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The plateau glacier in the Sierra de Béjar (Iberian Central System) during its maximum extent. Reconstruction and chronology

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ABSTRACT

A detailed study of the glacial morphology in the Sierra de Béjar (Iberian Central System) provided a data set of geomorphic indicators to reconstruct the paleoglaciers developed in this mountain area during the last glacial cycle (Late Pleistocene). Applying a physical-based glacier model and using the geomorphic indicators, a three dimensional reconstruction of the ice mass during the maximum extent of the glaciers has been carried out. We used this reconstruction to project hypsometric curves over the former glaciers and to estimate the ELAs (Equilibrium Line Altitudes) of the paleoglaciers for their stage of maximum extent. At this stage the Sierra de Béjar hosted a plateau glacier, considered as a dome-shaped icecap around 57 km^2 in area. According to our estimations, the maximum thickness of the ice was 211 m, the minimum elevation of paleoglaciers 1210 m asl, and the regional ELA was at 2010 m asl. During later stages, reduction in ice mass due to deglaciation caused the icecap to evolve into an icefield, and finally the main glacier was fragmented in valley and cirque glaciers. The geochronological data obtained with ^{10}Be provides an age of ~27 ka for the maximum extent of the glaciers (GM), whereas the global Last Glacial Maximum (LGM) represents a younger stage of the Sierra de Béjar glacier evolution. Finally, the new data obtained in the Sierra de Béjar allow evaluating the influence of some factors such as the continentality and latitudinal location, in the development of glacial processes in these areas of the Iberian Central System.

1. Introduction

The updated data provided by the Climate Long-range Investigation Mapping and Prediction Project (CLIMAP, 1976), referring to climate reconstructions during the last glacial period, establish the Last Glacial Maximum (LGM) as a global reference stage for reconstructing the earth's climate and the glacial environments of the Late Pleistocene (Mix et al., 2001). Many research projects on paleoglaciers carried out in different regional contexts take this LGM as a base reference for establishing comparisons, when reconstructing ice masses and conducting paleoclimatic interpretations.

The paleoglaciers of the Iberian Peninsula are highly valuable climatic indicators of the Pleistocene cold periods since, like other Mediterranean areas that hosted mountain glaciers, their relatively low latitudinal position and small dimensions make them very sensitive to climate changes (e.g., Messerli, 1980; Hughes et al., 2006; Vieira, 2008; Cowton et al., 2009). The reconstructions of ice masses must be supported by chronologies to place the processes within their evolutionary context. The chronologies obtained for paleoglaciers from some regions of the Iberian Peninsula provide numerical ages for the maximum glacier advance during the last glacial period that precedes the global Last Glacial Maximum (LGM), while in other regions the dates are in agreement with the LGM (e.g., Garcia-Ruíz et al., 2010; Pallàs et al., 2010).

The diachrony of the maximum glacier extent during the last glacial period at different latitudes in Europe has been previously pointed out, especially between the Mediterranean region and the rest of the continent (Seret et al., 1990; Florineth and Schlüchter, 2000; Hughes et al., 2006). However, in the mountains of the Iberian Peninsula, geographic factors such as latitude, orientation, altitude, continentality, etc, do not seem to be enough to explain the reported differences in chronology. Such chronological discrepancies may be related, at least in some cases, to assumptions regarding the dating methods, the use of inadequate dating techniques, or the use of unsuitable materials (e.g., Garcia-Ruíz et al., 2010; Pallàs et al., 2010).

This research in the Sierra de Béjar, a sector of the Iberian Central System, illustrates a phased methodology towards defining the useful geomorphic indicators for a rigorous approach to the chronology and reconstruction of ice masses. The paleoglaciers in the Sierra de Béjar are among the most important in the Iberian Central System and

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were traditionally classified as valley and cirque glaciers (Schmieder, 1915; Carandell, 1924; Sanz Donaire, 1979; Rubio Campos, 1990). The paleoglaciers in Sierra de Béjar have been recently re-classified as a plateau glacier (Carrasco and Pedraza, 1995) comparable with that of the Serra da Estrela, the only sector of the Iberian Central System where this type of paleoglacier had been traditionally described (Lautensach, 1929).

Glacier characterization and a chronological framework are fundamental issues when studying paleoglaciers. However, these aspects regarding the glaciations in the Iberian Peninsula are still under discussion (e.g., García-Ruiz et al., 2003; Perez Alberti et al., 2004; Garcia-Ruíz et al., 2010; Pallàs et al., 2010). In the research carried out in the Iberian Central System, a new morphological indicator of the maximum extent of glaciers has been recently identified (Pedraza et al., 2011), as well as the participation of the paraglacial processes in the generation of moraines (Carrasco et al., 2010). These new data indicate the need for setting out detailed geomorphological mapping, in order to perform a suitable reconstruction of the glaciers and the sampling for the absolute dating of the glacial maximum in the Sierra de Bejar. The aims of this research are to carry out a tridimensional reconstruction of the Sierra de Béjar paleoglacier during its maximum extent, and the calculation of the paleo-ELAs (Equilibrium Line Altitude) as paleoclimatic indicators. We use the ^{10}Be method to date the geomorphic indicators of the maximum glacial extent to provide insight on its chronology.

2. Regional setting

The Sierra de Béjar (Fig. 1) is a NE–SW mountain range of the Iberian Central System. This is an intraplate mountain belt formed during the Alpine orogeny (mainly during the Miocene–Pliocene) by the uplift of the Hercynian or Variscan basement, with a morphostructure determined by fault-bounded blocks with summits at elevations between 1700 and 2300 m asl (e.g., Pedraza, 1994; Casas-Sainz and de Vicente, 2009). This morphology was a crucial factor in the development of plateau glaciers in some of these summits during the Late Pleistocene.

The predominant lithologies in the Sierra de Béjar correspond to granitoids (i.e., monzogranites, granodiorites; Bellido, 2004, 2006). Migmatites, metasediments and quartzitic schists are also present. The Quaternary cover has a limited extent (less than 10% of the land area) and has a limited thickness (1–5 m). It consists of fluvial, glacial, periglacial and landslide deposits (Carrasco, 1997). Glacial till, generally boulders and large boulders with a coarse-grained matrix, is lithologically homogeneous, mostly composed of granitoids and their sandy weathering products. The typical sequence found in the till exposures includes, from the base to top, subglacial traction till (or basal deformation till), subglacial accretion till, subglacial melt-out till, and supraglacial melt-out till (Carrasco et al., 2011).

From the climatic perspective, the Iberian Central System can be classified as a medium Mediterranean mountain with notable Atlantic

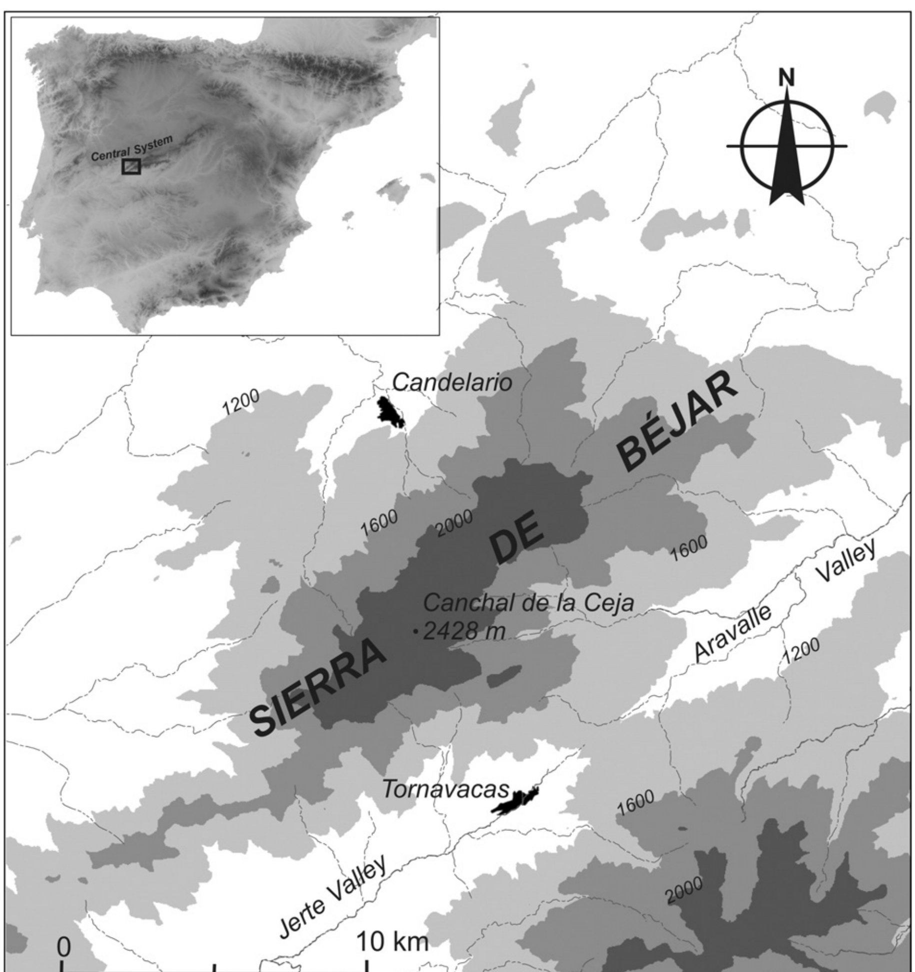

Fig. 1. Location of the Sierra de Béjar (Iberian Central System).

Fig. 2. Oblique aerial view of the Sierra de Béjar after a snow event. (Photo: C. García Royo).

influence in the west (i.e., a wetter climate) and continental in the east (a dryer climate with marked seasons). The Sierra de Béjar presents a climatic environment midway between these two end-members. Its central-west position means that the continental factor has a clear influence and that abundant moisture reaches it from Atlantic depressions. Moreover, it is one of the massifs in the Iberian

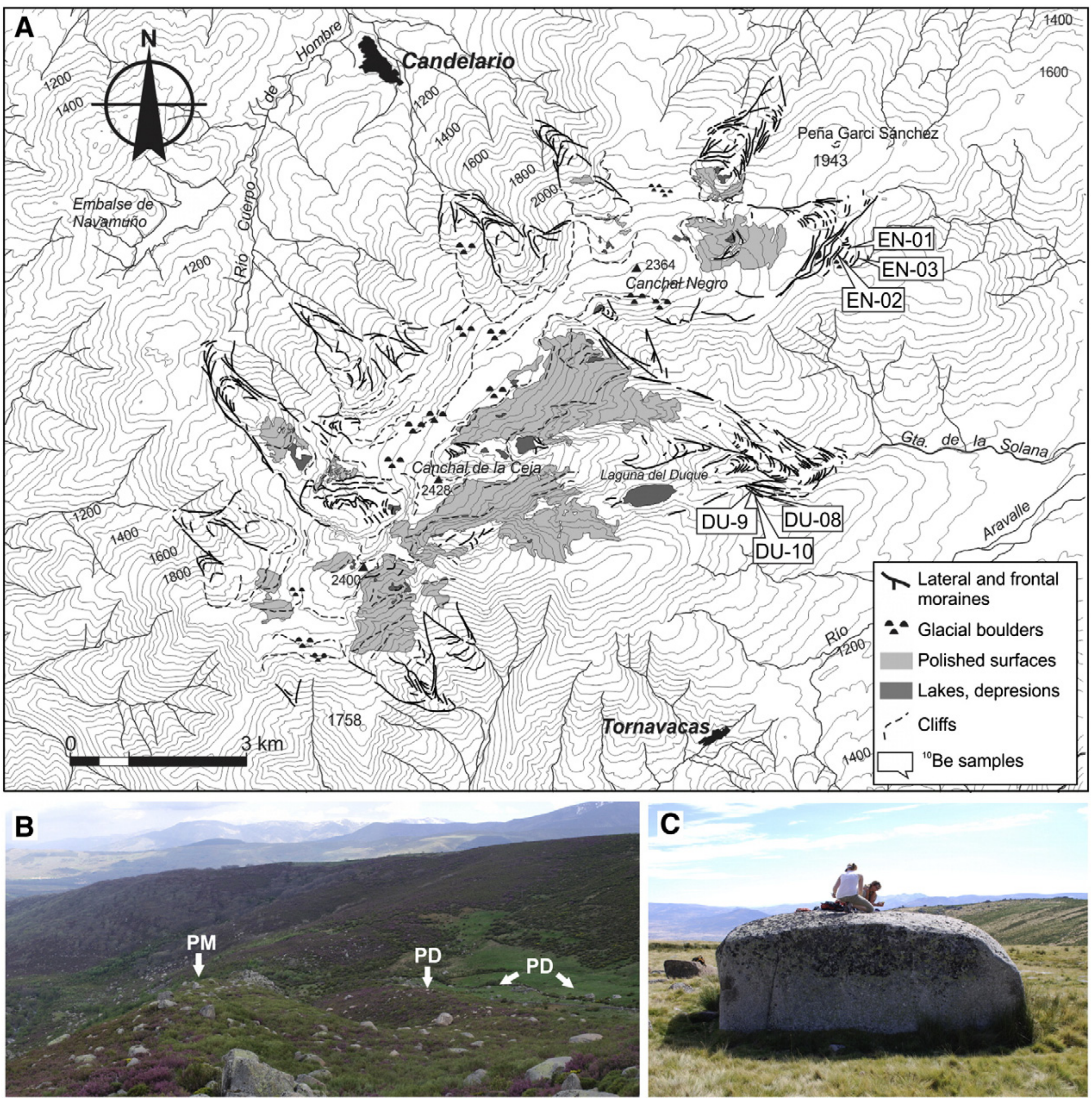

Fig. 3. A. Map showing the glacial morphology of the Sierra de Béjar. The labels indicate the location of the boulder samples selected for ^{10}Be dating. B. Peripheral deposits (PD) and principal moraine (PM) in the Duque Valley. C. Example of granite boulder sampled for ^{10}Be dating in the Endrinal Valley.

Central System with a more southerly position and maximum temperatures are slightly higher than in the more northerly areas. The mean annual maximum temperatures on the summits of the Sierra de Béjar range from 12.5 to 15.0 °C, (up to 5 °C higher than in other massifs from the Iberian Central System) and mean annual precipitation varies between 1400 and 1800 mm; these values are close to those of the westernmost sector of the Iberian Central System, and higher than in the eastern sectors, where the mean annual precipitation is 1000–1400 mm (AEMET/IM, 2011).

Glacial landforms in the Sierra de Béjar have only been identified where the summits are higher than 2000 m asl, and paleoglacier dimensions are larger with higher elevations of the massifs. Where the peaks do not reach this height, geomorphic features of glacial origin have not been identified. The mean height of the peaks of the Sierra de Béjar is 2200 m asl (culminating in the Canchal de La Ceja, 2428 m asl) with a surface area of 32.76 km^2 above 2000 m asl.

2.1. Glacial morphology of the Sierra de Béjar

The summit of the Sierra de Béjar consists of an extensive plateau (Fig. 2) with frequent outcrops displaying evidence of subglacial erosion (glacial polishing, *roches moutonnées*, striation, hollows or small overdeepened basins), and erratic boulders. The presence of dispersed erratic boulders is especially common in the north sector, where the summit is a wider plateau with a few rocky protruding outcrops remodelled by post-glacial periglacial processes.

In the northern edge of the plateau-like summit and above 2200 m asl, there are several cirque-type depressions. These features represent the initial sectors of outlets radiated out from the plateau glacier. In the southern sector, the topography of the summit is more irregular, with hills and mounds projecting above the overall level of the plateau, to reach the maximum elevations of the Sierra de Béjar. This sector is characterized by a system of coalescent basins with a series of valleys radiating out from them. These valleys are clearly controlled by tectonic structures that facilitated their excavation. This system of coalescent basins propitiated significant accumulations of ice and the development of large tongues as in El Duque-Trampal and Cuerpo de Hombre valleys.

Although the Sierra de Béjar ice mass was a single glacier system and in general terms could be classified as a plateau glacier, from the differences mentioned between the N and S sectors, it can be deduced that ice flow in the northern sector was conditioned to a lesser extent by the bed topography than in the southern sector. Since topographical conditions are considered when establishing the plateau glacier type (Sugden and John, 1976; Benn and Evans, 2010), the northern sector displays morphological and dynamic features more prone to develop a plateau icecap, whereas the southern sector is more conductive to the formation of a plateau icefield (Fig. 2). However, regardless the basal topography, the volume of ice accumulated in the summit (i.e., dome-shaped ice body covering the basal topography or a flatter ice surface with outstanding nunataks) determines the glacier type during different stages (Golledge, 2007).

The morphostratigraphic sequence of the last glaciation in the Sierra de Béjar has been established using the moraine formations and other associated deposits as the main indicators (Fig. 3). Three sequences have been recently identified in these areas (Pedraza et al., 2011). The first sequence has been called “peripheral deposits” and is formed by a series of small moraines (with up to three moraines identified in some valleys) and/or areas covered by dispersed erratic boulders. The most external ridge or set of erratic boulders of these “peripheral deposits” indicate the “glacial maximum” in this areas (GM). The second sequence corresponds to the best developed and continuous lateral moraines (identified in all the valley paleoglaciers), called “principal moraine”, which represents the onset of deglaciation in this area (Fig. 4). Finally, the third sequence is located in internal positions in relation to the principal moraine, and is formed by various “recession moraine” complexes (with up to three complexes identified in some valleys) and various sequences of “erratic boulders”. This third sequence constitutes the record of stages of deglaciation.

The chronology of these paleoglaciers has traditionally been based on regional correlations, using the alpine chronology as a reference. Initially, two glaciations were proposed equivalent to the Alpine Riss and Würm (Obermaier and Carandell, 1917). On the basis of more precise research, the chronology was reduced to a single phase equivalent to the Würm (Butzer and Franzle, 1959) and two well differentiated sub-stages called Würm A and Würm B (Pedraza and Fernández, 1981). These relative chronologies have been used until recently, when the application of absolute dating methods started. The data obtained so far confirm that the evidence of paleoglaciers in the Iberian Central System belong to the last glaciation.

3. Methods

To establish the chronology and the limits of the ice masses during the GM and to calculate its thickness, the geomorphologic indicators

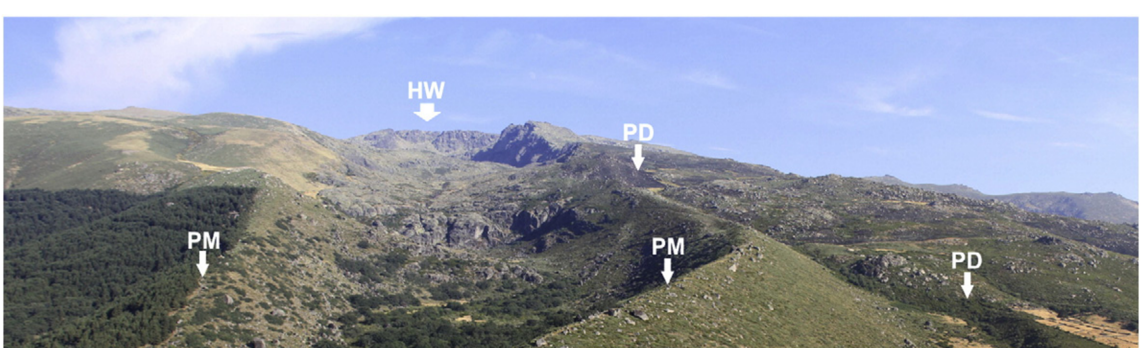

Fig. 4. Picture of the Cuerpo de Hombre paleoglacier. PD: peripheral deposits; PM: principal moraine; HW: headwall.

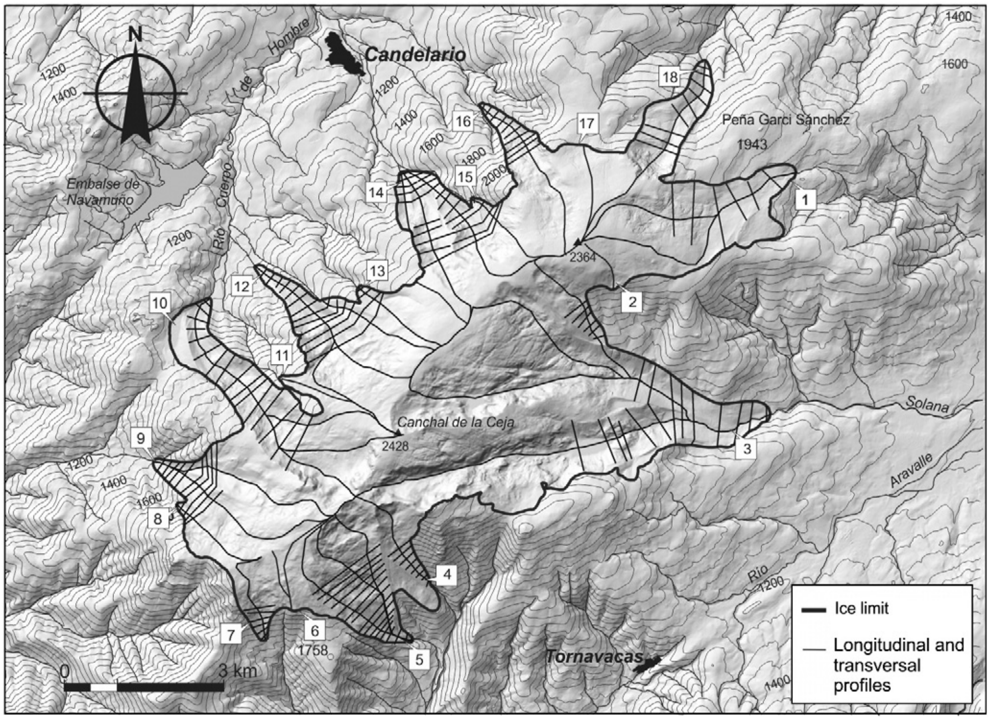

Fig. 5. Map showing the location of longitudinal and transverse profiles used to reconstruct the plateau paleoglacier from Sierra de Béjar. 1. Endrinal; 2. Dehesa Boyal; 3. Duque-Trampal; 4. Talamanca; 5. Regajo Grande; 6. Collado de la Nijarra; 7. Nijarra; 8. Pinajarro; 9. Espinarejo; 10. Cuerpo de Hombre; 11. Canterón; 12. Regajo Vicioso; 13. Hornillo; 14. Candelario; 15. Canchalón 16. Oso; 17. Las Cobatillas; 18. Peña Negra.

used were the "peripheral deposits". The identification of these deposits is problematic, as in some places they have been partially covered by the principal moraine, which represents a later evolutionary stage. Detailed field surveys complemented by geomorphologic photointerpretation have helped us map the peripheral deposits and the principal moraine deposits.

To assign a chronology to the GM stage, absolute dating was performed using in situ terrestrial cosmogenic nuclides. ^{10}Be was the chosen method since it is the most appropriate nuclide for granites and migmatites (Gosse and Phillips, 2001), which are the dominant lithologies in this area. Based on the maps of geomorphic indicators, two representative valleys were selected for the chronological study: Endrinal and Duque-Trampal (Fig. 3). A total of 6 blocks were sampled with sizes ranging from 6 to 20 m^3. The abundant large blocks present in the valleys allowed blocks to be selected with a high level of confidence that they had not been buried and subsequently exposed. The selection of erratic boulders or those on *arêtes* also minimizes the risk of choosing blocks which have undergone rotation. Cosmogenic isotopes were extracted and purified following the standard method (e.g., Kohl and Nishiizumi, 1992) and analyzed with an Accelerator Mass Spectrometer (AMS) at PRIME Laboratory in the Purdue University. Ages were calculated using the Cronus-Earth online calculator (Balco et al., 2008) applying the scaling scheme for spallation of Lifton et al. (2005). Topographic and snow cover shielding factors were considered. Exposure ages are calculated for two erosion rate scenarios: ER = 0 and ER-model. The former considers a negligible erosion rate since the rock was exposed after glacier retreat. The latter incorporates an erosion rate model that is altitude dependent, providing a value for each particular sampling location. The model was constructed from erosion of selected sites that represent different sub-stages (and ages) during the stage of deglaciation (Domínguez-Villar et al., 2011). Erosion rate obtained for the region of interest range from 0.3 to 0.7 $mm ka^{-1}$. We consider the calculated exposure age accounting for the modeled erosion rate as the best chronological output, whereas ER = 0 is provided for comparison.

Reconstructing paleoglaciers from well-defined geomorphologic indicators (e.g.: moraines, trimlines) presents few problems. However, when there is a lack of geomorphologic indicators in some sectors, or the data are scarce, as occurs in the central part of the accumulation areas of the dome-shaped plateaus glaciers, the estimation of the ice thickness is more complicated and must be based on empirical methods. One of the most commonly used procedures is a combination of physical-based models supported by geomorphic data to allow validation of results (Schilling and Hollin, 1981; Ackerly, 1989; Rea and Evans, 2007; Vieira, 2008). Using this procedure, reconstruction was carried out by producing theoretical glacier surface profiles using simple steady-state models that assume a perfectly plastic ice rheology. In this research the method described by Benn and Hulton (2010) was used, applying the alternative proposed in the Profiler v.2 spreadsheet. More specifically, this was applied to reconstruct the topography of the ice mass accumulated on the summits of the Sierra de Béjar, based on data from those areas where the plateau glacier was connected with outlets generally confined to the

Table 1
Shape factor measurements for the Sierra de Béjar valleys.

	Average	Maximum	Minimum
Endrinal	0.57	0.66	0.51
Duque-Trampal	0.54	0.62	0.41
Talamanca	0.57	0.63	0.50
Regajo Grande	0.56	0.63	0.43
Nijarra	0.58	0.64	0.54
Pinajarro	0.60	0.65	0.56
Espinarejo	0.59	0.69	0.49
Cuerpo de Hombre	0.57	0.66	0.50
Regajo Vicioso	0.56	0.63	0.49
Hornillo	0.50	0.54	0.47
Candelario	0.52	0.65	0.35
Canchalón	0.57	0.66	0.46
Oso	0.55	0.60	0.50
Peña Negra	0.48	0.57	0.40

valleys. The topographic control is included in the model through a shape factor (Nye, 1952).

A total of 27 longitudinal profiles were completed in the Sierra de Béjar following the maximum flow lines obtained from geomorphologic indicators, and 192 transversal profiles were drawn and shape factors were calculated for each transversal profile (Fig. 5; Table 1). To calculate all these parameters a digital elevation model with 5 m grid resolution was used (PNOA, 2007).

However, this model is not applicable to the areas where there is little excavation (the ice was not confined) and the glacial maximum is determined only by the peripheral dispersed boulders. In this case, the method applied to obtain the topography of ice masses was based on a model that uses the distances from the margin to the ice divides, using a constant basal stress value of 50 kPa (Orowan, 1949; Rea et al., 1998; Evans et al., 2002; McDougall, 1995; Cowton et al., 2009). This is defined as Eq. (1):

$$h = \left(\frac{2\tau_B x}{\rho g}\right)^{1/2} \quad (1)$$

where h is the height of the ice in the centre, τ_B is the basal stress, x is the distance from the margin to the ice divide, ρ is the density of the ice (0.9167 $\mathrm{g cm^{-3}}$), and g the gravitational acceleration (9.81 $\mathrm{m s^{-2}}$).

Thus, Eq. (1) was applied to 6 longitudinal profiles corresponding to the Dehesa Boyal, Collado de la Nijarra, El Canterón and Las Cobatillas (Fig. 5).

To obtain the final ice mass geometry, a geographic information system was created with the data obtained from the 33 longitudinal profiles. When the isohypses of the ice surface had been obtained, ARCGIS 10 software was used to generate a triangulation, and this was then interpolated into a digital elevation model with a grid size of 50 m^2 (Golledge, 2007; Carrasco et al., 2010). The thickness of the ice mass was obtained by subtracting the current topographical surface to the digital elevation model of the ice surface.

The final mapping of the Sierra de Bejar plateau glacier was used as the basis for calculating the Equilibrium Line Altitude (ELA). From the different existing ELA calculation methods (e.g.: Meierding, 1982; Benn and Lehmkuhl, 2000; Porter, 2001; Benn et al., 2005; Osmaston, 2005), the following were used in this paper:

The Maximum Elevation of Lateral Moraines (MELM) is the most similar method to those used by early researchers in the Iberian Peninsula (Penck, 1883; Obermaier and Carandell, 1915; Schmitz, 1969; Brosche, 1978). Although we are concerned by the limitations of this method we show the results obtained in Sierra de Béjar in order to be able to compare with other regions and to evaluate results produced by other methods.

The Accumulation Area Ratio (AAR) method assumes that in mid- and high-latitude glaciers are in equilibrium conditions, the value of the [accumulation area]/[total area] ratio will oscillate between 0.5 and 0.8 (Benn and Evans, 2010), with the most frequent interval between 0.55 and 0.65 (Porter, 1975, 2001; Nesje, 2007). However, the values obtained for the ELA using this method may vary considerably for plateau and piedemont glaciers or for debris-covered glaciers (Clark et al., 1994; Benn and Lehmkuhl, 2000). For the calculations made here, the values 0.5, 0.6 and 0.8 are used to be able to compare the results with those obtained in other areas of the Iberian Peninsula.

An alternative to the methods described above is the Area × Altitude Balance Ratio (BR/AABR) approach. In this method the detailed hypsometry of the glacier surface is considered using a balance ratio (BR), that depends on the different ablation and accumulation gradients (Osmaston, 1975; Furbish and Andrews, 1984). For the ELA reconstruction on the plateau glacier of the Serra da Estrela in Portugal, Vieira (2008) assumes a BR value of 2, which may be considered as representative of the current mid-latitude glaciers with a maritime-influenced climate (Benn and Gemmell, 1997; Rea, 2009). To calculate the ELA by this method in the Sierra de Béjar, we used the spread sheet designed by Osmaston (2005), which applies a range of BR factors to estimate the ELA. Considering that all the glaciers studied are included in the same regional climatic context, subsequently, we proceeded to perform a self-validation of the results (Osmaston, 2005). An ANOVA statistical analysis was performed to obtain a single statistically significant ELA value. The ANOVA test allows the equivalence (initial hypothesis) of the means of the samples considered to be tested.

4. Results

The previously existing maps in the region were updated (e.g., Carrasco, 1997; Bellido, 2004, 2006), paying special attention to indicators of the GM stage. This map includes new outcrops of peripheral deposits, which had not been previously identified, and is the basis for the reconstruction of the plateau glacier of the Sierra de Béjar (Fig. 3). The ^{10}Be dating results in the most external of the peripheral deposits suggest an age around 27 ka BP for the maximum extent of the ice in the Sierra de Bejar (GM). The boulders sampled from the inner ridges of the peripheral deposits gave ages ranging from 19–22 ka (Table 2).

Using the ice surface reconstructed from the profiles (Fig. 6), the topography of the plateau glacier was calculated and then the 3D surface grid constructed (Fig. 7A). According to our estimates, during the GM this glacier covered a surface of 57.4 km^2 and the maximum thickness of the ice mass was 211 m (Fig. 7B; Table 3). The greatest thicknesses were found in the accumulation depressions where the large ice tongues originated, such as those in the Valle del Duque-Trampal (211 m) and Cuerpo de Hombre (180 m). Thicknesses of 105 to 155 m have been estimated for the accumulation depressions where the shorter outlets originated, whereas 60 to 105 m values (with extreme values of up to 120 m) correspond to the glaciated zones on the summit of the plateau. Finally, minimum thicknesses were estimated on the boundaries of the plateau, in some outlet type overflows with values up to 40–60 m.

Table 2
^{10}Be concentrations and exposure ages.

Sample name	Latitude (DD)	Longitude (DD)	Elevation (m asl)	^{10}Be concentration (10 at/g)	Sample thickness (cm)	Shielding factor	Exposure age (ka) [ER = 0][a,b]	Exposure age (ka) *[ER = model]* [a,c]
ESP-08-EN-01	40.34076	5.65176	1867	338.8 ± 15.3	5	1	18.8 ± 2.1	19.0 ± 2.1
ESP-08-EN-02	40.33981	5.65273	1871	341.6 ± 16.7	5	1	18.9 ± 2.1	19.1 ± 2.1
ESP-08-EN-03	40.34005	5.65112	1858	477.4 ± 15.3	5	0.99	26.4 ± 2.8	26.7 ± 2.8
ESP-08-DU-08	40.30416	5.66468	1455	292.1 ± 1.2	2.5	1	21.8 ± 2.2	21.8 ± 2.2
ESP-08-DU-09	40.30416	5.66468	1455	276.1 ± 1.1	2.5	1	20.6 ± 2.1	20.7 ± 2.1
ESP-08-DU-10	40.30337	5.66458	1433	336.7 ± 1.0	3	0.93	27.1 ± 2.7	27.2 ± 2.7

[a] The ages have been calculated using Cronus-Earth calculator v.2.2 (Balco et al., 2008). No inheritance has been considered and the scaling scheme used for spallation is from Lifton et al. (2005).
[b] [ER = 0] assumes an erosion rate of 0 $\mathrm{mm ka^{-1}}$.
[c] [ER = model] incorporates a modeled erosion rate for each location based on field measurements from the Iberian Central System. The modeled erosion rates oscillate between 0.3 and 0.7 $\mathrm{mm ka^{-1}}$ (Domínguez-Villar et al., 2011).

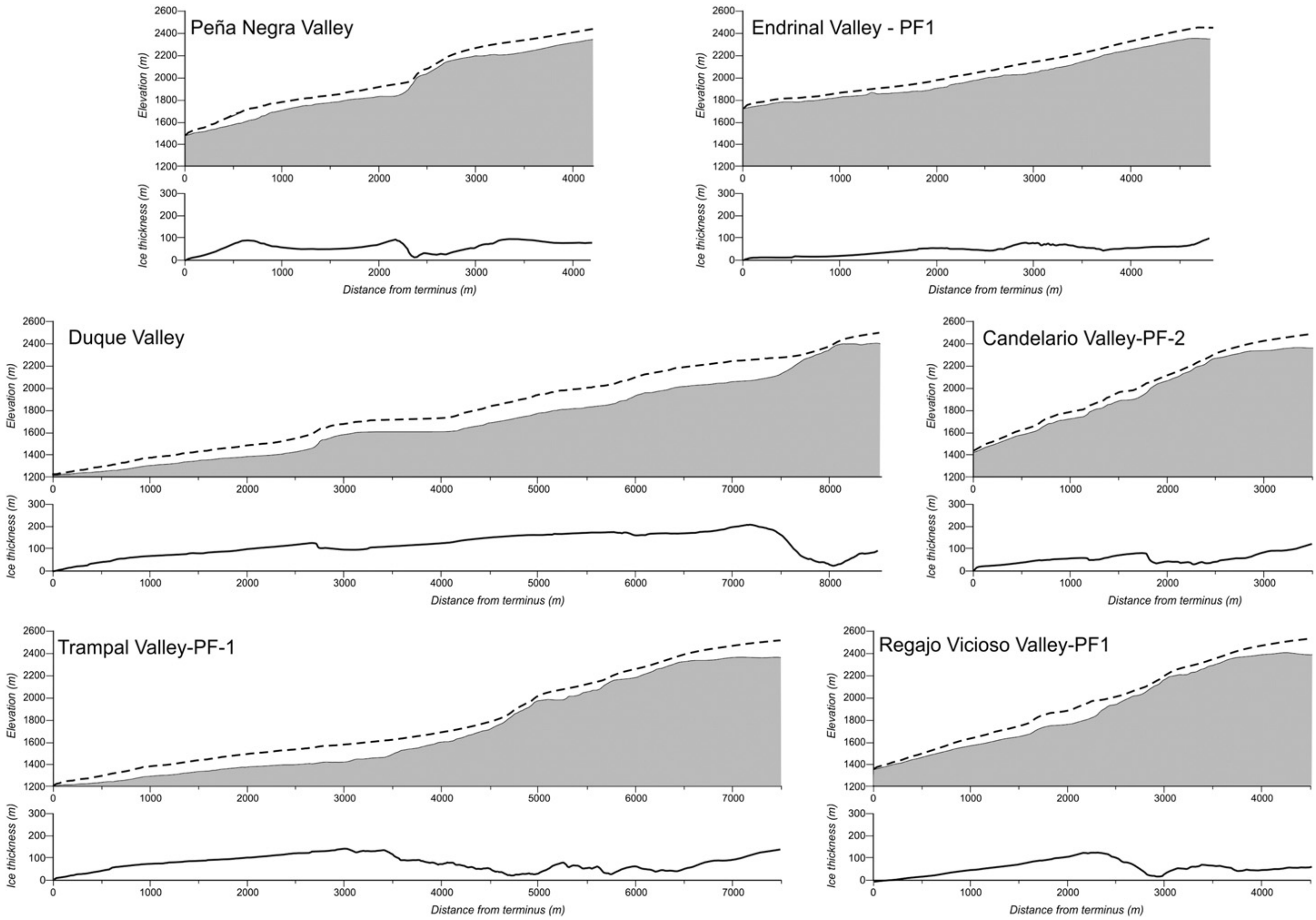

Fig. 6. Examples of longitudinal profiles from the Sierra de Béjar paleoglaciers. Reconstructed ice surface (dashed line), bedrock topography in the center of the valley (grey area) and ice thickness (solid line).

The volume of the ice was in the order of 3×10^9 m^3 and more than half of this ice mass (52.5%) was accumulated in two glaciers; Duque-Trampal and Cuerpo de Hombre. The minimum altitude reached by the ice is found in the Valle del Duque-Trampal at 1220 m asl. This is the longest glacier in this range with 8267 m.

The shape factor calculated for 192 cross-sections gives fairly homogeneous values ranging from 0.40 to 0.65 (Table 1). These homogeneous values obtained for the shape factor may be explained by the predominance in the Sierra de Béjar of crystalline materials transformed by weathering processes. Some extreme values lower than 0.40 and higher than 0.65 were recorded, but in principle these should be considered anomalies. The highest values (>0.65) are associated with the areas which present a dense fracturing network and are therefore least resistant to erosion. In contrast, the values lower than 0.40 are linked to differential erosion processes in the most resistant lithologies (fine grain granodiorite and quartzite schist).

The ELA values were calculated for the Sierra de Béjar for the GM stage using different methods (Table 4). The values estimated with the MELM method locate the ELAs at an altitude over 1800 m, with two anomalous figures, Duque-Trampal (1650 m) and Talamanca (1700 m).

Using the AAR method with 0.6 ratio value, the extreme values mentioned above disappear. The highest ELA ranges are found on the NW slope (>1890 m asl), with significantly smaller ranges (1780 to 1994 m asl) on the other slopes. A notable decrease in the ELA can be observed in the Endrinal and Peña Negra glaciers, which may respond to the so-called hypsometric effect (Rea and Evans, 2007).

With the BR/AABR method more homogeneous values are obtained and the ELAs of the Endrinal and Peña Negra glaciers do not show the deviation obtained with the AAR method. For the glaciers as a whole, the estimated ELA value varies from 1819 to 2243 m asl with balance ratios ranging from 1 to 3. To calculate the regional ELA, an ANOVA statistical analysis was carried out. The results do not present a statistically significant difference between the means and so the sample with the lowest variance was selected (i.e., BR = 1.5). Thus, using the AABR method, the value of the regional ELA for the GM has been estimated at 2010 m asl.

5. Discussion

The spread sheet application developed by Benn and Hulton (2010) was used for the reconstruction of the paleoglaciers from quantitative data when geomorphic indicators of the ice thickness were available. This is the case of the paleoglaciers with well-defined tongues, which were flanked by lateral moraine complexes. However, this model is not applicable to the zones where these indicators do not appear and the GM stage is only indicated by dispersed erratic boulders. This is the situation in some zones where the limit of the ice mass was located at the edge of the topographic plateau and the outlets were small, causing limited excavation. Given that these are transition stretches with confined ice tongues between them, an alternative solution to the problem is the interpolation of thicknesses

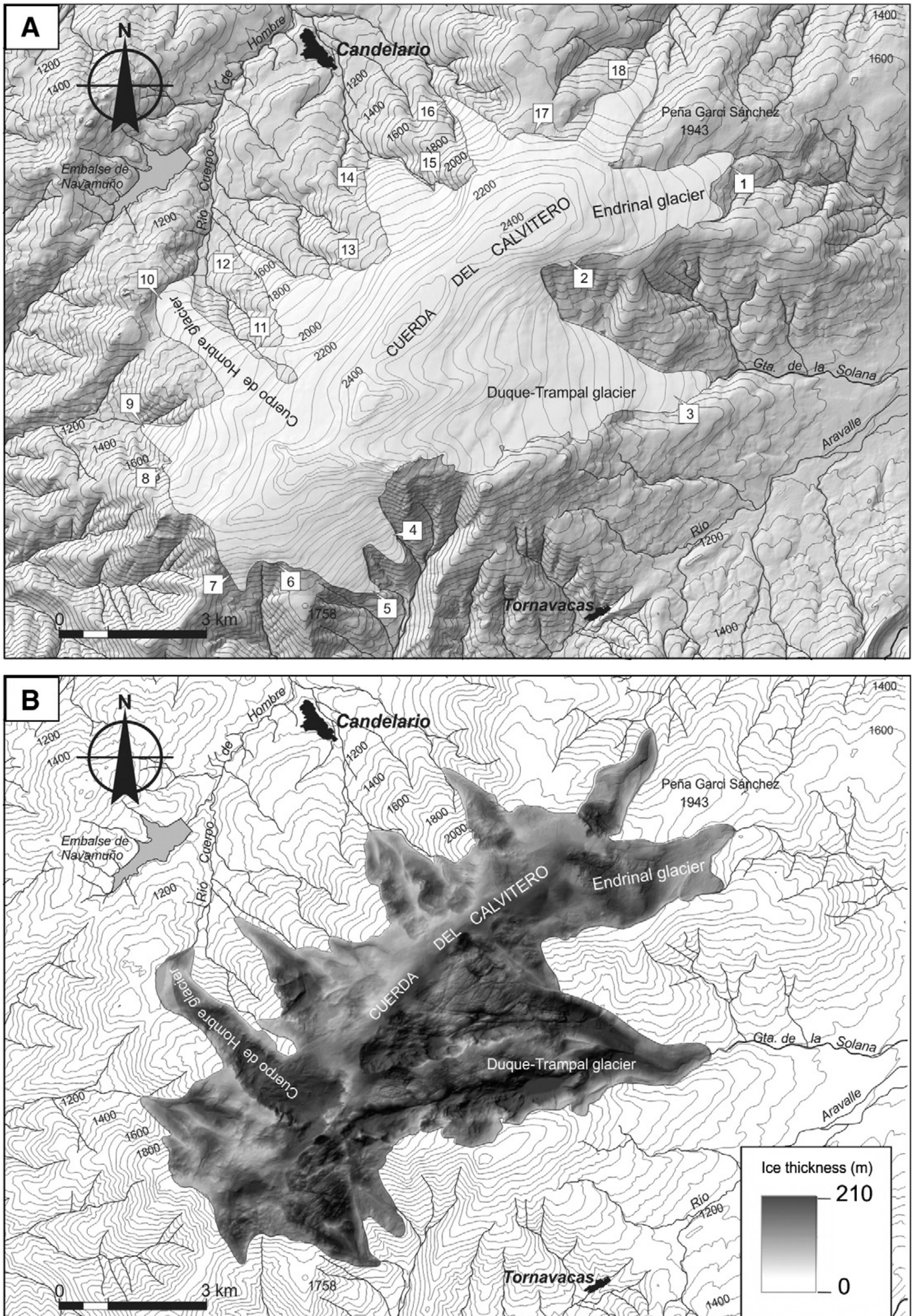

Fig. 7. Plateau glacier of the Sierra de Béjar during the maximum extent of the ice masses (GM). A. Reconstructed hypsometry of the paleoglacier. The numbers refer to individual paleoglaciers composing the plateau glacier system. (See Table 3 for paleoglaciers identification). B. Digital ice thickness model.

from the nearest data, i.e. those calculated in the paleoglaciers with well-defined indicators. When this alternative was applied, notable deviations were observed in the interpolated thickness values. We have used the model of the distance from the margin to the ice divides as a solution to perform the 3D reconstruction in these sectors. However, this method has its limitations, as it starts from a constant basal stress value to calculate thickness, and consequently could overlook local variation. However, the data obtained allow a reconstruction of the ice mass topography, which gives a more congruent result, better reflecting the effects of the subglacial topography, than just applying the interpolation method from nearby data.

The current morphology of the summits of the Sierra de Béjar displays a very clear contrast between the northern and southern sectors. The former is an elevated peneplain without significant

Table 3
Summary of spatial measurements of the reconstructed paleo-glaciers of the Sierra de Béjar.

		Aspect	Length (m)	Min. altitude (m asl)	Max. altitude (m asl)	Area		Max. ice thickness (m)	Volume	
						(km^2)	(%)		(m^3)	(%)
1	Endrinal	ENE	4580	1730	2374	4.61	8.02	105	1.91×10^8	6.45
2	Dehesa Boyal	S	1264	2040	2496	1.13	1.96	48	4.55×10^7	1.54
3	Duque-Trampal	E	8267	1210	2428	19.24	33.48	211	1.18×10^9	39.88
4	Talamanca	SE	2239	1472	2370	1.36	2.36	65	3.66×10^7	1.24
5	Regajo Grande	SE	3216	1270	2400	3.25	5.65	103	1.65×10^8	5.57
6	Collado de la Nijarra	S	2282	1940	2396	0.98	1.71	36	3.65×10^7	1.23
7	Nijarra	S	1670	1675	2212	0.89	1.55	64	3.7×10^7	1.25
8	Pinajarro	NW	1175	1680	2099	0.48	0.84	76	1.77×10^7	0.60
9	Espinarejo	NW	4314	1390	2398	4.46	7.77	98	2.09×10^8	7.07
10	Cuerpo de Hombre	NW	6038	1350	2428	5.33	9.28	180	3.73×10^8	12.61
11	Canterón	NW	2490	1350	2428	1.08	1.88	69	4.78×10^7	1.62
12	Regajo Vicioso	NW	4247	1349	2397	3.74	6.51	155	1.71×10^8	5.77
13	Hornillo	NW	2165	1817	2397	1.22	2.13	65	4×10^7	1.35
14	Candelario	NW	3400	1427	2367	3.53	6.14	113	1.52×10^8	5.15
15	Canchalón	NW	1672	1832	2367	0.80	1.38	78	2.55×10^7	0.86
16	Oso	NW	3353	1467	2373	2.39	4.15	93	1.18×10^8	4.00
17	Las Cobatillas	N	1960	1978	2362	1.09	1.90	44	4.05×10^7	1.37
18	Peña Negra	NNE	4205	1487	2219	1.87	3.26	115	7.22×10^7	2.44
						57.46			2.96 × 109	
									~3 × 109	

topographic projections, in which the overdeepened basins are not connected and limited to the edges of the plateau. The southern sector is a system of hills, mounds and *arêtes*, which form the divides between coalescent headwalls or cirques of large valleys originating from overdeepening along major fractures. On the other hand, the thickness of the ice accumulated during the GM in the great coalescent basins, up to 211 m in the Duque paleoglacier and 180 m in the Cuerpo de Hombre, suggests that in this evolutive period the ice covered practically all the rock substratum giving rise to a dome-shaped summit and the whole system can be considered as a plateau icecap.

The paleoglacier configuration was modified in subsequent stages. From the geomorphic indicators present in the valleys, it can be deduced that during the stage recorded by the later peripheral deposits, a reduction in the thickness of accumulated ice on the plateau had occur. Initially, this was interpreted as the disappearance of the plateau glacier from the summits of Sierra de Béjar, leading to a valley glacier stage (Carrasco, 1997). However, the detailed work carried out for the paleoglacier reconstruction has revealed continuity between the principal moraine and the trimlines originated in the accumulation basins of the southern sector of the Béjar Plateau. The continuity of these trimlines between different valleys means that the ice masses were still inter-connected during the principal moraine accumulation. On the other hand, the preservation of trimlines in some of the outstanding peaks of the southern sector, correlative to the principal moraine evolutionary stage, shows that part of the bedrock in the plateau was not covered by ice, and formed rocky nunatak-type projections. This confirms the presence of coalescing accumulation basins forming an icefield.

The evolutive sequence of these paleoglaciers was completed with progressive disconnection from the head of glaciers and disappearance of the plateau glacier, giving way to true valley and cirque glaciers, which were finally reduced to small cirque glaciers. These processes took place during the last deglaciation stages, recorded by the internal moraines or recessional moraine complexes.

The chronology for the GM is based on the first results of the ^{10}Be dating, which has provided ages of 27.2 ± 2.7 and 26.7 ± 2.8 ka in El

Table 4
Equilibrium Lines Altitude (ELAs) calculated for the reconstructed paleo-glaciers of the Sierra de Béjar during the maximum extent of the ice mass refereed in m asl.

		MELM	AAR 0.5	AAR = 0.6	AAR = 0.8	BR = 1	BR = 1.5	BR = 2	BR = 2.5	BR = 3
1	Endrinal	2034	1968	1925	1832	2036	2010	1991	1978	1967
2	Dehesa Boyal	–	2178	2127	2083	–	–	–	–	–
3	Duque-Trampal	1650	1955	1850	1646	1948	1925	1888	1859	1835
4	Talamanca	1700	1882	1795	1471	1938	1894	1875	1840	1822
5	Regajo Grande	1930	1969	1882	1693	1962	1945	1911	1886	1841
6	Collado de la Nijarra	–	2055	1961	1881	–	–	–	–	–
7	Nijarra	1850	2055	1994	1881	2068	2041	2022	2007	1945
8	Pinajarro	1816	1916	1897	1850	1954	1939	1927	1918	1911
9	Espinarejo	1816	2005	1956	1822	2026	2010	1984	1963	1953
10	Cuerpo de Hombre	1986	2054	1942	1678	2025	1975	1938	1909	1885
11	Canterón	2030	2205	2170	2071	2243	2222	2206	2194	2184
12	Regajo Vicioso	1920	1963	1913	1758	2012	1971	1957	1919	1900
13	Hornillo	2000	2135	2086	1976	2177	2151	2132	2118	2106
14	Candelario	1840	1979	1894	1714	2010	1978	1946	1921	1901
15	Canchalón	1890	2142	2100	1978	2181	2154	2135	2119	2107
16	Oso	1836	2103	2057	1859	2119	2078	2049	2025	2006
17	Las Cobatillas	–	1812	1763	1704	–	–	–	–	–
18	Peña Negra	1887	1812	1780	1704	1880	1862	1859	1831	1819

MELM, maximum elevation lateral moraines; AAR, area accumulation ratio; BR, balance ratio. The error of each of the applied methods considers the standard error of the mean for the studied paleo-glaciers: ±35 m (MELM), ±25 m asl (AAR 0.5), ±28 m asl (AAR 0.6), ±28 m asl (AAR 0.8), ±27 m asl (BR1), ±26 m asl (BR1.5), ±27 m asl (BR2), ±28 m asl (BR2.5), ±29 m asl (BR3).

Endrinal and Duque-Trampal paleoglaciers. Although the ages we report here are older than those previously obtained for the most external ridges in the Garganta de Gredos using ^{36}Cl dating (25.2 ± 1.2 and 24.2 ± 0.9; Palacios et al., 2011), considering the large error margin of the chronologies, they partly overlap. Similarly, when the reported errors are considered, the presented chronology for the maximum extent of the ice fits with the available chronology in the Serra da Estrela, 30.0 ± 4.5 and 33.1 ± 5.0 ka, obtained by thermoluminescence dating (Vieira, 2008). The internal ridges of the peripheral deposits in Sierra de Béjar provide ages from 19.0 ± 2.1 to 21.8 ± 2.2 ka. The peripheral deposits represent the end of the first sequence described by Pedraza et al. (2011), whereas the second sequence, that represent the onset of deglaciation, start with the principal moraine.

Comparing the three methods used to calculate the ELAs, the most spatially homogeneous values are obtained with the AABR method, as these avoid possible errors due to the hypsometric effect in the AAR and MELM methods. This agrees with the conclusions reached by other researchers working on plateau icefields (Benn and Gemmell, 1997; Rea and Evans, 2007). The values calculated by the MELM method are more variable as a result of over- and infra-estimations due to the method limitations (Nesje, 2007). In some paleoglaciers of the Sierra de Béjar the overlapping of moraines from different evolutionary stages has been detected (Carrasco et al., 2010; Pedraza et al., 2011), which expalins the over-estimation ELA values reported in Table 4 for some particular paleoglaciers.

The regional ELA value obtained for the glaciers in the Sierra de Béjar through statistical analysis is 2010 m asl using a BR = 1.5. In the Serra da Estrela (Portugal), a range also situated within Iberian Central System ~160 km to the west, the ELAs were recently estimated (Vieira, 2008). This author used a BR = 2, assuming that this value is representative of existing mid-latitude glaciers with a maritime influence climate (Benn and Gemmell, 1997; Rea, 2009). However, the Sierra de Béjar is a Mediterranean mountain located in the interior of Iberia with less maritime influence due to the increased continental factor. Similar cases of low ELA values in zones situated close to sources of humidity have been documented in the literature (e.g., Owen et al., 2009).

The values obtained with our calculations using a BR = 1.5 with the AABR method give a better fit for the hypsometric paleoclimatic indicators. In the Sierra de Béjar, the mean minimum altitude of the massif summits with paleoglaciers is always over 2000 m asl. As a comparative reference, the mean minimum height of the summits with paleoglaciers is around 1700 m asl in the Serra da Estrela (ELA 1650 with BR2; Vieira, 2008) and around 1800 m in Sanabria (ELA 1687 m asl with BR = 2, Cowton et al., 2009). On the other hand, the minimum altitude reached by the ice during the Glacial Maximum was 750 m asl in the Serra da Estrela (Valle del Zezere) and 950 m asl in Sanabria (Valle del Tera), while in the Sierra de Béjar the minimum elevation is 1210 m asl (Valle del Duque-Trampal).

These differences in the ELAs and the altitudinal distribution of the geomorphologic indicators can be explained by the effects of its southern and continental location (e.g., Obermaier and Carandell, 1915; Brosche, 1978). However, considering that the current mean annual precipitation in the Sierra de Béjar is similar to that of the Serra da Estrela and of Sanabria, between 1400 and 1800 mm (AEMET/IM, 2011), it cannot be ruled out that some of these differences are associated with different atmospheric circulation patterns during the glacial periods and their effects on Mediterranean regions. This hypothesis is still under discussion (e.g., Butzer, 1957; Ruddiman and Mcintyre, 1981; Hughes and Braithwaite, 2008; Felis and Rimbu, 2010). It is worth noting that the ELAs in the east-facing slopes of the Sierra de Béjar were 50 m lower in altitude during the GM stage in relation to those on the west-facing slopes. This effect could be related to the snow drift due to the western circulation in mid-latitudes.

6. Conclusions

The updated cartography of geomorphic indicators has been used to produce glacier hypsometric reconstructions and select the most appropriate boulders to date the stage of maximum extent of the glaciers in this region (GM). Two samples from different paleoglaciers provided an age estimate of 27 ka (27.2 ± 2.7 and 26.7 ± 2.8) for the GM. Although more dates are needed in order to properly constrain the glacial chronology in the region, the validity of the available data is supported by the consistency of the ages obtained in different valleys.

The northern and southern sectors of Sierra de Béjar show contrasting morphologies. The former represents a plain with limited ice-flow constraints, whereas in the latter ice was confined within deep valleys that were coalescent at the summit. During the GM stage, the ice masses covered the summits of the Sierra de Béjar and formed a dome-shaped glacier that could be classified as a plateau icecap. According to our estimates, during this period the glacier had an area of 57.4 km^2, a total ice volume of 3×10^9 m^3 and a maximum ice thickness of 211 m. In subsequent stages, the reduction of ice volume favoured the exposure of nunatak-type inliers surrounded by the ice mass, forming a plateau icefield instead of a plateau icecap. According to the cosmogenic nuclide dates, this change in the paleoglacier morphology could have taken place during the accumulation of the last peripheral deposits at ca. 19–22 ka.

The regional ELA obtained for the GM at Sierra de Béjar is 2010 m asl using the AABR method with a BR of 1.5. The higher ELA in the Sierra de Béjar (>300 m) compared to those estimated in other massifs of Iberian Peninsula by the AABR method (i.e., Serra da Estrela and Sanabria), supports the influence of the more continental and southern position of this range. These two factors are in agreement with previous studies dealing with ELAs over the Iberian Peninsula. However, it cannot be ruled out that some of these differences are associated with modified atmospheric circulation patterns during the glacial periods.

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References

Ackerly, S.C., 1989. Reconstructions of mountain glacier profiles, northeastern United States. Geological Society of America Bulletin 101, 561–572.

AEMET/IM, 2011. Atlas Climático Ibérico—Iberian Climate Atlas. AEMET and IM, Madrid. http://www.aemet.es/es/divulgacion/publicaciones/.

Balco, G., Stone, J., Lifton, N., Dunai, T., 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements. Quaternary Geochronology 3, 174–195.

Bellido, F. (Ed.), 2004. Mapa Geológico de Béjar, 1:50 000. Map 553. Instituto Geológico y Minero de España. Madrid. (http://www.igme.es/).

Bellido, F. (Ed.), 2006. Mapa Geológico de Cabezuela del Valle, 1:50 000. Map 576. Instituto Geológico y Minero de España. Madrid. (http://www.igme.es/).

Benn, D.I., Evans, D.J.A., 2010. Glaciers and Glaciation. Hodder Education, London. 802 pp.

Benn, D.I., Gemmell, A.M.D., 1997. Calculating equilibrium-line altitudes of former glaciers by the balance ratio method: a new computer spreadsheet. Glacial Geology and Geomorphology 7 pp. (http://ggg.qub.ac.uk/ggg/).

Benn, D.I., Hulton, N.R.J., 2010. An Excel™ spreadsheet program for reconstructing the surface profile of former mountain glaciers and ice caps. Computers & Geosciences 36, 605–610.

Benn, D.I., Lehmkuhl, F., 2000. Mass balance and equilibrium-line altitudes of glaciers in high-mountain environments. Quaternary International 65–66, 15–29.

Benn, D.I., Owen, L.A., Osmaston, H., Seltzer, G.O., Porter, S.C., Mark, B., 2005. Reconstruction of equilibrium line altitudes for tropical and sub-tropical glaciers. Quaternary International 138–139, 8–21.

Brosche, K.U., 1978. Beiträge zum rezenten und vorzeitlichen periglazialen Formenschatz auf der Iberischen Halbinsel. Abhandlungen des Geographischen Instituts, Sonderhefte, Band I. Selbstverlag des Geographischen Instituts der Freien, Universität Berlin.
Butzer, K.W., 1957. Mediterranean pluvials and the general circulation of the Pleistocene. Geografiska Annaler 39, 48–53.
Butzer, K.W., Franzle, O., 1959. Observations on pre-Würm glaciations of the Iberian Peninsula. Zeitschrift für Geomorphologie 3, 85–87.
Carandell, J., 1924. La topografía glaciar del macizo Trampal-Calvitero (Béjar). Boletín del Instituto Geológico y Minero de España 5, 1–24.
Carrasco, R.M., 1997. Estudio Geomorfológico del Valle del Jerte (Sistema Central Español): secuencia de procesos y dinámica morfogenética actual. Ph.D. Thesis, Complutense Univ. Madrid, Spain. 340 pp.
Carrasco, R.M., Pedraza, J., 1995. Morfología glaciar de las cimas en la Sierra de Gredos: monteras de hielo. In: Aleixandre, T., Pérez-González, A. (Eds.), Reconstrucción de paleoambientes y cambios climáticos durante el Cuaternario. Centro de Ciencias Medioambientales, CSIC, Madrid, pp. 227–238.
Carrasco, R.M., Pedraza, J., Sanz, M.A., Domínguez-Villar, D., Willenbring, J., 2010. El glaciar de Cuerpo de Hombre (Sierra de Béjar, Sistema Central Español) durante la deglaciación: génesis primaria del till supraglaciar de Los Hermanitos. Geogaceta 49, 39–42. http://www.sociedadgeologica.es/publicaciones.html.
Carrasco, R.M., Pedraza, J., Razola, L., Dominguez-Villar, D., Willenbring, J.K., Ruiz-Zapata, M.B., 2011. Typologies of genetic tills in the Sierra de Gredos (Spanish Central System). XVIII INQUA, Abstract, ID 1029, Bern, Switzerland. http://www.inqua2011.ch/.
Casas-Sainz, A.M., de Vicente, G., 2009. On the tectonic origin of Iberian topography. Tectonophysics 474, 214–235.
Clark, D.H., Clark, M.M., Gillespie, A.R., 1994. Debris-covered glaciers in the Sierra Nevada, California, and their implication for snowline reconstructions. Quaternary Research 41, 139–153.
CLIMAP Project Members, 1976. The surface of the ice-age Earth. Science 191, 1131–1137.
Cowton, T., Hughes, P.D., Gibbard, P.L., 2009. Palaeoglaciation of Parque Natural Lago de Sanabria, northwest Spain. Geomorphology 108, 282–291.
Domínguez-Villar, D., Willenbring, J., Carrasco, R.M., Pedraza, J., 2011. Sub-aerial granite and gneiss weathering rates in Spanish Central System and their implications for terrestrial cosmogenic nuclide dating. Geophysical Research Abstracts 13 EGU2011-1808. (http://www.geophysical-research-abstracts.net/).
Evans, D.J.A., Rea, B.R., Hansom, J.D., Whalley, W.B., 2002. Geomorphology and style of plateau icefield deglaciation in fjord terrains: the example of Troms-Finnmark, north Norway. Journal of Quaternary Science 17, 221–239.
Felis, T., Rimbu, N., 2010. Mediterranean climate variability documented in oxygen isotope records from northern Red Sea corals—a review. Global and Planetary Change 71, 232–241.
Florineth, D., Schlüchter, C., 2000. Alpine evidence for atmospheric circulation patterns in Europe during the Last Glacial maximum. Quaternary Research 54, 295–308.
Furbish, D.J., Andrews, J.T., 1984. The use of hypsometry to indicate long term stability and response of valley glaciers to changes in mass transfer. Journal of Glaciology 30, 199–211.
García-Ruiz, J.M., Valero-Garcés, B.L., Martí-Bono, C., González-Sampériz, P., 2003. Asynchroneity of maximum glacier advances in the central Spanish Pyrenees. Journal of Quaternary Science 18, 61–72.
Garcia-Ruíz, J.M., Moreno, A., González-Sampériz, P., Valero, B., Martí-Bono, C., 2010. La cronología del último ciclo glaciar en las montañas de Europa. Una revisión. Cuaternario y Geomorfología 24 (1–2), 35–46.
Golledge, N.R., 2007. An ice cap landsystem for palaeoglaciological reconstructions: characterizing the Younger Dryas in western Scotland. Quaternary Science Reviews 26, 213–229.
Gosse, J.C., Phillips, F.M., 2001. Terrestrial in situ cosmogenic nuclides: theory and application. Quaternary Science Reviews 20, 1475–1560.
Hughes, P.D., Braithwaite, R.J., 2008. Application of a degree-day model to reconstruct Pleistocene glacial climates. Quaternary Research 69, 110–116.
Hughes, P.D., Woodward, J.C., Gibbard, P.L., 2006. Late Pleistocene glaciers and climate in the Mediterranean region. Global and Planetary Change 46, 83–98.
Kohl, C.P., Nishiizumi, K., 1992. Chemical isolation of quartz for measurement of in situ produced cosmogenic nuclides. Geochimica et Cosmochimica Acta 56, 3583–3587.
Lautensach, H., 1929. Eiszeitstudien in der Serra da Estrela (Portugal). Zeitschrift für Gletscherkunde 17, 324–369.
Lifton, N., Bieber, J., Clem, J., Duldig, M., Evenson, P., Humble, J., Pyle, R., 2005. Addressing solar modulation and long-term uncertainties in scaling secondary cosmic rays for in situ cosmogenic nuclide applications. Earth and Planetary Science Letters 239, 140–161.
McDougall, D.A., 1995. The identification of plateau glaciers in the geomorphological record: a case study from the Lake District, northwest England. In: McLelland, S.J., Skellern, A.R., Porter, P.R. (Eds.), Postgraduate Research in Geomorphology: Selected Papers from the 17th BGRG Postgraduate Symposium. BGRG, Leeds, pp. 1–8.
Meierding, T.C., 1982. Late Pleistocene glacial equilibrium-line in the Colorado Front Range: a comparison of methods. Quaternary Research 18, 289–310.
Messerli, B., 1980. Mountain glaciers in the Mediterranean area and in Africa. World Glacier Inventory, International Association of Hydrological Sciences 126, 197–211.
Mix, A.C., Bard, E., Schneider, R., 2001. Environmental processes of the Ice Age: land, oceans, glaciers (EPILOG). Quaternary Science Reviews 20, 627–657.
Nesje, A., 2007. Paleo ELAs. In: Elias, S.A. (Ed.), Encyclopedia of Quaternary Science. Elsevier, Amsterdam, pp. 882–892.
Nye, J.F., 1952. A method of calculating the thickness of ice-sheets. Nature 169, 529–530.
Obermaier, H., Carandell, J., 1915. Datos para la climatología cuaternaria en España. Boletín de la Real Sociedad Española de Historia Natural 15, 402–411.
Obermaier, H., Carandell, J., 1917. Los glaciares cuaternarios de la Sierra de Guadarrama. Trabajos del Museo Nacional de CC: Naturales, 19. Madrid. 94 pp.
Orowan, E., 1949. Remarks at joint meeting of the British Geological Society, the British Rheologists Club and the Institute of Metals. Journal of Glaciology 1, 231–236.
Osmaston, H., 1975. Models for the estimation of firnlines of Present and Pleistocene Glaciers. In: Peel, R.F., Chisholm, M.D.I., Haggett, P. (Eds.), Processes in Physical and Human Geography: Bristol essays. Heinemann Educational Books Ltd, London UK, pp. 218–245.
Osmaston, H., 2005. Estimates of glacier equilibrium line altitudes by the Area × Altitude, the Area × Altitude Balance Ratio and the Area × Altitude Balance Index methods and their validation. Quaternary International 138–139, 22–31.
Owen, L.A., Thackray, G., Anderson, R.S., Briner, J., Kaufman, D., Roe, G., Pfeffer, W., Yi, C., 2009. Integrated research on mountain glaciers: current status, priorities and future prospects. Geomorphology 103, 158–171.
Palacios, D., de Marcos, J., Lorenzo Vázquez-Selem, L., 2011. Last Glacial Maximum and deglaciation of Sierra de Gredos, central Iberian Peninsula. Quaternary International 233, 16–26.
Pallàs, R., Rodés, A., Braucher, R., Bourlès, D., Delmas, M., Calvet, M., Gunnell, Y., 2010. Small, isolated glacial catchments as priority targets for cosmogenic surface exposure dating of Pleistocene climate fluctuations, southeastern Pyrenees. Geology 38, 891–894.
Pedraza, J., 1994. Geomorfología del Sistema Central. In: Gutiérrez Elorza, M. (Ed.), Geomorfología de España. Rueda, Madrid, pp. 63–100.
Pedraza, J., Fernández, P., 1981. Cuaternario y Terciario. In: Ruiz, P., Gabaldón, V. (Eds.), Mapa Geológico de Bohoyo. Map 577. Instituto Geológico de España (IGME). Madrid. (http://www.igme.es/).
Pedraza, J., Carrasco, R.M., Dominguez-Villar, D., Willenbring, J.K., 2011. Late Pleistocene glacial evolutionary stages in the Spanish Central System. XVIII INQUA, Abstract, ID 1438, Bern, Switzerland. http://www.inqua2011.ch/.
Penck, A., 1883. La période glaciaire dans les Pyrénées. Bulletin de la Société d'Histoire Naturelle de Toulouse 19, 105–200.
PNOA, 2007. Plan Nacional de Ortofotografía Aérea. Instituto Geográfico Nacional, Madrid. http://www.ign.es/PNOA/.
Perez Alberti, A., Valcarcel Diaz, M., Blanco Chao, R., 2004. Pleistocene glaciation in Spain. In: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary Glaciations—Extent and Chronology. Europe, 1. Elsevier, Amsterdam, pp. 389–394.
Porter, S.C., 1975. Equilibrium line altitudes of late Quaternary glaciers in the Southern Alps, New Zealand. Quaternary Research 5, 27–47.
Porter, S.C., 2001. Snowline depression in the tropics during the Last Glaciation. Quaternary Science Reviews 20, 1067–1091.
Rea, B.R., 2009. Defining modern day Area-Altitude Balance Ratios (AABRs) and their use in glacier-climate reconstructions. Quaternary Science Reviews 28, 237–248.
Rea, B.R., Evans, D.J.A., 2007. Quantifying climate and glacier mass balance in North Norway during the Younger Dryas. Palaeogeography, Palaeoclimatology, Palaeoecology 246, 307–330.
Rea, B.R., Whalley, W.B., Evans, D.J.A., Gordon, J.E., McDougall, D.A., 1998. Plateau icefields: geomorphology and dynamics. In: Owen, L.A. (Ed.), Mountain Glaciation: Quaternary Proceedings, vol. 6, pp. 35–54.
Rubio Campos, J.C., 1990. Geomorfología y Cuaternario de la sierras de la Nava y Béjar (Sistema Central Español). Ph.D. Thesis, Complutense Univ. Madrid, Spain. 353 pp.
Ruddiman, W.F., McIntyre, A., 1981. The North Atlantic during the last deglaciation. Paleogeography, Paleoclimatology, Paleoecology 35, 145–214.
Sanz Donaire, J.J., 1979. El corredor de Béjar. Instituto de Geografía Aplicada, CSIC, Madrid. 195 pp.
Schilling, D.H., Hollin, J., 1981. Numerical reconstructions of valley glaciers and small ice caps. In: Denton, G.H., Hughes, T.J. (Eds.), The Last Great Ice Sheets. Wiley, New York, pp. 207–220.
Schmieder, O., 1915. Die Sierra de Gredos. Mitteilunger der Geographischen Gesellschaft in München, Zehnter Band 1. 60 pp.
Schmitz, H., 1969. Glazialmorphologische Untersuchungen in Bergland Nordwestspaniens (Galicia-León). Kölner Geographische Arbeiten 23, 1–57.
Seret, G., Guiot, E., Wansard, G., 1990. Evidence for an early glacial maximum in the French Vosges during the last glacial cycle. Nature 346, 453–456.
Sugden, D.E., John, B.S., 1976. Glaciers and Landscape. Arnold, London. 376 pp.
Vieira, G., 2008. Combined numerical and geomorphological reconstruction of the Serra da Estrela plateau icefield, Portugal. Geomorphology 97, 190–207.