

DEGLACIATION IN THE CANTABRIAN MOUNTAINS: PATTERN AND EVOLUTION

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ABSTRACT. *The last deglaciation of the Cantabrian Mountain began later than 30 ka ago, after a local glacier maximum. After this glaciation a moderate glacier retreat occurred during a less cold period, followed by a new glacier advance that deposited moraines close to the maximum extension moraine complexes. This cold but very dry period occurred between ~ 22-18 ka and it was related to European LGM. Dating made during the last 12 years support a distinctive model of deglaciation history for the last glacial cycle, different to North European and analogous to NW Iberian Mountains and the Pyrenees. The most important deglaciation phase began after 18 ka, when ice disappeared of the lower massifs, icefields withdraw and the main tongue glaciers divided in minor tongues. From ~14 to ~11 ka a new cold period implied a glacier growth dominated by topoclimatic factors in the massifs above 2100. Only on the highest massifs glaciers developed in all orientations, together with rock glaciers established mainly to the North orientations. During the Holocene there are not evidences of glacial stages and the deglaciation was complete. Only four small glaciers were developed during the Little Ice Age in the Picos de Europa, disappearing at the end of the XIX century.*

Deglaciación en la Cordillera Cantábrica: modelo y evolución

RESUMEN. *La última deglaciación de la Cordillera Cantábrica comenzó hace menos de 30 ka, cuando se produjo un máximo glacial local. Tras esta deglaciación se sucede un periodo menos frío que ocasiona un retroceso glacial después del cual un nuevo avance de los glaciares generó formas y depósitos glaciares muy próximas a los complejos morrénicos de la fase anterior. Este es un periodo frío y seco acaecido entre ~ 22 y 18 ka que se relaciona con el LGM europeo. Las dataciones realizadas durante los últimos doce años permiten establecer un modelo de deglaciación distinto al del norte de Europa, pero similar al de los Pirineos y las montañas del NW peninsular. La fase de deglaciación más importante tendrá lugar después de 18 ka, cuando los macizos menos altos quedan*

libres de hielo definitivamente, los icefields desaparecen y las lenguas glaciares de mayor tamaño se dividen y quedan alojadas en las porciones altas de los valles. De ~14 a ~11 ka se registra un nuevo avance, la fase de altura, con desarrollo de glaciares por encima de los 2000 metros condicionados por los factores topoclimáticos. Sólo en los macizos más elevados los glaciares se ubican en cualquier orientación aunque sus dimensiones son reducidas. En este periodo se desarrollan numerosos glaciares rocosos, en su mayoría en orientaciones N. Durante el Holoceno no hay pruebas de avances glaciares y la deglaciación es completa en la Montaña Cantábrica. Sólo cuatro pequeños glaciares se forman durante la Pequeña Edad del Hielo en Picos de Europa, desaparecidos a finales del siglo XIX.

Key words: glaciations, deglaciation, Quaternary, Cantabrian Mountains.

Palabras clave: glaciario, deglaciación, Cuaternario, Cordillera Cantábrica.

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1. Introduction

The Cantabrian Mountain was occupied by glaciers during the Upper Pleistocene, and glaciers had a significant effect on climate and human communities during the last glaciation. Many geomorphologists have investigated the glacial history of the Cantabrian Mountains, being the early visits of Casiano del Prado or Albrecht Penck the ones that fostered interest in the region. Studies in the Picos de Europa and western area led to controversy over the development of small glaciers spread by several massifs, or a wider glaciation affecting all massifs. Later debate concerned the number of glaciations. First, two Quaternary glaciations –the polyglacial theory– were attributed to Riss and Würm (Penck, 1897; Obermaier, 1914; Saenz, 1935; Hernández-Pacheco, 1944, 1961; Nussbaum and Gigax, 1952; Lotze, 1962), and later only one and recent glaciation –the monoglacial theory– was deduced (Martínez de Pisón and Arenillas, 1979; Muñoz-Jiménez, 1980; Arenillas and Alonso-Otero, 1981; Alonso-Otero *et al.*, 1982; Smart, 1986; Alonso-Herrero, 1987, 2002; Frochoso, 1990; Castañón and Frochoso, 1992; Ugarte, 1992; Gale and Hoare, 1997; Frochoso and Castañón, 1998; Serrano and González-Trueba, 2002; Serrano and Gutiérrez-Morillo, 2002; González-Trueba, 2007a, 2007b), all of them from sediments and morphostratigraphic analysis. Studies were based on morphosequences showing features of glaciers retreat. During the 70's and 80's contributions focused on the delimitation of the maximum ice extent. Retreat stages were established during the nineties and first years of 21st century but today there is a lack of continuous, well-dated, high-resolution records of the changes in environmental conditions during deglaciation. Only during the last decade absolute dating has been obtained and glacial stages, mainly the glacial maximum, are located in time. The deglaciation history of the Cantabrian

Mountain is closely related to that of neighbouring Pyrenees, where an asynchronicity of maximum glacier advances related to the European glaciations was detected (Jalut *et al.*, 1992; García-Ruiz *et al.*, 2003, 2010, 2013; Delmas, 2005; González-Sampériz *et al.*, 2006). Different authors have pointed that the maximum extent of the Pyrenean glaciers occurred before 30 ka BP with a later, less extensive advance during the European coldest period around 20 ka BP. The asynchronicity of the maximum advances have been explained by different regional responses to climatic forcing and by the southern latitudes of the Iberian Peninsula (González-Sampériz *et al.*, 2006; Delmas *et al.*, 2008; García-Ruiz *et al.*, 2010, 2013; Serrano *et al.*, 2013). The present day controversy is on the possible synchrony between the Iberian Peninsula and European LGM in the Pyrenees or the Central System (Pallás *et al.*, 2007; Calvet *et al.*, 2011; Palacios *et al.*, 2011), although some recent dates suggest an early maximum also for the Central System (Domínguez-Villar *et al.*, 2013) and different evolution models have been proposed for the Mediterranean area (Hughes *et al.*, 2006, 2008), including older phases than the last glacial cycle.

The Cantabrian Mountain is located in a climatically sensitive geographic position between the Atlantic seacoast and the Mediterranean environment of the inner Iberian Peninsula. During Pleistocene this transitional environment was very important for glaciers development on the northern and southern sides. Changes in the position of the polar front during the last glacial cycle implied variations in extent and activity of glaciers in the Cantabrian Mountains. In this climatic context, the Pleistocene glaciation was limited to the highest massifs (Fig. 1), configuring individualized glacial units very close together. These were of small size compared with the large glaciers that developed towards the east in the Pyrenean or alpine chains, but in accordance with the size and distribution of the glaciers in the westernmost and southernmost mountains of the Iberian Peninsula.

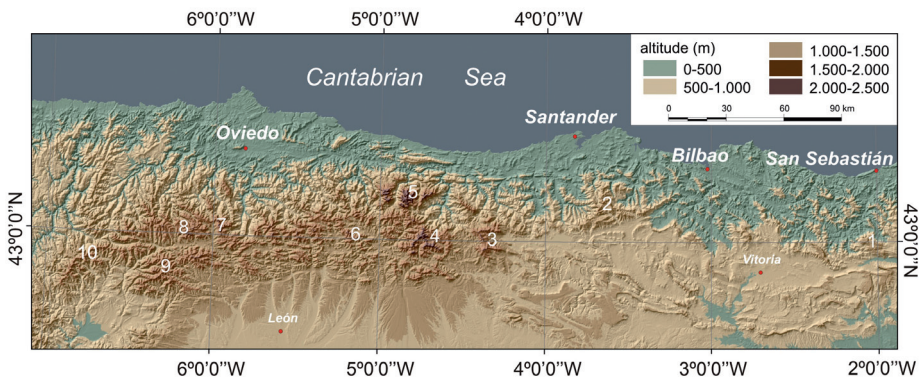


Figure 1. The Cantabrian Mountains and location of the highest massifs. 1: Aralar (1430 m a.s.l.). 2: Pas Mountain (1717 m a.s.l.). 3: Alto Campoo-Valdecebollas (2174 m a.s.l.). 4: Fuentes Carrionas (2539 m a.s.l.). 5: Picos de Europa (2647 m a.s.l.). 6: Mampodre (2192 m a.s.l.). 7: Peña Ubiña (2411 m a.s.l.). 8: Somiedo (2191 m a.s.l.). 9: Catoute (2112 m a.s.l.). 10: Ancares (1992 m a.s.l.).

2. Geographical setting

The Cantabrian Mountains, located in the Northern Iberian Peninsula, is a 450 km length mountain system between the Pyrenees and the Galician mountains (from 7°0' to 2°0' W long. and 43° N lat.). The maximum altitude is located in the Picos de Europa massif, reaching 2648 m a.s.l. (Torrecerredo). The Cantabrian Mountains can be divided into two main geological units (Fig. 2) affecting the relief and glacial features:

- The western area is composed of the Ordovician and Carboniferous Asturian basement of slate, quartzite, limestone, sandstone and conglomerate. The complex structure, Paleozoic lithology and differential erosion, configures isolated massifs and ranges of moderate altitude individualized between lengthened depressions. Limestone, quartzite and sandstone shape positive and abrupt reliefs, and slate and turbidites, the depressions. The main massif is composed of Paleozoic limestone featuring alpine glaciokarstic reliefs (like Picos de Europa, Peña Ubiña, Espigüete) and sandstone relief (Fuentes Carrionas). On limestone massifs, the karstic landscape works together an important endokarstic network, where caves more than 1000 meters depth are common. Nowadays, some ice caves maintain metamorphic ice since Little Ice Age (Gómez Lende *et al.*, 2014). To the north, the hydrography cuts the structures longitudinally, individualizing the massifs and generating high relief forms, whereas to the south it adapts to the structures.
- The eastern area, where altitudes are more moderate, is composed of Mesozoic outcrops and folded structures. The dominant rocks are Triassic sandstones and conglomerates, Jurassic and Cretaceous marl, sandstone, limestone and turbidites, and Tertiary terrestrial sedimentary rocks. Limestone spreads on the entire area and karstic landscapes are common. Endokarst has a limited depth but there are large horizontal cave systems. The incision of the Cantabrian rivers dissects the relief to the north, which develops deep valleys. To the southern side, the valleys are adapted to the folded structures.

The Cantabrian Mountain is exposed to the Polar Front, and its relative height and proximity to the sea (30 km aprox. to Cantabrian sea) determine the climatic conditions. The north-facing side has a hyperhumid oceanic mountain environment with a mean annual precipitation exceeding 2500 mm/year, whilst in the south-facing slope the climate is transitional Atlantic-Mediterranean, with precipitation ranging between 600-800 and 1800-2000 mm year⁻¹. Thus, the Cantabrian Mountains are an important fluvial and environmental threshold between the Atlantic and Mediterranean basins.

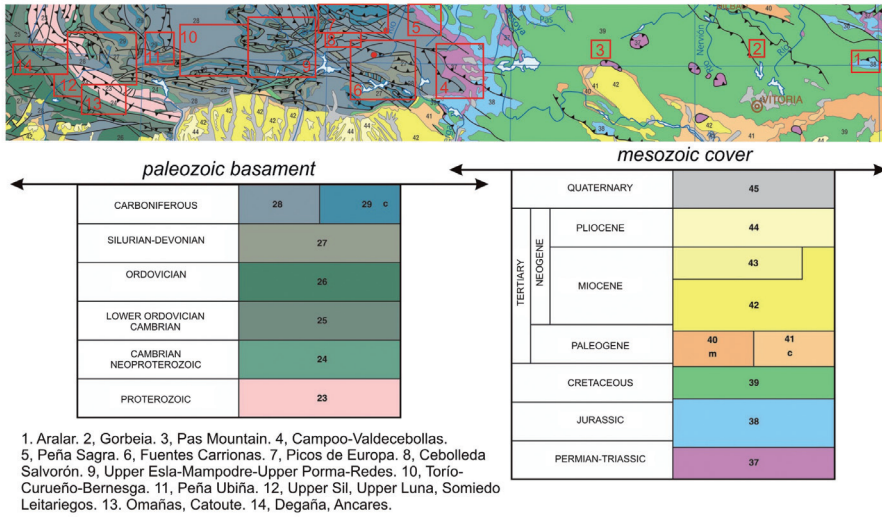


Figure 2. Geological sketch of the Cantabrian Mountain with location of the main glaciated areas.

Glacial morphology dominates all summits above 1900 m a.s.l., with a progressive lower altitude imprint up to 1300 m high on the divides of westernmost side of the range. Glacial morphology in the Cantabrian Mountain corresponds to highly varied glacial systems, like cirque glaciers with moraines forming small frontal arcs, large glaciated valleys with tongues few km. long, and several large icefields fed by the Atlantic snowfalls, with outlets between 16 and 51 km long. Glacier fronts reached 400-600 m a.s.l. in the Northern side and 700 to 900 m in the south side.

3. Landforms and mapping of glacial features

The glacial morphology of the Cantabrian Mountain occupies nearly all summit areas of the so-called “Asturian Massif”, while is less developed in the Eastern part of the range. Cirque glaciers appear located close to divides of moderate altitude (1200-1400 m) on the western side, and were also frequent in recession stages in the higher summits of the Main Divide. Glaciated valleys with tongues from 5 km to 15 km long occupy the upper valleys in the area between Ancares to Campoo. Icefields have been clearly interpreted in the Picos de Europa, Pas Mountain, Aralar, Sil Valley and Upper Esla, formed after a broad extension of the accumulation areas. Nevertheless, it is not possible to find erosional features like cirques and over-deepened basins in the areas that were occupied by the icefields, although there are relevant glacial troughs reaching moderate altitudes in the south side (750 m a.s.l.). Icefield outlets also deposited lateral and frontal moraine complexes. Table 1 shows the morphological characteristics of the main massifs in the Cantabrian Mountains at different stages. LIA moraines are not included in the Table because the historical glaciation was generated once the deglaciation completed, and a limited ice growth in the highest cirques of Picos de Europa occurred (González-Trueba, 2006, 2007; González-Trueba *et al.*, 2008).

Table 1. Morphological characters of Upper Pleistocene glaciated areas in the Cantabrian Mountains¹.

	Anceres	Somiedo	UpperSil, Laciana Babia	Omaña	Ubiña	Curueño Torro Canseco	Porma Esla	Nalón	Picos	Fuentes Carrionas	Campoo	Pas Mountain	Aralar
Altitude Summit	1992	2191	2188	2157	2411	2142	2192	2115	2647	2536	2143	1718	1430
Glaciers Type	Alpine	Alpine	Icefield	Alpine	Alpine	Alpine	Icefield	Alpine	Icefields	Alpine	Alpine	Icefield	Icefield
Tongue length km	13	13	51	16	7	16	20	6	8	15	6	15	5
Stage I	700 N 825 S	800 N 850 S	750	1190N 1130S	1000N 1480S	1120 N 1280 S	1150	950	650N 850S	1240N 1460S	1250N 1400S	400 N 740 S	800
Deglaciation: ~8 ka duration. Glacial retreat and advance													
Type	Cirque	Alpine	Alpine	Cirque	Cirque	Alpine	Icefield	Alpine	Alpine	Alpine	Cirque	Icefield	Definitive
Tongue length km	4.5	--	10-13	5-9	3.5	14.5	--	4	6.2	12.9	2.6	12.5	--
Stage II	1400	1400	910	1250	1700	1370	--	1300	880	1260	1250	780	--
Altitude fronts m	1800	1500		1300	1550	1230		1500		1450	1870	1040	
a.s.l. ²													
Deglaciation: ~4 ka duration. Moraines in the upper valleys. Glacial disjunction phases													
Type	Cirque ³	Cirque ³	Cirque ³	Cirque ³	Cirque	Cirque	Cirque ³	Cirque ³	Cirque ³	Cirque ³	Cirque ³	Cirque ³	Cirque ³
Tonguelength km	0.8	0.6N	7.5	0.7N	1.2N	0.4	--	1.3N	1	4.8	0.4N	0.9N	--
Altitude fronts	1400	1500	1400	1860	1950	1930	1500	1500	660	1580	1700	870	--
m a.s.l. ²													
Deglaciation: Entire glacier disappearance of Cantabrian Mountain until LIA													
Stage	Type	--	--	--	--	--	--	--	Cirque	--	--	--	--
IV	Tonguelength km	--	--	--	--	--	--	--	0.4	--	--	--	--
	Altitude fronts	--	--	--	--	--	--	--	2190	--	--	--	--
	LLA	ma.s.l.							2320				

1. Based on: Muñoz-Jiménez, 1980; Arenillas and Alonso-Otero, 1981; Castañón, 1983; Alonso-Herrero, 1987, 2002; Pérez-Alberti *et al.*, 1992; Menéndez and Marquinez, 1996; Jiménez-Sánchez, 1996; González-Amushásteigui, 2000; González-Gutiérrez, 2002; Valcárcel and Pérez-Alberti, 2002; Redondo, 2002; Serrano and Gutiérrez-Morillo, 2002; González-Trueba, 2007; Santos, 2010; Redondo *et al.*, 2010; Pellitero *et al.*, 2011; Rico, 2011; Serrano *et al.*, 2013; Pellitero, 2013; Santos *et al.*, 2013; Rodríguez-Rodríguez *et al.*, 2014; Gallinar *et al.*, 2014.

2. Maximum and minimum altitudes of glacier fronts. 3. Presence of rock glaciers on cirques and slopes.

4. Dating and deglaciation pattern

The maximum extent of glaciers in the Cantabrian Mountains corresponded to the development of icefields –Pas, Aralar, Picos de Europa, Upper Porma-Redes, Upper Sil-Babia–; alpine glaciers –Cebollada, Fuentes Carrionas, Ancares, Omañas, Solvorón, Campoo–; and cirque glaciers –Valdecebollas, Peña Sagra, Gorbeia, Pajares–. Recent studies on distinct Cantabrian Mountain massifs have provided radiocarbon dates (^{14}C , AMS) in Redes, Sil Valley, Picos de Europa and Pas Mountains (Jiménez-Sánchez and Farias, 2002; Jiménez-Sánchez *et al.*, 2013; Jalut *et al.*, 2010; Moreno *et al.*, 2010; Serrano *et al.*, 2011, 2012, Nieuwendam *et al.*, 2015), and U/Th and optically stimulated luminescence (OSL) dates from the Fuentes Carrionas and Pas Mountains (Pellitero, 2011, 2014; Serrano *et al.*, 2012; Frochoso *et al.*, 2013). The glacial morphosequences analysed and available dates have facilitated a first approximation to the Late Pleistocene glacial chronology and deglaciation pattern in the Cantabrian Mountains, where three main Pleistocene glacial phases have been detected (Jiménez-Sánchez *et al.*, 2013; Serrano *et al.*, 2013a,b; Rodríguez-Rodríguez *et al.*, 2014).

Dates (table 2) for the maximal extent of glaciers show ages between 44.9 ka and 28.9 ka in six cases, 4 by ^{14}C and 2 by OSL. In the Picos de Europa the maximum glacial extent has been dated as previous to 40 kyr in Enol (Moreno *et al.*, 2010), $40,480 \pm 820$ BP in Comeya (Jiménez-Sánchez and Farias, 2002), $35,700\text{--}34,850$ cal yr BP in the Duje valley (Serrano *et al.*, 2012) and 37.2 kyr cal BP in the Belbin basin (Nieuwendam *et al.*, 2015). The minimum age obtained for the glacial maximum in the Fuentes Carrionas massifs is $36,028 \pm 2350$ yr BP (Pellitero, 2011, 2014; Serrano *et al.*, 2012) and in the TruebaValley (Pas Mountains) the age is prior to $29,149\text{--}28,572$ cal yr BP (Serrano *et al.*, 2012, 2013) and $44,980 \pm 2300$ yr BP (Frochoso *et al.*, 2013) on the north side. The western massif shows the same chronologies: $28,990 \pm 230$ yr BP in Redes (Jiménez *et al.*, 2002, 2013) and around 44 kyr in the Sil Valley (Jalut *et al.*, 2010). All dates, obtained from different deposits (lacustrine, peat bog and till) and using distinct techniques (AMS and OSL) confirm the maximum extent of glaciers during the MIS3. The sedimentary sequence of Belbín shows a coetaneous intense periglacial activity in the region, with deposition of colluviums between 37.2 and 29 cal kyr BP (Nieuwendam *et al.*, 2015). Thus, the first glacial stage seems to have behaved differently compared to northern Europe glacial maximum, during a cold and wet environment related to cold and humid masses that came from the N, NW and SW, when the jet stream was located at lower latitudes.

After $\sim 35\text{--}29$ ka BP there was a brief glacial retreat. Glacier fronts moved away from the frontal moraine complexes. Over-deepened basins were occupied with proglacial lakes, and proglacial complexes developed in the lower sectors of glacial troughs. The entity of deglaciation between glacial stages I and II is not known yet, although González-Sampériz *et al.* (2006) suggested an important reduction of the ice tongues in the Pyrenees.

Table 2. Dating of the glacial maximum in the Cantabrian Mountains.

Place	Site	Tecnicque	Sediment	Depth (m)	¹⁴ C Age yr BP OSL age U/Th age	Ages cal yr BP	Ref.
Picos de Europa	Áliva	AMS	Lacustrine	15.50	31,200+/-440	35,700-34,850	1
	Comeya	AMS	Lacustrine	35.5	40,480±820	43,230-45,000	2
		OSL	Glaciofluvial sand	42.7	45,000±330	----	3
	Enol	AMS	Lacustrine	4.39	36,200+1100	40,023-42,250	4
		AMS	Lacustrine	5.30	32,500+500	37,065-38,689	
	Belbín	AMS	Bulksediment	5,39	32,530 ± 430	36,718 ± 1203	5
Pas Mountain	Trueba	AMS	Peat	1	26,082+/-118	30,676-31,348	6
	Soba valley	OSL	Till	3.5	44,98±2,3	--	
		OSL	Till	2.5	40,43±5,14	--	
		OSL	Till	5	64,600±510	--	
		OSL	Till	6.5	75,100±520	--	
Altos Asón	OSL	Till	9.5	78,500±720	--	7	
Fuentes Carrionas	Vega de Naranco	OSL	Supraglacial	0.50	36,028±2350	--	8
Upper Sil	Castro lake	AMS	Pollen	7.81	39,300+1000	42,605-44,190	9
		AMS	Sandy clay	8.85	34,000+1400	36,843-40,523	
	La Mata	AMS	Clay	5.22	> 35,000	----	
Redes Natural Park	Monasterio	¹⁴ C	Lacustrine clastic	35.6	28,990±230	33,123-33,847	10
		OSL	Till	2.30	24,000±180	---	
	Tarna Valley	OSL	Lacustrine	42	44,966±3337	---	3

1, Serrano *et al.*, 2012. 2, Jiménez-Sánchez and Farias, 2002. 3, Jiménez Sánchez *et al.*, 2013. 4, Moreno *et al.*, 2010. 5, Nieuwendam *et al.*, 2015. 6, Serrano *et al.*, 2013. 7, Frochoso *et al.*, 2013. 8, Pellitero, 2011. 9, Jalut *et al.*, 2010.

A second glacial stage was established from sedimentological and geomorphological features. The varied lithological composition of the moraines at Vega del Naranco (Fuentes Carrionas, Fig. 3), the two infill deposits in the Trueba Valley (Pas Mountain), and the changing directions of glacial flows in the Picos de Europa show a glacial retreat and re-advance to positions very close to the previous stage (Turú *et al.*, 2007; Pellitero, 2011; Serrano *et al.*, 2012, 2013). This stage can be correlated with a second stage of deglaciation dated in the Alto Nalón at ~20.6 kyr BP (Jiménez-Sánchez *et al.*, 2002) and in Enol lake between 20 and 18 ka (Moreno *et al.*, 2010). A minimum lost on ignition (LOI) in the lacustrine sediments of Áliva, dated between 21,500-21,390 cal yr BP, and the cooling detected between ~22.0 and 17.7 kyr cal BP in the Belbin Depression (Nieuwendam *et al.*, 2015) are consistent with Nalón and Enol dates, and all point to a cold period with a second advance.

Deglaciation between stages II and III brought the individualization of large icefields into smaller and individual glacial tongues in the tributary valleys, which can be tracked by the disjunction moraines (Pérez-Alberti *et al.*, 2002; González-Gutiérrez, 2002; Santos, 2010; Pellitero, 2012, 2014; Santos *et al.*, 2013). Dissociation dynamics during

deglaciation have been pointed in Picos de Europa, Pas Mountain, Ancares, Alto Sil, Curueño and Fuentes Carrionas. Most of the glaciers had fronts situated above 1600 m and 1700 m a.s.l., which means a massive deglaciation in the lowest, westernmost part of the range (table 1 and 3).

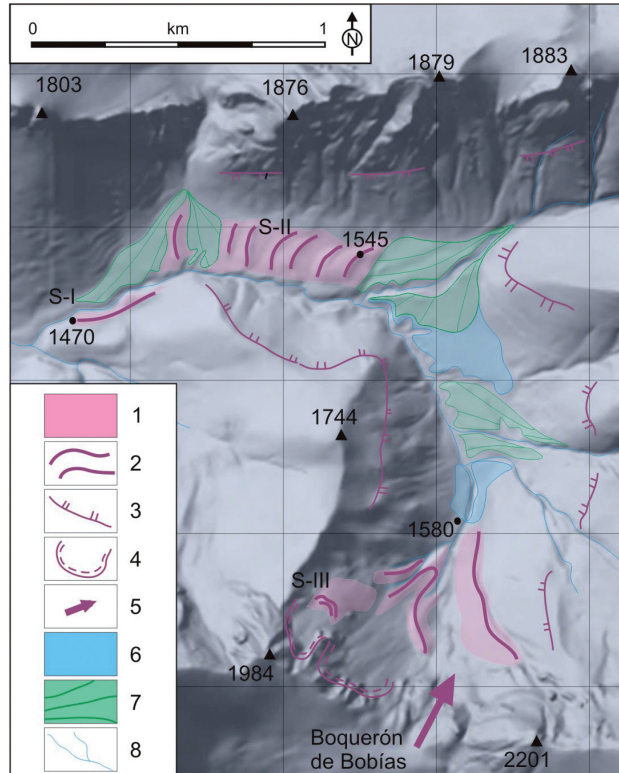


Figure 3. Glaciomorphological sketch of Vega de Naranco Valley (Fuentes Carrionas, León). The representative frontal moraine complex shows the glacial stages (S-I, S-II and S-III) represented in the valley (Modified from Pellitero, 2012).

Moraines located in the vicinity of high cirques above 1800-2000 m a.s.l. indicate the existence of an “altitude stage” (stage III), mapped in all massifs around 2000 (Fig. 3). This stage is characterised by short valley and cirque glaciers situated above all on north-facing slopes. Sil valley, Omañas, Babia valley, Upper Porma and Curueño, Peña Ubiña, Mampodre, Fuentes Carrionas, Alto Campoo-Valdecebollas (Fig. 4), Peña Sagra and Picos de Europa would have kept glaciers from this stage. Well-preserved moraine complexes are very frequent and point to a period of equilibrium and minor advance. The largest glaciers at this stage were located in Picos de Europa and Fuentes Carrionas, where two different pulsations have been established (González-Trueba, 2007, Pellitero, 2013). Glaciers developed nearby rock glaciers, mainly on north-facing slopes in massifs with summits around 2000

metres. The lowest massifs in the eastern and western sectors would be definitively deglaciated (Ancares, Laciana, Gorbeia, Aralar).

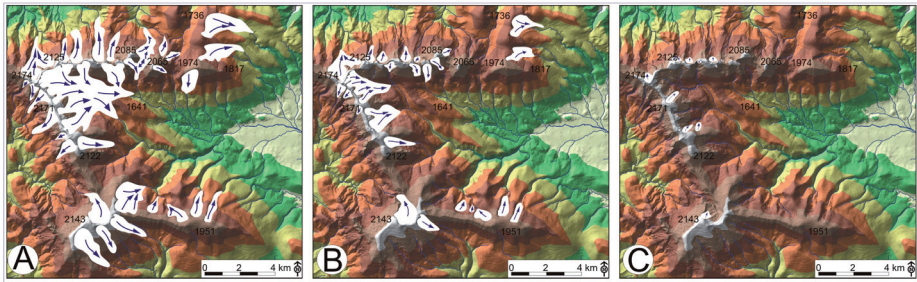


Figure 4. Glacial evolution in the Alto Campoo-Valdecebollas massifs. A: Stage I, with development of tongue glaciers. B: Stage II, small tongue glaciers, mainly in the north facing cirques and slopes. C: Stage III. Only small cirque glaciers oriented to the north are located under the highest peaks.

The formation of rock glaciers was common across the range during this stage, with up to 160 relict rock glaciers inventoried (Redondo *et al.*, 2010; Gómez-Villar *et al.*, 2011; Pellitero *et al.*, 2011). Rock glaciers are located preferentially to the west of the Porma valley, including Redes, San Isidro, Curueño, Upper Luna, Somiedo, Laciana, Upper Sil, Omañas, Degaña and Ancares, with a 73% of the entire rock glacier population. Rock glaciers are indicators of permafrost environments, although their altitudinal distribution and preferential north orientation (100% between NW and NE, and 70% in north orientation) limit the permafrost environment to the highest portion of cirques in north-facing slopes. This is also related to the larger availability of debris in the more heavily glaciated, eroded –and therefore steeper– north-facing cirques. The high presence of rock glaciers to the west could be related to the moderate altitude of summits, all of them lower than 2200 m, allowing a wide periglacial environment. These facts are consistent with the development of rock glacier in the lowest glaciated massifs in the central and Eastern Cantabrian Mountain, such as Cebolleda, Peña Ten, Mampodre or Peña Sagra.

This period has a high degree of uncertainty because no dating has been made on moraines or lacustrine deposits related to the cirque moraines, and chronologies are based on indirect data. Only three evidences of the occurrence of a cold period can be correlated with the highest moraines, all of them in the Picos de Europa: (i) In the lacustrine deposits of Enol, Moreno *et al.* (2010, 2011) have detected equilibrium in the Ca content between 14.5 and 13.5 ka and a cooling between 13.5–11.6 cal ka BP, indicating a cold and dry phase endorsed to the Younger Dryas. (ii) Serrano *et al.* (2012) recorded a moderate minimum LOI in the lacustrine sediments of Áliva ca. 13.9 cal ka BP, also interpreted as a climatic cooling. (iii) Finally, a cold period has been recorded between 13 and 8.1 cal ka BP in the lacustrine sediments of Belbin depression (Nieuwendam *et al.*, 2015).

Table 3. Synthesis of glacial and deglaciation stages in the Cantabrian Mountains.

Era	Stage	Morphostratigraphic Name	MIS *	Peaks ma.s.l. **	Glaciated Massifs	Glacial period	
Holocene	IV	Cirque glaciers, L.I.A.	MIS 1	> 2600	Picos de Europa	Historical	
		Postglacial DEGLACIATION			DEGLACIATION Definitive ice free massifs	Postglacial	
Pleistocene	IIIb	Confined glacial cirques	MIS 2	> 2140	Gistredo, Ubiña, Esla, Picos, Cebolleda, Salvorón, Fuentes Carrionas	Lateglacial	
	IIIa	Altitude stage Glacial Advance and Equilibrium Rock glaciers		> 2040	Ancares, Gistredo, Somiedo, Sil, Esla, Omañas, Ubiña, Picos, Cebolleda, Salvorón, Fuentes Carrionas, Campoo		
	DEGLACIATION				DEGLACIATION Most massif are glaciers free		Finiglacial
	DEGLACIATION Minor Glacier advances and Equilibrium (Disjunction phase)				> 1750	Ubiña, Esla, Curueño, Picos, Cebolleda, Salvorón, Fuentes Carrionas, Campoo	
	II	Glacial Advance		> 1430	All massifs		
	DEGLACIATION			DEGLACIATION		Last Glacial Cycle	
	I	Local Glacial Maximum	MIS 3	> 1430	All massifs		
	0	Pre- Maximum		MIS 12 MIS 22	> 2100	Sil, Degaña, Redes, Picos, Fuentes Carrionas	Pre-Last Glacial Cycle

* Marine Isotopic Stadium. ** Maximum altitude of summits of glaciated massifs.

5. Deglaciation and climate evolution in Cantabrian Mountains

Partial deglaciation of Cantabrian Mountain occurred after ~35-29 ka BP, when glaciers retreated in Picos de Europa, Sil and Redes massifs. The basal age of deposits of Enol (~40 ka), Villaseca and La Mata (~44 ka), Áliva (~35 ka), Belbín (~37 ka), Espinosa de los Monteros (~29 ka) and Asón (~44 ka) confirm that the last deglaciation occurred at the same time that in the Pyrenees, and earlier than in northern latitudes of Europe, an

important fact for animal and human occupation of Cantabrian Mountains (Álvarez-Lao and García, 2011; Serrano *et al.*, 2015). So, after 35 ka a deglaciation period began on the Cantabrian Mountains.

From 50 to 30 ka ago cold-adapted large mammals occupied the entire Iberian Peninsula, with a maximum spread between 42 and 31 cal ka BP, including Northern Cantabrian side (Álvarez-Lao and García, 2010, 2011). The same authors show that between 30 and 20 ka the cold fauna was dramatically reduced and only *Mammuthus primigenius* appears in one site in the Cantabrian Coast. After glacial stage I, in the Enol and Belbin depressions, just 2.5 km away, the deglaciation processes generated a high production and redistribution of sediment, similar to what happened in the Duje valley, where an increase of organic matter is detected (Moreno *et al.*, 2011; Serrano *et al.*, 2012; Nieuwendam *et al.* 2015). Dryness could be responsible for the retreat of the glaciers between 26 and 20 ka (Moreno *et al.*, 2010). A high frequency of freeze-thaw cycles, frost weathering and high moisture content during an extended cold period has been deduced from angular grains and sharp features of the silty deposit (Nieuwendam *et al.*, 2015). As we mentioned above, the entity of glacier retreat is unknown, and although in the Pyrenees could have been very intense (Gonzalez-Sampériz *et al.*, 2006), various facts point to not very cold conditions with periglacial environment in the high mountain.

Sedimentological, palynological and geomorphological evidences indicate a cold phase and a new episode of glacial readvance, glacial stage II, between 21 and 18 ka in the Picos de Europa and between 23 and 19 ka in the whole Cantabrian Mountains (Jiménez-Sánchez and Farias, 2002; Jiménez-Sánchez *et al.*, 2013; Serrano *et al.*, 2012, 2013; Rodríguez-Rodríguez *et al.*, 2014). The second stage have been characterised by a small reduction in the extent of glaciers, resulting in shorter and thicker glaciers, although with an increase in volume in the frontal portions (Serrano *et al.*, 2012, 2013, 2015). Cold-adapted large mammals were detected again in the Cantabrian Coast after 25 ka (Álvarez-Lao and García, 2011) and the environmental conditions could be characterised by a cold, dry and more stable climate with glaciers fed by snowfalls from cold, dry air masses from the N and NW, and could be coetaneous with the European LGM. On the basis of the small-mammal assemblages in archaeological sites, Carrión *et al.* (2012) showed that the climatic conditions, which are evident in the rest of Europe, are not detected in Cantabrian sites between 20 and 17.8 ka ago, although the mean annual temperatures were lower than today and the environment was dominated by wet open meadows.

A new deglaciation period began after ~18 ka when glaciers retreated to the upper cirques and troughs. The Valle glacial cirque (Somiedo Valley) was free of ice around 17.5 ± 0.3 cal kyr BP, when the sedimentation of lacustrine deposits begun (Allen *et al.*, 1996). Similarly, a warmer period was identified in Belbin depression between ~17.4 and 13.4 cal kyr BP. Jalut *et al.* (2010) detected in the Pyrenees a deglaciation phase between 15 and 13.3 kyr, and Palacios *et al.* (2015) between 16 and 11 kyr, all of them consistent with the timeline in the Cantabrian Mountain. A substantial deglaciation could affect to all massifs of Cantabrian Mountain, and periglacial and permafrost environments

occupied the highest ranges. During deglaciation, glacier tongues were divided into smaller tongues staying in the upper valleys above 1600 and 1700 m a.s.l.

During the last glacial advance in most Cantabrian massifs, the “altitude stage”, the development of glaciers and rock glaciers were determined by topoclimatic factors. Although in the Pyrenees it has been pointed the hypothesis that small glaciers and rock glaciers developed close to the cirque headwalls could correspond to the last phase of glacial decay (Palacios *et al.* 2015), we think that a new cold phase permitted the growth of glaciers and the existence of periglacial conditions. Intense cold permitted the genesis of rock glaciers, always northern-oriented, although snowfalls were not enough for the development of large glaciers. Frontal moraine complexes and rock glaciers are spread on many cirques, creating a typical landscape on all massifs above 2000 meters. This stage has been related with the Younger Dryas event, well characterized as a cold and arid phase in the Enol lake sequence between 14.5 and 11.6 ka (Moreno *et al.*, 2010, 2011). Since 13.5 ka BP the Enol Lake shows a low lacustrine productivity and low carbonate content, which is interpreted as a response to colder temperatures and decrease in rainfall (Moreno *et al.*, 2011). Younger Dryas (YD) in the NW of the Iberian Peninsula has been defined as a cold and dry period from sea cores (Martrat *et al.*, 2007; Vegas *et al.*, 2013; Salgueiro *et al.*, 2014), analysis of speleothems (Stoll *et al.*, 2014; Morales-Molino and García-Antón, 2014) and palynological records (Naughton *et al.*, 2007; Jalut *et al.*, 2010). Also, the organic content decreased in proglacial sediments of Picos de Europa (Moreno *et al.*, 2010; Serrano *et al.*, 2013). Although in the Enol lake there was not significant changes in the sedimentological and geochemical values, the low in-lake productivity between 12.7-11.6 cal ka BP points to an abrupt cooling disturbing all basin (Moreno *et al.*, 2010). These authors have interpreted an interruption in sedimentation of Enol Lake during the Younger Dryas as a frozen period of the lake, although this period was not long enough to result in a substantial glacier re-advance. Therefore, environmental changes could not to be as dramatic as they were in previous stages in Cantabrian Mountains, such that glacial advances and permafrost environments were only possible in the highest altitudes.

Post Younger Dryas climate changed to warmer conditions, as observed in Enol records (Moreno *et al.*, 2011). According to archaeological data, a humid phase began between 12-7 cal ka BP, with a thermal optimum around 9 ka (Pérez-Obiol *et al.*, 2011; Naughton *et al.*, 2007). Since 11.6 ka onwards an increase of carbonates and organic matter was registered in Enol Lake, which is interpreted as an increase in rainfall, consistent with the warmer and wetter conditions in NW Iberian Peninsula (Muñoz-Sobrino *et al.*, 2001; Naughton *et al.*, 2007). Cantabrian Mountain possibly was free of ice in the Early Holocene, between 11.5 and 9 ka BP, and no evidences of Holocene glacial advances exist nowadays. The 8.2 event and cooling and drier conditions deduced from palynological proxies (Muñoz-Sobrino *et al.*, 2004, 2007, Pérez-Obiol *et al.*, 2011) does not seem to be reflected in the glacial record.

The last glacial advance, located only in the Picos de Europa, has been well defined by glacial features and historical documents as a 1°C cooling (González-Trueba, 2006, 2007) that finished at the end of XIX century, when glaciers turned into icepatches

(Serrano *et al.*, 2011). Pollen records cannot mark this change because of the intense landscape transformation and territory over-exploitation in the preceding centuries (Muñoz-Sobrino *et al.*, 2005), although in some Pyrenean lake deposits the Little Ice Age has been tracked to colder and more humid conditions, showing a strong link between periods of more positive water balance and phases of reduced solar activity (Morellón *et al.*, 2009, 2012).

Compared to global reconstruction of glaciers and climate, the deglaciation model proposed shows a maximum previous to European LGM, as pointed by several authors (Jiménez-Sánchez and Farias, 2002; Moreno *et al.*, 2010; Jalut *et al.*, 2010; Serrano *et al.*, 2012, 2013; Jiménez-Sánchez *et al.*, 2013; Rodríguez-Rodríguez, 2014). The post-LGM deglaciation was consistent with climate conditions in the Alps and Pyrenees (Ivy-Ochs *et al.*, 2008; García-Ruiz *et al.*, 2013, Jalut *et al.*, 2010), with a Lateglacial cooling that formed glaciers only in the highest areas, and a short Late Holocene episode in the XIX century.

6. Conclusions

The last deglaciation of Cantabrian Mountain began after a local glacier maximum, represented by external moraine complexes of Brañagallones, Salgardas, Pido, Enol, Belbín, Vega del Naranco, Upper Carrión and Cardaño, El Valle or Espinosa de los Monteros, which occurred before 30 ka ago. New dates obtained in the last few years support the model of a distinctive history for Cantabrian glaciers, consistent with the glacial evolution and deglaciation in the North Iberian Peninsula, Galician Mountain, Sanabria and the Pyrenees. This glaciation was followed by a moderate retreat during a short and less cold period. A new glacier advance, reaching a position close to the maximum extension of moraine complexes, took place at ~22-18 ka BP. It was a cold and very dry period related to European LGM.

After the second glacial stage there was an important deglaciation phase when ice disappeared of the lower massifs previously glaciated. Deglaciation occurred between 18 and 14 ka BP, with several equilibrium phases, when icefields disappeared and the main glaciers divided into minor tongues located in the upper part of valleys and slopes.

The *Altitude* stage implied a glacier growth dominated by topoclimatic factors in the massifs above 2100 meters, except in the highest massifs (Picos de Europa, Peña Prieta and Peña Ubiña), where glaciers developed in all orientations. The last glacier advances occurred necessarily later than 14 ka BP, although only indirect local arguments point to the Younger Dryas. During this 'Lateglacial', rock glaciers developed, and there was nonglacial activity below 2000 m a.s.l..

The proposed glacial timeline is essentially similar to the model established in the Central and Eastern Pyrenees for the old Upper Pleistocene glaciations (Jalut *et al.*, 1992; García-Ruiz *et al.*, 2003; Delmas, 2005), and the new scenarios with advances between 14-11.7 ka (Palacios *et al.*, 2015). After 11 ka the deglaciation was complete in the lowest massifs of Cantabrian Mountain and no evidences of glacial stages have been detected during most of the Holocene. Finally, new glacial features, mainly moraines, were built

by glaciers in the Little Ice Age, which have decayed into present day icepatches. Only four small glaciers in historical times briefly occupied glacio-karstic cirques on the north-facing slopes of the highest peaks in Picos de Europa, disappearing at the end of the XIX century, when the Cantabrian Mountain was totally deglaciated.

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