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Morphometric analysis of cirques on the Iberian Peninsula provides insights into climate during past glaciations

Ramón Pellitero [a,*], Iestyn Barr [b], Matteo Spagnolo [c], Matthew Tomkins [d]

[a] Departamento de Geografía, Universidad Nacional de Educación a Distancia, Spain
[b] Department of Natural Sciences, Manchester Metropolitan University, Manchester, UK
[c] Department of Geography and the Environment, School of Geosciences, University of Aberdeen, UK
[d] Department of Geography, University of Manchester, UK

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ABSTRACT

We present the first comprehensive geodatabase of glacial cirques on the Iberian Peninsula, excluding the Pyrenees. A total of 1519 cirques were mapped using Google Earth, guided by published literature. Cirque morphometry was retrieved using the ACME GIS tool. Cirques on the Iberian Peninsula are mostly located in the Cantabrian Range, with smaller populations in the Iberian, Central and Betic ranges. Cirque lowest point elevation increases from N to S and W to E, following the glacier equilibrium-line altitude during the local Last Glacial Maximum. Cirque location, orientation, shape and size suggest they developed during marginal glaciations, except in certain subregions of the Cantabrian Range. Cirque location and orientation indicate that during cirque development atmospheric circulation was similar to present.

1. Introduction

Mountain range morphology has been defined as a palimpsest, as it reflects a combination of depositional and erosive processes, with considerable uncertainty as to the relative importance of different erosional systems (Koppes and Montgomery, 2009; Bernard et al., 2019; Tomkins, 2019). Over orogenic timescales, the rate of glacial erosion has been shown to decrease with successive glaciations (Kaplan et al., 2009; Egholm et al., 2012), with the highest erosion rates during periods dominated by warm-based glaciers (Barr and Spagnolo, 2013; Crest et al., 2017). Alongside basal thermal regime (Alley et al., 2019; Patton et al., 2022), glacier size plays a critical role in the spatial focusing of erosion. On the Iberian Peninsula, the largest Quaternary glaciers formed in the Pyrenees and in some subregions of the Central Cantabrian Range. Evidence of extensive glacier erosion at low elevations is present in both regions. By comparison, most other mountain ranges of the Iberian Peninsula were characterised by marginal (small-scale) glaciations during the Pleistocene (Oliva et al., 2022a, and references therein). Under such conditions, glacial erosion was focused at higher elevations, with glacial cirques developing as some of the most prominent and obvious glacial landforms.

Cirque altitudes can provide information about equilibrium-line altitudes (ELAs) during former periods of small-scale (cirque-confined) mountain glaciation (Rose et al., 2013; Barr and Spagnolo, 2015a), which can, in turn, be used to obtain quantitative information about past climates (Ohmura et al., 1992; Ohmura and Boettcher, 2018) or even track the onset of glaciation (Barr et al., 2022). Moreover, cirque orientation can provide information about prevailing winds at the time of cirque glacier formation (Evans, 1977, 2006). Finally, cirque morphometry can be used to assess the importance and intensity of glacial and even periglacial erosion in the study area (Barr and Spagnolo, 2015a). Cirques on the Iberian Peninsula, their location, morphometry and altitude can therefore help understand the predominant climatic conditions during Quaternary glaciations.

Cirque distribution in specific areas of the Iberian Peninsula was the focus of several papers. Pedraza et al. (2019) studied 97 cirques in the Eastern Central Range, where they highlight the importance of structure in cirque location and propose a similar atmospheric circulation during glaciation to present day. Ruiz-Fernández et al. (2009) mapped 129 cirques in the Central Cantabrian Range, where they point to the structural control of cirques in Picos de Europa but not in nearby areas within the range, where glacial erosion is largely controlled by elevation. García-Ruiz et al. (2000) measured 196 cirques in the Central Pyrenees, where cirques developed with all aspects and where a positive

* Corresponding author at: Departamento de Geografía, Facultad de Geografía e Historia, Ps/Senda del Rey, 7, 28030 Madrid, Spain.
E-mail addresses: rpellitero@geo.uned.es (R. Pellitero), I.Barr@mmu.ac.uk (I. Barr), m.spagnolo@abdn.ac.uk (M. Spagnolo), matthew.tomkins@manchester.ac.uk (M. Tomkins).

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correlation between cirque length and length of glaciation was established. Finally, Palma et al. (2017) mapped 65 cirques in Sierra Nevada, suggesting that large cirques are a result of the highly weathered bedrock that favoured erosion.

The present study is the first comprehensive, consistent mapping effort and morphometric study of cirques on the Iberian Peninsula. We study cirques in mountain ranges across the peninsula (including the Cantabrian Range, the Central Range, the Iberian Range and the Betic Range) but because our focus is on regions where former glaciers were comparatively small (i.e., regions of 'marginal' glaciation) we exclude the Pyrenees which underwent considerable and extensive glaciations throughout the Quaternary (Calvet et al., 2011; Delmas et al., 2022). Based on the above approach, we investigate the climatic and lithological controls on cirque elevation, distribution and morphometry across the Peninsula, use this information to reconstruct past glacial and climatic conditions during the Quaternary and reassess the inferences drawn from prior studies of Iberian cirque morphometry.

2. Settings

Cirques are divided into four different regions: the Cantabrian Range, Iberian Range, Central Range, and Sierra Nevada. The latter is the only glaciated area in the Betic Range. (Fig. 1).

2.1. The Cantabrian Range

The largest region is the Cantabrian Range, the mountain chain that runs from W (43.20°N, 8.30°W) to E (43.04°N, 1.57°W) from the Atlantic Ocean to the W tip of the Pyrenees, parallel to the Bay of Biscaye coast. Although geologically the Cantabrian Range does not encompass the mountains of Galicia, N Portugal and Sanabria-Teleno, which are more closely related to the Central Range in terms of the geological structure and lithology (Quesada and Oliveira, 2019a, 2019b), they together create an uninterrupted continuum of mountains which we analysed as a single unit. The elevation of peaks increases gradually from around 1000 m asl at the E and W ends of the chain to >2500 m asl in the central sector.

Due to the wide spatial distribution and the large number of cirques in this mountain range, we have distinguished six different subregions (Fig. 2). The mountains of Galicia and N Portugal, here called Galician Mountains, are geologically part of the Hesperian Massif (Dirección General del Instituto Geográfico Nacional, 2015), with igneous rocks dominating the lithology and flat-top morphology, similar to the Central Range. Here glaciation occurred at very low elevation, often in an ice cap style, so cirque formation was not widespread (see Valcárcel Díaz, 2018; Valcarcel and Pérez-Alberti, 2022). It is worth noting that, although glaciated areas of N Portugal are described in Pérez-Alberti (2022), the exact extension of past glaciers in the mountains of NW Portugal is yet to be fully described (Vieira et al., 2015). The Sanabria-

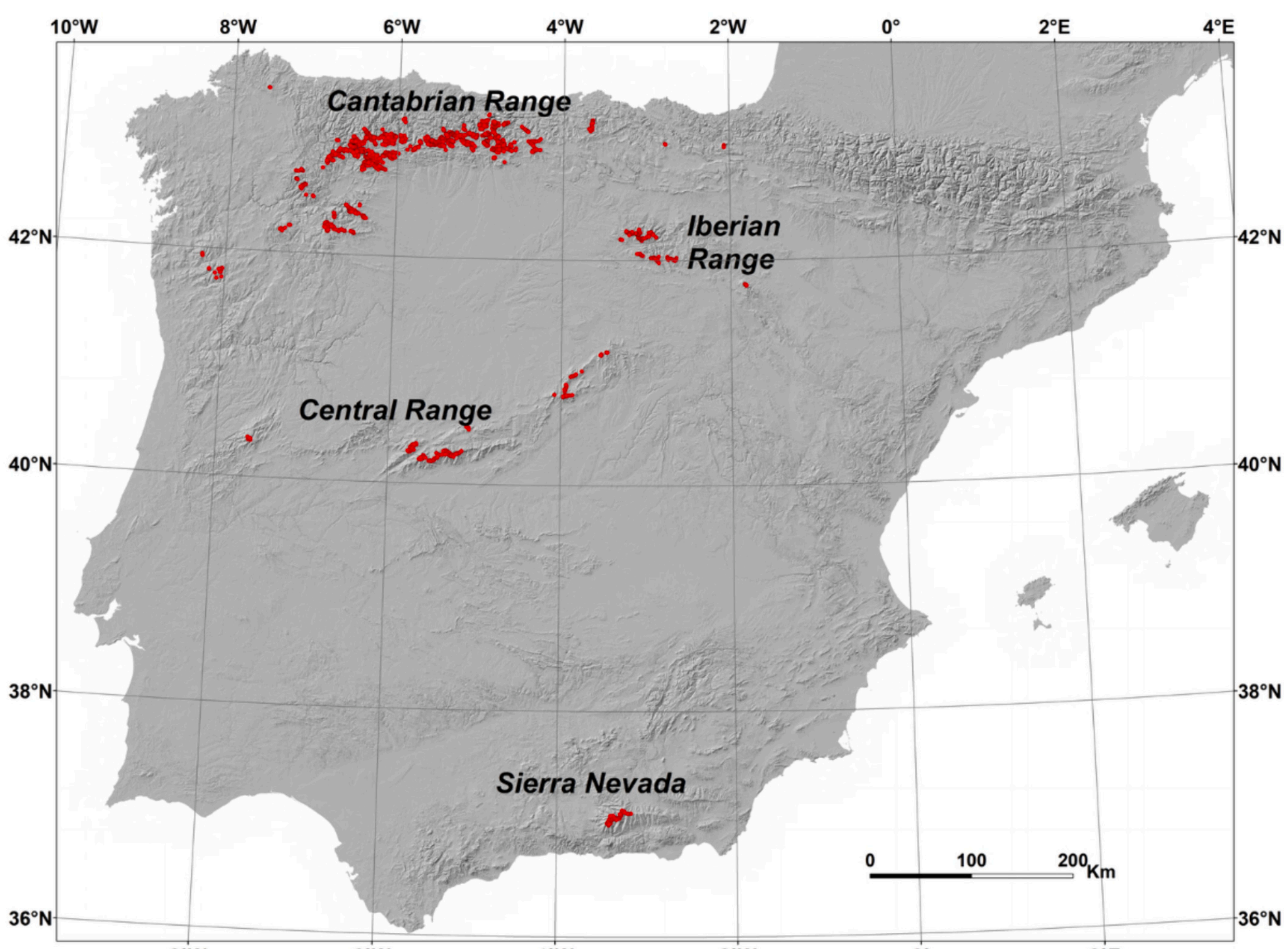

Fig. 1. Cirque distribution across Iberia, excluding the Pyrenees (n = 1519). The four main regions are labelled. Distribution is as follows: Cantabrian Range: 1196 cirques; Iberian Range: 114 cirques; Central Range: 142 cirques; Sierra Nevada: 67 cirques.

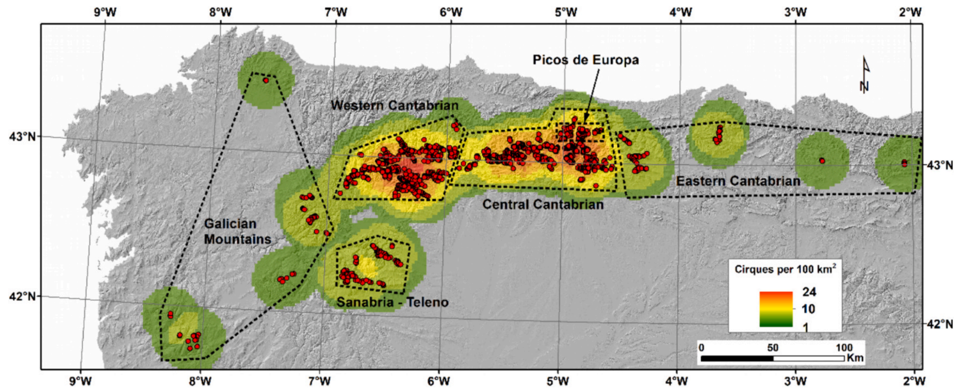

Fig. 2. Cirque distribution in the Cantabrian Range ($n = 1196$). The six subregions are labelled and outlined. Background colour shows cirque density per 100 km^2. Distribution is as follows: Galician mountains: 55 cirques; Sanabria-Teleno: 81 cirques; Western Cantabrian: 453 cirques; Central Cantabrian: 471 cirques; Eastern Cantabrian: 58 cirques; Picos de Europa: 78 cirques.

Teleno area (42.10°N, 6.70°W) is composed of a high elevation plateau (over 1700 m) which was formerly covered by a large ice cap (Pérez-Alberti and Valcarcel, 2022; Rodríguez-Rodríguez et al., 2022) and also some high mountain lineations where glaciation was more limited. They differ from the Galician Mountains in being located further inland but geologically they form a continuum with them. Here, glaciers developed at higher elevations (Redondo-Vega et al., 2022). The Western Cantabrian Mountains are located at the present border between Castilla y León, Asturias and Galicia regions. Here, a large icefield in the Sil valley (42.94°N, 6.25°W) developed and flowed southwards into the Bierzo basin, whereas the northern glaciers were much shorter (Ruiz-Fernández et al., 2022a; Santos-González et al., 2022) due to the steeper descent towards the coast. The Central Cantabrian mountains had a similar pattern, with larger valley glaciers/icefields in the S area, generally at higher elevations than in all the other subregions in the Cantabrian Range (Pellitero, 2022; Santos-González et al., 2022). The Eastern Cantabrian mountains are not a single continuum of glacierized mountains, but sparse mountains high enough to have hosted glaciers of different types (ice cap, valley or cirque). However, all glaciated mountains are close (within 30–40 km) to the Bay of Biscaye and show low cirque elevations. Finally, we have differentiated a sixth subregion, Picos de Europa (43.18°N, 4.83°W), which is a highly karstified limestone massif over which ice accumulated (Ruiz-Fernández et al., 2022b), creating an alpine landscape. The mapped cirques in this subregion correspond to secondary cirques which developed within pre-existing karstic hollows (dolines) (Smart, 1987; Ruiz-Fernández et al., 2009), creating a distinctive glacio-karstic landform locally named as "jou" or "hoyo". This situation impacts the location, elevation, orientation and shape of cirques in this area.

2.2. The Iberian Range

The Iberian mountain range runs in a NW-SE direction in the centre of the Iberian Peninsula, between the Cantabrian Range at the South of the Basque Country (SE corner of the Bay of Biscaye) and the Betic Range at the S of the Valencian Region (Nao Cape area, W of the Balearic Islands). The main centre of former glaciation here is located in the Demanda-Urbión-Cebollera mountains (42.00°N, 2.92°W) (Supplementary, Fig. 1), a set of mountains just over 2000 m asl at the limit between Castilla y León and La Rioja. Further E, the Moncayo (41.78°N, 1.83°W) is an isolated mountain which constitutes the highest point of the mountain range (2314 m). SE of Moncayo the elevation is lower, and no obvious glacial landforms have been described, although the Sierra de Albarracín area (40.52°N, 1.65°W) was recently described as the southernmost glaciated area in the Iberian Range (García-Ruiz, 2022).

2.3. The Central Range

The Central Range runs in a W-E direction at the centre of the Iberian Peninsula. Geologically, it is part of the same Hesperian Massif as the Galician Mountains. Geomorphologically, it is a series of flat-topped horsts and graben, with mostly igneous (granite) and metamorphic (gneiss, shales) rocks. Three main glaciated subregions can be distinguished in this region: the Serra da Estrela (40.32°N, 7.61°W) (Supplementary, Fig. 2) is the westernmost and the closest to the Atlantic Ocean. Glaciers here developed lower than in the other mountains, in a more humid climate (Vieira and Woronko, 2022), so an ice-cap formed on its top (Daveau, 1971). The Sierra de Gredos (40.26°N, 5.29°W) is the central and highest subregion. It is where the largest glaciers developed (Carrasco et al., 2022a) and where glacial erosion is clearer, so the initial flat tops have evolved into a serrated landscape with horns and arêtes. The Guadarrama, Somosierra and Ayllón mountains (40.84°N, 3.95°W) represent the easternmost subregion with glacial landforms, where glaciers were limited to the cirques (Carrasco et al., 2022b).

2.4. Sierra Nevada

Sierra Nevada is the highest mountain area within the Betic Range in S Spain. The Betic Range features several mountain areas over 2000 m asl but, because of its dry and warm Mediterranean climate, which also prevailed during the Pleistocene (Tarroso et al., 2016), only the Sierra Nevada was sufficiently tall to exceed the regional palaeo-ELA (Oliva et al., 2022a). Sierra Nevada is a relatively young W-E mountain lineation (~7 Ma) which is still under uplift (Braga et al., 2003; Reinhardt et al., 2007). Its W section is a continuous ridge between 2000 and 3479 m asl (this maximum altitude corresponds to Mulhacén, highest mountain at the Iberian Peninsula, 37.05°N, 3.31°W) (Supplementary, Fig. 3). Glacier development in the area was limited to cirque glaciers and short valley glaciers, <10 km long in all cases, which only in few cases descended below 2000 m (Palma et al., 2017).

3. Methods

3.1. Cirque mapping and morphometry calculations

Cirques were mapped in Google Earth and were identified as large hollows occupying valley-head or valley-side settings, bounded upslope by arcuate (in plan) headwalls and open down-valley (Barr et al., 2017). Cirque headwalls were typically straightforward to identify, but cirque lower limits are often more challenging, and in some cases lacked a distinct 'threshold' demarcating the cirque from the valley below (Evans and Cox, 1995). Following Barr and Spagnolo (2015a) the lower limits of each cirque were drawn in these cases by simply joining the two lateral spurs where the threshold was missing (Fig. 3). Results were saved as .kmz files and imported in ArcGIS for subsequent analysis. It is likely that minor refinements to the record will be required in future, such as to include overlooked cirques or exclude subtle cirque-like forms, but these refinements are unlikely to have a significant impact on the conclusions reached here, given the spatial scale of the analysis and our focus on readily identifiable cirques (Grades I, II, III, either well defined cirques or cirques where there is no question about their status, sensu Evans and Cox, 1995) and cirques mapped in the referenced papers.

Published maps of glacial landforms were used, where available, to help identify the location of potential cirques, although all cirques were digitised following the methods described above for consistency. Specifically, cirques in the Portuguese and Galician mountains were mapped with the aid of Daveau (1971), Vieira et al. (2015), Pérez-Alberti (2022), Valcárcel and Pérez-Alberti (2022) and Pérez-Alberti and Valcarcel (2022). Cirques in the Cantabrian Range were mapped following Santos-González et al. (2022), González-Trueba (2007), Ruiz-Fernández et al. (2009), Serrano et al. (2015), Pellitero (2014), Rico (2011), González-Amuchastegui (2000) and Serrano et al. (2022). For the Iberian Range, García-Ruiz (2022), García-Ruiz et al. (2020), Martínez de Pisón and Arenillas (1977), Pellicer (1989), Sanz (2005) and Ortigosa (1986) were used. Cirques in the Central Range were identified in Pedraza and Carrasco (2006), Campos et al. (2018), Carrasco et al. (2020), Pedraza et al. (2013), (2019) and Palacios et al. (2012). Finally, Sierra Nevada glacial cirques were mapped with the aid of Gómez-Ortiz (1987), Gómez-Ortiz et al. (2015) and Palma et al. (2017). Overall, the glacial cirque record assembled here is the first comprehensive glacial cirque dataset of the mountains on the Iberian Peninsula (excluding the Pyrenees).

For each cirque, metrics were calculated using the Automated Cirque Metric Extraction (ACME) GIS tool of Spagnolo et al. (2017). The values extracted and discussed in this paper are central point latitude (LAT) and longitude (LON) in the UTM ERTS1989 30 T projection, perimeter length (Perimeter; m), area (Area; m^2), circularity (CIR), length (L; m), width (W; m), length-width ratio (L/W), hypsometric index (HI), lowest and highest point elevations (LPE, HPE; m asl), cirque depth (H; m), average slope (AS; °) and cirque aspect vector mean (VM; °). Cirque elevation data were retrieved from the ALOS PALSAR DEM, which is available for the Iberian Peninsula at a horizontal resolution of 28 m, hence adequate for the morphometric analysis carried out here. VM was considered to represent the cirque general orientation, and cirques were subsequently binned into four main groups according to this variable: cirque orientation to the N include angles between 316° and 45°, E is between 46° and 135°, S is between 136° and 225°and W is for cirque orientations between 226° and 315°.

3.2. Cirque location, elevation and aspect normalization and regression analysis

A regression analysis can point to the relationship between variables and explain the variability of a dependent variable (in this case, cirque elevation) with some potential explanatory variables (cirque location, calculated as the central point of the cirque and orientation, which potentially exposed glaciers to variable climatic conditions across the Iberian Peninsula). This form of multiple regression has been used to investigate controls on cirque elevation in a number of other regions globally (Barr and Spagnolo, 2015b; Barr et al., 2017; Oien et al., 2022). As a first step in this analysis, LAT, LON and LPE were normalized to *Z*-scores (Eq. (1)):

$$z = \frac{x - \mu}{\sigma} \tag{1}$$

where: *x* is the original value, *μ* is the population average and *σ* is the population standard deviation, being the population the entire Iberian cirque dataset.

The Z-score conversion allows the comparison of LAT, LON and LPE eliminating the influence of scale, as resulting values are typically within +1/−1 values (equivalent to ±1 std). VM cannot be normalized, so two additional calculations were performed: VM cosine of the angle value in radians recalculated cirque orientation to values between 1 (for 0/360°) and − 1 (180°), hence giving a Northing value (NOR). VM sine of the angle value in radians between 1 (90°) and − 1 (270°) provided an

Fig. 3. Three cirques mapped in the Cantabrian Range (42.96°N, −6.57°E). The southernmost cirque (left in the figure) features a clear threshold which eases mapping, whereas the northernmost one (right in the figure) lacks a threshold. In this case, the cirque outline has been closed by simply joining the two lateral spurs.

Easting value (EAS).

The multiple linear regression analysis was performed in blocks using SPSS, so the contribution of each of the variables could be analysed separately and the variables were added to the model hierarchically following the highest R^2 of the individual regression between LPE and each variable. The resulting order was LAT, LON, NOR, EAS.

3.3. Vector strength calculation

Vector strength (VS) was calculated following Evans (1977) to investigate the degree of concentration of cirque aspects using each cirque's VM (Barr and Spagnolo, 2015a). This measurement was performed for the entire population, for the four regions separately (Cantabrian Range, Iberian Range, Central Range and Sierra Nevada) and for the six subregions within the Cantabrian Range (Galician Mountains, Sanabria-Teleno, Western Cantabrian Mountains, Picos de Europa, Central Cantabrian Mountains and Eastern Cantabrian Mountains) (Figs. 1 and 2).

3.4. Cirque growth

Cirque size was calculated based on the following equation (Eq. (2)) (Evans, 2006):

$$S = \sqrt[3]{LWH} \tag{2}$$

where S = Size; L = Length, W = Width and H = depth, considered as the highest minus the lowest elevation in the cirque.

Subsequently, power regression equations between cirque size and length, width and depth were calculated. The power exponents were used to assess the nature of cirque growth (i.e. whether allometric or isometric) (Barr and Spagnolo, 2015a). This measurement was performed for the entire population and the same regions and subregions as Section 3.3.

3.5. Influence of cirque aspect on other variables

The four cirque aspect bins explained in Section 3.1 were considered as factors for an Analysis of Variance (ANOVA) test, performed in SPSS. The ANOVA was performed, and significant ($p < 0.05$) variables were checked for homoscedasticity, then the Bonferroni test was used to post-hoc check which bins were statistically different for each of the variables and compute the value, significance and direction of differences in variables between pairs of aspect bins.

3.6. Influence of cirque lithology on other variables

Geological variations in folding structure, fault and thrusting lineation as well as lithology are factors that play a role in cirque location and morphometry (Barr and Spagnolo, 2015a and references therein). Bedrock layer changes, fault directions or other geological lineations and structures influence the aspect and size of cirques, but their role is primarily local, and a wide population of cirques makes this influence less apparent (Evans, 2006). Given the size of our cirque population, our analysis was limited to the consideration of lithology as an influencing factor for cirque morphometry. Cirque lithology has been extracted from the 1:1000000 lithological map (IGME, 2009) and the Carta Geológica Nacional de Portugal 1:1000000 (LNEG, 2010). Both maps represent a simplification of bedrock lithology. Cirque lithology was classified based on the dominant type within each cirque (largest area), grouped as: "granite", "gneiss", "quartzite", "shales", "schists", "limestone", "sandstone/conglomerates" and "lime/sandstone and shales", this last one for cirques that feature an alternation between hard and soft sedimentary/metamorphic layers, which in the mentioned IGME (2009) 1:1000000 map is named as "limestone, sandstone and shales". The eight cirque lithology groups were considered as factors for an ANOVA test, performed in SPSS. Once the ANOVA was performed, significant ($p < 0.05$) variables were checked for homoscedasticity and the post-hoc Bonferroni test was used to check which bins were statistically different for each of the variables and remove spurious correlations.

4. Results

4.1. Cirque distribution and Iberian glaciation

Most of the 1519 mapped glacial cirques are clustered in the N regions of the Iberian Peninsula. Excluding the Pyrenees, which are not considered in this paper, ~78.7 % (1196) of the total 1519 cirque population is located in the Cantabrian Range, ~9.3 % (142) in the Central Range, ~7.5 % (114) in the Iberian Range and ~ 4.2 % (67) in Sierra Nevada (Fig. 1). This cirque distribution reflects the general glacier concentration during the Pleistocene (see Section 2). In the Cantabrian Range, most cirques are located in the Western Cantabrian and Central Cantabrian regions ($n = 924$; 77 %), with smaller cirque populations elsewhere ($n = 272$; 23 %; Fig. 2). This dataset extends the previous glacial cirque mapping contributions mentioned in Section 3.1, which only covered part of the glaciated ranges in all cases except Sierra Nevada, where Palma et al. (2017) mapped 65 cirques.

4.2. Cirque elevation: one equation to explain them all?

Using multiple linear regression, we found an equation that relates the minimum elevation of cirques (LPE) with their location (LAT and LON) and their orientation (EAS and NOR) which explains 53 % of the LPE variability ($R^2 = 0.53$; ANOVA F = 430.6; significance = 0.000, see also Table 1 in supplementary).

$$LPE = 0.084\text{–}0.539(LAT) + 0.301(LON) - 0.166(NOR) - 0.107(EAS) \tag{3}$$

If each of these four factors is considered separately, latitude explains 44.2 % of elevation variability, longitude explains 26 %, cirque northing orientation 3 % and cirque easting orientation 0.02 % (Supplementary, Fig. 4). Note that, considered altogether, these percentages do not sum to 50 % because their control on LPE variability is not independent. Also, because all the factors are standardized, their relative effects in

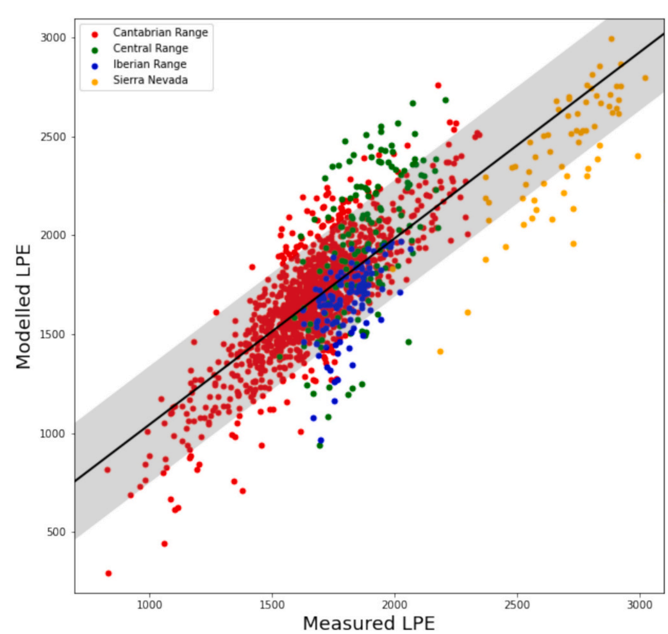

Fig. 4. Measured cirque lowest point elevation (LPE) compared to the value predicted by Eq. (3). The shadowed area corresponds to ±1 LPE std. dev.

combination are more interesting than their simple effects.

As seen in Fig. 4, 87 % (1320) of the total cirque population have their LPE derived from Eq. (3) within 1 std. dev (=295 m) of the measured LPE. 7.1 % (109) are located >1 std. dev over their predicted lowest point and 5.9 % (90) are located >1 std. dev below their predicted lowest point.

4.3. Cirque lowest point and Equilibrium-line Altitude

Our LPE dataset shows a 0.76 Pearson correlation with the interpolated ELA (see Figs. 5 and 6) of all Iberian palaeoglaciers at their maximum extent during the Last Glacial Maximum (LGM) (Oliva et al., 2022b), which is not exactly synchronous in all mountain areas (Oliva et al., 2019). The LPE and ELA patterns over the entire Iberian Peninsula show a very strong N-S and W-E trend, which is likely determined first by a latitudinal temperature gradient, decreasing moving N, and a longitudinal precipitation gradient, decreasing moving inland from the W coast to the E.

4.4. Cirque aspect

Iberian cirques show a dominant N and NE aspect distribution. However, the general pattern shown in Fig. 7 is mostly influenced by the Cantabrian Range, where most cirques are located. The dominant aspect varies between mountain ranges. The Iberian Range shows the highest VS (75 %), with cirques mostly having a NE orientation (average VM = 49°). In the Central Range and Cantabrian Range, cirques also show a NE aspect preference (average VM = 64° and 41°, respectively), but comparatively low VS (36 % and 43 %, respectively). In Sierra Nevada, the dominant cirque aspect is towards the E/SE (average VM = 104°), but VS is very low (31 %).

The dominant cirque aspect and VS vary between subregions of the Cantabrian Range (Fig. 8). In general, the western subregions (Galician mountains, Sanabria-Teleno and the Western Cantabrian Mountains) have the highest VS, whereas the Central Cantabrian, Picos de Europa and Eastern Cantabrian Mountains show values below 50 %.

4.5. Cirque size

Cirque size shows high variability between different regions (Table 1). It is noteworthy that the Central Range and Sierra Nevada have significantly larger cirques than the other regions. The Cantabrian Range subregions with the most cirques are those that were most heavily glaciated – the Central and Western Cantabrian, as well as the Picos de Europa – though cirques here are small. More marginally glaciated subregions, such as the Sanabria and Eastern Cantabrian, have fewer but notably larger cirques. In terms of depth, Sierra Nevada features notably deeper cirques, followed by Picos de Europa in the Cantabrian Range. The Iberian Range and Galician mountains have the least deep cirques on average.

4.6. Allometric cirque growth

When cirque size is plotted against L, W and H, power exponents are generally larger for cirque L than W or H (Table 2), with the L value always higher than 1. This suggests allometric growth, with cirques lengthening faster than they widen or deepen. However, there are significant variations between mountain ranges (Table 2). The Cantabrian Range shows nearly isometric growth, and this is true of both the Central and Western Cantabrian subregions. The subregions showing greatest

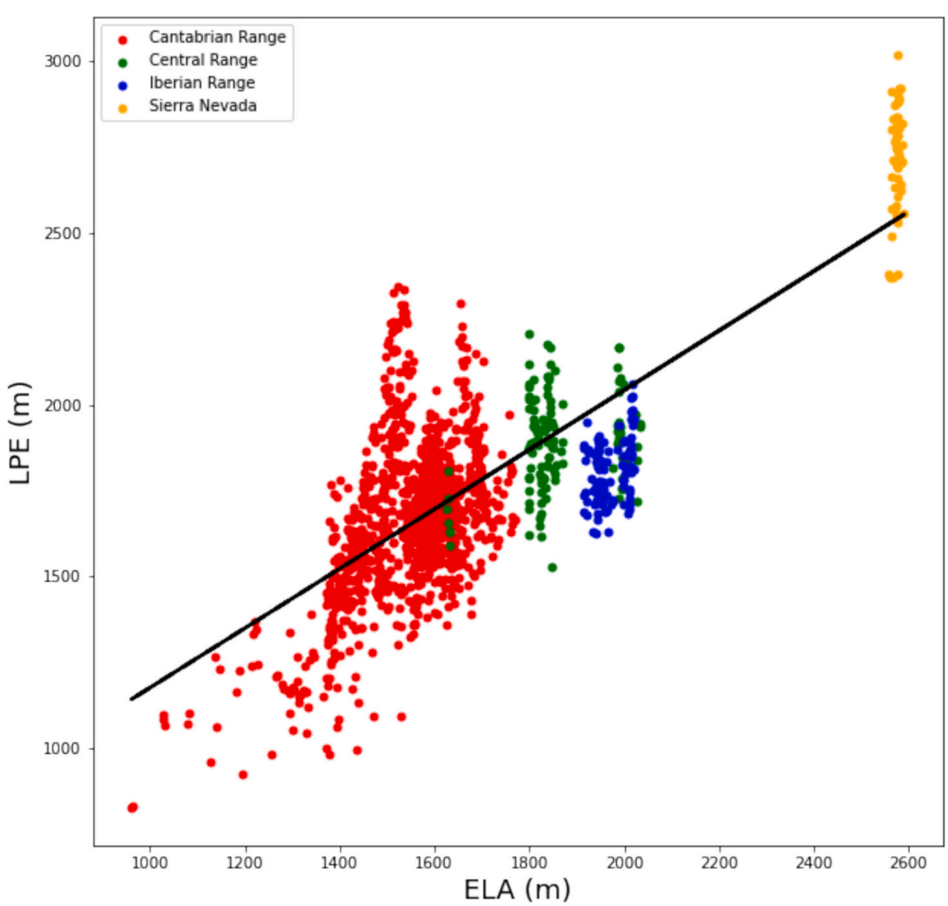

Fig. 5. Measured cirque lowest point elevation (LPE) compared to the interpolated ELA of the Iberian palaeoglaciers at their maximum extent during the LGM (from Oliva et al., 2022b).

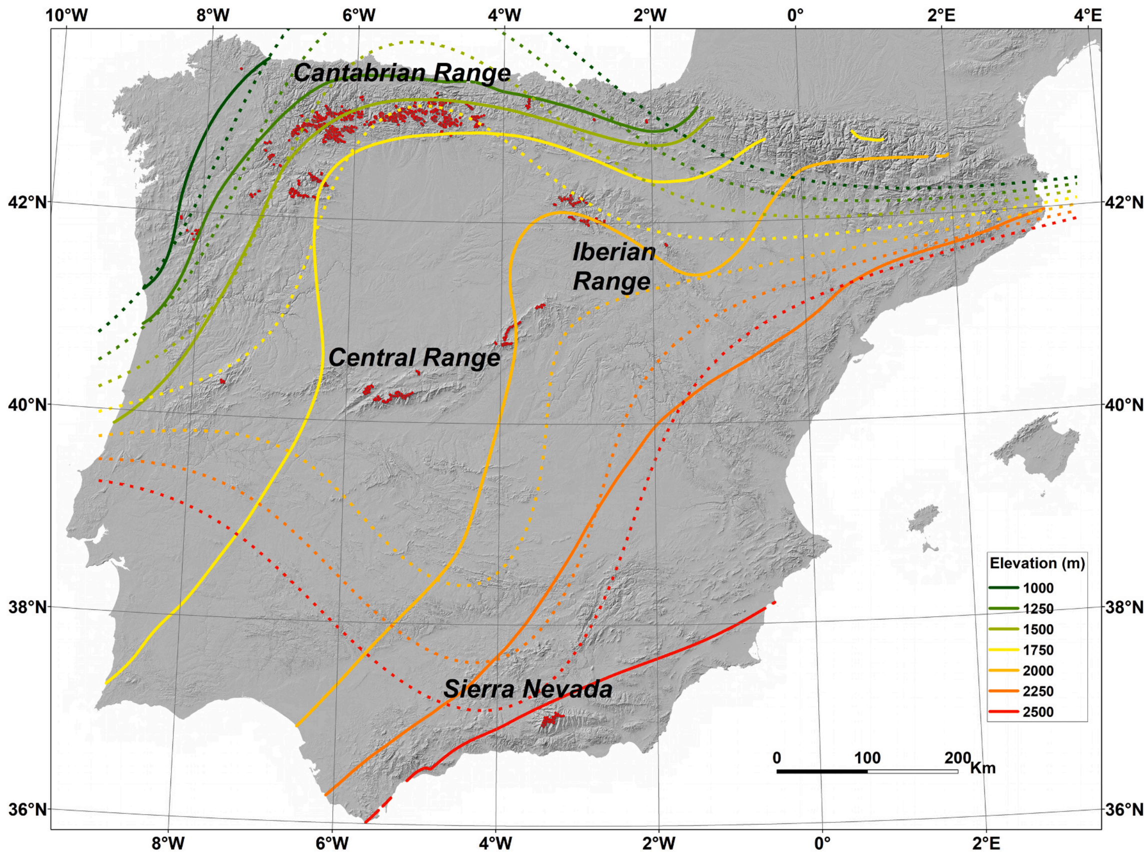

Fig. 6. LGM ELA contours (solid lines) (from Oliva et al., 2022b) and cirque lowest point altitude (LPE) contours (dashed lines) across the Iberian Peninsula, calculated by interpolation of cirques LPE with a third-degree global polynomial interpolation. Colour ramp is common for both datasets.

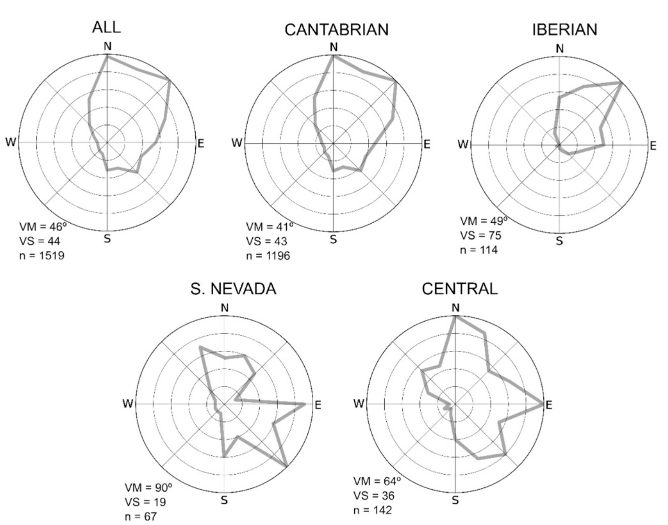

Fig. 7. Cirque aspect information per region of the Iberian Peninsula. VM is the aspect vector mean (°) for each of the regions. VS is the aspect vector strength (%).

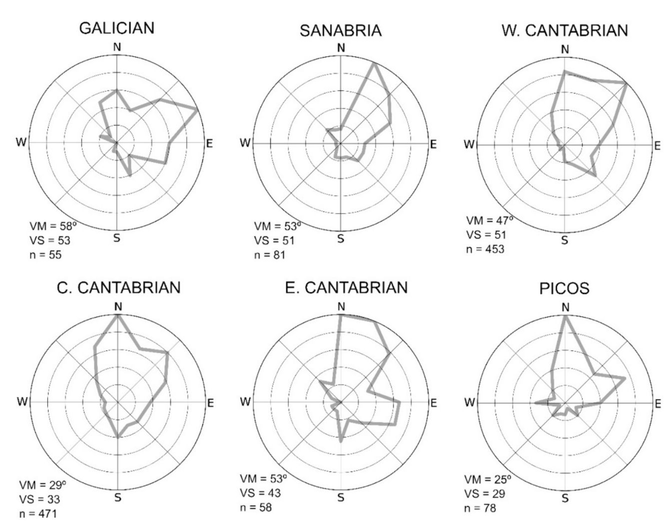

Fig. 8. Cirque aspect information per sub-region within the Cantabrian Range. VM is the aspect vector mean (°) for each of the sub-regions. VS is the aspect vector strength (%).

allometry are those located in the glacially marginal situations, i.e., the Galician Mountains and the Eastern Cantabrian mountains (Table 3). The values are close to 1 in the Sierra Nevada too, although here the length value is higher. The Central Range shows the lowest width value and the highest H value. Finally, the most allometric (uneven) values are those of the Iberian Range, where widening and lengthening clearly outpaced deepening.

4.7. Variable correlations

Shape related variables (L/W and CIR) show no strong (>Abs 0.5) Pearson correlation with any other variable. The same is true of variables related to VM. Size-related attributes (L, W, perimeter and area) only show cross-correlations among themselves and with H (larger cirques tend to be deeper). Finally, elevation values (LPE and HPE) correlate with the location variables (NOR and EAS), as identified in

Table 1
Average values for cirque morphometrics across the Iberian Peninsula.

Region	Perimeter (m)	Area (m^2)	CIR	L (m)	W (m)	L/W	HI	LPE (m)	HPE (m)	H (m)	AS (°)
All	2065	311,520	1.13	551	570	1.01	0.54	1743	2002	258	25
Iberian Range	1594	187,725	1.13	415	454	0.91	0.54	1803	1981	178	23
Central Range	2651	501,660	1.13	770	677	1.14	0.56	1878	2170	291	23
Sierra Nevada	2936	635,094	1.14	828	750	1.2	0.52	2685	3032	347	24
Cantabrian Range	1991	282,618	1.13	517	552	0.94	0.54	1669	1926	258	25
Galician M.	1854	264,945	1.08	551	530	1.04	0.56	1219	1434	215	24
Sanabria	2370	387,212	1.12	619	650	0.95	0.58	1684	1954	270	24
W. Cantab	2002	289,545	1.12	517	567	0.91	0.56	1629	1884	255	24
C. Cantab	1848	243,804	1.13	478	520	0.92	0.56	1715	1968	253	26
E. Cantab	2772	455,411	1.21	711	676	1.05	0.53	1502	1794	292	22
Picos de Europa	1922	252,125	1.16	474	497	0.95	0.51	2044	2339	295	30

Table 2
Allometric values for the different regions considered in this study.

	Central	S. Nevada	Cantabrian	Iberian	All
L	1.07	1.03	1.04	1.12	1.07
W	0.93	1.01	0.98	1.11	0.97
H	1.00	0.96	0.97	0.77	0.96

Section 4.2.

Low but significant correlations (>Abs 0.1 and < 0.5, $p < 0.05$) are more informative. NOR and EAS (calculated as outlined in Section 3.2.) correlate with all the elevation variables and with CIR. HPE relates positively with all size-related values. AS only correlates significantly with H (steep cirques tend to be deeper), but also relates negatively with W, L, area and perimeter, since large cirques usually have a well-developed bowl shape with a large flat floor. EAS is positively correlated with CIR, whereas NOR is negatively correlated with all size-related variables (Fig. 9).

4.8. *The impact of cirque orientation on other variables*

All the location variables show statistically significant differences (*p*

Table 3
Allometric values for the subregions within the Cantabrian Range.

	Galician Mountains	Western Cantabrian	Sanabria-Teleno	Picos de Europa	Central Cantabrian	Eastern Cantabrian
L	1.13	1.00	1.05	1.08	1.05	1.12
W	0.88	0.98	0.95	0.99	1.01	0.72
H	0.99	1.02	1.00	0.93	0.94	1.16

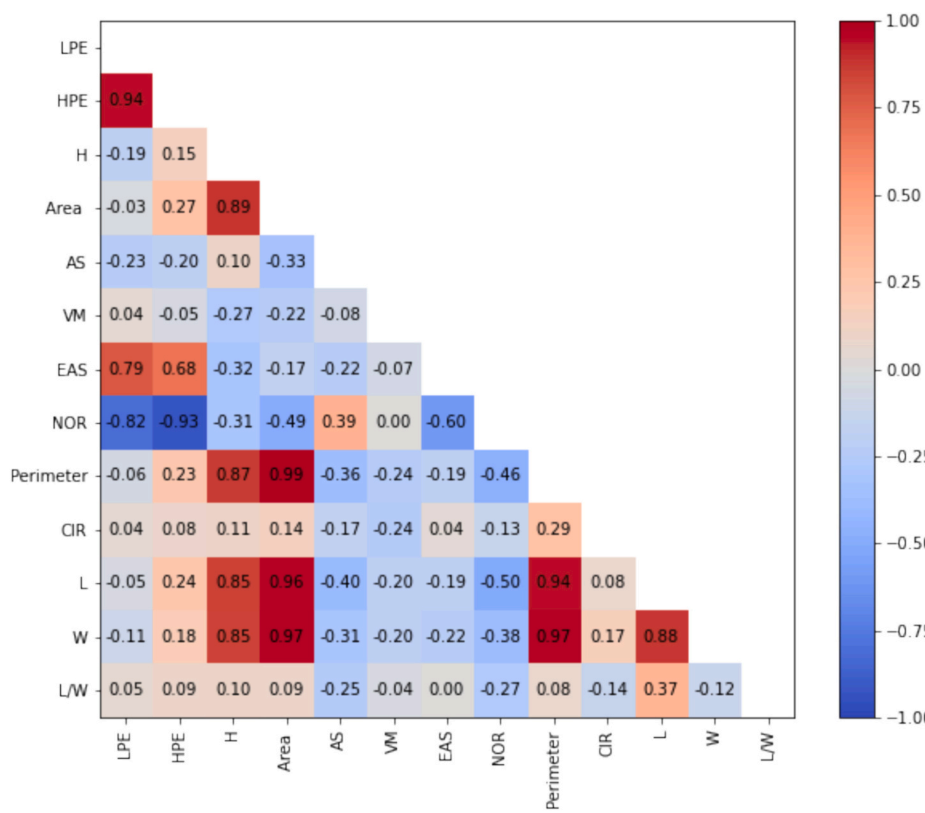

Fig. 9. Pearson correlation matrix for different cirque attributes/variables across the Iberian Peninsula.

< 0.05) depending on the cirque aspect bins (N, E, S, W), according to ANOVA. Of the shape related values, L/W, AS and H show statistically significant differences depending on the aspect bin (see Table 4). These ANOVA values are confirmed by correlations of shape related variables and NOR/EAS in Fig. 9. NOR correlates negatively with H, L/W, W and L, and positively with AS. EAS correlates negatively with all the mentioned variables but L/W (no correlation).

In terms of cirque shape, Bonferroni test results show that CIR is significantly higher for N oriented cirques than those oriented E or S, but not W. Width is also significantly higher for cirques facing N rather than S, while N facing cirques are significantly deeper than S and E facing ones. S oriented cirques are significantly more elongated than N oriented ones. In terms of AS, N oriented cirques are steeper than all others, followed by W oriented and E oriented cirques, which are significantly steeper than those oriented S.(Table 2, supplementary).

4.9. *The impact of lithology on cirque morphometry*

The ANOVA analysis shows high significance for all variables (L, W, L/W, CIR, Perimeter, Area, HI and AS). The Bonferroni test indicates significant paired correlations and lets us identify positive/negative differences in relation to their means (Table 3, supplementary). In terms of size (Perimeter, area, L and W), granite, gneiss and schist cirques are significantly different (and larger) compared to limestone, quartzite, lime/sandstone and shales and sandstone/conglomerates. Schist cirques are the largest and quartzite the smallest. Circularity and L/W show few significant differences, although granite and schist are also the most elongated, whereas lime/sandstone and shales as well as quartzite cirques are significantly widened. HI, which is a proxy for the amount of cirque erosion, shows that schist and limestone are the most eroded, with shales and gneiss as the least eroded. Schist, limestone and granite are the deepest (highest H), whereas shales, quartzite and lime/sandstone and shales cirques are the shallowest. Finally, in terms of AS all lithologies are similar except for gneiss (whose AS is significantly larger than all other lithologies) and limestone, which shows the opposite situation.

5. Discussion

5.1. *Cirque LPE and climate*

Eq. (3) indicates that the main control on cirque elevation for the Iberian Peninsula is temperature, represented by the LAT variable, with a secondary precipitation factor (LON). The equation better represents, in terms of R^2, cirque LPE variability on the Iberian Peninsula than it does in other areas, such as the British Isles (Barr et al., 2017), Kamchatka (Barr and Spagnolo, 2015b) or British Columbia (Evans, 2006). This strong climatic control on cirque elevation is likely indicative of marginal glacial conditions during former glaciations, with glaciers (and therefore cirques) unable to develop at low elevations in some regions (i.e., at low latitudes and/or in the peninsula's interior). However, there are cirques that do not fit well with this multiple regression. Where cirques that do not fit the LPE/climate regression are randomly distributed, they possibly indicate errors in cirque identification and/or mapping, e.g. false identification of non-glacial topographic depressions as cirques. However, where they are non-randomly distributed but clustered this might reflect meaningful spatial patterns in cirque altitude which would merit a detailed study.

Table 4
ANOVA of shape and location variability for the four different cirque aspect bins (N, E, S, W).

Variable	Sig.
H	<0.001
LPE	<0.001
HPE	<0.001
AS	<0.001
L/W	0.002
W	0.166
L	0.59
CIR	0.007
Perimeter	0.308
Area	0.746

5.2. *Cirque LPE and paleo ELA*

The lowest elevation of a cirque is often taken as a proxy for the ELA of any small-scale (largely cirque-confined valley) glacier that formerly occupied it, and a large database of cirques in a region can therefore be used to reconstruct a regional palaeo ELA, with the important caveat that it is usually unknown whether all cirques were occupied by cirque glaciers at the same time, i.e. they could represent a time-transgressive database (Barr and Spagnolo, 2015a). The fact that the Iberian Peninsula did not develop ice sheet glaciation during the LGM and most of the glaciers were valley/cirque type favours a direct relation between LPE and ELA. In this study, we have found that cirque LPE across the Iberian Peninsula generally replicates the distribution of ELA during the LGM, which suggests that this variable is a good ELA indicator, bearing in mind that the maximum ice extent in Iberian mountains was not synchronous along the Peninsula, predating the LGM in some areas and being synchronous with the LGM in others (Oliva et al., 2019). Both LPE and ELA are the result of broad, peninsula-wide, temperature (N/S increase) and precipitation (W/E decrease) patterns, with the exception of a region of high precipitation at the E part of the Bay of Biscaye. This pattern is broadly similar to present conditions (Ortega Villazán and Morales Rodríguez, 2015). Hence, we suggest that palaeoclimatic trends during the formation of the glacial cirques were similar to the current ones in terms of regional atmospheric circulation and precipitation distribution, which is in line with Pedraza et al. (2019) conclusions for the Central Range. The Iberian Peninsula experienced more marginal glaciation during the Pleistocene glacial phases than in other regions of Western Europe such as the Alps or the British Isles (Ehlers and Gibbard, 2004), so whether glaciers were able to form in a particular location or not was strongly dependent on spatial differences in climate. In this context LPE can reliably be used as an ELA/palaeoclimate proxy during the local glacial maximum.

5.3. *Cirque aspect distribution*

Previous studies have noted a strong tendency for cirques to show a N to E aspect bias in the Northern Hemisphere (Evans, 1977, 2006), which is also observed in our dataset (see Fig. 4) and can be explained by a protection from insolation for N-facing cirques and more snow accumulation for E-facing cirques which occupy slopes on the lee side of prevailing western winds (Vidal-Box, 1948; Palacios et al., 2012; Carrasco et al., 2022b). An added factor in promoting the formation of E/NE-facing cirques is that east facing slopes receive much of their direct solar radiation in the early part of the morning, when air temperatures are relatively low, thereby limiting overall ice and snow melt (Evans, 1977). The aspect VM of 45° identified for the entire population of cirques analysed in this study suggest that these topoclimatic factors also acted to regulate cirque aspect across the Iberian Peninsula. The ENE (64°) VS for Central Range and the strong VM for the Central Range reflect a greater westerly wind effect related to snow drifting off the flat-topped areas. This also applies to the Galician and Sanabria subregions, whereas the NNE VMs for Picos de Europa and C. Cantabrian (25° and 29°) probably reflect less importance of snow drifting due to the high relief, several mountain chains and serrated ridges.

Barr and Spagnolo (2015a) suggested that differences in aspect VS can be used to infer the extent of past glaciation. Specifically, in regions where VS is low, cirques are found with a variety of aspects, suggesting that former glaciation was extensive, with ice forming even on climatically less-favourable slopes. By contrast, high VS (i.e. cirques showing strong aspect asymmetry) suggests that former glaciation was marginal, with ice-masses only able to form on the most climatically favourable slopes. On this basis, the high VS in the Iberian Range points to a marginal glaciation, with only the most climatically favourable orientations able to form glaciers. Cirques (and glaciers) found to have high VS and a NNE orientation in the Northern Hemisphere, are a possible indicator that former glaciers developed under comparatively cloud-free ablation season conditions, thereby maximising aspect-related variations in direct solar radiation (and therefore melt) (Barr and Spagnolo, 2015a). Both ideas point to increased aridity or seasonality in interior regions of the Iberian Peninsula during former periods of glaciation, conditions typical of continental climates (Evans, 1977). However, this logic is brought into question by the Cantabrian Range, the most coastal region, which has a 43 % VS while the Central Range and Sierra Nevada have a VS of 36 % and 31 %, respectively, despite the presumably arid climate. We suggest that the comparatively low VS in the Sierra Nevada should not be read in terms of a palaeoclimatic signature, since this range is a single massif with the main ridges extending in only two directions, SW-NE and W-E. As a result, cirques developed bimodally, either N-S or NW-SE oriented. This is the likely explanation for the 104° aspect vector mean and the weak VS. The Central Range also shows this structural control on cirque aspect, as it comprises a series of W-E crests that turn in a SW-NE direction in its eastern region (Guadarrama), where the westerlies accumulated snow on the lee side, creating the most developed cirques on SE oriented slopes (Pedraza et al., 2019).

VS in the Cantabrian Range is weak enough to infer formerly extensive glaciation and a minor role for aspect-related variations in solar radiation during the ablation season, suggesting that the present-day typically cloudy (and wet) weather in this area during summer (Ortega Villazán and Morales Rodríguez, 2015) might have been common in the past. The lower VS in the easternmost subregion of the Cantabrian Range, as well as in the Picos de Europa might be explained by climate, since at present these are areas where cloudy/foggy weather is common during summer, as the Azores High is usually located W of the Iberian Peninsula and generates humid, northerly winds from the Cantabrian Sea into the coastal mountains (Uriarte, 1980; Viedma, 2005). Such conditions, enhanced by colder waters in the Bay of Biscay, may have resulted in pervasive clouds on coastal mountains and therefore glaciers with more varied aspects than in the Western Cantabrian Range, where the Azores High usually brings sunny weather.

VM values in our dataset show similarly preferred orientations to nearly every previously investigated cirque population in Western and Central Europe, i.e. between 30° and 70° (see Barr and Spagnolo, 2015a, Table 2). Only the Sierra Nevada shows a different pattern, which we suspect is related to the structural setting of the mountain range and its control on former glacier locations, as suggested for VS too.

5.4. *Which cirque orientation LPE best matches the LGM ELA?*

In this study we found a linear regression that explains cirque LPE for the entire Iberian Peninsula excluding the Pyrenees. We have also compared trends in the LPE to trends in the LGM ELA. In general Northern Hemisphere cirques with a N and E aspect tend to form at lower elevations than those with S and W aspects, because local shading and a colder local climate favour a lower ELA on these orientations compared to W and S.

By comparing the average difference and absolute average difference from modelled LPE and the LGM ELA (see Section 3.4), we can conclude that: 1. Overall differences between modelled LPE and LGM ELA vary little from one aspect bin to another and 2. LPE for cirques with N orientations most closely match LGM ELA according to the model error but correlation between LPE and ELA is highest for S orientations (see Table 5 and supplementary Fig. 5).

Table 5
Elevation differences between cirque lowest point elevation (LPE) and LGM ELA according to aspect bins.

	Average elevation diff. (m)	Absolute elevation dif. (m)	Model error (Z scores)	Abs. Model error (Z scores)
N	−57.6	148.1	−0.03	0.52
E	−94	162.1	0.05	0.55
S	−130.6	168.3	−0.06	0.53
W	−169.5	200	0.09	0.53

5.5. *Cirque size and allometric growth*

Cirque L, W, H and area on the Iberian Peninsula show a remarkable variety depending on the region (see Section 3.6). When compared to a global dataset, cirques are smaller than the global average (Barr and Spagnolo, 2015a, Table 4), with values similar to other nearby areas such as the French and Spanish Pyrenees (Delmas et al., 2014; García-Ruiz et al., 2000), the Tatra Mountains (Křížek and Mida, 2013) or the Scottish Western Highlands (Gordon, 1977). In the Sierra Nevada and Central Range, the cirques have dimensions comparable to cirques in areas such as Kamchatka (Barr and Spagnolo, 2013) and Scandinavia (Hassinen, 1998) in terms of mean and maximum length, width or depth. Given the varied climates and lithologies (see Section 5.8) of these different places, it is difficult to make any robust palaeoclimatic inferences from cirque size alone.

The allometric exponents on the Iberian Peninsula typically show lengthening to outpace widening, which in turn outpaces deepening. This is similar to other nearby areas such as the Central Pyrenees (García-Ruiz et al., 2000), French Pyrenees (Delmas et al., 2014) and Romania (Mîndrescu et al., 2010). Despite this overall pattern, in some of the most heavily glaciated regions of the Iberian Peninsula, such as in the Cantabrian Range, cirque growth is almost isometric (with cirques growing equally in all dimensions). This might indicate that cirques experiencing marginal glaciation only partly preserve the shape of the long, narrow and shallow fluvial depressions from which they developed. As these cirques are progressively shaped by glacial erosion, this fluvial signature is gradually lost as both deepening and widening generate a classic bowl-shaped depression. The higher depth values in the Central Range might be due to structural reasons, because of the steep drop on the S face of the Gredos mountains, which created several very steep but not deeply eroded cirques.

The comparatively large cirque widths in the Iberian Range are comparable to other continental and mediterranean areas such as the Zardkuh Mountains (Seif and Ebrahimi, 2014), the Maritime Alps (Federici and Spagnolo, 2004) or the mountains of Greece (Bathrellos et al., 2014).

Likewise, average circularity for the Iberian cirques (1.13) is very similar to values elsewhere in Europe, such as the French Pyrenees (Delmas et al., 2014), the Tatra mountains (Křížek and Mida, 2013) or the Maritime Alps (Federici and Spagnolo, 2004, see also Barr and Spagnolo, 2015a, Table 5). Internal variability in circularity is also very low.

All the regions/subregions with large cirques correspond to mountain regions where slope angles are low on average. The Central and Western Cantabrian subregions, by contrast, feature steeper slopes, and here the number and density of cirques is very high, but their size is smaller on average. The Central and Western Cantabrian mountains developed large icefields during the LGM, so cirque size, at least on the Iberian Peninsula, cannot be considered to directly reflect the intensity, duration and/or nature of glacial erosion and periglacial weathering (Barr and Spagnolo, 2015a).

The isometric growth of cirques in the Cantabrian Range could reveal long-lasting glaciation in this region, which is in line with the present knowledge about glaciation in the area (Oliva et al., 2019). For example, if we compare the different areas in the Cantabrian Range, the most extensively glaciated, the Central and Western Cantabrian subregions, show the closest to isometric values, whereas the most allometric are located in the most glacially marginal subregions, the Galician Mountains and the Eastern Cantabrian. Here glaciation would have lasted less time, perhaps with cirques adapted to fluvial valley heads, not having time to widen and deepen. For the Iberian Range, widening outpacing lengthening and deepening can be interpreted as diagnostic of marginal glaciation, with very limited valley glacier formation and glacial trough deepening (see Fernández-Fernández et al., 2017; García-Ruiz et al., 2020), which is mostly driven by subglacial erosion and the importance of the interplay between glacial and periglacial processes in cirque evolution (Barr and Spagnolo, 2015a).

5.6. Variable correlations

High correlation between cirque maximum elevation and cirque size attributes confirms that higher cirques are also larger, probably because of having experienced erosional glacial conditions for a longer time than the lower altitude cirques. Direct (inverse) correlation between longitude (latitude) and cirque-size values can be interpreted with the idea that cirque evolution due to glacial erosion lasted longer in regions such as the Iberian Range or the Central Range than the Cantabrian Range, where cirque erosion was halted in many cases by the evolution of glaciers to icefields with cold-based ice on accumulation areas, especially in the Central and Western Cantabrian Mountains, where most of the cirques are located.

NOR and EAS correlate negatively with LPE and HPE (i.e. N oriented cirques are located at lower altitudes). Correlations are stronger for NOR than EAS in all cases. NOR correlates positively with H (N oriented cirques are deeper) and AS (they are also steeper), but EAS shows a statistically significant negative correlation for both, so E facing cirques are generally less steep and deep than those oriented to the W. Delmas et al. (2014, 2015) and Federici and Spagnolo (2004) pointed to larger and deeper cirques on N aspects and interpreted them as the result of S oriented glaciers being short-lived and allowing periglacial widening. Positive correlation of CIR with NOR can be interpreted likewise.

5.7. The role of aspect in cirque development

ANOVA-Bonferroni analysis showed that cirque aspect has a significant impact on cirque LPE, H and circularity. These results are similar to Křížek and Mida (2013) for the Tatra Mountains. It has been argued that favourable climatic conditions might mean a generally lower LPE for N and E facing cirques (Evans, 2006; Barr and Spagnolo, 2015a). This pattern is possibly also seen on the Iberian Peninsula. N facing cirques reach significantly lower elevations than any others, whereas E oriented cirques are significantly lower than S and W oriented ones. The same pattern exists for the maximum elevation. These morphometric relations suggest longer lasting or recurrent glaciation of N oriented cirques, and to a lesser extent of the E oriented cirques. By contrast, there is no significant influence of aspect on the size of cirques.

5.8. The role of lithology in cirque morphometry

Results in Section 4.9 point to several differences in cirque size, shape and depth relative to different lithologies. However, these results must be considered conservatively and put in the context of the distribution of lithologies, which is extremely clustered. Difference in cirque size point to some lithologies, especially schists, granite and gneiss, as prone to significantly larger cirques than all sedimentary lithologies. However, all our schist cirques are located in Sierra Nevada, 82 % of granitic cirques and 69 % of gneiss cirques formed in the Central Range. Moreover, these two ranges lack cirques on different lithologies. Therefore, it is impossible to distinguish the climatic and lithological impact on cirque morphometry in these three classes.

Not far from our study area, in the Pyrenees, Delmas et al. (2015) found cirques eroded in granites and gneiss to best reflect climate influence, whereas others such as schist are more related to bedrock structures. Likewise, García-Ruiz et al. (2000) found that granite cirques are the largest in the Central Pyrenees, but this could be due to their location in the most heavily glaciated areas. Palma et al. (2017) point to the importance of the easily erodible schist in the formation of large cirques in Sierra Nevada. Finally, Hughes et al. (2007) found limestone cirques be larger than ophiolite cirques in Northern Greece.

Limestone, quartzite, lime/sandstone and shales and sandstone/conglomerates are more widely distributed within the Cantabrian Range. Statistically significant differences in morphometry are few among them and mostly relate to the profile along the longitudinal axis. HI is significantly lower for limestone cirques, which we interpret as the result of previous karstic erosion and the creation of dolines. Sandstone/conglomerates also have significantly lower HI than quartzite, where high HI can be interpreted by the rock resistance to glacial erosion and its susceptibility to freeze-thaw weathering, which usually forms extensive talus at the foot of cirque walls (Sellier, 2013).

6. Conclusions

Cirques are ubiquitous throughout the glaciated mountain ranges of the Iberian Peninsula, with a particular concentration in the Cantabrian Range and smaller populations elsewhere, a pattern which ultimately reflects the duration and severity of cold conditions during past glacial stages. Alongside this, trends in cirque morphometry and distribution, both within and between individual mountain regions, provide insights into the factors influencing cirque formation, as well as an improved understanding of palaeo-glaciation and palaeoclimate. Analysis of cirques of the Iberian Peninsula is of particular value in that regard, due to the absence of extensive glaciation throughout the Pleistocene (Oliva et al., 2022a). By comparison, cirque records from other regions cannot be unequivocally linked to marginal (small-scale) glaciation, given the envelopment of cirques by larger ice-sheets and ice-fields, such as in the British Isles (Barr et al., 2017), Antarctica (Barr et al., 2022) or Kamchatka (Barr and Spagnolo, 2015b). While cirque morphology can be preserved in these settings, due to the presence of cold-based ice or the spatial focusing of erosion (Barr et al., 2017), subsequent modification of cirques by larger ice masses cannot be ruled-out. On the Iberian Peninsula, the longevity of marginal glaciation and the absence of extensive glaciation ensures that the contemporary cirque record (as studied here) better reflects cirque and cirque-glacier evolution, and ultimately palaeoclimate and/or glacial history.

Across the Iberian Peninsula, cirque elevation, a potentially useful proxy for past equilibrium-line altitudes, is most strongly correlated with latitude and longitude ($R^2 = 0.51$, see Table 1 in supplementary), which primarily reflects latitudinal gradients in temperature and longitudinal gradients in precipitation. In general, cirque elevations increase towards the SE, which points to an increase in temperature and aridity in the same direction during the Pleistocene, a pattern which is consistent with current climate trends. While cirque elevations are less strongly associated with aspect, cirques do show a N and E aspect bias, which is indicative of marginal glaciation for much of the peninsula, with former glaciers often restricted to climatically favourable slopes. This pattern does not hold in regions where glaciation was more widespread (e.g., Cantabrian Range), which are characterised by more varied cirque orientations. In these regions, evidence of isometric cirque growth (cirque lengthening ≈ widening ≈ deepening) also points to long-lasting glaciation, sufficient for cirques to obtain a least resistance form (Barr et al., 2017). In summary, cirque size, elevation and orientation permit the characterization of extensive glaciation patterns in the Central and Western Cantabrian subregion and more marginal glaciation elsewhere in the Iberian Peninsula (Pyrenees not included), either because mountains were low, as for example the coastal mountains in the NW and the Eastern Cantabrian, or because of an increased continentality and higher temperatures, such as in the Iberian Range, the

Central Range and Sierra Nevada.

The detailed analysis of cirques across the Iberian Peninsula can help understand past glacial development, dynamics and climatic conditions during the Pleistocene, making cirques a useful testimony of the Iberian Peninsula's climatic past.

CRediT authorship contribution statement

Ramón Pellitero: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Iestyn Barr:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Matteo Spagnolo:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Matthew Tomkins:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data is now accesible in a public repository

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Appendix A. Supplementary data

The Iberian cirques dataset can be found here. Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2024.109318.

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