POST-LITTLE ICE AGE PATTERNED GROUND DEVELOPMENT ON TWO PYRENEAN PROGLACIAL AREAS: FROM DEGLACIATION TO PERIGLACIATION

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ABSTRACT. This study aims to observe post-Little Ice Age glacier retreat and the constitutive patterned ground development at two French Pyrenean glacier forelands (Taillon Glacier and Pays Baché Glacier). Periglacial feature observations are associated with periods of deglaciation using aerial photos and archive files. Four conclusions are drawn. (1) The two glaciers have lost respectively 68% and 92% of their surface since 1850, which corroborates observations on other Pyrenean glaciers. (2) Patterned ground can develop very rapidly, sometimes only 10 years after deglaciation. (3) Patterned ground size does not systematically increase as a function of the time elapsed since deglaciation. (4) All the forms, even those developing near the Little Ice Age moraines, are active. We propose that the location, activity and size of patterned ground are more probably linked to drift characteristics and local wetness conditions than to the time elapsed since deglaciation.

Key words: deglaciation, patterned ground, periglacial features

Introduction

The *Little Ice Age* (*LIA*) is the most recent and one of the most important glacial advance sequences of the Holocene (Grove 1988), following a warmer period (Medieval Climate Optimum). The precise chronology of this sequence varies between massifs. It is claimed that the LIA began in the thirteenth century with a few cold winters, but most authors agree that the maximum extent of glaciers occurred between the seventeenth and the mid-nineteenth centuries. This glacier extension led to many moraine ridges being formed in most high cirques of mid-latitude mountains. From the LIA maximum extent, temperatures have been tending to increase. Julián and Chueca (1998) estimated, by calculating the rise of the glacial equilibrium line elevation in the central Spanish Pyrenees (around 200 m), that the *mean annual air temperature* (*MAAT*) increases by 0.9°C. Dessens and Bücher (1995) found an identical increase in the MAAT at the Pic du Midi (+0.94°C) between 1882 and 1984, mainly explained by the rise in minimal temperatures (+2.4°C). Values are similar or slightly higher in the Alps (Haeberli 1990; Mangini *et al*. 2005).

This increase in temperature has consequences on the spatial distribution of periglacial features. Indeed, it causes glacial retreats, resulting in the exposure of recent deglaciated terrains to freezing during snow-free periods. These areas are thus subject to a development of patterned ground, all the more so as till and wetness are favourable to their growth. Patterned ground, very common forms in periglacial environments, includes all the more or less geometric forms developing on regolith subjected to freezing. The regolith has to show a contrast of frost susceptibility, leading to differential frost heave (Washburn 1979; Van Vliet-Lanoë 1991; Peterson and Krantz 2008). The most common forms are circles, polygons and stripes, which can be sorted or non-sorted. Their dimensions vary from a few centimetres to several metres. In the Pyrenees, patterned ground has been little studied, compared to the Alps (Cailleux and Hupé 1947; Boyé 1952; Philberth 1961; Höllermann 1967; Soutadé 1980; Serrano *et al*. 2000, 2001; Bertran *et al*. 2010; Feuillet, 2011). Their lower limit is located at around 2300 m a.s.l., i.e. close to the annual isotherm of +2.5°C (Feuillet 2011), but tends to increase in the eastern part of the ridge in relation to increased continentality of the climate.

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If the stages of the deglaciation are known, a detailed observation of the patterned ground development enables the age of forms and their period of activity to be dated in a relative way, as some authors have already shown in the sub-Arctic environment: Ballantyne and Matthews (1982; 1983); Matthews (1992); Matthews *et al*. (1998); Haugland (2004, 2006); Haugland and Beatty (2005). These authors concluded that, in general, patterned ground develops rapidly after deglaciation (10–20 years) and that this development and the associated pedogenesis tend to stabilize after a few decades (30–70 years). We propose here to apply these observations to two Pyrenean proglacial areas, both patterned ground-rich and with a well-known deglaciation chronology: the Taillon Glacier and the Pays Baché Glacier. This work will (1) extend the knowledge about regional post-LIA deglaciation and (2) determine the velocity of development of patterned ground based on relative dating. This approach, not previously used in mid-latitude massifs, will enable the results obtained to be compared with those from high latitudes, leading to the identification of special features linked to regional characteristics.

The study site

The Pyrenees is a mountain range extending 430 km between the Atlantic Ocean and the Mediterranean Sea (Fig. 1). Its highest point is Pico d'Aneto (3404 m a.s.l.), in the central Spanish section. Twenty-eight glaciers remain (René 2008) but their small size makes them very susceptible to climatic fluctuations. These glaciers have been observed and monitored since the end of the eighteenth century, first by Ramond (1789), then by de Charpentier (1823) in the first half of the nineteenth century, and finally by a series of scientists and Pyreneists in the second half of the nineteenth century (Trutat 1875; Vallot 1887; Bonaparte 1891; Schrader 1894). These accounts confirm that the glacier surface areas have noticeably decreased since 1850 (Table 1). Around this date, glaciers occurred in more than 100 cirques in 15 massifs (Gonzáles Trueba *et al*. 2007, 2008). Their total area at this time varied, according to different authors, between 2000 and 4000 ha (Schrader 1894; Boucau 1922; René 2008), while today it is 350 ha (René 2008).

In the Pyrenees, the LIA maximal advance of glaciers dates from the middle of the 1850s and followed around four decades of stagnation (Michelier 1887). According to the story of an izard hunter recorded by Michelier (1887), 1856 corresponds to the time during which the Pays Baché Glacier rested on its frontal moraine. Similar dates have been proposed for the glaciers of Ossoue (Grove and Gellatly 1995; 1997), Maladeta (Chueca *et al*. 2005) and Taillon (Gellatly *et al*. 1995; McGregor *et al*. 1995). The glacier retreat would have been rapid from the 1860s (Trutat 1875).

In this study, because of the scarcity of patterned ground, only two glacier forelands have been investigated: the Taillon zone and the Pays Baché zone, i.e. two of the highest French Pyrenean Massifs (Fig. 1). The first is located on the western side of the Cirque de Gavarnie (42° 41′ N, 00° 03′ W), on the northern slope of the Taillon, culminating at 3144 m a.s.l. The current glacier has an area of 12 ha and its proglacial zone is located around 2550 m a.s.l. (Fig. 1). The site is mainly composed of sandstone, limestone and sandy limestone from the Mesozoic and Cenozoic eras. The proglacial area (Fig. 2) is composed of heterometric till material, including large angular blocks with a 1 m long axis, but a high fine content (glacial meal) as well. The largest blocks are systematically supplied by the sandstone walls. The second site is located on the eastern slope of the Pic Long (3192 m a.s.l.), in the Néouvielle Massif (42° 48′ N, 00° 06′ W). The Pays Baché Glacier, mainly covered by debris, has an area of around 2.5 ha. The current glacial foreland is located between 2800 and 2900 m a.s.l. (Figs 1 and 3). The lithology is granodiorite according to the regional geological map. Till material covering the proglacial area is heterometric, including larger blocks than at the Taillon, reaching 5 m in diameter. The openwork structure causes an illuviation of fines, accumulating into small confined beaches. The regional periglacial climate is characterized by a strong oceanic influence, marked by a relatively weak annual amplitude of the MAAT and significant snow cover (220 days per year at 2450 m a.s.l. on the northern slope). According to Météo France data, the MAAT was –1.3°C at 2880 m a.s.l. (Pic du Midi de Bigorre) between 1959 and 1984, with February being the coldest month (–7.5°C) and July the warmest (6.9°C). According to a regional annual lapse rate of 5.9°C km^{-1} (Feuillet 2011), the annual isotherm of 0°C is at around 2650 m a.s.l. Precipitation can reach 2000 mm yr^{-1} at the highest elevations and occurs mainly in winter. Thus, snow cover is

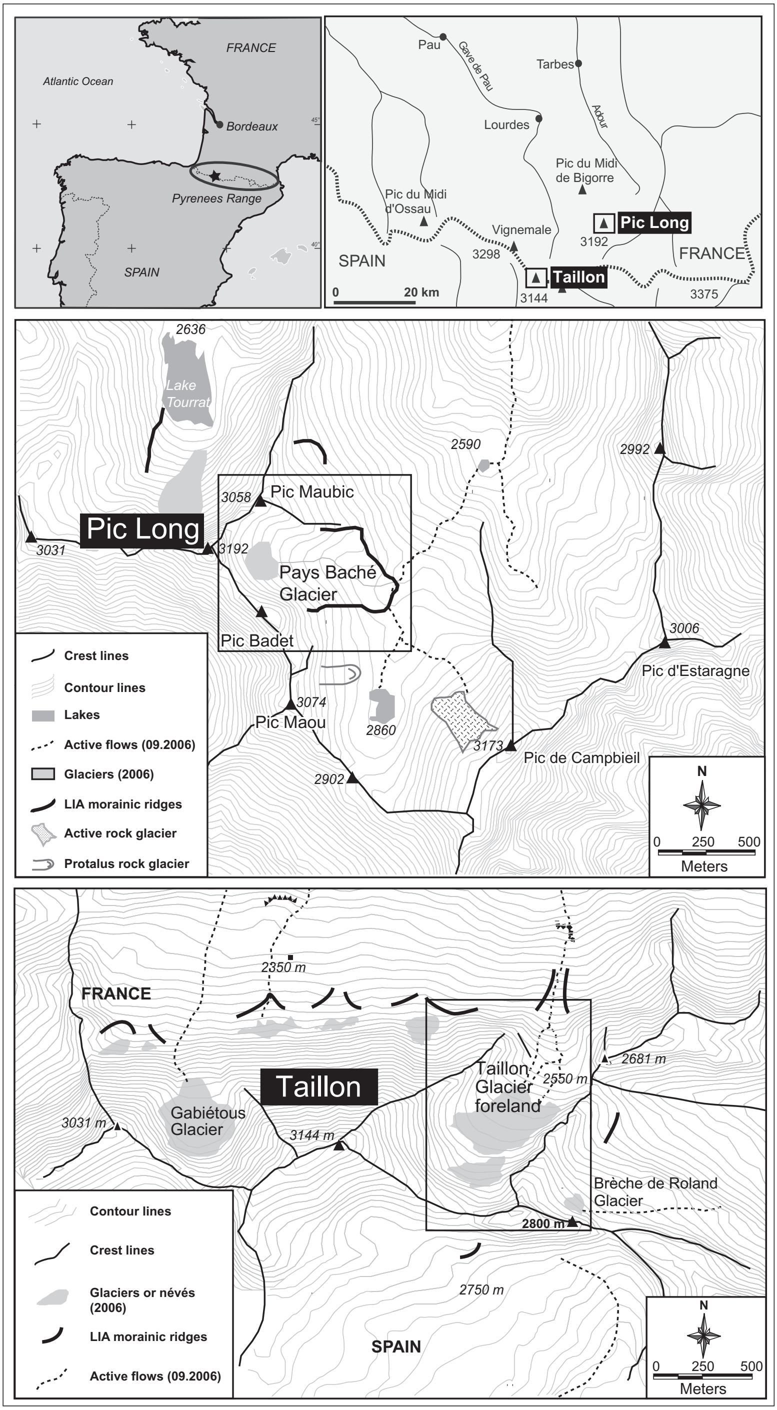

Fig. 1. Location map.

Table 1. Changes in the total area of Pyrenean glaciers since 1850.

Year	Number of glaciers	Area (ha)	References
2006	28	350	René (2008)
2000	44	500	René (2008)
1984	41	810	Serrat and Ventura (1993)
1950	?	1280	René (Unpubl.)
~1890	44	3300	Schrader (1894)
~1850	?	2000/4000	Various

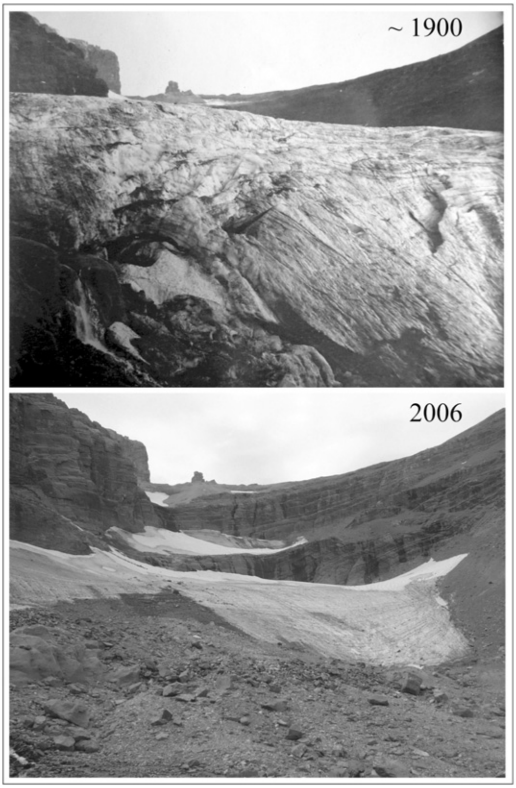

Fig. 2. Taillon Glacier retreat between the beginning of the twentieth century (*Fonds Ledormeur*) and 2006.

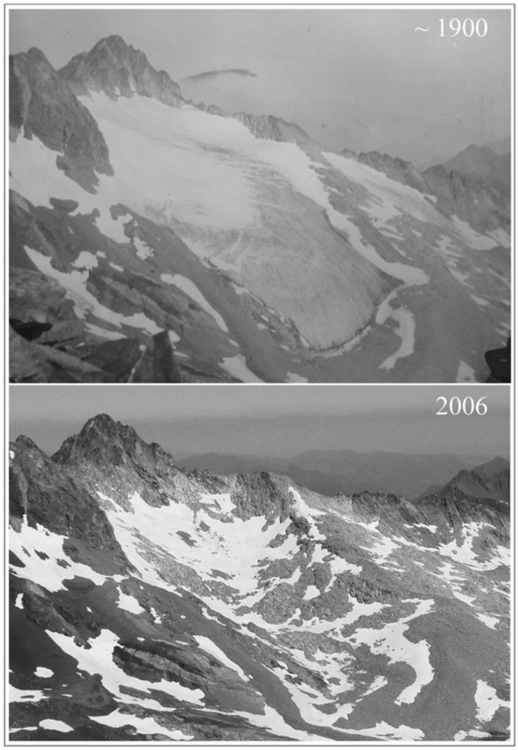

Fig. 3. Pays Baché Glacier seen from the Pic de Campbieil (3172 m a.s.l.). Top: at the beginning of the twentieth century (*Fonds Ledormeur*). Bottom: in 2006. Note the disappearance of the Maubic Glacier, to the right of the photos.

long-lasting and deep, particularly on the eastern and northern slopes, so that the seasonal ground freezing is often superficial.

Regional ground thermal regime

Three years of ground thermal regime monitoring (2004–2007) have been carried out on the southern section of the Taillon Massif, at 2700 m a.s.l. (Feuillet 2010). Three measurement stations were installed around a hillock and each station had a thermal datalogger (a.b.i data, model DL 400 E) with four sensors. These sensors were distributed in the following way: (1) one sensor in the rock wall (at a depth of 3 cm) at around 1 m above the ground; (2) one sensor at the ground surface (at around –1 cm); (3) one sensor at –10 cm; (4) one sensor at –30 cm. The stations were located in various topographical conditions. The first was in a talus near a cave entrance, with an eastern exposure. The second was installed on the southern slope of the talus dominating the cave. Finally, the third was located on the western slope of the same mound. The ground is composed of diamict, reworked by active solifluction. The results show that the *mean annual ground surface temperature* (*MAGST*) ranged from 1.5 to 3°C depending on the location. Freezing ground is generally superficial, concerning only the first centimetres. There are fewer than 50 freeze/thaw cycles per year, occurring from autumn to spring, at the ground surface but up to 88 per year on the rock wall. Nevertheless, the spatio-temporal variability of freeze/thaw cycles and freezing depth is marked and is a function of the snow cover discontinuity i.e. exposure and topography. When snow melting occurs in winter, which is occasionally the case on this southern slope, the annual freezing can reach a depth of 1 m (value determined by modelling). Furthermore, those values enable excluding the possibility of permafrost occurrence on this site, despite a high altitude (2700 m a.s.l.), either in the ground or on the rockwall. At the Pyrenees scale, it is assumed, according to the elevational distribution of active rock glaciers, that the lower limit of discontinuous permafrost is located at around 2700 m a.s.l. on northern slopes and 2900 m a.s.l. on southern slopes (Serrano *et al*. 1999; Julián and Chueca 2007). In fact, these limits are schematic and strongly depend upon topographical factors and snow cover discontinuity. Serrano *et al*. (2001) and Lugon *et al*. (2004) evidenced, by thermal observations, permafrost occurrence below 2700 m in the Posets Glacier forefield, related to the lack of snow in winter (itself due to wind factor). The authors calculated MAGST ranging from –0.5 to –1.8°C and extreme values reaching –15°C.

At the two studied proglacial areas, no ground thermal observation has been carried out. However, given the topographical positions of those sites (north- and east-facing sides) resulting in a prolonged snow-covered period, we can state that the freezing depth is probably less pronounced than at the Taillon southern slope. No geomorphological evidence of permafrost occurrence (e.g. creeping features) has been observed on the proglacial areas. Nevertheless, an active rock glacier is present right in front of the Pays Baché Glacier, under the Pic de Campbieil (front at 2900 m a.s.l.).

Methods

Deglaciation chronology

Although the LIA maximum glacier extent is visible thanks to the presence of morainic ridges, the precise deglaciation chronology requires other sources. Thus, the knowledge of the deglaciation of both sites is based on three complementary methods. (1) First, historical sources (historical photographs) were used. More precisely, a special archive of 8000 photos of the high mountains (*Fonds Ledormeur*), dating from the beginning of the twentieth century and available at the *Musée Pyrénéen de Lourdes*, was studied (Figs 2 and 3). (2) Second, bibliographic and map sources for the end of the nineteenth century were consulted. In particular, the French *Service des Eaux et Forêts* carried out several surveys of the fluctuations of the Taillon Glacier between 1945 and 1989. On the Pays Baché Glacier, Eydoux and Maury (1907) produced a very precise and useful glacier map in 1906. These first two methods (historical and bibliographic sources) are nevertheless insufficient to establish the precise limits of the fluctuations throughout the twentieth century. For example, the *Service des Eaux et Forêts* often confused glacier ice with snow patches. (3) Therefore, we corrected and mapped the precise glacier delimitations from aerial photos taken by the National Geographical Institute of France (IGN). All the available photographic missions carried out when snow patches were absent were kept i.e. 1935, 1957, 1983, 1995 and 2006 for the Taillon Glacier and 1948 and 2006 for the Pays Baché Glacier. Unfortunately, on the latter site, the photos from 1963, 1983 and 1995 did not enable the glacier limits to be distinguished because of the snow cover. Next, all the aerial photos were georeferenced and superposed with MapInfo Software, in order to digitalize the former limits.

Patterned ground mapping

The two glacier forelands are small in size thus they could be observed in a systematic way i.e. along transects covering the entire surface. The mapped patterned ground was exclusively sorted circles and polygons (Fig. 4), developed on very flat terrain (<1°). A patterned ground-rich sector was considered as a site where features are close together (less than 1 m apart). Each form diameter was measured excluding the stone border (cell diameter). According to the classification of Wilson and Clark (1991), we consider a form as miniature when its diameter does not exceed 20 cm. Precise observation locations were made with a manual GPS (Garmin G60) and then input to a GIS (MapInfo software) to superpose orthophotos and observations. The frequency of patterned ground feature occurrence was assessed by using a grid of absence/presence. The two proglacial areas, from the glacier front to LIA moraines, were cut into equal squares of 25 × 25 m. Each square is characterized by absence or presence of patterned ground. Their frequency of occurrence corresponds to the percentage of presence squares by the total number of squares.

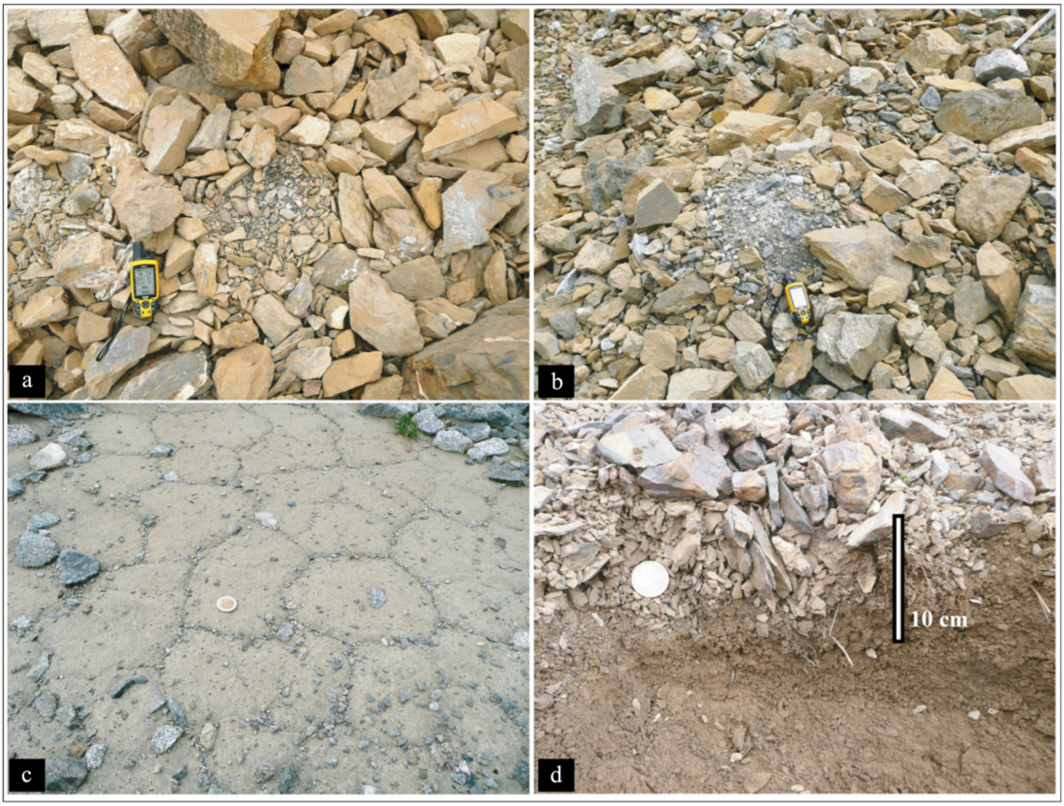

Fig. 4. a) Flat sorted circles located near the LIA moraines (Sarradets Pass, 2565 m a.s.l.). Lithology: sandstone and limestone; b) raised centre sorted circles at the Taillon (2555 m a.s.l.); c) miniature sorted polygons observed in the third class (1856-1906) of the Pays Baché Glacier proglacial area, 2870 m a.s.l. d) example of sorting depth in the gutter of sorted polygons (approximately 10 cm) at the Pays Baché Glacier, 2810 m a.s.l.

Results

Patterned ground characteristics and frequency of occurrence

All of the studied patterned ground develops on till material. Their dimensions range from 15 cm to 90 cm. The sorted circles were of two kinds: either soil cells were flat (Fig. 4a), or raised (Fig. 4b). The height/length index (ratio between the height and the length of the longest axe) on those circles varied from 2.7 to 6. Sorted polygon meshes were mostly small in size (<50 cm, see Fig. 4c). The sorting depth (maximum depth of the stone gutters) did not exceed 10 cm (Fig. 4d) and these forms thus may be considered as 'floating' features (Bertran *et al*. 2010).

The frequency of occurrence varies site by site. At the Taillon site (Fig. 5), the potential area of patterned ground development covers a surface of 4075 m^2 and 11% of this surface is concerned by periglacial feature occurrence (450 m^2). At the Pays Baché site (Fig. 6), patterned ground occurs on only 5% (325 m^2) of the total potential surface, partly because of a larger proglacial area (6375 m^2) than at the Taillon site.

Taillon Glacier foreland

Deglaciation The LIA moraines are very visible. They show an LIA glacier front at around 2250 m a.s.l., which extends to the Pouey Aspé Valley. Laterally, the glacier reaches the current Sarradets Pass (2585 m a.s.l.). In the upper part, the glacier was probably associated with the Brèche de Roland Glacier by the transfluence pass on the northern side of the Pointe Bazillac. Indeed, Schrader (1894) reported that the two glaciers were close at the end of the nineteenth century. The total area during the middle of the 1850s would have

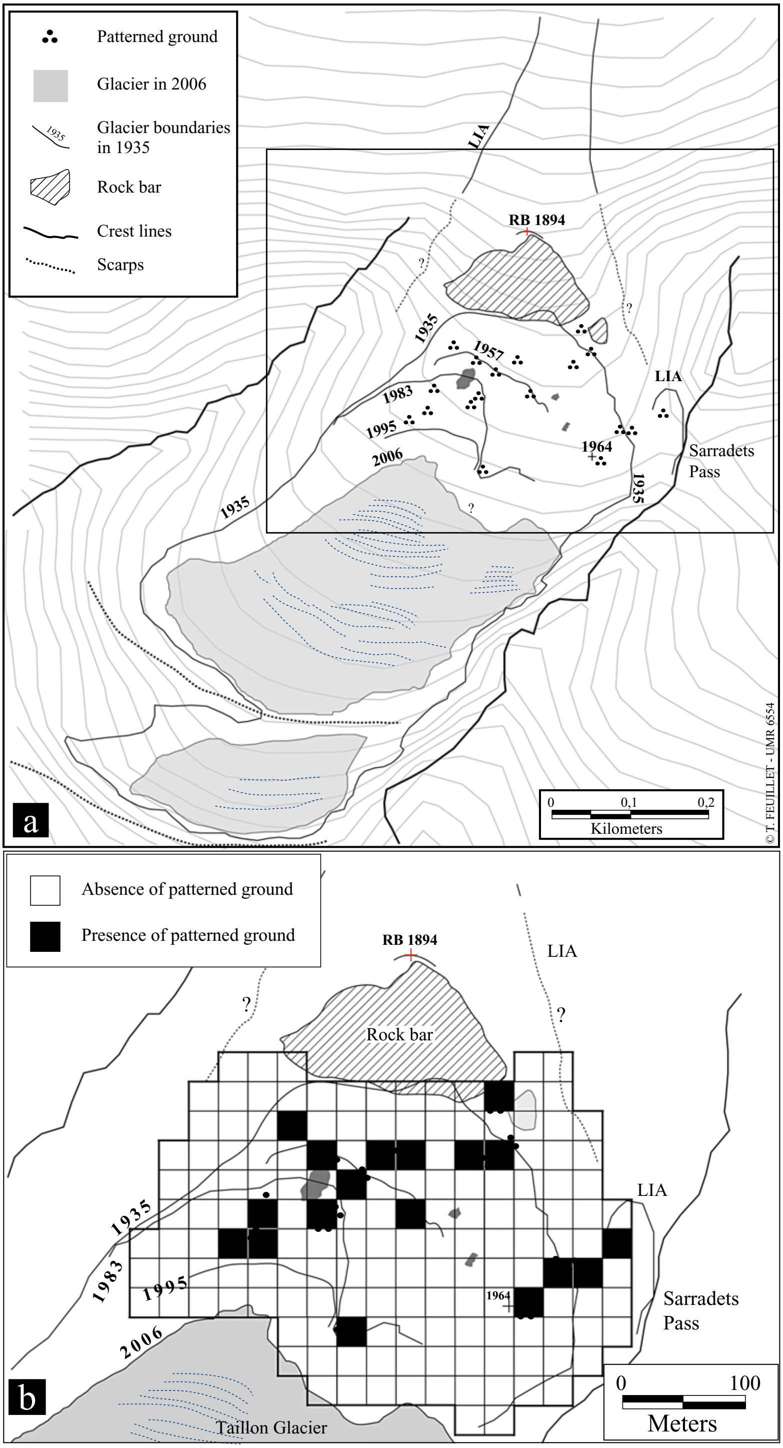

Fig. 5. Deglaciation chronology and frequency of occurrence of patterned ground (11% of the total surface) in the Taillon proglacial area.

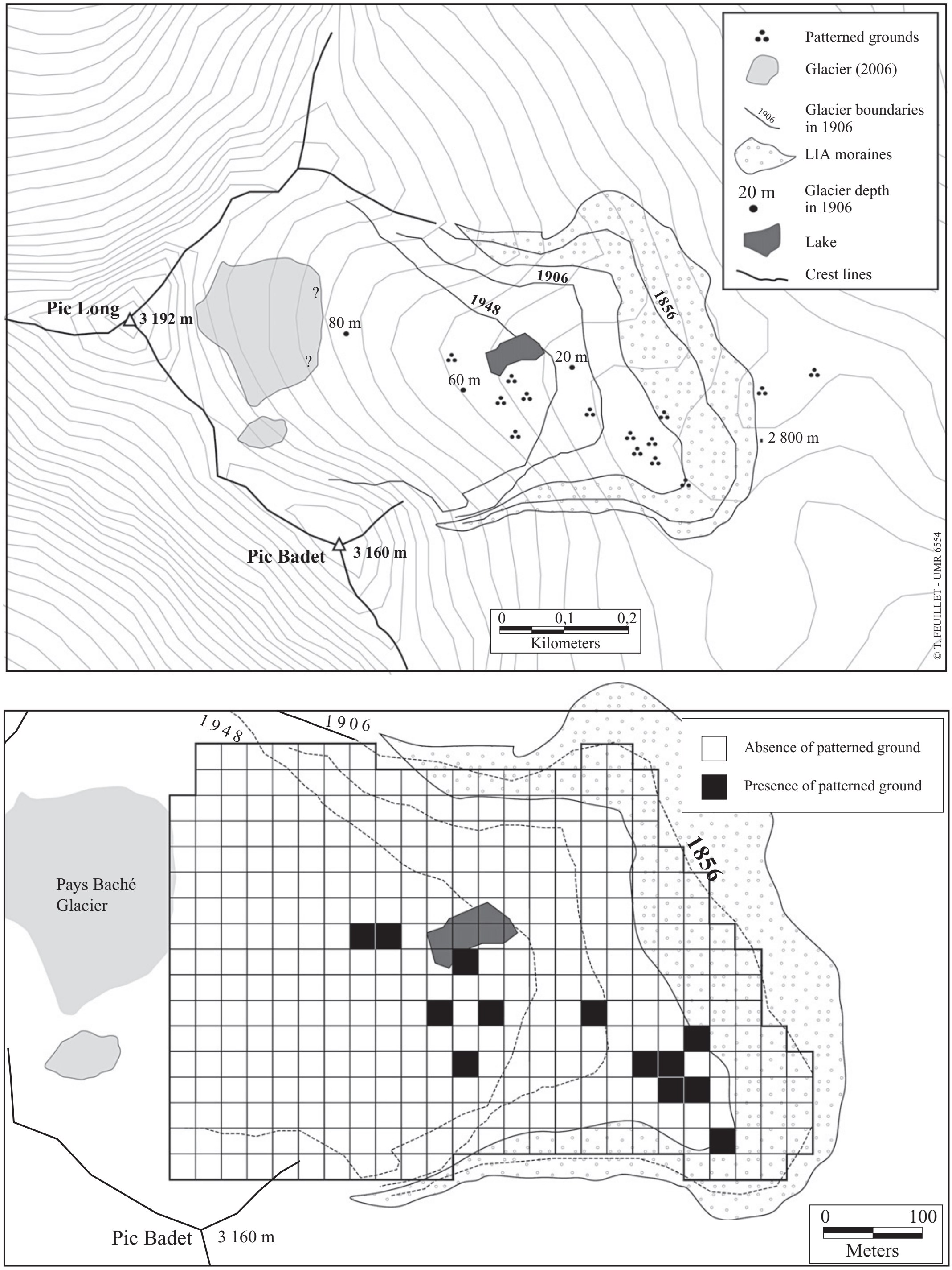

Fig. 6. Deglaciation chronology and frequency of occurrence of patterned ground (5% of the total surface) in the Pays Baché proglacial area.

Year	Elevation front	Area (ha)	References
2006	2570	12	This work
2001	2545	?	René (2003)
1991	2526	20	Gellatly *et al.* (1995)
1964	2541	?	*Eaux et Forêts*
1945	2535	22.1	*Eaux et Forêts*
1935	2540	23	Aerial photos (this work)
~1915	?	31	Gaurier (1921)
~1910	2470	33.5	Schrader (1914)
1893	2360	?	Marking RB 1893 (Bonaparte)
~1850	2250	~38	LIA moraines

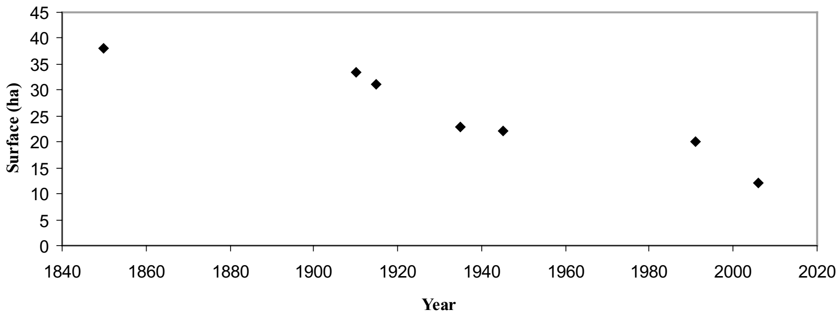

Fig. 7. Taillon Glacier retreat since 1850.

been around 40 ha (Fig. 7). Studies and marking by Prince R. Bonaparte at the end of the nineteenth century suggest that the glacial front was located at the rock bar foot, at 2360 m a.s.l., in 1893 (Fig. 5). At the beginning of the twentieth century, the front was located in the rock bar (Gaurier 1921, Fig. 5). Subsequently, glacial fluctuations were restricted to the upper part of the rock bar, in the flat area where all the patterned ground was observed (Figs 2 and 5). These fluctuations were monitored by the *Service des Eaux et Forêts* at several times during the second half of the twentieth century. This enabled several short phases of advance or stagnation to be defined (e.g. 1926–1928/1945/1963–1964), in spite of a general trend of retreat (McGregor *et al.* 1995).

Deglaciation/patterned ground relationship In the proglacial area, 18 patterned ground-rich sectors were identified (Fig. 5). These features were associated with four time period classes, defined as a function of the available aerial photos (1995–1983, 1957–1983, 1935–1957 and <1935). The results show that five patterned ground sites are later than 1983 (class 1), five are located between 1957 and 1983 (class 2), four between 1935 and 1957 (class 3) while three are located beyond the 1935 limit (class 4). Three sorted circle areas, which are part of the first class, near the 1995 limit, have necessarily developed during a short period (around a decade). They consist of adjoining sorted circles with diameters of about 20 cm. In classes 2 and 3, the circles are larger, about 50 cm in diameter. This is the case for the forms observed close to the '1964' marking made by the *Service des Eaux et Forêts*. Finally, class 4 forms can reach 90 cm in diameter. Circles of 50 cm diameter were observed at a bend formed by the LIA moraines, just below the Sarradets Pass (Fig. 5). This is interesting because it concerns the most distant forms from the current glacier front that we have observed. Their development could have occurred just after the LIA maximum. It should be noted that patterned ground from classes 3 and 4 is active: there is no evidence of plant colonization.

Pays Baché Glacier foreland

Deglaciation During the LIA, the Pic Long supported three glaciers: the Lac Tourrat Glacier (northern side), the Maubic Glacier (northeastern side, today disappeared) and the Pays Baché Glacier on the eastern side, which is the object of this study. Its LIA boundaries are very easily distinguishable due to the latero-frontal moraines (Fig. 6). It was probably associated with the Maubic Glacier, as indicated by the absence of lichen at the transfluence pass (at 3000 m a.s.l.).

This glacier has been regularly observed since the end of the nineteenth century, beginning with Michelier (1887). In September 1883, he noticed that the front was located 120 m from the LIA morainic ridge. Nevertheless, he did not map the continuous boundary, unlike Eydoux and Maury (1907). These authors made a remarkably precise map showing that, in September 1906, the front was located 210 m from the moraine, i.e. a retreat of 90 m in 23 years. We georeferenced this document, as well as the orthophoto from 1948, to make a map of the deglaciation steps, following the same method as used for the Taillon Glacier (Fig. 6). Unfortunately, neither the aerial photos from 1963, 1983 and 1995, nor the surface photo from 1963 taken by Höllermann (1968), enable the precise boundary of the glacier between 1948 and today to be visualized (snow cover too great). The limits of 1989, mapped by Grove and Gellatly (1997), seem equivocal because the front is too advanced compared to the situation in 1948 so these have not been considered. Finally, the current glacier limits are invisible in some places, because the main part of the ice, except for just under the rock walls, is covered by debris (Fig. 8). Thus, the 2.5 ha given in Table 2 is only an estimation.

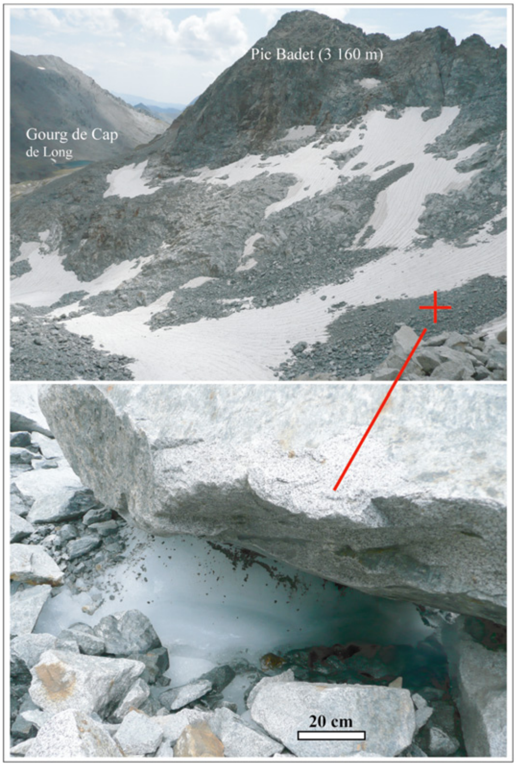

Fig. 8. Supraglacial debris on the Pays Baché Glacier. The precise limits of the glacier are difficult to distinguish.

Table 2. Pays Baché Glacier retreat since 1850.

Year	Area (ha)	References
2006	~2.5	This work
1948	19	This work
1906	23	Eydoux and Maury (1907)
1856	~33	LIA moraines (this work)

Deglaciation/patterned ground relationship 12 patterned ground-rich sectors were located and associated with three period classes (>1948, 1906–1948 and <1906): five sectors are later than 1948 (class 1), only one is located between 1906 and 1948 (class 2) and six are visible between the LIA moraines and the 1906 boundary (class 3). In a general sense, the patterned ground in this glacier foreland (sorted circles and polygons) are small in size and often confined to small areas of sandy regolith (Fig. 4B). Their sizes are not correlated to the distance from the front; class 3 includes as many miniature forms (<20 cm) as larger ones (>50 cm, particularly on LIA moraines). However, class 1 patterned ground is always miniature. As on the Taillon site, all the forms, even when located near the LIA moraines, are active (raised cells, absence of vegetation). Nevertheless, a difference arises in relation to the distance of the closest forms from the front. In contrast to Taillon, the patterned ground here is less widespread and restricted to the lower half of the proglacial area. This is explained by the unfavourable site conditions of the upper half of the area: either the drift is only composed of large blocks falling from rock walls (openwork structure) or the roches moutonnées contain no fines, i.e. no frost-susceptible regolith. The granodioritic lithology, combined with a paraglacial debris supply, minimizes the expression of freezing dynamics.

Discussion

Rhythm of glacier retreat

In spite of periods of stagnation or short re-advances, the two glaciers followed a generally regular retreat since 1850. The Taillon Glacier lost approximately 68% of its surface since this date, while the Pays Baché Glacier lost 92%. This corroborates the evolution of other Pyrenean glaciers, although this varies depending on the initial size of the glacier (63% for the Maladeta Glacier according to Chueca *et al*. 2005; 58% for the Oulettes Glacier and 47% for the Ossoue Glacier (René 2003)) or the neighbour massif of Picos de Europa (from 62 to 100% of surface-loss, Gonzáles Trueba *et al*., 2008). At the Maladeta Glacier, Chueca *et al*. (2005) highlighted that the glacier surface loss rate is correlated with annual temperature and winter precipitation, but not with summer temperatures or annual precipitation. According to these authors, these relationships are characteristic of the climate of temperate mid-latitude context (snow precipitation limited to the winter period and high temperatures occurring from spring to autumn) and hence probably concern our study sites as well.

Velocity of patterned ground development

Recently deglaciated terrains promote an increase of periglacial dynamics. We showed that patterned ground appears only 10 years after deglaciation, as observed at the Taillon massif. Nevertheless, this duration is longer at the Pic Long but cannot be assessed because of the invisibility of the current glacial front and the absence of aerial photos since 1948. At the Taillon site, the area near the glacial front hence appears to be particularly rich in patterned ground. Those results are in agreement with other studies (Ballantyne and Matthews 1983; Matthews *et al*. 1998; Haugland 2004). Indeed, Haugland (2004) defines a 'periglacial zone' around the glacial front, where patterned ground develops in the Jotunheimen during the 10 to 20 years following deglaciation, while Ballantyne and Matthews (1983) highlighted that cracks form only 2 to 6 years after deglaciation.

Relationship between patterned ground characteristics and the distance to the glacial front

Two conclusions have been highlighted. First, we noticed that an increase in patterned ground size as a function of the time elapsed since deglaciation has been confirmed only at the Taillon Glacier, but not at the Pic Long, where miniature patterned ground is present, even on the LIA moraines. Second, the majority of the patterned ground studied here, even those most distant from the current front, do not present signs of stabilization. These conclusions can imply two hypotheses:

1. The period of patterned ground formation is not necessarily associated with the age of the closest moraine. This hypothesis would have supposed that forms close to the LIA moraines are recent.
2. The location of patterned ground and its sustained maintenance could depend more on the presence of ideal drift (i.e. fine-rich till) than on the presence and the melting of a glacier. The origin of a part of the forms would be due to regional climatic conditions associated with the favourable till granulometry and would not have a paraglacial origin. For example, the sorted circles located in the bend of the Taillon LIA moraines occur largely in the zone subjected to melt wash. If the wetness is greater in this bend than elsewhere, this is because of the late presence of snow patches in summer, but not because of the proximity of the glacier. Therefore, micro-topography is very important. Nevertheless, it is possible that glaciers have an indirect influence by maintaining a cold microclimate in the cirque, which favours the late snow melting and restricts the vegetative growth. Even if these forms appeared in the 1860's or 1870's and have a paraglacial origin, their maintenance and their current activity probably do not.

Those results partly diverge from Jotunheimen studies. For example, Ballantyne and Matthews (1982) concluded that patterned ground diameter systematically increases as a function of the distance from the glacial front. The authors express three possible explanations; (1) forms took more time to develop; (2) former features developed under colder conditions; (3) their preferential development on the lower part is due to the more favourable conditions of the terminal moraines, but they never assumed that the forms developing away from the glacial front could be recent. They, as well as other authors (Ballantyne and Matthews 1983; Matthews 1992; Matthews *et al*. 1998; Haugland and Beatty 2005; Haugland 2006), concluded also that circle growth becomes blurred after the few decades following deglaciation (about 50 years). This stabilization is not considered by the authors as a consequence of regional climatic warming but as an effect of changes in local wetness and temperatures. Indeed, they show that grounds located close to the glacial front have colder summer temperatures and higher water content, which favour circle development, than other grounds in the proglacial area. The paleoclimatic significance of these glacial front circles is, therefore, different from circles in unglaciated environments.

The hypothesis according a real importance to the nature of the regolith also explains the disparities observed at the Pays Baché Glacier. Indeed, it is clear that, at this site, the location and size of patterned ground depends on the presence and the characteristics of a fine-rich till. In areas close to the glacial front, in spite of the probably ideal wetness and thermal conditions, the presence of large blocks restricts patterned ground development. Furthermore, grain size can also control the form diameter. Goldthwait (1976) showed that there is a link between grain size and patterned ground diameter: the larger the sediments, the greater the diameter. On the Pays Baché site, either the blocks are too large to enable form development or the sandy granitic grain size enables only small patterned ground. Therefore, the time elapsed since deglaciation cannot alone, in all cases, explain the patterned ground size.

Conclusions

This Pyrenean study about the relationship between deglaciation and patterned ground development has highlighted several elements.

1. The post-LIA retreat of the two studied glaciers has been very fast. Since 1850, the Taillon Glacier and the Pays Baché Glacier lost, respectively, 68% and 92% of their surface.
2. Recently deglaciated terrains appear to be highly favourable to the development of patterned ground. Some sorted circles on the Taillon proglacial area have developed in only 10 years.
3. Nevertheless, the location, size and activity of forms on the two studied sites seem to be linked more with the occurrence and granulometry of a favourable drift (fine-rich till) than with the time elapsed since deglaciation, but that must be evidenced by further grain-size studies. This observation partly diverges from Jotunheimen studies, although the general scheme regarding patterned ground development velocity and form characteristics is similar between the two areas.

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