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PALSAS, LITHALSAS AND REMNANTS OF THESE PERIGLACIAL MOUNDS. A PROGRESS REPORT

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Abstract

There is no general agreement about the meaning of the word 'palsa'. Usage and recent suggested definitions indicate that the word is chiefly used for cryogenic mounds covered by peat that were formed by an accumulation of segregation ice in the discontinuous permafrost zone. Lithalsas are similar mounds, but without any peat cover. The thickness of aggradation ice on the top of lithalsas can be considerable. Use of development and decay palsas as indicators of climatic change is difficult. The climatic conditions in which lithalsas form are much more restricted than those for palsas and, as a consequence, regions where lithalsas exist are rather rare. After melting, lithalsas leave ramparted depressions; the mass movements on the peaty slopes of palsas are less propitious to the formation of ramparts. Some of the pingo remnants described in western Europe are, more accurately, lithalsa traces.

The excellent article by Seppälä (1988) is the most recent restatement about the 'palsa family' of permafrost mounds according to an expression used by Allard *et al.* (1996). In this paper, I give a personal assessment of the new evidence that has been published subsequent to Seppälä's paper, and discuss developments in terminology.

I. Terminology: palsas and lithalsas

At present there is no general agreement about the meaning of the word 'palsa'. In 1983, in an often quoted paper, Washburn (p. 42), after an inventory of the characteristics of palsas suggested by different authors, proposed the following definition: 'Palsas are peaty permafrost mounds ranging from c. 0.5 to 10m in height and exceeding c.2m in average diameter comprising (1) aggradation forms due to permafrost aggradation at an active layer/permafrost zone, and (2) similar appearing degradation forms due to disintegration of an extensive peaty deposit'.

Although Washburn's definition often re-appears, few authors have accepted it during the last decade, except Nelson *et al.* (1991: 305), who consider that the term palsa 'should be used only in a morphologic context but can be modified adjectivally to communicate genetic information'. More recent definitions deviate from Washburn's in two ways: (1) giving a genetic meaning to the word 'palsa' and thus restricting it to mounds formed by segregation ice; and (2) considering that palsas are found only in the discontinuous permafrost zone.

Newer définitions appear in Seppälä's paper (1988), in the *Glossary of permafrost and related ground-ice terms* prepared in Canada by a Committee on Geotechnical Research (Associate Committee on Geotechnical Research (A.C.G.R.-N.R.C.), 1988), and also in the *Multi-language glossary of permafrost and related ground-ice terms*, by van Everdingen (1998), under the auspices of the International Permafrost Association. Van Everdingen (definitions, p. 45) writes: 'It is proposed therefore that the term ''palsa'' be restricted to those features where the internal structure shows the presence of segregated ice and where the environment lacks high hydraulic potentials, provided that other parameters (size, shape, location in wetlands) are also satisfied. The term ''frost mound'' should be used as a non-genetic term to describe the range of morphologically similar, but genetically different, features that occur in permafrost terrain'. If, in this definition, the discontinuous permafrost zone is not expressly mentioned, it is implied, because such a high mound due to segregation ice can form only in the discontinuous permafrost zone: water supply is limited in continuous permafrost zone by the small thickness of the active layer.

I am quite in favour of van Everdingen's proposal. Consequently, in this paper, I shall use the term 'palsa' to refer to *perennial mounds covered by peat, situated in the discontinuous permafrost zone and due chiefly to segregation ice fed by cryosuction*. Following van Everdingen, I suggest that other terms be used when the mounds do not square with this definition.

On the other hand, Seppälä (1988) strongly rejects the term 'minerai palsa' for similar mounds with no peat cover. He explains that the expression was proposed by people who do not know Lapland, from where the term 'palsa' came. However, it was the proposal of a Scandinavian, Ahman (1977: 145), who wrote: 'A palsa is a hillock or a more elongate rise in the ground formed by the built-up of segregated ice in soil, minerogenic or peat or in combination', a definition adopted by Dionne (1978). Those features, described for the first time by Wramner in 1972a, have been designated by various terms, reviewed by Matthews *et al.* (1997) and by Pissart *et al.* (1998): 'palsa-like frost mounds in pure mineral soil' (Wramner, 1972a), 'domed-hummocky peatbogs' (Spalanskaya and Evseyev, 1973), 'buttes minérales cryogènes' (Payette *et al.*, 1976), 'pure mineral soil palsa with no peat, purely minerogenic palsa with no peat' (Ahman, 1977), 'palse minérale' (Dionne, 1978; Pissart and Gangloff, 1984), 'cryogenic mounds' (Lagarec, 1982; An and Allard, 1995), 'mineral permafrost mounds and permafrost plateaux' (Allard *et al.*, 1986; Matthews *et al.*, 1997), 'palsas-like mounds and lithalsas' (Harris, 1993).

The last term, 'lithalsa', created by Harris (1993), has been proposed to define, from now on, mounds that are palsas with no peat (Figure 1) and, in this way, to emerge from a fruitless terminological discussion (Pissart *et al.*, 1998). The word 'lithalsa' sounds like the term 'palsa' and their fortunate morphological resemblance evokes a common origin. Matthews *et al.* (1997: 119) suggest keeping the word 'palsas' for mounds that have had, at the beginning of their growth, a very thin peat cover, even if the peat has later disappeared. Like many other authors, they insist on the existence of a 'genetic continuum between palsas and mineral permafrost mounds', which will always make difficult the differentiation of the transition forms.

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I completely agree with this observation, which has some implications: a palsa with a few centimetres of peat cover is similar to a lithalsa and probably leaves the same trace after the ice has melted.

Even if the genesis of lithalsas is similar to the genesis of palsas, it should be pointed out, as noted by Allard *et al.* (2000: 208) that the permafrost plateaux (lithalsa plateaux) can be higher (up to 10 m). But in a personnal communication, M. Allard wrote that it was probably an error because he subsequently never measured any lithalsa higher than 7m.

The type of lithalsa described in Yukon by Pissart *et al.* (1998) is consistent with the chosen definition. Described at a location near Whitehorse, this type of lithalsa is covered by purely mineral lacustrine sediments of very low density, which act as an insulating layer. The role of peat has been taken, here, by these sediments, which allowed the birth of this lithalsa where the mean annual temperature is too high for the growth of normal lithalsas in clayey silts. No specific name has been suggested for this type of lithalsa, fundamentally different from the other, but probably very rare.

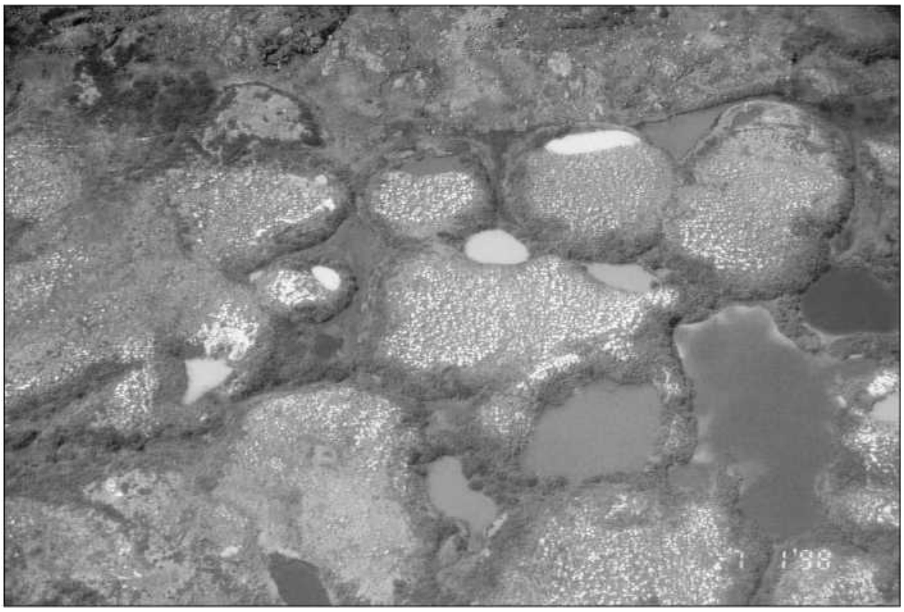
Also in the discontinuous permafrost zone, some features have been called 'floating palsas', firstly by Zoltai (1972), later by Harris *et al.* (1992), and finally by Harris (1998). The forms described in 1998 were floating islands of vegetation-covered peat, with a height of up to 70 cm. Developed only in peat floating on a body of water (like an iceberg), they exhibit increased ice content because of the addition of meteoric water from above. If one accepts the definition I have chosen, such mounds could be excluded from the palsas. Of course, it should be noted that floating peat does not necessarily consist of perennial ice, for similar floating peat is known in temperate areas (Bailly *et al.*, 1975).

All in all, we can see that no definitive agreement exists with regard to terminology. This is clearly demonstrated by the fact that, in a recent paper, specialists such as Allard and Rousseau (1999) feel it necessary to explain, in the title, that their palsa and peat plateau are ice-segregation mounds. Increasing knowledge will perhaps eventually lead to convergence of viewpoints. Ten years ago, lithalsas were not well known but, more recently, understanding of these features has improved significantly.

I do not think the terms should be used without a genetic connotation. A field of palsas or of lithalsas, indeed, cannot exist without an accumulation of segregation ice; they cannot be mistaken for pingos, which are always isolated or in groups of two or three mounds. Floating palsas, always low, are easily identified just as they are, at least if all of them are like the forms described by Harris *et al.* (1992), which are clearly floating peat islands at the surface of a pond.

Whatever final terminological choices are made, the present situation is unsatis- factory, because everybody has to define their terminology each time.

Figure 1 *Aerial view of a field of lithalsas in northern Québec.*



Some lithalsas are melting, leaving ramparts (photo A. Pissart)

II. Internal composition of palsas and lithalsas

Fifty years ago, palsas were considered to consist of ice-rich peat only. In the 1960s and 1970s, it became evident that a frozen mineral core does exist in most instances and that, for the most part, the ice happens to be in that mineral core. Since 1972, cryogenic mounds looking like palsas, but without peat, have been described. As recommended above, we should now call them 'lithalsas'. I am not going to hark back to the question of the organic or minerai nature of the palsas, which has been presented by Seppälä (1988) and recently restated by Pissart *et al.* (1998); instead the nature of the ice existing in these features will be discussed.

The ice found in the palsas is segregation ice fed at depth by cryosuction; this fact is generally admitted. The outstanding study of a permafrost plateau of Northern Quebec by Allard *et al.* (1996) has revealed new evidence in this area. Allard *et al.* (1996: 225) make it clear that 'the studied plateau is similar to thousands of others and is also comparable (albeit for the absence of peat cover) to thousands of palsas and peat plateaux formed in the Subarctic during the Holocene in clayey silts'. They feel their observations apply to most of the cryogenic mounds we study. For the first time, the ice at depth was described, in a detailed and coherent way and the authors were able to explain the nature of the ice found in 25 drillings, 3-4.5 m deep, in a complex lithalsa plateau. Thanks to so many drillings, they could describe the stratigraphy of the frozen formations.

They also evidenced the existence, near the permafrost table, of aggradation ice (ice lenses formed in the lower part of the active layer and incorporated into the permafrost) and they showed its importance. Under the 80-cm-thick active layer on the studied plateau (Figure 2), this type of ice comprises, 50-80% by volume of a layer some 150 cm thick. The hillock being

5.60 m, this ice is responsible for 15% of its height (0.85 m), something that had never been calculated before. Harris (1988: 367) had already stressed the importance of the fixation of meteoric water in palsas: 'Although palsas may be initiated by water moving to the freezing front under the mound from the adjacent unfrozen fen, subsequent growth may be due to surface water added to the permafrost core from above over time'. Allard et al's (1996) paper establishes that their lithalsas are not only formed by cryosuction of water from underneath but, also, near the surface, by percolating meteoric water; for his part, Harris believes meteoric water is deeply percolating in palsas. In 1988, Seppälä (p. 265) wrote: 'In the upper part of the core, the ice content is often very high, being equivalent to more than 100% of the dry weight of the soil'. However, the sentence 'Palsas are thus formed by freezing from above' (Seppälä, 1988: 269) shows that this supply of meteoric water was not taken into account in the growth of palsas. Allard *et al.* (1996: 224) write: 'Such an enrichment in ice near the permafrost table was also found in other silty permafrost mounds in northern Quebec by drilling (Fortier *et al.*, 1991, 1992), and imaged with ground penetrating radar (Pilon *et al.*, 1992; Allard *et al.*, 1992)'. The mathematical model of An and Allard (1995) also evidenced this type of ice at the top of lithalsas or palsas when the peat cover was thinner than the active layer. The presence of aggradation ice is sub- stantiated by many observations and is the only possible explanation of the high amount of ice in the upper part of the permafrost but, as far as we know, nobody before Allard *et al.* (1996) had shown that the ice of the permafrost table is aggradation ice.

Under the zone that contains much aggradation ice, Allard *et al.* (1996) observed two other zones also containing ice (Figure 2). First, a 2.5-m-thick layer with 10-30% ice by volume, very thin lenses and about 1mm veins. Then, underneath, another zone where there is more ice (50-80%), in 1- to 4-cm-thick lenses at regular intervals. Near the permafrost base, however, an ice lens of more than 20cm has been found. Depending on the importance of the thermokarstic processes that took place from the surface and removed some of the surface layers, different ice layers may exist immediately under the active layer. Until recently, the availability of only isolated observations had not permitted the correct interpretation of the variations of ice content that had been described immediately under the active layer.

Allard *et al.* (1996) also show that the aggradation ice layer progressively appears after the first heaving of the plateau; thus the mounds grow by simultaneous formation of segregation ice at depth and superficial accumulation of aggradation ice. The most important accumulation of ice is, of course, at depth. The observations reported by Allard and Rousseau (1999) and the model of An and Allard (1995), however, tend to demonstrate that the aggradation ice appears only if the active layer is thicker than the peat layer, and that it forms in the underlying mineral material.

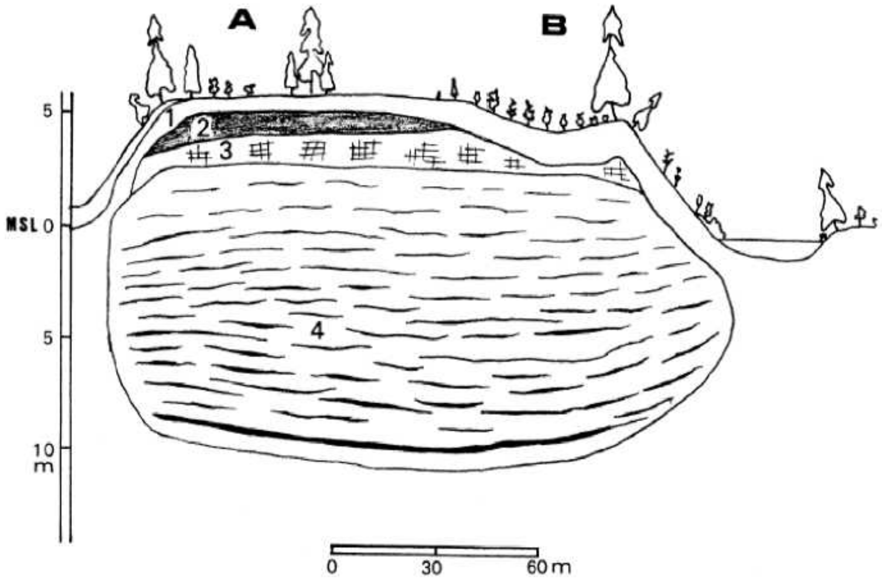
How palsas and lithalsas grow and evolve seems clearly established, but Dever *et al.* (1984) have demonstrated by an isotopic study ($\delta^{18}O$, δD and ^{3}H), the feeding of ice lenses within three palsas 2-3m high covered by an organic horizon 50-100 cm thick, of which the upper 30cm was peat sensu stricto. The high isotopic abundance of tritium is explained by the supply of recent water to some ice lenses of these palsas deep in the underlying permafrost. High activity levels alternate with horizons that contain no tritium, or very little. The authors propose two hypotheses. The first one is that permafrost remains permeable, explaining how rain water subsequent to 1952 (when, for the first time, humans injected great amounts of tritium into the atmosphere) could circulate within the palsa where temperature is less than 0°C, but where notable amounts of salts exist (because the deposits have a marine origin and have recently emerged from the sea by isostatic rebound). The second hypothesis is that the growth of the ice lenses is the result of successive freezing, in cold points of the profile, of recent atmospheric vapour containing tritium that has moved through discontinuities of the nonsaturated zone (between the ice lenses).

Some unpublished observations from borings in lithalsas made in 2000 were reported in an oral presentation by G. Delisle and M. Allard on 28 March 2001, during the First European Permafrost Conference in Rome. They showed that the level of water in a permafrost mound was in hydraulic equilibrium with the level of a bordering pound. A part of the water in the permafrost should be not frozen and therefore should be able to move along the thermal or hydraulic gradients. This observation indicates that Dever's first explanation is probably correct.

A second isotopic study (Harris *et al.*, 1992, 1993) examined the distribution of $\delta^{18}O$ and δD within the thick peat (at some places more than 5m) of a 1- to 1.5-m-high palsa plateau situated in southern central Yukon territory, near Francis Lake, about 120 km to the north of Watson Lake. Within the permafrost of the palsa plateau, only the ice from the peat layer has been studied, not the ice from the underlying mineral material. In the peat, the relative amounts of the $\delta^{18}O$ and δD are similar to that in the active layer ice, and very similar to that in the precipitation at Whitehorse. In the water of the neigh- bouring fen, the results are different. The authors' inference (Harris *et al.*, 1992: 24) is that 'the bulk of the ice that forms the peat plateau must derive from the precipitation entering the mound from above, rather than being fen waters that moved through the sediment at the freezing plane at the base of the permafrost'. Later, Burn (1993) cast doubts on this, however, and suggested that the data analyses may not support the conclusions of Harris *et al.* (1992).

More observations are necessary to clear the matter up. The 20 holes drilled through lithalsas in July 2000 near Umiujag in Nunavik (Northern Québec) to obtain cores and install geophysical instrumentation in the permafrost (Allard *et al.*, 2001) will surely soon solve this problem. Comparing data from peat ice with data from mineral soil ice seems questionable. In the mineral soil, the superficial aggradation ice is very massive and, according to Fortier *et al.* (1991), it must prevent surface water from percolating. How peat reacts to segregation ice and particularly to aggradation ice is not very well known, but Wramner (1972b), in laboratory experiments, has demonstrated that all peat samples showed frost heave capacity but the fine-grained mineral soils showed somewhat higher frost heave rates than the peat samples. The field experience of M. Allard (personal communication, 2000) is that fibrous peat (*Sphagnum*, wood, etc.) is not favourable to segregation ice, unlike minerotrophic peat (Cyperaceae often decayed and infiltrated by silt and clay), which allows formation of segregation ice, but less than in silts. Allard and Rousseau (1999) however describe aggradational ice under the peat cover of a palsa.

Figure 2. *Distribution of ice in a lithalsa plateau in Northern Québec described by Allard et al. (1996).*



The cryostratigraphical divisions, in Arabic figures, are taken from the same article. 1, Active layer; 2, ice- rich layer (50-80% in volume), aggradational ice; 3, low ice content (10-30% in volume), reticulated ice; 4, thick and regularly spaced lenses of segregation ice (50-80% in volume); near the permafrost base there is a layer thicker than 20 cm. The figure shows that the aggradational ice melted on part B of the plateau. A minor modification of the original figure was made because I do not believe in continuous ice lenses throughout the entire plateau.

III. Local conditions determining development and melting of palsas and lithalsas

To explain the initiation of a palsa, the widely held hypothesis invokes the existence of a snow cover that is either discontinuous or at least of very unequal thickness. Where the cover is thin, freezing deeply penetrates the soil and induces a heaving. Seppälä (1995) carried out experiments in the field: during three winters, at the same place, he removed, several times, the snow cover and observed a subsequent 30cm heave of the soil surface. Many authors agree on the importance of this factor, but other causes are sometimes evoked. Matthews *et al.* (1997: 117) point out the influence of the moss cover and its effect on the albedo. They do not believe, for the case they have studied, in the influence of snow cover distribution.

From the same point of view, Zoltaï (1995: 46) has stressed that 'in the discontinuous permafrost zone, permafrost formation is initiated in peatlands mainly as particular conditions are created by the vegetation'. Two sequences are described. In the first one, Sphagnum pillows appear at the surface of the fen and they insulate the seasonal frost against summer thawing. With the upheaval of the surface by the frost, the cushions dry and their insulation value increases. The other sequence, which seems more frequent, at least at the southern border of the discontinuous permafrost, is the appearance, in the marsh, of patches of several square metres of trees, with dense tree canopy (*Picea marina*). These trees intercept much of the snow, resulting in a much reduced snow cover under the trees, increasing the heat loss during the winter.

The influence of the snow in the subsequent development and conservation of the features is admitted: the tops of the palsas, where snow has been blown away, stand in contrast to the surrounding snow accumulation (Seppälä, 1994). This role is perfectly evidenced by Allard *et al.* (1996) who underline another influence of the bush cover. They found that if trees are growing on the top of a mound, they bring about a thicker snow cover that, insulating against winter frost, can initiate melting.

With regard to the disappearance of the palsas, all the authors agree that formation and melting of palsas can occur at the same time and place, independently of any climatic change; the major conditions lie in the snow cover, the plant cover and the albedo. Dionne (1984: 178) writes that, since the 1950s, some papers mention a cyclical evolution of palsas; consequently, it is difficult to use mound formation or degradation as indicators of regional climatic change. This point of view has already been espoused by Svensson (1970), Zoltai (1972) and Thie (1974), who have demonstrated that a regional study of palsa fields is indispensable before concluding that palsa studies are indicative of warming. Seppälä (1988: 273) has expressed the same opinion: '... changes of climate are not the exclusive cause of palsa collapse...'.

However, Zuidhoff and Kolstrup (2000) believe that climatic warming, probably in combination with increased snowfall is responsible for collapsing features of the southernmost palsa marsh of Sweden. In this marsh, the palsas lost half their extent between 1960 and 1997, while the mean annual temperature in northern Sweden has increased 1-1.5°C since 1930. Harris and Schmidt (1994) explain that palsas can gradually become smaller, without any melting, due to faster accumulation of peat around them than on their top. They measured the increasing thickness of peat thanks to a volcanic ash horizon (the White River Ash) deposited 1200 years B.P.

IV. Climatic conditions allowing growth of palsas and lithalsas

1 PALSAS

The definition of palsa I advocate ties the existence of palsas to the presence of discontinuous permafrost. The accepted opinion is that palsas, the first permafrost islets, cannot appear if the average annual temperature is not below 0°C. Dionne (1984), in a paper quoted by Seppälä (1988), presents a comprehensive study of the southernmost palsas of the Northern Hemisphere. He shows that palsas exist up to the point where average annual air temperatures are between 0 and -1°C, but active palsas are not numerous within this limit. The southernmost palsas mentioned by Dionne (1984) could have been initiated under colder conditions; the Blanc-Sablon palsas (near the mouth of the St Lawrence River) may have formed during the Little Ice Age. Subsequent measurements of the air temperature in this palsa field reveal (M. Allard, personal communication, 2000) that the average annual air temperature is negative, not positive as Dionne claimed.

The northern limit of palsas, if our chosen definition is accepted, runs along the border between discontinuous and continuous permafrost. In continuous permafrost, high cryogenic mounds must be pingos: the features called 'palsas' by Washburn (1983) are fed only by the water that is contained in the active layer, as indicated by Seppälä (1988: 273). At the limit of continuous permafrost, which is also the limit of palsas, the average annual température of the air generally varies between -6°C and -8°C (French, 1996).

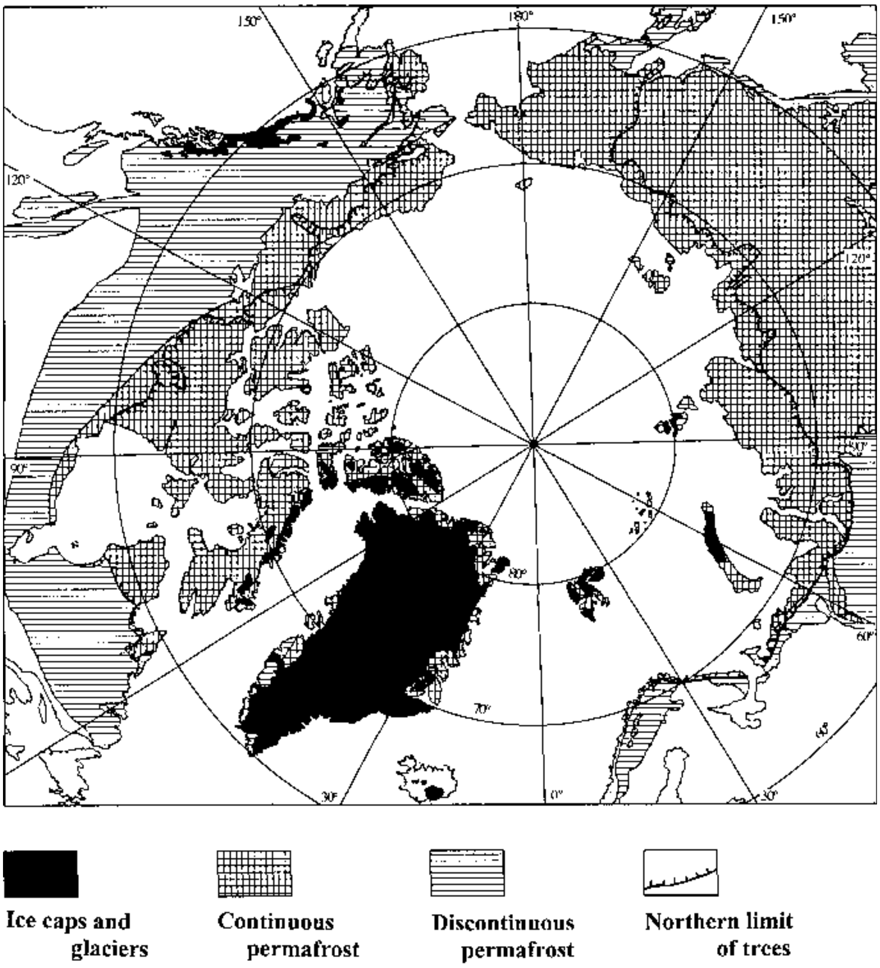
2 LITHALSAS

Although palsas are found everywhere within discontinuous permafrost, the lithalsa zone is much more confined. It agrees with the figure drawn by Seppälä (1988) who presents a general model of maximum peat thickness in different regions with negative annual temperature, and the minimum thickness of insulating peat layer needed for palsa formation. This model shows that, when the mean annual temperature is -6°C, peat is not necessary for the growing of lithalsas. The essential condition permitting lithalsa development is cool summers, during which the ice formed in the soil does not melt, in spite of the absence of peat. In an inventory of climatic conditions of the zones where lithalsas have been described, Pissart (2000b) shows that, in northern Quebec, indeed the few zones where lithalsas exist have average annual air temperatures between -4.3°C and -6°C, whilst the average temperature of the warmest month is between +9.2°C and +10.7°C (Allard and Seguin, 1987; An and Allard, 1995; Worsley *et al.*, 1995; Allard and Rousseau, 1999). In Scandinavia, because the features are found at higher altitudes, the calculated values are from -3°C to -4.4°C for the average annual temperature and from +7°C to +8.3°C for the mean temperature of the warmest month (Wramner, 1973; Lagerback and Rohde, 1985; Akerman and Malmstrom, 1986; Matthews *et al.*, 1997). On the whole, according to these observations, lithalsas require an average annual air temperature between -3°C and -6°C and a mean temperature of the warmest month between +7°C and +10°C. Taking into account only the Hudsonian data, stemming from thousands of lithalsas and more reliable than the data from Lapland, we can estimate from the published data the following values: between -4°C and -6°C (average annual air temperature) and from +7°C to +11°C (mean temperature of the warmest month).

V. Likely world distribution of lithalsas

Temperature conditions under which lithalsas can appear are constrained. They are restricted to regions where the temperature of the warmest month is less than or near to +10°C (tree line) and where permafrost is discontinuous (Pissart, 2000a). If these criteria are accepted, such regions can be identified on the map of Northern Hemisphere permafrost (Brown *et al.*, 1997), which is partly reproduced as Figure 3. This map also shows the northern tree line (10°C isotherm of warmest month). In North America the tree line adjoins the discontinuous permafrost limit in northern Quebec, to the north of Great Slave Lake and at the western end of Alaska. Tree line and discontinuous permafrost limit are also next to each other in Lapland and, on both sides of the Ural Mountains, in Russia. Beyond the Ienissei River, in Siberia, the tree line winds within the continuous permafrost zone and, therefore, lithalsas cannot form because the summers are too warm. They could appear in the Kamtchatka Peninsula and in a narrow Siberian coastal fringe near the Sea of Okhotsk. Consequently, the regions where lithalsas are possible are very restricted. Northern Quebec and Lapland, where lithalsas are known at the present time, should, in fact, be the main regions where such features can appear (Pissart, 2000b).

***Figure 3**. Distribution of continuous permafrost and discontinuous permafrost from the permafrost map of Brown et al. (1997).*



The tree line is taken from the same document. Lithalsas can form only in places where the tree line and the continuous permafrost limit are close to each other. From east to west, it embraces Hudson Bay and a region to the north of the Slave lake in Canada, the western end of Alaska, Sakhalin and Siberia near the sea of Okhotsk, both sides of the Ural Mountains and, finally, Lapland

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VI. Traces of palsas and lithalsas after their melting

In the literature, palsas and lithalsas are not clearly separated and the thermokarst features presented by both these mounds are not distinguished. Several authors emphasize that mounds with peat and without peat have the same origin and are found close to each other. For the most typical palsas born in marshes, the melting of the ice leaves only depressions. These depressions are explained, as Harris and Schmidt (1994) demonstrated, by the speed of peat accumulation, which is greater in the fens than on the surface of the peat plateaux: there is less peat on the mounds than around them. However, as soon as depressions appear, peat forms thicker deposits in them than around them; progressively, it fills them up and they disappear. Seppälä (1988: 271) repeats the sentence of Lundqvist (1969): '...once a palsa has disappeared by thawing, almost no sign is left in the stratigraphy to demonstrate its former existence'.

For mounds clearly classified as lithalsas (mineral palsas), Dionne (1978) describes ramparts. Lagarec (1973: 478) writes that near lithalsas hollows occur that are more or less circular with sometimes a low rim ('plus ou moins circulaires bordées quelquefois par un bourrelet peu marqué'). Pissart and Gangloff (1984), Pissart (1998, 2000a,b) emphasize the presence of ramparts around remnants of lithalsas. In Lapland, the existence of a rim has often been an argument for an interpretation of forms as pingo remnants (Svensson, 1964, 1969; Seppälä, 1972).

Some descriptions (Seppälä, 1988; Van Vliet and Vergne, 1994) point to low rims around some traces of palsas showing that ramparts may be formed by mounds with a thin peat cover. Allard and Rousseau (1999) have reported material slipping down the flanks of palsas mounds where the peat cover had been partly eroded. Therefore, there is no reason to believe that palsas with a thin peat cover do not create ramparts the same as lithalsas.

In the remnants of Pleistocene lithalsas of the Hautes Fagnes in Belgium (Figure 4), Pissart and Juvigné (1980) demonstrated that the ramparts were made in two different ways: (1) The most efficient is the descent of mineral material on the slopes of the mounds. A peat cover is surely less favourable to mass movements of superficial material and protects the silty material below from cycles of freezing and thawing which are the main cause of creep and solifluxion. (2) The second process is the lateral displacement of the upheaved material during the growth of the mound and its vertical sinking during the melting, movements that create a minor part of the rim. This process may produce a low circular relief after the melting of palsas. Although observations of rim formation at present-day mounds are difficult, we obviously need more information about the processes acting on the slopes of the mounds and the traces that remain after the melting of different cryogenic mounds.

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VII. Recognizing Quaternary lithalsa traces and palaeoclimatological implications

Before the 1980s, closed and ramparted depressions of the temperate regions had a single periglacial explanation: they were considered as pingo traces. However, as early as the 1970s, it was clear that pingos could not have formed on the Hautes Fagnes plateau (Belgium), where such ramparted depressions are numerous (Pissart *et al.*, 1975; Pissart, 1976). During the same decade the first descriptions of lithalsas were published (Wramner, 1972a) and these cryogenic mounds of another kind could perhaps explain the Hautes Fagnes 'viviers'. At the time, these lithalsas were termed 'mineral palsas'; Pissart and Gangloff (1984) suggested they were the features that were responsible for the appearance of the 'viviers'. Nowadays, our knowledge of the question has advanced considerably; pingo traces and lithalsa traces can no longer be mistaken, at least where remnants of former lithalsa fields exist. Lithalsas appear in close groups, often very numerous, and in high concentration. On the contrary pingos develop at widely spaced intervals, their number per unit area is low, in both open and closed systems. In the closed system case, Stager (1956) reports a density of 20 pingos per square mile, or less than 8 pingos per square km, in an area where, according to him, their concentration is at a maximum in the Mackenzie delta. In the open system case, the density is less than 1 pingo km-2, judging by the studies of Holmes *et al.* (1968) in Alaska and of Hughes (1969) in Yukon.

Moreover, the genetic mechanisms are not identical: lithalsas appear only in silty materials, very favourable to segregation ice, whilst pingos require, at depth, a permeable material that allows the easy circulation of water and thus the formation of injection ice. The open system type can appear only in places where hydrostatic pressure from higher slopes is possible; in the closed system, a pocket of unfrozen sediments is necessary and it requires either a lake or a river.

According to the former criteria, a small number of closed and ramparted depressions, formed during the Younger Dryas, which had been taken for pingo traces, may now be reckoned as lithalsa remnants (Pissart and Gangloff, 1984; Gurney, 1995; Worsley *et al.*, 1995; Pissart, 2000a,b); they are: the viviers of the Hautes Fagnes plateau, Belgium (Pissart, 1956), the features of Wales (Pissart, 1963; Watson, 1971, 1972; Watson and Watson, 1972, 1974), and the Irish depressions (Mitchell, 1971, 1973; Coxon, 1986; Warren, 1987; Coxon and O'Callaghan, 1987). Moreover, the forms described by Sparks *et al.* (1972) in East Anglia, which had not been considered as pingos by the authors because they are too close to one another, might also be traces of lithalsas formed before the Younger Dryas and also the features described by Kasse and Bohncke (1992) in The Netherlands (Pissart, 2000a,b). Such forms are an indication that, when they were formed, the average annual temperature was between -4°C and -7°C and the mean temperature of the warmest month between +7°C and +11°C (Pissart, 2000b); such values are in agreement with the climatic data reconstructed by Isarin (1997) and Isarin and Bohncke (1999) for the Younger Dryas of western Europe.

Figure 4. *Remnants of lithalsas formed during the Younger Dryas on the Hautes Fagnes plateau (Belgium), close to the German border, 620m above sea level.*

Juxtaposition of circular and more complex forms (photo A. Pissart)

VIII. Conclusion

During recent years, significant advances have been made. Researchers are warmly invited to imitate the detailed studies, with numerous drillings, presently being performed in Québec by M. Allard (Centre d'études nordiques, Université Laval) and G. Delisle (Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, Germany). Such an approach is necessary for a better understanding of the various types of cryogenic mounds. The additional isotopic studies they will generate will also be useful in dispelling the remaining doubts about the genesis of the ice found in palsas. Lastly, a better knowledge of the climatic conditions is essential to validate the palaeoclimato- logical deductions inferred from the lithalsa remnants identified from western Europe.

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