J. Mt. Sci. (2018) 15(10): 2103-2119 e-mail: jms@imde.ac.cn http://jms.imde.ac.cn
https://doi.org/10.1007/s11629-018-4873-x

Spatial distribution of morphometric parameters of glacial cirques in the Central Pyrenees (Aran and Boí valleys)

Luis LOPES[1*] http://orcid.org/0000-0002-5132-9258; e-mail: luis.filipelopes@live.com.pt

Marc OLIVA[2] http://orcid.org/0000-0001-6521-6388; e-mail: oliva_marc@yahoo.com

Marcelo FERNANDES[1] http://orcid.org/0000-0001-6840-4317; e-mail: marcelo.fernandes@live.com

Paulo PEREIRA[3] http://orcid.org/0000-0003-0227-2010; e-mail: pereiraub@gmail.com

Pedro PALMA[1] http://orcid.org/0000-0002-5399-9730; e-mail: p.palma@campus.ul.pt

Jesús RUIZ-FERNÁNDEZ[4] http://orcid.org/0000-0001-7161-3320; e-mail: ruizjesus@uniovi.es

**Corresponding author*

1 Centre for Geographical Studies – IGOT, Universidade de Lisboa, Lisbon 1600-276, Portugal

2 Department of Geography, University of Barcelona, Barcelona 08001, Spain

3 Environmental Management Center, Mykolas Romeris University, Vilnius LT-08303, Lithuania

4 Department of Geography, University of Oviedo, Oviedo 33011, Spain

Citation: Lopes L, Oliva M, Fernandes M, et al. (2018) Spatial distribution of morphometric parameters of glacial cirques in the Central Pyrenees (Aran and Boí valleys). Journal of Mountain Science 15(10). https://doi.org/10.1007/s11629-018-4873-x

Abstract: Glacial cirques are typical landscape features of mid-latitude mountain environments like the Central Pyrenees. Their morphology as well as their spatial distribution provides insights about past glaciers and climates. In this study, we examine the distribution, morphometrical and topographical characteristics of glacial cirques in two U-shaped glacial valleys located in the Central Pyrenees – the Aran and the Boí valleys. They are located in different aspects of this mountain range (north vs south) under different climatic influences that promoted distinct glaciation patterns during the late Pleistocene. The spatial mapping of these landforms was carried out using high-resolution imagery and field observations. We analysed the data of the morphometrical and topographical variables of the glacial cirques by using different statistical and geospatial methods in order to unveil the factors controlling their formation and development. A total of 186 glacial cirques were mapped in the study area, including 119 in the Aran and 67 in the Boí valleys. The local topography and microclimate conditions lead to substantial differences in both areas in terms of the morphology and dimensions of the cirques. Glacial cirques in Boí are distributed at slightly higher elevations than in Aran and they are also larger, though their dimensions decrease with elevation in both valleys. Aran cirques are mostly oriented NE, while Boí landforms do not show any prevailing aspect. Even though lithology does not control the distribution of the glacial cirques, some specific lithological settings may favour the development of larger cirques. In general, glacial cirques in the Aran and the Boí valleys show morphometrical properties similar to those reported in other mid-latitude mountain ranges.

Received: 31 January 2018
1st Revision: 19 April 2018
2nd Revision: 13 July 2018
Accepted: 21 August 2018

Keywords: Central Pyrenees; Aran and Boí valleys; glacial cirques; topography; morphometry.

Introduction

The extent and chronology of Quaternary glaciations in the Pyrenees have generated an intense debate over recent years (García-Ruiz et al. 2010, 2016; Palacios et al. 2015a). The higher age accuracy provided by modern absolute dating techniques has improved our understanding of the timing of maximum glacial expansion in the Pyrenees, which is crucial for a better knowledge of landscape evolution in this mountain range (Calvet et al. 2011). However, there are still discrepancies between the timing of maximum ice extent in different mountain systems on Earth (Clark et al. 2009). These age differences are also observed at a regional scale, such as in the Iberian Peninsula (Hughes et al. 2006; Delmas et al. 2008; García-Ruiz et al. 2010), and even at a local level, with important differences between valleys located in different geomorphological settings within the same mountain range (Turu et al. 2016). The existing geochronological data for the last glacial Pleistocene cycle indicate that the Pyrenean maximum ice extent occurred prior to the Last Glacial Maximum (LGM), being contemporaneous with Marine Isotope Stage 4 (Delmas 2015). However, studies point out very distinct age differences within the same mountain range (e.g. Pallàs et al. 2006; Delmas et al. 2008; Palacios et al. 2016; Turu et al. 2016) which may be attributed to the use of different dating methods, microscale topography and local paleoclimatic variations (Palacios et al. 2015b).

The widespread use of glacial records in the Mediterranean mountains, such as paleoclimatic records, is related to the rapid response of glaciers to climate variability in this climatically sensitive region (Hughes et al. 2006; Domínguez-Villar et al. 2013). One of the most characteristic landscape features shaped by glaciers are glacial cirques, which have been defined as hollow areas formed by glacier erosion, limited upslope by a crest with steep slope (headwall) and open downslope, presenting a shallow, flat or overdeepened zone (García-Ruiz et al. 2000; Barr and Spagnolo 2015).

The study of glacial cirques goes back more than 150 years (Barr and Spagnolo 2015), though their use as paleoindicators is more recent (e.g. Derbyshire and Evans 1976; Evans 1977; Gordon 1977; Aniya and Welch 1981; Evans 1990). The spatial distribution and dimensions of glacial cirques are a consequence of both glacial erosion and periglacial activity (Evans 2006a; Barr and Spagnolo 2015), together with pre-glacial relief and post-glacial processes. Their morphology and distribution is a consequence of specific palaeoenvironmental conditions, in addition to lithology and structure (Federici and Spagnolo 2004; Ruiz-Fernández et al. 2009), and therefore their characterization provides quantitative and qualitative information about the characteristics of past glaciers and climates (Barr and Spagnolo 2015). However, Evans and Cox (2015) raised the problem that the assessment of glacial cirque inventories is limited by the different methods used for calculating topographical and morphometrical parameters, which makes comparisons difficult between different areas. The recent widespread use of Geographical Information System (GIS) techniques has brought about new perspectives that facilitate the comparison of their characteristics in different areas (Barr and Spagnolo 2015).

In the Iberian Peninsula, there have been a few attempts to characterize the distribution and morphometry of glacial cirques. García-Ruiz (2000) showed that these glacial erosion landforms in the Central Pyrenees are highly variable in shape and dimensions. Ruiz-Fernández et al. (2009) compared the size and morphometry in two distinct lithological environments in the Cantabrian Mountains. Delmas et al. (2014) examined environmental controls on alpine cirque size, noting that cirques are complex landforms resulting from many climatic and non-climatic processes. Lastly, Gómez-Vilar et al. (2015) pointed out that environmental variables (such as altitude, aspect, and lithology) can have a stronger influence on the location and size of cirques than the duration of glacial occupancy. Within this context, and using a multivariate statistical approach, in this paper we examine the distribution, morphometrical and topographical characteristics of glacial cirques in two valleys in the Central Pyrenees located on different slope aspects of this mountain range: Aran (north-facing) and Boí (south-facing). Nowadays, both valleys are affected by different climatic regimes, which also promoted a distinct pattern of glaciation during the late Pleistocene (Vilaplana 1983; Bordonau 1992). An accurate characterization of their geographical distribution will show the key variables involved in the development of glacial cirques in both areas, allowing for paleoclimatic inferences.

1 Study Area

The Pyrenees are located between latitudes 42° and 43° N, with a maximum width of 150 km. This mountain range stretches W-E across ca. 450 km between the Atlantic Ocean and the Mediterranean Sea, with the highest elevations located in its central part (Aneto, 3404 m asl; Posets, 3370 m; Monte Perdido, 3350 m). The longitude and width act as barriers to atmospheric circulation, provoking N-S and E-W climatic asymmetries: while the western fringe is strongly affected by the Atlantic climate, the eastern part is under a Mediterranean climate regime (Pallàs et al. 2006). However, the most significant asymmetry takes place between the north- and south-facing slopes in terms of precipitation and insolation as well as in terms of slope extension, since the south-facing side has much greater development than the north-facing side (Calvet 2004).

This research focuses on two spatially close U-shaped glacial valleys located in the Central Pyrenees: the Aran and the Boí valleys (Figure 1). The Aran valley is a north-exposed valley elongated E-W with a total surface of 550 km² crossed by the Garonne river, which flows northwards; the elevation ranges from 670 to 3010 m (Mulleres, 3010 m; Bessiberri Nord, 3008 m). The Boí valley is a south-facing valley whose limits are defined by the Noguera de Tor basin, encompassing a surface of 247 km². The valley follows a NE-SO orientation, with elevations ranging from 850 to 3029 m (Comaloforno, 3029 m; Bessiberri, Sud 3023 m).

The Aran valley is mostly composed of granite, carbonated rocks such as conglomerates or lutite and limestone, as well as some metamorphic outcrops, mainly slate (Serrat et al. 1994a). The Boí valley can be subdivided into three major Paleozoic units: granite is distributed in the highlands, limestone and shale are abundant in most of the central valley except for the Taüll area, where sandstone and shale appear, while Mesozoic shale,

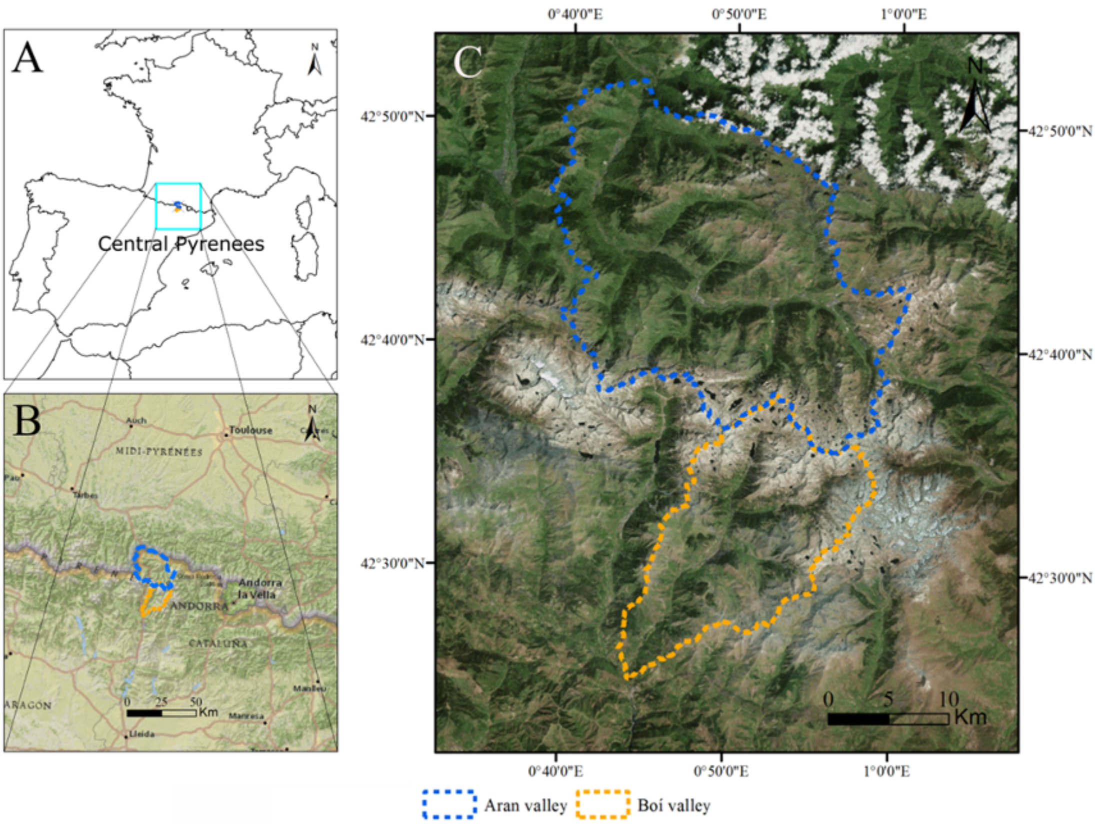

Figure 1 Location of Boí and Aran valleys (C), within the Iberian Peninsula (A) and within the Central Pyrenees (B).

chalk and carniola alternate in the lowest part of the valley.

Both valleys were intensely shaped by Quaternary glaciations. In the case of the Aran valley, during the Last Glaciation the glacier flowed along 88 km to 400 m asl in the lowlands, with a maximum ice thickness of ca. 800 m (Montserrat 1988; Bordonau 1992; Fernandes et al. 2017). Contemporaneously, the Boí glacier extended until 890 m asl with a maximum thickness of ca. 600 m, without connecting with the Noguera Ribargorçana glacier (Vilaplana 1983). Several erosion and accumulation glacial landforms, including various moraine deposits, are distributed across the valleys, showing evidence of distinct glacial stages during the Last Glaciation. Today, there are no glaciers in the valleys under study, since the present-day Equilibrium Line Altitude at the Central Pyrenees lies at approximately 2900-2950 m and active glaciers only persist in the highest massifs with peaks exceeding 3200-3400 m (Hughes 2014; López-Moreno et al. 2016).

The climate in the Aran valley is strongly influenced by the Atlantic Ocean, whereas the Boí valley has a Mediterranean high-mountain climate, with a certain Atlantic influence in the westernmost highest parts (Chueca and Julián 2011). At high altitudes, annual precipitation reaches 1232 mm at 2266 m asl (Bonaigua, Aran) and 1160 mm at 2535 m asl (Boí). The mean annual temperature varies from 2.9˚C at 2266 m asl (Bonaigua, Aran) to 1.9˚C at 2535 m asl (Boí), with negative monthly temperatures from November to April.

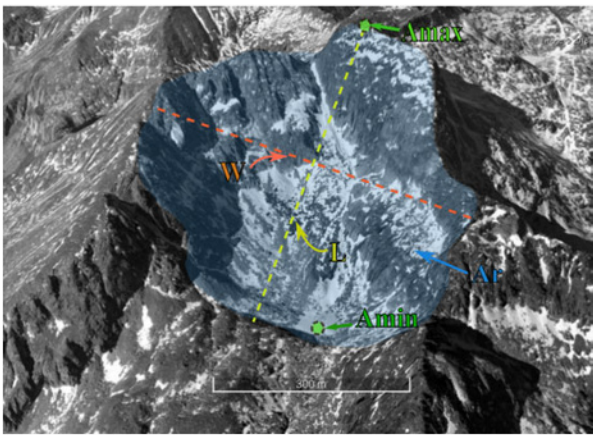

Figure 2 Basic parameters used in this research projected on the southeast glacial cirque of Comaloformo peak. The acronyms are described in Table 1.

The vegetation is representative of mid-latitude alpine environments, with three elevation belts at the glacial cirque elevation level: (i) up to 2300 m there is the subalpine stage, characterized by the presence of coniferous woods; (ii) between 2300 and 2800 m there is the alpine stage with widespread grasslands, and (iii) above 2800 m there is the nival stage, with scarce vegetation and perpetual and/or long-lasting snow cover; a clear dissymmetry is observed between slopes, with elevation belts always significantly lower in north-facing environments (de Bolós 2001).

2 Methodology

2.1 Identification of glacial cirques and parameters analysed

The mapping of the glacial cirques presented in this paper complements the first detailed geomorphological maps for the Central Pyrenees, which date back from the 1970s-1980s (summary in Serrat et al. 1994b). The cartography of the cirques existing in both valleys was conducted through photointerpretation using high resolution imagery (25 cm pixel size) provided by the Institut Cartogràfic i Geològic de Catalunya and complemented with Basemap ESRI images and Google Earth Pro. Subsequently, they were validated with 1:5000 scale topographical maps and field observations. The lithological information was obtained from 1:50000 scale geological maps, which included five lithological groups in the study areas: 1) granite 2) limestone, 3) limestone and shale, 4) sandstone and shale, and 5) detrital sedimentary.

The limits of the cirques were drawn in a GIS environment (ARCGIS) that allowed the automatic calculation of several topographical and morphometrical parameters of the glacial cirques commonly examined in the scientific literature (Figure 2) (García-Ruiz et al. 2000; Ruiz-Fernández et al. 2009; Barr and Spagnolo 2015; Gómez-Villar et al. 2015). They are summarized in Table 1.

2.2 Statistics and mapping

Cirque morphometry data did not follow the

Table 1 Summary of the parameters of the glacial cirques examined in this research.

Parameter	Acronym (units)	Description
Area	Ar (ha)	Surface occupied by the glacial cirque
Aspect	As	Main cirque orientation
Max. altitude	Amax (m)	Highest elevation of the glacial cirque
Min. altitude	Amin (m)	Lowest elevation of the glacial cirque
Mean altitude	Amean (m)	Sum of each altitude cell value divided by the number of cases
Length	L (m)	Distance between the headwall of the cirque along the median axis of the cirque until its furthest point
Width	W (m)	Maximum distance between the lateral walls of the cirque along a line transverse to the cirque length
Slope	Smean (°)	Mean slope of the area limited by glacial cirque
Amplitude	H (m)	Difference between the maximum and the minimum altitude, also known as cirque relief
Index L/W	L/W	Ratio between length and width, indicator of horizontal cirque shape
Index L/H	L/H	Ratio between length and cirque relief, indicator of glacial incision
Index W/H	W/H	Ratio between width and cirque relief, indicator of glacial incision
LogV	LogV	Logarithm of cirques volume

normality and homogeneity of the variances. Thus, the non-parametric Mann-Whitney test was performed to compare statistical differences between cirques, and a Kruskall-Wallis ANOVA test was applied to compare the variables studied among the different expositions in each valley. If significant differences were identified, a Tukey post-hoc test was applied. The Spearman correlation coefficient was used to identify the relationship among variables in each valley. Significant differences were considered at a $p<0.05$. A Principal Component Analysis (PCA) was carried out based on the correlation matrix, using the data of both valleys, in order to identify the correlations between all the variables in the study areas. Statistical analyses were carried out using Statistics 10.0. Using the scores obtained from the retained factors we analysed the spatial autocorrelation of each one using the Moran's I index, to identify the spatial clustering of the studied variables. A detailed description of these indexes can be consulted in Pereira et al. (2015) and Depellegrin et al. (2016). Geospatial analysis was carried out using ArcGIS 10.2.

3 Results

A total of 186 glacial cirques were identified, with 119 distributed in the Aran valley and 67 in the Boí valley (Figure 3).

The density of glacial cirques according to the total area for each studied valley is 0.22 per km² in the Aran valley and 0.27 per km² in the Boí valley.

3.1 Topographical and lithological conditions

The data reveal substantial variations in terms of elevation, aspect and lithology between the two studied valleys.

In the Aran valley (Figure 4), the Amin range of the glacial cirques varied between 1589 m and 2642 m, with an average of 2114 m. The Amax range was between 1953 and 2935 m, with an average of 2495 m. The Amean of the glacial cirques is 2268 m. The H has a minimum value of 65 m and maximum of 865 m, with a mean value of 339 m (Table 2).

In the Boí valley (Figure 5), the Amin ranges from 1765 m to 2697 m, with an average of 2323 m. The Amax range is between 2417 m to 3019 m, resulting in an average of 2811 m. The Amean of the cirques is 2538 m. The H shows a minimum value of 135 m and maximum of 947 m, with a mean value of 448 m (Table 2).

The glacial cirques are generally distributed at lower altitudes in the Aran valley than in the Boí valley (Figure 4), with 8.4% of the landforms placed below 2000 m. Most of the glacial cirques sit between 2200 and 2400 m (42.9%) and decrease remarkably at higher elevations, with 18.5% in the range 2400-2600 m. Only four cirques (3.3%) are located in terrain above 2600 m.

In the Boí valley, glacial cirques do not exist below 2000 m and, in contrast with the Aran valley, the elevation range of 2200-2400 m does not include most of the landforms (29.8%). The interval between 2400 and 2600 m corresponds to

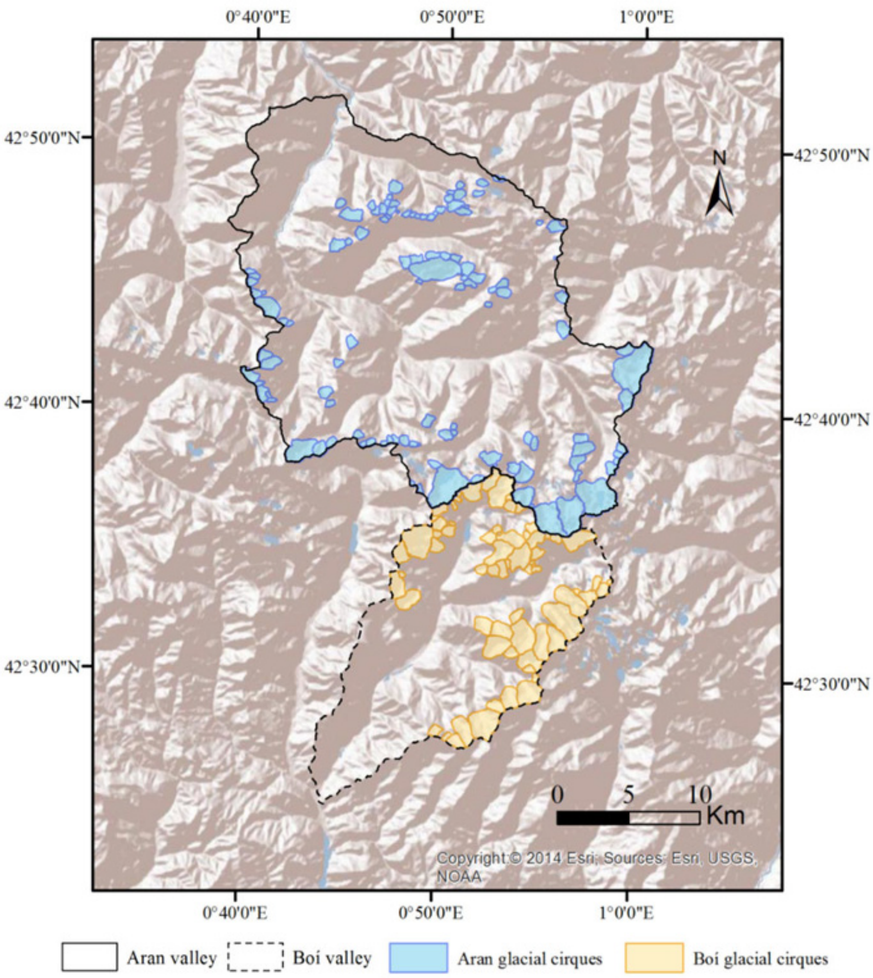

Figure 3 Map of the distribution of the glacial cirques in each valley.

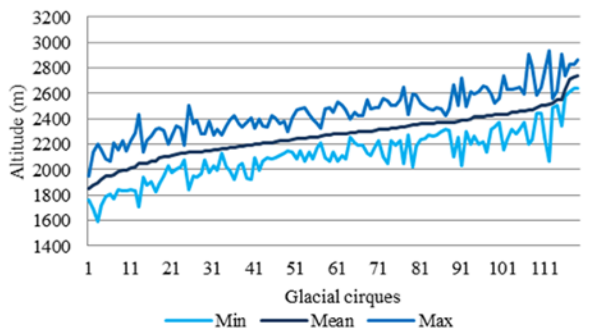

Figure 4 Distribution of Aran glacial cirques (arranged according to cirque elevation).

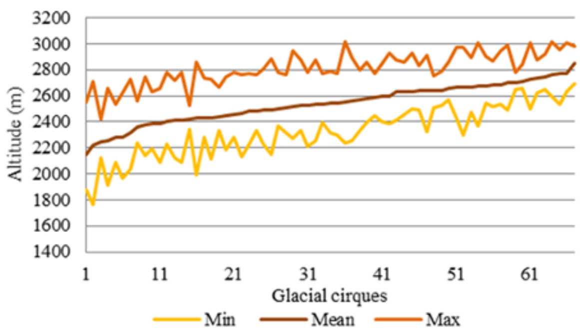

Figure 5 Distribution of Boí glacial cirques (arranged according to cirque elevation).

47.7% (Figure 6). Unlike the Aran valley, 13.4% of the glacial cirques developed above 2600 m.

Aran cirques show a prevailing NE aspect, which concentrates 39 units of the total (32.8%; Figure 5). The remaining cirques show prevailing N (16.8%), NW (12.6%), E (11.8%) and SE (11.8%) aspects, with the remainder concentrating less than 10% of the landforms. In the Boí valley, the glacial cirques do not show a clear prevailing aspect, with more landforms distributed SE (16.4%), S (16.4%) and N, NE and NW (14.9%) (Figure 7).

The analysis of the lithological composition of the glacial cirques in the Aran valley (Figure 8) does not reveal a dominant underlying lithology;

granite rocks are the most representative (36%), followed by a significant proportion of cirques shaped in detrital sedimentary rocks (33%) and limestone (31%). In the case of the Boí valley, the dominant lithological composition of the glacial cirques is granite (84%; Figure 8), with the remaining cirques divided between mixed limestone with shales (12%) and mixed sandstone with shales (4%).

3.2 The morphometry of glacial cirques

The morphometry of the cirque values shows significant differences between the valleys in terms of area, length, width and slope gradient.

In the Aran valley, the cirque area ranges from 3 to 614 ha, with a mean surface of 62 ha. The length of the glacial cirques ranges between 114 and 1821 m, and the widths between 306 and 1212 m, with average values of 385 and 257 m, respectively (Table 2). The mean cirque slopes are between 14° and 44°, with a mean of 28°. The area of glacial cirques in the Boí valley varies between 5 and 430 ha, with an average of 102 ha. The lengths range between 163 and 1666 m, and the widths between 100 and 1025 m, with averages of 385 and 390 m, respectively (Table 2). In this valley, the minimum mean slope of the cirques is 22° and the maximum 48°, with an average of 30°.

The maximum length and width of glacial cirques in the Aran valley increase at higher elevations. The longest cirques observed are within the range of 2400-2500 m (mean of 646 m), whereas the widest are found at 2500-2600 m (mean of 437 m) (Table 3). In cirques located at higher elevations, both values decrease considerably (265 and 137 m, respectively). This decline is also observable in H index, being relatively stable up to 2600 m (values between 299 and 389 m) but considerably lower above this level (196 m).

In the Boí valley, the glacial cirques show greater length, width and amplitude at higher altitudes. The longest (870 m) and widest (528 m) cirques are located within the elevation range of 2300-2400 m (Table 3). On the other hand, the cirque's amplitude presents a clear decreasing trend as elevations increase, the maximum being at 2000-2100 m (676 m) and the minimum in cirques above 2600 m (319 m).

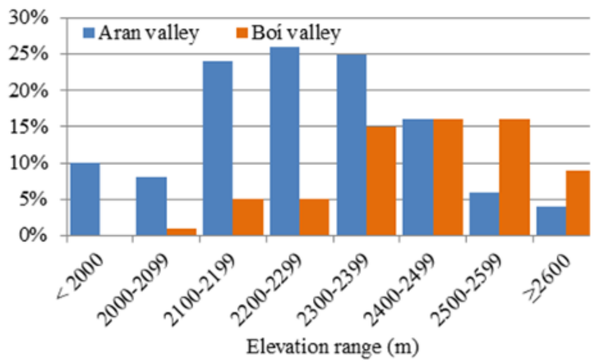

Figure 6 Distribution of glacial cirques in both valleys according to elevation range.

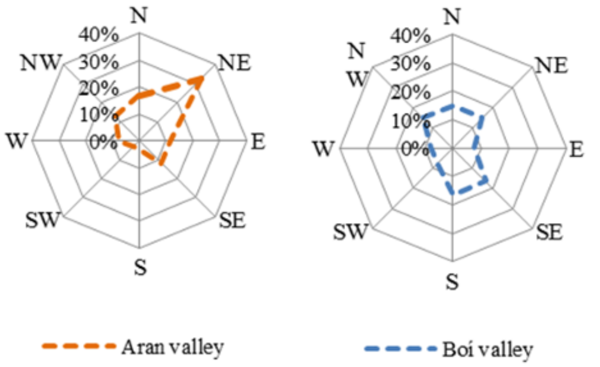

Figure 7 Distribution of glacial cirques in both valleys according to aspect.

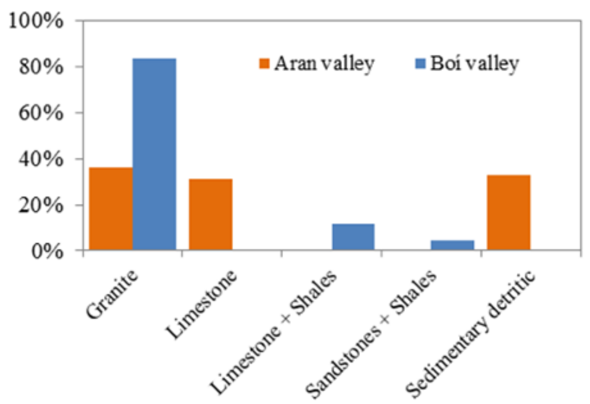

Figure 8 Distribution of glacial cirques according to underlying lithology.

The different morphology of the cirques in both valleys is reflected in the morphometrical ratios. Up to 2200 m, the L/W ratio indicates that Aran cirques have a more elongated shape than Boí units (2.0 versus 1.7). At higher elevations, within 2200-2600 m, cirques in both valleys present similar values; above 2600 m, Aran cirques reach a ratio of 1.9 but Boí cirques remain almost stable (1.6).

The L/H, indicator of cirque incision (Barr and Spagnolo 2015), reflects on both valleys an increasing trend up to 2400 m (Table 3). At this level, the ratios of Boí cirques decrease significantly, reaching the minimum value at 2500-2600 m (1.1), while Aran cirques start decreasing at 2500 m, reaching the minimum value at ≥ 2600 m (1.4). Another ratio indicator of cirque incision is W/H (Barr and Spagnolo 2015; Hughes et al. 2007; Krizek and Mida 2013), which shows a very similar pattern with altitude in both valleys (Table 3). However, at the highest altitudes this pattern changes, with Aran cirques on the elevation range of 2400-2600 m showing considerable differences to the values in the Boí valley (1.7 vs 1.2 in 2400-2500 m and 1.6 vs 1.1 in 2500-2600 m). This indicates a stronger incision in the Boí valley. In general, in both valleys, the values of size, length and width of glacial cirques increase (or decrease) significantly as altitude increases, whereas cirque relief (H index) increases at a lower rate.

3.3 Descriptive statistics of glacial cirque morphometry and correlation between variables

The descriptive statistics of the morphometrical parameters in the two valleys are summarized in Table 2. Amin, Amean, Amax, H, L, W, logV and Smean were significantly higher in Boí than in the Aran valley. No significant differences were observed in the remaining parameters. Regarding the different aspects, north-exposed cirques showed significant differences in Amin, Amean and Amax. NE cirques show significant differences in all the altitude parameters and H. In E and W aspects, significant differences were observed in Amean, Amax, H, W and LogV. In the case of W cirques, we also identified significant differences in Area, while NW units showed significant differences in Amin, Amean, Amax, H, L, Area and logV. In all the cases, the values were significantly higher in Boí than in the Aran valley. The comparison between the different aspects in the cirques located in the same valley did not reveal significant statistical differences (Table 4).

Overall, morphometrical parameters show a high correlation between both valleys (Table 5a and b). In the Aran valley, L showed high positive correlations with W, Area and logV. LogV also had high positive correlations with H, W and Area. Finally, Smean had high negative correlations with L/W and W/H. In the Boí valley, we also identified high positive correlations between L and W and Area and logV. Height had a high positive correlation with L, W, Area and logV. Finally, logV showed a high positive correlation with Area (Table 5).

3.4 Principal Component Analysis and spatial correlation and distribution analysis

Factor 1 explained 40.2% of the variance, while factors 2, 3 and 4 explained 25.1% 13.2% and 10.4% of the total variance, respectively. Factor 1 showed high negative loadings in H, L, W, Area, L/H. W/H and logV. Factor 2 identified high positive loadings in Amin, Amean, Amax, and Factor 3 in Smean. Finally, L/W had a high negative loading in factor 4 (Table 6). The relation between Factor 1 and 2 showed that the glacial cirques have different characteristics in the studied valleys (Figure 9). Morans *I* index analysis showed that F1, F2 and F3 had a significant clustered pattern, while F4 had a random distribution (Table 7) in the entire study area. The maps of the retained factors are shown in Figure 10. The valleys with high values in the variables explained by Factor 1 (negative loading) were located in the southern part of the Aran valley, while the valleys with high scores in factor 2 were clustered in the S of the Boí valley. The variables with high mean slope (factor 3) were located at N and E of the Aran valley and in the east of the Boí valley. Finally, the valleys with high L/W did not show any specific geographical distribution.

4 Discussion

4.1 Controls on cirque distribution and morphology in the Aran and the Boí valleys

The morphostructure of the Aran valley conditioned a larger number of glacial cirques than in the Boí valley. In the Aran valley, N and NE orientations prevail. In fact, previous works on other areas of the Pyrenees (García-Ruiz et al.

Table 2 Descriptive statistics of the studied variables in the different valleys. Bold letters represent significant differences at a p<0.05.

Parameters	Mean	Median	Min	Max	10 percentile	90 percentile	Standard deviation
	Aran / Boí / All	Aran / Boí / All	Aran / Boí / All	Aran / Boí / All	Aran / Boí / All	Aran / Boí / All	Aran / Boí / All
Amin	2113.9/2323.1/2189.2	**2111.3b/ 2330.0a**/2193.0	1589.3/1765.2/1589.3	2641.9/2696.9/2696.9	1834.7/2085.0/1884.9	2332.9/2593.7/2504.4	201.1/203.9 /225.3
Amean	2268.4/2537.7/2365.4	**2276.4b/2539.6a**/2369.0	1850/2146.3/1850.0	2736.6/2849.4/2849.4	2025.4/2315.0/2103.5	2471.8/2727.2/2663.8	176.9/152.0/212.2
Amax	2453.0/2811.3/2582.1	**2452.7b/2795.0a**/2560.5	1952.9/2416.9/1952.9	2935.1/3019.0/3019.0	2205.4/2634.3/2269.7	2668.8/2981.6/2905.0	187.1/130.4/241.1
H	339.2/488.2/392.8	**319.3b/469.6a**/385.62	66.9/134.6/66.9	865.1/947.5/947.5	170.4/273.9/187.7	560.0/686.7/625.1	146.9/165.4/162.3
L	462.6/637.1/ 528.6	**384.7b/534.3a**/443.2	114.3/163.3/114.3	1821.4/1666.2/1821.4	226.7/236.1/232.6	762.3/1140.9/991.7	306.2/351.9/332.7
W	306.6/410.6 /344	**256.8b/390.3a**/284.5	57.2/99.5/57.2	1212.9/1024.7/1212.9	136.6/152.7/142.2	471.5/696.7/617.3	198.1/214.2/209.5
Ar	62.6/102/76.8	31.1/61.7/39.2	2.9/5.1/2.9	614.2/430.1/614.2	10.0/14.9/11.3	117.2/247.1/197.2	103.1/99.0/103.1
L/H	1.4/1.3/1.4	1.2/1.2/1.2	0.60/0.60/0.60	3.6/2.3/3.6	0.86/0.8/0.8	2.2/1.9/2.2	0.59/0.43/ 0.54
L/W	1.6/1.6/1.6	1.5/1.4/1.5	1.0/1.0/1.0	2.8/2.7/2.8	1.2/1.1/1.1	2.1/2.2/2.1	0.35/0.42/0.38
W/H	0.92/0.82/0.88	0.85/0.81/0.82	0.29/0.30/0.29	2.1/1.5/2.1	0.53/0.50/0.53	1.5/1.2/1.3	0.36/0.26/0.33
logV	7.5/8.0/7.7	**7.5b/8a**/7.6	5.9/6.3/5.9	9.1/9.1/9.1	6.7/ 7.1/6.9	8.4/8.7/8.5	0.62/0.62/0.64
S_{mean}	28.4/31.1/29.4	**28.3b/30.2a** /29.5	14.3/21.7/14.3	44.5/47.7/47.7	20.3/26.2/21.8	36.7/37.8/36.7	6.0/4.7/5.7

Table 4 Median values for the studied values according to the different aspects. Bold letters represent significant differences at a p<0.05.

	N	NE	E	W	NW	KW p value	
	Aran / Boí / All	Aran / Boí / All	Aran / Boí / All	Aran / Boí / All	Aran / Boí / All	Aran	Boí
N of cirques	23 / 13 / 36	43 / 15 / 58	13 / 7 / 20	10 / 14 / 24	30 / 18 / 48		
Amin	**2084.4^{b}/2455.0^{a}**/2192.7	**2148.6^{b}/2315.2^{a}**/2193.5	2129.3/2298.4/2202.5	2153.2/2303.8/2244.6	**2078.9^{b}/2305.0^{a}**/ 2141.3	p=0.44	p=0.72
Amean	**2256.8^{b}/2642.5^{a}**/2365.7	**2292.9^{b}/2506.8^{a}**/2335.0	**2297.2^{b}/2598.2^{a}**/2413.8	**2306.1^{b}/2523.8^{a}**/ 2427.4	**2226.1^{b}/2485.1^{a}**/2353.6	p=0.52	p=0.32
Amax	**2427.5^{b}/2859.2^{a}**/2591.7	**2482.7^{b}/2780.0^{a}**/2525.9	**2482.9^{b}/2845.7^{a}**/2630.0	**2474.5^{b}/2828.0^{a}**/2648.2	**2415.8^{b}/2819.2^{a}**/2519.3	p=0.50	p=0.56
H	327.9/477.3/370.8	**306.7^{b}/441.4^{a}**/ 327.9	**359.0^{b}/568.7^{a}**/412.0	**285.8^{b}/503.3^{a}**/412.9	**320.5^{b}/484.8^{a}**/388.7	p=0.73	p=0.47
L	437.3/486.9/462.1	377.4/452.9/430.2	332.8/832.2/408.9	428.7/610.5/476.5	**380.2^{b}/593.5^{a}**/416.9	p=0.83	p=0.71
W	252.4/305.8/262.3	256.8/357.5/269.0	**239.3^{b}/512.3^{a}**/266.2	**295.4^{b}/438.9^{a}**/329.7	263.0/373.0/277.1	p=0.93	p=0.39
Ar	39.5/59.7/40.1	31.1/51.1/37.0	26.5/133.9/34.9	**42.5^{b}/79.3^{a}**/53.7	**31.0^{b}/ 67.6^{a}**/ 34.3	p=0.88	p=0.52
L/H	1.3/1.2/1.3	1.2/1.1/1.2	1.1/1.4/1.2	1.4/1.3/1.3	1.2/1.1/1.2	p=0.47	p=0.79
L/W	1.6/1.7/1.6	1.5/1.6/1.5	1.5/1.4/1.5	1.5/1.3/1.4	1.5/1.4/1.4	p=0.88	p=0.75
W/H	0.81/0.67/0.81	0.88/0.81/0.82	0.82/0.98/0.9	1.1/0.9/0.9	0.9/0.7/0.8	p=0.56	p=0.22
logV	7.5/8.0/7.6	7.6/7.9/7.6	**7.4^{b}/8.4^{a}**/7.6	**7.6^{b}/8.1^{a}**/7.9	**7.4^{b}/8.1^{a}**/7.6	p=0.92	p=0.50
S_{mean}	27.4/35.9/30.5	28.9/33.1/29.2	29.5/33.5/29.5	24.3/32.6/29.2	28.3/37.8/29.3	p=0.56	p=0.19

Table 3 Morphometric values by valleys and by elevation range (Aran/Boí).

Elevation range (m)	< 2000	2000-2099	2100-2199	2200-2299	2300-2399	2400-2499	2500-2599	≥ 2600
∑ elements	10/0	8/1	24/5	26/5	25/15	16/16	6/16	4 /9
H	368/0	375/676	340/619	299/527	330/552	373/515	389/432	196 /319
L	455/0	425/690	445/792	389/721	487/870	646/613	625/480	265 /402
W	319/0	263/525	226/470	252/410	318/528	419/443	437/307	137 /252
L/W	1.4/0	1.6/1.3	2.0/1.7	1.5/1.8	1.5/1.7	1.5/1.4	1.4/1.7	1.9/1.6
L/H	1.2/0	1.1/1.0	1.3/1.3	1.3/1.4	1.5/1.6	1.7/1.2	1.6/1.1	1.4/1.7
W/H	0.87/0	0.7/0.78	0.66/0.76	0.84/0.78	0.96/0.96	1.1 / 0.86	1.1/0.71	0.7/0.79

Table 5 Spearman correlation coefficient of the studied variables in: (a) Aran valley, and (b) Boí valley. Significant differences were considered at $p<0.05^{*}$, $p<0.01^{**}$, and $p>0.001^{***}$

A	Amin	Amean	Amax	H	L	W	Ar	L/H	L/W	W/H	LogV	S_{mean}
Amin	-											
Amean	0.90^{***}	-										
Amax	0.71^{***}	0.92^{***}	-									
H	-0.50^{***}	-0.14	0.18^{*}	-								
L	-0.16	0.08	0.28^{**}	0.66^{***}	-							
W	-0.27^{**}	-0.03	0.18^{*}	0.68^{***}	0.89^{***}	-						
Ar	-0.22^{*}	0.02	0.23^{*}	0.68^{***}	0.97^{***}	0.97^{***}	-					
L/H	0.41^{***}	0.35^{***}	0.26^{**}	-0.21	0.52^{***}	0.38^{***}	0.46^{***}	-				
L/W	0.14	0.14	0.15	-0.05	0.19	-0.24^{**}	-0.03	0.25^{**}	-			
W/H	0.31^{***}	0.25^{**}	0.15	-0.18	0.42^{***}	0.51^{***}	0.48^{***}	0.83^{***}	-0.27^{**}	-		
logV	-0.34^{***}	-0.04	0.23^{*}	0.85^{***}	0.93^{***}	0.94^{***}	0.96^{***}	0.25^{**}	-0.05	0.28^{**}	-	
S_{mean}	-0.33^{***}	-0.24^{**}	-0.15	0.19	-0.43^{***}	-0.44^{***}	-0.45^{***}	-0.81^{***}	0.08	-0.87^{***}	0.25^{**}	-
B	Amin	Amean	Amax	H	L	W	Ar	L/H	L/W	W/H	LogV	S_{mean}
Amin	-											
Amean	0.91^{***}	-										
Amax	0.61^{***}	0.82^{***}	-									
H	-0.76^{***}	-0.48^{***}	-0.01	-								
L	-0.63^{***}	-0.44^{***}	-0.00	0.82^{***}	-							
W	-0.62^{***}	-0.43^{***}	-0.02	0.80^{***}	0.91^{***}	-						
Ar	-0.63^{***}	-0.43^{***}	0.00	0.83^{***}	0.98^{***}	0.97^{***}	-					
L/H	-0.28^{*}	-0.23	-0.04	0.33^{**}	0.78^{***}	0.67^{***}	0.74^{***}	-				
L/W	-0.04	-0.02	0.06	0.09	0.29^{*}	-0.09	0.11	0.40^{***}	-			
W/H	-0.18	-0.14	-0.03	0.23	0.58^{***}	0.74^{***}	0.66^{***}	0.75^{***}	-0.26^{*}	-		
logV	-0.68^{***}	-0.46^{***}	-0.01	0.89^{***}	0.97^{***}	0.96^{***}	0.99^{***}	0.67^{***}	0.11	0.58^{***}	-	
S_{mean}	0.32^{**}	0.39^{**}	0.31^{*}	-0.17	-0.48^{***}	-0.47^{***}	-0.48^{***}	0.68^{***}	-0.06	-0.65^{***}	-0.43^{***}	-

2000), the Cantabrian Mountains (Ruiz-Fernández et al. 2009; Gómez-Villar et al. 2015), the Western French-Italian Alps (Federici and Spagnolo 2004), and the Tatras Mountains (Krizek and Mida 2013) showed evidence that most of the cirques in European mountain ranges developed in northern aspects,; this is also a widespread pattern in the Northern Hemisphere (Trenhaile 1975; Evans 1977; Evans and Cox 1995).

In mid-high latitude environments (30°-70°) there is a strong contrast in the activity of glacial and periglacial processes shaping glacial cirques between north and south-facing slopes (Evans 2006a). Most of the cirques in the Aran valley have a NE aspect, and thus receive more radiation during the morning when temperatures are lower; this leads to limited malting of snow and ice and therefore favours glacial development due to the lower ice mass loss (Coleman et al. 2009). In addition, the eastward pattern of the cirques may also be favoured by the wind-drifted snow due to prevailing W and SW winds, as also observed in other European massifs (Mindrescu and Evans 2014; Barr et al. 2017). In the south-exposed and N-S elongated Boí valley, the preglacial relief determines a complex spatial pattern with prevailing S and SE aspects, although several mountain ridges also favoured the development of cirques in northern aspects (N, NW, NE). More intense and frequent northern winds during Quaternary glacial stages may also have promoted the transport of snow from the summit surfaces to S and SE cirques, as observed by Delmas et al. (2014) in the Eastern Pyrenees.

The lithology of the study areas conditions the dimensions and morphology of the cirques. While in the Aran valley most cirques are located on sedimentary and granitic rocks, in the Boí valley they are shaped mainly on granite bedrock. The cirques shaped in detrital sedimentary and granite materials are larger, showing greater width and length except for those located at low altitudes. In the Western Pyrenees, García-Ruiz et al. (2000) observed that the majority of the cirques were located on limestone rocks, while Delmas et al. (2014) identified that the greater abundance occurred on gneiss and schist. In other Iberian massifs such as the Cantabrian Mountains, Ruiz-Fernández et al. (2009) and Gómez-Villar et al. (2015) found that glacial cirques were mostly located on quartzite, limestone, sandstone and slate, which constitute the predominant rocky substrate in this mountain range.

Preglacial relief also determines the elevation of the cirques, though its role is difficult to assess (Ruiz-Fernández et al. 2009). The northern aspect of the Aran valley explains the lower elevation of

Table 6 Factor scores for the variables studied in Aran and Boí valleys. Bold numbers represent the variables retained by each factor.

	Factor 1	Factor 2	Factor 3	Factor 4
Amin	0.102	**0.836**	-0.529	0.076
Amean	-0.142	**0.942**	-0.288	0.058
Amax	-0.390	**0.913**	-0.036	0.056
H	**-0.698**	0.192	0.659	-0.022
L	**-0.964**	0.011	0.121	-0.193
W	**-0.960**	-0.019	0.147	0.192
Ar	**-0.939**	-0.004	0.087	-0.010
L/H	**-0.652**	-0.242	-0.623	-0.294
L/W	-0.032	0.133	-0.069	**-0.984**
W/H	**-0.661**	-0.315	-0.585	0.298
logV	**-0.889**	0.041	0.343	0.023
S_{mean}	-0.472	0.419	**0.661**	-0.022

Table 7 Summary of Moran's I spatial autocorrelation index.

	Morans I index	z-score	*p*
Factor 1	0.330	7.224	0.0000
Factor 2	0.609	13.131	0.0000
Factor 3	0.216	4.759	0.0000
Factor 4	0.053	1.261	0.2070

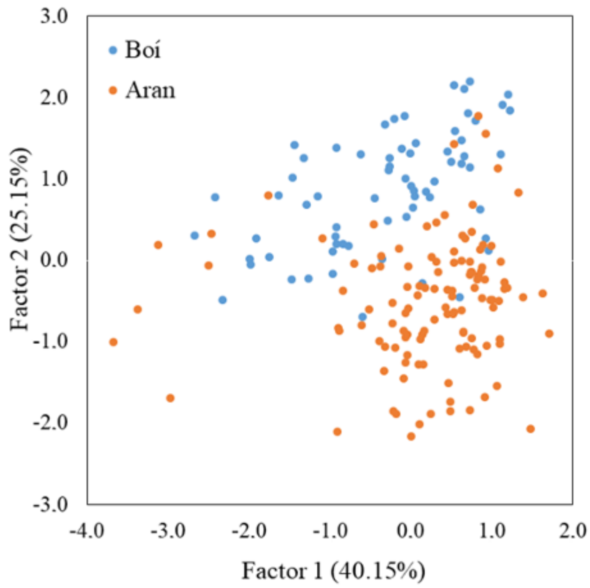

Figure 9 Relation between Factor 1 (glacial cirques dimensions variables) and Factor 2 (altitudinal variables).

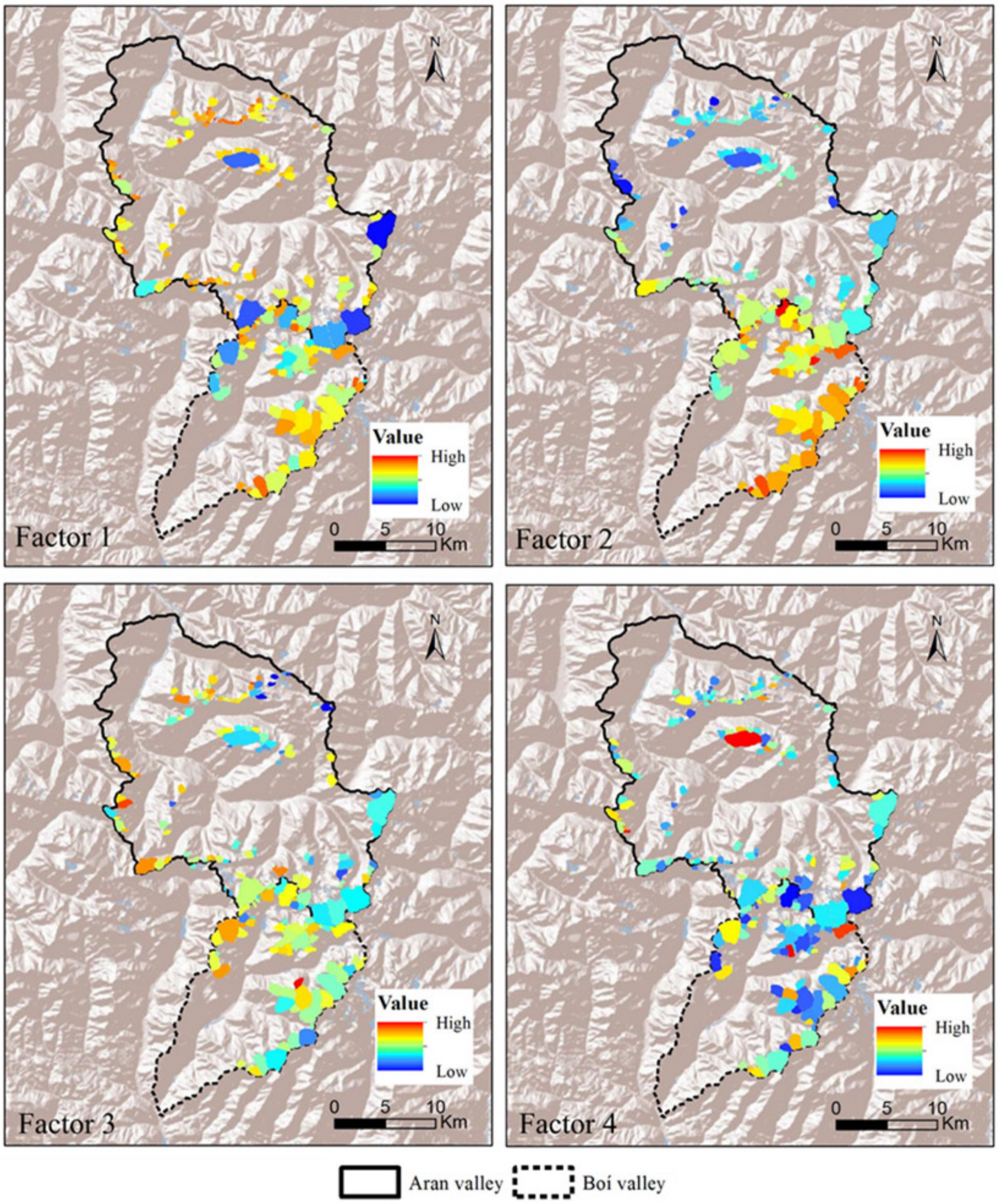

Figure 10 Spatial distribution of factor scores.

the glacial cirques when compared to the Boí valley. The altitude values of the cirques (Amin, Amean, Amax) are higher in the Boí valley than in Aran. This is conditioned, in many cases, by the lower elevation of the mountain ridges, where the intensity and duration of the glaciations was not enough to carve the hollows characteristic of the glacial cirques (Barr and Spagnolo 2015). Besides, their southern exposure did not favour snow accumulation and subsequent transformation into ice during Quaternary glaciations, impeding the deepening of these concavities by means of glacial erosion.

The cirques located in the Boí valley show very high H, L, and W and Log V values, and therefore represent larger features than Aran landforms. This situation was also observed when comparing the values of the different aspects (Table 4). The differences among the morphometric variables were especially different at the glacial cirques exposed NE. Overall, the Aran valley has a high number of glacial cirques, but they are larger in the Boí valley because here they are formed in sedimentary rocks. Another two secondary factors may influence their development: (1) Orientation may strongly increase the amount of snowfall within a mountain range, creating corridors for the penetration of air masses. 2) Glacier cirqus enlargement is strongly affected by freeze-thaw cycles, and a south-oriented valley in the Northern Hemisphere may experience wider temperature amplitudes than a north-facing valley (Federici and Spagnolo 2004; Hughes et al. 2007). These cycles increase rock weathering and geomorphological processes, contributing to valley excavation and increasing the main morphometric variables of cirques. Freeze-thaw cycles are especially active in detrital sedimentary rocks, which are very vulnerable to this process (Ni et al. 2017). Previous works on the Pyrenees (García-Ruiz et al. 2000; Delmas et al. 2014) and on the Alps (Federici and Spagnolo 2004) concur with our results. In this regard, Barr et al. (2017) observed that deeper glacier cirques are the ones closest to the coast and are more exposed to maritime air masses.

We identified a high correlation significant among cirque Area, LogV, H, L and M in both valleys, showing that the dimension of the glacial cirque is closely related to the difference between the highest and the lowest point, maximum distance between lateral walls and length of the median axis. This was also observed by Krizek and Mida (2013) in the Tatras Mountains and by García-Ruiz et al. (2000) in the Western Pyrenees. In the Aran valley we found a high correlation between Smean, L/H and W/H, showing that slope increase is linked to glacial incision, as observed by Krizek and Mida (2013). PCA grouped in Factor 1 glacial cirques dimensions variables (H, L, W, Log V and Area) and glacial incision indicators (L/H and L/W). In factor 2, altitudinal variables were grouped, whereas factor 3 explained Smean and factor 4 retained the indicator cirque shape (L/W). Larger cirques were located especially in the S of the Aran valley (Figure 3). This clustered pattern is confirmed by the Moran' I result and is coincident with the areas with granitic bedrock, confirming the idea that larger cirques are developed on this rock type. The formation of large cirques in granite is very likely attributed to the existence of faults that favour rock weathering (García-Ruiz et al. 2000). Factor 2 variables were also highly clustered in the eastern area and northern area of the Boí valley, where the elevation of the cirques is higher, also in granite areas. Slope inclination of the cirques is high in some areas located west of the Aran and Boí valley, and distributed across the different geological settings (granite, shale, sedimentary material). Therefore, the development of the cirques may be more dependent on topography than on lithology. Finally, cirques with a horizontal shape have a random distribution in the studied valleys. This shape is not associated to any topographic or geological characteristics, since this type of glacial cirque is present in very diverse topographic and lithological contexts (Figures 8 and 10).

The progressive increase (or decrease, in some cases) of the horizontal dimensions of the glacial cirques (size, length and width) in both valleys as altitude increases while vertical dimensions increase less shows evidence that the development of the glacial cirques studied follows an allometric model, as proposed by Evans (2004 and 2006b). This implies that the retreat of the headwall is faster than the erosion of the bottom of the cirque.

4.2 Morphology of the Aran and Boí cirques in comparison with other mountain areas

We have compared the morphometrical and topographical data of glacial cirques in the Aran and the Boí valleys with values from other mountain regions (Table 8) in order to increase our understanding of the processes driving the development of glacial cirques in the Central Pyrenees.

García-Ruiz et al. (2010) examined the spatial distribution and morphometry of glacial cirques in the southern side of the Central Pyrenees, upper Aragón and the Gállego basins, and observed that these features are concentrated between 2000 and 2200 m (Amin) and between 2500 and 2700 m (Amax). These data are similar to the average values in our study area (Amax: 2560 m; Amin: 2193 m), although cirques in the southern Boí valley show slightly higher elevations. With regard to aspect, the pattern is similar to the Boí valley, where glacial cirques show prevailing N and S aspects. In contrast, glacial cirques inventoried in this study show a substantially larger area (Table 8). However, as deduced from the L/H ratio showing analogous values in both valleys, glacier erosion

Table 8 Comparison of the morphometric parameters of the cirques in our study area with features from other mid-latitude mountains.

Parameters	Pyrenees			Other	
	Aran/Boí/All	Central Pyrenees	Eastern Pyrenees	W Alps	N Pindus
H	488.2/339.2/392.8	364	223	355	331
L	637.1/462.6/528.6	519	489	672	787
W	410.6/306.6/344.0	691	482	663	662
Ar	102.0/62.6/76.8	34	21	42	–
L/W	1.6/1.6/1.6	0.79	1.1	1.1	1.2
L/H	1.3/1.4/1.4	1.5	2.2	1.9	–
W/H	0.92/0.82/0.88	–	2.5	1.9	2.7
Reference	This study	García-Ruiz et al. (2000)	Delmas et al. (2014)	Federici and Spagnolo (2004)	Hughes et al. (2007)
Parameters	Pyrenees Aran/Boí/All	Upper Sil River basin	Central Mountains	W Picos de Europa	Sierras SW Asturias
H	488.2/339.2/392.8	277	237	294	255
L	637.1/462.6/528.6	625	468	295	487
W	410.6/306.6/344.0	707	655	467	594
Ar	102.0/62.6/76.8	37	24	11	23
L/W	1.6/1.6/1.6	0.96	0.8	0.78	0.9
L/H	1.3/1.4/1.4	2.3	2.1	1.08	2.0
W/H	0.92/0.82/0.88	2.5	3.0	1.7	2.5
Reference	This study	Gómez-Villar et al. (2015)	Gómez-Villar et al. (2015)	Ruiz-Fernández et al. (2009)	Ruiz-Fernández et al. (2009)

does not change significantly over relatively short distances. Glacial cirques studied in the Eastern Pyrenees by Delmas et al. (2014) have, on average, shorter lengths, greater widths, less relief (H index) and smaller surfaces than those studied in the Boí and Aran valleys (Table 8).

Previous studies of glacial cirques from different parts of the Cantabrian Mountains (Ruiz-Fernández et al. 2009; Gómez-Villar et al. 2015) examined how the differences in altitude, lithology and aspect explain the differences of the morphometrical parameters of glacial cirques within this mountain range. Ruiz-Fernández et al. (2009) presented the data of glacial cirques from two separate areas which showed significant differences: the Western Massif of Picos de Europa and the sierras of SW Asturias; Gómez-Villar et al. (2015) studied the glacial cirques of the Upper Sil River basin, and the Torío and Curueño river basins. In these regions, several glacial cirques with Amin below 1500 m were identified, but none of them shows an Amax located above 2220 m. In contrast, in the Aran and the Boí valleys, Amin, Amean and Amax show significantly higher values due to the higher elevation of the terrain in the Central Pyrenees (see Table 2). Generally, indexes of glacial excavation are higher in the Cantabrian Mountains (L/H of 1.1 and W/H of 1.7 in the Western Massif of Picos de Europa, L/H and W/H of 2.0 and 2.5 respectively in the sierras of SW Asturias; Ruiz-Fernández et al. 2009) than in the Boí and Aran valleys (L/H of 1.4 and W/H of 0.82 in Boí, and L/H of 1.3 and W/H of 0.88 in Aran). In the Upper Sil basin and the Torío and Curueño river basins, glacial cirques present a slightly higher incision with a similar H index but minor horizontal axes (L, W and Ar) (Gómez-Villar et al. 2015).

In spite of these differences, the aspect distribution of the glacial cirques follows the patterns previously identified in the Northern Hemisphere, also known as 'morning–afternoon' radiation contrast (Evans 1977; Delmas et al. 2014; Gómez-Villar et al. 2015). This is observed in the prevailing N and NE-facing slopes of these features, almost absent glacial cirques in W and SW, as well as increased dispersion at higher altitudes. However, in the Boí valley there is a remarkably high distribution of S and SE-facing glacial cirques due to the organization of the valley's relief (Figure 7).

The global dataset of glacial cirques examined in Barr and Spagnolo (2015) enables one to infer the spatial patterns of the morphometrical properties of glacial cirques in different cold-climate regions. As shown in the Aran and the Boí valleys, Barr and Spagnolo (2015) also highlight the role of geological material, valley orientation and regional and local climate characteristics in the geographical pattern of cirque morphology and distribution. The largest cirques are located in Antarctica and the smallest in mid-latitude areas, although with remarkable differences in similar latitudes such as cirques in New Hampshire (Davis 1999), Spain (García-Ruiz et al. 2000; Ruiz-Fernández et al. 2009; Gómez-Villar et al. 2015) or the Gilort Basin in Romania (Marinescu 2007). The horizontal mean values of the cirques in the Aran and the Boí valleys are lower than the average of all the studies considered in Barr and Spagnolo (2015) (L = 528 m vs 744 m, W = 344 vs 749 m). The average H index of the glacial cirques in our study areas (H = 392 m) is similar to the values obtained in the Gilort Basin, Romania (H = 358; Marinescu 2007), and Norway, Sweden and Finland (H = 400; Hassinen 1998).

5 Conclusions

We conducted an accurate spatial and morphometrical analysis of the glacial cirques in two valleys of the Central Pyrenees – one north-exposed (the Aran valley), and the other south-exposed (the Boí valley) – in order to better understand the factors controlling their distribution and development. Data on the topographic, morphometrical and lithological properties of the glacial cirques also enable one to infer that the paleoclimate conditions that trigger their formation and growth.

Glacial cirques in the Aran and the Boí valleys show morphometrical properties similar to those reported in other mid-latitude environments. The local topography and microclimate conditions impose substantial differences on both valleys in terms of the morphology and dimensions of the cirques. While these landforms in the Aran valley are predominantly NE oriented, with the cirque floors mostly distributed between 2200 and 2400 m (43%), in the Boí valley these features show no prevailing aspect at altitudes mainly concentrated between 2400 and 2600 m (48%). Glacial cirques in the Boí valley are larger than in Aran, though the dimensions of the cirques decrease with elevation in both valleys. Lithology does not control the distribution of the cirques, but it conditions their morphology, as shown by some lithological settings (i.e. granite) that favour the development of larger cirques.

Our understanding of the spatial properties and development process of the cirques allow one to define the role of Quaternary glaciations and post-glacial environmental dynamics in the shaping of the landscape of the highest lands in the Pyrenees. In this context, an accurate and thorough understanding of the different land systems interacting in mountain environments is of the utmost importance in order to better understand current landscape dynamics in high mountains, as well as to assess management policies in environmental protected areas such as the Aigüestortes and Sant Maurici Lake National Park, located in the study areas.

Acknowledgements

Field work was supported by the Research Group Climate Change and Environmental Systems (ZEPHYRUS) of the Institute of Geography and Spatial Planning of the University of Lisbon and a grant from the Erasmus + LLP Programme Grant funding the research stay of Luis Lopes at the University of Barcelona. Marc Oliva is supported by the Ramón y Cajal Program of the Spanish Ministry of Economy and Competitiveness (RYC-2015-17597). Financial support was also provided by the research group ANTALP (Antarctic, Arctic and Alpine environments, 2017-SGR-1102) and the PALEOGREEN (CTM2017-87976-P) and CRONOANTAR (CTM2016-77878-P) projects of the Spanish Ministry of Economy and Competitiveness.

References

Aniya M, Welch R (1981) Morphometric analyses of Antarctic cirques from photogrammetric measurements. Geografiska Annaler: Series A, Physical Geography 63(1-2): 41-53. https://doi.org/10.2307/520563

Barr LD, Spagnolo M (2015) Glacial cirques as palaeoenvironmental indicators: Their potential and limitations. Earth-Science Reviews 151: 48-78. https://doi.org/10.1016/j.earscirev.2015.10.004

Barr ID, Ely JC, Spagnolo M, et al. (2017) Climate patterns during forming periods of mountain glaciation in Britain

and Ireland: Inferences from cirque record. Palaeogegraphy, Palaeoclimatology, Palaeoecology 485: 466-475.
https://doi.org/10.1016/j.palaeo.2017.07.001
Bordonau J (1992) Els complexos glacio-lacustres relacionats amb el darrer cicle glacial als Pirineus. PhD Thesis, Barcelona University, Barcelona, Spain. (The glacier-lacustrine complexes related to the last glacial cycle in the Pyrenees (In Catalan))
Calvet C, Delmas M, Gunnell Y, et al. (2011) Recent Advances in research on Quaternary glaciations in the Pyrenees. In: Ehlers J, Gibbard PL, Hughes PD, editors: Developments in Quaternary Science, Vol. 15, Amsterdam, The Netherlands. pp. 127-139.
https://doi.org/10.1016/B978-0-444-53447-7.00011-8
Calvet M (2004) The Quaternary glaciation of the Pyrenees. Ehlers J, Gibbard P (Eds.) Quaternary Glaciations - Extent and Chronology, Part I: Europe. Elsevier, Amsterdam, Holland. pp 119-128.
https://doi.org/10.1016/s1571-0866(04)80062-9
Chueca J, Julián A (2011) Besiberris glacigenic rock glacier (Central Pyrenees, Spain): mapping surface horizontal and vertical movement (1993-2003). Cuadernos de Investigación Geográfica, 37 (2): 7-24.
https://doi.org/10.18172/cig.1254
Clark PU, Dyke AS, Shakun JD, et al. (2009) The Last Glacial Maximum. Science 325: 710.
https://doi.org/10.1126/science.1172873
Coleman CG, Carr SJ, Parker AG (2009) Modelling topoclimatic controls on palaeoglaciers: implications for inferring palaeoclimate from geomorphic evidence. Quaternary Science Reviews 28 (3): 249-259.
https://doi.org/10.1016/j.quascirev.2008.10.016
De Bolós O (2001) Vegetació dels Països Catalans. Aster Editorial, Terrassa. (In Catalan)
Davis PT (1999) Cirques of the Presidential Range, New Hampshire, and surrounding alpine areas in the northeastern United States. Géographie physique et Quaternaire 53 (1): 25-45.
https://doi.org/10.7202/004784ar
Delmas M (2015) The last maximum ice extent and subsequent deglaciation of the Pyrenees: an overview of recent research. Cuadernos de Investigación Geográfica 41 (2): 359-387. https://doi.org/10.18172/cig.2708
Delmas M, Gunnell Y, Braucher R, et al. (2008). Exposure age chronology of the last Glaciation in the eastern Pyrenees. Quaternary Research, 69 (2): 231-241.
https://doi.org/10.1016/j.yqres.2007.11.004
Delmas M, Gunnell Y, Calvet M (2014) Environmental controls on alpine cirque size. Geomorphology 206: 318-329. https://doi.org/10.1016/j.geomorph.2013.09.037
Depellegrin D, Pereira P, Misiune I, et al. (2016) Mapping ecosystem services potential in Lithuania. International Journal of Sustainable Development & World Ecology 23: 441-455.
https://doi.org/10.1080/13504509.2016.1146176
Derbyshire E, Evans IS (1976). The climatic factor in cirque variation. In: Derbyshire E (ed.): Geomorphology and Climate. John Wiley & Sons. Chichester, UK. pp 447-494.
Domínguez-Villar D, Carrasco RM, Pedraza J, et al. (2013) Early maximum extent of paleoglaciers from Mediterranean mountains during the Last Glaciation. Scientific Reports, 3, 2034.
https://doi.org/10.1038/srep02034
Evans IS (1977) World-wide variations in the direction and concentration of cirque and glaciers aspects. Geografiska Annaler, Series A, Physical Geography 59 (3-4): 151-169.
https://doi.org/10.2307/520797
Evans IS (1990) Climatic effect on glacier distribution across the southern coast mountains. B. C., Canada. Annals of Glaciology 14: 58-64.
https://doi.org/10.3189/s0260305500008272
Evans IS (2004) Cirque, glacial. In: Goudie AS (ed.), Encyclopedia of Geomorphology. Routledge, London, UK. pp 154-158.
Evans IS (2006a) Local aspect asymmetry of mountain glaciation: A global survey of consistency of favored directions for glacier number and altitudes. Geomorphology 73: 166-184.
https://doi.org/10.1016/j.geomorph.2005.07.009
Evans IS (2006b) Allometric development of glacial cirque form: Geological, relief and regional effects on the cirques of Wales. Geomorphology 80: 245-266.
https://doi.org/10.1016/j.geomorph.2006.02.013
Evans IS, Cox NJ (1995) The form of glacial cirques in the English Lake District, Cumbria. Zeitschrift für Geomorphologie, N.F. 39 (2): 175-202.
Evans IS, Cox NJ (2015) Size and shape of glacial cirques: comparative data in specific geomorphometry. In: Jasiewicz J et al. (eds.), Adam Mickiewicz University in Poznań - Institute of Geoecology and Geoinformation, International Society for Geomorphometry, Poznań, Poland. pp 79-82. ISBN: 978-83-7986-059-3
Federici PR, Spagnolo M (2004) Morphometric analysis on the size, shape and areal distribution of glacial cirques in the Maritime Alps (Western French-Italian Alps). Geografiska Annaler: Series A, Physical Geography 86 (3): 235-248.
https://doi.org/10.1111/j.0435-3676.2004.00228.x
Fernandes M, Oliva M, Palma P, et al. (2017) Glacial stages and post-glacial environmental evolution in the Upper Garonne valley, Central Pyrenees. Science of the Total Environment 584-585: 1282-1299.
https://doi.org/10.1016/j.scitotenv.2017.01.209
García Ruiz JM, Gómez-Villar A, Ortigosa L, et al. (2000) Morphometry of glacial cirques in the Central Spanish Pyrenees. Geografiska Annaler: Series A, Physical Geography 82A (4): 433-442.
https://doi.org/10.1111/j.0435-3676.2000.00132.x
García-Ruiz JM, Moreno A, González-Sampériz P, et al. (2010) La cronología del último ciclo glaciar en las montañas del sur de Europa. Una revisión. Revista Cuaternario y Geomorfología 24 (1-2): 35-46. ISSN: 0214-1744. (The chronology of the last glacial cycle in the mountains of southern Europe. A review. (In Spanish))
García-Ruiz JM, Palacios D, González-Sampériz P, et al. (2016) Mountain glacier evolution in the Iberian Peninsula during the Younger Dryas. Quaternary Science Reviews 138: 16-30.
https://doi.org/10.1016/j.quascirev.2016.02.022
Gómez-Villar A, Santos-González J, González-Gutiérrez RB, et al. (2015) Glacial cirques in the southern side of the Cantabrian Mountains of southwestern Europe. Geografiska Annaler: Series A, Physical Geography 97: 633-651. https://doi.org/10.1111/geoa.12104
Gordon JE (1977) Morphometry of cirques in the Kintail–Affric–Cannich area of northwest Scotland. Geografiska Annaler Series A Physical Geography 59: 177-194.
https://doi.org/10.2307/520798
Hassinen S (1998) A morpho-statistical study of cirques and cirque glaciers in the Senja-Kilpisjärvi area, northern Scandinavia. Norsk Geografisk Tidsskrift-Norwegian Journal of Geography 52(1): 27-36.
https://doi.org/10.1080/00291959808552381
Hughes PD, Woodward JC, Gibbard PL (2006) Quaternary glacial history of the Mediterranean mountains. Progress

in Physical Geography 30 (3): 334-364.
https://doi.org/10.1191/0309133306pp481ra

Hughes PD, Gibbard PL, Woodward JC (2007) Geological controls on Pleistocene glaciation and cirques form in Greece. Geomorphology 88: 242-253.
https://doi.org/10.1016/j.geomorph.2006.11.008

Hughes PD (2014) Little Ice Age glaciers in the Mediterranean mountains - Glaciers du petit âge de glace en Méditerranée. Méditerranée n 122.
https://doi.org/10.4000/mediterranee.7146

Krizek M, Mida P (2013) The influence of aspect and altitude on the size, shape and spatial distribution of glacial cirques in the High Tatras (Slovakia, Poland). Geomorphology 198: 57-68.
https://doi.org/10.1016/j.geomorph.2013.05.012

López-Moreno JI, Revuelto J, Rico I, et al. (2016) Thinning of the Monte Perdido Glacier in the Spanish Pyrenees since 1981. The Cryosphere 10: 681-694.
https://doi.org/10.5194/tc-10-681-2016

Marinescu E (2007) The morphometry of the glacial cirques within the Gilort Basin. Analele Universităţii din Craiova. Seria Geografie 10: 5-12.

Mindrescu M, Evans IS (2014) Cirque form and development in Romania: Allometry and the buzzsaw hypothesis. Geomorphology 208: 117-136.
https://doi.org/10.1016/j.geomorph.2013.11.019

Monserrat MS (1988) Estudi geomorfològic del massís central de la Vall d'Aran (Pirineu Central). BSc Thesis, Barcelona University, Barcelona, Spain. (Geomorphological study of the central massif of the Vall d'Aran (Central Pyrenees) (In Catalan))

Ni J, Chen Y-L, Wang P, et al. (2017) Effects of chemical erosion and freeze-thaw cycling on the physical and mechanical characteristics of granites. Bulletin of Engineering Geology and the Environment 76: 169-179.
https://doi.org/10.1007/s10064-016-0891-5

Palacios D, Andrés N, López-Moreno JI, et al. (2015a) Late Pleistocene deglaciation in the upper Gállego Valley, central Pyrenees. Quaternary Research 83(3): 397-414.
https://doi.org/10.1016/j.yqres.2015.01.010

Palacios D, Gómez-Ortiz A, Andrés N, et al. (2015b) Maximum extent of Late Pleistocene glaciers and last deglaciation of La Cerdanya mountains, Southeastern Pyrenees. Geomorphology 231: 116-129.
https://doi.org/10.1016/j.geomorph.2014.10.037

Palacios D, Gómez-Ortiz A, Andrés N, et al. (2016) Timing and new geomorphologic evidence of the last deglaciation stages in Sierra Nevada (southern Spain). Quaternary Science Reviews 150: 110-129.
https://doi.org/10.1016/j.quascirev.2016.08.012

Pallàs R, Rodés A, Braucherb R, et al. (2006) Late Pleistocene and Holocene glaciation in the Pyrenees: a critical review and new evidence from ^{10}Be exposure ages, south-central Pyrenees. Quaternary Science Reviews 25 (21-22): 2937-2963.
https://doi.org/10.1016/j.quascirev.2006.04.004

Pereira P, Cerdà A, Úbeda X, et al. (2015) Modelling the impacts of wildfire on ash thickness in a short-term period. Land Degradation and Development 26: 180-192.
https://doi.org/10.1002/ldr.2195

Ruiz-Fernández J, Poblete-Piedrabuena MA, Serrano-Muela MP, et al. (2009) Morphometry of glacial cirques in the Cantabrian Range (Northwest Spain). Zeitschrift für Geomorphologie 53 (1): 47-68.
https://doi.org/10.1127/0372-8854/2009/0053-0047

Serrat D, Martí M, Bordunau J (1994a) Geologia, Geomofologia e Risques, em: Geografia Física. Atlas comarcau de Catalunya-Val d'Aran. Institut Cartogràfic de Catalunya. Generalitat de Catalunya.

Serrat D, Bordonau J, Bru J, et al. (1994b) Síntesis cartográfica del glaciarismo surpirenaico oriental. Martí Bono C, García-Ruiz JM (eds.), El Glaciarismo Surpirenaico: Nuevas Aportaciones. Geoforma Ediciones, Logroño, Spain. pp 9-15. (Cartographic synthesis of the oriental surpirenaico glaciarismo. Martí Bono C, García-Ruiz JM (eds.): The Surpirenaic Glaciarism: New Contributions. (In Spanish))

Trenhaile AS (1975) Cirque elevation in the Canadian Cordillera. Annals of the Association of American Geographers, 65(4): 517-529.
https://doi.org/10.1111/j.1467-8306.1975.tb01059.x

Turu V, Calvet M, Bordonau J, et al. (2016) Did Pyrenean glaciers dance to the beat of global climatic events? Evidence from the Würmian sequence stratigraphy of an ice-dammed palaeolake depocentre in Andorra. In: Hughes PD et al. (eds.), Quaternary Glaciation in the Mediterranean Mountains. Geological Society, Special Publications, London, UK. pp 433.
https://doi.org/10.1144/SP433.6#2016

Vilaplana JM (1983) Estudi del glaciarisme quaternari de les Altes Valls de la Ribargorça. PhD Thesis, Barcelona University, Barcelona, Spain. (Study of the quaternary glaciation of the high valleys of La Ribagorça (In Catalan))