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PALSAS AND LITHALSAS

GLOSSARY

Active layer: The top layer of ground subject to annual thawing and freezing in areas underlain by permafrost (Glossary of permafrost and related ground-ice terms, Technical memorandum, 142, National Research Council, Canada (1988)).

Aggradational ice: Segregation ice formed in the lower part of the active layer and incorporated into the permafrost.

Cryogenic structures: Distinct soil micromorphology resulting from the effects of freezing and mainly from the formation of segregation ice in the ground.

Cryosuction: A suction of water in the ground to the freezing front in fine-grained material.

Frost thrusting: Lateral movement of mineral soil in relation to freezing of water in the soil.

Gelifluction: The slow downslope flow of unfrozen earth materials on a frozen substrate.

Little ice age: A period of cooling and glacier expansion that covers a period extending from the sixteenth to the nineteenth centuries.

Mud boils or frost boils: Small mounds of soil material formed by frost action and corresponding in section to cryoturbations.

ABSTRACT

Palsas and lithalsas are mounds that contain lenses of segregation ice. They are islands of permafrost. These two kinds of mounds are very similar in shape, size, and origin. However, the palsas have a cover of peat which does not exist in lithalsas. The formation of ice in the core of these mounds requires material in which capillary water undergoes slow freezing. The remnants of lithalsas are depressions surrounded by ramparts, which does not exist after the melting of palsas. The processes involved in the formation of segregation ice are described in the beginning of the chapter.

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Introduction

Palsas and lithalsas are types of frost mounds. They both have the same origin, forms, and sizes. However, they do not have the same geographical distribution and they do not result in similar morphology following thaw degradation (Sections 8.16.3.10 and 8.16.4.7).

The definition of 'palsas' proposed by Van Everdingen (1994) is adopted in the present chapter: "perennial mounds covered by peat, situated in the discontinuous permafrost zone and due chiefly to segregation ice fed by cryosuction." The nomenclature problem of why use of the term 'lithalsas' for mounds without peat does not agree with van Everdingen's definition is discussed later (Section 8.16.4.1).

The main process involved in the formation of both palsas and lithalsas is the growth of segregation ice inside the mounds.

Segregation Ice

Pipkrakes are ice crystals that grow upward at the surface by the freezing of water moving from within the soil. They are a form of segregation ice, with the same origin as the ice lenses that appear when humid silty soils freeze slowly **(Figure 1).** The lenses range from less than 1 mm to several decimeters in thickness. Segregation ice forms when groundwater moves to the freezing front by cryosuction in the same way that water moves by capillarity to the surface of a drying soil. In the latter, water becomes vapor. In the process of freezing, another phase change occurs: water is transformed into ice. The movement of capillary water to a frost front is termed cryosuction.

Silt is the best sediment for the formation of segregation ice because capillary water is usually present, and it migrates easily because of the material permeability. In coarse sands where little or no capillary water is present, no cryosuction is possible and no segregation ice may appear. In clay, permeability is very low and segregation may only appear when freezing is very slow.

During freezing, latent heat is released by the change of water into ice. If not enough water reaches the ice lens, not enough heat is released and the freezing front advances. A new ice lens appears where enough water is present; it grows as long as the water arrives in sufficient amounts. The first ice lens continues to grow slowly by cryosuction, but when no more capillary water arrives no more ice lenses are developed.

In summary, segregation ice requires:

1. Material that is not too coarse and not too fine. The best is silt which has sufficient permeability yet may hold capillary water. In sand, no segregation lenses form due to absence of Capillary water. In clay, although the growth of thin segregation lenses is possible, because of low permeability very slow freezing is needed. In peat, segregation ice lenses may appear if mineral material is included; in pure fibrous peat no segregation ice is formed (Allard and Rousseau, 1999; Seppala and Kujala, 2009).
2. Slow freezing: If the freezing front penetrates too quickly, water has no time to migrate. The wet sediment freezes abruptly and water remains where it was.
3. At depth, as frost always penetrates more slowly, the ice lenses are thicker.
4. Water in the sediment: If a source of water does not exist, the process of cryosuction is starved and segregation lenses are limited. An external source of water is necessary in order

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for the ice volume to exceed the pore spaces (i.e., to form 'excess ice').

Segregation ice lenses grow parallel to the freezing front. Their position shows the direction of advance of frost in the ground.

Another kind of segregation ice is 'aggradational ice' (**Figure** 2). This appears at the base of the active layer. At the beginning of winter, freezing fronts advance not only downward from the surface but also from the top of the permafrost upward to the surface. Aggradational ice forms at the permafrost table in exactly the same way as ordinary segregation ice but in a reverse position: water comes from the surface and the frost line shifts upward from the top of the permafrost. This ice is preserved if there is sediment deposition at the surface or if thinning of the active layer occurs, as may happen if climate gets colder.

Segregation ice gives rise to a distinct cryogenic structure of highly compacted material which remains visible in undisturbed soil for a long time (Figure 3).

***Figure 1**. Segregation ice lenses made in laboratory experiments (Pissart, 1964). Loess mixed with a large amount of water had, in a refrigerator, undergone a slow freezing from the top with a heating source below. Segregation lenses have appeared and also faults filled with ice. Water moved to the freezing front; at depth the material was drying, forming a polygonal net of dessication cracks visible through the pane at the bottom of the box. A good picture of segregation ice in a palsa was given by Svensson (1964b).*

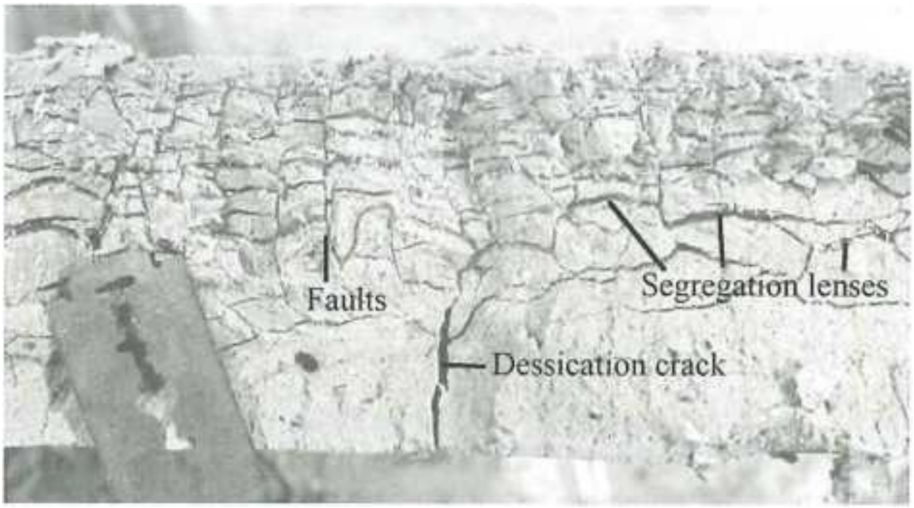

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Figure 2. *Aggradational ice in the upper part of a melting wooded lithalsa in Yukon (Pissart et al., 1998).*

Figure 3. *Aggregates of silts just below the peat in the palsa shown in Figure 4. These very highly compacted angular lumps of silt are a cryostructure due to the formation of segregation ice.*

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Palsas

TERMINOLOGY

'The word 'pals' (plural: palses) was inUoduced into the scientific literature by Fries and Bergström (1910) (Friedman et al., 1971). It is a Finnish and Lappish word. In German, the term is 'pals' (plural: Palsen), in French 'palse' (plural: palses), and in English 'palsa' (plural: palsas) (Lundqvist, 1969). The original word means, in northern Scandinavia, "a dry low ridge in a bog" (Svensson, 1969) or a "drier hillock within mire" (Seppälä, 1988) (Figure 4). Seppälä added to the definition in 1972a by stating "with a core of perennial frost" and that these mounds are "in areas of sporadic and discontinuous permafrost."

Ahman (1977) adds the idea that palsas are "formed by a build up of segregated ice in mineral soil or in peat." According to Evseev (1973), this idea was first proposed by Popov in 1951, who called them "migrational frost mounds." The word 'migrational' does not indicate the actual displacement of the mound but the movement of water to feed the growing lenses of segregation ice.

Figure 4. *A single dome-shaped paisa near Varanger fjord (Lapland, Norway). The silty core in which the segregation ice appears is visible below the peat. Cracks crisscross the peat and form falling blocks on the steep slope.*

Washbum (1983) gives a quite different definition: "palsas are peaty permafrost mounds ranging from *c.* 0.5 to 10 m in height and exceeding c. 2 m in average diameter, comprising (1) aggradation forms due to permafrost aggradation at an active-layer/permafrost contact zone and (2) similar- appearing degradation forms due to disintegration of an extensive peaty deposit." With this definition, Washburn (1983) extends the occurrence of palsas to peaty hillocks present in the continuous permafrost zone. This definition accepts the use of the name 'palsas' for mounds formed by mechanisms other than the growth of segregation ice. The term is also used for features that occur in the continuous permafrost zone, a zone that does not exist in Scandinavia. This definition of the word palsa is not widely accepted.

Adjectives have been used to give more information about palsas. Ahman (1976) proposed to distinguish the forms of the mounds by the following terms: "Esker palsas, string palsas, conical palsas and palsas complex." Washburn (1983) suggested using 'sinuate palsas' instead of esker palsas. Zoltaï (1972) was probably the first to use 'peat plateau' for a peaty area that had been uniformly upheaved by segregation ice. In French, the term has been translated as 'plateau

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palsique' (Payette et al., 1976) and as 'terrasse palsique' (Dionne, 1978).

Concerning the nature of the mound, Forsgren (1968) used the name of 'minerogenic palsas' for palsas which have a core of not only peat but also mineral material. Dionne (1978) further distinguished between 'organic palsas' (with a peat cover) and 'mineral palsas' (without any peat cover). Washburn (1983) proposed to use 'mineral palsas' for "forms whose volume of mineral soil exceeds the volume of peat"; this last proposal, impossible to apply in the field, was never used. This term 'mineral palsa' was later replaced by the now widely accepted term 'lithalsa' by Harris (1993).

Concerning the location of palsas in the physical environment, the term 'wooded palsas' was introduced by Zoltaï and Tamocaï (1971). This was translated in French as 'palses boisées' (Payette et al.z 1976). Payette and Rochefort (2002) also used the terms "palses et plateaux palsiques lichéniques." Harris and Nyrose (1992) talk about "floating and grounded palsas."

Concerning the origin of the mounds, Schunke (1973) used the term 'cryokarst mound' for 'degradational palsas' that formed from the melting of peat plateaus. Washburn (1983) proposed the term 'aggradational palsas' as opposed to 'degradational palsas.' Outcalt et al. (1986) use the name of 'aggradation palsas' and 'anthropogenic palsas' for mounds which, in continuous permafrost, were due to man (e.g., construction of roads), and Seppälä (1986) used the term 'man-made palsa' for a 30 cm high mound which appeared after the snow had been cleared in the same place on several occasions during the winter.

FORMS AND DIMENSIONS

Palsas are rarely isolated and usually appear as 'fields' or 'families' that have variable spatial densities **(Figures 5** and **6).**

The maximum height of palsas varies between 7 and 10 m (Lundqvist, 1969; Hamelin and Cailleux, 1969; Svensson, 1966; Payette et al., 1976; Seppälä, 1982b, 1988; Dionne, 1978; Pissart and Gangloff, 1984 (**Figure 7**); Allard and Seguin, 1987; Kershaw and Gill, 1979; Dever et al., 1984; Seppälä, 1988; Evseev, 1973; Lagarec, 1982). The average height of the palsas is usually lower.

Palsas vary from singular well-confined individual mounds to complexes of hillocks. Svensson (1966) and Wramner (1967) distinguished five different morphological types of palsas: (1) single more or less dome-shaped palsas; (2) vast palsas with a flat surface (peat plateaus); (3) low palsas, less than one meter high; (4) string palsas; and (5) cluster of coalescent palsas.

Their size is related to their shape, as Ahman's (1976) descriptions showed clearly; he recognized: (1) esker palsas, parallel to the slope inclination, 2-6 m in height, 50-500 m in length; (2) string palsas, perpendicular to the slope inclination, 1-2 m in height, 25-100 m in length; (3) conical palsas, circular to oval, 2-6 m in height; and (4) palsa complexes, from 1 to 9 m in height. Other morphological classifications of palsas were given later by Salmi (1968), Dionne (1978), and Seppälä (1988).

The size of the palsas varies according to biophysical environment: in Hudson Bay region, Payette et al. (1976) reported that palsas are between 1.70 and 7 m in height, and wooded palsas and the palsas plateaux are between 1 and 2.50 m in height. In Manitoba, Zoltaï (1972) observed that the peat plateaus with a several square kilometer surface are 1 m in height, although individual palsas may be approximately 3 m in height.

In Iceland, palsas (cryokarst mounds or degraded peat plateaus; see Schunke, 1973) are between 0.5 and 2.5 m in height (**Figure 4**). Everywhere, peat plateaus are lower than most conical palsas.

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PEAT ON PALSAS AND ICE IN PEAT

According to the definition given by van Everdingen, the name 'palsa' is restricted to mounds covered by peat.

***Figure 5**. Field of palsas in Lapland near Varanger fjord.*

***Figure 6**. Field of palsas near the Aveneau valley (58°8' latitude N; 67°48' longitude W), northern Québec (Canada).*

***Figure 7**. Eight meter high palsa near the Aveneau valley (58°8' latitude N; 67°48' longitude W), northern Québec, Canada.*

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The maximum reported thickness of peat by Seppälä (1980) was 7 m; 5 m was observed by Kershaw and Gill (1979) and Harris and Schmidt (1994). Zoltaï and Tarnocaï (1975) reported averages of 3.55 and 2.67 m for 18 palsas. Lagarec (1982) wrote that the thickness of peat on palsas in the Hudson Bay region varied between 0 and 2.5 m, and Seppälä (1979) wrote that the thickness of peat in Fennoscandinavia is more than 1.6 m on average.

Fifty years ago, palsas were considered as consisting of ice- rich peat only. During the 1960s and 1970s, it became evident that a frozen mineral core exists in almost all instances and that most ice accumulates in the mineral core, which always consists of silty material. However, Seppälä (1979) described a section in a palsa where permafrost does not reach the mineral soil. Later, Seppälä (1997) confirmed that small developing palsas may not reach the mineral soil. Finally, Seppälä and Kujala (2009) explained that peat is not a frost-susceptible material. That is in agreement with Allard and Rousseau (1999), who said that only pore ice is present in peat. For all these authors, fibrous peat is not favorable to ice segregation, unlike minerotrophic peat (peat with silt and clay). However, descriptions of ice in peat were given: thin lenses of ice (Forsgren, 1968), 25 cm lenses (Kershaw and Gill, 1979), and 5-10 cm lenses (Seppälä, 1988). However, Zoltaï and Tarnocaï (1975) wrote that "Ice accumulations in the peat are rare although thin (up to 20 cm)." The details on the nature of the peat are not found in these papers.

SURFACE CHARACTERISTICS

Palsas form dry sites with either a barren peat surface or a surface covered by low shrubs and lichens. Palsas present open cracks oriented in different directions. Adjacent to the mounds is a zone with free water. This was explained (Lundqvist, 1951, 1969) as being due to the surrounding bog surface being depressed under the weight of the palsa (Figure 8).

Svensson (1961) explains that the cracking on the surface may be the result of (1) upheaval by interior force, (2) thermal contraction, or (3) drying. These three possible explanations were accepted by Ahman (1977), but Allard and Seguin (1987) found that ice wedges, resulting from thermal contraction cracking, were found only under one site (a 30 cm wide ice wedge at the top of the permafrost table) on peat plateaus in northern Québec. Zoltaï and Tarnocaï (1971, 1975) and Harris and Schmidt (1994) give some descriptions of wooded palsas. The cover of vegetation is scattered black spruce *(Picea mariana)* with abundant lichens and some ericaceous shrubs.

THE MINERAL CORE, SEGREGATION ICE, AND AGGRADATIONAL ICE

The growth of a palsa is due to the formation of lenses of segregation ice in the mineral core. This was shown by Svensson as early as 1964. The granulometry of the mineral core of a palsa is usually composed of more than 50% silt. Allard and Rousseau (1999) mentioned that in

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northern Quebec, where the silty deposits were deposited from the Tyrell Sea, underneath are nonfrost sensitive sediments (sands) in which no ice lenses exist. The role of this layer may be important as a water source for the feeding of the ice lenses during the growth of the mound.

***Figure 8**. Around this palsa in Lapland, a still wetter zone with free water was explained by Lundqvist (1951) and Svensson (1966) as the result of the depressed bog surface under the weight of the palsa.*

The mean thickness of the ice lenses in the palsa studied in detail by Allard and Rousseau (1999) was 11.3 mm, and the amount of ice corresponds to 135% of dry weight. Michaud et al. (1994) reported thicknesses from a few millimeters to 25 cm. Spolanskaya and Evseyev (1973) wrote that lenses of pure ice are generally less than 35 cm. Fortier et al. (1991) wrote that the richest ice zones are at the base and at the top of the palsas.

It is now unanimously accepted that the greater amount of ice is accumulated on the top of permafrost at the organic-soil interface. Up to 1-m thick pure ice is common in the mounds studied by Zoltaï and Tarnocaï (1975). The great amount of ice at this level was also observed by Allard and Seguin (1987), Allard and Rousseau (1999), and Fortier et al. (1991). This ice is probably aggradational ice, as indicated by the brecciated structure (Altman, 1977). More recently, Carlson (2005) mentioned that aggradational ice at the base of the active layer was the prevalent ice type observed in a study of the thermodynamic evolution of a palsa.

Allard and Rousseau (1999, p. 385) explain that, if the peat cover is cleaned by erosion, a palsa does not necessarily initiate degradation because "the top of the mound protrudes high enough above the surrounding snow cover and is exposed to sufficiently cold conditions." These colder conditions elevate the permafrost table on the top of the mound and explain the formation of aggradational ice (Mackay, 1972; Pissart, 1975; Mackay, 1983; Burn, 1988). This explains why aggradational ice is ubiquitous on the top of the mounds.

In peat plateaus, lenses of ice are predominantly horizontal (Allard and Rousseau, 1999). However, in palsas, the same authors described lenses of ice that are inclined parallel to the slope. This observation suggests either tilting of horizontal layers during growth of the palsa or an oblique penetration of the freezing front.

Faults were reported in the mineral core of both palsas and lithalsas (Fortier et al., 1992; Allard and Rousseau, 1999). Allard and Rousseau (1999) wrote: "Some fractures have non-measurable

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displacements; others are faults with displacements up to several centimetres. The faults and the fracture planes contain ice 'veins' of a thickness in the same order than the lenses they cross-cut."

The faulting that appears during ice segregation can be observed in laboratory experiments (Figure 1). The same structures were described earlier by Taber (1929, 1930). They were explained by Taber as flaws in the continuities of water flow in the freezing fringe due to irregularities in the material. Desiccation cracks appear at the origin of these structures. They occur when water is moving to the freezing front, as shown in laboratory experiments (Pissart, 1964). Later, water moves by cryosuction to the cracks, where it freezes.

CLIMATE AND THE DISTRIBUTION OF PALSAS

Palsas occur almost everywhere in the discontinuous circumpolar permafrost zone provided that a sufficiently thick peat layer is present. They are the first islands of permafrost met if you go to the North. Most are described from Fennoscandinava and Québec but palsas also exist in Iceland (Friedman et al., 1971; Schunke, 1973), Ontario (Railton and Sparling, 1973), Manitoba (Zoltaï and Tarnocaï, 1971), Saskatchewan (Brown, 1965), along the Mackenzie between 60 and 70° N latitude (Zoltai and Tarnocai, 1975), Yukon Territory (Kershaw and Gill, 1979; Harris and Schmidt, 1994), British Columbia (Seppälä, 1980), Wyoming (Collins et al., 1984), Alaska (Péwé, 1975), northern European Russia (Evseev, 1973; Barcan, 2010), and western Siberia (Evseev, 1973; Spolanskaya and Evseyev, 1973). Dionne (1984) proposed that the typical mean annual temperature for palsa bogs is between — 2 and — 3 °C in Scandinavia, — 4 and - 6 °C in Québec and between — 2 and

— 5 °C in the rest of Canada. Most authors agree that palsas can occur when the mean annual temperature is close to

— 1 °C (Seppälä, 1982b, 1986, 1987, 1988, 1997) in Finland, or between 0 and — 1 °C (Ahman, 1977).

Palsas do not occur in the continuous permafrost zone because they have no possible alimentation from below to feed the ice lenses. Accordingly, their northern limit corresponds to the limit of discontinuous permafrost; this is close to

— 6 °C air temperature.

Dionne (1984) described some palsas near Blanc Sablon and Matagami (Québec) at latitude 51°29', that are outside of the limit of permafrost drawn by Brown et al. (1997). He considers these to be relict features formed under cooler conditions than today.

Temperature is not the only climatic factor which explains the distribution of palsas: Low precipitation and thin snow cover are, with temperature, the most prominent limiting factors (Seppälä, 1986).

AGE OF PALSAS

The first and simplest conclusions are that palsas are either younger than the retreat of the Late Quaternary glaciers (Svensson, 1964a) or that their oldest possible age is the age of the raised beach on which they may be found (Svensson, 1966; Hamelin and Cailleux, 1969). Spolanskaya and Evseyev (1973) estimated the speed of accumulation of peat on the top of palsas and in the peat bog in proximity to determine age. In Iceland and in the North West Territories, Canada,

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layers of tephra were used as reference deposits for palsa dating (Schunke, 1973; Kershaw and Gill, 1979). Dendrochronology is also sometimes used to date the growth of palsas (Dever et al., 1984). Precise ages can be deduced from the peat which is on the mound. As soon as the palsa grows out of the bog, erophilous humus peat is replaced by hydrophilous peat. The age may be approached by palynology (Allard and Seguin, 1987) and ^{14}C dates of the time when this change in vegetation occurred (Seppälä, 1988).

Palsas do not all appear at the same time in the same bog. Allard and Seguin (1987) indicate that three generations of palsas occur in the Hudson Bay region: 1500-1050 BP, 650-200 BP, and very recent. Later, Allard and Rousseau (1999) wrote that, for the palsas they have studied, the age of formation is between AD 1580 and 1880 (the Little Ice Age). In Fennoscandinavia, palsas were mainly formed between 1000 and 3000 BP, but some palsas are much younger; for example, an age of not more than 100 years has been given for a palsa in northern Sweden described by Vorren and Vorren (1975) (Seppälä, 1988).

ORIGIN OF PALSAS

If palsas result from the formation of segregation ice, how can they remain in equilibrium with climate over many years?

The first explanation is that, when palsas form, the snow cover, an excellent insulator, is absent or thin on their summits (Fries and Bergström, 1910; Svensson, 1966; Forsgren, 1968; Lundqvist 1969; Zoltaï and Tarnocaï, 1971; Seppälä, 1976a). These authors were the first to champion this influence, which is now unanimously accepted. A second explanation relates to the peat cover, although this is not so critical. Peat insulates the frozen core during the summer. This was mentioned by Svensson (1969), Zoltaï and Tarnocaï (1971), and Ahman (1976). An important advance in the evolution of ideas concerning palsa growth was made by Brown (1966) (witlı reference to Tyrtikov, 1959); he stressed that the thermal conductivity of unfrozen peat is much lower than the thermal conductivity of frozen peat. Consequently, freezing is more effective than thawing. This fact (with data from measurements of conductivity) was reported in Washburn (1979), but is rarely mentioned by searchers.

Secondary factors that influence palsa formation and growth include: (1) the lower albedo of the vegetation on the palsas with the change of vegetation as the mound grows and becomes dryer (Railton and Sparling, 1973; Moore, 1984; Seppälä, 1988); (2) the density of snow, which is different on the palsa and on its sides (Kershaw and Gill, 1979; Seppälä, 1990); and (3) the vegetation cover and the role of trees, which retain snow in their branches (Zoltaï and Tarnocaï, 1975; Payette et al., 1976).

It is easy to understand why palsas grow as the mounds are soon cleaned of snow by the wind in winter, but the problem of their first appearance remains. Seppälä (1976b) thinks that subde differences in the drifted snow before any upheaval may explain the formation of palsas. He demonstrated, by experiment in the field, that an area 5 m × 5 m of normal, wet mire (i.e., bog tundra), several times cleared of snow during the winter, gave a small man-made 30 cm high palsa with a core which remained frozen for almost 8 years (Seppälä, 1982a, 1995).

However, Salmi (1968) suggested that growing palsas resulted, in part, from the buoyancy of frozen peat in the mires. However, Zoltaï (1972) calculated the buoyancy of the frozen mass of a peat plateau is not sufficient to float on the saturated peat. Ahman (1977) thought that embryonic palsas normally float, and Harris and Nyrose (1992) speak of 'floating' palsas and 'floating' peat plateau. Seppälä and Kujala (2009) explain how the buoyancy effect might actually work: buoyancy lifts the frozen peat during the summer, causing water to accumulate under the frozen core where it freezes during the next winter. This forms a thin ice layer in the peat. This process ceases when frost reaches the underlying mineral soil, and a 'grounded' palsa is then born.

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Some palsa fields are the result of the breakdown and degradation of large peat plateaus (Schunke, 1973; Dionne, 1978; Lagarec, 1980; Washburn, 1983; Allard and Seguin, 1987; Laprise and Payette, 1988; Laberge and Payette, 1995) **(Figure 9).** Breakdown is the consequence of thermokarstic processes initiated along cracks and drainage patterns formed on the peat plateaus. These forms were called 'degradational palsas' by Washburn (1983), in contrast to 'aggradational palsas.' LJnfortunateIy, it is sometimes difficult to distinguish these from ordinary palsas.

Dever et al. (1984) demonstrated, using isotopes ($\delta^{18}O$, δD, and ^3H), how the ice lenses within three palsas are fed (1.4, 1.90, and 3.70 m in height). The palsas are covered by a 0.5-1.0 m thick organic horizon in which there is 30 cm of peat *sensu stricto.* The maximum amount of tritium (as much as 300 UT) was found in an ice lens at 4.70 m below the summit of the palsa and at approximately 4 m from the borders of the palsa. This lens was 1 m below the water level around the palsa. These observations show that permafrost remains permeable and that rain water subsequent to 1952 (when, for the first time, humans injected great amounts of tritium into the atmosphere) circulates within the palsa where temperature is less than 0°C. This observation proves that palsa growth occurs not only from the bottom but also from the feeding of ice lenses inside the palsas during maturity. However, the increase of tritium at a depth of 1.90 m, a maximum not far from 300 UT, agrees with the recent formation of aggradational ice.

Figure 9. *Professor Dr. E. Schunke (Göttingen) showing a degradational palsa in Iceland. The peat plateau from which the small palsa appeared is visible in the background.*

THE THAW OF PALSAS AND THEIR CYCLIC DEVELOPMENT

Svensson (1961) was the first to indicate that the presence of degenerated and collapsed palsas does not indicate climate warming. Later, Lundqvist (1969) noted that climatic amelioration must destroy a palsa but, as the palsa apparently thaws, growth also occurs. This suggests that the causes of thawing lie within the palsas themselves.

This observation led to the idea of a cyclic development of palsas (Wramner, 1967; Brown, 1966; Lundqvist, 1969; Zoltaï and Tarnocaï 1971, 1975; Ahman, 1977; Seppälä, 1979, 1982a, 1988), a concept that was only challenged by Allard and Rousseau (1999), who argued that it is not a universally applicable concept.

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More recently, the disappearance of palsas has been attributed to climatic change; Zuidhoff and Kolstrup (2000) suggested that the present decay of palsas in Sweden could be the result of 1.0-1.5 °C increase in mean annual temperature during the past *c.* 100 years, probably in combination with increased snowfall since *c.* 1930.

Fronzek et al. (2006) consider the potential effect of climate change on the distribution of palsa mires in Fennoscandia. Luoto and Seppälä (2003) and Luoto et al. (2004), using the mapping of thermokarst ponds resulting from thawing palsas in a 95 km long transect in Finnish Lapland, observed that palsa degradation generally occurs in the marginal parts of the palsa distribution area. In fact, the current palsa distribution represents only a small remnant of its earlier, much wider distribution; the total distribution area has decreased by more than 65%, probably since the Little Ice Age. These changes are mainly attributed to changes in precipitation: not only an increase in snow cover which thermally insulates the mounds in winter but also an increase in precipitation in summer, which increases the thermal conductivity of peat. Likewise, Allard and Seguin (1987) indicate that the abundance of thermokarstic ponds over mounds and the evident evolution of peat plateau in the Hudson Bay area clearly show that permafrost was formerly more widespread than today. They conclude Lhat degradation has been dominant for the past 150 years but stress that each palsa has its own thermal regime, which is mainly regulated by the snow cover distribution. However, Barcan (2010) concludes that, on the Kola Peninsula, the height and the number of bog mounds as well as the thickness of the active layer has remained unchanged over the past 80 years.

The destruction of palsas arises from several processes. Svensson (1961) indicates that thaw of the frozen sides of the palsas occurs due to the presence of waters at the palsa limit (Figure 4). Wind may be very important (Svensson, 1966). White et al. (1969) associated the thaw of palsas with the disappearance of the insulating peat cover. Wramner (1967) and Ahman (1977) describe the block erosion of peat which results from thaw of the side with eventual overhanging of the peat and its collapse. Spolanskaya and Evseyev (1973) consider that the main degradation mechanism is thaw from below.

REMNANTS AFTER MELTING

Following thaw, palsas leave only small traces of their former presence: A light depression which is wetter than the nearby bog. However, Hamelin and Cailleux (1969) indicated that the bog usually shows some irregularities, with visible blocks of peat. That same year, Lundqvist (1969) wrote that "fossil palsas are insignificant and easily overlooked if the palsa did not exist for a very long time. On the bog surface, nothing will be seen of the former palsa except for a wetter part of the surface, comparable with a shallow thaw lake."

When 'Iithalsas' were regarded as being the same as 'palsas,' there were a few descriptions of palsa remnants that consisted of a rounded body of water surrounded by low walls (Wramner, 1967). Seppälä (1980), when describing palsas with only 7 cm of peat on their summits in British Columbia, observed that after melting, round ponds remain surrounded by rim ridges approximately 0.5 m in height. This example clearly shows that transitions exist between palsas and Iithalsas.

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Lithalsas

TERMINOLOGY

Cryogenic mounds without a peat cover were first mentioned by Lundqvist (1951) and Svensson (1964a, 1969). These mounds were subsequently described in detail by Wramner (1972) and were given various names. The terminology has been reviewed by both Matthews et al. (1997) and Pissart (2002): "palsa like frost mounds in pure mineral soil" (Wramner, 1972), "mounds consisting of purely mineral material" (Spolanskaya and Evseyev, 1973), "buttes minérales cryogènes, cryogenic mineral mounds, wooded cryogenic mineral plateau" (Payette et al., 1976, Lagarec, 1982), "pure mineral soil palsa with no peat, purely minerogenic palsas with no peat" (Airman, 1977), "palse minérale, mineral palsas" (Dionne, 1978; Pissart and Ganglofif, 1984; Akerman and Malmström, 1986), "cryogenic mounds" (Lagarec, 1982; An and Allard, 1995), "mineral permafrost mounds and permafrost plateaus" (Allard et al., 1986; Matthews et al., 1997), 'palsas-like mounds' and 'Iithalsas' (Harris, 1993), "nonpeat-covered mound" (Allard and Rousseau, 1999).

The term 'lithalsa' is now adopted by most researchers to mean a palsa without a peat cover. This follows from a terminological discussion (Pissart, 2002) that took into account the arguments of Seppälä (1988), who rejected the term palsa and especially 'mineral palsa' for a mound without a peat cover. Seppälä points out that in Lapland (whence the term palsa comes) the meaning of the word is a mound necessarily covered by peat. For this reason, it was proposed to use the word 'lithalsa' created by Harris (1993).

Matthews et al. (1997) suggest keeping the word palsas for mounds that, at thebeginning of their growth, possessed a very thin peat cover, even if the peat later disappears. Like many other authors, they insist on the existence of a "genetic continuum between palsas and mineral permafrost mounds." This must always complicate the differentiation of thetransitional forms. Earlier, this excellent remark had been made by Allard et al. (1986): A thin cover of peat has no influence on the processes involved in the evolution of the mound; consequently, there are all the transitions between pure palsas and pure lithalsas. For clear and unambiguous description, it is best to abandon the term 'palsas' as soon as the peat cover has disappeared.

Another terminological problem concerns the permafrost mounds which are described as pingos. Because palsas typically degrade to form circular rims around water-filled depressions, it was argued by many that they might be small collapsed pingos (e.g., Rapp and Rudberg, 1960; Lundqvist, 1962, 1969; Svensson, 1963, 1964a, 1969, 1976; Rapp and Annersten, 1969; Rapp and Clark, 1971; Seppälä, 1972b, 1982b; Wramner, 1972; Aartolahti, 1974; Lagerback and Rohde, 1985; Akerman and Malmstrom, 1986). In particular, Svensson (1964a) and Seppälä (1972b) describe the similarity in morphology between collapsed pingos and the remnants of lithalsas of the Hautes Fagnes (Belgium), which were, at that time, interpreted as pingo remnants.

MORPHOLOGY

The size and morphology of lithalsas are are not much different from those of palsas. They occur in patterns **(Figure 10).** For example, Seguin and Allard (1984) described permafrost landscape patterns in the Nataposca River area: parallel and elongated mounds transverse to valleys, individual mounds, and permafrost plateaus. The latter are made of large heaved surfaces over 200 m across.

The best known lithalsa has been studied by Calmels in his thesis (Calmels, 2005), prepared at Université Laval under the guidance of Michel Allard. This lithalsa is almost perfectly round, with a diameter of 50 m and a maximum height of 3.40 m **(Figure 11).** The top is rather flat, with

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steep slopes on the borders. It was chosen as a typical lithalsa in the Hudson Bay region and was called the BGR lithalsa because the BundesanstaIt für Geowissenschaften und Rohstoffe (Hanover, Germany) investigated this mound in collaboration with the Centre d etudes nordiques (Université Laval, Québec).

Figure 10. *Lithalsas and remnants of lithalsas in northern Quebec.*

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Figure 11. *The BGR lithalsa studied by Calmels. Location: 56°36.63 N, 76°12.85 W (from his thesis, 2005).*

SURFACE CHARACTERISTICS

Because of the absence of peat, the surface of a lithalsa differs from the surface of a palsa. The thermal isolation provided by peat does not exist, and the active layer is thicker than on palsas: Allard et al. (1986) report a depth of 1.00-1.25 m in silts and more in sands. In the surface silty material, a wide-spread net of mudboils is typically observed on the top of the mounds. On slopes as low than 1°, the mudboils are elongated to slope direction by gelifluction (Allard et al., 1986). On the steeper outer slopes, gelifluction is more active and sometimes induces small landslides.

MINERAL COMPOSITION AND ICE SEGREGATION

Several borings made in the BGR lithalsa are reported in the thesis of Calmels (2005) and in subsequent publications (e.g., Delisle and Allard, 2003; Delisle et al., 2003; Calmels and Allard, 2008; Calmels et al., 2008a, 2008b). They provide the best information we have at present on the internal structure of a lithalsa. Six borings were made as far as the underlying bedrock (gneiss), which is between 9.58 and 13.14 m from the surface.

This section summarizes the information obtained from the borehole that reached bedrock at a depth of 11.45 m.

The sediments underlying the lithalsa are glaciomarine fine silt and clay that was deposited in the Tyrrell Sea during deglaciation. For the first 6.60 m of depth, the granulometry was homogeneous, with 21-29% of silt, 78-79% of clay, and a maximum 1.3% of sand. At a depth of 10 m, a sand unit coarsens downward to small gravels. This permeable layer could be of great importance in the formation of a lithalsa because silty sediments are highly frost susceptible, whereas sandy material is not. Ice segregation has separated the original sediments into polyhedrons of irregular shapes that have been consolidated by cryosucction (see Van Vliet-

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Lanoë et al., 1984) (Figure 3). The clumps between the ice veins appear as composites between layered and suspended cryostructures (Murton and French, 1994). Description of the segregation ice is the same as inside a palsa.

The ice lenses are between a few centimeters to a few decimeters in thickness. In borehole sections of 25 cm, the volumetric ice content varied between 41 and 80%. The maximum ice content was observed immediately below the active layer, at 1.5 m in depth. It is here that aggradational ice, reflecting the thermal gradient inversion at the beginning of the cold season, was observed.

From the permafrost table to 2.5 m in depth, the ice layers are horizontal. Below, the ice lenses have high dip angles and are crossed by a dense network of ice-filled fault planes similar to those in the palsa described by Allard and Rousseau (1999). Such ice-filled faults are probably without meaning as they appear during the growth of segregation ice. However, it is well known that segregation ice lenses form parallel to the freezing front, and they indicate the direction of the freezing front.

Calmels and Allard (2004) used a medical scanner to view the ice and gas bubbles which occur in sediments. The volume of the bubbles is between 1 and 4% of the boring. These bubbles of gas are often elongated, following the freezing front propagation (i.e., orthogonal to ice lenses and parallel to crystallization) (Calmels and Allard, 2004). The origin of these bubbles may be: (1) gas dissolved in the water which is expelled during freezing; (2) gas which may be trapped in the sediment before freezing; or (3) CO_2 expelled from dissolved bicarbonates which precipitate during freezing (Ek and Pissart, 1965).

CLIMATE AND LITHALSA DISTRIBUTION

Lithalsas are only known from northern Québec and Fennoscandinavia, the coldest parts of these subarctic regions. This fact is connected with the absence of peat, which is characteristic of the lithalsas. Seppälä (1988) published a general model of the relation between mean annual tem- perature and minimum thickness of the insulating peat layer needed for palsa formation (Figure 12). The graph shows that the required thickness of peat diminishes from 1.1 to 0.1 m for mean annual temperatures from 0 to — 6 °C. Most important is annual summer temperature. In northern Québec, data indicate mean temperatures of the warmest month between + 8.5 and + 11.5 for all lithalsa locations and a mean temperature between —4.3 and —6.7 for the coldest month (Pissart, 2000, 2003). The lithalsas are located near the timber line, which corresponds to a mean summer temperature of around 10 °C. The thickness of snow is relatively thin. In Lapland, similarly, it is the maritime influence which induces the cool summer necessary for the growth of lithalsas.

Lithalsas are also known to occur in places where mean temperature of the warmest month is between +7.2 and + 12 °C and mean annual temperature is between — 1 to — 4.4 °C. Here, the lithalsas sites are also at the limit of the forest (Pissart et al., 1998).

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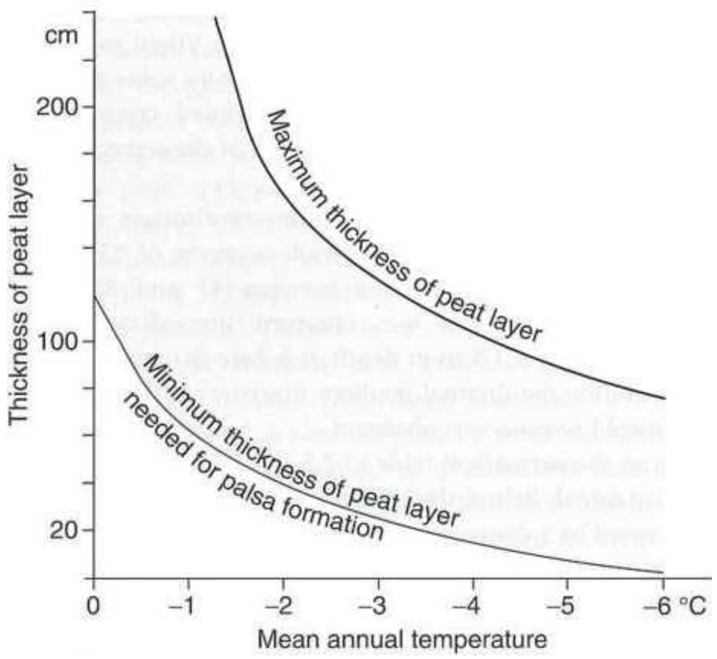
Figure 12. *Model of relation between thickness of peat and mean annual temperature on palsas. Reproduced with permission from Clark, M.J. (Ed.), (1988) Advances in periglacial geomorphology. The International Geographical Union, Commission on the Significance of Periglacial Phenomena. Wiley, Chichester, New York.*



In conclusion, lithalsas are located in the discontinuous permafrost zone but near the limit of the forest (mean summer temperature of 10 °C). The IPA map of northern hemisphere permafrost (Brown et al., 1997) shows that, almost everywhere, the forest limit is the boundary between the continuous and discontinuous permafrost zones (Pissart, 2003). This reflects the continental climate with warm summers. This is why lithalsas cannot develop there. The climatic conditions favorable to the growth of lithalsas only exist in a relatively few localities: they have never been described, up to now, from outside of Fennoscandinavia, the Kola Peninsula, and northern Québec. (Pissart, 2003).

MECHANISM OF FORMATION

There are transitions between true lithalsas, which never have any peat on their surface, and true palsas with a cover of peat (Allard et al., 1986; Matthews et al., 1997).

The processes which are responsible for the growth of lithalsas are the same as those for the formation of palsas.

Tritium determinations at the 2.0, 3.0, 4.0, 5.0, and 6.0 m levels were made in core sections from the BGR lithalsa (Calmels et al., 2008b). In the four upper samples, tritium contents are between 1.9 and 2.5 T.U., indicating a mixture between submodem and recent water. "The measurement value at 6.0 m depth (< 0.8 T.U.) shows that the ice was made before 1952 and does not contain modern or recent supply" (Calmels et al., 2008b, p. 37). These results confirm the data of Dever et al. (1984), which show the permeability of permafrost and indicate that water feeding the segregation ices was coming from the sides of the palsa.

The only clear differences between palsas and Hthalsas are a consequence of the presence of silt

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instead of peat on the surface. In these conditions, mass movements by solifluction on the slopes of lithalsas occur in a thick active layer. Accumulation of this material around the mound forms the ramparts which remain after thawing of the lithalsas. These ramparts indicate the previous existence of a lithalsa and not a palsa. There is no doubt about the presence of displaced material at the border of the mound; slope deposits due to solifluction processes and other slope phenomena have been described by Allard and Seguin (1987) and by Calmels (2005) on the BCR lithalsa, and the sections cut in ramparts of the Hautes Fagnes features (Pissart and Juvigné, 1980) (Figure 13) show that the slope deposits constitute the majority of the ramparts.

Figure 13*. A remnant of lithalsa in which a section was cut to study the genesis of the rampart. The lithalsa was formed during the Last Dryas time, at 600 m asl in the Hautes Fagnes, Belgium.*

Another process may also contribute to the formation of the ramparts, namely the process of frost thrusting (Figure 14). The main arguments in favor of this proposal (Pissart, 2007, 2008, 2010b; Pissart et al., 2011) are:

1. The gentle slopes on the top of the lithalsas. The BGR lithalsa is a good example: the mudboils which cover the summit are elongated following the slope and indicate mass movements on slopes as row as 1°. But it is not clear if the lifetime of the. lithalsa is long enough to constitute the whole rampart.
2. In the BGR lithalsa, the segregation lenses are not horizontal but, clearly, are dipping. Such dipping was also observed for segregation lenses in palsas (Allard and Rousseau, 1999). This may indicate that frost did not penetrate vertically from the top of the lithalsa but rather from the sides of the mound.
3. Sections observed in the Hautes Fagnes (Pissart and Juvigné, 1980) clearly show that a part of the rampart is not composed of slope deposits but material displaced beneath the layer of peat that formed before the growth of the lithalsas.
4. Some papers describe the enlargement of the mound. Matthews et al. (1997) wrote that "an increase in size and height has been achieved by further growth of the permafrost core," Rapp and Rudberg (1960) state that the 10-20 m wide circular or elliptical lakes are surrounded by ridges of pressed soil, with tangentially oriented boulders.

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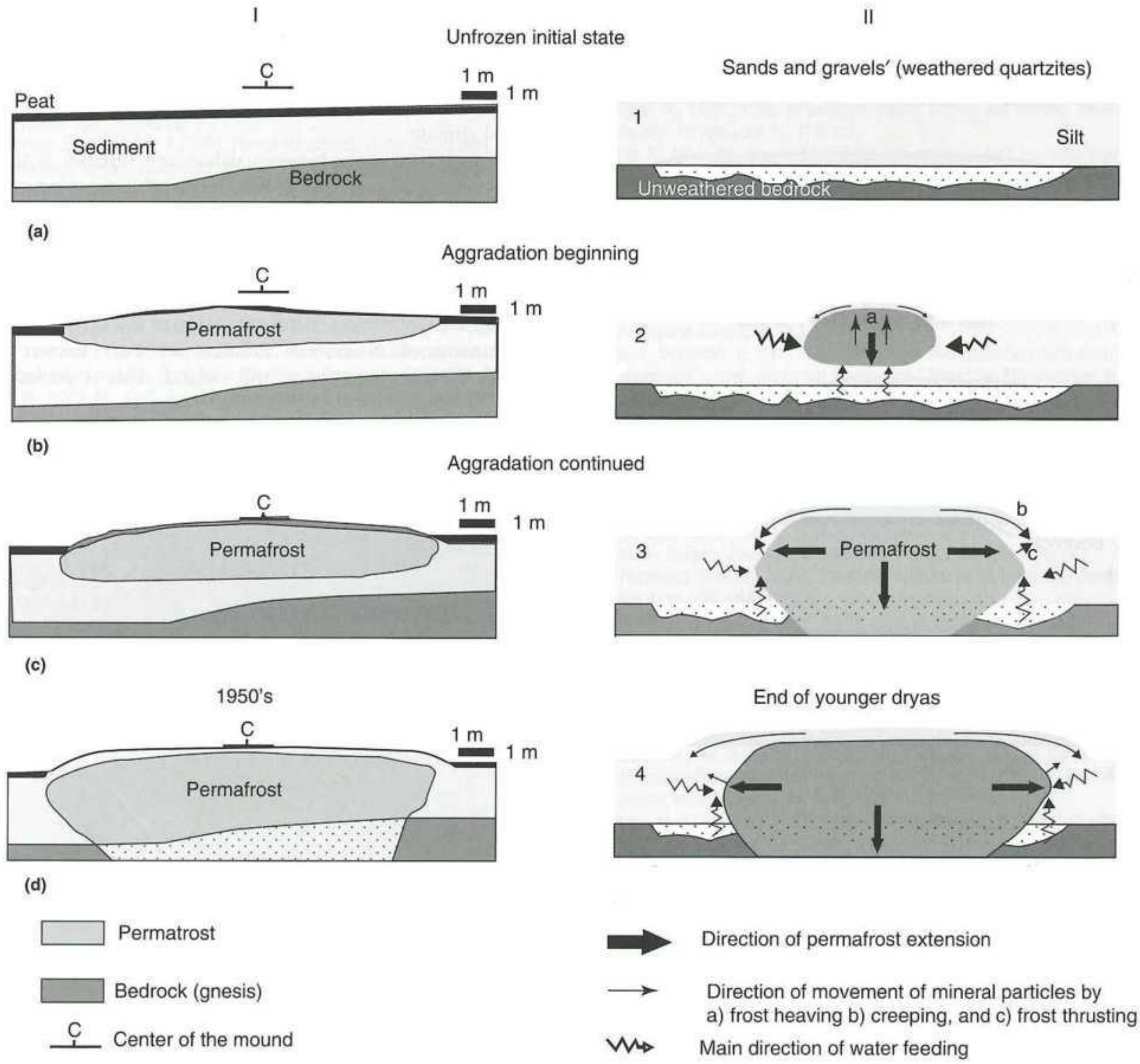
***Figure 14**. Models of formation of lithalsa in the opinions of Calmels and Pissart (Pissart et al., 2011). The model of Calmels (on the left) shows only an upheaval of the mound without any enlargement. The model of Pissart (on the right) shows a lateral enlargement of the mound by frost thrusting (Pissart, 2010b; Pissart et al., 2011) and a permeable material on the top of the bedrock (Pissart, 2010a). Reproduced from Pissart, A., Calmels, F., Wastiaux, C., 2011. The potential lateral growth of lithalsas. Quaternary Research 75, 371-377.*



These arguments suggest that lithalsas grow not only by vertical upheaving but also by lateral expansion of the permafrost. The latter is produced by "frost thrusting" (Washbum, 1979) of the mineral material on the side of the mound, perhaps during the initial stage of lithalsa formation. This process could give a lateral growth to the mounds (Figure 14).

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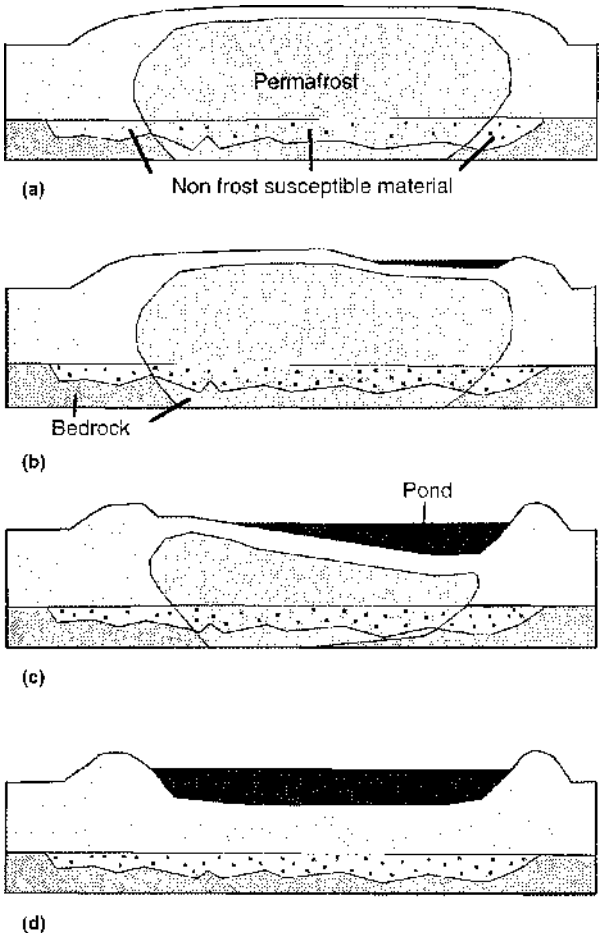
THAWING OF LITHALSAS

The different thaw stages of lithalsa evolution (Figure 15) are easy to observe in northern Québec. This last stage in the cyclic evolution of the Iithalsa is not controversial. The sketch is similar to the drawing by Calmels et al. (2008a). At the beginning, a general subsidence occurs and the wall, absolutely not visible before, begins to appear.

Figure 15*. Stages of melting of lithalsas and appearance of ramparts in accordance with the observations of Calmels et al. (2008a). (a) Lithalsa at maturity, (b) Melting begins at the side and a rampart becomes visible, (c) Thermokarstic evolution of the pond, (d) The ice inside the lithalsas is completely melted. Segregation ice never existed inside the nonfrost susceptible material on the bedrock.*



Then a pool comes into view near the border of the lithalsa at the inner limit of the rampart. This pool is located on the slope convexity, where slope processes have eroded part of the active layer and do not receive the same amount of mineral material from the gentle slopes of the summit. As soon as the pool is present, it evolves and grows by classical thermokarstic processes: warmth from the pond enlarges it, all ice within the lithalsa disappears, and a hollow remains, surrounded by a rampart.

Conclusion

Palsas and lithalsas are similar mounds that grow by the formation of segregation ice in silty material. Palsas have a cover of peat which does not exist on lithalsas. palsas exist throughout

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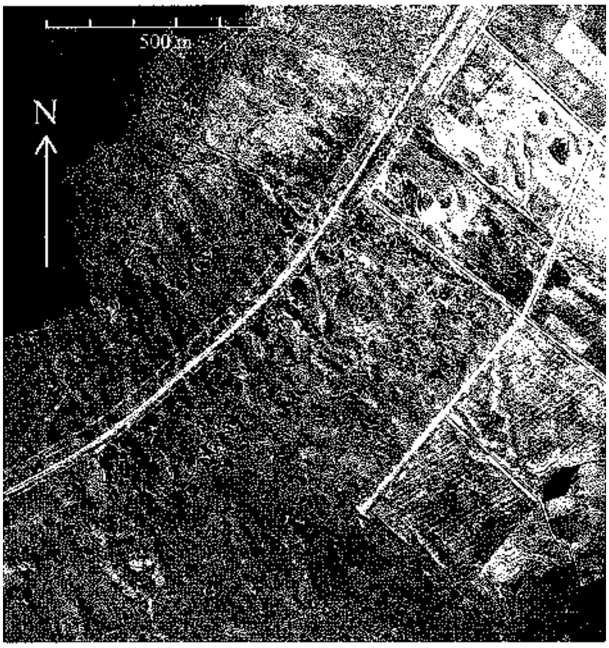
the discontinuous permafrost zone, whereas lithalsas occur only at the northern border of the discontinuous zone where climate is oceanic, as in northern Québec and Fennoscandinavia. Lithalsas need cool summers; these do not exist in discontinuous permafrost areas of continental climate.

The main difference between palsas and IithaIsas is that palsas, after thaw, leave almost no trace. After the thaw of a lithalsa (or a palsa with a thin cover of peat), ramparts remain that surround enclosed or open depressions. These ramparts are mainly made of sediments, which accumulate by solifluction on the external slopes of the lithalsa, but also probably from material thrusted during lateral expansion of the lithalsa.

Remnants of Pleistocene lithalsas are only known in Belgium (Figure 16), Wales, and Ireland. This is probably because the climatic conditions favorable for their formation were very limited. During the Last Dryas time, they existed only in limited places. The observations of a permeable layer between the bedrock and the base of the silts in which the segregation ice lenses have grown is known from the BGR lithalsa in northern Quebec (Calmels et al., 2008a) and in the Hautes Fagnes (Pissart, 2010a).

Figure 16. *Remnants of Late Dryas lithalsas on a gentle slope near Simmerath (Germany) on the border between Germany and Belgium. Photo MET du 9-10-1953. Copyright Service Public de Wallonie: Secrétariat général-Département de la Géomatique. Direction de la Géométrologie.*



This permeable material is probably necessary for the formation of lithalsas. In addition to climate, it is a limiting factor for their distribution. More excavations and deep borings in present-day lithalsas are necessary for increasing knowledge of these periglacial mounds.

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