observed in other sites (lacking cryoturbation) of the Scandinavian Subarctic region, the Bs is usually cemented (Femund lake, 1000 m, central Norway; Lakselv, northern Norway).

Cryogenic processes

From the above-mentioned observations, different mechanisms of cryoturbation can be inferred such as load casting and differential frost heave.

In the bottom of humid depressions at Hietatievat, simple cryoturbations occur which relate to differential frost heave, to the local frost susceptibility gradient and to a desiccation crack pattern, open by the lowering of the water table in spring. The occurrence of a Bs horizon, rich in amorphous compounds in moist sites, promotes the development of a negative gradient of frost susceptibility, similar to that existing at sites with shallow glacio-lacustrine silt below the dune sand. Injections of the Bs follow the crack pattern. These features are identical to those previously studied on permafrost at the Gåsebu site (Svalbard), developed in aeolian sands at wet locations (Van Vliet-Lanoë 1985, 1988). Gåsebu features are related to a shallow water table at the onset of frost (about 25 to 30 cm below the surface). This water table position observed in Gåsebu is not very different from the water level observed after thaw in depressions at Hietatievat.

Hummocky microrelief (site 1, Fig. 3-1) has developed around depressions characterized by simple cryoturbations, as it occurs normally when water is available for cryosuction (suction induced by thermal gradient and water crystallization) and frost heave. The heave ratios of the superposed soil horizons are not very significant but sufficient to promote a different expression (pF 2.5–3) in autumn. On both sides of the esker, all the profiles excavated in similar structures of various sizes (from 30 cm to 1 m in diameter) showed similar patterns. The mounds or hummocks result in a relief which corresponds approximately to the heaving of previous injections, following a crack pattern which churns the pre-existing soil horizons (Figs 5A, 6). This deformation seems specific for a negative gradient of frost susceptibility (Van Vliet-Lanoë 1988). The hummocky type of injections occurs by differential frost heave together with a lowering of the water table. It develops in topographic continuity with simple cryoturbations active in the lowermost position.

The most complex hummocks develop in lacustrine silt and also surround a depression (Fig. 6). They correspond exactly to those with central injection, leading commonly to the summital occurrence of mud boils, which are often described from the Mackenzie delta (e.g. Mackay 1983) and commonly associated with permafrost. No evidence of post-Atlantic permafrost at Hietatievat has been found, except in palsa bogs. Moreover, these large, fully developed hummocky forms, are buried close to the foothills by a post-fire solifluction probably associated with snowmelt water. Grass-bounded lobes (Fig. 3-2) buried the peat, leading on the east side of the esker (Fig. 7A) to stratified deposits (Jahn 1970). As in site 1, these hummocks are only located on the sides of the depression occupied by peaty cryoturbation and in topographic continuity with that cryoturbation. Their heave seems also related with a previous lowering of the water table.

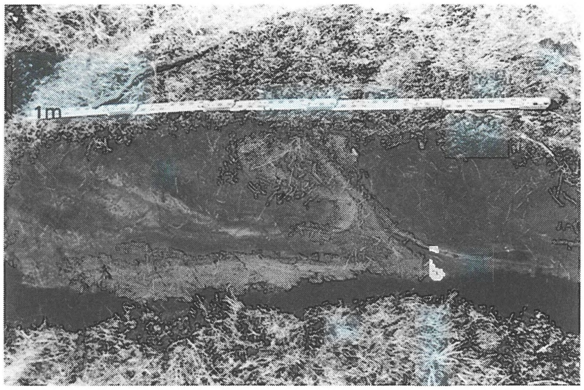

Fig. 6. Pseudo-convective hummock, located in the SW basin of Hietatievat (site 2). Stratification remains horizontal below the injection.

Load casting constitutes the second possible explanation, as proposed by Cegla & Dzulinski (1970) and Vandenberghe (1988). In this case, the density gradient is negative, soil horizons being less heavy than the original sand. The observed soil deformations at Hietatievat are similar to those observed in load casting but the drainage regime in spring, as discussed above, does not permit the required water supersaturation for this mechanism (Van Vliet-Lanoë 1991). Deformations by syngenetic frost-creep (Figs 3-3, 4, 7) demonstrate the activity of cryoturbations on low-angle, unsaturated slopes like in Gåsebu. Deformation induced by loading from sand accumulation, as discussed by Schwan (1990), cannot be advocated in Hietatievat, as in most of the sites cryoturbation developed before the deposition of the cover sands E and F.

The cohesion of the weakly cemented Bs horizon in site 1 (Fig. 5C) normally impedes liquefaction. The disruption of iron precipitations by ice and the heaving of the fragments observed in thin section show that cryogenic pressures develop seasonally before the formation of ice lenses (see Van Vliet-Lanoë 1988). As the geochemical conditions are unsuited for the formation of silty caps (stabilisation

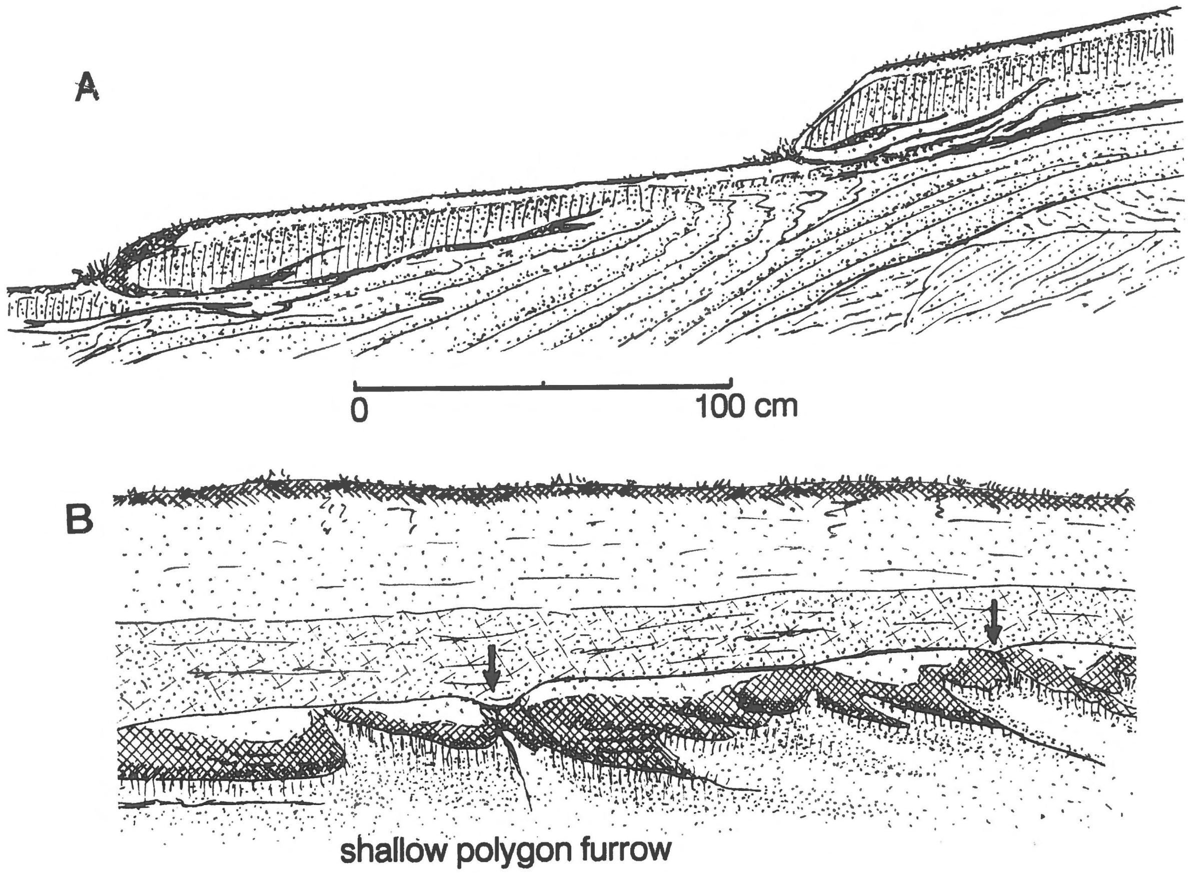

Fig. 7. Solifluction features at Hietatievat. A) Grass-bounded lobes, disrupting the main podsol, on the east flank of the esker ridge; B) features of cryoturbation associated with syngenetic frost creep: notice the shallowness of the thermal cracks (arrows); site 3. Same legend as in Fig. 3.

of fines by amorphous clays and Al hydroxypolymers), it is impossible to date this modification of frost penetration.

Datings and palaeoclimatic discussion

Before sketching the Holocene record of Hietatievat dune field activities, the available datings should be considered. Charcoal ^{14}C datings give ages from about 6000 to 600 BP for the forest fires in Kuttanen, Enontekiö (Seppälä 1981, 1984), with maximum activity between 6000 and 3500 BP (Fig. 8). For the Holocene we follow the new proposal of Fairbanks (1989) and Bard et al. (1990). As the fire cycles in taiga and boreal forest have a frequency of about one per century (Viereck 1973), we believe that most of these fires were probably natural, particularly during the Atlantic. Thermoluminescence datings of the sands give an age of 7230 and 7220 (± 400 BP) for units B and C (Radiocarbon Laboratory, University of Helsinki, H. Jungner). The boundary between these units only results from a small change in wind direction. The sand supply was local and resulted in large deflation basins which were occupied by lakes when the climate became more humid (Seppälä 1972). Unit E dates from 720 ± 230 BP and unit F from 670 ± 230 BP in the NE deflation basin (Fig. 3-3). These dates fit rather well with the ^{14}C age of the most recent fires and with the initiation of the deflation basins on the western face of the esker. The age of the deflation basins is also estimated between 500 and 1000 years on the basis of the evolution of the cryogenic microfabric in gla-

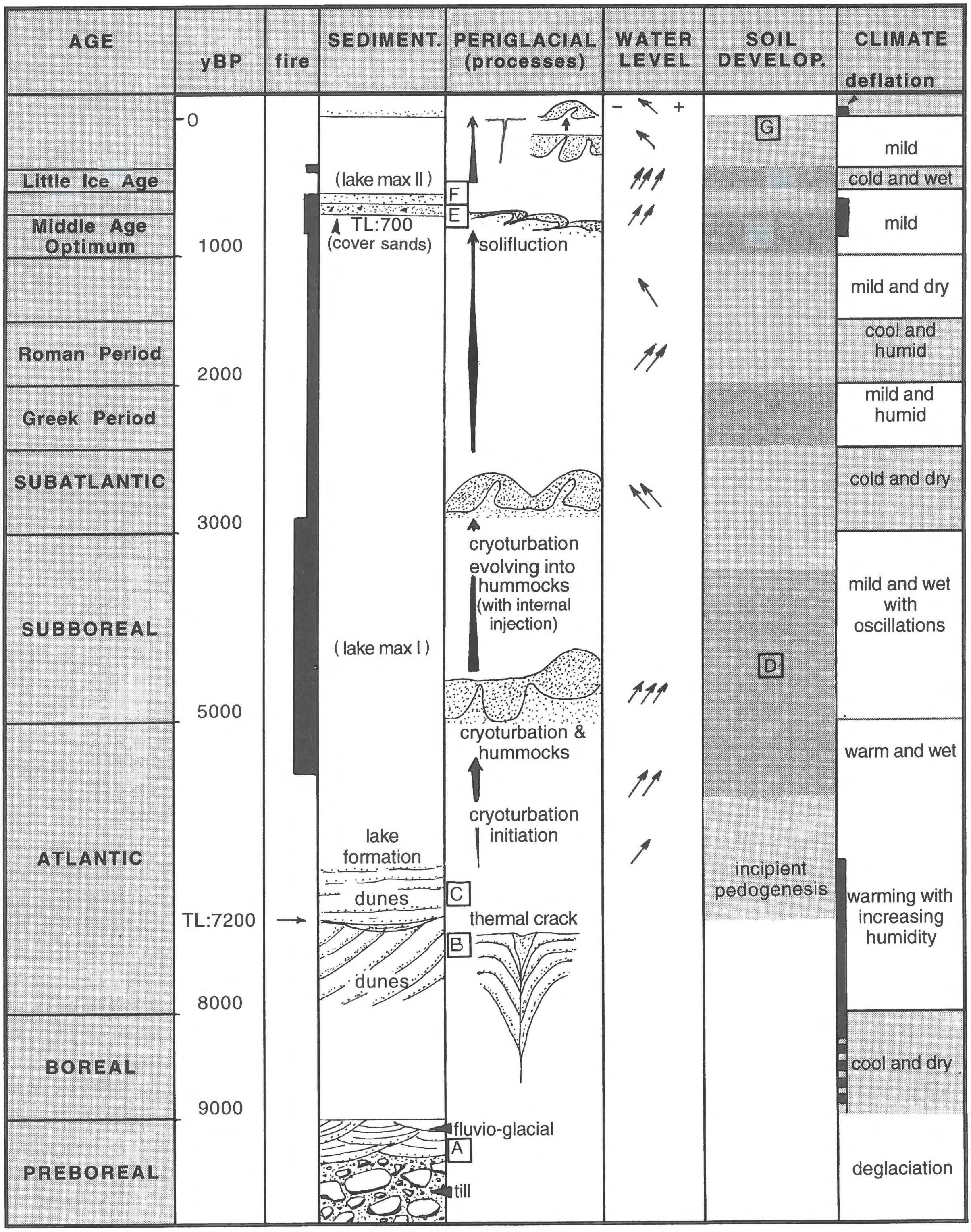

Fig. 8. Recapitulative pedostratigraphical log of dune field at Hietatievat. Climate, periods and boundary dates of the Holocene follow the proposal of Fairbanks (1989) and Bard et al. (1990). TL: thermoluminescence dates.

cio-lacustrine silts (thickness of the silt cap related to one effective freezing cycle/year, Van Vliet-Lanoë 1985) associated with the development of spring sand wedges (desiccation cracks) previously described by Seppälä (1982) (Fig. 9).

From these datings and the above-discussed observations (Fig. 8), it is clear that the buried soil (unit D) developed between the end of the Boreal and the end of the Atlantic in already humid conditions. Subsequently, this soil was perturbed by cryoturbation. By a rise in the water level (Fig. 10), most of the shallow depressions, which are currently surrounded by hummocks, were flooded. In the adjacent Kaamasjoki dune field, older field data result in a similar conclusion based upon dune dynamics (Seppälä 1971). Forest fires also took place during the Atlantic but apparently without any morphological implication (perhaps because of the high water table). The lowering of the water table related to hummocky development observed in sites 1 and 2 is also recorded in the northeast at site 3: the buried cryoturbated podsol is perched about 2 metres above the present-day water table (Fig. 3-3). Along the eastern lake shore (site 1), the E-F sand unit buried the hummocky peat, corresponding to a water level at least 50 cm higher than today (Fig. 3-1). These elements also argue for the existence of a general lowering of the water table at a time of frequent forest fires (humus burns when the soil is desiccated). This occurred somewhere between the end of the Atlantic and the post-fire solifluction in site 5. During the Subatlantic, usually dryer and colder in the Subarctic and Arctic regions (ex-Subboreal; Baranowski 1977, Nichols 1972), pedogenesis and fire were still active but with little impact (no aeolian deposits recorded at Hietatievat, weak weathering). Since the end of the Subatlantic, the moisture regime is more favourable for podsolization, cryoturbation and solifluction. Late Middle Age fires promoted the strongest reactivation of the dune field with initiations of the deflation basin (fallen trees, Fig. 4) and solifluction by destruction of the root mat. Fillion et al. (1990) arrived at similar conclusions for the inland dunes of N. Québec. Afterwards, the dune field was again stable for some time. Currently, it seems reactivated; the last recorded forest fire occurred about 1825 AD (Seppälä 1966). Its reactivation probably results from a combination of human interventions such as wood exploitation and overgrazing by reindeers. From evidence found at site 1, viz. the activation of a hummocky microtopographical evolution after the deposition of the E-F unit, we may assume that the dune remobilization of unit F also corresponds to a recent lowering of the water table. Around the eastern lake, the surface of the E-F unit forms a terrace. This general lowering of the water level could be attributed partly to the Little Ice Age but also to a possible present-day cooling (Petit-Renaud 1976, Eriksson 1987, Jones 1990). In northern latitudes, a warming trend raises the level of precipitation and a cooling trend lowers it (CLIMAP 1981, Bolin et al. 1986).

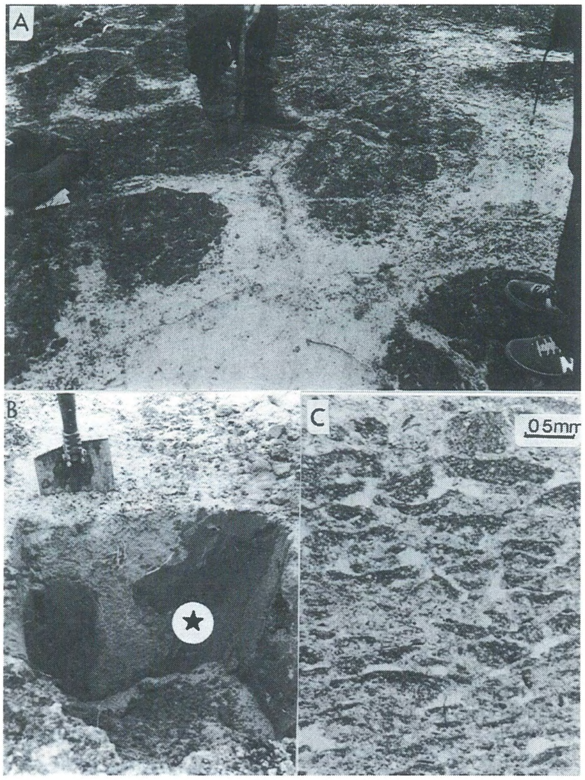

Fig. 9. Patterned ground in a glacio-lacustrine silt; deflation basin on the west flank of the Hietatievat esker ridge (site 5). A) Opening of the desiccation crack, 15 june 1989; B) wedge-like sandy infilling at the crack location, somewhat deformed by differential frost heave; C) microphotograph of the freeze-thaw microfabric in the silt (sample indicated by star in Fig. 9B).

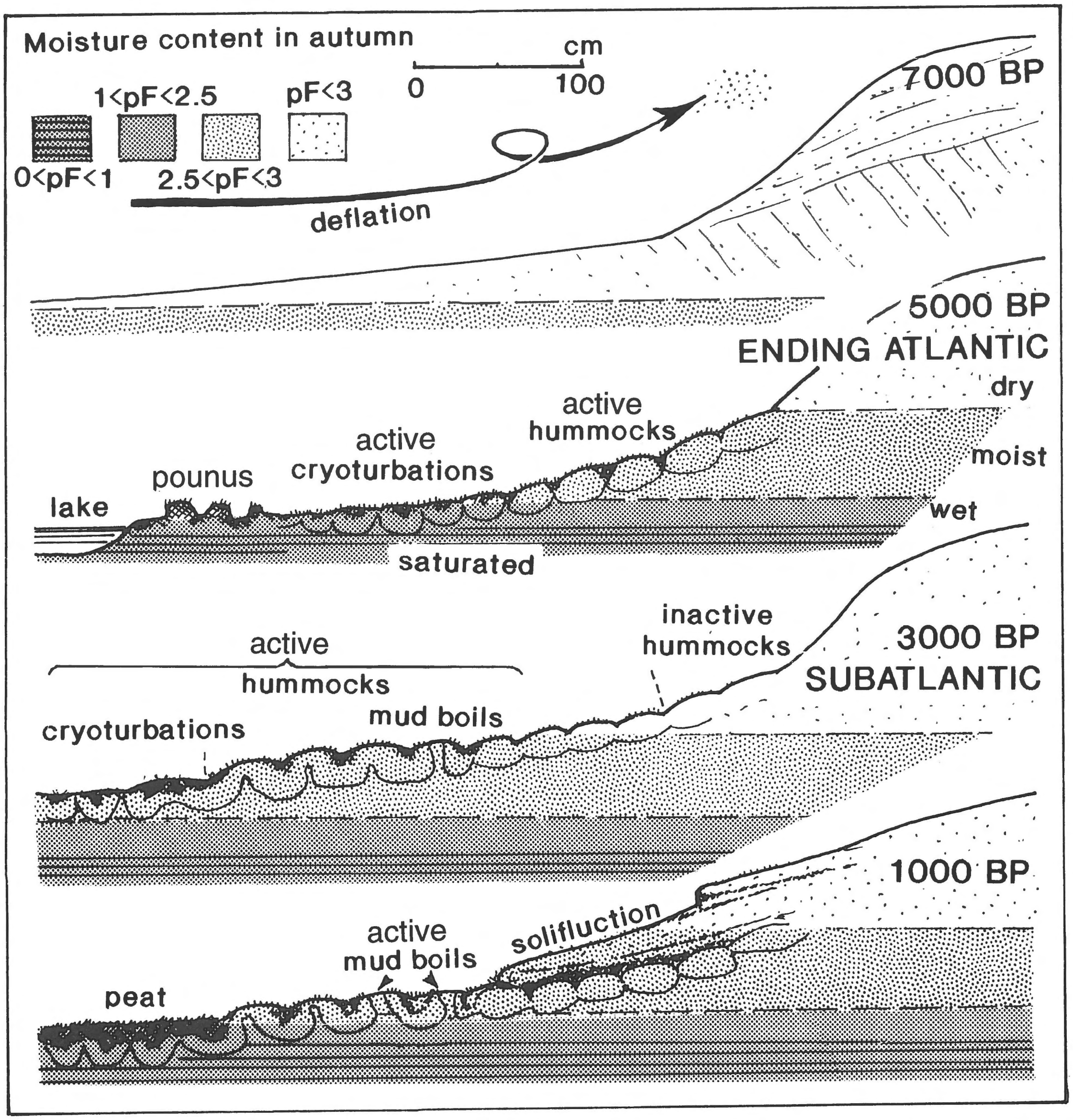

Fig. 10. General sketch of the Holocene evolution of the cryoturbated soil at Hietatievat, showing its relations with the probable change in the hydraulic regime.

Conclusion

Coordinated detailed studies performed on the same site allow a better understanding of the relations of aeolian activity, cryoturbation dynamics and the stratigraphic record with Holocene climate changes. This approach is coherent with recent developments in lake studies (Harrison et al. 1991). It illustrates that in the study area, cryoturbation is related to seasonal freezing rather than to permafrost. Cryoturbation is primarily associated with a higher water table. In relation to deep seasonal frost, most of the cryoturbation features can develop only in wet depressions outside permafrost areas. This observation is something to consider when interpreting the buried cryoturbation phenomena in western Europe for palaeoclimatic purposes (Van Vliet-Lanoë 1985, Seppälä 1987).

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