

SURGE GLACIERS DURING THE LITTLE ICE AGE IN THE PYRENEES

E. SERRANO¹, R. MARTÍN-MORENO²

¹Dpto. Geografía. Universidad de Valladolid, Spain.

²Dpto. Didácticas Específicas, Universidad Autónoma de Madrid, Spain.

ABSTRACT. *Historical moraine complexes and erosional features are interesting elements to discern the historical climate changes and evolution, with a complex chronologies that help us to understand the dynamics and glacier evolution during the Little Ice Age (LIA). The existence of landforms as crevasses-squeeze ridges, hummocky moraines and flutes, related to different glacier advances and retreats, allows understanding in a better way the LIA glacier evolution in the Pyrenees. The aim of this work is to show how many LIA moraine complexes have traces of fast flow ice; when the surge dynamic happened; his extent and the environmental meaning. Based on glacier landsystem analysis we have established a work hypothesis on the fast flow or surge dynamic glaciers during the LIA, with geomorphological features, as flutes and push and hummocky moraines, at least in 17 LIA glacier complexes. The analysis of morphosquences by fieldwork, photo interpretation and historical sources in 8 selected LIA moraine complexes have been compared with previous climatic reconstructions creating a hypothesis about the response of the LIA glaciers to the short time changes in temperature and moisture.*

The glacier cirques with fast flow features are found in the highest mountains with summits above 3000 m., mainly northern oriented (88%) and without a significant lithology. The studied complexes (Central Infierno, Eastern Infierno, Oulettes de Gaube, Monte Perdido, Marboré, La Paúl, Literola and Tempestades) show 4 morphological units: a frontal moraine system (U1); a more voluminous moraine (U2); a little push and hummocky moraines complex linking with flutes (U3); and minor arcs up valley (U4). The U3 belongs to a fast flow stage or surging and by morphostratigraphy we can point out that the surge processes were produced between 1820 and 1840, at the end of the LIA. We related it with a possible climatic response to sudden cooling and the increase of winter precipitation with melt-water availability and quick ice melting during the summer, generating hydrodynamic changes in the small glaciers and quick dynamic response.

Glaciares de oleada durante la Pequeña Edad del Hielo en los Pirineos

RESUMEN. *Los complejos morrénicos históricos de los Pirineos contienen elementos de interés para conocer los cambios climáticos históricos y su evolu-*

ción. La complejidad temporal que muestran permiten aproximarnos a la evolución y la dinámica de los glaciares durante la Pequeña Edad de Hielo (PEH). Además, la presencia de formas de modelado glaciar como crestas de compresión, morrenas hummocky y flutes señalan una dinámica glaciar definida por la presencia de flujos rápidos. La idea de este trabajo es mostrar la existencia de formas de modelado asociadas a flujos de hielo rápido o glaciares de oleada, así como su extensión, temporalidad y significado ambiental. Basados en el análisis de sistemas de formas glaciares (glacier landsystem), a partir de las huellas geomorfológicas como flutes, morrenas de empuje y morrenas hummocky en 17 complejos glaciares, se establece la existencia de flujos de hielo rápidos o glaciares de oleada durante la PEH. El análisis de morfosecuencias mediante trabajo de campo, fotointerpretación y fuentes históricas en 8 complejos morrénicos de la PEH y su comparación con reconstrucciones previas del clima en la Península Ibérica y Europa han permitido establecer como hipótesis una rápida respuesta de los glaciares a los breves cambios temporales de temperatura y humedad.

Los circos glaciares con huellas de flujos rápidos se sitúan en los macizos más altos, siempre con las cumbres por encima de 3000 m, y están orientados prioritariamente al norte (88%). Los complejos morrénicos estudiados (Infierno Central, Infierno Oriental, Oulettes de Gaube, Monte Perdido, Marboré, La Paül, Literola y Tempestades) están formados por cuatro unidades morfológicas principales: un sistema de morrenas frontales (U1); morrenas laterales o frontales más voluminosas (U2); complejos morrénicos menores con morrenas de empuje y hummocky que enlazan con flutes (U3); y arcos menores situados valle arriba (U4), no existentes en todos los casos. La Unidad 3 pertenece a una etapa con flujos rápidos del hielo o glaciares de oleada y a partir de la morfoestratigrafía se puede establecer que estos procesos se produjeron en torno a 1820-1840, en un lapso temporal de 20-35 años, ya al final de la PEH. Esta unidad la relacionamos con una posible respuesta climática a un enfriamiento repentino y al aumento de las precipitaciones invernales que incrementa la disponibilidad de agua de fusión nival y la rápida fusión del hielo durante el verano, generando rápidos cambios hidrodinámicos en los pequeños glaciares.

Key words: Glacial Landsystems, surge glaciers, Little Ice Age, flutes, Pyrenees.

Palabras clave: Sistemas de formas glaciares, oleadas glaciares, Pequeña Edad del Hielo, flutes, Pirineos.

Received: 11 August 2017

Accepted: 15 October 2017

*Corresponding author: Enrique Serrano, Departamento de Geografía, Universidad de Valladolid, España. E-mail address: serrano@fyl.uva.es

1. Introduction

Pyrenean glaciers developed around of the highest summits during the Little Ice Age (LIA), growing during near five centuries. Glaciers advanced forming cirque and tongue glaciers and modifying the present day high mountain by mean of new moraine complexes, over deepened basin or erosion on cirque walls. The LIA was the last glacier advance known, global and historical, that in the Iberian Peninsula only affected the highest mountains: Pyrenees, Cantabrian Mountains and Sierra Nevada (González Trueba *et al.*, 2008; Hughes, 2014; Oliva *et al.*, 2018). The proximity in time, the good conservation of landforms and the connection with the current glaciers and icepatches, make its study a field of growing interest. The LIA features and the moraine complexes are interesting elements to know the historical climate changes and evolution, the most used since Le Roy Ladurie looked for the LIA consequences in the historical sources and Alpine glaciers evolution. In the Iberian Peninsula until the 90s, the main information sources on LIA were the Pyrenean glaciers. The study of the LIA glaciers has been mainly focused on the glaciers existence, chronology and glacial retreat, related with the current glacier investigations (Nicolás, 1981; Martínez de Pisón and Arenillas, 1988; Serrano, 1988, 1991, 1996, 1998; Copons and Bordonau, 1994; Lampre, 1994, 1998; Grove and Gellaly, 1995; Chueca *et al.*, 1998; López Moreno, 2000; Serrano *et al.*, 2002; Grove, 2004; Martín-Moreno, 2006; González-Trueba *et al.*, 2008; René, 2011; García-Ruiz *et al.*, 2015; Martí *et al.*, 2015). The LIA glacial evolution helps us to understand the dynamic and glacier evolution, in a period when both climate change responses and internal rheological variations of the ice masses were present. The existence of several morphologies associated with the different glacier advances and retreats –confirmed by fieldwork, aerial photography and historical references– help us to understand in a better way the LIA glacier evolution in the Pyrenees. The presence of different types of deposits and moraines, glaciectonic ridges, crevasses-squeeze ridges, hummocky moraines and flutes, show the behavior of the glaciers during the LIA within the glacier landsystem, as it has been defined in Evans (2003), context and morphosequence analysis.

Based on morphogenetic and morphoclimatic environments, several types of glacier landsystems in the Pyrenees could exist: “Active Temperate Glacial Landsystem” (ATGL), “Glaciated Valley Landsystem” (GVL) and “Surging Glacier Landsystem” (SGL), all of them characteristics of the temperate mountain environments (Evans *et al.*, 2003; Benn and Evans, 2010).

The “Glaciated Valley Landsystem” (GVL, Table 1) is a compendium of common typologies of mountains such as the Pyrenees. In the external zone only in some cases are found eroded moraines with superimposed flutes and small hummocks (Benn *et al.*, 2003). According to the same authors, the moraines show imbricate thrust, with thicker sediment layers (reaching dozens of meters) and flutes, usually associated with polythermal and surges glaciers, and in the margin of temperate glaciers (Benn and Evans, 2010). The GVL are characterized by the importance of the topography and landforms in the sediment transport, and also by the predominance of the supraglacial debris sources in the glacial sedimentary load, involving a great variety of associated landsystems (Benn *et al.*, 2003).

Table 1. Glaciated landsystem organization.

Glacial Landsystem	Glacial Environments		
	Zone	Processes and deposits	
Glaciated Valley ⁽¹⁾ GVL	Erosive	Abrasion features on rocky outcrops	
	Intermediate	Erosion and deposition, thin and disperse tills among the rocky outcrops	
	External	Continuous till coverage and subglacial traction till.	
		Three sequential environments	Marginal moraines
Subglacial			
Glaciofluvial/glaciolacustrine			
Surge Glacial ⁽²⁾ SGL	Proximal	Subglacial till, low amplitude flutes (crevasse-squeeze ridges) and concertina eskers	
	Intermediate	Gradual transition to patchy hummocky moraine, push moraines and thrust blocks	
	External	Formed by riding tills and push moraines (with deformed pre-surge sediments)	

(1) Boulton and Eyles, 1979; Benn et al., 2003. (2) Evans et al., 1999, 2007, 2009; Evans and Rea, 1999, 2003.

Surge glacial Landsystems (SGL, Table 1) are characterized by fast flows of ice, in very variable cyclical periods. Surging glaciers are defined as glaciers that accelerate suddenly (Benn and Evans, 2010), when their fronts advance annually or seasonally. This rapid advance produces high subglacial erosion over the soft bedded sediments, generating thrusts, folding, supraglacial debris, ice fractures due to the high water pressures and large areas of ice cored and hummocky moraines (Evans and Rea, 1999; 2003; Evans *et al.*, 2007, 2009). In the SGL the three environment zones (Table 1) can be located contiguous or superimposed, and the most common features are concertina eskers, crevasses-squeeze ridges, flutes and hummocky moraines, blow out structures and ice-cored sandur. Some sources indicate that the combination of landforms and sediments, and their organization, is what define the terrestrial SGL thus enabling us to identify them (Evans *et al.*, 1999; Evans and Rea, 2003; Benn and Evans, 2010; Brynjólfsson *et al.*, 2014; Farnsworth *et al.*, 2016).

Surges may be due to two mechanisms: hydrological switch model and thermal switch model (that one only for polythermal glaciers). The rapid advance of the temperate glaciers is linked to changes in the basal hydrology. Surges in temperate glaciers happen quickly and with a short duration (when compared with the polythermal ones), which means the presence of an important amount of meltwater responsible of the surge trigger (Benn and Evans, 2010). Besides, the lubrication of the bed, the deformation of the subglacial sediments (Björnson, 1998), are linked to the subglacial cavity network (Benn and Evans, 2010).

The analyzed features and landform systems associated have allowed us to establish a working hypothesis on the fast flow or surge dynamic glaciers during the LIA. Fast flow processes affected at least 17 LIA glacier complexes, which could be either synchronous or in different stages. These surges modified the preexisting moraines, which means a maximum advances but not necessarily more volume of ice. The main aims of this work are (1) to show how many moraine complexes have landforms related to fast flow glaciers; (2) to understand

what happened in the LIA morainic complexes during the surges and when did it happen; (3) to characterize the extent that LIA recorded in relation to previous and current ice extents; and finally (4) to interpret the meaning (hydrological, climatic, morphologic...) of this behavior, which has been scarcely studied in small mountain glaciers of temperate regions.

2. The LIA in the Pyrenees: a review of glacier stages

During the LIA glaciers were developed in the Pyrenees in more than 19 different massifs (Table 2) and at least 111 cirques have been featured by LIA glaciers, with moraine complexes related to cirque glaciers and very reduced or absent tongues (González-Trueba *et al.*, 2008). The temperature decrease affected mainly the highest mountains, and largely to the Northern faces, showing the relative marginality of the glacial processes during the LIA. The largest cold areas in the Iberian Peninsula are located in the north- and south-face of the high Pyrenees, where temperature went down to create a new landscape and changes in the hydrology, geomorphological processes (periglacial, glacial, torrential) and ecosystems. The maximum reconstructed surface of a single glacier corresponds to the Aneto glacier with 236 ha (González-Trueba *et al.*, 2008), but the Pyrenean glaciers extent reached more than 2700 ha in 1850 (Schrader, 1936). The drop of temperature implied a decline of the Equilibrium Line Altitude (ELA) and the glacial advance. The study of the Pyrenean ELAs, the Medium Equilibrium Line Altitude (MELAS) and temperatures estimations in several massifs (Serrano, 1991, 1998; Lampre, 1994, 1998; Chueca *et al.*, 1998a, 1998b; López Moreno, 2000) have allowed to approach the environmental conditions during the LIA. In the maximum extension of glaciers, MELAs have been estimated between 2620 and 2945 m, depending on the massif and aspect. The range of local ELAs is wide and each massif has notorious asymmetry between northern and southern faces. If in the Western massifs as Balaitous and Infierno the MELAs are located at 2650 m a.s.l., influenced by oceanic climate and higher altitudes, in Maladeta or Posets massifs, where the continental conditions are dominant, the MELA altitude is located around 2900 m a.s.l. The temperature decline have been estimated in several massifs, showing fluctuations and variations between about 0.7-0.75°C in Maladeta and Infierno-Panticosa, or temperatures 0.9°C lower than present day in other massifs coinciding with the 0.92°C temperature decline in all Pyrenees (Serrano, 1996, 1998; Lampre, 1994, 1998; Chueca *et al.*, 1998; López Moreno, 2000; Serrano *et al.*, 2002).

LIA glaciers in the Pyrenees advanced and retreated significantly during several phases and they are witnesses of climate variations during the last 500 years. Different authors -by means of diverse techniques- have estimated the historical maximum in several dates. In the Maladeta massif by lichenometry, 1600-1620 (Julián and Chueca, 1998), René (2011) pointed the age of 1820-1830 to the formation of the big moraines, in contact with glaciers until 1830-1850 and after 1850 a definitive glacier retreat. By dendrochronology and morphostratigraphy the LIA maximum has been established between the 17-18th centuries (Creus, 1991; Copons and Bordonau, 1994, 1997; Saz and Creus, 2001). The last one is accepted as the maximum extension in the Alpine glaciers (Le Roy Ladurie, 2004, 2006), during the Maunder Minimum (1645-1700 AD), and we consider that the historical maximum extent of glaciers in the Pyrenees could have occurred between 1680 and 1750 AD, period characterised by cold and wet conditions (Oliva *et al.*, 2018).

Table 2. Synthesis on LIA features in the Pyrenees (modified from González-Trueba et al., 2008).

Massif	Altitude Summits m	Cirques with LIA glaciers features	Or.	LIA Glaciers	Present day Glacier ¹
Balaitous	3144	12	N	Las Néous, Pabat, Arraille, Batcrabère, Frondellas.	Las Néous
Panticosa	3082	> 14	N	Infierno W, Infierno E, Punta Zarra.	Infierno
Tendeñera	2853	3	N	Sabocos, Tendeñera,	
Vignemale	3298	6	N, S	Gaube, Petit Vignemale, Oulettes Gaube Montferrat, Clot de la Hount, Tapou-Montferrat, Cervillona.	Ossoue Oulettes de Gaube Petit Vignemale
Mt. Perdido-Marboré	3355	15	N, S	Epaule, Cascade, Marboré	Monte Perdido Gabietous Taillón
La Munia	3133	7	N	Munia, Barroude.	Munia
Neouvielle	3192	2	N	Maniportet, Tourrat, Pays Baché	
Posets	3375	5	N,NE NW	La Paul, Bardamina, Posets, Llardaneta.	Llardana La Paül
Gourg Blancs-Perdiguero	3222	16	N, S	Perdiguero, Literola, Spijeoles, Belloc, Poucherges, Cabrioules, Maupás, Graoués.	Seil de la Baque Boum Portillon d'Oo
Maladeta	3404	25	N, S	Aneto, Maladeta, Coronas, Alba, Barrancs, Tempestades.	Aneto Maladeta Barrancs Tempestades
Others massifs	--	< 13	N	Castillo de Acher, Cambalés, Ardiden, Culfreda-Batua, Bachimala, Besiberri, Cotiella, Mont Vallier.	Mont Vallier

1. From Rico et al., 2017

The historical sources, lichenometry, dendrochronology and morphostratigraphy techniques have permitted to establish different glacier LIA stages related to glacial dynamics as a response to climate fluctuations (Nicolás, 1981; Martínez de Pisón and Arenillas, 1988; Serrano and Martínez de Pisón, 1994; Copons and Bordonau, 1994; Lampre, 1998; Creus 1991; Serrano, 1988; 1991, 1996; Chueca and Julián, 1998; Chueca *et al.*, 1998, 2003; Mateo and Gómez Ortiz, 1998, 2000, 2004; Saz and Creus, 2001; Serrano *et al.*, 2002; Grove, 2004; Martín, 2004, 2006; López-Moreno, 2000; González-Trueba *et al.*, 2008; García-Ruiz *et al.*, 2015; Marti *et al.*, 2015). A sequence of 7 morphogenetical stages for the Pyrenees was established (González-Trueba *et al.*, 2008). The LIA glacier maximum (1) is represented by the external frontal and lateral moraines that permit to rebuilt glaciers shorter than 2 km, mainly shorter than 1 km and without tongues. A retreat and small readvances (2) occurred between

1750 and 1800, building numerous but small moraines as a response to minor cool phases at the end of 18th century and the beginning of the 19th (Creus, 1991; Saz and Creus, 2001; Mateo and Gómez Ortiz, 2004), but Ramond de Carbonnières in 1797 still describes the Monte Perdido glacier reaching the “edge of the lake” (Ramond, 1802), an extent similar to the LIA maximum. A glacial advance (3) implied a fast but short growth of glacier when most of the glacier fronts were located close to the frontal moraines at the beginning of the XIX century as it is point out by pyreneists that explored and mapped the Pyrenees. F. Schrader, A. Lequeutre, A. de Franqueville, P.L. Michelier, H. Russell or E. Viollet le Duc supported with texts and maps the extent of glaciers with areas similar to the maximum, although glaciers were thinner (Schrader, 1936). This stage is linked to cold period generated by the Dalton Minimum of solar activity and the volcanic eruptions.

LIA glaciers advance have been dated in Maladeta in 1820-1830 (Julián and Chueca, 1998), in Andorra in 1805-1829 (Mateo and Gómez-Ortiz, 2004) and Monte Perdido in 1790-1830 (García-Ruiz *et al.*, 2015). Historical sources permit us to locate the maximum previous to 1830 in the Maladeta Glacier. Finally, the melting of the ice begins during the stage of glacial recession (4), when glaciers are separated from the moraine around the 70s of the 19th century, as was recorded by the contemporary observers (Vallot, Shrader, Trutat). The temperature increased since the middle of the 19th century steered a very strike glacial retreat (Chueca *et al.*, 2008). Minor readvances and glacier equilibrium (5) occur during the last decades of the 19th century, with a common advance around 1890, until the twenties of the 20th century, after the LIA has finished. Later, glaciers retreat accelerated with small and intermittent advances in some glaciers, as Oulettes of Gaube with short progress in 1945 and 1964 (Grove and Gellatly, 1995; René, 2013), until the drastic retreat with sudden lost of mass, as response to strong disequilibrium with current climate conditions (Chueca *et al.*, 2007; López-Moreno *et al.*, 2016), interrupted only by small equilibrium periods at the end of the 70's and 80's (Martínez de Pisón and Arenillas, 1988; Martínez de Pisón *et al.*, 1995; Grove and Gellatly, 1995; René, 2001, 2003, 2013), before the disappearance of the most LIA glaciers and the conservation of only 19 glaciers in 2016 (Rico *et al.*, 2017).

3. Methodology

This work is based on the glacier landsystem analysis and on the study of morphosquences and characteristic landform systems following the methodology described by Boulton and Eyles (1979), Evans *et al.* (1999), Benn *et al.* (2003), Evans and Rea (2003), Benn and Evans (2010). By fieldwork and photo interpretation we have detected flutes and push and hummocky moraines in 17 places with geomorphological traces of fast ice flow. We have selected 8 for being the most representative (Fig. 1). The used database for the geomorphological cartography is coming from fieldworks, aerial photography and digital elevation models (DEM) from the IGN (National Geographical Institute) with 5 m resolution. We have analyzed cirques and moraine complexes where flutes and front moraines have been detected, interpreting and classifying by genesis. The moraines, which point

out the LIA glacier extent and retreat stages, were mapped on the field and by color orthophotos of Spanish and French Geographical National Institutes, and color aerial photos of the ERHIN Programme (1996). From the fieldworks and aerial photos we made the interpretation according to the distribution of landforms and the linkages between the different GVL and SGL sectors to establish differentiated dynamic environments (Sharp, 1985; Evans and Rea, 1999, 2003; Farnworths *et al.*, 2016).

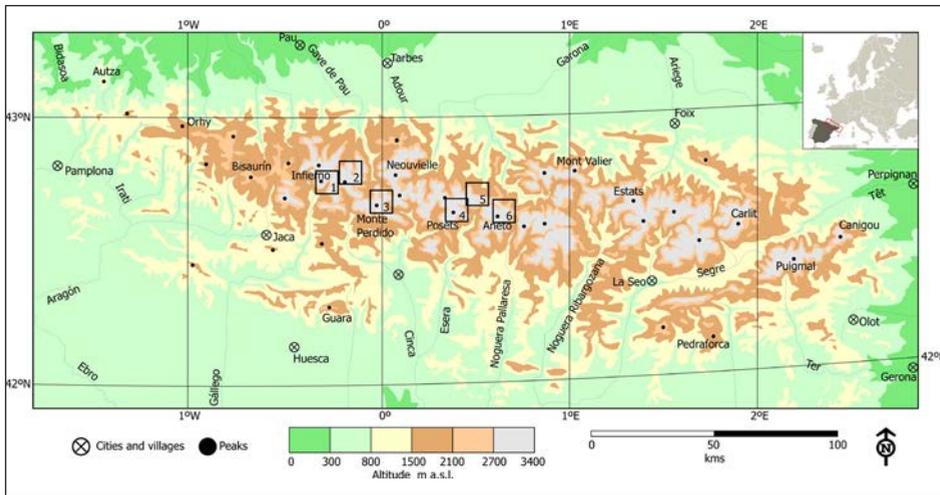


Figure 1. Location in the Pyrenees of massifs where LIA moraine complexes have been studied. 1, Infierno massifs, Eastern and Western Infierno moraine complexes. 2, Vignemale massif, Oulettes de Gaube moraine complex. 3, Monte Perdido massif, Monte Perdido and Marboré moraine complexes. 4, Posets massif, La Paül moraine complex. 5, Literola moraine complex. 6, Maladeta massif, Tempestades moraine complex.

The height, distances, slopes and orientation of the flutes are obtained from the aerial photos and cartography. The results were compared with the fieldwork observations. We have cartographed the main landforms features from the studied mountain cirques, distinguishing the characteristic morphosquences of each area. We have establish in each morainic complex the morphosquences based on the morphostratigraphy (Lukas, 2006; Hughes, 2007, 2010), which in such as recent and well-preserved moraines allows a very accurate spatial and chronology relationships. Flutes are very useful not only to know about the glacier size and morphology, but also to establish the morphogenetic stages. In this way, we can correlate the different types of geomorphologies and reconstruct the evolution of the glaciers during the LIA and its possible connection with environmental changes. Finally, from the LIA data and climatic reconstructions from previous investigations on the Iberian Peninsula and Southern France (Creus *et al.*, 1996; Barriendos, 1997; Saz and Creus, 2001; Saz, 2003; Le Roy Ladurie, 2004, 2006; Le Roy Ladurie *et al.*, 2011; Liñán *et al.*, 2012; Alberola, 2014; Luterbacher *et al.*, 2016; Tejedor *et al.*, 2016, 2017; Oliva

et al., 2018), we have reconstructed the different cooling periods and variations in humidity in relation with the glacier evolution, creating a hypothesis about the response of the LIA glaciers to the short time changes in temperature and moisture during the 19th century.

4. Results on the LIA glacial landsystems and moraine complexes in the Pyrenees

There are 17 glacier cirques with flutes and associated push moraine systems in the Pyrenees. All of them are found in the highest mountains of the Central Pyrenees >3000 m, that show complex moraine systems (with ground, lateral and terminal moraines), and which still there are eight actives glaciers (Table 3). Eight of the moraine systems show morphosquences with flutes and frontal moraines, identifiable as GVL or SGL, which we have studied in detail.

Table 3. Cirques with flutes detected on morainic complexes in the Pyrenees.

Nº	Glacier	Or.	Alt. m a.s.l.	Rock ¹	Basin ²	Climate ³	Present day ice ⁴
1	Infierno Occ	N	3081	S	S	OT	Gl
2	Infierno Or	N	3076	S	S	OT	Ip
3	Oulettes de Gaube	N	3299	L, S	N	O	Gl
4	Monte Perdido	N	3325	L, Sd	S	M	Gl
5	Marboré	NNE	3251	Sd, L	S	M	Ip
6	La Paúl	NNE	3321	S	S	CM	G
7	Literola	S	3107	G	S	CM	-
8	Tempestades	NNE	3345	G	S	CM	G
9	Barrancs	NNE	3404	G	S	CM	G
10	Las Neous	N	3146	G	N	O	G
11	Gourg Blancs	N	3064	G	N	CM	Ip
12	Cabrioules	N	3107	G	N	CM	Ip
13	Maupas	N	3111	G	N	CM	Ip
14	Bugarret		3038	G	N	CO	Ip
15	Aneto	N	3354	G	S	CM	G
16	Perdiguero	NE	3219	G	S	CM	-
17	Coronas	SW	3404	G	S	CM	-

1. S, shales. L, limestone. Sd, sandstone. G, granite. 2. S, Southern basin. N, Northern basin.

3. OT oceanic transition. O, oceanic. M, Mediterranean. MT, Mediterranean transition. CM, Mediterranean continental. 4. Gl, glacier. Ip, Ice patch.

The studied moraine systems indicate a predominance of the Northern orientation (88%), while the most developed flutes are found in the only cirque with Southern orientation. The locations are also Southern dominant (88%), with a predominance of the Mediterranean environments (62.5%), over the Atlantic ones

(37.5%). The lithology is not significant, with equitable presence of shales, limestone and sandstones, and granitic rocks, neither the altitude, climate nor lithology with the presence of flutes (Table 4). The most important variables in the presence of flutes are the altitude, the concentration in the Pyrenean Southern faces and the Mediterranean environments.

Table 4. Flutes-moraines system in the LIA Pyrenean moraine complexes.

LIA complex (U3)	Flutes				Frontal moraines			Total Unevenness m	Rock
	Altitude, m		Lenght m	Type ¹	Altitude, m		Lenght m		
	max	min			max	min			
Infierno Occ	2630	2550	210	PS F	2575	2570	25	80	Shales
Infierno Or	2820	2750	175	PS	2790	2740	20-30	80	Shales
Oulettes de Gaube	2350	2200	520	PS	2200	2200	40	150	Limestone
Monte Perdido	2520	2450	520	PS F	2440	2450	120	110	Limestone
Marboré	2800	2760	100	PS	2760	2760	90	40	Limestone
La Paúl	2780	2700	200	PS	2680	2700	75	100	Shale, granite
Literola	2845	2790	220	PS	--	--	--	55	Granite
Tempestades	2680	2470	250	PS F	2550	2470	25	210	Granite

1. PS, parallel-side flutes. PSF, parallel side flutes and like-fan directions.

4.1. The Central Infierno LIA complex

The Northern Infierno cirques show significant erosional and depositional glacial features (Russell, 1908; Barrère, 1956; Martínez de Pisón and Arenillas, 1988; Serrano and Agudo, 1988; Serrano, 1991, 1998) with a complex moraine system at 2580 m a.s.l. (Fig. 2). This one is composed by a frontal moraine system formed at least by 4 minor arcs (U1), a maximum advance with the ELA at 2725 ± 25 m a.s.l. (Serrano, 1994). After a recession with minor pulsations, a more voluminous lateral moraines is formed (U2), and a complex formed by little push and hummocky moraines linking with flutes (U3) indicate an advance until the frontal moraine. Finally a recent minor pulsation built minor arcs up valley deteriorated by melt water and fluvioglacial recovering (U4) (Figs. 3 and 4D). There are not data from the historical evolution, except of the work by A. Lequeutre that described in 1874 that he reached the glacier walking through the moraine. Additionally, in the map from Schrader (1887) the glacier is already towards the morainic complex. Therefore, is in the 70s of the 19th century when the ice started the retreat and thinning, separating from the push moraine system, and the flutes surfaced.

The push and hummocky moraines seem as little arcs without continuity and low elevation, formed by very heterometric boulders linking to the flutes. Flutes are parallel-sided showing an expansion movement in the front. Flutes have been formed down

valley from the last glacial rock-bar on a ramp of 20° slope scattered by marble boulder on a till formed mainly by shales. They are conserved between 2560 y 2630 m a.s.l. and occupy 210 m length.

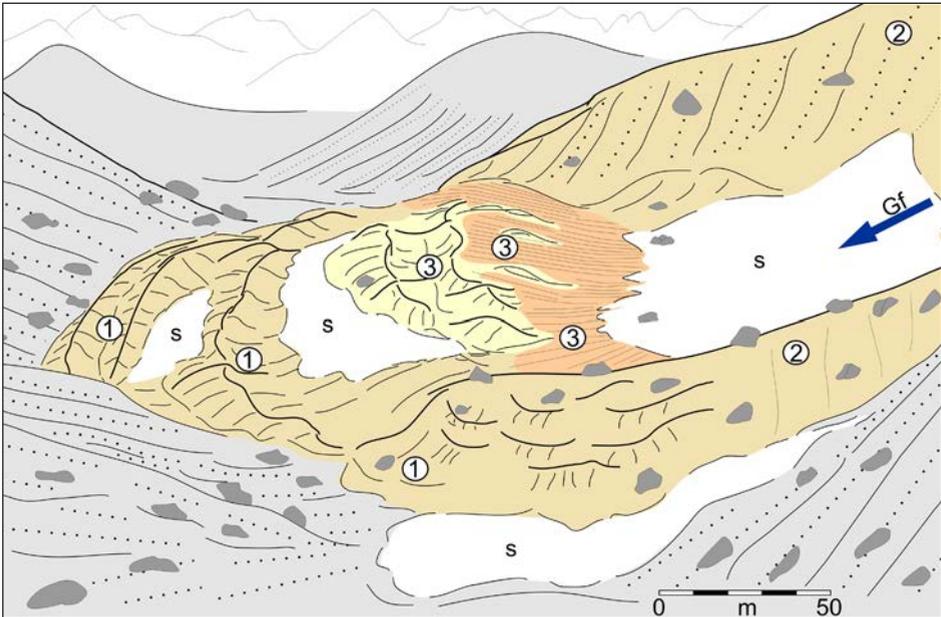


Figure 2. View of the LIA frontal moraine system of Western Infierno. 1, External frontal moraines (U1). 2, Lateral moraines (U2). 3. Moraine complex with flutes and little push moraines (U3). S, snow patches. Gf, direction of glacial flow.

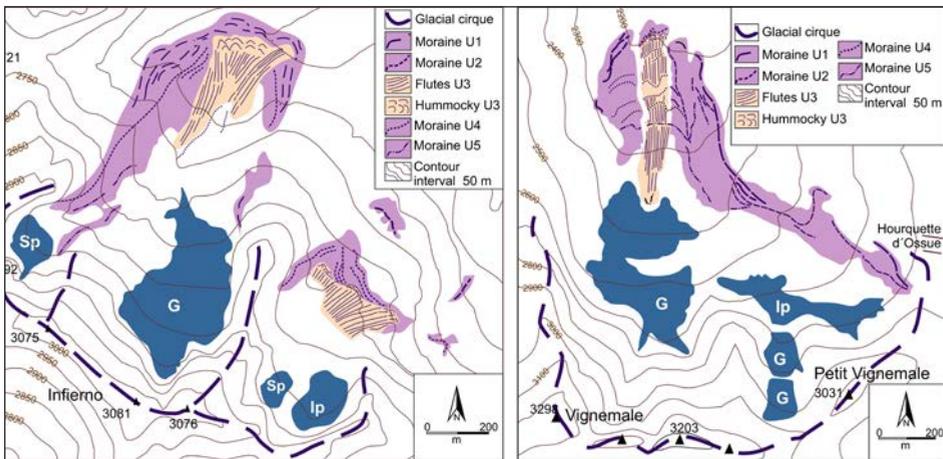


Figure 3. Glacio-geomorphological sketch of Infierno (left) and Oulettes de Gaube (Vignemale massif) (right). G: glacier; Ip: ice patch; Sp: snow patch.

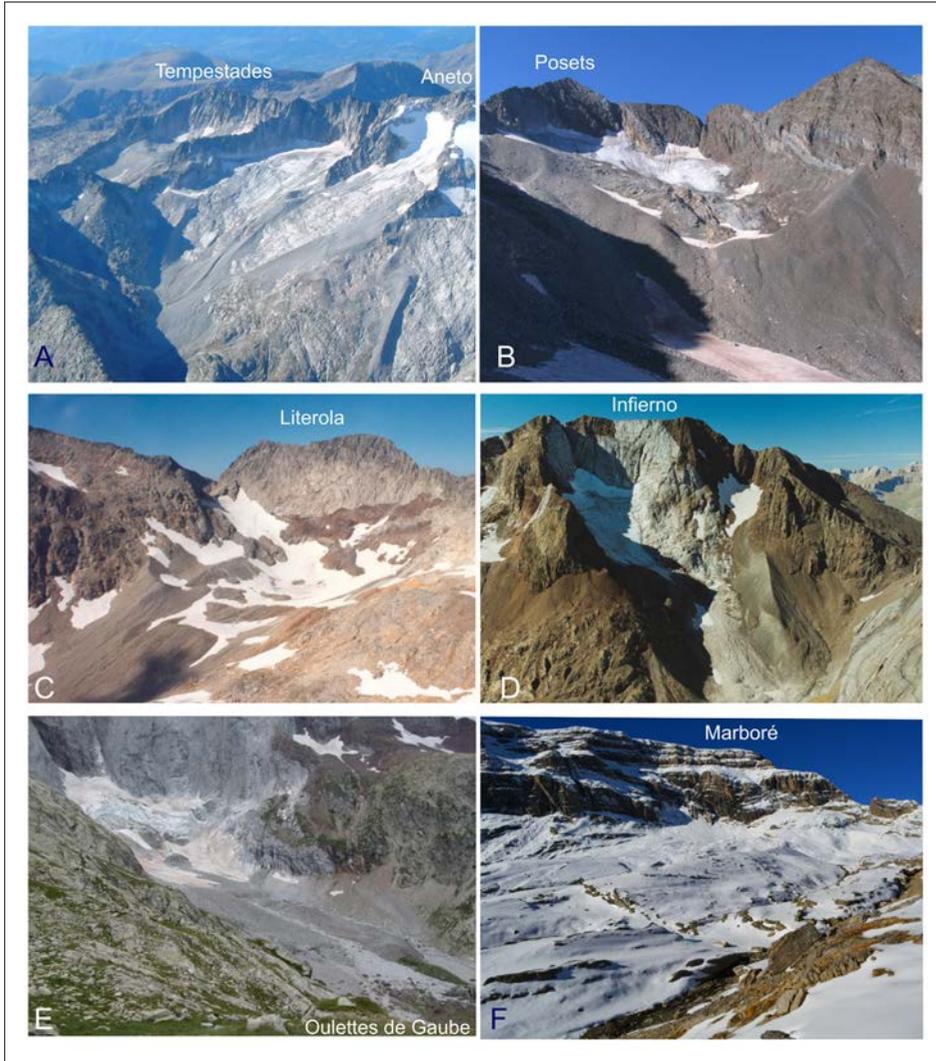


Figure 4. Cirques and LIA moraine complexes studied. A: Tempestades, Maladeta massif. B: La Paúl, Posets massif. C: Literola (picture by Eduardo Martínez de Pisón). D: Western glacier, Infierno massif (picture by Eduardo Martínez de Pisón). E: Oulettes de Gaube, Vignemale massif. F: Tucarroya cirque, Monte Perdido-Marboré massif.

4.2. The Eastern Infierno LIA complex

The cirque shows two morainic complexes, separated by a glacial rock bar, mapped previously by Barrère (1953), Martínez de Pisón and Arenillas (1988) and Serrano (1988, 1991, 1998). The external moraines (Fig. 3) are located at 2640 m a.s.l., formed by a disturbed frontal moraine (U1) during the maximum advance. After a recession

of, at least, 150 m up-valley from the previous moraines, a second complex consists on greater moraines together with minor arcs (U2). Again, a small recession in the inner part of the moraine complex resulted in a group of small push and hummocky moraines linking with flutes (U3). Flutes show parallel erosion lines of between 50 and 160 m length; they developed in a counterslope on the moraine complex of 26.5° slope. Finally, a clear glacial recession until nowadays has occurred. As in the Central Infierno complex, Schrader represented, in the Central Pyrenees map (edited in 1887), the glacier near the moraines, so the beginning of the U3 retreated is before that date.

4.3. The Oulettes de Gaube LIA complex

Located in the Vignemale Massif under the big north face, a 400 high wall and the Couloir de Gaube feeding the cirque with avalanches. The glacial retreat after the LIA has been studied, showing important thinning and recession of glaciers of Ossue and Oulettes de Gaube, the first one losing more than 1.5 km length and 200 m of altitude in 60 years (Russell, 1908; Grove and Gellatly, 1995; Grove, 2004; René, 2001, 2003, 2011, 2013). The second one underwent the same progression from the 18th when historical records have permitted to date the maximum advance (Grove and Gellatly, 1995).

The Oulettes cirque has an important LIA complex, formed when the glacier reached 1.5 km length, located the front at 2160 m a.s.l., and the ice was 120 m thick in the central sector (Figs. 3 and 4E). The morainic complex shows the most external moraines as lateral, because the frontal portion has been eroded by proglacial water. The external lateral moraine indicates an important expansion period forming the larger moraines (U1), correlated with the LIA maximum extent and completed by small recession arcs on the moraine slopes (U1). After an important recession a second lower lateral moraine (U2) was built, pointing out the new extent but with significant lower thickness than during the previous advance. An advance and equilibrium stage reached alike length that in the previous phase but the ice mass was thinner; after a new recession up valley, other advance deformed the till and built pushed moraines lined on the external moraines and flutes (U3) that occupy only the central portion of the glacier. Finally a succession of seven minor arcs crossing all moraine deposits (U4) have been dated between 1890 and 1997 (René, 2013), corresponding to the post-LIA recession. This glacier can be wider in extent, but the subglacial erosional power affected only to a narrow fringe of less than 100 m width. Finally, the transversal ridges crossing all U3 correspond with a short equilibrium phase estimated by René (2011) using historical maps and photographs, mainly belonging to 20th century, during 1888-1892, 1915-1920, 1940-1945, 1965-1980 and the last one in 1996-1998. The last one is separated only around 30-50 meters from the glacier, which have retreated 475 m during the last 160 years (46% lost), with quick recessions (1850-1885, 1894-1904, 1945-1950, 1992-1995) and equilibrium (René, 2011, 2013), although the flutes have been conserved during all the ice melting episode.

The push moraines occupy a narrow portion in contact with the external moraine (2200 m), no more than 40 m length, but the flutes are extended until 2350 m in a ramp of 17° slope. Intermittent and one direction parallel-side flutes go down until the frontal moraine. They are crossed by small, metric thickness frontal moraines, attributed to

stabilization microstades (René, 2011). Their small size, position and relation with flutes (Fig. 5B), permit to be interpreted as small push moraines deforming the till, originated by supraglacial debris, but also as crevasses-squeeze ridges generated subglacially during the recession phases.

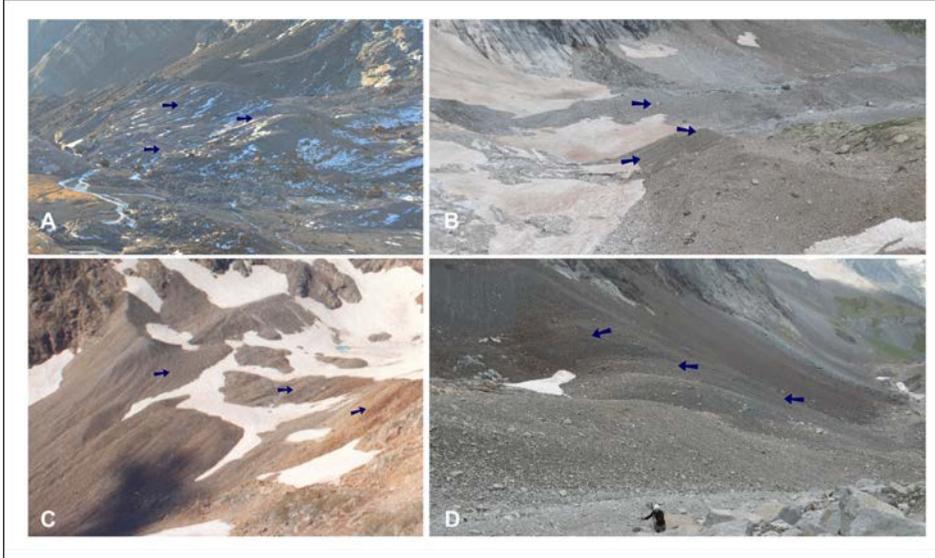


Figure 5. LIA moraine complexes with flutes. A: Monte Perdido. B: Oulettes de Gaube, Vignemale massif. C: Literola (picture by Eduardo Martínez de Pisón). D: La Paúl, Posets massif. Arrows point out the flutes on moraines.

The abundance of historical sources (maps, drawings, pictures, studies, alpinists descriptions) helps to date the moraines. According to “Les cartes d’État Major, 1:80,000” (edited in 1852), the glacier front was around 2200 m a.s.l., placing U3 next to external frontal moraines (U2) or right behind them (Grove and Gellatly, 1995; Grove, 2004; René, 2011). Before 1850 there was an advance prior to the general retreat that occurred between 1850 and 1885. This advance affected U2 and deposited U3, resulting in a modification of the former moraines and flutes along the complex. The retreat was fast, so that by 1887 the ice had retreated 320 m ($\sim 9 \text{ m yr}^{-1}$). The first pictures from 1887 show flutes over the U2 moraines. René (2011) notes the moraine formation in 1820-1830, just before the thinning of the ice that occurred between 1830 and 1850, and the moraine separation from 1850. Therefore, the glacier advance that deformed the subglacial till could be dated before 1850 (1820-1840?), but after the advance responsible of U2.

4.4. The Monte Perdido LIA complex

Monte Perdido (3348 m a.s.l.) is the third highest peak in the Pyrenees. On its North face the fourth largest glacier of the Pyrenees is located, as well as and

an important LIA moraine complex (Fig. 6). From the first climb by Ramond de Carbornières, the glacier and moraines have been studied in detail (Ramond, 1802; Tonnellé –in 1858– 1977; Schrader –in 1854– 1936; Gaurier –from 1900 to 1909– 1921; Gómez de Llarena, 1936; Hernández Pacheco and Vidal Box, 1946; Boyé, 1952; Martínez de Pisón and Arenillas, 1988; Nicolás, 1981, 1986; Ferrer *et al.*, 2003; García-Ruiz and Martí-Bono, 2001; Martín-Moreno, 2004, 2006; García-Ruiz *et al.*, 2014; López-Moreno *et al.*, 2016), and mapped and pictured by Schrader, Beck, Trutat, Briet or Gaurier.

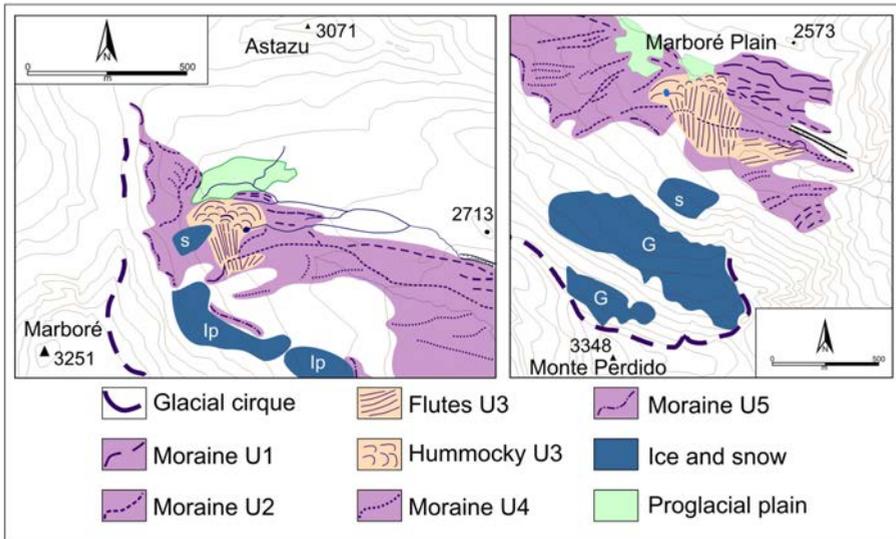


Figure 6. Glacio-geomorphological sketch of Monte Perdido (right) and Marboré (left). G: Glacier; S: snow; Ip: ice patch.

The Northern Monte Perdido cirque has a moraine complex attributed to several phases from Younger Dryas to LIA (Nicolás, 1981, 1986; Martín-Moreno, 2004, 2006; García-Ruiz *et al.*, 2014). The LIA complex is formed by 4 units, the external reaching 2470 m a.s.l., and is composed of front-lateral moraines (U1) because the ice flows to the east towards the Pineta Valley (Upper Cinca Valley). The second one is formed by a big lateral moraine (U2) formed when the glacier turned east toward Pineta, dividing the floor of the valley between the glaciated area, in the South side, and deglaciated in the north side, with a proglacial creek from the Cilindro and Marboré glaciers. The U2 and the till cover appears deformed and eroded, forming flutes and push moraines (U3) overcoming U2 and reaching U1. Upslope minor arcs point the location of the glacier during the XX century, when a big icefall descended from the north face of the Monte Perdido Peak.

Flutes mainly define the U3 (Fig. 5A). They are parallel-sided with two flow directions, ENE and N, from 2520 m a.s.l. to 2450 m a.s.l. toward ENE, and

2512 m a.s.l. toward the north. Both have low gradient: only 13° and 2.9°, respectively. It is clear by the flutes directions that they modified both sides of the moraine, overcoming the arc in the west part and generating small new push moraines on the moraine ridge. The ice pushed till on the U1, and slid over the moraine through the external side, where possibly deposited covered ice and hummocky structures. A picture of Trutat dated from 1896 shows a glacier ice portion recovered by debris in a hummocky topography with ice and lagoons. It is interpreted as debris covered stagnating surge snout affected by outwash channels from the Cilindro and Marboré glaciers.

The historical documents allow us to date the glacier during the LIA. Ramond (1802) placed the Monte Perdido glacier near the current Tucarroya Lake in 1797. This was an exaggerated description, as Schrader (1898) noted, although the ice still formed a single body from Cilindro and Monte Perdido. Schrader described in 1874 this single glacier, although it appeared divided into two ice masses by 1914; however, it is difficult to know if this was due to new interpretations or new observations. The description of Ramond (1802) may be correlated with the U1, i.e. the maximum extent of the LIA, and the Schrader description of 1874 with the U2, or from the 1914 text with the U3, when the glacier was close to the U2, although clearly thinner (Schrader, 1936). The first pictures from 1884 showed that the ice had already retreated respect to U2 and U3, partly surfacing the flutes, but very close (~50 m) to U2, which means that the glacier before 1884 had advanced over U2 and after that it had thinned and retreated 250 m approximately. Although we do not know the U2 chronology, it is located between the retreat after 1797 and the U3 advance (right after the map from Schrader), which place U2 between the mid 18th century and the beginning of the 19th century. During this period, between U2 and U3, the retreat was around 5-7 m yr⁻¹. Ten years later (1892), the ice stayed in a similar place, and in 1896 still dead-ice and stagnant-ice topographies persisted in the bottom of the valley, although two years later (1898) the glacier show supraglacial debris and a thinner front with well preserved flutes in the proglacial area. Thus, a fast retreat occurred from before 1880 and 1890, with the ice mass thinning and dead ice at the front, remaining at the same position until the 40s of the 20th century. To sum up, the ice of the Monte Perdido glacier has retreated from the largest moraines (U2) in the 70s of the 19th century, which means that the advance that created the flutes, the push moraines and like-hummocky topography must be previous and thus must have happened earlier than 1850.

4.5. *The Marboré LIA complex*

In the Monte Perdido-Marboré massif there are 15 cirques shaped by LIA glaciers, but the most relevant locates in the north face of the Monte Perdido, Cilindro and Marboré peaks. In the Western extreme of the large Tucarroya-Marboré cirque, the LIA complex of the Marboré glacier is located between 2780 and 2870 m a.s.l., connecting today with the Marboré ice patch underneath the more than 300 m high walls.

The LIA complex (Figs. 4F and 6) is formed by an external moraine system of small lateral ones (U1) located at 2780 m a.s.l., and a long and voluminous lateral moraine (U2) located between 2670 and 2830 m a.s.l. A glacier of ca. 1.5 km joined the Cilindro and Monte Perdido glacier, occupying the southern sector of the Tucarroya cirque. Between U1 and U2 a moraine complex is developed, formed by push and hummocky moraines with a chaotic topography where it is possible differentiate several discontinuous and overimposed arcs (U3). Up slope they connect with flutes (U3) shaped on the lateral moraine and eroded in the upper part. During this phase, the main tongue of the Marboré glacier went down to the ENE, but a small ice flow exceed the lateral moraine and went down by the other side, forming the fluted-hummocky-pushed system.

The flutes are parallel-sided, 100 m length, oriented to the north, between 2770 and 2800 m a.s.l. Flutes occupy the external slope of the lateral moraine, with a gradient of 17°, and are composed of till. They have continuity with the moraine complex, formed by big boulders in hollows and arcs that have been interpreted as a possible rock glacier (García-Ruiz *et al.*, 2014; Ventura, 2016). We interpret the discontinuous and poorly defined morainic arcs, with a chaotic topography and linked with the flutes, as a possible fast flow from the main Marboré glacier. The map from Schrader (edited in 1874), the only historical record, represents a very imprecise glacier limits (U2). The map from 1914 (E.1/20,000) shows the glacier extending over the entire morainic complex, so it is quite difficult to make reconstructions from these cartographies.

4.6. La Paúl LIA complex

La Paúl cirque is located in the north face of the Posets peak (3369 m), the second highest massif in the Pyrenees, below a 250 m height shale wall. The LIA glacier evolution has been analyzed through mapping and dynamic studies on moraines and rock glaciers (Alonso *et al.*, 1983; Martínez de Pisón and Arenillas, 1988; Serrano *et al.*, 2002, 2009, 2011; Lugon *et al.*, 2004). During the maximum LIA advance the ELA has been estimated at 2825 m a.s.l. in La Paul (Serrano *et al.*, 2002), and three main units have been differentiated (Figs. 4B and 7). An external moraine complex formed by lateral and frontal moraines (U1) divided into two arcs in the frontal portion. The glacier eroded La Paúl rock glacier and incorporated material (ice and debris possibly) from the rock glacier to the moraines. After an important ice recession of 250 m, a new and voluminous moraine arc (U2) was deposited at 2780 m. After the equilibrium period and a new recession, the glacier advanced and eroded the moraine arcs, forming flutes on the moraines (U3) in counterslope and going down toward the U1 (Fig. 5C). A new chaotic push moraine formed by debris recovering ice with discontinuous arcs and hummocky topography (U3) is located on U1. Still in 2001 buried dead ice appeared between the LIA debris in the frontal complex (Lugon *et al.*, 2004; Delaloyé, 2004). Above the flutes, in the inner of the U2 complex, the last equilibrium period placed at 2790 m a.s.l., scattered till in lee-side of the *roches mutonneés* on a granitic rock-

bar, and small moraines with two little arcs (U4). It was the last equilibrium stage before the continuous recession of ice from U4 until the present day.

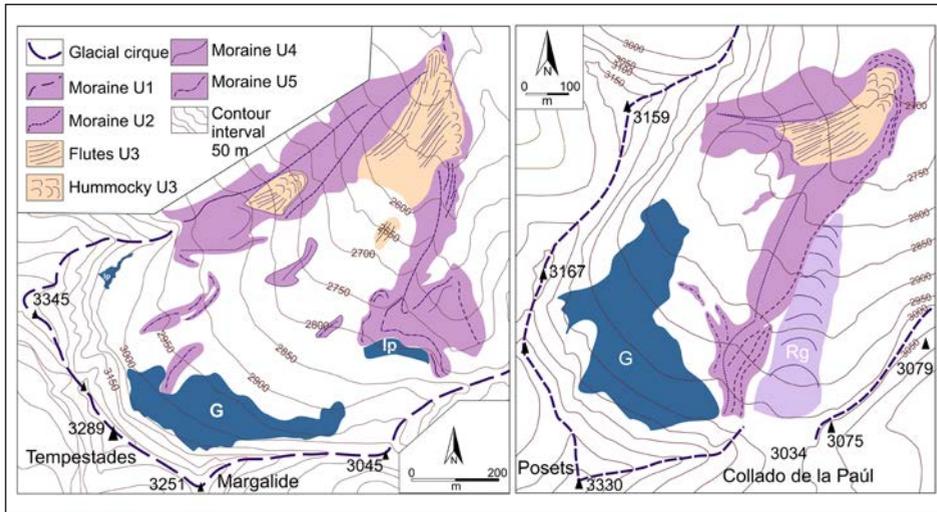


Figure 7. Glacio-geomorphological sketch of Tempestades (Maladeta massif) (left) and La Paúl (Posets massif) (right). G: glacier; Ip: Ice patch.

There are no documents on La Paúl valley and glacier until the 20th century (around the 1920s) when the ice was located next to the U4 and the visible till in the picture is today partially missing by postglacial erosion.

Flutes developed between 2780 and 2700 m, in the frontal portion of the glacier showing an advance limited to a narrow fringe that reshaped the upper moraines. Flutes surpassed the counterslope of the moraine and fell on a slope of 21° where the parallel-side flutes occur. This is the last important advance of the La Paul Glacier. Retreat between the 1950s of the 19th century and 1920s of the 20th century have been estimated around 4.7 m yr⁻¹.

4.7. The Literola LIA complex

The Literola LIA cirque is small but shows a complex evolution (Figs. 4C and 5C). According to Martínez de Pisón *et al.* (1995) there are 3 moraine arcs: (U1) an external moraine well developed, which belongs to the LIA glacier maximum; (U2) simple front moraines, inside the LIA maximum, attributable to retreat positions; and (U3) a recent and single front moraine. Our works (Martín-Moreno, 2004; González-Trueba *et al.*, 2008) and fieldwork observations show a more complex model, where there are up to 4 frontal moraine sequences, some with flutes. Here, the flutes are more defined in the internal part of the moraines and over subglacial

sediments. These flutes finalize suddenly in the mean external moraine (U1), which means that the ice advance could not surpass the LIA maximum.

4.8. The Tempestades LIA complex

The Tempestades cirque is located in the Maladeta granitic massif, the highest of the Pyrenees, to the East of Aneto peak. A high crest between the highest peak (3345 m), Tempestades (3289 m) and Salenques (2932 m), forms a cirque on the headwalls of the Barrancs valley where the frontal LIA moraines are located at 2470 m a.s.l. (Fig. 4A). The strong unevenness of 775 m and the gradient permit to reach a low point by means of a very steep glacier that not shaped an overdeepened basin and rock bar landforms. Therefore, the LIA glacier had 50-60 m thickness in the middle point and a very steep tongue of approximately 700 m length. LIA landforms and moraine (Fig. 7) have been studied in parallel to the other cirques of the massif, such as the Aneto cirque (4 moraine arcs), Maladeta cirque (three moraine arcs) or Coronas cirque (two moraine arcs). In total, sixteen cirque glaciers with LIA features have been analysed (Martínez de Pisón and Arenillas, 1988; Copons and Bordonau, 1994; Lampre, 1998; Chueca *et al.*, 2005; González-Trueba *et al.*, 2008). Copons and Bordonau (1994) established a maximum advance with three small periods located at the beginning of the 18th century and a second one at around 1820 with a continuous retreat until current times. In the Aneto cirque Chueca *et al.* (2005) pointed out three phases of glacial stabilization (1820-30 to 1857; 1914-20 to 1934-35; 1957 to 1981), and two fast glacial recession, the first one between 1857 to 1901-04, and the second one between 1981 and 2000. Pictures and gravures of Maladeta glacier (Fig. 8) show that in 1833 the glacier was in contact with the most voluminous frontal and lateral moraines in 1833, but 24 years later (1857) the ice was separated and 73 year later (1901) clearly separated more than one hundred meters and the ice thinned several tens of meters. As Schrader said, in the second half of 19th century the ice was close to the moraines although it was thinned.

In the Tempestades cirque 4 main units have been differentiated (Fig. 7, left): the external moraine complex formed by a small arc in the frontal portion (U1) and possibility by small lateral arcs. Upslope of the previous moraines and mounted on them, two voluminous lateral moraines (U2) between 2450 and 2750 m a.s.l. draw the LIA glacier. After an important recession of at least 400 m, the glacier advance eroded the frontal moraine arcs (U2), forming flutes and chaotic push moraine (U4) next to the U1 moraine. The frontal push and chaotic moraines are located between 2470 and 2550 m a.s.l. in a narrow area less than 25 meters. Between 2470 and 2680 parallel-side flutes developed showing two flow directions, N and NE, and the opening of a fan-like of the ice flow in the frontal section of the glacier. The flutes are divided forming small groups at 2650 and 2750 m a.s.l. (those of the north side limiting the Barrancs glacier lateral moraine). In the lowest sector a continuous, 250 m length flutes system developed linking with the outermost moraines. Upslope of the flutes there are small arcs (U4) showing two small ancient tongues of the Tempestades LIA glacier.

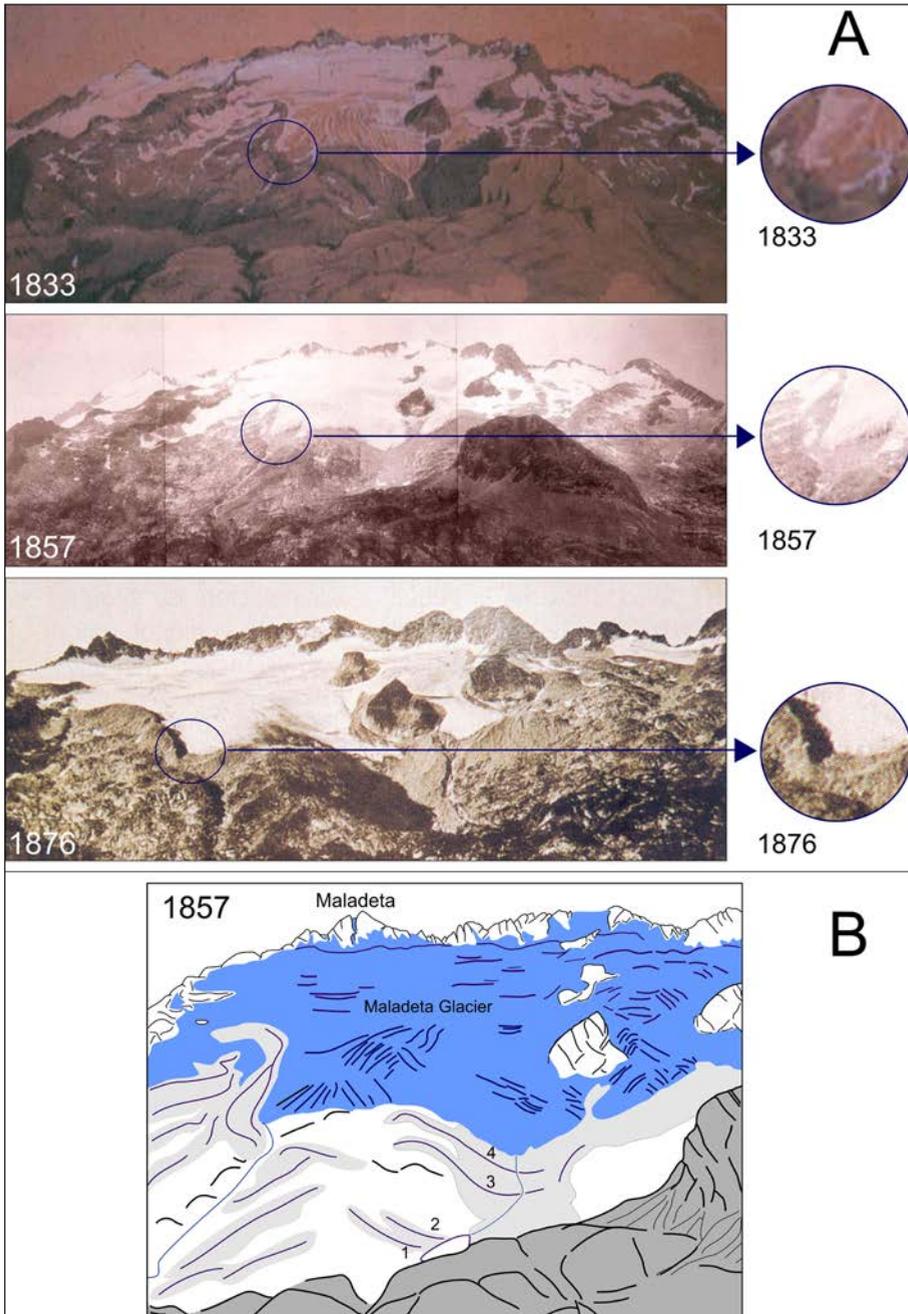


Figure 8. A: Pictures showing the position of the ice related to the LIA moraines in Maladeta glacier during the 19th century. 1833 pictured by E. Violet le Duc, 1857 pictured by Aimé Civiale, and 1876 pictured by Ch. Fabre, all modified. B: Interpretative drawing of A. Civiale picture (1857) where it is possible to observe the moraine sequence with several retreat arches from 1 to 4.

Documents of the year 1876 on the Tempestades glacier show the ice separated of the U2 moraines, consistent with the Maladeta images, and the flutes structures partially free in the lower sector, with a long tongue around of 400 m length (Fig. 9). A design of André Slomczynski drawn previously to 1909 (published in 1920) show a small tongue of two hundred meters length. An estimated retreat of $\sim 5.5 \text{ m a}^{-1}$ between 1876 and 1909 coincides with the fast glacial recession pointed by Chueca *et al.* (2005). An initial recession between 1830, when the ice was in contact with the moraines in the Maladeta cirque, and 1876 shows an average retreat of approximately 2.8 m a^{-1} while in the 20th century (1905–2002) the medium retreat was around 6.4 m a^{-1} , and 13.8 m a^{-1} during the last decades (2002–2015).

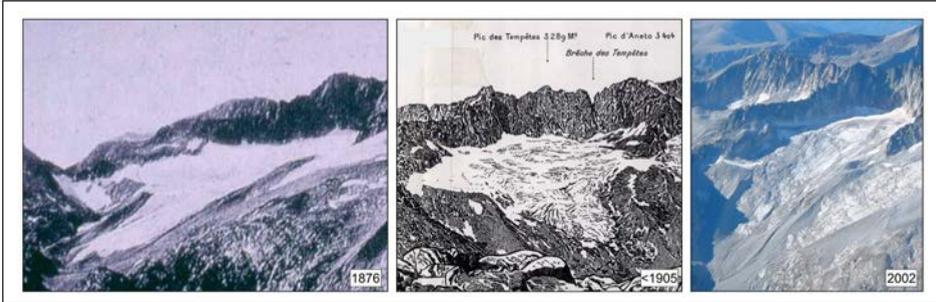


Figure 9. The Tempestades glacier (Maladeta massif) post-LIA retreat. 1876, pictured by Ch. Fabre (modified from *Annuaire Club Alpine Française*), 1905 by André Slomczynski, and 2002 by Eduardo Martínez de Pisón. It can be observed the fast retreat occurred during the last quarter of the 19th century (5.5 m a^{-1}), enhanced during the next decades until today.

5. Discussion on LIA glaciers advances

5.1. Fast flow processes and chronologies in the Pyrenean LIA moraine complexes

Six of the studied moraine complexes show a morphostratigraphic sequence defined by the succession of several meters length flutes, and small size frontal push moraines. Benn *et al.* (2003) propose that in some margins of temperate glaciers subglacial moraines with imbricate thrust and flutes may create, although only the crevasses-squeeze ridges are related with surge processes, as we have observed in the Oulettes de Gaube glacier. But the succession of landforms and sediments may also be used to detect terrestrial SGL (Brynjólfsson *et al.*, 2014; Farnsworth *et al.*, 2016). In that case, the formation of well developed parallel-side flutes and the associated push moraines indicate fast flow of ice.

The morphosequences described in the Pyrenees, characterized by the deformation of the till, the superimposed flutes and small hummocks, are interpreted as GVL, rare and associated to the margins of temperate glaciers (Benn *et al.*, 2003; Benn and Evans, 2003), but SGL as well. In that case, it is common the succession of push moraines, the deformation of the pre-surges sediments, gradual transition to a patchy hummocky moraines, and low amplitude flute with crevasse-squeezed ridges and subglacial till (Evans *et al.*, 1999, 2007, 2009; Evans and Rea, 1999, 2003). Despite the last two elements, there are successions in the U3 of Infierno, Oulettes de Gaube, Monte Perdido, Marboré, La Paúl and Tempestades

cirques, all of them formed in temperate environments and with small dimensions compared with the Arctic GVL and SGL. The presence of landforms and deposits, just like that the sequences described above, confirms the fast flows of ice in the studied glaciers, related with surge dynamics. Glacier surges in alpine environments, either in oceanic and continental environments, as the recent surges in the Belvedere glacier, Monte Rosa (Haeberli *et al.*, 2002) or the subsequent advances during the LIA in Vernagtferner, Austria (Hoinkes, 1969), combined with the described morphosequences, support the hypothesis of the fast flow of ice or surges during the LIA in the Pyrenees.

The maximum glacial advance during the LIA has been established for the 18th century in Oulettes de Gaube, Monte Perdido and Maladeta (Copons and Bordonau, 1994; Grove and Gellatly, 1995; García-Ruiz *et al.*, 2014). While the description made by Ramond (1802) only permits to know that the ice in Tucarroya had a large thickness prior to 1797, in Maladeta massif Copons and Bordonau (1994) established the maximum advance at the beginning of the 18th century with several subsequent minor equilibrium stages. Therefore, we can establish that the external moraines (U1) are previous to 19th century, probably formed during the 18th century.

More difficult is to establish the age of U2. It was formed posterior to the maximum, dated at the early 18th century, and before the U3 advance because this unit is superimposed to and deformed the U2. Pyreneists of the 19th century described glaciers next to the larger moraines of LIA (U2), but after 1850, and very well known by maps, gravures and pictures, the separation between the moraines (U2) and the thinning ice occurred. As U3 advance is previous to the E. Violet le Duc design (1833), when the Maladeta glacier contacted the U2, les Cartes d'État Major (1852), the A. Civiale picture (1857), the F. Schrader map (1874) or undoubtedly the Ch. Fabre (1876) and L. Briet (1887) pictures, the U2 should be deposited between mid-18th and early 19th centuries. So, the first pictures in Tempestades (1876) and Monte Perdido (1887) show the flutes free of ice, pointing out quick recession. In Aneto and Oulettes de Gaube, Chueca *et al.* (2005) and René (2011) have been established a glacial stabilization between 1820 and 1830, before a glacier thinning between 1830 and 1850 in Oulettes de Gaube.

Studies and documents indicate that a glacier advance previous to the glacial recession occurred between 1850 and 1885, pointed in Oulettes de Gaube, where the glacier was located next to U2 or overimposed in Monte Perdido, Infierno and Maladeta (Cartes d'État Major, 1852; Grove and Gellatly, 1995; Grove, 2004; René, 2011). The advance modifies deposits and landforms of U2 and generates flutes and push moraines (U3). So, we can date the glacial advance deforming the subglacial till as earlier as 1850 and later than 1820 if we accept the age of U2 between the late 18th century and 1820-1830 decades. Before 1850 there was a small advance followed by a continuous recession until the 1920s of 20th century, which is considered the post-LIA recession.

We can deduce that the ice advance generating the U3 landsystem is the last advance during the LIA, developed for a period of 20-35 years as fast flows or surge glaciers and the subsequent melting, all of them between the 1920s and 1940s of the 19th century. So,

it is consistent with the Schrader and pyreneists views, with glaciers slightly separated from U2 moraines and thinned.

5.2. Environmental and climate significance of LIA fast flows in the Pyrenees

The presence of fast flow glacier dynamics or surges in the Pyrenees coinciding with the end of the LIA -after the most important glacier advance and equilibrium of this cooling period-, lead us to think in a glacier response to environmental changes, more than endoglacial behaviors or individual responses to the deglaciation. The glaciers react to environmental factors, such as winter precipitation and summer temperatures, making thus possible to link the morphostratigraphy of the LIA moraine complexes with the historical climatic evolution.

During the LIA the colder conditions in the Iberian Peninsula occurred from 1300 to 1850 (Oliva *et al.*, 2018) with several warmer and colder periods caused by natural events, mainly associated to solar forcing and volcanic activity. Although there is no an agreement on the timing of the transition between the Medieval Climate Optimum and LIA, the 14th century is generally accepted as the beginning of the LIA. In the Iberian Peninsula and SW Europe, the LIA began with a moderate cooling together with an increasing climate variability from 1300 to 1480. Afterwards, relatively warmer conditions and less frequent extreme events were recorded until 1570 (Jones and Mann, 2004; Barriendos and Rodrigo, 2006; Oliva *et al.*, 2018). From 1570 to 1620 a gradual climate cooling was recorded while glaciers grew in the highest mountains of Europe to finally reach the maximal extent by the middle 17th century (Le Roy Ladurie, 2004). Nevertheless, the coldest climate conditions occurred between 1620 and 1715, during the Maunder Minimum, when cold and droughts took place in all Southern Europe. In fact, during that interval the coldest decade of the millennium (1691-1700) was recorded (Jones *et al.*, 1998; Luterbacher *et al.*, 2016). During this climate period, in the Iberian Peninsula cold and very dry conditions have been observed, with temperatures ca. 1°C lower than around 1850, in average, and ca. 2°C lower than present-day values (Domínguez-Castro *et al.*, 2010; Oliva *et al.*, 2018). U1 in the studied LIA moraine complexes have been correlated to the beginning of 18th century.

After the late 17th and early 18th century cooling, a warmer and relatively stable period (1715-1760), when glaciers in the western Alps retreated (Nussbaumer and Zumbühl, 2012) and some glaciers extinted in Sierra Nevada (Oliva and Gómez-Ortiz, 2012), was followed by cold conditions and highly variable climate from 1760 to 1800. In France, colder temperatures were registered from 1763, with a cold sequence until 1774. Coherently, glaciers in the Alps advanced from 1770, with a seven years lag as response to climatic change observed in all glaciers during the LIA (Le Roy Ladurie, 2006; Le Roy Ladurie *et al.*, 2011). The Laki volcanic eruption (1783-84) contributed to the cooling in the North Hemisphere, affecting Iberia and the Pyrenees (Prohom *et al.*, 2016), and linking with the Dalton Minimum (1790-1820), a cold period that favoured glacial advances during the late 18th century and early 19th century. This time interval was then characterized by cold temperatures and advances in the Pyrenean glaciers until the proximities of previous moraines. In Northern Iberian Peninsula a cold period

between 1630 and 1790 implied a decrease of winter temperatures around 0.25-1.2°C and spring temperatures around 0.25-0.5°C (Saz, 2003; Tejedor *et al.*, 2016, 2017).

The first half of the 19th century was defined in the Iberian Peninsula by highly variable climate conditions with three periods (Oliva *et al.*, 2018):

- (i) Relative stability phase (1800-1815). It was a period of stability coinciding with the Dalton Minimum until that a new volcanic eruption, the Tambora one (1815), implied a global cooling of ca. 0.5°C (Fischer *et al.*, 2007; Auchmann *et al.*, 2012). In the Iberian Peninsula summer temperatures were 2-3°C colder (Trigo *et al.*, 2009) and the glacier response in the Pyrenees was observed as an important advance, shaping the bigger moraines of the LIA (U2) and reaching the maximum extent during the first decades of the 19th century. During the next years, between 1818 and 1821, a maximum advance in the alpine glaciers was registered (Mer de Glace, Argentière, Bossons, Grindewald). Glaciers grew until the 1860 decade when the glacial recession in the Alps began (Rhône, Grindewald, Aletch) (Nussbaumer *et al.*, 2007; Zumbühl *et al.*, 2008; Nussbaumer and Zumbühl, 2012). However, in the Pyrenees we have not accurate data on the maximum extent, although we know that glacier recession began before 1833 or 1857 in the Maladeta, 1852 in Oulettes de Gaube and 1874 in Monte Perdido. Along this period the flutes were shaped, the main moraines (U2) were correlated with advances produced during the late 18th and early 19th centuries, until post-Tambora ice growth ca. 1820-1830 decades, according to the Chueca *et al.* (2005) and René (2011) chronologies in Aneto and Oulettes de Gaube LIA moraine complexes. After this period, Pyrenean glaciers could start a general recession only interrupted by a short fast flow located between 1820-1830 and 1850, when glaciers advanced again.
- (ii) Phase of extreme events (1815-1835): It was characterised in Europe by alternating warm and dry summers (1818, 1822, 1825, 1826), hot summers (1827-1831) and cold ones (1829-1830), but mainly from 1827 weather was rainy, with a “Wet five-year” (1827-1832) period (Le Roy Ladurie, 2006). Climate conditions in the Iberian Peninsula were characterized by a very cold period (associated to the Dalton Minimum 1810-1838) that was also very humid (1810-1821) and with summer temperatures, between 2-3°C colder (Saz, 2003; Trigo *et al.*, 2009). All these characteristics implied a potential good snow accumulation in the Pyrenean glaciers.
- (iii) Phase of slight warming trend with intense hydrometeorological events (1835-1850): It is defined by a cool sequence with fresh summers, spring-summer temperatures 0.4°C lower, and extremely cold winters (1838, 1841, 1845, 1847), representing a cool and wet period between 1838 and 1839 (Le Roy Ladurie, 2006). So, the 1837-1845 period was characterised by cool summers and wet and cold winters with abundant snowfalls, all of them causing glacier advances in the Alps, peaking in 1855 (Le Roy Ladurie *et al.*, 2011; Brönnimann, 2015). Humid and cold winters (1815-1835) and cool summers (1835-1850) were favorable to glacier advances, resulting in fast ice flows and surges.

Surges are related with humid mountain environments (Western Alps, South Alaska, Yukon, British Columbia, Iceland), but also with continental ones (Central Alps, Caucasus, Tien Shan, Tibet and Pamir-Karakorum) and the Arctic (Greenland, Novaya Zembla, Svalbard). The relationships between surges and climate are not well understood since, for example, the hydrological changes that produce the surges are unknown (Eisen *et al.*, 2001; Sevestre, 2015; Sevestre and Benn, 2015). However, there are studies that link surges with climatic oscillations (Hoinkes, 1969); the intensification in the surge cycles has been mainly related with an increase in precipitation and a decrease in temperature (Kotliakov, 2009; Striberger *et al.*, 2011). Therefore, continued positive mass balance -and the appearance of water at the glacier base-, destabilizes the ice mass and increases suddenly the velocity due to the lower friction between the glacier and the bed. In cold and thin glaciers, without surging dynamics currently, there are evidences of fast flows from the LIA (Sevestre, 2015).

The formation of flutes requires a great amount of meltwater (Benn and Evans, 2010), which fills the glacier drainage system, saturates the bed and enhances the glacier basal sliding (Björnson, 1998). The subglacial erosion over the soft-bedded sediments by melt water saturation deforms the subglacial deposits with flutes over the till and moraines, forming push moraines and hummocky morphologies. In that context, the fast ice flows from the 1830s and 1850s in the Pyrenees could be a response to the cool summers and the increase of snow precipitation during the 1820s. The small size of these glaciers could mean a faster response than in the Alps, for example. The abundant meltwater during the cool summers in a temperate mountain such as the Pyrenees, where there is abundant solar radiation, could have causes that the Pyrenean glaciers saturated their drainage system producing fast flows of ice due to the basal sliding, resulting in the deformation of the basal and frontal saturated sediments. In the short period of 20-30 years, at the end of the LIA (around 1850), in a context of general retreat but with the last cooling and precipitation increase, at least 17 glaciers responded with fast flow or surging that modified the morainic complexes in flutes, push moraines and hummocky moraines. Shortly after, a fast retreat and ice melting of between 4 and 9 m a⁻¹ began, stretching and thinning the ice mass. The mountaineers from the 19th century described extensive but thin glaciers, which reached the U2 complexes, and rapidly retreated far away from the main moraines. The existence of fast flow features in at least 14% of Pyrenean glaciers, and the fact that they are grouped in a short time of 30-40 years, is an indicator of a possible response to the regional or global environmental conditions.

6. Conclusions

We have found fast flow stages or surging during the LIA in the Pyrenees. The flutes occur over till, basal and lateral moraines, in slopes between 15-25° and counterslopes, and push moraines with an ice core, conserved until the end of the 19th century (at least until 1870). The glacial fast flow processes eroded and modified the U2 moraines by pushing over the saturated sediments. These processes were associated in all of the studied glaciers with the period between 1820 and 1840, at the end of the LIA, just before the main post-LIA deglaciation. The occurrence of fast flow or surges in a period

of 20-35 years, subsequent to the formation of the LIA moraine, affected more than 17 glaciers in the whole Pyrenees. We related it with a possible climatic response to the changing conditions after the Dalton Minimum and the end of the coldest years of the 1820s. The sudden cooling and the increase of winter precipitation could produce the environmental conditions –water availability from snow and ice melting during the summer–, to generate hydrodynamic changes in the small glaciers, as a quick response to the new environmental conditions. It can be stated the existence of terrestrial surge glacial landsystem in temperate mountains associated to climatic changes related with the retreat of the small mountain glaciers, analogous to what is happening now in the Belvedere Glacier (Alps).

Acknowledgements

To the Professor Francisco Alonso Otero, who introduced us the questions regarding the presence of flutes in the Pyrenees decades ago, and motivated this investigation thanks to his observation skills on the field. This research has been funded by I+D+I project CGL2015-68144-R (MINECO of Spanish government-FEDER). We thank the contributions of two referees, Ana Moreno and an anonymous one, whose corrections and suggestions have contributed to improve the manuscript.

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