MORPHOMETRY OF GLACIAL CIRQUES IN THE CENTRAL SPANISH PYRENEES

BY
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ABSTRACT. A total of 206 glacial cirques have been identified in the high valleys of the Aragón and Gállego rivers, Central Spanish Pyrenees, in order to study the environmental factors explaining their distribution (altitude, aspect, lithology) and diverse morphometric features (area, width, length, *L/W* relations, etc.). The use of bivariate and multivariate statistical analyses confirms that a part of the morphometric variability of the glacial cirques is explained by the environmental factors considered here, but their influence is relatively limited. Altitude is identified as the most important factor, affecting both the length and the degree of over-deepening of the cirques. The role of lithology is less obvious because of its interaction with altitude.

Key words: glacial cirques, cirque morphometry, cirque distribution, cirque classification, Pyrenees

Introduction

Scientific literature on the study of Pyrenean Pleistocene glaciers (see Martínez de Pisón and Antón 1981; García-Ruiz and Martí-Bono 1994; Bordonau 1994; Chueca *et al.* 1998) has focused especially on location and dating of glacial and glaciolacustrine deposits. These deposits have been used as a reference for assessing the maximum extent of the Quaternary Pyrenean glaciers and the successive stages of stagnation and retreat. Nevertheless, very few references exist on glacial forms, with only short descriptions confirming the importance of Quaternary glacial erosion. The studies of Martínez de Pisón (1989) and Serrano (1998) are exceptions to this general rule.

Studies on cirque morphometry have been relatively frequent in other mountains of the world. Thus Embleton and Hamann (1988) compared the cirque forms between the Austrian Alps and the Highlands of Scotland; Aniya and Welch (1981) realized a morphometric analysis of the Antarctic cirques; Trenhaile (1976) analysed the cirque morphometry in the Canadian Rocky Mountains; Unwin (1973) studied the aspect and distribution of cirques and nivation holes in Wales; Vilborg (1984) analysed the cirque forms in central Sweden; Rudberg (1984) and Rapp (1984) have studied cirques and nivation holes at low altitudes in central and southern Sweden respectively; and Evans and Cox (1995) have studied the cirque forms in the Lake District, England. On a world scale, Evans (1977) has analysed the distribution of cirques according to aspect. Recently, Alonso (1994) has related various morphometric features of glacial cirques to lithology, aspect and geological structure in the Cantabrian Mountains, northern Spain.

Available geomorphological maps from the Central Spanish Pyrenees (García-Ruiz 1991; García-Ruiz *et al.* 1994) confirm that glacial cirques have a great variety of forms and sizes. Such diversity is related to a series of topographic and structural factors that have encouraged glacial erosion. The main purpose of this paper is to analyse the morphometric diversity of glacial cirques, to classify them morphometrically and to explain the relative influence of different environmental factors.

The study area

The study area coincides with the upper Aragón and Gállego river basins, in the Central Spanish Pyrenees (Fig. 1). All of these valleys run from north to south, crossing the geological structure of the Pyrenees, which is organized in parallel bands from west to east (Fig. 2). The northernmost part corresponds to the Axial or Palaeozoic Pyrenees, with predominance of Devonian slate and schist, Carboniferous limestone and Permian clay and sandstone, and the granitic batholiths of Panticosa and Balaitus. Both lithological diversity and tectonic complexity explain the strong contrast of re-

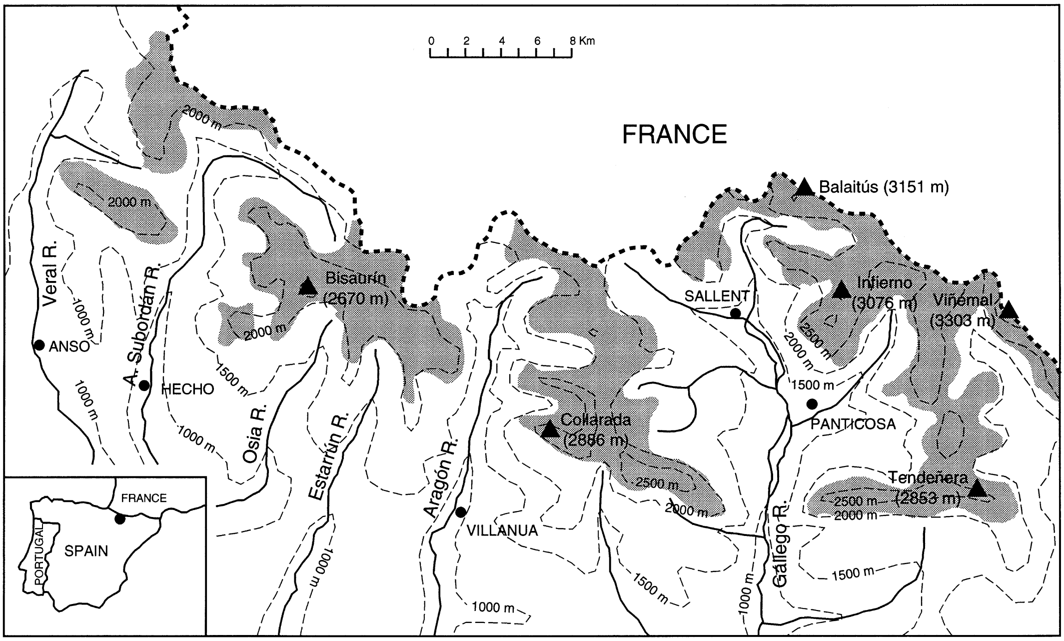

Fig. 1. The study area. Dark areas correspond to the sectors where glacial cirques are located.

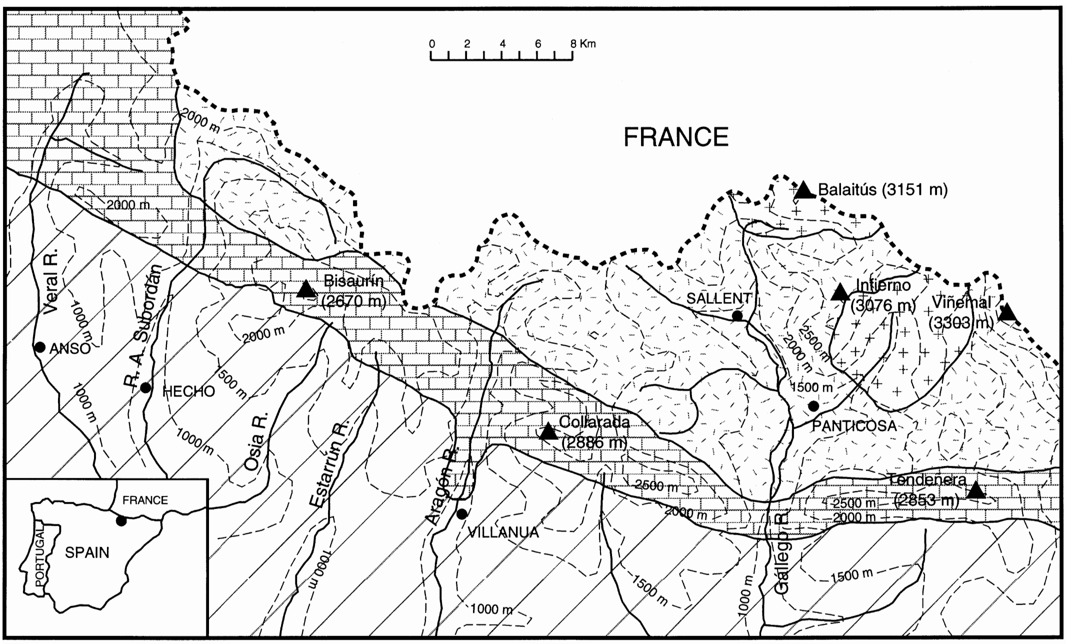

Fig. 2. Structural, simplified framework of the upper valleys of the Aragón and Gállego rivers. 1, Axial, Palaeozoic Pyrenees; 2, granitic massifs; 3, inner sierras (Cretaceous and Eocene); 4, flysch sector, Eocene.

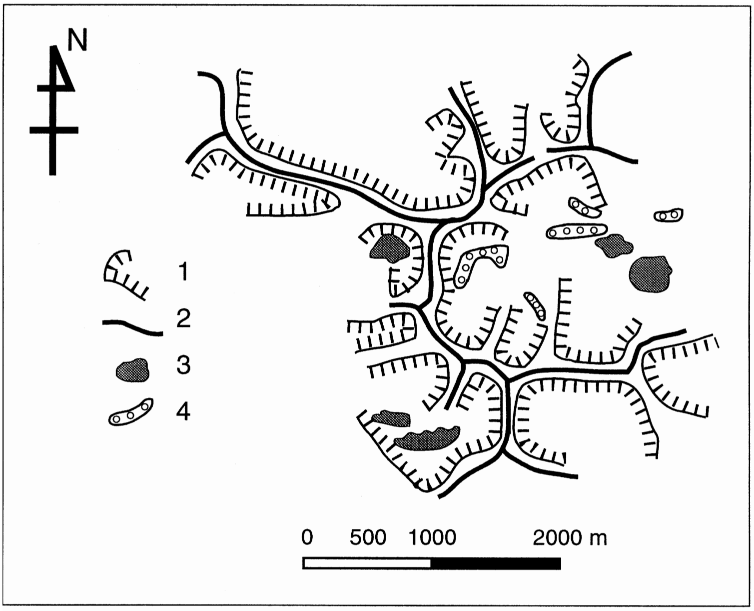

Fig. 3. Glacial cirques in the Infierno Massif, Central Spanish Pyrenees. (1) Glacial cirque; (2) Main divides; (3) Lake; (4) Moraines.

lief, dominated by smooth gradients in the slaty areas and by rough cliffs in the calcareous outcrops. The highest altitudes of this sector are reached in the granitic batholiths or in their metamorphic aureole (Balaitus Peak, 3151 m).

Further south, the Inner Sierras form a great overthrusting anticline, which is composed of Cretaceous and Eocene limestone and sandstone. Relief is very craggy and increases in height towards the east.

Finally, the Eocene flysch sector is intensively folded, though the lithological uniformity results in a more uniform relief, with smooth divides rarely exceeding 2000 m a.s.l.

During the Pleistocene period the main glaciers (Aragón Subordán, Aragón and Gállego valleys) started from the Axial Pyrenees, while the secondary ones (Veral, Osia, Estarrún, Aurín and other valleys of smaller areas) started from the Inner Sierras. All of them reached the flysch sector, where they finally melted in wide terminal basins (Penck, 1883; Panzer 1948; Barrère 1966; García-Ruiz and Martí-Bono 1994; Serrano and Martínez de Pisón 1994; Martí Bono 1996; Chueca *et al.* 1998; Serrano 1998).

Methods

In order to realize geomorphic hazard maps of the upper Aragón and Gállego river basins, geomorphological mapping of four sheets of the National Topographic Map was carried out, corresponding to Zuriza (no. 118), Anso (no. 144), Sallent (no. 145) and Jaca (no. 176) (García-Ruiz *et al.* 1994), on a 1: 50,000 scale. Geomorphological maps allow the indentification of 206 glacial cirques, with the basic characteristics emphasized by various authors: relatively depressed areas located immediately below the divide, surrounded by very steep slopes, arcuate in plane and with a more gently sloping floor (Trenhaile 1975) (see an example in Fig. 3); they correspond to glacier sources in which a surplus of snow accumulation either supports (or supported) a cirque glacier or has contributed to the development of a valley glacier (Evans and Cox 1995). The presence of morainic deposits confirms the existence of a Pleistocene ice mass.

In the cirques, the following parameters were measured (Fig. 4):

- highest elevation (*M*) of the divide located immediately above the glacial cirque;
- minimum altitude (*m*): measured in the lowest part of the cirque, coinciding most of the time with a narrowing between the lateral walls or with a glacial threshold;
- length (*L*): distance between the backwall and the point where the minimum altitude was measured, along the median axis of the cirque;

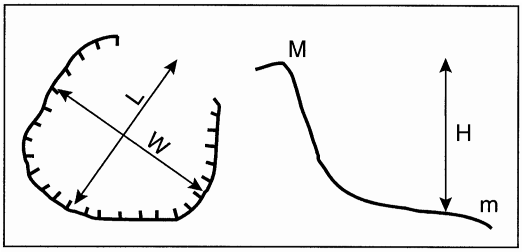

Fig. 4. Morphometric parameters considered in the glacial cirques

- width (*W*): maximum distance between the lateral walls, along the transverse line to the median axis of the cirque;
- cirque area (in ha), obtained with a planimeter;
- aspect: eight categories have been distinguished (north, northeast, east, southeast, south, southwest, west and northwest);
- lithology: the lithological diversity of the study area has been summarized in seven categories from the lithological map of Soler and Puigdefábregas (1972): (1) limestones; (2) flysch; (3) Permo-Triassic sandstone, clay and conglomerates; (4) slate; (5) sandstone; (6) granite; (7) quartzite/slate.

In addition to the previous variables, information has been augmented with the following morphometric indices:

- the difference between the maximum and minimum altitudes (*H* index) of each cirque, measured in metres (Aniya and Welch 1981);
- the relationship between length and width (*L/W* index), a good indicator of the cirque shape;
- the relationship between length and the *H* index (*L/H* index).

This information has been codified and organized in a data base for statistical analysis (SPSS v.8), from which the basic descriptive figures were obtained (tables, frequency histograms), as well as other indicators of contrast (ANOVAS) and association (correlations and regressions). Multivariate procedures have been used to detect patterns in both distribution and morphometric diversity of the glacial cirques: conglomerate (cluster) analysis has been used in order to obtain a reduced number of cirque groups (minimization of euclidean distances and selection from the dendrogram), considering exclusively the morphometric variables. Homogeneity analysis (HOMALS) separates levels of nominal variables and divides cases into homogeneous subgroups. Discriminant analysis has contributed to describing the cirque groups in relation to geo-environmental variables.

Results

Distribution of glacial cirques

The maximum altitude is concentrated around 2500–2700 m. Under 2100 m the presence of cirques is very low, so that a threshold of 2000 m is the lowest altitude favouring the development of cirques during the coldest Pleistocene stages.

The minimum altitude oscillates between 1680 and 2800 m, reaching its greatest frequency between 2000 and 2200 m.

As for aspect, there are two classes which stand out from the rest: north (22%) and south (16%). The rest of the classes each represent around 10%. This distribution suggests that, in the study area, glacial cirques could develop in any aspect. The relatively greater presence of cirques on north and south aspects is related to the organization of the Pyrenean structure, with dominant ridges from west to east, notably the Inner Sierras and the main divide between France and Spain.

Finally, of the lithologies (Fig. 5), limestone (more than 50% of the cirques) stands out against slate (around 15%) and quartzite/slate (around 12%).

Morphometric characteristics of the glacial cirques

Cirques show large morphometric variability (Table 1). Width concentrates especially between 200 and 1000 m (182 cirques in total), with a mean value of 653 m. Length has a mean value of 503 m. This means that cirques are of moderate size, with

Table 1. Morphometric features of glacial cirques in the Central Spanish Pyrenees.

	Arithmetic mean	Max. value	Min. value	Standard deviation	Standard error
Area (ha)	34	314	3	39	2.7
Width (m)	691	2700	200	395	27.5
Length (m)	519	1600	100	284	19.8
H index (m)	364	943	100	138	9.6
L/W index	0.79	2.00	0.25	0.31	0.02
L/H index	1.48	3.98	0.39	0.69	0.05

N= 206 glacial cirques

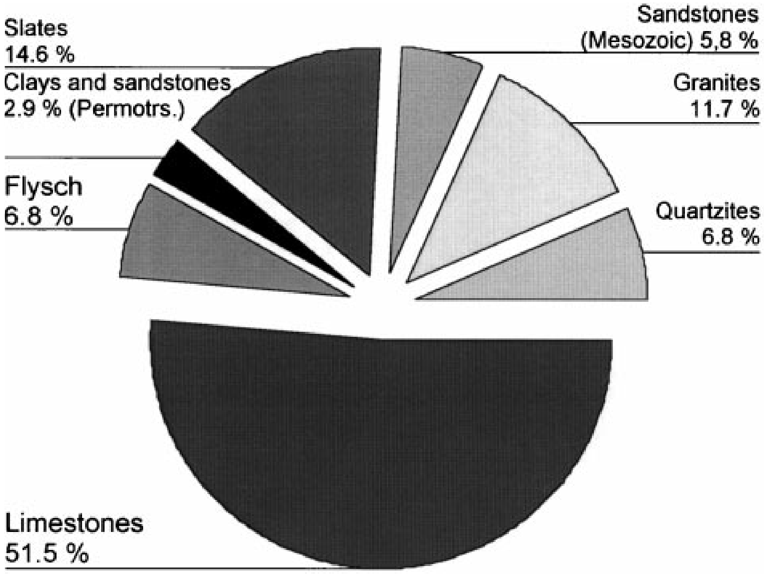

Fig. 5. Distribution of glacial cirques according to lithology.

a mean area of 34 ha, similar to that calculated by Ortigosa (1986) in the Cebollera Ridge, Iberian Range, and to that estimated by other authors in European mountains affected by intense glaciation (Bennett 1990). Cirques are relatively deep (*L*/*H* index = 1.43), as a consequence of an active process of excavation, although they are below the values estimated by Aniya and Welch (1981) in Antarctica and by Manley (1959) in northwest England.

With the morphometric information a conglomerate multivariate analysis has been realized, allowing the classification of cirques into four groups, representing 92.4% of the total (194 cirques). Twelve unclassified cirques were excluded. The four groups are as follows (Table 2).

(i) Group 1: very wide and deep cirques, with variable sizes and *L*/*W* index of 0.4. Average area is 45.6 ha for 21 cirques.
(ii) Group 2: long and narrow cirques, with gently sloping floor, without over-deepening. This group consists of 17 cirques, with an average area of 25.7 ha. The *L*/*W* index is 1.48.
(iii) Group 3: rounded and deep cirques. This group consists of 122 cirques and can be con-

Table 2. Mean and standard error of the morphometric parameters of the glacial cirques.

Cirques	No.	Statistics	Width (m)	Length (m)	*H* (m)	Area (ha)	*L*/*W*	*L*/*H*
Group 1	21	Mean	1052.38	433.33	391.33	45.857	0.40	1.09
		SE	133.74	61.85	42.82	12.294	0.02	0.07
Group 2	17	Mean	453.53	659.41	435,35	25,747	1.46	1.47
		SE	44.85	67.52	21.10	6.009	0.07	0.08
Group 3	122	Mean	569.88	432.99	375.00	22.044	0.76	1.17
		SE	19.49	17.57	11.40	1.582	0.01	0.03
Group 4	34	Mean	804.41	722.65	286.41	49.610	0.89	2.52
		SE	52.41	51.11	18.53	6.326	0.02	0.08
All	194	Mean	653.02	503.63	366.53	29.149	0.81	1.43
		SE	24.46	18.70	9.69	2.214	0.02	0.04

SE = standard error of the arithmetic mean.

Table 3. Correlation matrix for morphopmetric and altitudinal indicators.

	Max. alt.	Min. alt.	Width	Length	*M-m*	*L/W*	*L/H*	Area
Max. alt.	–	0.876(**)	0.148(*)	0.363(**)	0.397(**)	0.346(**)	0.062	0.239(**)
Min. alt.	0.876(**)	–	–0.133	0.112	–0.095	0.338(**)	0.188(**)	–0.032
Width	0.148(*)	–0.133	–	0.678(**)	0.559(**)	–0.270(**)	0.299(**)	0.901(**)
Length	0.363(**)	0.112	0.678(**)	–	0.537(**)	0.422(**)	0.649(**)	0.846(**)
M-m	0.397(**)	–0.095	0.559(**)	0.537(**)	–	0.071	–0.229(**)	0.554(**)
L/W	0.346(**)	0.338(**)	–0.270(**)	0.422(**)	0.071	–	0.395(**)	0.017
L/H	0.062	0.188(**)	0.299(**)	0.649(**)	–0.229(**)	0.395(**)	–	0.448(**)
Area	0.239(**)	–0.032	0.901(**)	0.846(**)	0.554(**)	0.017	0.448(**)	–

** Bilateral statistical significance equal to or higher than 0.01 level.
* Bilateral statistical significance equal to or higher than 0.05 level.

sidered as the most typical form of glacial cirque in the study area. Average area is 22 ha and the *L/W* index is 0.76.

(iv) Group 4: rounded cirques, with gentle gradient, without over-deepening. This group consists of 34 cirques, with an average area of 49.6 ha. The *L/W* index is 0.9.

Factors in the morphometry of glacial cirques

Glacial cirques are present in a great variety of topographic environments, provided that the divide above the cirque is located at least at 2000 m a.s.l. Likewise, there is a large diversity both in shape and size. In order to explain this diversity, altitude, aspect and lithology will be considered as conditioning factors (independent variables) of shape and size of the cirques, while the morphometric parameters behave as dependent variables.

Correlations (Pearson's *r*) show, in general, few significant associations (Table 3). Thus linear correlation between the maximum altitude and the area of the cirques is $r = 0.239$, that is, altitude as a unique factor explains only 5.7% (determination coefficient) of the size of glacial cirques. Some other correlations are higher, but they contribute very little to explaining the morphometric features of the cirques, as is the case for the linear association between width and length ($r = 0.678$).

Analyses of variance (ANOVAS) show little association between environmental factors and cirque morphology, although in some cases a relatively high significance is seen (>90 confidence level). Tables 4, 5 and 6 include the synthesized results from the variance analyses tested with different morphometric variables (factors) according to the categories (groups) of altitude, aspect and lithology.

Table 4 shows that altitude plays a positive role in determining cirque length, in such a manner that cirques tend to be longer as the altitude of the divide increases. In fact, the length clearly increases as the altitude does, while the width is poorly related to altitude. Likewise, the relationship between length and width (*L/W* index) increases towards the highest areas: thus, the lowest cirques tend to be clearly

Table 4. Mean values and statistical significances (p) of analyses of variance of morphometric variables according to altitudinal categories.

Alt. cirque bottom (m)	Number of cirques	Area (ha)	Length (m)	Width (m)	*L/W*	*L/H*	*H* (m)
–2000	24	24	434	648	0.68	1.41	331
2000–2200	39	36	433	701	0.66	1.44	328
2200–2400	49	39	510	706	0.78	1.43	366
2400–2600	56	42	562	718	0.83	1.48	389
2600–2800	22	36	559	668	0.90	1.60	366
+2800	16	42	673	617	1.11	1.71	403
Total	206	37	519	691	0.80	1.49	364
		p = 0.777	p = 0.031	p = 0.939	p = 0.000	p = 0.703	p = 0.213

p = probability of statistical significance.

Table 5. Mean values and statistical significances (p) of analyses of variance of morphometric variables according to the aspect.

Aspect	Number of cirques	Area (ha)	Length (m)	Width (m)	*L/W*	*L/H*	*H* (m)
N	45	35	497	753	0.76	1.32	404
NE	25	36	506	710	0.81	1.45	345
E	20	26	484	671	0.76	1.53	343
SE	21	23	483	569	0.87	1.41	364
S	33	25	460	620	0.75	1.37	353
SW	20	29	493	727	0.73	1.66	307
W	22	56	773	842	0.95	1.92	409
NW	20	29	499	588	0.83	1.48	340
Total	206	33	519	691	0.80	1.49	364
		p = 0.094	p = 0.004	p = 0.251	p = 0.202	p = 0.051	p = 0.120

p = probability of statistical significance.

wider, while the highest cirques tend to have equal length and width or to be longer. It is important to note that indicators of over-deepening (*L*/*H* and *H* indices) also increase in the cirques located at higher altitudes, although in this case the statistical significance is low.

As for the influence of the aspect (Table 5), cirques facing west are the largest; cirques oriented south and southeast are the smallest. It is important to note that cirques facing west are dominated by higher peaks and divides (2736 m on average), followed by the cirques facing north (2604 m) and northwest (2554 m). In contrast, cirques facing east and northeast are located, on average, at lower altitudes (2338 m and 2483 m respectively).

Finally, it is difficult to separate the influence of lithology from that of altitude, because both factors are relatively well related in many areas of the Pyrenees. However, Table 6 demonstrates that cirques on granites are the broadest, as well as the longest and those with the highest *L/W* and *L*/*H* indices. In contrast, cirques on flysch are the shortest and have moderate sizes and a low *L/W* relationship. The rest of the lithologies show intermediate values.

In order to assess the influence of environmental factors (lithology, altitude and aspect) on glacial cirque morphometry, two complementary statistical procedures have been used: the homogeneity analysis (HOMALS) and the discriminant analysis. Both multifactorial techniques allow the use of nominal variables, though in the case of the discriminant analysis they have had to be transformed into binary variables (0, 1).

The homogeneity analysis estimates associations between the categories of a number of nominal variables by means of scores based on statistical dimensions. Figure 6 shows the distribution of scores in the two first dimensions. According to the quantifications of dimension 1, glacial cirques belonging to groups 2 and 4 are clearly opposed to group 1, being especially associated to different altitudinal and lithological classes. Thus, cirques

Table 6. Mean values and statistical significances (p) of analyses of variance of morphometric variables according to lithologies.

Lithology	Number of cirques	Area (ha)	Length (m)	Width (m)	*L/W*	*L/H*	*H* (m)
Limestones	106	29	468	646	0.78	1.34	363
Flysch	14	21	389	682	0.57	1.38	294
Perm. and Triassic sandstones and clays	6	47	558	628	0.72	1.32	426
Slates	30	31	548	692	0.84	1.70	341
Sandstones	12	28	475	754	0.73	1.28	385
Granites	24	55	791	776	1.01	2.05	407
Quartzite/slates	14	32	526	743	0.83	1.48	367
Total	206	33	519	691	0.80	1.49	364
		p = 0.088	p = 0.000	p = 0.570	p = 0.001	p = 0.000	p = 0.220

p = probability of statistical significance.

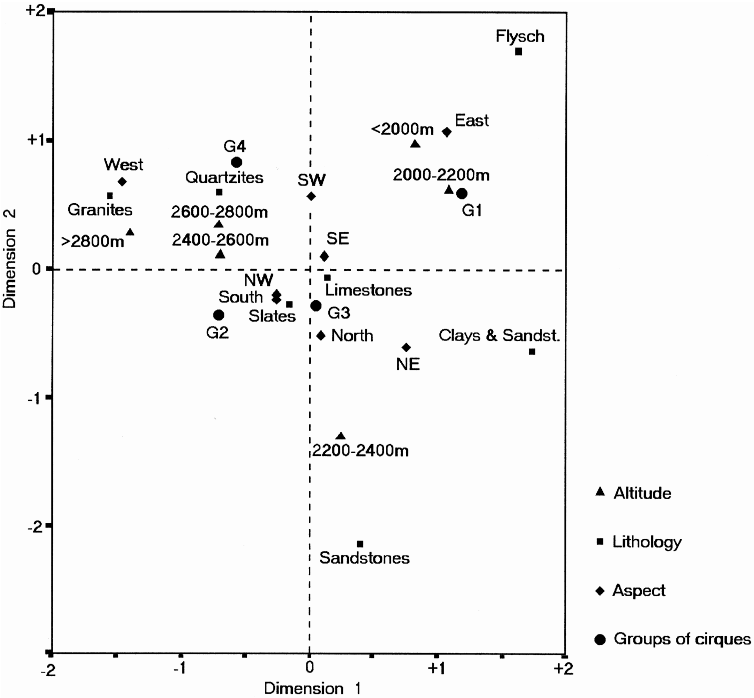

Fig. 6. Homogeneity analysis on the distribution of the cirque groups

from group 1 are linked to the lowest altitudes (<2400 m) and to the less consistent lithologies (flysch and Permo-Triassic sandstones and clays). Groups 2 and 4 are linked to the highest altitudes (>2400 m) and to slate, quartzite and granite. Dimension 2 highlights the effect of the aspect. Thus, sunny exposures encourage the development of cirques of groups 4 and 1. Group 3 does not show clear associations with any altitudinal or lithological category. This is very important since this group of cirques is the most abundant in the Central Spanish Pyrenees.

Table 7. Table of classification between the groups of glacial cirques observed and predicted by discriminant analysis

Predicted groups	Observed groups Group 1	Group 2	Group 3	Group 4
Group 1	6	0	5	0
Group 2	0	6	7	3
Group 3	15	11	107	21
Group 4	0	0	3	10
Cases	21	17	122	34

A total of 66.5% of the original cases, accurately predicted.

The discriminant analysis has been used for assessing the reliability of the cirque groups in relation to the environmental factor. Table 7 shows the final classification between the observed and predicted groups of cirques: 66.5% of the cases have been adequately classified, confirming the relatively limited effect of the environmental factors considered here on glacial morphometry. Another important point is that there are almost no incorrect classifications between groups 1, 2 and 4. Group 3 assumes most of the incorrect classifications. Since group 3 represents the most common cirque morphology in the Pyrenees, one can deduce that the "extreme" morphologies (groups 1, 2 and 4) are partially related to the environmental factors.

Discussion and conclusions

Glacial cirques of the Central Spanish Pyrenees are located in a wide range of altitudes and aspects, and have developed in all lithologies, where the divide reaches at least 2000 m a.s.l. The front of the lowest cirques is located around 1700 m, a limit noticeably higher in the Central Pyrenees than in other more westerly mountains in Spain (Alonso 1994), due to the greater continentality of the Central Pyrenees.

Table 8. Morphometric characteristics and geo-environmental preferences of the cirque groups.

Cirque group	Morphological description	Environmental preference
1	Very wide and relatively deep cirques, with scarce longitudinal development and large surface area	Low altitudinal levels (2400 m), flysch and Permo-triassic rocks. Sunny aspects
2	Long, very narrow, and deep cirques	High altitudes (>2400 m) Palaeozoic slate. Shady aspects
3	Rounded and deep cirques, with equilibrated morphology and medium size	Shady aspects. No other environmental preferences
4	Very long and wide cirques, scarcely excavated and large area	High altitudes (>2400 m), Quartzite and granite. Sunny aspects

A very interesting matter is that glacial cirques have developed in all aspects. This result suggests that in mountains with a great altitudinal range the aspect was not a limiting factor, because even southern aspects recorded sufficient snow accumulation. Furthermore, in the case of the Pyrenees the aspect of the glacial cirques is partially controlled by the organization of the Pyrenean preglacial relief, with frequent west–east divides favouring a greater presence of cirques oriented north and south (Serrano 1998).

This paper has demonstrated that some environmental variables (altitude, aspect and lithology) have a limited influence on both shape and size of the glacial forms. According to discriminant analysis these factors explain the classification of around 66% of the cirques. The rest would be conditioned by factors such as the presence of faults, the resistance of rocks and preglacial relief (Unwin 1973; Martínez de Pisón and Arenillas 1976; Serrano 1998). In fact the diversity of cirque forms and a clear absence of determination in the relations between factors and morphometric parameters would suggest that glacial cirques are very much conditioned by initial forms (see also Evans and Cox 1995, p. 200). One could even conclude that many cirques are developed independently of the environmental factors, as would be the case of group 3 cirques. If this is true, only the cirques located in “extreme” situations (i.e., the highest and lowest altitudes) would be clearly related to the environmental factors. In spite of that, some relations can be detected.

Thus altitude affects the length of the cirques and the *L/W* relation. At lower altitudes glacial cirques are clearly wider than they are long, while in the highest areas both the width and length tend to be equal. This trend suggests that the increase in length is a sign of maturity or of a long evolution of the cirques; in fact, the highest cirques, that is, those which have been subject to a more intense and lengthy glaciation period, are also the longest of the study area. In other words, as time passes, the length tends to increase more than the width of the cirques (see also Derbyshire and Evans 1976; Gordon 1977). Nevertheless, some authors consider that altitude has a very limited morphometric effect (Evans and Cox 1995), controlling the distribution more than the shape or size of the cirques.

The role of lithology is, in the Central Spanish Pyrenees, less obvious. Cirques on granite are the largest and longest, while on flysch they are small, short and have a low *L/W* index; but this paper has not been able to separate these results from the effect of altitude. In spite of that, both aerial photographs and field work indicate that, on granite, rounded or arcuate, over-deepened cirques prevail, favouring the existence of many lakes of glacial origin. At similar altitudes, limestone, quartzite or Permo-Triassic sandstone include only a few examples of well developed glacial cirques, thus supporting the importance given to lithology by other authors (Vilborg 1984; Alonso 1994).

Table 8 summarizes the relationships found in this paper between cirque groups, morphometric features and environmental preferences. Cirques belonging to group 1 are clearly related to low altitudes, sunny aspects as well as flysch and Permo-Triassic rocks. Cirques of group 4 are related to the highest altitudes, quartzites and granites. Cirques of group 2 are also located at high altitudes, though in slate and shady aspects. Group 3, with almost the same figures for width, length and height, does not show environmental preferences (except for the shady aspects), thus suggesting that a number of cirques are characterized by a typical, rounded morphology which seems to be independent of the environmental factors considered here.

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