Published in : Quaternary Research (2011), vol. 75, pp. 371-377
DOI:10.1016/j.yqres.2011.01.001
Status : Postprint (Author's version)

THE POTENTIAL LATERAL GROWTH OF LITHALSAS

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KEYWORDS: Lithalsa ; Hudson Bay ; Hautes-Fagnes ; Frost thrusting

ABSTRACT

The lithalsas in the Hudson Bay region of northern Quebec, Canada, are the closest modern analogs of ancient features that collapsed to form conspicuous circular depressions ("viviers") common in the Hautes-Fagnes, a region in Belgium. Observations made in both regions are complementary and suggest that these mounds formed by frost heaving displacing soil not only upward, as previously assumed, but also laterally. This lateral displacement is consistent with diverse observations and inferences, which include (1) the simple rounded outline, either circular or oval, typical of both active and relic lithalsas; (2) evidence of local lateral extension inferred from exposures of the relic forms; (3) the relative inefficiency of solifluction in accumulating surface material to form the peripheral ramparts of remnant lithalsas due to the very gentle slopes of the mounds; and (4) the dip of ice lenses within a lithalsa in the Hudson Bay region, perhaps indicating that the freezing front dipped outward along its periphery. The growth of segregation ice is the primary driver for the vertical growth and lateral enlargement of a lithalsa.

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Introduction

The viviers of Hautes-Fagnes, Belgium, are perfectly preserved remnants of lithalsas (Pissart, 2000, 2003). Typically they consist of peat-filled depressions enclosed by a rampart on level surfaces (Fig. 1). The depressions are most frequently circular, sometimes displaying irregularities on their slopes. Commonly, they show some elongation on the slopes, which is always perpendicular to contours. Frequently, they are open upward, and the rampart has a horseshoe shape. The circular "viviers" have an 80-m average diameter, whereas the elongated forms can be hundreds meters in length. Because the depressions are filled with peat, their ramparts are more noticeable when seen from outside, rising up to 4 m above the surrounding surface. The depths of peat-filled basins vary from 1 to 7.5 m (the last thickness for a "vivier" filled up until the top of the rampart). Pissart (2010) demonstrates that remnants of lithalsas in Belgium occurred only on weathered quartzite rocks of Cambro-Ordovician Massif of Stavelot, being probably attributable to local hydrological conditions. These lithalsas were active between 13,000 and 11,650 cal yr BP during the Younger Dryas (Pissart, 2000, 2003).

Recently, a series of papers (Calmels and Allard 2004, 2008; Calmels et al. 2008a; Calmels et al., 2008b), based on Calmels' (2005) doctoral research, addressed several aspects of palsas, lithalsas, and permafrost plateaus. Much of this work focused on a typical lithalsa that was the subject of an exceptionally complete survey; it is located 56°36.63'N; 76°12.85' W. Previous work on the same site has been published by Delisle and Allard (2003) and Delisle et al. (2003); as the survey was conducted in collaboration with the "Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, Germany" the site was named BGR. During these field investigations, several boreholes were drilled down to the bedrock (gneiss) at an average depth of 10 m. Subsequently, thermal sensors were installed in the boreholes, allowing ground temperature monitoring for over than 5 yr. The permafrost samples, kept frozen for laboratory analyses, were particularly well studied by the use of an innovative and nonedestructive method, CAT Scanning (Computerized Axial Tomography), using a medical scanner (Calmels and Allard, 2004). This methodology allowed the imaging and description of the ice distribution as well as the calculation of the ice content. The cryostratigraphy was accurately reported.

The detailed data from the study of Calmels and from the fossil lithalsas of the Hautes-Fagnes suggest that lateral growth, as well as vertical growth, are involved in the formation of these frost-heaved mounds. The present paper presents and explores this hypothesis.

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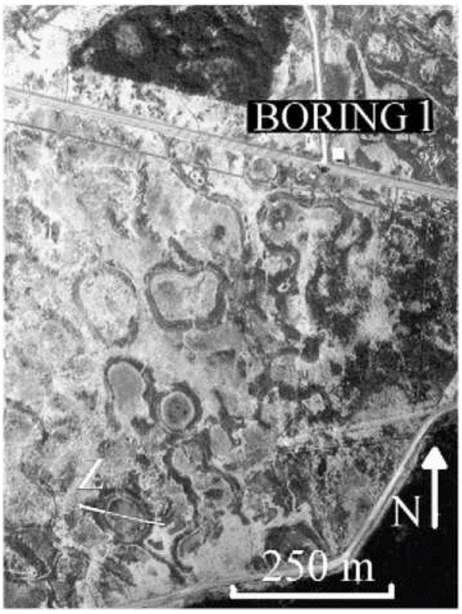
Facts

REGULAR CIRCULAR OR OVAL SHAPE OF LITHALSAS IN BELGIUM AND HUDSONIA

Except for elongated features, a number of fossil lithalsas in the Hautes-Fagnes have almost perfect circular or oval contours (Figs. 1 and 2). A few look like multiple joined circular forms, especially in the Hudson Bay region (Fig. 3). The one studied by Calmels was selected for its simple circular geometry to facilitate thermal modeling.

Figure 1. *Aerial photo of the remnants of lithalsas in the Brackvenn (Hautes-Fagnes, Belgium) with locations of remnant lithalsa Z (profile Fig. 7C) and of deep borehole (25 m) under the name "Boring 1."*

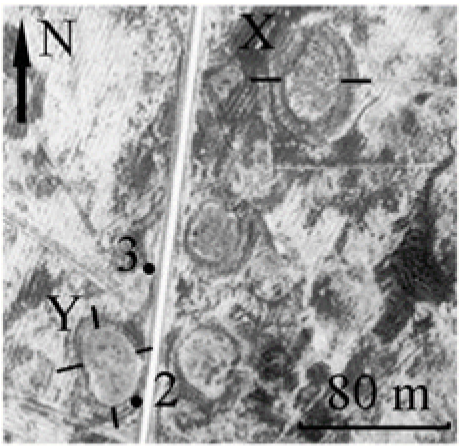


LATERAL MOVEMENTS EVIDENT IN THE RAMPARTS OF THE HAUTES-FAGNES (BELGIUM)

Figure 4 shows a vertical section of the rampart of a lithalsa in the Hautes-Fagnes in Belgium (Pissart and Juvigné, 1980; Pissart, 2000, 2002, 2003). Thickly bedded stratified sediments deposited by water flowing directly over the peat layer, reflect the location of the concavity that represented the base of the outer border of the rampart. Firstly, this concavity was located in site 1. Later, it moved in site 2, due to the heaving of the peat layer and other formation beneath it. Subsequently, solifluction moved the concavity from site 2 to site 3, outside the left border of Figure 4. Figure 5 shows a reconstruction of the evolution of this rampart, and this figure summarizes the observations made within the ramparts on 10 similar sections from other similar ramparts.

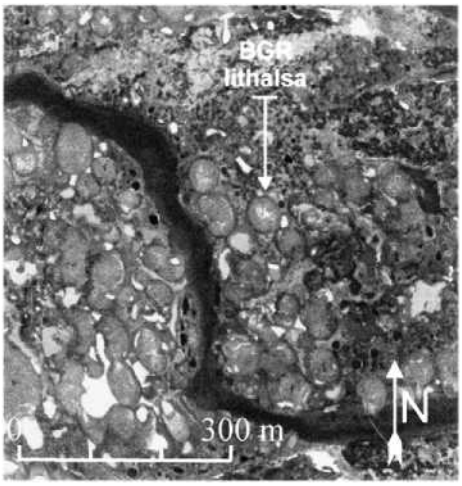
These sections, first described more than 20 yr ago, show that the displacement of the concavity, which represents the outer limit of the rampart, preceded the emplacement of the solifluction deposits. This lateral growth is recorded in the first section (Fig. 4) along a 15-m length. The lateral movement of 7 m from position 1 to position 2 is attributable to a thrust of the sedimentary formation under the peat. The subsequent 8 m resulted from solifluction at the border of the lithalsa. For this particular section (Fig. 4), 38% of the rampart are attributable to the radial thrusting over of the deep layers, and 62% to slope processes.

Figure 2. *Aerial photo of oval remnants of lithalsas in Hautes-Fagnes, Belgium.*



Points 2 and 3: locations of deep boreholes. The lines indicate the location of topographic profiles X (Fig. 7A) and Y (Fig. 7B).

Figure 3. *Aerial view of the lithalsas in the Hudson Bay region, with location of the BRG lithalsa (56°36.63'N; 76°12.85'W) studied by Calmels.*



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MORPHOLOGY OF LITHALSAS (BELGIUM AND HUDSON BAY REGION)

Lithalsas, with diverse shape (circular to oval) and diameter (from a few meters to more than 70 m), are common in the eastern Hudson Bay region (Fig. 3). They are relatively gentle topographic features. Their summits are generally almost horizontal to slightly domed and do not exceed 7 m in height (Michel Allard, personal communication, 2002).

The lithalsa studied by Calmels was 50 m in diameter and 3.5 m high. Slopes are steep only in the outer ~10 m of the mound (Fig. 6, profiles without vertical exaggeration).

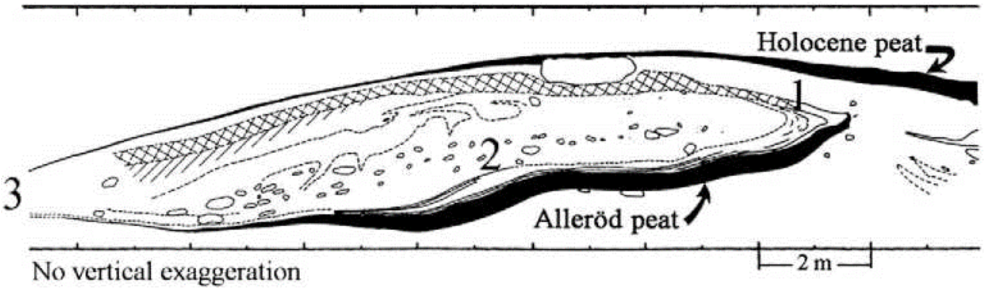
On the steep external slope, solifluction and other mass movements are very active today. On the mound flat surface, the elongation of mud boils, reflecting the solifluction direction from the center to the border, demonstrates clearly solifluction to the borders of the lithalsas. However, due the very gentle slope of the surface of the lithalsas, this slow, radial mass displacement may not suffice to form the depressions. A few mounds still have a partial peat cover, with discontinuous patches presumably in transit toward the border. In the Hautes-Fagnes, the external slope of the ramparts sometimes reaches 20°. These slopes were preserved since the Holocene, partly because the vegetation cover protects the sites from erosion.

PROFILES OF THE PEAT-FILLED DEPRESSIONS OF HAUTES-FAGNES

The topography of the former lithalsas, which are now flat- bottomed hollows, was probably very similar to that observed on active features in Nunavik with only very gentle slopes on their upper part. Figure 7, as well as the few following paragraphs, briefly describe the morphology of the peat-filled depressions.

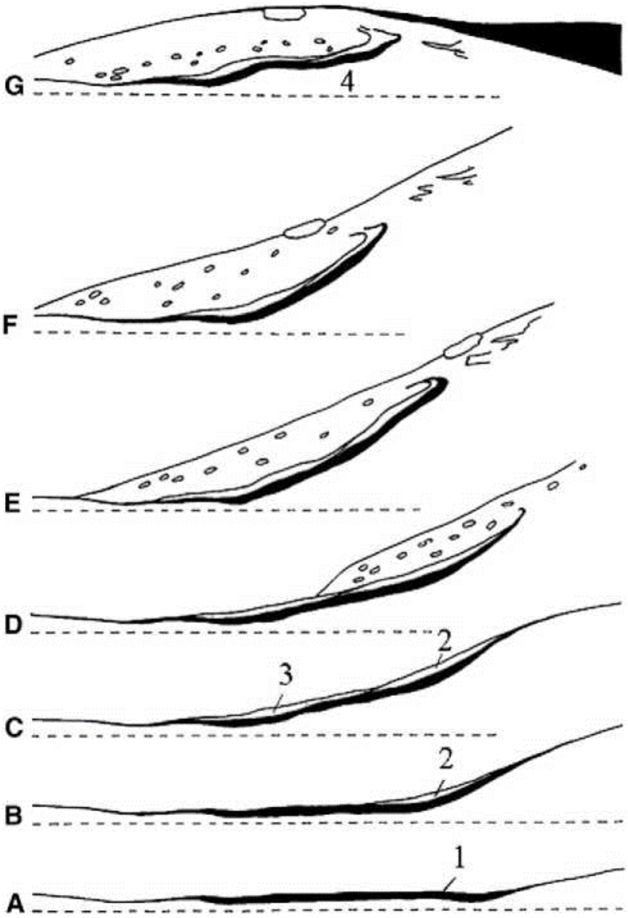
Between 1998 and 2003, a 280-km-long shallow ground penetrating radar (GPR) survey yielded GPS positioned, profiles in peated areas (50°32'10"N; 6°05'00"E) of the plateau of Hautes-Fagnes (Wastiaux and Schumacker, 2003). Parallel profiles were surveyed about 50 m apart, approximately perpendicular to the general slope. They defined the peat layer thickness, with an accuracy of ~5%, and revealed many fossil lithalsas now covered by peat. The peat occurring outside of the depression started to accumulate around the end of the Boreal or at the beginning of the Atlantic periods, ca. 8000 yr ago. The features have been inactive since then.

Figure 4. *Vertical cross-section across a rampart of a remnant lithalsa in Hautes-Fagnes (Belgium) from Pissart and Juvigné (1980).*



The Alleröd peat dated by ^{14}C and tephrostratigraphy shows that the lithalsa formed during the Younger Dryas. The thickness of layers of washed silt shows that the external concavity of the rampart was first in 1 and later in 2. Now the external concavity is in 3. The displacement from 1 to 2 results from enlargement of the lithalsa by internal thrust. The displacement from 2 to 3 is due to solifluction. The explanation is outlined in Fig. 5.

Figure 5.



Suggested formation of rampart shown in Fig. 4: (A-F) growth of the border of lithalsa; (D) when the slope is steep enough, solifluction material accumulates to form the rampart; (G) present-day section, after the melting. (1) Alleröd peat; (2) lens of washed silty material showing the location of the concavity during deposition; (3) above lens 2, other lens of silty material; (4) the upheaved peat layer which remains after the thawing demonstrates the accumulation of material in depth presumably thrusted below the rampart.

Two hundred traces and more than 40 probable traces of nearly circular lithalsas were recognized in the profiles. However, the profiles were too far apart to detect all the remnant lithalsas. Only one elongated form was recognized and was intersected by several profiles. In addition, the profiles of some depressions are known from probing by driving metal rods in the peat (Fig. 7).

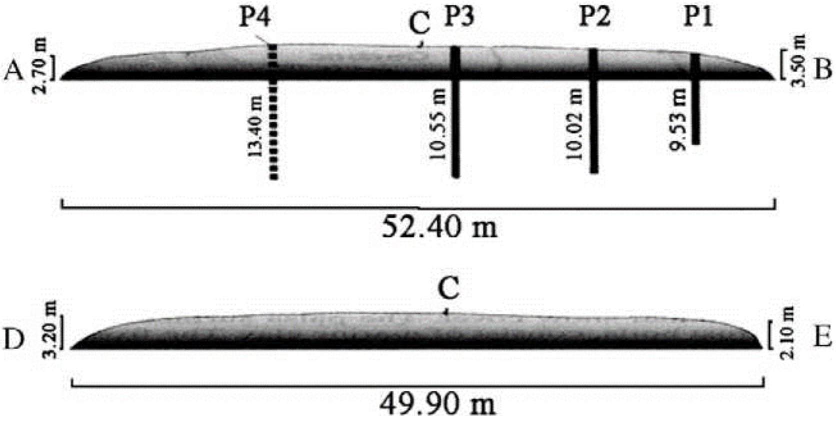
By these means, it is known that beside the shallow depressions illustrated in Figure 7A and B, with a flat bottom and a mean depth of 2 m relative to the original ground surface, some depressions were deeper, reaching depths of 3.5 m (Fig. 7C). This difference in depression depths may reflect differences in the thickness of silty Quaternary colluvium, where ice segregation occurred. Pissart (1974) reported observations from a 25-m-deep borehole at the border of the fossil lithalsa Y (location on Fig. 2, number 2). A silt layer extends from the surface to a depth of 3.5 m, white clay with fragments of quartzite extends from 3.50 to 11.05 m, the top of the highly altered bedrock, a Cambrian quartzophyllite. The alteration, which occurred before the Cretaceous, extends to a depth of 25 m. The white clay was never observed in the ramparts, and it is probable that little or no ice segregation occurred in this material. Boring 3, located less than 80 m to the north (Fig. 2, number 3) and only 35 m from lithalsa Y revealed silt favorable for ice segregation in the upper 2.6 m and fragments of altered black phyllites in clay with visible schistosity at a depth of 3.10 m. Observations were missing between 2.60 and 3.10 m.

In view of the stratigraphy, ice segregation would be largely limited to the silt horizons for flat-bottom lithalsas X and Y; consequently, their height was also probably restricted. The maximum height of lithalsa Y was probably 1.95 m with a flat summit assuming properties representative of contemporary lithalsas in the eastern Hudson Bay region (Calmels, 2005): a 65% ice content in a 3.50-m-thick silt layer and 0.5-m ice-poor active layer. On the other hand, the deeper depression (Fig. 7C, location in Fig. 1) is in an area with thicker silts. A 23-m-deep boring at Nasthief Parking, 600 m northeast of lithalsa Z (Fig. 1), revealed 14 m of silty colluvium (Pissart, 1974; Juvigne and Pissart, 1979). Ice segregation probably developed in these 14 m. Assuming a 65% ice content for the entire 14-m depth and subtracting the ~0.5 m of active layer, the maximum height of the lithalsa could have reached nearly 9 m.

The topography of only one depression is well defined by a set of GPR profiles 5 m apart in the "Fagne des Deux Series." This depression is completely covered by peat; the peat-silt contact is illustrated in Figure 8 with a contour interval of 0.4 m. The lithalsa is on an 8% slope, descending to the north. The depth of the depression relative to the rampart crest averages 4 m and 2.4 m on the south and north sides, respectively. The maximum depth, relative to the prelithalsa ground surface is 1.80 m. It is important to note that, in contrast to the summits of the ramparts that trace out rough circle in plan views, the depression is rather triangular. The shape of the depression probably reflects the outline of the former lithalsa; however, with detailed geometric information of only one particular depression, it is hazardous to interpret and generalize this form. The interpretation of numerous GPR profiles is tricky because they generally do not traverse the forms along their centers. Nevertheless, they show that an important number of depressions have flat bottoms, which should reflect the original shape of the lithalsas' summit.

These observations indicate that the Belgian lithalsas were generally less than 5 m high and probably had a gently tilted surface, comparable to those of Hudson Bay region mounds. The flat and regular aspect of the depressions' bottom suggests that material coming from the entire area of the mound has accumulated within the peripheral region of the ramparts. If the rampart was solely formed by solifluction along the outer slopes of the mound, one can expect that material would remain after the thaw of the mound in the center of the basin, where erosion was less active.

Figure 6. *Perpendicular profiles showing the topography with no vertical exaggeration of the BGR lithalsa in the Hudson Bay region and the location of the boreholes studied by Calmels.*



P1-P4 gives the locations of boreholes; C is the center of the mound.

OBSERVATIONS AT THE BORDER OF A CURRENT LITHALSA (HUDSON BAY REGION)

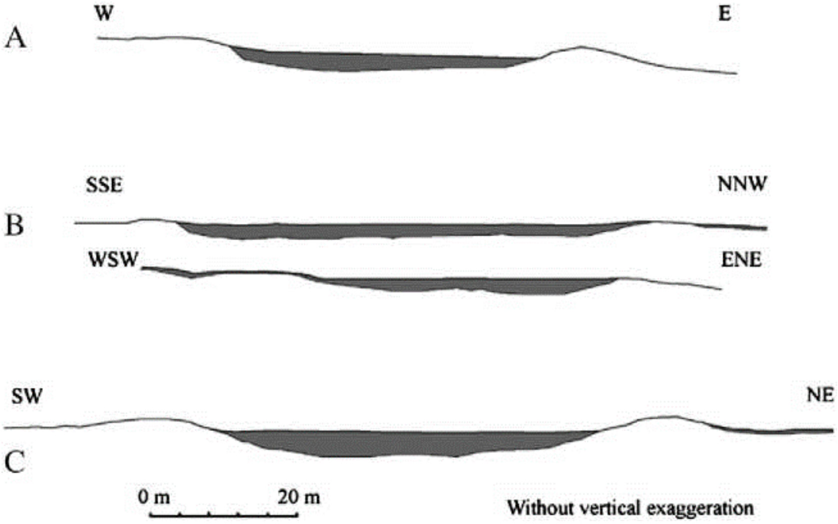
Aerial photos of the degrading lithalsas in Nunavik show that their ramparts are similar in size to those of the Hautes-Fagnes. Figure 9 (from Calmels et al., 2008b) illustrates the temperature measurements in borehole P1, which is 7 m away from the steep peripheral slope of the lithalsa (see location on Fig. 6). The ground was unfrozen to a depth of nearly 6 m, and temperatures were close to 0°C in the peripheral section of the lithalsa. On September 1, 2002, temperatures in P1 showed that a section of the profile was slightly colder than 0°C (the precision of the temperature is 0.2°C); the modeling of the temperature between P1 and the border by Calmels et al. (2008b) conservatively assumes that the ground temperatures exceeds 0°C immediately beyond the border; i.e., there is no permafrost, due largely to the insulating role of the snow cover in winter. The observation of the absence of permafrost there confirms that the rampart has already formed well before the thaw of the ice of the lithalsa. At the borehole location, the lithalsa is comprised uniquely of mineral soil, which will later form the rampart. For this particular lithalsa, the height of the remaining rampart is approximately 75% of the maximum height of the mound based on the topographical survey and the amount of ice found in the borehole samples.

These observations over a period of 5 yr and extending to a depth of 10 m are most instructive, but they are unique or rare partly because of the difficulty coring in such remote areas. Among other things, they show that, down to depth of 5 m, the top of the permafrost dips outward, roughly parallel to the ground surface at the periphery of the lithalsa.

INCLINATION OF ICE LENSES IN DEPTH (HUDSON BAY REGION)

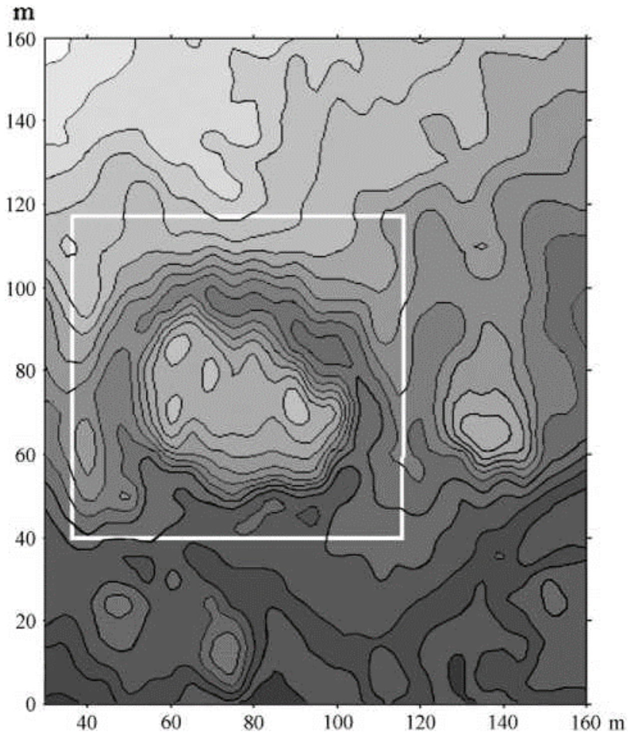
The orientation of the core samples collected in the BGR lithalsa is unknown, hence the strike (direction) of the ice lenses is also not known but useful information exists about their dip (inclination). Calmels et al. (2008b) concluded that "from the permafrost table to 2.5 m," (approximately 1 m of thickness) "most of the ice lenses are horizontal and vertical joints and faults are not abundant. From 2.5 m downward, the lenses have high dip angles." As ice lenses generally grow parallel to the freezing front, this observation strongly suggests that a nearly horizontal freezing front descended vertically through the upper part of the lithalsa. In contrast, the freezing front geometry became more complex at depth, resulting in the growth of inclined ice lenses, which could induce lateral as well as vertical frost heave. As the new inclined ice lenses become part of the permafrost, they are preserved for the life of the mound.

Figure 7. *Profiles through remnants of lithalsas in Belgium.*



(A) Lithalsa X of Fig. 2 The volume of the hollow below the prelithalsa surface was calculated; it approximately equals the volume of the ramparts (Bastin et al., 1974). (B) Lithalsa Y. Location of these profiles are shown in Fig. 2. (C) Lithalsa Z in Fig. 1. This form, not completely filled with peat, is one of the most spectacular remnant of lithalsas in the Hautes-Fagnes (Belgium).

Figure 8. *The only well-known morphology of a remnant of lithalsas in Belgium, which now is buried and preserved under the peat cover, was observed by a series of radar profiles 2.5 m apart in the "Fagnes des Deux series" by L. Michel's diploma (under the supervison of Professor G. Grandjean).*



The contact between peat and silt is shown with 0.4-m contour intervals and highlighted with shading. The remnant of the lithalsa is in the white square.

Discussion

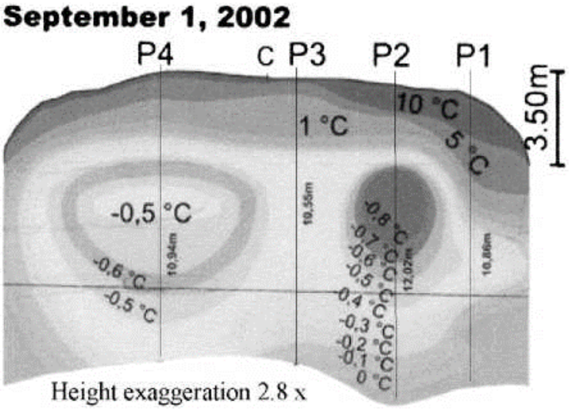
The flat tops of the modern and former lithalsas (reconstructed from the depressions that are partly filled with peat, as shown in Figs. 7 and 8) raise questions concerning the formation of the ramparts. Until now, they were explained simply by the accumulation of material originating from the mound surface.

Calmels et al. (2008a) suggested that the soil on active lithalsas, which are slightly domed, would naturally move radially toward the border by creep (solifluction), especially in the absence of the stabilizing effect of vegetation; in this way soil builds up at the periphery later forming the rampart. This type of creep was evident in some permafrost mounds of George River, Ungava Bay, where old casings of boreholes were strongly tilted downslope by differential solifluction.

This loss of soil from the center of the mound would, however, be expected to impact the mound evolution. Erosion of the top of the lithalsa (i.e., the active layer) should thaw the ice-rich level (>65%) below the permafrost table. As a consequence of the resulting thaw consolidation, the ground surface and permafrost table would both subside, thereby maintaining the active layer thickness despite the erosion and initiating the thermokart processes that ultimately degrade the lithalsa. One of us (F.C.), however, does not believe in this argument and believes that this erosion of the top of the lithalsa would not have such a detrimental impact if the erosion began as soon as the early stage of the lithalsa's growth (i.e., during permafrost aggradation), when the cool climate effectively compensates for the loss of surface insulation due to the erosion.

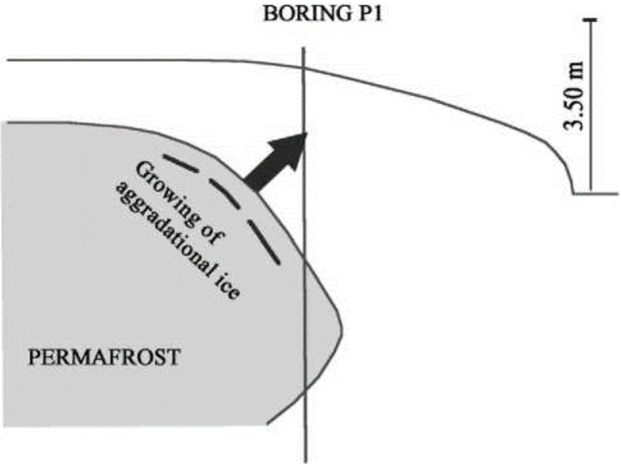
Direct evidence for active lateral growth of lithalsas is lacking. No growth could be detected over a 60-yr period for the lithalsas studied by Pissart and Gangloff (1984) near Kuujjuaq. However, these lithalsas could have expanded several meters because of the relatively low-resolution information available from a comparison of aerial photographs in 1947 and recent Google Earth images. More precise observations here and elsewhere in Hudson Bay region would be needed to confirm radial expansion of active lithalsas.

Figure 9. *End of summer temperatures, with 0.2°C accuracy, in BRG lithalsa (Calmels et al., 2008b).*



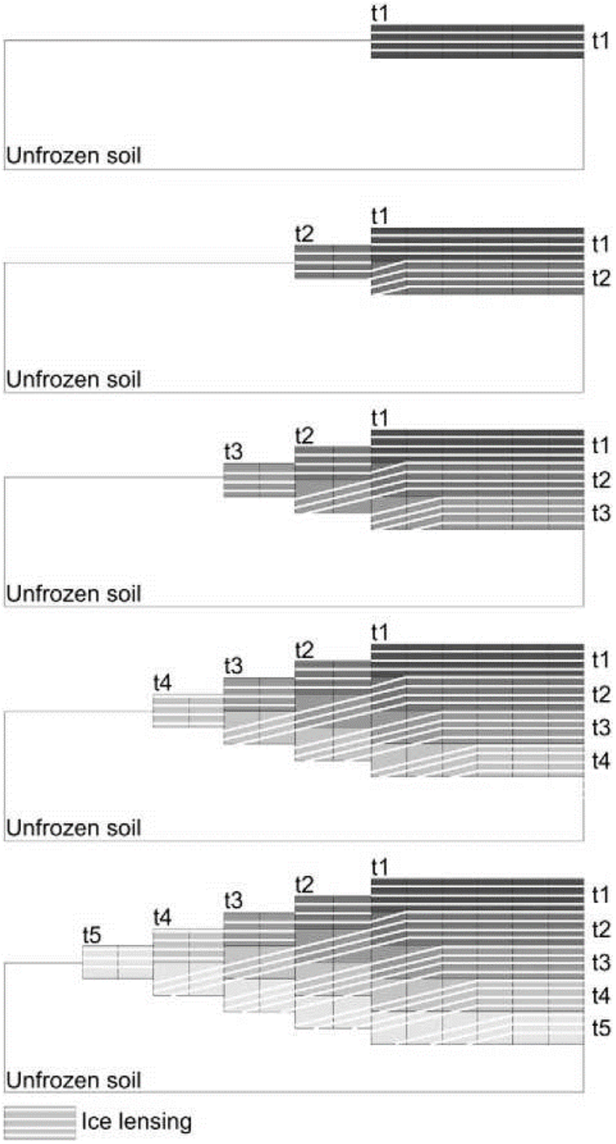
Temperature observations are not available near the right border beyond the borehole P1. If permafrost exists below P1, it is deep (> 6 m) and is very restricted.

Figure 10. *Possible direction of the thrust related to the formation of aggradational ice on the steep slope of the lithalsa.*



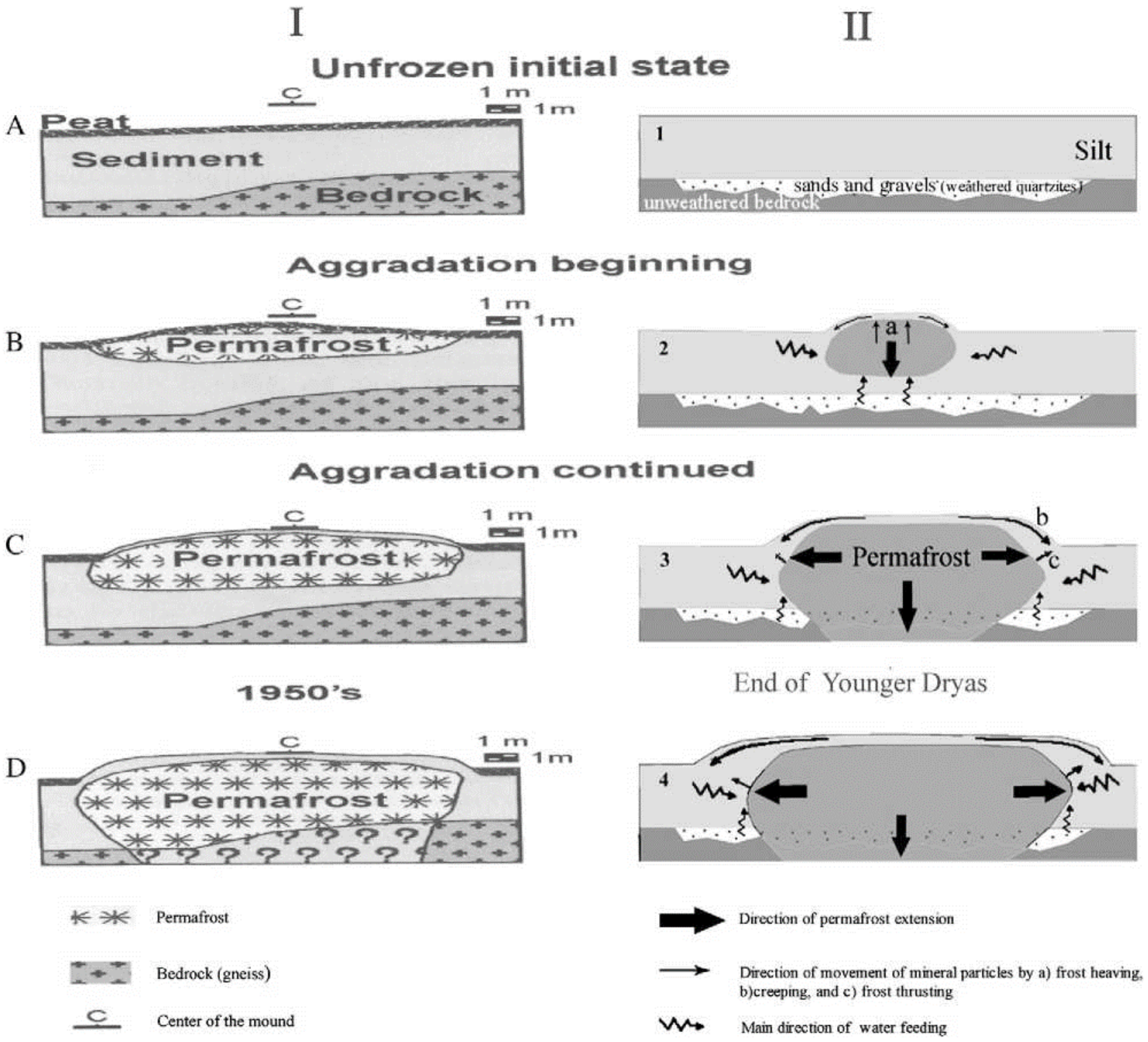
The profile and the limit of the permafrost are the ones found in BGR lithalsa near the boring P1 as shown by Calmels et al. (2008b). No vertical exaggeration.

Figure 11. *Lateral enlargement of a lithalsa by downward permafrost aggradation.*



t1 marks the time at the beginning of permafrost aggradation; t2, t3, t4 and t5 represent subsequent aggradation periods.

Figure 12. *Mechanisms for the growth of lithalsas from observations in northern Quebec (I) suggested by Calmels and in the Hautes-Fagnes (II) in the hypothesis of Pissart.*



The main difference is the lateral growth in mechanism II. In I, permafrost appears and grows in depth but not laterally. The sketch outlines key steps in the evolution of the BGR lithalsa, as suggested by Calmels et al. (2008a) from initial non-permafrost terrain (A) to the situation in the 1950s (D). Location C is a georeferenced point used for topographical measurements since July 2000. (A) Initial non-permafrost terrain. Presence of a peat cover. (B) Beginning of the permafrost aggradation. Frost-heave occurs but its magnitude is unknown. (C) Aggradation continues, and erosion of the peat occurs induced by weathering and solifluction processes. (D) Full-growth lithalsa during the 1950s. The active layer at the border of the mound is thicker because of the snow accumulation creates warmer ground conditions. The question marks refer to the unknown permafrost extension in the bedrock in the past and during the 1950s. In II, (1) subsurface structures preceding the lithalsas as in the Hautes-Fagnes (Belgium). The lithalsas appeared on weathered Cambrian quartzites where local hydrological conditions were conducive to frost heaving (Pissart, 2010). The thickness of the different material is schematic in this figure. (2) Formation of the lithalsa by segregation ice. The roles of the water and the weathered rock are probably very important. Frost creep on the side of the mound begins immediately after the mound appears. (3) Gravel and sands are frozen below the lithalsa. Segregation ice cannot appear in this material and the lithalsa cannot continue to grow. On the steep slope of the lithalsa, frost creeping of the material is very active. At depth, below the sides of the mound, segregation ice growth continues, aided by the water supplied through the weathered rocks, giving rise to frost thrusting. (4) The processes continue. The ramparts are the result of creeping on the slopes and also of frost thrusting. We do not know if at the end of the Younger Dryas, the lithalsas were or not at their maximum development.

FROST THRUSTING AS A POSSIBLE LATERAL GROWTH MECHANISM OF THE LITHALSAS

Figure 10, modified from Calmels (2005) and Calmels et al. (2008a), represents schematically the active layer/permafrost profile in the border of the BGR lithalsa, as envisioned by the authors. This profile also is similar to the one in Delisle and Allard (2003) but here it is presented without vertical exaggeration. The measured ground temperatures in P1 and P2 (Fig. 9) guide our sketch of the inclined permafrost table and the ground surface.

When segregation ice forms where the isotherms are tilted, frost heaving can displace material laterally as well as vertically (Fig. 10). The lateral component was described by Washburn (1979, p. 79) and named “frost thrusting”; it has received very little attention in periglacial geomorphology, although long ago Eakin (1916, p. 76,80) proposed that it played a role in the evolution of sorted polygonal soils.

The maximum heaving pressure is largely a function of the lowest temperature attained in the soil (e.g., Radd and Oertel, 1973; Dash et al., 1995). In general, it is ample to lift or move laterally a substantial layer of soil or unconsolidated sediments; even with a temperature of only 1°C below the freezing point, segregation ice growth can generate heaving pressures in excess of 1 MPa, which corresponds to the weight per unit area of ~50 m of unconsolidated, saturated mineral material. Heaving pressures could be higher provided the temperature was lower, and the granulometry was conducive to segregation ice growth.

LATERAL ENLARGEMENT BY DOWNWARD PERMAFROST AGGRADATION

If lithalsas grew laterally as proposed, they probably did so in their early formative stages, notably during cooler and less snowy winters than in the present day, and when the slopes of their border were more gentle, a factor that reduces the accumulation of snow. As observed by Calmels and others (Seppälä, 1986, 1990; Yershov, 1998), substantial snow accumulation along the border of the lithalsa can thermally hinder or prevent such growth.

Calmels (2005) did not identify aggradation ice in the profile of the BGR site nor evidence for lateral thrust in the unfrozen ground surrounding the lithalsa. This leads him to propose the following alternate hypothesis (Fig. 11). The original dimension and shape of the incipient mound (i.e., where permafrost started to develop and the mound to heave, t1 in Fig. 11) remain unknown, but it is improbable that this surface was circular. As time passes and permafrost aggrades (from t2, earlier time to t5 later time, in Fig. 11), the surface would presumably evolve during the early stage of mound formation due to differential frost heave both vertically and laterally, with less and later heaving in the border than in the center of the mound. This differential heaving could cause numerous syngenetic faulting, as reported by Calmels on such mounds, as well the outward tilt of the ice lenses. According to this hypothesis, the upper ice lenses are initially mostly horizontal, paralleling the flat ground surface; later, with the increasing doming and tilting of the ground surface, radially dipping ice lenses profiling the outer portion of the mound. The gentle slopes at the border, during the early growth phase, would prevent thick snow accumulation.

Conclusions

Numerous arguments, based on remnants of lithalsas in Belgium and modern lithalsas in Eastern Hudson Bay, point to lateral growth as an important element of lithalsa development. We present here two plausible mechanisms for lateral growth as shown in Figure 12. Figure 12(I) illustrates the mechanism, preferred by Calmels, by which the rampart is composed entirely of material that crept down the outer slopes of the lithalsa. Figure 12(II) illustrates the lateral thrusting mechanism proposed by Pissart. A promising approach to assess these mechanisms would be to study excavations of the borders of active lithalsas, as previously done on some pingos (Pissart, 1967; Pissart and French, 1976), or even on a lithalsa (Pissart and Gangloff, 1984). The latter was degrading, however, which prevented detailed study of the rampart structure. Sections should be easily exposed in eastern Hudson Bay, because the fine-grained sediment constituting these mounds could be excavated readily.

Acknowledgments

Bernard Hallet gave me numerous valuable remarks and suggestions, both editorial and scientific. I thank him very much for his help and encouragements. I am also grateful to two anonymous referees who made suggestions of great interest and finally to my friends Amand Lucas and Jean Grimberieux who improved my English text.

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