An experimental study of the formation of palsas

MATTI SEPPÄLÄ
Department of Geography, University of Helsinki, Hallituskatu 11-13, SF-00100 Helsinki 10, Finland

A hypothesis of palsa formation has been tested experimentally in the field in northern Finland. Snow layers were deliberately removed from a peat bog surface several times during three winters. This caused the seasonally frozen layer to almost double in thickness below the surface of the experimental square, and part of this frost then survived through the summer. The cyclic development of palsas is discussed and a process of palsa formation exemplified. It was shown that the thickness of the snow-cover is the main factor controlling palsa formation in subarctic conditions.

L'auteur a testé expérimentalement *in situ* une hypothèse de formation de palses dans le Nord de la Finlande. A plusieurs reprises au cours de trois hivers successifs, on a enlevé la neige de la surface d'une tourbière. Il en est résulté un doublement de l'épaisseur du gélisol sous la parcelle expérimentale et une partie de celui-ci a persisté tout l'été. Ceci permet à l'auteur de discuter le cycle de développement des palses et d'illustrer un processus de leur formation. Il apparaît que l'épaisseur du couvert nival est le principal facteur contrôlant la formation des palses en milieu subarctique.

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Introduction

Palsas are ice-cored peat hummocks which can have a frozen mineral soil core and rise above the surface of peat bogs. They are especially common in the zone of discontinuous permafrost (Lundqvist 1969; Seppälä 1972). Their morphology varies from round- or oval-shaped single cones to elongated ridges or to very complex amoeba-like hummocks and large peat plateaus (e.g., Åhman 1977; Seppälä 1979). In northern Finland, the relief of palsas ranges from 0.5 to 7 m. According to the literature, palsas are found in northern Fennoscandia, in the Kola peninsula (Åhman 1977; Vorren 1967), in Iceland (Friedman *et al.* 1971; Schunke 1973), Canada (Brown 1970; Lagarec 1982; Seppälä 1980; Zoltai 1972), and Siberia (Washburn 1979). The distribution of palsas is dependent on climatic factors such as a low annual mean temperature (at least -1°C), a relatively thin snow cover, temperature below 0°C during more than 200 to 210 days a year (Lundqvist 1962), and sufficiently thick layers of peat to insulate the frozen core effectively against the effects of warm air in summer. The thickness of peat, which is critical, may also depend on the amount of precipitation during the season when temperature is above the freezing point, because the thermal conductivity of wet peat is much higher than that of dry peat (Washburn 1979, p. 177). The less summer rain the better for the development and persistence of palsas, but, for peat formation, some rain is needed.

This study examines why palsas occur on some mires but are absent from other physiognomically similar peat surfaces in the same region.

Several hypotheses have been proposed to explain the origin of palsas (e.g. Åhman 1977; Washburn 1979, p. 177-178) and particularly to discover why the frost is able to penetrate so deeply into the peat layers that it does not thaw during the summer season but forms over year-old frost which could persist and be called permafrost. Among the hypotheses of palsa development is one presented recently by Jahn (1976) describing aggradation and degradation in relation to palsa development. Unfortunately, Jahn made several assumptions which do not correspond with observed conditions and facts in northern Finland. According to Jahn (1976, fig. 3), the peat is completely absent from the areas between palsas although in northern Finland it is normally thickest there. Jahn claimed that permafrost also occurs in the basin between the palsas, though in Finland these only contain seasonal frost and thaw completely during the summer (Seppälä 1976*b*). No permafrost occurs in the surrounding terrain. It is true that on a palsa bog, uplifting by frost heaving and thaw settlement may take place which can make the topography of a palsa bog very complicated.

One theory for the origin of palsas was published as early as 1910 by Fries and Bergström. The same hypothesis for palsa formation was presented independently by Seppälä (1976*a*). According to this hypothesis the wind controls the thickness of snow-cover on the bog surface. Where the snow-cover is thin, the frost penetrates deeply into the peat. In these places, frost does not disappear completely during the seasonal thaw but part of it remains under the insulating peat. As the same process is repeated during the succeeding winters, the unthawed layer of frost becomes thicker and the mound starts to rise. The wind carries the snow away from the exposed hump more easily than before and the freezing process accelerates.

This hypothesis has now been studied experi-

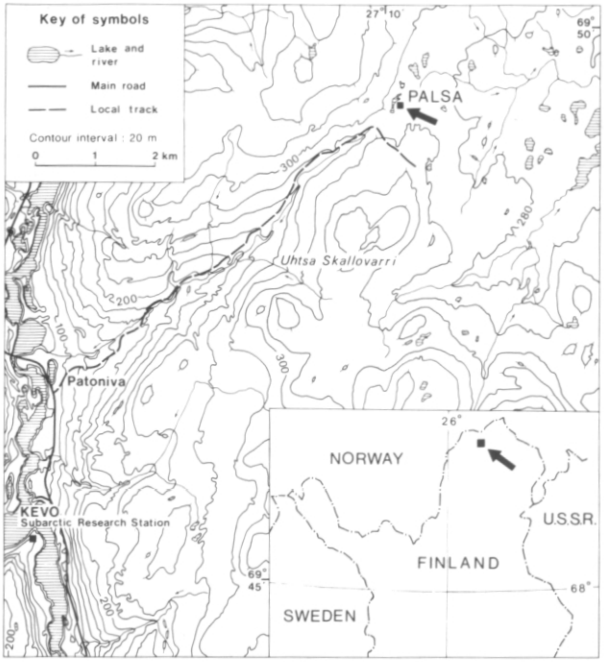

FIGURE 1. Map of the general location of the Skallovarri palsa bog. (Redrawn from topographic map no. 3932 1 and published with the permission of Maanmittaushallitus, Finland).

mentally in northern Finland, at the Skallovarri palsa bog some 12 km NE from the Kevo Subarctic Research Station (about 69°49'N, 27°10'E), and is reported on here (Figure 1).

Field Experiment

In October 1976, a square plot 5 by 5 m was marked on the flat unfrozen peat surface on a palsa bog close to Skallovarri fell on which *Sphagnum*, *Carex*, and *Eriophorum* grew (Figure 2). In the middle of the square, a plank was sunk down to a depth of 2 m with probes for temperature recordings placed at depths of 0.0, 0.2, 0.5, 1.0, and 2.0 m. A second plank was sunk 5 m outside the square as a control with thermoprobes installed at the same depths. Adjacent to these two sites, probes were sited at heights of 0.5, 1.0, and 2.0 m above the mire surface to record temperatures of the air and in the snow. The temperatures were recorded every hour in each of the 20 points with a Grant self-recording battery-operated instrument. The recording tape was changed every 20 days and the batteries were changed every 10 days.

Four frost- and snow-gauge tubes were also sunk into the peat to measure the thickness of the frozen layer and to determine the thickness of the snow cover. The frost gauges were constructed of two concentric plastic tubes. The inner tube was transparent and filled with an aqueous solution of methylene blue, which loses its colour on freezing.

When the melting from the surface began, this type of frost gauge was no longer reliable because the water ran down along the tube and melted the adjacent peat and its contents. Instead, the depth of the frost table and the base of the frozen peat were determined during the summer time with an iron rod pushed through the peat until resistance was noted.

In addition, one more frost gauge (Point 5 in Figure 3) was added in the vicinity of a thermokarst hollow 15 m wide surrounded by palsas 2 m high.

During the succeeding winters the experimental area was cleared of snow several times (dates indicated by arrows and vertical lines *see* Figure 3). At the control points the snow cover was left untouched in its natural condition.

Development of Frost Layer and the Depth of Snow Cover

During the first winter (1976-77) the experimental site was cleared of snow 13 times. The maximum thickness of the snow cover during that winter was about 80 cm at undisturbed sites, but at the measurement square the depth of snow reached 90 cm because the snow pit collected much drifting snow.

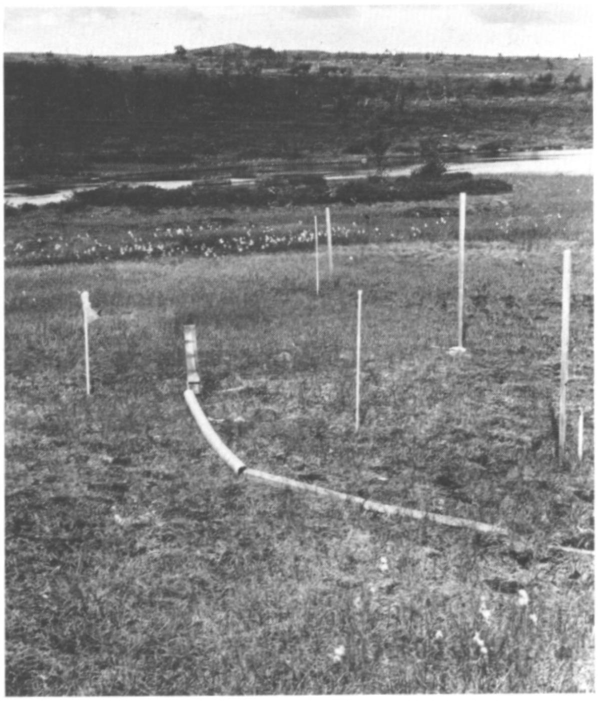

FIGURE 2. Experimental site with instrumentation on Skallovarri palsa bog. (Photographed by the author, 1 June, 1977).

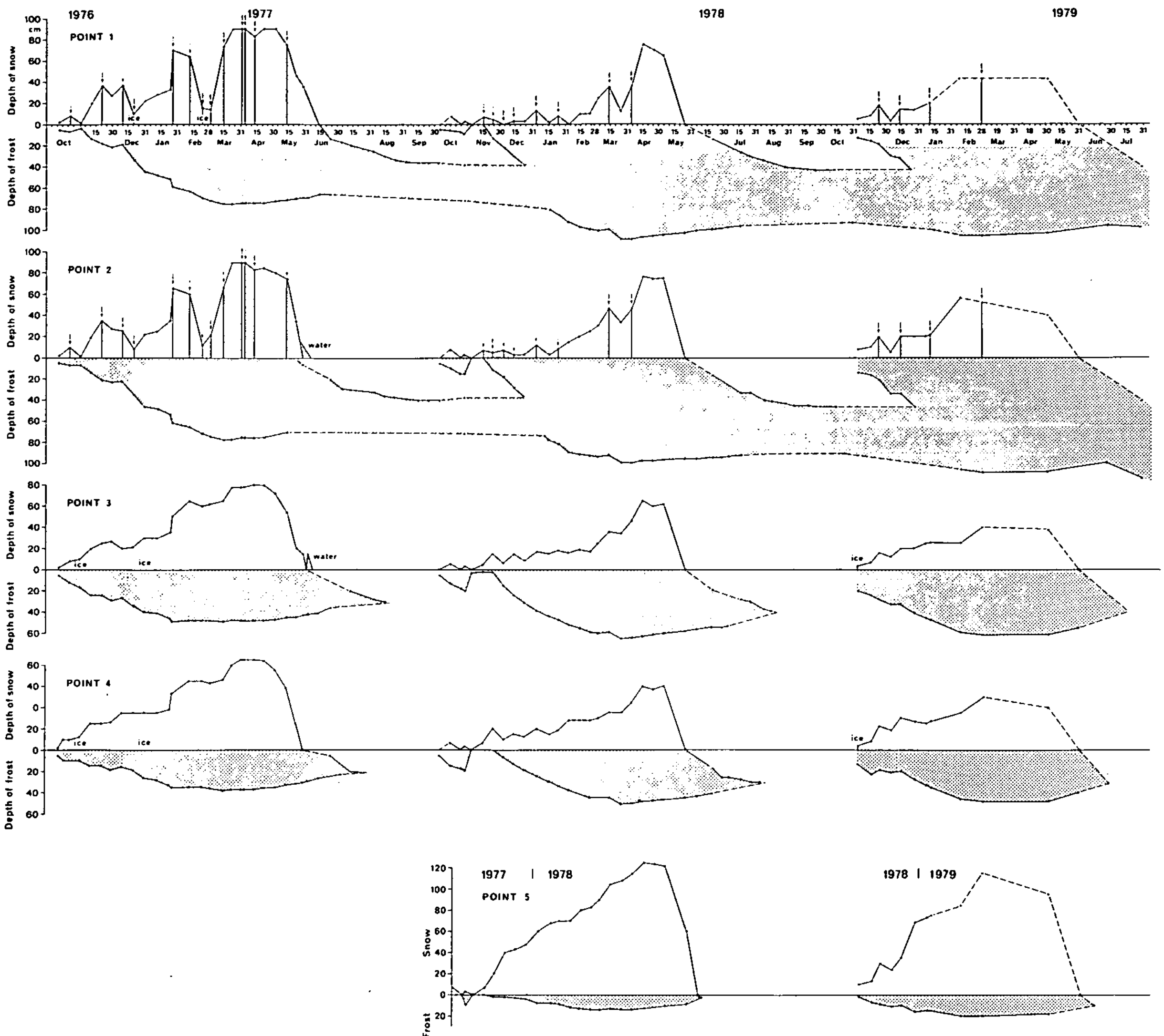

FIGURE 3. Diagrams showing the observed depths of snow cover and frost layer at points 1 to 5. Points 1 and 2 are from the experimental square, points 3 and 4 are control points close by the square, and Point 5 is located in a thermokarst hollow some 30 m from the square. Arrows and vertical lines indicate the snow clearing operations.

The first frost was recorded at the beginning of October 1976, and on October 10 the frozen layer was some 5 cm thick. The thickness of the frozen layer increased slowly up to December 10 and the rate of frost formation increased rapidly during the coldest period when the temperature sank below −40°C (Figure 4). The maximum thickness of frost was attained in the middle of March, when the frost had penetrated into the peat to a depth of about 78 cm at the experimental site, Point 2 (*see* Figure 3), to about 48 cm, at the control Point 3, and to less than 40 cm at Point 4. At the control points, the maximum thickness of frost was reached by the middle of January 1977.

During the 1977 melt season, the seasonal frost thawed completely from the control points by the middle of August. However, at the centre of the experimental site, about 35 cm of frost still persisted when freezing from the surface started again in early October (*see* Figure 3).

In the winter 1977-78, the square was cleared of snow on eight occasions and the frost penetrated down to a depth of 104 cm at the experimental site, to 64 cm at control Point 3, and to 45 cm at Point 4. The maximum thickness of the snow cover, about 78 cm, was at the square; under natural conditions it was less than 70 cm. Much more snow (maximum thickness measured 125 cm) accumulated in the thermokarst hollow at Point 5 (*see* Figure 3) and consequently the seasonal frost did not penetrate deeper than 15 cm into the peat at that point. In this hollow, the frost layer thawed immediately after the snow had melted during the first week of June, 1978. The thick frozen layer at the experimental site extended towards the creek which crosses the bog some 10 m from the square, but most of the extended layer thawed during the summer of 1978. Within the square, the pillow-like form of the frost layer was observed at the end of the thawing season when the thickness of the remaining frost layer at the centre was about 50 cm.

During the winter 1978-79, the square was cleared of snow only four times. The snow cover was generally thinner (some 50 cm) than during the two previous winters, and the frost penetrated to a depth of 60 cm at Point 3 (*see* Figure 3). At Point 1 in the square, the bottom of the frozen layer remained approximately at the same level as during the past winter, but at Point 2 the depth still increased, to a maximum of 108 cm. A deeper penetration of 114 cm was obtained at the end of July, 1979. At Point 5 the frost also penetrated deeper (20 cm) because of the somewhat thinner snow-cover (115 cm) at the end of February. During the last experimental year, no snow or frost recordings were carried out during March or April.

The normal thickness of the active layer on the summit of the palsas on this mire was 60 to 65 cm which corresponds with the observations published earlier from Enontekiö, in the western part of Finnish Lapland (Seppälä 1976*b*). The active layer on the experimental palsa was thinner (37 to 43 cm) than that on the natural palsas which were present on the same mire and which rose 1 to 3 m above its surface.

General Climatological Data on the Region

A large number of temperature measurements are available from different points on the bog, and when the processing and analysis of these data are completed, the results will be published as a separate study. Climatological data have been recorded at the Kevo Subarctic Research Station since 1962. The station lies in the Utsjoki river valley more than 200 m below the study square in the palsa bog (*see* Figure 1). It is apparent that the temperatures at the Kevo Station are some 1.5 to 2°C higher than those at the experimental site according to the normal gradient of air temperature, but it has also been reported that during the winter, the colder air concentrates in the valleys (Kärenlampi 1972; Niemelä 1979). The mean annual temperature of the Kevo Research Station during the ten-year period 1962 to 1971 was −2.5°C (Seppälä 1976*a*), the mean temperature of the coldest month, February, was −16.8°C, and the warmest, July, was +11.8°C. When the study period at Kevo is compared with the ten-year records, it is evident that the year 1977 (−2.1°C, Fig. 4) was close to mean, 1978 (−3.0°C) was somewhat colder, and 1979 milder than average. The lowest temperature ever measured at Kevo was −47.9°C on February 1, 1966. During the winters of the study minimum temperatures of close to −40°C were reached in December and January (*see* Figure 4) during the period when the snow-cover was still increasing.

Average precipitation in the Kevo region is about 415 mm/yr (Seppälä 1976*a*) and 54 per cent of the annual total precipitation occurs between June and September. About 30 to 35 per cent of the annual pre-

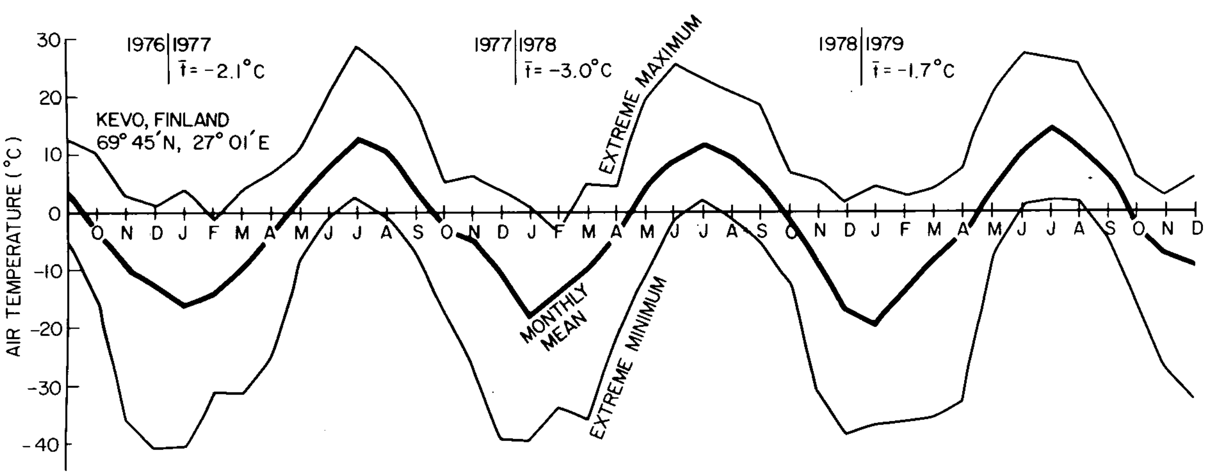

FIGURE 4. Monthly temperature fluctuations at Kevo Subarctic Research Station from September 1976 to December 1979, according to the Meteorological Yearbook of Finland (1976-1979).

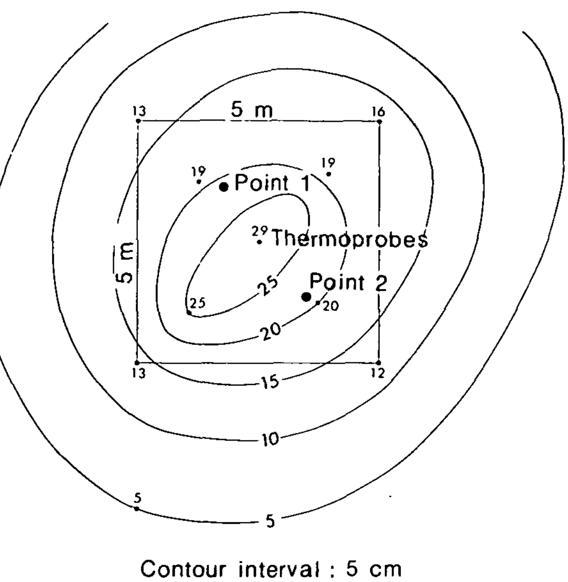

FIGURE 5. Detailed map of the man-made palsa on Škallovarri palsa bog as measured on 29 July, 1979.

cipitation occurs in the form of snow. The average maximum thickness of snow in the valley of the area is 77 cm. Thus, during the first winter (1976-77), the amount of snow was somewhat above normal while in the second winter it was close to normal. The snowfall during the third winter was unusually low. Local variations in snow-cover are very apparent because of the accumulation of wind-drifted snow.

Wind recordings from the palsa bog during the winter time are not available because the instruments froze, but, during the summer, a wind speed of 50 m/s was recorded on one occasion and this is much higher than any reading previously recorded from the valley.

Morphological Evidence for the Formation of the New Palsa

After the first winter, during the thaw season 1977, the surface of the experimental site had heaved some 10 cm above the surrounding level of the bog. The grasses (*Carex* and *Eriophorum*) on the surface of the experimental square died and mosses (*Sphagnum*) also became somewhat thinner. At the beginning of the thaw season, fine cracks could be seen in the frozen surface of the square.

At the end of the summer of 1978, the centre of the experimental site was about 20 cm above the surrounding area. During the summer of 1979, the surface was measured again; this time the local height was some 30 cm (Figure 5). The mosses on the surface of the square had died and the square differed from the surrounding peat surface in that it was drier and lighter coloured, but it had not yet been colonised by the shrubs or lichens typical of palsa surfaces. Fine cracks on the peat surface are visible when the surface is frozen.

This heaving agrees with the observation of Lundqvist (1948, p. 410) reported a palsa upheaval of 35 cm in one winter in Swedish Lapland.

Discussion and Conclusions

The concept of a cyclic evolution of palsas has been reported in different connections (e.g., Seppälä 1979). According to the author's observations, the sequence of development can be summarised in the following way (Figure 6):

(A, B) the formation of a palsa begins when the snow cover is locally so thin that the frost penetrates so deeply during the winter that the summer heat cannot thaw it completely. The surface of the bog rises somewhat;

(C) during the succeeding winters the frost penetrates still deeper, the process accelerates, the hump shows further upheaving by expansion of freezing of pore water and segregated ice, and the wind is now more effective in drying the surface and keeping it clear of snow;

(D, E) when the frozen core of the palsa touches the till or silt layers at the bottom of the mire then the mature stage of the palsa has been reached; at this stage the palsa rises well above the surface of the bog, typically to a relief of about 7 m in western Finnish Lapland; and

(F) the degradation now begins and peat blocks from the edges of the palsa collapse along the cracks into pools surrounding the hummock; during later stages, the vegetation may be removed so that the palsa surface is exposed to deflation and rain erosion.

Old palsas are partly destroyed by thermokarst and they are full of pits and collapsed forms. Dead palsas are unfrozen remnants, either low (0.5 to 2 m) circular rim ridges, or only roundish open ponds and pond groups, or open peat surfaces without any vegetation. From a pool a new palsa may rise after a new phase of peat formation and the sequence of cyclic development recommences from the beginning.

All these stages of development can be found on the same mire in northern Finland (Kujansuu 1969; Seppälä 1979, 1981) as well as in other countries (Friedman *et al.* 1971; Lundqvist 1969; Seppälä 1980). The observations support the conclusion that changes in climate are not necessarily the reason for the collapse of palsas, but rather that collapse is an integral part of the cyclic development of these forms.

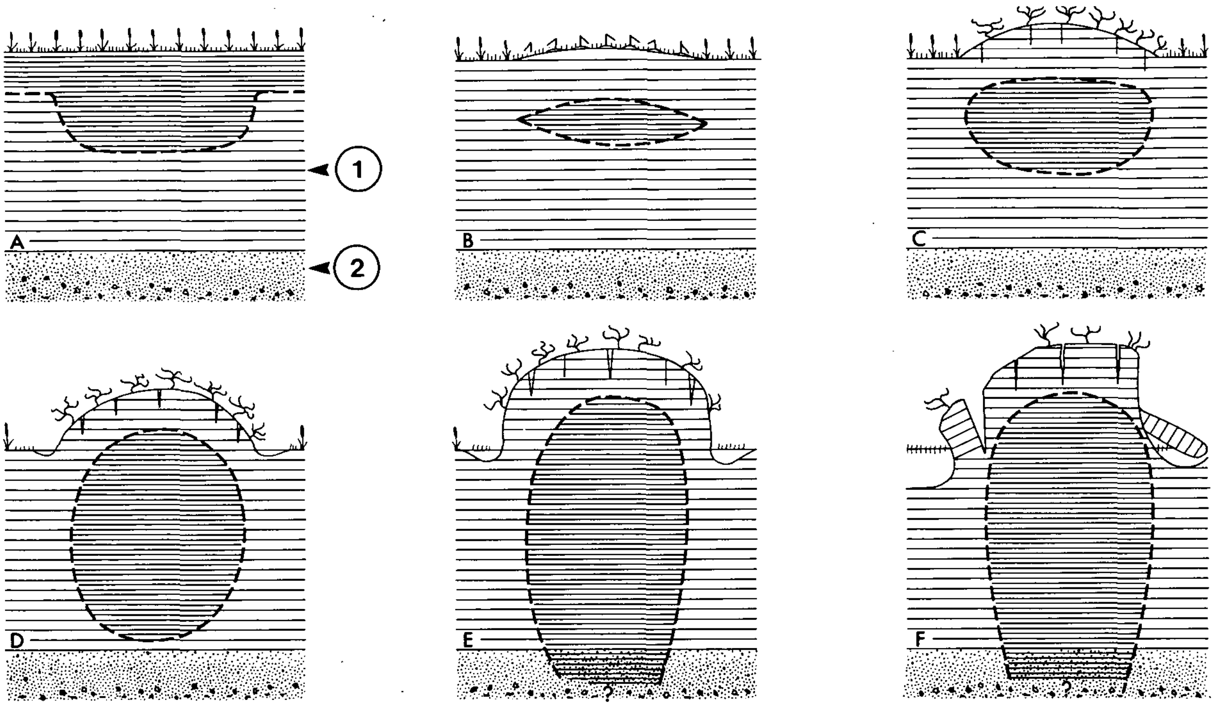

FIGURE 6. Formation of the frozen core of a palsa in a peat bog[1] with a till substratum[2]. **A** Beginning of thawing season. **B** End of the first thawing season with some frost. **C** Palsa embryo. **D** Young palsa. **E** Mature palsa. **F** Old, collapsing palsa. (Heights not to scale).

Differences between the formation of palsas and pingos can be summarized briefly (cf., Åhman 1976; Mackay 1978). Pingos classically belong to high arctic climatic conditions with continuous permafrost. Two different processes of pingo formation have been reported (e.g., Washburn 1979). According to the closed system pingo theory, in the initial stage in the residual pond of a drained lake the aggrading permafrost starts to freeze the unfrozen saturated sand and the hump is uplifted above the former lake bottom. According to the open system theory of pingo formation, however, the actual injection of ground water under hydrostatic pressure subsequently freezes because the permafrost is close to the ground surface and this then presses the soil upwards forming the hummock.

Palsas are formed by the cold air which freezes the water in the peat or silt and causes accretion of segregated ice, in stages, during successive winters. The cooling happens from the air downwards to the ground and the surrounding soil layers are warmer and unfrozen in contrast to the frozen core of the palsa. Seasonal cooling forms the layers of segregated ice and water moves from the surroundings to the cold core. Peat insulates the frozen core from the warm summer air.

Palsas have also been found in the zone of continuous permafrost in Spitsbergen on Brøggerhalvøya and Blomstrandshalvøya by the author, in Nordaustlandet (Salvigsen 1977) and in West Spitsbergen (Åkerman 1980). In these areas, peat occurs on the surface and the cold penetrates from the air downwards and not from the permafrost layer underneath.

The experiment has proven that the thickness of snow-cover is the main controlling factor of palsa formation in subarctic conditions. The main cause of the differences in snow depth is wind, causing drifting of snow which varies from place to place and the formation of wind channels with a thin snow cover where the frost is able to penetrate deeper into the peat layers.

In 1980, the artificial, man-made palsa was left to follow the course of nature and it will be interesting to see if it grows in height and size when it is somewhat above the surface of the mire and when the wind sweeps snow off its surface.

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