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*Published in:*
Land Degradation and Development

*DOI:*
10.1002/ldr.2975

*Publication date:*
2018

*Document Version*
Peer reviewed version

# Spatial heterogeneity in the paraglacial response to post-Little Ice Age deglaciation of four headwater cirques in the Western Alps

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**Abstract**

This paper aims to understand how the paraglacial response to recent glacier retreat varies between four cirques in the Western Alps. Post-Little Ice Age glacier retreat has created extensive forelands where a variety of gravitational and fluvial process operate on both till-floored and rock-floored cirques. These processes may effect transitions from subglacial to proglacial landsystems, by reworking sediment and reorganising drainage. Landsystems achieve a state of preservation once no more adjustment is possible due to buffering by channel network evolution, channel armouring, and sediment exhaustion. We find no consistent trajectory of change across all studied sites: paraglacial responses differ from the classical valley-glacier model, involving variable slope-channel coupling. Proglacial drainage networks on till surfaces have become more integrated by reducing their low-order bifurcation ratios, unlike streams locked into rock channels. Reasons for diverse and site-specific behaviour include cirque floor width, gradient, and surface materials (bedrock, fine till, and/or blocky till). At some cirques, these restrict the downstream diffusion of a paraglacial "signal" of fluvial-transported sediment. At others, increased sediment flux originated from the erosion of terminal moraines. A high proportion of glacial material generally remains within the glacier foreland, due to proglacial basin sediment traps, inefficiency of fluvial networks, armouring of floors by coarse tills, and rock-controlled channels. The millennial-timescale preservation potential of most recent primary glacial deposits and within-cirque paraglacial landforms appears to be high.

Key words: glacier retreat paraglaciation European Alps Little Ice Age moraine

## 1. Introduction

This paper seeks to understand the nature and causes of spatial variability in landscape response to glacier retreat from the Little Ice Age glacier (LIA) maximum of the mid-19th Century. The focus is on headwater cirques in the western European Alps, and includes common but previously unresearched bedrock forelands. Recent glacier retreat has opened up extensive cirque floor and slope landscapes, which provide potential sources of sediment for downstream transport (Knight & Harrison, 2014; Zanoner *et al*., 2017). These changes are attracting increasing research interest within the context of paraglacial landscape responses in mountain environments (Harrison, 2009; Knight & Harrison, 2009; Heckman *et al*., 2016). The classic paraglacial model (after Church & Ryder, 1972; Ballantyne, 2002) outlines a time-dependent increase in catchment sediment yield during and shortly after deglaciation followed by an asymptotic decline towards the so-called geological norm. A scale-dependence has been theorised in which the timescale over which the paraglacial cycle operates is longer for larger basins (Figure 1a). A process-dependence is also integral to the theory, whereby different process domains respond to deglaciation over a spectrum of timescales (Figure 1b).

The general model of paraglacial landscape response hides much local variability related to specific environments and process domains (Cossart *et al*., 2013). Accelerated sediment yields may be sourced from the large lateral moraines of temperate glaciers (Ballantyne & Benn, 1994; Harrison & Winchester, 1997; Curry *et al*., 2006), and at high latitudes from ice-cored moraine degradation (Lukas *et al*., 2005; Ewertowski & Tomczyk, 2015; Tonkin *et al*., 2016). Sediment may also be supplied by reworking of alluvium (Lønne & Lyså, 2005; Barnard et al., 2006) and slope deposits (Barnard *et al*., 2009; Mercier *et al*., 2009) and from rock slope failures (Cossart *et al*., 2013; Deline *et al*., 2015a).

The evidence base for the rapid, short-timescale response of small headwater catchments is, however, less clear than the model suggests. Some studies show that headwater basins yield well below their potential paraglacial delivery due to variable slope-valley connectivity and inefficiencies in fluvial export of material (Cossart, 2008; Cossart & Fort, 2008; Lane *et al*., 2017). The spatiality of response becomes more important as the scale of inquiry is reduced. Knight & Harrison (2009) further suggest that local controls become more important relative to regional climate controls as the "paraglacial zone" retreats during climate warming to higher altitudes and latitudes. Thus, while a catchment-scale paraglacial signal following major glaciations may be clear (Ballantyne, 2002), it may not follow that a clear time-dependence of downstream sediment transfer is similarly applicable to post-LIA glacier retreats. Quantified rates of slope adjustment to deglaciation have focused on proximal lateral moraine slopes (Ballantyne & Benn, 1994; Ballantyne, 1995; Harrison &

Winchester, 1997; Curry, 1999; Curry *et al*., 2006; Deline *et al*., 2015a), which represent localised zones of maximum erosion which may not be representativeof a wider catchment response.

Most previous work has focused on single catchments, or on particular process domains, so that the spatial dimension to paraglacial response is poorly understood (Carrivick & Heckmann, 2017). This paper approaches the question of spatial variability by presenting detailed mapping of four cirques. These comprise the cirques of the Evettes, Grand Méan and Mulinet glaciers in the Frontier Range of France, and the Estelette cirque on the Italian flank of the Mont Blanc massif (Figure 2). The populous valleys of the western Alps are fringed with cirques currently undergoing deglaciation, and small glaciers in headwater basins are the dominant glacier type in this region, with glaciers < 1.0 $km^2$ in area comprising 88 % of French glaciers (Gardent *et al*., 2014). By providing an inventory of landforms related to post Little-Ice Age glacier retreat, potential variability in landscape response can be identified both within and between cirques. The selection of cirques for study has been informed by the need to include contrasting forms. In particular, variable cirque-floor gradients and material properties reflect energy gradients and material resistance to entrainment, both of which may *a priori* affect sediment mobility. The paper tests the extent to which post-LIA maximum landscape response follows the rapid, short-timescale paraglacial trajectory predicted by the standard time-dependent model, and the spatial effects that might cause deviations from this. These are important considerations when predicting the likely downstream hazards associated with remobilised glacial sediment evacuated from headwater cirques.



## 2. Glacier fluctuations since the Little Ice Age maximum in the Western Alps

Climate variation over the last 200 years has caused regionally coherent fluctuations in glacier length in the Western Alps (Figure 3). Two significant 19$^{th}$ Century advances affected most glaciers in the region, peaking at c. 1820 and 1860 (Zumbuhl *et al*. 2008; Deline *et al*., 2012). Some glaciers attained a slightly larger LIA maximum at the earlier time, others later. In the Western Alps, the 1820 maximum was probably most widespread. Subsequent retreat phases were punctuated by minor readvances which affected most, but not all glaciers, and peaked around 1900-1930 and 1985-1990. Post-1990 retreats have been uninterrupted and at many glaciers dramatic. Over the whole period, the most rapid retreat rates were observed in the mid 20$^{th}$ and early 21$^{st}$ centuries (Zemp *et al*. 2015).

Glaciers in the study cirques have largely fluctuated in accord with the regional pattern. All show a major LIA maximum moraine formed around 1860. In the early 20$^{th}$ century, Glacier des Evettes left two moraine ridges at c. 1900 and 1920 (Guisset, 2003; Jobard, 2005). Glacier d'Estelette deposited a small but distinct moraine and till sheet in the 1920s, but no equivalent moraines are preserved at either Grand Méan or Mulinet glaciers. Late 20th Century readvances are similarly well-marked at Evettes and Estelette only. This contrast may reflect the lack of debris in transport at the rock-bedded glaciers rather than any contrast in dynamic response to climatic variation. If paraglaciation is defined as a period of time during and after glacier retreat, the main paraglacial phase of the last two centuries has been post-1920 and continuing to the present.

## 3. Methods

The Evettes and Estelette cirques were mapped in the field at large scale, then neat copies produced for digitising at scales of 1:11,350 and 1:12,050 respectively. Forelands of the Mulinet and Grand Méan glaciers were initially mapped onto aerial photographs then symbols transcribed onto enlarged topographic maps at scales of 1:7,800 and 1:15,050 respectively. Both sites were visited in the field in August 2016, but detailed mapping was carried out remotely. Hand-drawn maps were georeferenced and digitised in a GIS software (QGIS), where detailed geomorphological mapping was carried out using high resolution orthoimages from IGN Geoportail, Google Earth and Bing Maps Aerial through WMS (Web Map Service). The diversity of these images dating from 2010 to 2015 avoided masking by shadow and snow cover. Measurements were made from the digital maps of the physical attributes of each cirque (Table 1) and the areas of cirque floor landforms and sediments (Table 2).

A second level of analysis involved extraction of features of interest from the primary landform inventory. This stage focused on active geomorphological processes in relation to changing ice margin positions, and includes actively eroding moraine slopes, active, transient and relict meltwater routes, and alluvial deposits. Together, these show the locations of paraglacial activity, and dated ice margin positions constrain the timing of activity at each locality. To assess slope-channel connectivity, the lengths of moraine ridges whose base was located within 50 m of a permanently or transiently active river channel were measured, along with both the total length of LIA moraine crests in each cirque, and the length of the main LIA moraine ridges bordering the cirque floor (Table 3). By this method the changing spatial pattern of paraglacial landscape response can be examined in detail.

## 4. Geomorphology of the study cirques

Examination of a large number of cirques using Google Earth Pro™ led to a natural division into two main types: cirques with till floors, and the more numerous cirques with rock floors. Two examples of each were selected for detailed mapping. The till-floored Estelette cirque has been the site of glaciological surveys since 2004 (Kirkbride & Deline, 2013; Deline *et al.*, 2015b; Deline & Kirkbride, 2017). The till-floored Evettes cirque was mapped in the field in July 2016. The neighbouring rock-floored cirques of Mulinet and Grand Méan were observed during this field visit, then mapped in detail from Google orthoimages. Descriptions of the geomorphology of each cirque are given below and summarised in Tables 1 and 2.

***Estelette***

This cirque is incised below the Aiguille des Glaciers (3816 m) in the southwestern Mont Blanc massif (Figure 2). A thick bed of lodgement till extends upslope from the LIA terminal moraine for 0.7 km to the moraine of the early 20th century readvance (Figure 4). The proglacial stream occupies a gully within this till sheet. Upslope from the younger moraine, the cirque floor comprises bouldery supraglacial melt-out till with localised patches of finer-grained alluvium. The stream occupies an armoured channel with boulder berms and step-pool sequences. Above c. 2500 m, a rock step marks the upper margin of the sediment cover, above which the glacier terminus has retreated since 2012.

A 35 m-high gullied right-lateral moraine extends for 1.5 km and marks the outside of a gentle curve in the LIA glacier margin. The left margin has a much smaller grassy moraine. At the LIA maximum, the main glacier axis was towards the right (south) side in the shallow trough occupied by the present proglacial stream. A thin lobe of ice spread over elevated ground to the north, supplying two minor termini. Each supplied a proglacial stream at its maximum position.

The cirque has a 600 m headwall with a mean gradient of 50°, from which radiate very steep sidewalls bounding both sides of the accumulation zone. The 500 m high south-western side wall supplied the debris for the large right-lateral moraine, while the <300 m high northern side wall supplied a less stable ice margin whose marginal deposits are nested minor moraines.

***Evettes***

The Evettes cirque is a large compound cirque in which several small accumulation basins supplied a single glacier lobe at the LIA maximum whose position is marked by well-preserved lateral and terminal moraines, drift limits, and boulder lines (Figure 4). The extensive foreland of the Plan des Evettes is a sediment-filled rock basin (Moreau, 2010) whose lower outlet is pinned by resistant granite-gneiss at the head of the Gorge de Reculaz. Above this, the LIA glacier advanced repeatedly across a low gradient sediment plain which rises southwards by only 70 m in 2 km. The present glacier has retreated rapidly up a 120 m high rock step, and now terminates at the margin of a 1 $km^2$ ice plateau supplied by icefall tributaries and avalanching and enclosed by a crest line at 3300-3600 m elevation.

During 2.5 km retreat from the LIA maximum, several tributaries became detached. First, confluent ice from the south basin of the Grand Méan cirque detached prior to the early 20th Century readvance. Subsequently, three other accumulation basins have separated. Meltwater from a niche glacieret west of Pointe de Séa (Figure 4) percolates through the eastern lateral moraine of the main lobe. High shelf glaciers to the south-west supply meltwater and avalanches to a zone of detached debris-covered ice below the present terminal rock step. Two shallow west-facing basins to the south-east are now deglaciated. Thus, paraglacial landscape response in this cirque is potentially complex because of the large retreat distance and complex glacial and proglacial morphology.

The northern parts of the Plan des Evettes comprise assemblages of bouldery moraine ridges, coalescent and overlapping alluvial fans, and pond fills associated with abandoned meltwater channels traceable to ice front positions dated by historical photography to c. 1900 and c. 1920 (Guisset, 2003; Jobard, 2005). A single proglacial stream occupies a narrow active corridor in a central location. The rest of the foreland is mostly a fluted lodgement till plain laced with abandoned or transient fluvial channels. The plain is bounded by steep lateral moraines with gullied sections on both the west and east sides.

***Grand Méan***

Glacier du Grand Méan occupies a cirque whose crest is in the range 3200-3400 m, and divides into distributary glaciers either side of the small peak of Mont Seti (3153 m). At the LIA maximum, the southern distributary was confluent with the Glacier des Evettes, while the northern outlet (the subject of study) occupied a steep narrow valley leading to an independent terminus at c. 2450 m altitude. Retreat of c. 1.5 km has formed a narrow rock bed incised by two main proglacial streams which join at c. 2625 m altitude (Figure 4). The entire northern margin is bounded by a sharp-crested lateral moraine up to 30 m high. The upper part of the southern margin is formed by the rock slope and talus of Mont Seti, from which a lateral moraine ridge extends WNW for 0.5 km. The rock bed terminates downslope at the head of relict colluvial cones which formed during LIA advances and have subsequently been incised. The focus of fan aggradation has shifted downstream as a result.

***Mulinet***

This shallow west-facing cirque comprises a glacierised upper basin with a gradient of 12-15° above a deglaciated rock bed which extends downslope to the LIA terminus position, steepening to c. 25° in its lower 300 m distance. 40 m-high lateral moraines extend for c. 1km along both margins of the cirque (Figure 4). The headwall culminates at 3200-3400 m but reaches only 100 to 200 m high along its whole length. These characteristics are typical of many rock-floored cirques along the France-Italy frontier in the region.

## 5. Space-time patterns of paraglacial landscape activity

***Sediment beds***

The Estelette foreland shows a clear pattern of development since the LIA glacier maximum (Figure 5A). At this time, the trilobate glacier terminus fed multiple outwash streams, which converged to form four streams entering large gullies at the steepening of the cirque lip. This break-of-slope is thickly mantled with older (Lateglacial?) tills incised by proglacial runoff. The main outwash stream occupies the southern gully and has probably been active throughout the Holocene. During the 600 m retreat from the LIA maximum, fluted lodgement till was exposed and incised by the main stream. Incision into this matrix-rich till was probably rapid but limited by armouring of the channel by exhumed boulders. Between 1860 and 1920, the glacier surface lowered against the tall right-lateral moraine by c. 10 m. The exposed proximal moraine slope would have provided rockfall into lateral supraglacial transport, augmenting the debris from gullies and faces upvalley, and covering the right side of the glacier. This debris cover was later responsible for the formation of a substantial ice-cored moraine below the lateral moraine wall. The 1920 glacier maximum is marked by a small moraine loop and a bouldery supraglacial melt-out till sheet. Meltwater streams occupied three of the pre-existing proglacial gullies, the fourth being abandoned soon after the LIA maximum (Figure 5A). It appears that paraglacial activity in the late 19$^{th}$ and early 20$^{th}$ centuries was not significant when compared to proglacial processes which operated throughout LIA readvance cycles.

At the 1990 readvance maximum, a small marginal moraine loop was deposited across the cirque floor and meltwater flowed around the ice margin to join the main stream channel (Figure 5A). Upstream of the 1920 moraine, the main stream has not incised into the supraglacial melt-out till (Figure 6). Glacial deposits from the late 20$^{th}$Century readvance comprise a fluted lodgement till underlying a veneer of retreat-phase supraglacial melt-out till, retrogressively deposited by the retreating thinly debris-covered ice margin.This coarse till armours the main outwash stream to impede incision. Furthermore, the diminishing glacier ablation zone has probably reduced peak melt discharges and competence to entrain coarse bedload.

The pattern of proglacial and paraglacial activity at Glacier des Evettes is complex. At the LIA maximum extent, multiple outwash springs from the 0.6 km-long glacier front aggraded the plain between the terminus and the opposing rock slope (Figure 5B). All meltwater was forced eastwards to the Reculaz gorge. Post-1860 retreat of c. 0.6 km was followed by two small readvances around 1900 and 1920 (Guisset, 2003), each leaving a moraine arc and supplying proglacial streams via 4 to 5 ice-front tunnels. These streams have left a series of small incised channels and overlapping alluvial spreads and fans. Their paraglacial activity was limited to reworking the late 19$^{th}$ Century moraine ridges. Overall aggradation of the foreland indicates high debris discharge from the glacier rather than paraglacial removal of foreland sediments. Glacier retreat from the 1860 maximum separated the Glacier des Evettes from the southern branch of the Glacier de Grand Méan. Meltwater followed the eastern margin of the Evettes glacier, a position occupied by a tributary stream ever since. This stream has not incised, but follows a narrowly anastamosing course through coarse tills.

The dynamic character of the foreland changed during 20$^{th}$ Century retreat of c.1.5 km (Figure 5B). Outwash routes through older terminal moraines were deactivated, and a single outwash stream has since dominated the sediment cascade of the cirque but without much paraglacial reworking of the fluted till plain. Greater integration of the proglacial drainage is shown by Strahler bifurcation ratios of first to second- order till-bed streams, which declined from 6 - 7 before post-1920 glacier retreat to 2 in the early 21$^{st}$ Century. Transient proglacial streams from the retreating ice margin do not show evidence of significant sediment remobilisation, probably due to their short life-time during rapid ice retreat. Each of the glacial readvance maxima is associated with a set of meltwater routes in the foreland, creating four cross-cutting generations of meltwater landforms (Figure 5B) together with a central river channel that has existed throughout. This drainage line probably operated as the central subglacial conduit prior to glacier retreat. The four generations of meltwater streams show that at each advance position, meltwater would take new routes through the foreland, and thereby be able to rework pre-existing glacial deposits. With the exception of the large 1860 moraine, preservation of each older terminal moraine ridge is less complete than that of succeeding moraines. The dominance of aggradational features suggests that much of the remobilised material was redeposited within the foreland. Proximal outwash of the Evettes stream is of finer calibre than that at the other study sites, suggesting less competent peak flows from the catchment.

Eroding lateral moraines have the potential to produce large paraglacial sediment yields. Moraines abandoned following the early 20$^{th}$ Century advances have gullied proximal slopes up to 40 m high along distances of c. 1 km on both valley sides (Figure 4). It is notable that the LIA maximum extent is not associated with steep moraine walls. Lateral glacier margins from 1860 are marked by small moraines and a distinct drift limit (especially on the western margin), which lie outside the steep eroding moraine faces.The glacier does not appear to have remained at the maximum LIA extent for long enough to construct larger moraines. Gullied moraine faces developed following the 1920 readvance, releasing debris into colluvial and talus aprons which lack connection to the fluvial network. Active gullied moraine slopes on both valley sides are separated from the main river by >250 m of till plain (Figure 4).

The only moraine source which has connected to the main channel is a failed segment of the eastern moraine located below the front of the hanging niche glacier. Here, moraine collapse along 400 m of its crest has generated large debris flows which extend 300 m across the cirque floor to the river (Figure 4). There is nothing to distinguish the lateral moraine at this location from other parts, and the cause appears to be elevated pore water pressure in the moraine generated by percolation of runoff from the hanging glacier and rock slabs immediately upslope. Thus, the paraglacial response (the moraine failure) is an indirect result of a singular topographic condition at this locality.

***Rock beds***

At the LIA maximum, Mulinet glacier terminated at the base of a steep rock slope and outwash was focused into a narrow valley. Subsequent retreat has revealed a wholly rock bed bordered by large lateral moraines. The glacier front has widened to release meltwater from several outlet points, and the number of proglacial streams crossing the bedrock foreland varies according to glacier melt rate and rainfall (Figure 7). The potential for paraglacial reworking of the moraines depends on whether proglacial streams are able to access the lateral moraine sediments to entrain them. The northernmost stream runs along the foot of the right lateral moraine, but is only in contact with the boulder apron below the moraine over a few short distances, and unable to migrate laterally due its bedrock constraint. Only at these juxtapositions does the proximal moraine slope show evidence of recent wash and minor gullying. The distal moraine slopes are unmodified. Extra-glacial hillslope drainage is by percolation through openwork debris, and the lateral moraines are not being significantly removed by runoff from upslope. The drainage configuration established early in retreat has probably been maintained throughout the 20$^{th}$ century, extending upslope as the glacier front has receded. The Mulinet stream network has maintained a Strahler bifurcation ratio > 4 throughout glacier retreat, with as many as 20 first-order streams draining the modern ice front. Streams are locked into rock beds and appear not to have enlarged their channels. Dispersal of proglacial drainage across a 1.5 km wide ice front, combined with low sediment delivery from the glacier, reduces the erosive power of any single channel.

Glacier de Grand Méan has a similar proglacial configuration but in a narrower valley with only two proglacial streams. These have been locked into bedrock channels during post-LIA maximum glacier retreat. Both channels have the form of former subglacial meltwater routes with sinuous courses between ice-moulded rock whalebacks, and neither appears to have been enlarged subsequently. The right-lateral moraine has been undercut by one stream since glacier retreat at this location, and supplies debris directly into the channel. The opposing valley side receives rockfall debris from the gullied mountain face above. Paraglacial debris sources at this site are localised and due to singular configurations of valley side and stream location, and are unable to develop more widely along the former glacier margins.

At both glaciers, meltwater is concentrated by stream convergence in the zone of the former glacier terminus. At the LIA glacier maximum, the glaciers were strongly coupled to proximal proglacial fans, and it is unlikely that complete terminal moraine loops ever formed. Where sizeable terminal moraines may have existed, fluvial erosion during glacier retreat has already censored these from the landscape. Post-LIA fan-head trenching has occurred below the Grand Méan glacier.

***Summary***

A contrast is apparent between till-floored and rock-floored forelands. The mobile beds of the former allow proglacial drainage networks to reorganise from an inefficient "glacial" mode with high bifurcation ratios into a more integrated "postglacial" mode. The glacial network is determined by the locations of meltwater outlets from glacier margins and by the obstructing effects of older moraines, and comprises multiple small and transient meltwater routes whose period of activity is inversely proportional to the rate of glacier retreat. The postglacial network is more established, and based around a single major stream with few tributaries. In the Evettes and Estelette cirques, c. 90% of preserved LIA moraine ridges lie >50 m from modern active and ephemeral river channels (Table 3), indicating a disconnected paraglacial sediment cascade.

Rock-floored cirques have little or no stream channel mobility, and postglacial stream networks are probably inherited from antecedent subglacial networks, especially in cases such as Mulinet cirque where the bedrock strike parallels the drainage lines. Glacier retreat here has simply revealed a pre-existing distributed network which is unable to adjust to becoming sub-aerial, except where glacier retreat cuts off water sources leading to stream abandonment.

Paraglacial sediment release from valley-side slopes is mainly from proximal moraine faces dating from the 1860 and 1920 moraines. Although quite large eroding faces are present in some places, these are mostly unconnected to the fluvial network (Table 3) because most cirques are wide and their floors have low lateral gradients towards a central proglacial stream. Till-floored cirques potentially allow greatest coupling because streams can migrate laterally, but observations show that channels migrate within narrow corridors which rarely access valley-side moraines, reflected in the small areas of fluvially-reworked till on the cirque floors (Table 2). The greatest paraglacial sediment release appears to have been from terminal moraines obstructing concentrated proglacial runoff, with the magnitude of the paraglacial response possibly reflecting the size of the moraines.

## 6. Discussion

### *Within-cirque connectivity*

Overall, mapping of the four cirques reveals that (1) most moraine sources have been poorly coupled to proglacial stream networks since glacier retreat, and (2) paraglacial response is conditioned mainly by fluvial rather than slope processes.

In till-floored cirques, the pattern of connectivity shown by reducing bifurcation ratios has been one of progressive integration of the stream network, as ephemeral meltwater streams specific to ice margin positions become abandoned as their glacier source is removed, and a single dominant central stream is established. This pattern is comparable to recent proglacial drainage evolution on Spitsbergen forelands (Roussel, 2005). In both Evettes and Estelette cirques, the main stream is decoupled from eroding moraine slopes by a till plain. Sediment sources for the proglacial stream are the glacier itself and localised bank erosion only: thus, the downstream impact will be modulated by the competence and capacity of the stream rather than by the rate of sediment release.

In rock-floored cirques, lateral moraines form the only significant sediment reservoir. Proglacial stream access to lateral moraines is stochastic, and occurs where rock-controlled channels happen to follow structural grains that lead towards the lateral margins. At intersections of rock-controlled streams and lateral moraines, entrainment may occur but be short-lived due to negative feedback: the rapid retreat of the moraine face soon isolates it from the channel.

In the two rock-floored cirques, LIA maximum terminal moraines were quickly eroded early in the retreat phase, and were an important source of the aggradational fans which have formed in front of these forelands. However, they are finite sediment sources and currently appear to contribute little sediment. The break of slope below the steeper rock beds of these glaciers corresponds to a loss in transport capacity which limits the downstream propagation of coarse sediment from nearby terminal moraine sources.

### *Evidence of alluvial aggradation downstream*

Three of the four study glaciers show evidence of recent alluvial aggradation downstream from their cirques. At Estelette, modest fan aggradation has occurred below the cirque lip at c. 2050 m altitude, and as a confluence fan on the valley floor downstream at c. 1980 m altitude. A lack of significant recent incision at the gullied cirque lip (Figure 5A) indicates that this downstream sedimentation is derived from channel incision into the LIA till bed below the 1920 moraine knickpoint (Figure 6). Most aggradation is associated with the Mulinet and Grand Méan streams, which have resurfaced proglacial fans immediately distal to their LIA termini, and extended a ribbon of alluvium along the course of their combined outwash for 2.75 km downstream until blocked by a small dam. In contrast, no similar aggradation is associated with the Evettes outwash stream, which has finer-grained proximal outwash pinned at the head of the Reculaz gorge.

Several studies show that most sediment is delivered to glacier forelands during periods of glacier advance, and that the response of the foreland during retreat is typically one of reduced sedimentation leading to incision (Maizels, 1983; Roussel *et al*., 2008; Wilkie & Clague, 2009; Owczarek *et al*., 2014), unless steep slopes above narrow valleys allow paraglacial sediment to enter proglacial rivers (Ballantyne & Benn, 1994; Carrivick & Rushmer, 2009). It is most likely that aggradation in the Mulinet and Grand Méan streams has resulted from erosion of the large LIA terminal moraines and fan-head incision at the latter site. Notably, the neighbouring rock-bed Glacier des Sources de l'Arc shows the same pattern of a terminal moraine source and downstream aggradation. In all cases, this remobilisation may have been taking place during glacier advances to the LIA maximum: the terminal moraine sources no longer appear to supply significant paraglacial loads to the rivers.

***The role of thresholds***

Mobilisation of coarse-grained debris within the sediment cascade requires high thresholds to be crossed, so that extreme events may play a significant role (e.g. Zanoner *et al*., 2017). This raises the issue of event magnitude/frequency within c. 150 year timescale of this study, as disturbance by rare events may mask the overall shape of the paraglacial relaxation curve (Figure 1b; Church, 2002; Etienne *et al*., 2008). The largest climatic events to have occurred since the LIA glacier maximum are integrated within our observed patterns of change. Thus, debris-flow generation from the right-lateral moraine at Evettes glacier may represent such a "one-off" event, indicating that a significant part of post-retreat landscape adjustment is associated with rare events. On the other hand, as Smart & Orwin (2004) suggest, progressive eluviation of fine sediment from proglacial surfaces, combined with armouring of active outwash channels and with drainage network changes, will have reduced the sensitivity of the proglacial landscape to weather event triggers. By implication, a decadal-scale decline in paraglacial sediment yield may reflect a more subtle increase in landscape resilience as well as exhaustion of sediment sources.

***Conceptualisation of paraglacial response of headwater cirques***

An appreciation of the complexity of potential trajectories of paraglacial landscape response can be understood with reference to the balance of force and resistance within the landscape. For simplicity, the forces acting on cirque materials are represented by proxy as the topographic gradient (Table 1) which facilitates the translation of potential into kinetic energy subject to the crossing of geomorphological thresholds (Figure 8A). Resistance to sediment remobilisation is represented by proxy as the properties of cirque materials, such as grain size and cohesion (bedrock). Figure 8A shows four extreme cases of combinations of high or low applied force acting on materials of high or low resistance. In classic landscape sensitivity terms (Brunsden & Thornes, 1979), the landscape is fast responding where a HF/LR combination allows frequent threshold crossings and rapid adjustment of slopes and channels. A HF/HR combination results in rare, large geomorphological events over a long-term tempo of adjustment which may create a similar landscape to HF/LR combinations but with a different magnitude/frequency distribution of sediment transport events. LF/HR results in little readjustment and preservation of unmodified glacial landforms and sediment stores, and LF/LR will lead to small-scale and low-frequency events and a slow, spatially limited adjustment to deglaciation.

Applying this reasoning to alpine cirques, the clearest distinction exists between rock-floored and till-floored cirques, especially where the till is fine-grained subglacial till. These represent extremes of the spectrum of landscape resistance. Following glacier retreat, least readjustment is seen in the two rock-floored cirques even though both have pronounced lateral moraines which comprise large sediment stores available for potential remobilisation. The main constraining factor which suppresses paraglacial response is the presence of proglacial streams locked into bedrock channels, or flowing as sheetflow over ice-scoured slabs.

Maps of post-retreat activity in the glacier forelands identify fluvial processes as being the key to understanding paraglacial response, because proglacial streams have the potential to migrate to access sediment stores. In contrast, eroding moraine slopes can supply sediment only to a confined slope-foot zone, and depend on rivers to link the downstream sediment cascade. Therefore an understanding of processes and patterns of river channel change during glacier retreat are important for understanding paraglacial response as a whole (Table 4). The potential for streams to remobilise glacial sediments is often not attained for a variety of reasons (Orwin & Smart, 2004;

Lane *et al.*, 2017). The present study demonstrates that the most effective fluvial reworking occurs during and after ice maxima where streams are able to incise into sediment cover. This appears to occur where such sediment comprises fine-grained lodgement tills (Figure 8B). The duration of incision, and therefore the quantity of remobilised sediment, is limited by the time taken for the stream bed to become armoured by a sufficient accumulation of large boulders from the till (cf. Orwin & Smart, 2004). This introduces a metastable state by raising the threshold for entrainment and thereby increases the magnitude of flood required to entrain bedload (Figure 8B). Such a change to outwash channels reduces landscape sensitivity to paraglacial remobilisation quite quickly following glacier retreat.

If lateral migration of streams is possible (Figure 8B) especially the main proglacial stream in a cirque, access to stored sediment is possible through bank erosion. The Evettes stream has thus been able to rework significant parts of the proglacial area (Figure 8C), but within a narrow corridor. This indicates that most fluvial transport is throughput from the glacier rather than export from the glacier foreland. Otherwise, small discharges render streams passive and unable to entrain significant sediment volumes. Many small inactive meltwater channels at the Evettes and Estelette glaciers are associated with readvance moraines, and with transient ice fronts during retreat. They transported sediment directly from the glacier for short periods (years to decades, based on known glacier retreat history) but performed little or no post-retreat paraglacial function.

In summary, spatial heteorogeneities in paraglacial activity exist within and between cirques which are mainly a result of complex and varied stream behaviours. Paraglacial response seems to be largely modulated by fluvial processes, irrespective of the rate and extent of activity of deglaciated sediment-mantled slopes.



## 7. **Conclusions**

The distribution of geomorphological activity in space and time since the maximum extent of LIA glaciers in four cirques is recorded in preserved landforms. Together with observations of the downstream extent of outwash stream aggradation, several conclusions can be made regarding paraglacial response to post-LIA maximum glacier retreat.

1. Trajectories of change at different cirques are varied, reflecting different patterns of geomorphological activity in space and time. Stores of glacial deposits on slopes are mostly poorly coupled with active streams. This contrasts to a high degree of coupling which was

provided at the LIA glacial maximum by glaciers linking slopes to rivers in the sediment cascade.

2. Localised “hotspots” of current activity occur stochastically within all study cirques, mainly where local topography allows the main outwash stream to come into contact with lateral moraines, or where exceptional lateral moraine failure has occurred.
3. Glacier forelands comprising glacial tills are associated with more dynamic lateral changes in stream courses especially shortly after readvance maxima, but in the longer term show a simpler organisation of drainage into a single dominant channel poorly coupled with sediment stores.
4. Proglacial streams crossing bedrock forelands are locked into rock channels and have little or no opportunity to rework glacial moraines and slope deposits. However, these cirques show most evidence of downstream alluvial aggradation, probably caused by erosion of latero-terminal moraines during and shortly after the LIA maximum, and trenching of proglacial fan heads.
5. Spatial contrasts in paraglacial response can be conceptualised as an evolving balance of force and resistance during glacier retreat and proglacial drainage evolution. In most cases, negative feedback militates against a sensitive paraglacial response of headwater cirques. The long-term effect on downstream catchments is likely to be noticeable but small, despite the abundance of such headwater basins in many alpine areas.
6. In keeping with other studies, it is hard to escape the conclusion that catchment connectivity is optimised during glacial maxima, when proglacial aggradation occurs. Since the LIA maximum, cirque slopes and the downstream catchment have become decoupled, and recent glacier retreat is likely to reduce downstream coarse sediment redeposition.

## 8. Acknowledgements

We are grateful to the four reviewers and the editor Sam McColl for the thorough and insightful work they contributed to improving our paper.

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**List of figures**

Figure 1.

A. Paraglaciation conceptualised as a time- and scale- dependent relaxation path (after Ballantyne 2002).
B. Paraglaciation conceptualised as a process- dependent relaxation path (after Ballantyne 2002).

Figure 2.
Location map of the four study cirques in the western European Alps.

Figure 3.
Summary of glacier fluctuations in the Mont Blanc massif since AD 1750 (Deline *et al*. 2012).

Figure 4.
Geomorphological maps of the four study cirques. Glacier d'Estelette (inset) lies 50 km north-west of the Frontier Range group (Fig. 2). Contour lines: 50 m.

Figure 5.
Evolution of proglacial drainage and moraine wall exposure at the two till-bed glacier forelands since the LIA maximum glacier extent, showing glacier readvance limits.

Figure 6.
Long profile of the proglacial stream of Glacier d'Estelette in relation to terminal moraine positions and zone of incision. Inset: long profile of the four study cirques, and that of the till-bedded Glacier des Fours (Vanoise massif).

Figure 7.
Proglacial drainage network at Mulinet Glacier, showing subparallel stream courses (some ephemeral) locked into strike-parallel bedrock grooves and channels. Inset: Google Earth vertical view of the right lateral margin.

Figure 8.
Conceptual model to show how trajectories of paraglacial landscape evolution are determined by combinations of landscape resistance (represented material properties) and applied force (represented by slope).

A. General model domain.
B. Classification of modes of proglacial stream behaviour within the model domain.
C. Examples from the study cirques.

**Tables**

Table 1. Location and morphological characteristics of the study cirques

| | Estelette | Evettes[4] | Mulinet | Grand Méan[5] |
|---|---|---|---|---|
| Area ($km^2$)[1] | 2.33 | 8.02 | 5.80 | 2.23 |
| LIA glacier area ($km^2$) (% of catchment)[2] | 1.03 (44) | 5.94 (74) | 4.39 (76) | 1.75 (78) |
| 2007 glacier area ($km^2$) (% of catchment)[3] | 0.45 (19) | 2.59 (32) | 2.17 (37) | 0.81 (36) |
| 2015 or 2016 glacier area ($km^2$) | 0.29 | 2.50 | 1.97 | 0.75 |
| Maximum elevation (m) | 3816 | 3637 | 3442 | 3425 |
| Minimum elevation (m) | 2230 | 2502 | c.2300 | c.2450 |
| Cirque floor gradient | 0.12-0.13 | 0.02-0.05 | 0.39-0.42 | 0.21-0.27 |
| Cirque floor type | till | till | rock | rock |
| Latitude | 45°46'N | 45°20'N | 45°23'N | 45°22'N |
| Longitude | 6°49'E | 7°07'E | 7°09'E | 7°09'E |
| Aspect | SE | N | W | NW |

[1]Calculated as area of entire catchment above the LIA glacier terminus.
[2]Measured from 1:25,000 scale IGN TOP25 series map sheets 3531ET and 3633ET.
[3] Glacier area as represented on the TOP25 series map series.
[4]Main basin only: excludes eastern tributary catchment.
[5]Measurements only of the true right lobe and its source area.

Table 2. Subdivision of the areas of each cirque within the Little Ice Age glacier maximum according to materials forming the cirque floors and margins. The bedrock areas at Evettes and Estelette cirques form steep rock slabs exposed by glacier retreat in the last 10 years; those at Grand Méan and Mulinet comprise most of the cirque floor extending to the LIA maximum moraine.

| Cirque | Bedrock | | Lodgement and fluted till | | Supraglacial melt-out till | | Water-worked till | | Total area (km$^2$) |
|---|---|---|---|---|---|---|---|---|---|
| | Area (km2) | % | Area (km$^2$) | % | Area (km2 | % | Area (km$^2$) | % | |
| Evettes | 0.21 | 14 | 0.34 | 22 | 0.9 | 59 | 0.08 | 5 | 1.53 |
| Estelette | 0.16 | 31 | 0.09 | 17 | 0.28 | 52 | 0.00 | 0 | 0.53 |
| Grand Méan North | 0.37 | 54 | 0.00 | 0 | 0.31 | 46 | 0.00 | 0 | 0.68 |
| Mulinet | 1.31 | 90 | 0.01 | 1 | 0.14 | 9 | 0.00 | 0 | 1.46 |



Table 3. The total lengths of Little Ice Age and post-LIA moraine ridges within each cirque ($\Sigma m_r$) compared to the lengths of moraine within ($m_r$ <50) and beyond ($m_r$ >50) 50 m of active river channels. These are indicators of the connectivity (or otherwise) of the erodible LIA morainic sediment store with the fluvial system. The right-hand columns (headed 'LIA') refer only to the lengths of the main LIA lateral moraines. See text for interpretation.

| Cirque | $\Sigma m_r$ (m) | % | $m_r$ <50 | % | $m_r$ >50 | % | LIA $\Sigma m_r$ (m) | % | LIA $\Sigma m_r$ <50 (m) | % |
|---|---|---|---|---|---|---|---|---|---|---|
| Evettes (till) | 13100 | 100 | 1450 | 11 | 11650 | 89 | 2450 | 100 | 310 | 13 |
| Grand Méan North (rock) | 4400 | 100 | 1050 | 24 | 3350 | 76 | 2075 | 100 | 1050 | 51 |
| Mulinet (rock) | 6700 | 100 | 2500 | 37 | 4200 | 63 | 3600 | 100 | 2500 | 69 |
| Estelette (till) | 8250 | 100 | 900 | 11 | 7350 | 89 | 2300 | 100 | 490 | 21 |

Table 4. Modes of proglacial stream behaviour in alpine cirques during glacier retreat.

| Stream type | Characteristic behaviour | Sensitivity to change | Paraglacial function | Examples from this study |
|---|---|---|---|---|
| Bedrock channel | Fixed position exploiting weak strata, joints or faults, usually removed from sediment reservoirs | Very low | Limited | Grand Méan, Mulinet |
| Bedrock sheetflow | Stream unable to form channel due to resistance of bedrock | Very low | Very limited | Mulinet |
| Passive | Small ephemeral meltwater streams associated with transient ice margin locations. | Low | Limited: short life expectancy during glacier retreat | Evettes: minor ephermeral meltwater streams |
| Metastable | Rapid armouring of channel during glacier retreat prevents entrainment of available sediment | Moderate to low | Declining activity over time as bed resistance increases | Estelette (between 1920 and 1860 moraines) |
| Wandering/braided | Lateral migration facilitated by low thresholds facilitates bank erosion | High | Ongoing and active sourcing of available sediment reservoirs by bank erosion | Evettes |
| Incised | Inset in deep gully prevents lateral migration but local slopes may provide sediment. | Low | Depends on sediment inputs by local slope processes on gully walls. | Estelette (below 1860 moraine) |

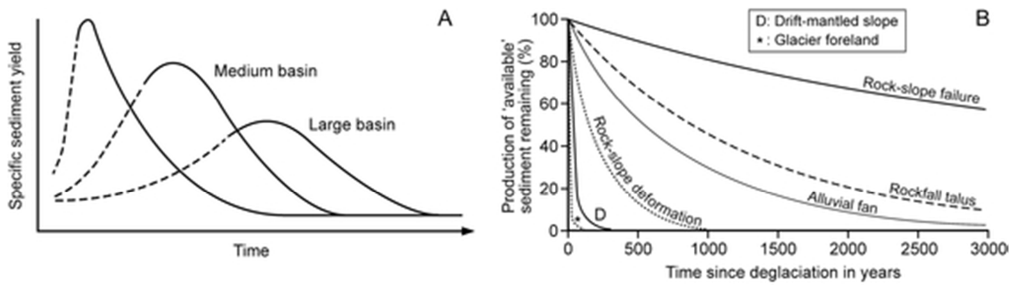


Figure 1.
A. Paraglaciation conceptualised as a time- and scale- dependent relaxation path (after Ballantyne 2002).
B. Paraglaciation conceptualised as a process- dependent relaxation path (after Ballantyne 2002).

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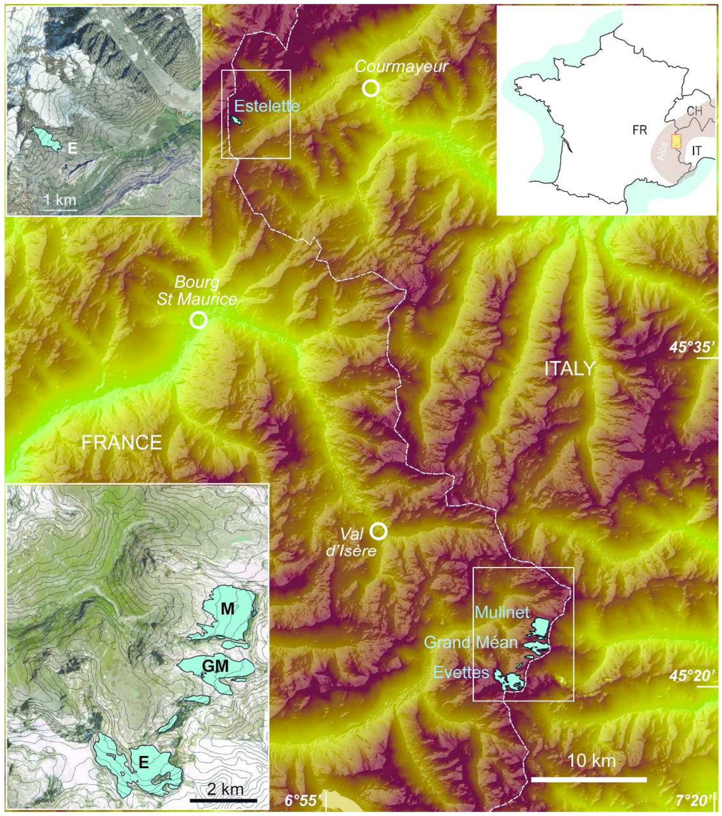


Figure 2.
Location map of the four study cirques in the western European Alps.

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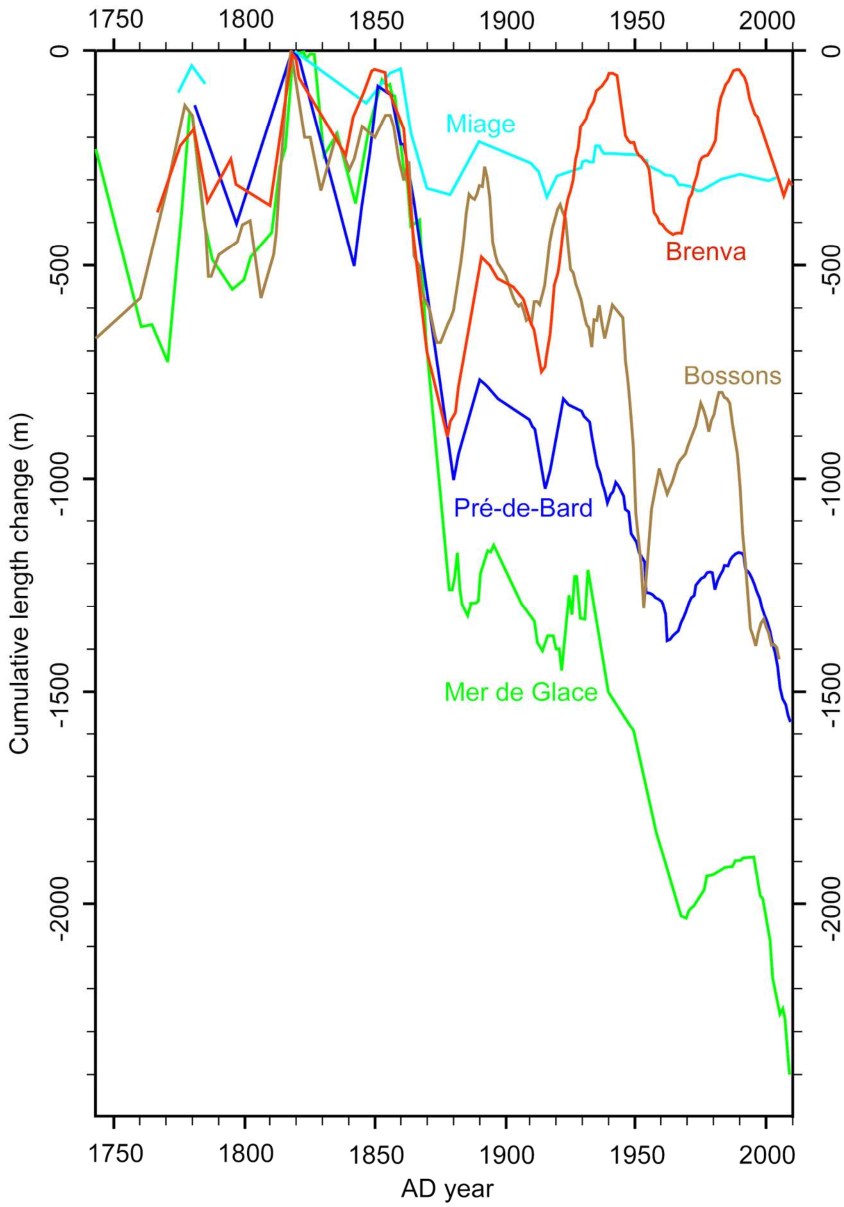


Figure 3.
Summary of glacier fluctuations in the Mont Blanc massif since AD 1750 (Deline et al. 2012).

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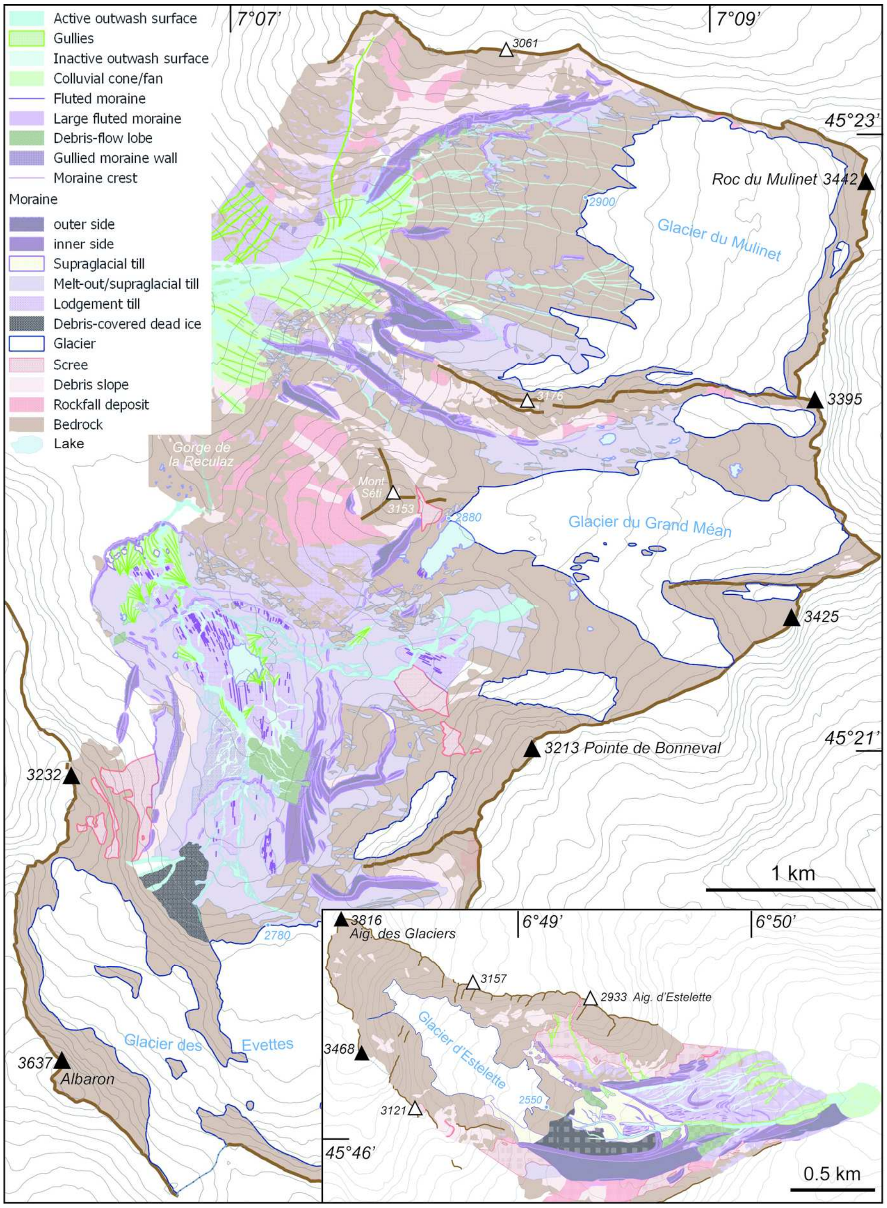


Figure 4.
Geomorphological maps of the four study cirques. Glacier d'Estelette (inset) lies 50 km north-west of the Frontier Range group (Fig. 2). Contour lines: 50 m.

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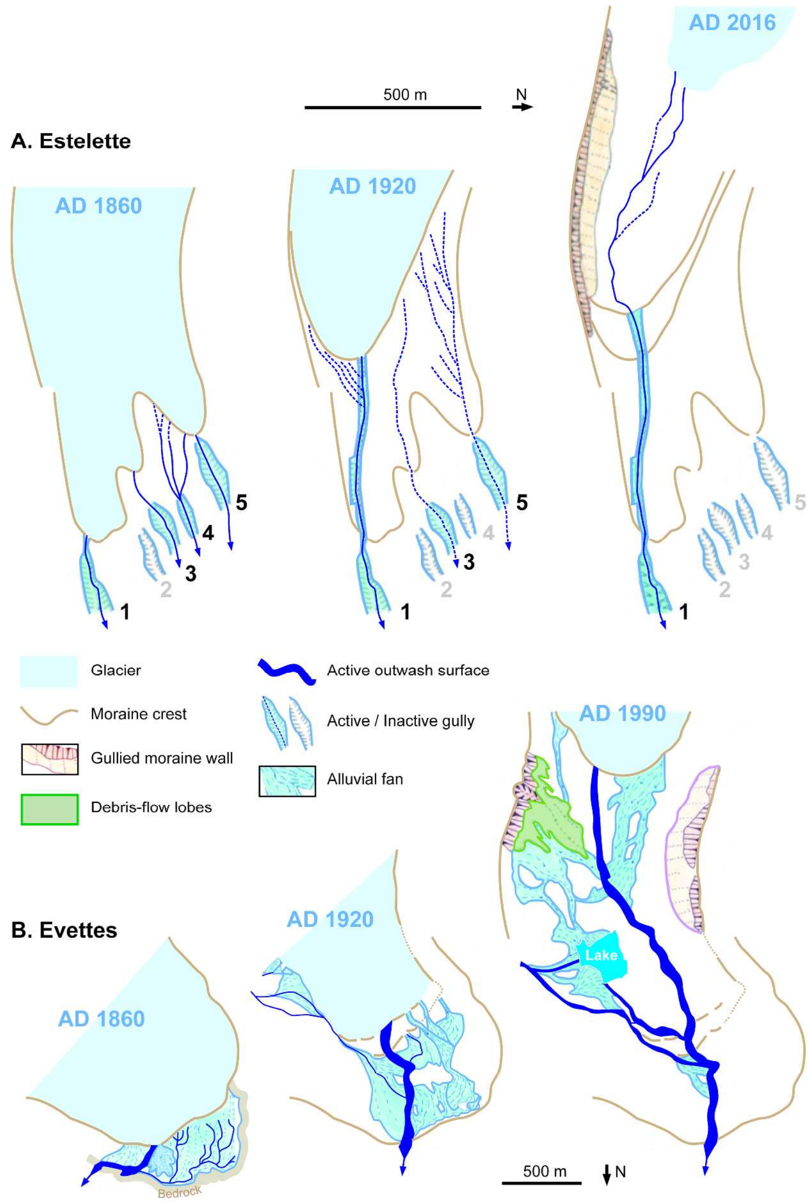


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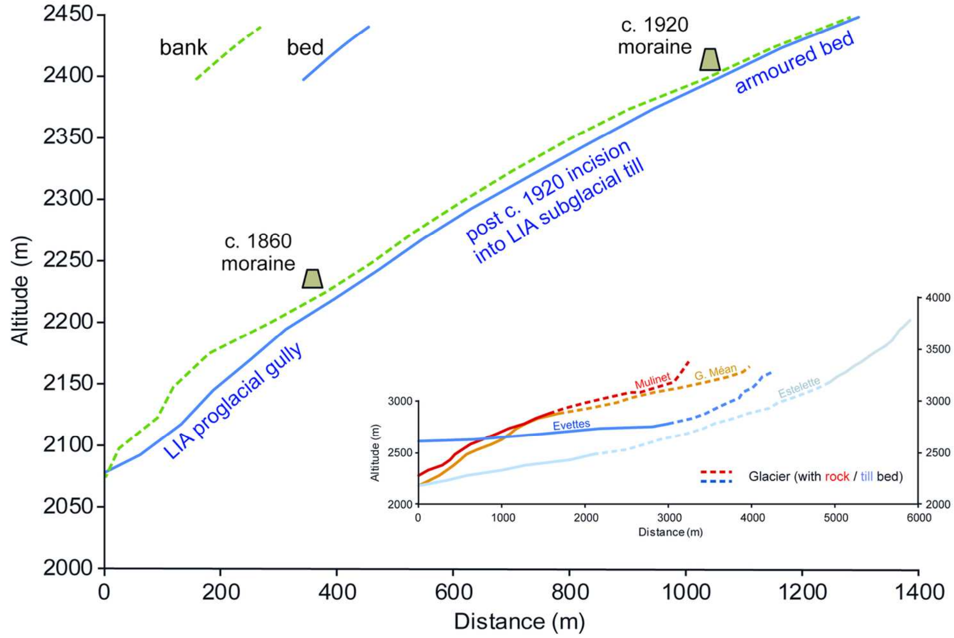


Figure 6

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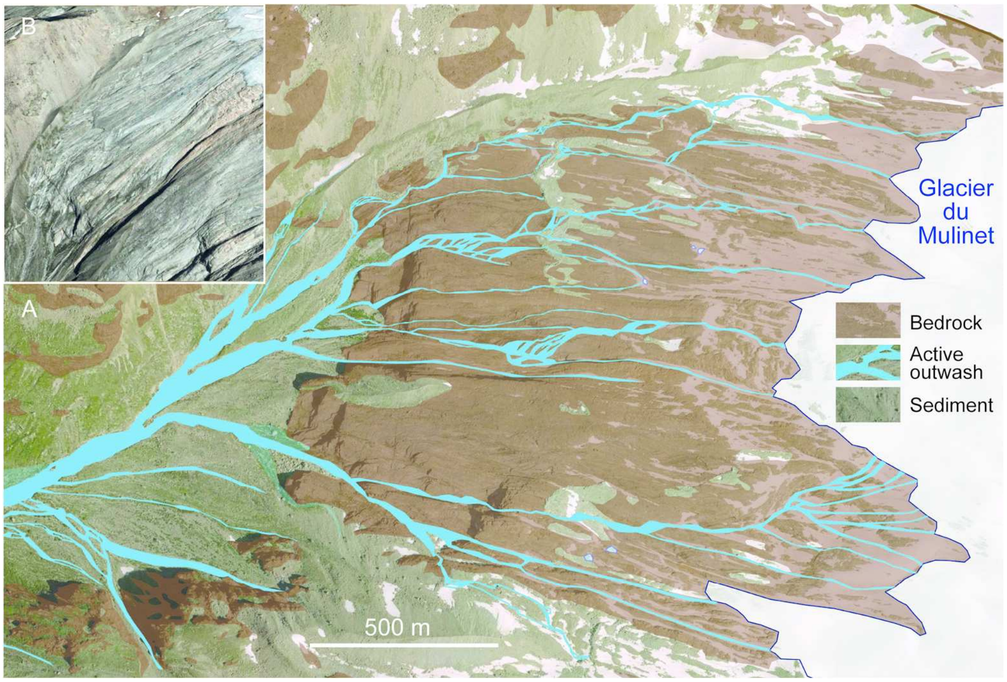


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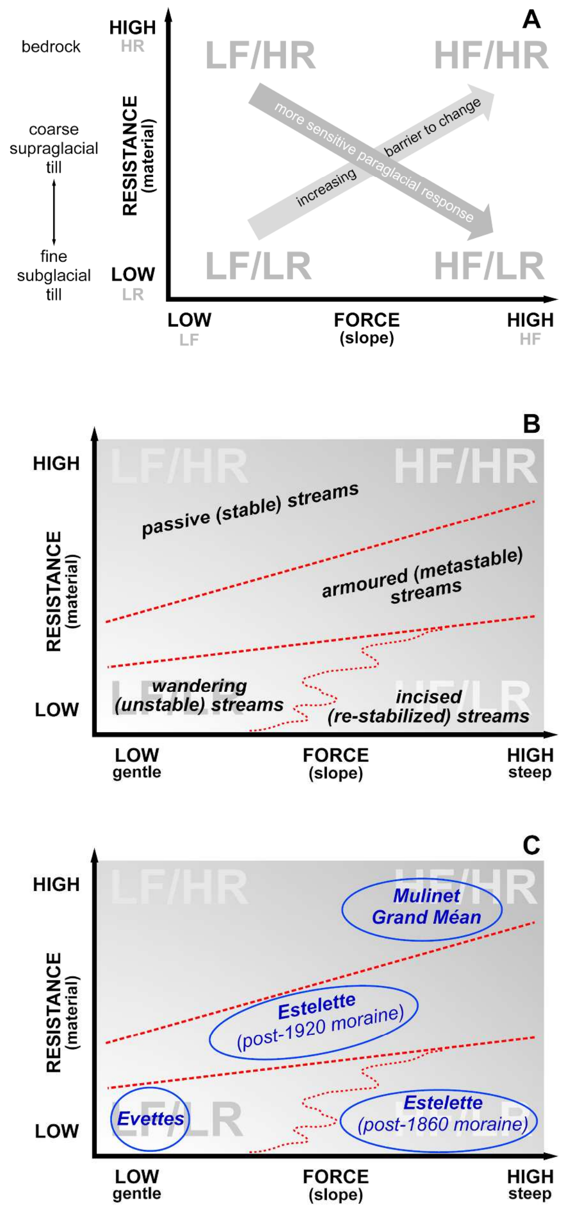


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B. Classification of modes of proglacial stream behaviour within the model domain.
C. Examples from the study cirques.

177x387mm (300 x 300 DPI)