The Periglacial Ramparted Depressions of the Hautes Fagnes Plateau: Traces of Late Weichselian Lithalsas

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Abstract

Once thought to be of human origin, ramparted circular or elongate depressions that densely cover many, but not all, summit surfaces of the Hautes Fagnes area, NE Ardenne, have been recognized since the 1950s to represent relics of periglacial mounds. We examine first the regional distribution of these periglacial ramparted depressions (PRDs), whose location seems controlled mainly by elevation and lithologic factors. Geomorphological characteristics of the PRDs and trenching data obtained from several ramparts consistently show that these landforms initially developed as lithalsas through accumulation of segregation ice in the mineral soil, whose later thaw produced the presently observed ramparted depressions. ^{14}C dating of, and pollen data from, peat layers pre- and postdating the formation of the periglacial mounds, further supported by the presence of the 12.9-ka-old Laacher See tephra in the underlying peat, point to a period of rapid formation during the second half of the Younger Dryas. Mean annual air temperature and mean temperature of July derived for the Hautes Fagnes area ($\sim$600 m asl) during the Younger Dryas from a compilation of NW European pollen data are in excellent agreement with the temperature values observed in the western Labrador Peninsula where lithalsas are currently active, showing that PRDs are valuable paleoclimate indicators.

Keywords

Periglacial geomorphology • Periglacial ramparted depression • Lithalsa • Younger Dryas • Paleoclimatic indicators • Hautes Fagnes

7.1 Introduction

At the turn of the twentieth century, it was seriously debated whether the Ardenne had been covered by an ice cap during the Quaternary glacial periods (Dewalque 1885; Lohest

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1896; Stamm 1912). However, a few decades later, with the rise of periglacial geomorphology, the main features on which this assertion relied, namely 3- to 10-m-thick mud bodies occurring in many valleys flowing down the Hautes Fagnes Plateau and showing an accumulation of large blocks at their surface, were identified as periglacial debris flows (Fourmarier 1933; Pissart 1953). From this time, observations of periglacial forms (cryopediments) and sedimentary structures (cryoturbations, ice wedge casts, stratified slope deposits) multiplied rapidly (see a synthesis in Pissart 1995), yielding strong support to the idea that periglacial conditions had reigned in Belgium during the glacial periods. In this context, studying ramparted circular depressions that occur in dense fields over many flat summit surfaces of the Hautes Fagnes area and that were previously believed to attest

prehistoric man action (Bouillenne and Bouillenne 1937), Pissart (1956) was the first to suggest that they were relics of periglacial mounds, which he initially interpreted as pingos.

Here, we describe these very particular and highly rare landforms in their geological and paleoenvironmental setting and expose the current understanding of their forming mechanisms. Referring to their modern analogues, we then underscore their use as paleoclimatic proxies, before briefly showing how new observations (re)opened important questions about their history and the conditions required for their formation. Following a recent use (e.g. Bryant and Carpenter 1987; Ross et al. 2011), we call this relict morphology of thawed ground-ice mounds now identified as lithalsas (Pissart 1998) periglacial ramparted depressions (PRDs) in order to distinguish them from non-ramparted depressions of simple thermokarstic origin (French 2007). The remarkable state of preservation of lithalsa-derived PRDs in the Hautes Fagnes, the fundamental multidisciplinary research conducted there for 60 years, and the rarity of these forms elsewhere in the world have ensured worldwide geomorphological recognition to the region.

7.2 Geographical and Geological Setting

PRDs have been mapped essentially in two areas of NE Ardenne, namely the Hautes Fagnes Plateau (Hohes Venn in German, culminating at 694 m asl at Botrange) and its western continuation by the Vecquée ridge, and the smaller Baraque de Fraiture, or Tailles, massif (with a maximum elevation of 652 m asl), some 25 km south of the Vecquée (Fig. 7.1). They are typically found on extended flat or very gently sloping (<2°) summit surfaces that make the bulk of the upland topography, incised by the drainage network especially along its margins, and correspond to remnants of a pre-Cretaceous erosion surface partly regraded in the Early Paleocene (see Chap. 5). In the Hautes Fagnes, this surface truncates the Revinian quartzites and phyllites of the core of the Caledonian Stavelot massif, while it cuts across Middle to Late Ordovician shales, and Lochkovian coarse quartzites of the Variscan envelope of this massif at Baraque de Fraiture. In both areas, a thick kaolinic weathering mantle of Early Cretaceous to Middle Miocene age (Yans 2003) is still preserved over large parts of the surface, with thicknesses ranging from 1–2 to several tens of metres (see Chap. 5). Its overall clayey texture tends to include a fine sand component in proportion with the abundance of quartzite layers, while it generally gives way to a mixture of clay and more or less fragmented rocks where the mantle thins, thus exposing the weathering front, or where thick quartzite layers predominate. Locally, the Mesozoic weathering mantle is still overlain by a few metres of clay-with-flint, in situ residues of the Upper Cretaceous chalk cover that once buried the

erosion surface (Fig. 7.1). Moreover, 10- to 25-m-deep boreholes in various locations have repeatedly shown that the weathering products are mixed in the upper metres with a predominant silt fraction attesting the presence of reworked loess deposits (Pissart 1974; Juvigné and Pissart 1979). Finally, owing to their mostly impervious substrate and high rainfall (P_{ann} > 1400 mm in the Hautes Fagnes), the flat top of the Baraque de Fraiture and, still more, the summit surfaces of the Hautes Fagnes are extensively covered by Holocene ombrotrophic peat bogs in the form of either a thin blanket bog or more localized active raised bogs.

7.3 The Ramparted Depressions: Characteristics and Distribution

The most typical PRDs are almost perfectly circular depressions occurring on quasi-horizontal surfaces (<1°) (Fig. 7.2). Their diameter varies between 30 and 90 m and the peripheral ∼10-m-wide rampart generally rises 1–3 m above the current surface of the depression and the surrounding ground. However, the overall high density of forms is often such that they are contiguous or coalesced into bilobate or more irregular depressions enclosed by sinuous ramparts (Fig. 7.3). On surfaces sloping between 1° and 2°, the circular forms give way to slope parallel elongate depressions up to 500–600 m in length (Fig. 7.3). Their rampart, poorly developed at the upslope end, well-defined and sinuous along both sides of the depression, and sharply closed at its downslope end, suggests a downslope development of the forms, including the possible coalescence of a string of smaller individuals.

Beyond their topographic signature, PRDs are also highlighted in the field as well as on aerial photographs and satellite images by the contrasted vegetation that grows on the surrounding ground, the ramparts, and in the depressions respectively. Within a moor landscape dominated by *Molinia caerulea* and dotted with shrubs, ramparts appear densely covered by varied species of *Vaccinium* and by *Calluna vulgaris* attesting the drier character of their mineral substrate. As for the depressions, if not completely filled, they generally host more or less floating *Sphagnum* mats and *Eriophorum* sp., however, rapidly replaced by the invading *Molinia* as soon as a depression is drained. In any case, sounding the ground of a PRD with a rod shows that it is made of a several metres thick peat fill.

The spatial distribution of PRDs in NE Ardenne is mainly known from field investigation and mapping from aerial photographs. However, in a ground-penetrating radar survey covering flat summit surfaces of the Baraque Michel area (Fig. 7.1) whose topography betrays only few PRDs, Wastiaux et al. (2000) revealed that innumerable similar forms existed beneath a thin continuous peat layer levelling the
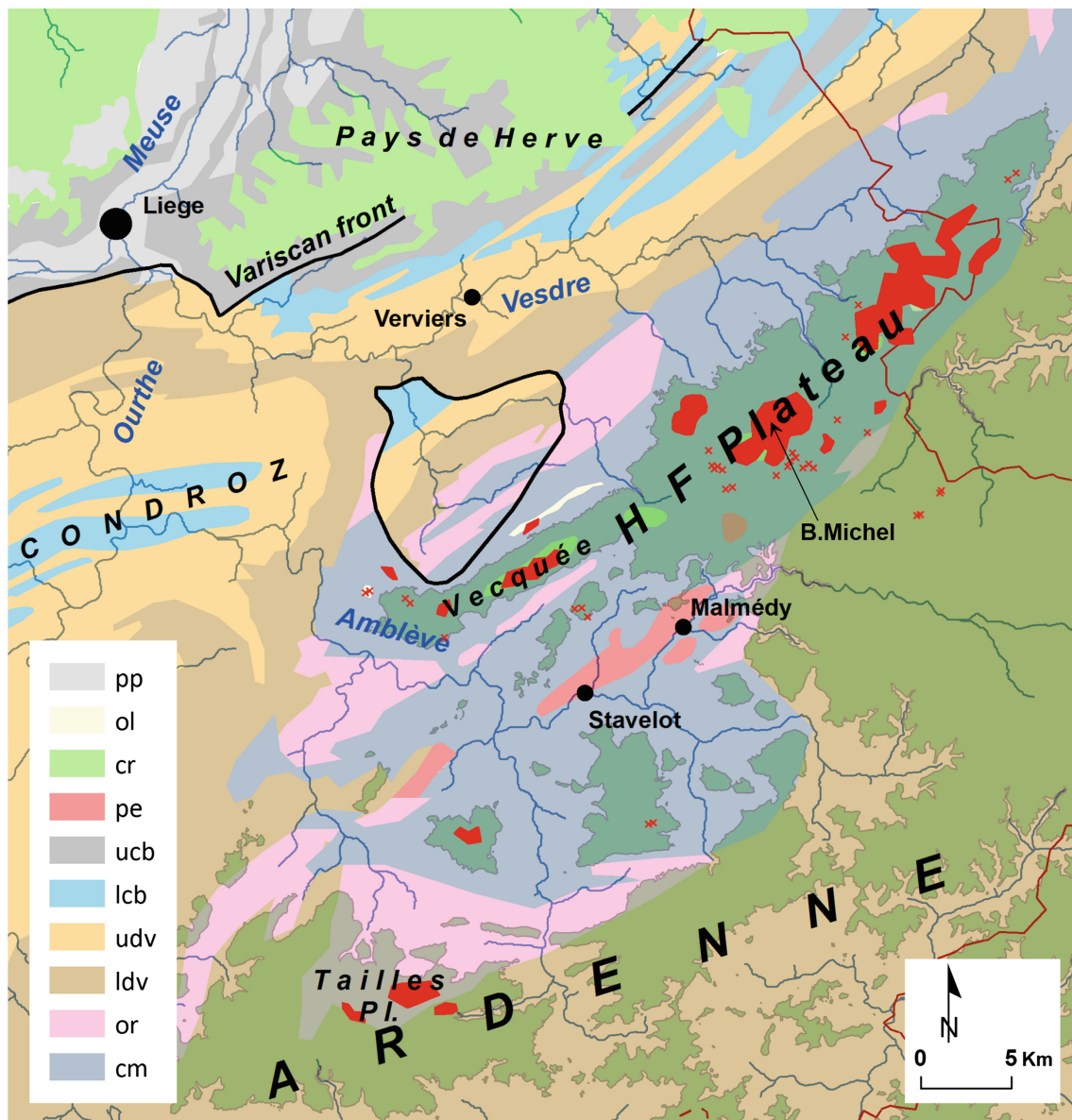
Fig. 7.1 Map of PRD fields (*in red*) and isolated forms (*red crosses*) in NE Ardenne, highlighting their distribution with respect to geology (*cm* Cambrian. *or* Ordovician. *ldv* Lower Devonian. *udv* Middle and Upper Devonian. *lcb* Lower Carboniferous. *ucb* Upper Carboniferous. *pe* Permian. *cr* Cretaceous. *ol* Oligocene. *pp* Plio–Pleistocene) and elevation (all areas above 500 m asl are outlined and appear in *greenish* transparency)

surface, making their density as high there as in the NE part of the massif. Moreover, the forests covering an important fraction of the region had so far largely prevented any exhaustive PRD mapping in these areas. The Lidar DTM of Wallonia recently made publicly available (SPW 2015) should soon remedy this lack of information (Fig. 7.3) but, although preliminary analysis already confirmed that many PRDs remain to be mapped, this is not expected to change the fundamental characteristics of their distribution, except maybe with respect to the minimum elevation above which periglacial mounds could form.

The PRDs' spatial distribution seems to be controlled by two main factors. First, in the Hautes Fagnes and at Baraque de Fraiture, but also in the very few other nearby places where they have been observed, they overwhelmingly occur above 500 m asl (Fig. 7.1). Only on benches interrupting the northern slope of the Vecquée ridge have a few small PRDs been mapped at 420–450 m elevations. However, the altitudinal control cannot account for the total lack of PRD on the many flat surfaces extending above 500 m asl in the Ardenne's interior and in the nearby Eifel. Therefore, Pissart (e.g. 2009) strongly insisted on the additional control of the

Fig. 7.2 Oblique aerial view of PRDs in the Brackvenn area (see location on Fig. 7.3) showing circular forms on a quasi-horizontal surface. Note a coalesced form on the *right* of the photo

lithology. Indeed, with the exception of a few PRDs occurring on Pragian shales and sandstones, all recorded forms are located in the outcrop areas of the Revinian 3–5 (interlayered phyllites and quartzites) and the Lochkovian of the Baraque de Fraiture zone (coarse sandstones). Pissart (2009) also drew attention to the indirect meaning of elevation, which, beyond a possible climatic effect, determines the presence of a weathering mantle: all remnants of the extensively weathered pre-Cretaceous and Early Paleocene erosion surfaces are situated above 500 m asl. within the Ardenne.

7.4 Trenches in PRD Ramparts

7.4.1 Trench Description

Several trenches were cut across PRD ramparts in the '70s in order to examine their internal structures and unravel the mechanisms at work in the formation and evolution of the forms that finally evolved in PRDs. Since then, one trench unveiling the downslope end of the rampart of an elongate PRD has been preserved for research and didactic purposes

in the Konnerzvenn (Fig. 7.3) and serves as a reference (Pissart and Juvigné 1980). Another trench across the rampart of a circular form has recently been cleaned again with a similar aim 700 m to the southwest in the same area. We describe the Konnerzvenn trench, which nicely displays all significant features observed elsewhere and, moreover, includes a peat layer at the base of the rampart, thus offering an opportunity for age determination (Fig. 7.4).

The local substratum is exposed in the bottom of the trench as a homogeneous bluish-grey clayey silt including rock fragments up to 50 cm in size (*a*, Fig. 7.4). In the internal part of the rampart, slight tongue-shaped colour variations of this material suggest outward displacement. Pertaining also to the original ground is then an overlying peat layer that shows a maximum thickness of ~ 0.3 m (*b*, Fig. 7.4). This peat layer is sloping outward (with respect to the central depression) and shows characteristic ramp and flat deformations. Though gradually thinning and finally fading out toward the depression, it is clearly overturned at its upper end. This peat is in turn overlain by a 0.2-m-thick package of thin layers of alternating grey silt and dark silty peat that show similar sloping and undulating deformation and inward overturn (*c*, Fig. 7.4). Finally, the bulk of the
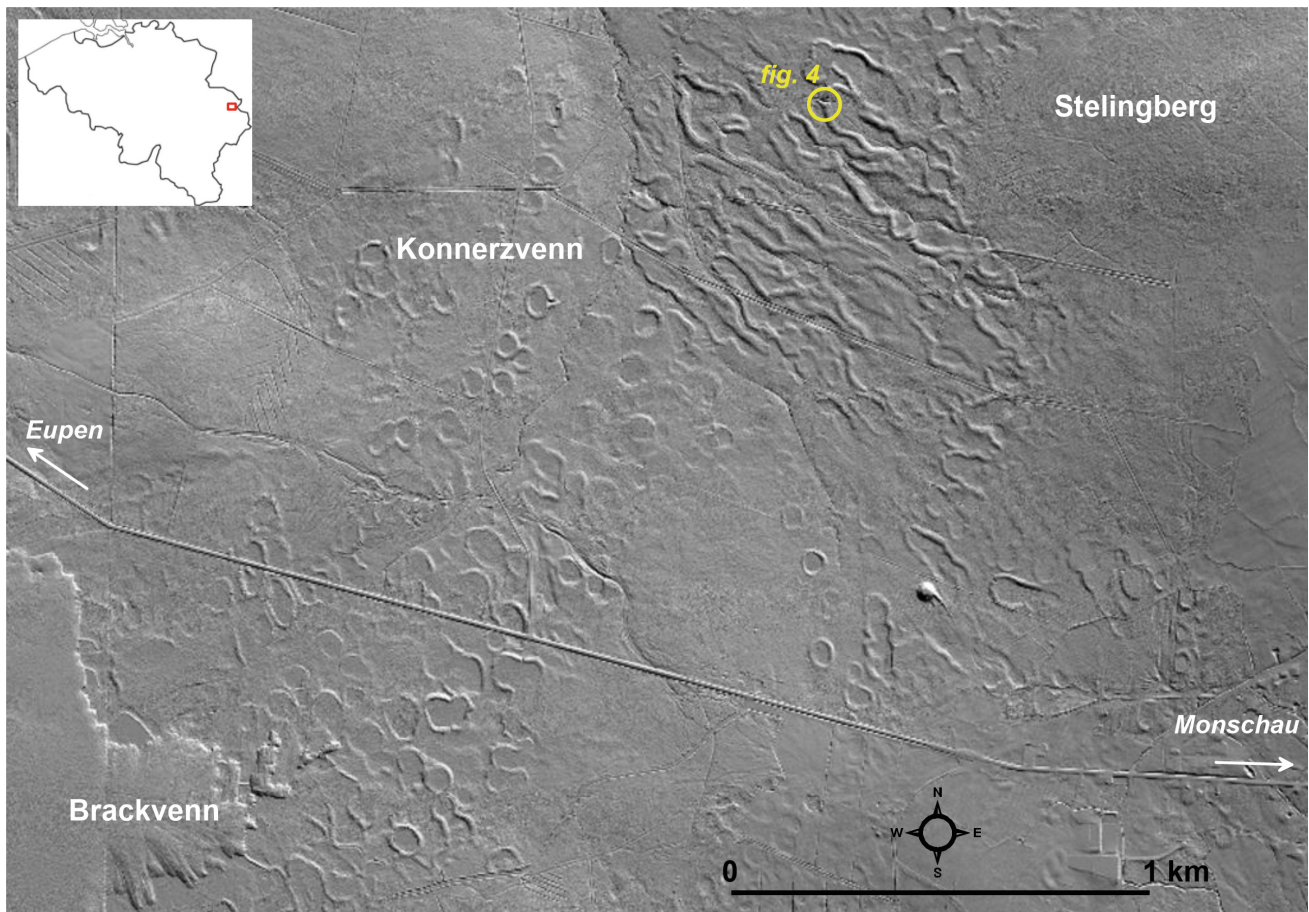
Fig. 7.3 Excerpt of the Lidar DTM of the Walloon Region in the Hautes Fagnes area *east* of Eupen (SPW 2015). Dense fields of round PRDs cover the flat surfaces of the Brackvenn and Konnerzvenn, while elongate forms are characteristic of the gentle footslopes linking the Stelingberg summit (660 m asl) to the subhorizontal Konnerzvenn surface *east* of the nascent creek of the Getzbach

rampart is made of ~ 2 m of grey to beige clayey silt with a varying part of quartzite gravels and blocks, and showing only faint disordered discontinuities (*d*, Fig. 7.4). On top of it, a thin, poorly developed Holocene soil (*e*, Fig. 7.4) ends up with an O horizon that rapidly thickens toward the depression and goes into a peat fill reaching a maximum depth of 4.2 m (Pissart and Juvigné 1980) (*f*, Fig. 7.4). Grain size (with a mode around 30 µm), heavy mineral assemblages, and the up to 11% carbonate content of the material beneath the bottom peat layer bear witness to the eolian origin and Late Weichselian age of the silt fraction in the shallow substratum and the reworked sediments of the rampart.

7.4.2 Palynostratigraphy

Although no palynological analysis was performed in the peat filling of the Konnerzvenn PRD, equivalent studies were carried out in several other forms of the Hautes Fagnes (e.g. Bouillenne and Bouillenne 1937; Florschütz and Van Oye 1938; Slotboom 1963; Woillard 1975) and Baraque de Fraiture regions (e.g. Mullenders 1963), bringing a consistent picture of their palynostratigraphy. Since the pioneering study of Bouillenne and Bouillenne (1937) in the Baraque Michel area, it was recognized that peat accumulation in the depressions began systematically with the earliest Holocene (Preboreal). However, this timing was long questioned because cold phase pollens were often observed in peaty silts at the very base of the sequence (Florschütz and Van Oye 1938; Woillard 1975) and suggested an end Late Glacial starting time of the filling. The debate was closed when proofs were provided of the presence of Younger Dryas deposits within the PRDs' ramparts (see below), and it is now admitted that the Late Glacial pollens at the base of the filling are reworked, having descended with their host material from the top of the rampart when the depression was created.

As already stated, the value of the Konnerzvenn trench especially lies in the presence of a peat layer at the base of
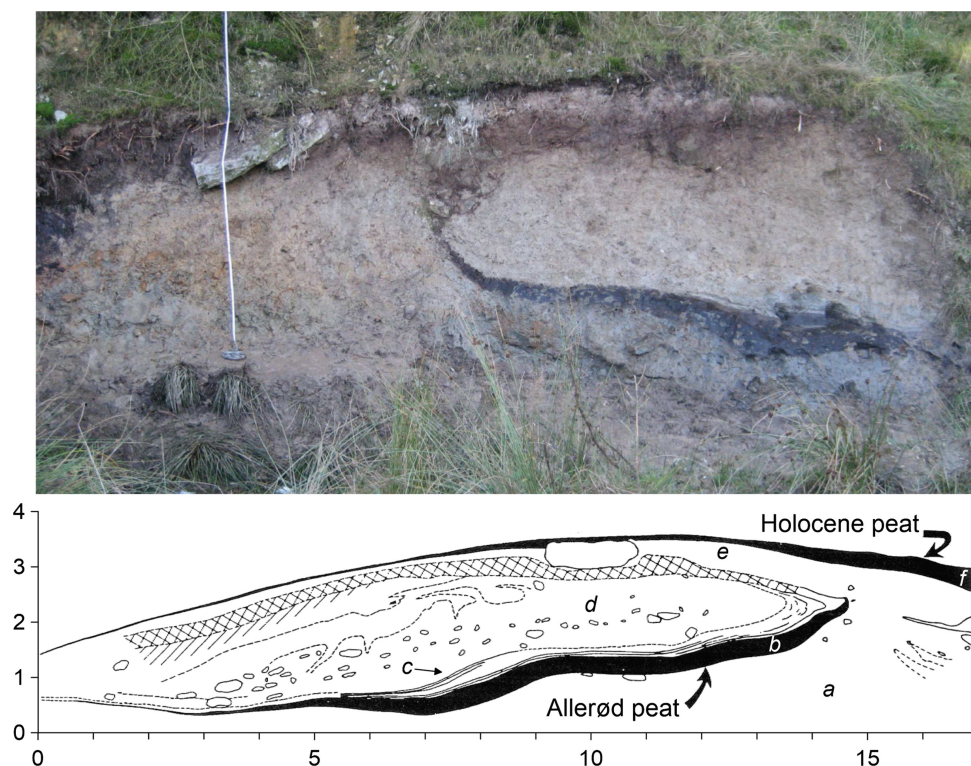
Fig. 7.4 Trench in the downstream part of an elongate periglacial rampart of the Konnerzvenn (see location of the PRD on Fig. 7.3). *Top* View of the southern wall of the trench, refreshed in September 2015 (*Photograph* E. Juvigné). *Bottom* The northern wall of the trench as exposed during initial trenching in 1978 and published by Pissart and Juvigné in 1980. Note in particular the Allerød peat layer predating the periglacial ground deformation and featuring a ramp/flat geometry and overturning of its raised end thinning to the right toward the depression. *Thin lines* above this peat layer, also overturned, correspond to parallel thin peat beds interlayered with clayey silts. *The dashed line* and hatched and cross-hatched areas delineate zones of differently coloured gravelly clayey silt. The big quartzite block on *top* of the trench is typical of the surface material covering the area. The Holocene peat thickens toward the centre of the depression

the rampart. Palynological analyses of this peat identified a vegetational sequence encompassing the period from the Bølling to the beginning of the Younger Dryas (Damblon and Bastin 1986; Damblon 1994), (Fig. 7.5). In this sequence, from bottom to top, a peak of *Selaginella selaginoides* marks the cooler and wetter transition between Bølling and Allerød, followed by the predominance of *Pinus* during the Allerød before the latter species suddenly regresses at the benefit of the *Cyperaceae* at the beginning of the Younger Dryas. Important new findings have recently been brought by Damblon et al. (2014), who examined the pollen and plant remain content of three thin silty peat laminae above the main peat and concluded that they clearly differ from that of the underlying layer and attest to the local vegetation during the early Younger Dryas (Fig. 7.5).

7.4.3 Age Determination

The peat layers in the Konnerzvenn trench offer the additional opportunity of ^{14}C dating of the rampart. First ^{14}C age estimates of the base and top of the main peat were obtained very early (Pissart and Juvigné 1980), additional dating being performed in the following decades. Summarized in Pissart (2000), they yield an age between 15,442 and 13,924 cal BP (from two estimates with their 68% confidence interval, using the IntCal13 curve) for the bottom of the layer, with a most probable value around 14,050 cal BP consistent with the pollen data. Three dates obtained at the height of a thin tephra layer situated ∼9 cm below the top of the peat consistently point to a calibrated age in the range 13,036–12,582 cal BP, while two samples taken at the top of the layer give slightly diverging numerical ages of 12,711–12,520 and 12,240–12,016 cal BP. Overall, this age data set is internally coherent and also perfectly matches the palynological results. Heavy mineral analysis of the tephra demonstrated that it originated from the Laacher See eruption in eastern Eifel (Pissart and Juvigné 1980), thus providing an additional chronological tie (Fig. 7.6a). Indeed, Van den Bogaard (1995) gives a ^{40}Ar/^{39}Ar numerical age of 12,900 ± 560 year BP for the Laacher See tephra, which fits well in the ^{14}C chronology of the Konnerzvenn trench.
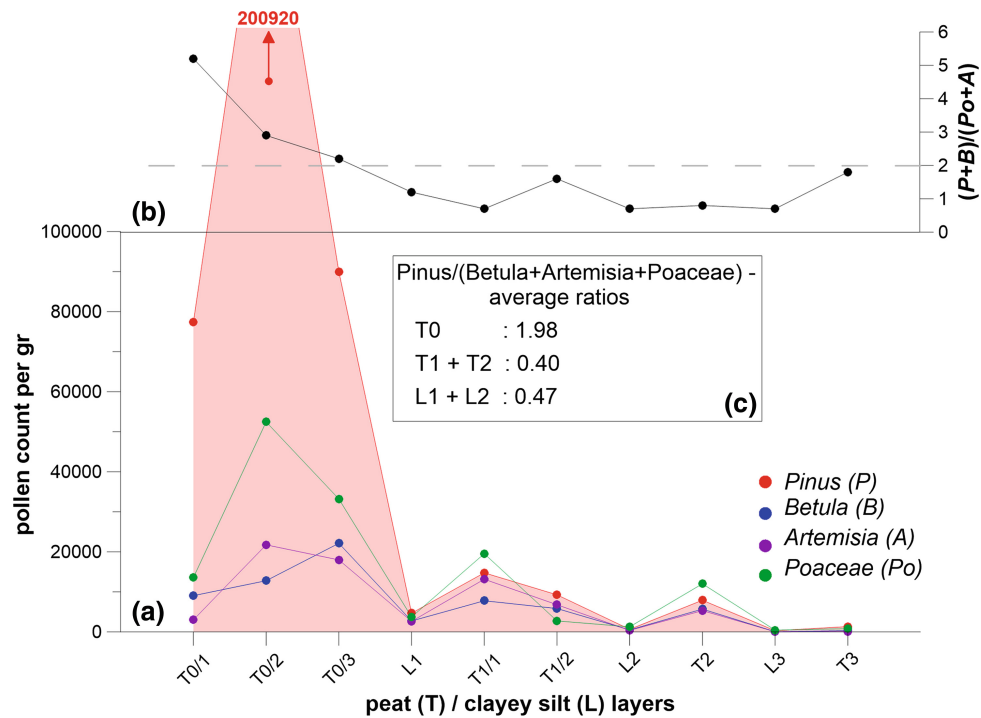
Fig. 7.5 Pollen data from the peat layers deformed in the rampart of the PRD described in the Konnerzvenn (see Fig. 7.4). **a** *Pinus*, *Betula*, *Artemisia*, and *Poaceae* counts in the main Allerød peat T0 and the thin overlying peat (T1, T2, T3) and silt (L1, L2, L3) layers. **b** Ratio between arborean (*Pinus*, *Betula*) and non-arborean (*Artemisia*, *Poaceae*) pollen contrasting the milder climate in which the main peat layer accumulated and the generally colder climate that followed. **c** Ratio between *Pinus* and the other counted pollens. The totally different ratios observed in T0 versus T1 and T2 show that the latter have not been reworked from T0. Their ratio is instead very close to that of L1 and L2

Recently, Juvigné and Streel (2007) produced a new set of ^{14}C ages not only for the thin peat laminae above the main layer but also for the top of the latter. Two clear laminae and a tenuous upper zone of enrichment in organic matter are successively dated to 12,652–12,377, 12,382–12,126 and 12,383–11,986 cal BP (Fig. 7.6b), and two dates agree on an age of 12,779–12,691 cal BP for the top of the thick peat. While the internal consistency of these ages is quite good, they show discrepancies with those previously published by Pissart (2000) for the top of the peat layer, possibly due to laboratory biases.

7.5 Interpreting the Data

7.5.1 Mechanism of Formation

The outward sloping of the sediment layers in the Konnerzvenn trench shows that the PRD's central depression has taken the place of a formerly upheaved mound. Moreover, the overturned upper end of the peat layer and the thin alternate silty/peaty laminae indicates that the slopes thus created were steep enough to allow mass transport to downbend them (Fig. 7.4). Finally, the ramp and flat geometry displayed by the deformed peat layer evidences that episodic lateral growth complemented upheaval of the mound.

The progressive buildup of the mound slopes caused successive sediment transport processes to take place. In the beginning, only runoff, possibly aided by frost creep, was able to occur on the initial gentle ground undulation. It was long held that all thin laminae, both silty and peaty, had been emplaced by runoff (Pissart and Juvigné 1980) but their recently obtained ^{14}C and palynological ages (Juvigné and Streel 2007; Damblon et al. 2014) rather suggest an evolution with alternating silt deposition by runoff under cool episodes and peat accumulation during milder interludes. At a later stage of the mound development, the sharp hinge of the peat overfold and the unstructured appearance of the overlying gravelly/blocky silt mass point to cold conditions and gelifluction as the most probable transport process of a seasonally thawed active layer above the underlying frozen ground of steepened slopes.

The evolution from a mound to the modern depression attests to the former presence of an ice accumulation in the ground, now thawed. While the original hypothesis of pingos formed by injection ice (Pissart 1956) was soon abandoned when it was recognized that the physical conditions
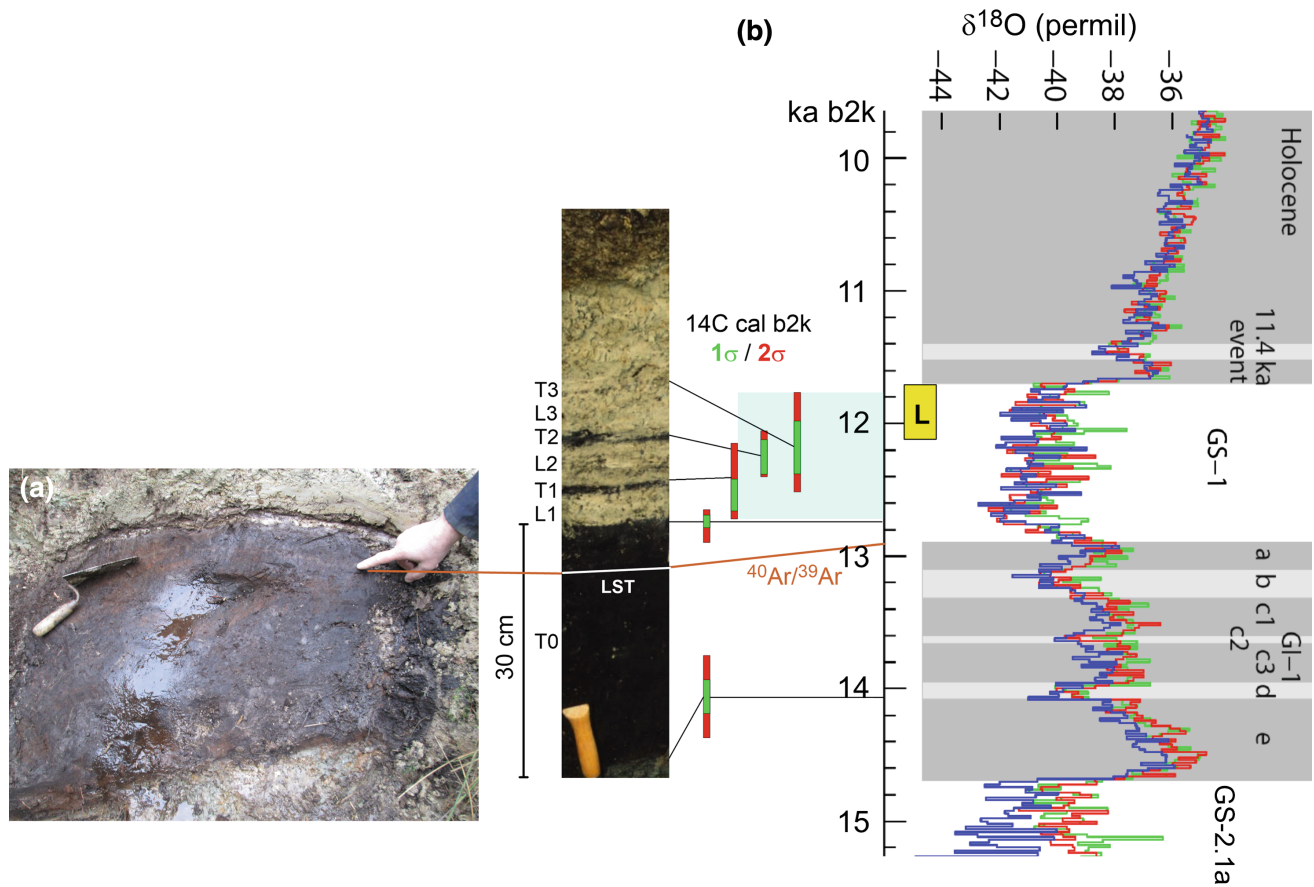
Fig. 7.6 Dating of the rampart of the PRD presented in the Konnerzvenn (Fig. 7.4). **a** Photo of the main peat layer with the Laacher See tephra appearing as a thin beige lamina a few centimetres below the top of the peat (between finger and trowel). **b** Compared with the $\delta^{18}O$ curves of three dated ice cores in central Greenland (*blue* NGRIP; *red* GRIP; *green* GISP2) (Rasmussen et al. 2014), the calibrated ^{14}C ages of the peat assign an Allerød (or Greenland interstadial GI-1) age to the main layer, supported by the Ar–Ar age of the Laacher See tephra (LST), and younger ages corresponding to the first half of the Younger Dryas (Greenland Stadial GS-1) to the overlying thin layers (T1, T2, T3). The latter ages suggest that the main phase of lithalsa formation occurred within a few centuries during the second, not necessarily coldest, half of the Younger Dryas (time window noted *L*, *highlighted in yellow*)

for such a process were not met in the Hautes Fagnes area (Pissart 1965, 1974), a large body of evidence (present-day analogues in northern Canada, laboratory experiments, microstructures in the PRD ramparts) now consistently indicates that accumulation of segregation ice was responsible for the development of the frost mounds (Taber 1929; Pissart 2009) (Fig. 7.7). The process of segregating ice in the ground corresponds to the growth of ice lenses in a water-saturated soil by freezing of water drawn from the surrounding substrate through cryosuction. Ice accumulates near the ground surface because water films depleted by freezing at the surface of the forming ice are replenished by capillary water migrating down a thermal gradient through the fine pore and cracks of the nearby unfrozen (though generally below 0 °C) ground toward the growing ice lens. When it comes in contact with the ice at the base of the lens, this water freezes in turn and the process keeps going as long

as free water is available, leading to the development of large masses of segregation ice that cause ground heave. Obviously, the first requirement for large-scale ice segregation is thus the juxtaposition of frozen and unfrozen ground, i.e. the presence of discontinuous permafrost where mound growth is related to the development of patches of frozen ground. Other conditions required for the process to work include a slow progression of the freezing front, which is favoured by the exothermic character of the water-to-ice phase change (liberating latent heat of fusion), and a grain size in the clay to silt range, which offers the optimal capillary diameter for water to migrate. In the Hautes Fagnes, the predominant silt fraction of eolian origin in the upper metres of the otherwise clayey cover material makes them especially apt at cryosuction.

Accumulation of segregation ice was identified as the cause of the formation of frost mounds in Finnish Lapland
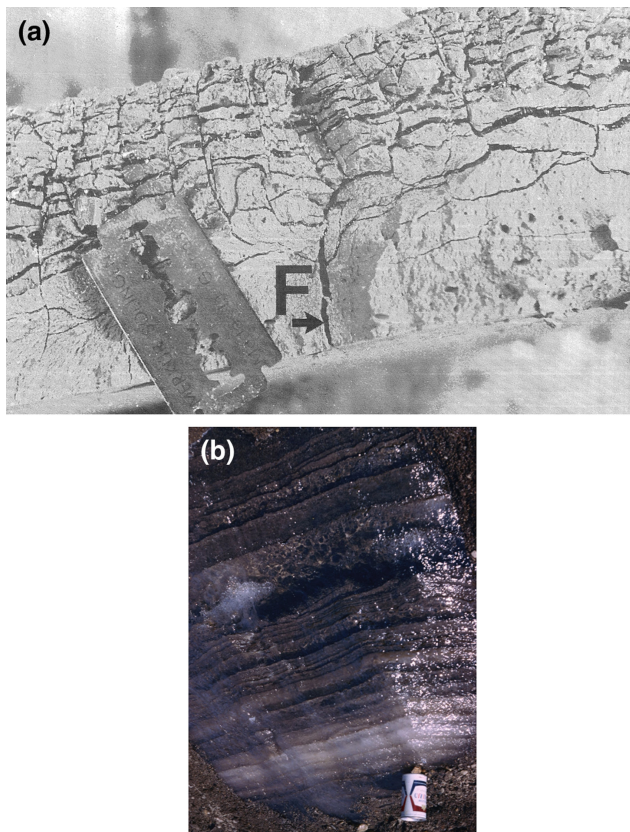
Fig. 7.7 a Segregation ice lenses developed upon slow freezing of a silt sample, experiment by Pissart (1987). F. Desiccation crack due to the migration of pore water toward the freezing front. **b** Segregation ice in a frozen soil near Inuvik, northwestern Canada (*Photo* A. Pissart)

by Seppälä (1986). These frost mounds, first described and called palsas by Fries and Bergstrom (1910), display individual and group characteristics very similar to those reconstructed for the cryogenic mounds to which the Hautes Fagnes PRDs bear witness, except that they are developed in peat-covered areas, with a core essentially made of frozen peat. Yet, in the Hautes Fagnes, no such extended peat blanket existed at the time of mound formation (the local peat layer observed in the Konnerzvenn trench is rather an exception and, in any case, disappears toward the centre of the form, where ice accumulated). Consequently, because they result from the same process as palsas but were formed within a mineral substrate, Pissart et al. (1998) called the Hautes Fagnes frost mounds lithalsas, after the name forged by Harris (1993). This difference in the nature of the substrate basically results in a difference in temperature conditions needed for the mounds to form. When peat is present, the contrast between dry peat insulating the ground against summer warmth and heat-conducting wet peat facilitating ground cooling in winter tends to maintain colder soils on

average and favours ice segregation for slightly milder air temperatures than in the case of mineral substrates. In other words, lithalsas require harsher conditions than palsas to form.

Finally, would lithalsas have been created solely by vertical upward push of the ground by growing ice lenses, they would have then simply resorbed without leaving traces when their core ice subsequently thawed under warming conditions. The remarkable relict form of the PRDs is therefore by itself clear evidence of the lateral, outward growth component of ice lens and mound, to some extent supplemented by the descent of material on the slopes of the mound.

7.5.2 Timing of Lithalsa Formation and Destruction

The time of lithalsa formation in the Hautes Fagnes was once hotly disputed. Since publication of the first pollen data (Bouillenne and Bouillenne 1937), extensive palynological evidence had been gathered and consistently indicated that the peat fill of the PRDs had started to accumulate in the early Preboreal, after thawing of their frozen core had destroyed the mounds as soon as temperature rose at the end of the Younger Dryas. However, this only defined a minimum age of the lithalsas and authors disagreed on whether they dated back to the Younger Dryas or the Tardiglacial. The debate came to an end when ^{14}C dating of the pre-lithalsa peat layer in the Konnerzvenn trench showed that it had been formed mainly during the Allerød (Pissart and Juvigné 1980), (Fig. 7.6). Furthermore, a heavy mineral assemblage signing the Laacher See tephra ($\sim$12.9 ka) was found not only in this peat layer but also in pre-lithalsa sediments in other trenches across PRD ramparts, strongly suggesting that all observed PRDs derive from a single generation of lithalsas produced during the Younger Dryas in the Hautes Fagnes and Baraque de Fraiture areas. This is also consistent with the similar state of preservation of all forms, whereas older PRDs would be hardly recognizable in the field, if any, due to overprinting by the next generation of cryogenic mounds.

However, Juvigné and Streel (2007) recently claimed that lithalsas were probably also produced during the cold stage that preceded the Bølling-Allerød warming, i.e. around 17–15 ka (Oldest Dryas, or Greenland Stadial 2.1a sensu Rasmussen et al. 2014). Indeed, noting that the Allerød peat layer in the Konnerzvenn trench obviously accumulated in a shallow depression, they argue that this depression attests to the thawing of an older lithalsa. Now, this claim for another generation of frost mounds is not supported by field
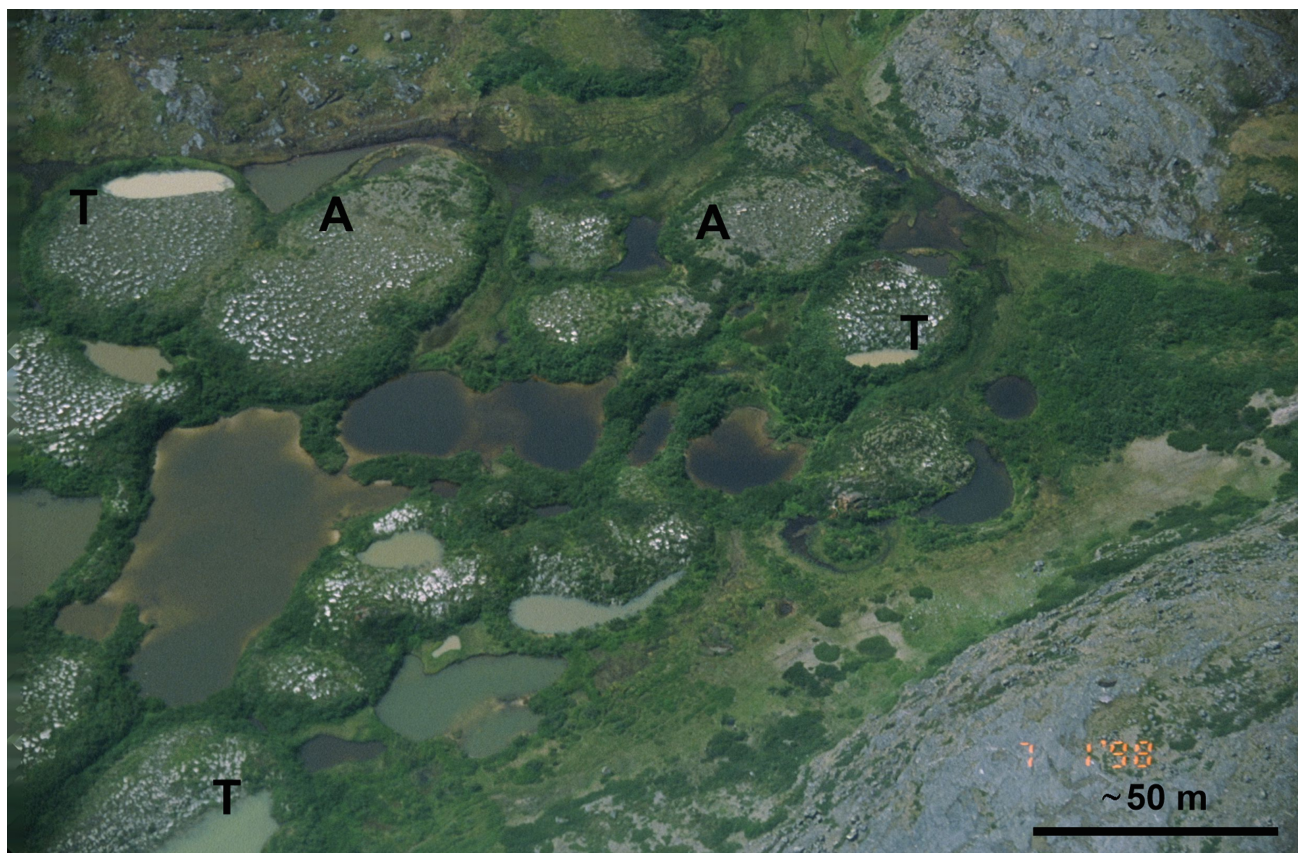
Fig. 7.8 Active periglacial mounds in west-central Labrador, close to the Boniface River ∼25 km inland from the eastern shore of the Hudson Bay at ∼57° 45′N. The photo shows active (*A*) and partly thawed (*T*) lithalsas. Note also the vegetational landscape in which these forms occur (*Photograph* A. Pissart)

evidence: (1) the depth and the diameter of the suspected PRD are much smaller than those of known forms, (2) no trace of the associated rampart is visible in the undisturbed area west of the trench (Fig. 7.3). Moreover, after more than 12 ky of uninterrupted very cold conditions, the Oldest Dryas permafrost was most probably continuous over the Hautes Fagnes area, thus ruling out significant ice segregation at this time.

More enlightening are the ^{14}C ages obtained for the organic laminae overlying the main peat layer (Juvigné and Streel 2007), which shed light on the time needed for a lithalsa to develop. They show that, although limited ice segregation was possibly initiated during cooler, drier time spans within the first half of the Younger Dryas, mound formation was each time aborted by the return of milder, wetter conditions manifested by thin peat accumulations, and it was not until the second, colder half of this stadial (from ∼12.2 ka onwards) that the lithalsas really began to grow (Fig. 7.6). This reduces the duration of the period favourable to lithalsa development and aggregation in dense

fields to ∼0.5 ky. Though apparently short, such a time span is consistent with observations by, e.g. Seppälä (1982) that vertical growth rates of palsas may reach several decimetres per year, with ^{14}C ages of palsas and lithalsas in the modern subarctic regions showing that many of them are only a few centuries old (Allard et al. 1987; Seppälä 2006; Wolfe et al. 2014), and with modelling results indicating that full development of palsas and lithalsas is achieved in a maximum of 200 years (An and Allard 1995).

7.6 PRDs as Paleoclimatic Proxies

Beyond the typical character of these PRD-covered landscapes of the Hautes Fagnes plateau and their geomorphic value, PRDs are also useful indicators of the paleoclimate that reigned over NE Ardenne during the Younger Dryas. Indeed, modern lithalsas are known to develop in very few areas worldwide, mainly northern Canada (Harris 1993; Calmels and Allard 2008; Wolfe et al. 2014) (Fig. 7.8) plus

rare occurrences in mountains of central Asia (Wünnemann et al. 2008; Iwahana et al. 2012), which correspond to a narrow range of climatic conditions. Lagarec (1982) noted in Northern Québec that, while palsas chiefly develop in the forest tundra zone, lithalsas are preferentially found in the shrub tundra zone, north of the treeline. Climatic parameters of the latter area meaningful for lithalsa development include mean annual air temperature (MAAT) between −4 and −7 °C, mean temperature of the warmest month between 9 and 10.5 °C, and rather low mean maximum snow thickness of ∼0.5 m. While Allard et al. (1987) summarize the required conditions to MAAT <−5 °C and July mean temperature <10 °C, Pissart (2003) slightly tightens the ranges to [−4.3 to −5.8 °C] and [9.5–10.7 °C], respectively. Importantly, he associates the MAAT lower bound with the mapped limit between discontinuous and continuous permafrost and the July 10 °C isotherm with the treeline, thus clearly defining the climatic and ecological conditions needed for lithalsa formation as those of the coldest part of the zone of discontinuous permafrost (Fig. 7.9). This is also in agreement with theoretical optimal ground temperatures between −3 and −8 °C for the growth of ice segregation lenses (Hales and Roering 2007).

Based on these modern observations, Pissart (2003) thus concluded that the Hautes Fagnes and Baraque de Fraiture areas underwent similar MAAT and mean July temperatures when lithalsas developed, i.e. during the colder half of the Younger Dryas (Juvigné and Streel 2007). Taking into account a temperature gradient of 0.6 °C per 100 m of elevation change, these estimates are fully confirmed by partly independent results of Isarin (1997) and Isarin and Bohncke (1999), who give a Younger Dryas MAAT of −2 °C at sea level, yielding a corrected [−5 to −6.2 °C] range for the Hautes Fagnes area, and a mean July temperature of ∼13.5 °C corrected for elevation to 9.3–10.5 °C, inferred from a spectrum of periglacial features and pollen and plant macrofossils, respectively (Fig. 7.10).

Finally, an intriguing issue remains: why are summit surfaces of central Ardenne above 500 m asl devoid of PRDs while they are so numerous in the Hautes Fagnes and Baraque de Fraiture massifs? Field evidence contradicts the suggestion by Pissart (1974, 2009) that small perched aquifers in quartzite-derived weathering sands might have provided only in these areas the amount of ground water needed for the buildup of large masses of segregation ice. In this respect, exploring why all PRD areas are aligned on the first high ridgeline that the Ardenne plateau presents to the prevailing winds from WNW and the implications thereof for snow cover and soil saturation during the Younger Dryas might be more promising.

Fig. 7.9 Location of the areas of mapped active lithalsas in Canada with respect to permafrost continuity and summer temperature conditions (*indicated by position of the tree line*) (from Wolfe et al. 2014)
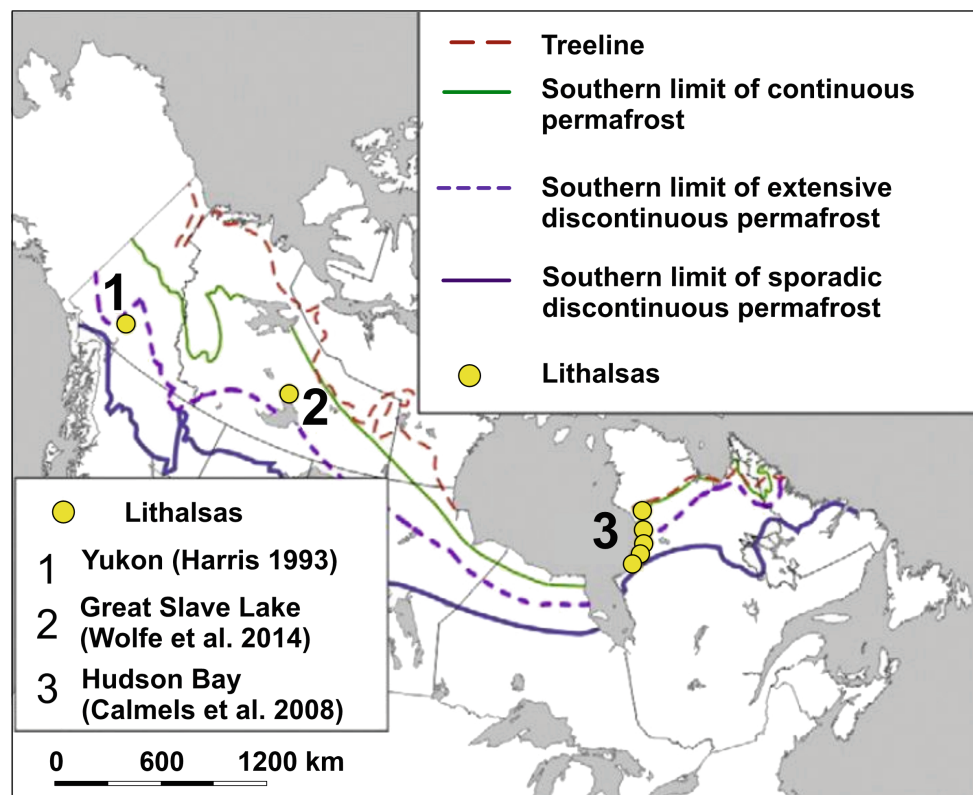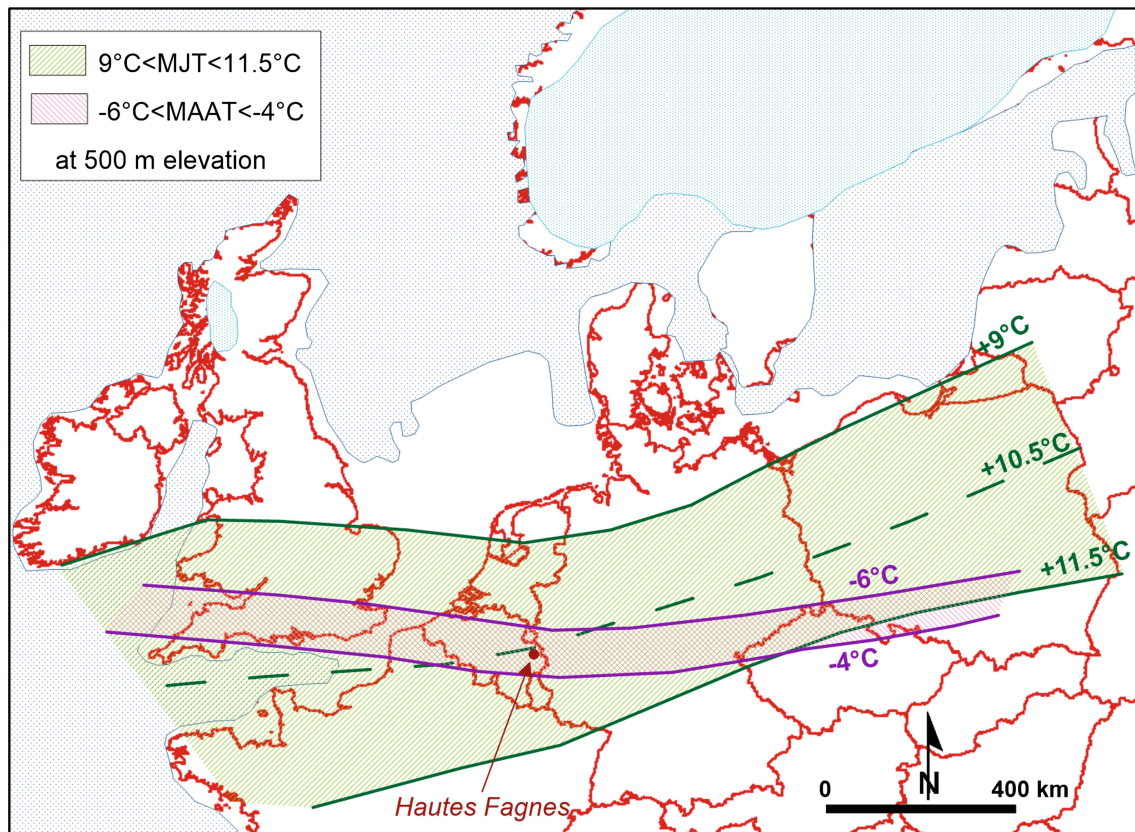
Fig. 7.10 Mean annual air temperature (MAAT) and mean July temperature (MJT) isotherms at 500 m elevation during the Younger Dryas, redrawn after Pissart (2000) from data of Isarin (1997). The Hautes Fagnes lithalsas were formed in the area where the combination of Younger Dryas MAAT (between −4 and −6 °C) and MJT (between +9 and +11.5 °C) was similar to that now observed in northern Canadian regions showing present lithalsa formation. *Light blue dots* ice caps; *middle blue dots* sea ice

7.7 Conclusion: The Geoheritage Perspective

The Hautes Fagnes plateau is the best among the rare places worldwide where PRDs attesting to periglacial environments of the last Glacial are preserved. Moreover, the area hosted a lot of research about not only PRDs but also many other periglacial landforms and highly contributed to their understanding for more than a century. As such, the Hautes Fagnes and their PRDs represent a unique geomorphosite of very high value. This quality led to the extension of the perimeter of the Hautes Fagnes domanial nature reserve first created in 1957 in order to include the zones displaying the most spectacular PRD fields in NE Hautes Fagnes, thus ensuring an adequate frame for their preservation. Since then, large-scale work supported by national and European funds has been achieved with the aim of maintaining and restoring the general character of wet areas of the Hautes Fagnes, which had been largely degraded in the last centuries by agropastoral practices, peat exploitation and, since the nineteenth century, extensive spruce planting. Owing to their real outstanding universal value as natural feature and landscape, an application is currently planned for the inscription of the PRDs of the Hautes Fagnes and the Baraque de Fraiture areas as World Natural Heritages properties of the UNESCO. Meanwhile, it is already not that rare that, walking across the beautiful misty landscapes of the Hautes Fagnes, you meet a naturalist or a geoscientist pursuing research about peat bogs and PRDs.

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