Glacial chronology, environmental changes and implications for human occupation during the Upper Pleistocene in the Eastern Cantabrian Mountains

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Abstract

Interest in the evolution of Pleistocene glaciers, environmental change and human occupation in southern Europe is now growing thanks to the availability of fresh datings in different mountains. The demise of Neanderthals in the north of the Iberian Peninsula and the expansion of anatomically modern humans took place between 40-30 ka (MIS3) under cold and wet climatic conditions. Hypotheses differ regarding the migration and demise of Neanderthals, relating to environmental, human or cultural factors. The aim of this study is to establish glacial evolution in the eastern Cantabrian Mountains related to environmental changes and climatic evolution during the MIS3 and MIS2 and human occupation including the Neanderthals' demise. The study is based on glaciomorphology by glacial reconstructions, morphostratrigraphic sequences, equilibrium line altitude estimation, absolute dating (^{14}C, AMS, and OSL), palaeoclimate sequences and human occupation.

Three glacial stages during MIS3 and MIS2 have been established. S-I took place during MIS3 in a cold and wet environment associated with snowfall coming from cold, humid masses from the N, NW and SW and available datings place S-I at 42-31 ka ago. S-II was characterised by shorter and thicker glaciers, which point to a cold, dry and more stable climate, and this is coetaneous with the European Last Glacial Maximum. S-III was a brief period, still poorly dated but attributed to the Late Glacial, characterised by small glaciers housed at altitude and absent from lower mountains.

A lack of harmony has been detected between environmental cooling and population and this may have been a response to environmental changes in N and NW Europe. Neanderthals disappeared from the Cantabrian region at the time of the S-I glacial advance during a cold and wet period at the end of the MIS3. If they had adapted to environmental changes, including abrupt cold events (H6, H5) with important environmental consequences, factors other than environmental ones may have been the cause. The weight of the cultural hypothesis seems more likely in view of the environmental changes, glacial evolution and the continuity of oceanic climates.

Key words: glaciations, Late Quaternary, MIS3, human occupation, Cantabrian Mountains.

1. Introduction

Interest in Pleistocene glaciers in the southern European context and the chronology of the different glacial stages is now increasing thanks to the availability of new datings in different mountains (Pérez Alberti et al., 2004; Hughes and Woodward, 2008; García Ruiz et al., 2010, Palacios et al., 2011, Jiménez et al., 2013). In the Iberian Peninsula considerable evidence has been collected of glacial stages prior to the Last Glacial Maximum (LGM) in the north of Europe in both Atlantic and Mediterranean environments (Jalut et al., 2010; Jiménez et al., 2002, 2013; Pérez-Alberti et al., 2004, 2011; González-Sampériz et al., 2006; García-Ruiz et al., 2003, 2010; Moreno et al., 2010; Serrano et al., 2012, 2013). The present day controversy is on the possible synchrony between the peninsular and European LGM in the Pyrenees or the Central System (Pallás, 2007; Calvet et al., 2011; Palacios et al., 2011).

There is a long history of studies on Pleistocene glacial stages in the Cantabrian mountains, which were first attributed to two Quaternary glaciations, Riss and Würm (Penck, 1897; Obermaier,1914; Saenz, 1935; Hernández-Pacheco, 1944, 1961; Nussbaum and Gigax, 1952) and later to a single recent Quaternary glacial period (Martínez de Pisón and Arenillas, 1979; Alonso et al., 1982; Smart, 1986; Frochoso and Castañón, 1986, 1998; Frochoso, 1990; Castañón and Frochoso, 1992; Gale and Hoare, 1997; Serrano and González-Trueba, 2002; González-Trueba, 2007). New datings and palaeoglacial reconstructions (Moreno et al., 2010; Jalut et al., 2010; Serrano et al., 2012, 2013) show that the glacial maximum of the Cantabrian Mountains may have been prior to the European LGM. All datings point to a distinct behaviour of Cantabrian glaciers compared with those of Europe during the end of MIS3 and MIS2.

The demise of the Neanderthals in the north of the Iberian Peninsula took place between 40-30 ka (MIS3) during a climate characterised by abrupt changes with periods alternating between cold and warm together with the expansion of the anatomically modern human (AMH) and changes in industrial and cultural typologies. The Neanderthal was specialized in exploiting ecotonic ecosystems with a wide variety of resources in small areas; moreover, the AMH was able to exploit open landscapes in cold and dry environments. The AMH survived and expanded in the Cantabrian Cordillera from 42-41 ka cal BP (Sepulcre et al., 2004; Hoffecker, 2009). According to Finlayson the temperature patterns and climate variability of the last 85 ka determined changes in habitat and distribution of hominids, cold stable periods were alternating with extinctions and warm periods with persistence (Finlayson, 2004, p.58). The main discussion on the hypothesis regarding the migration and demise of the Neanderthal focuses on whether it was triggered by the expansion and imposition of AMH and its direct competition by 'competitive exclusion' (Banks et al., 2008); by the assimilation by AMH, which shared some of its genes, which remains a very premature hypothesis (Havarti, 2012); or by migration and extinction related to environmental changes that occurred during MIS3 and the subsequent population dynamics of the species (Finlayson, 2004, Finlayson and Carrión, 2007).

2. Regional setting

The Cantabrian Mountains are located in the north of the Iberian Peninsula, (5º0´W to 2º0´W longitude, and 43ºN latitude) stretching 700 km in an east-west direction (Figure 1). The western area is formed by the Asturian basement of slates, quarzites, limestones, sandstones and conglomerate from the Devonian and Carboniferous age. The complex structure and differential erosion built up isolated massifs on limestones, quarzites and sandstones and eroded depressions on slates and turbidites. Rivers deeply eroded and cut structures on the north side, while adapting to structures in the south side. The eastern area was covered by Mesozoic outcrops: Triasic sandstones and conglomerates, Jurassic and Cretaceous marls, sandstones, limestones and turbidites. The climate was governed by the exposure of mountain ranges to the Polar Front, their relative height and proximity to the sea. The north side had a hyperhumid oceanic mountain environment with over 2,500 mm/year of rainfall, whereas to the south the climate was transitional Atlantic-Mediterranean, with around 600 mm/year of rainfall. The studied area is an important fluvial and environmental threshold between the Atlantic and Mediterranean basins.

3. Material and methods

We selected the glaciomorphological and palaeoclimate sequences, and human occupation information from previously published studies. The glacial sequence analyzed comprises: (i) glacial reconstructions based on geomorphological maps (1/10.000 to 1/25.000 scales) and morphostratrigraphic sequences (González Trueba, 2007; González Trueba and Serrano, 2010; González Trueba et al., 2011; Serrano et al., 2012, 2013; Pellitero, 2009, 2014). (ii) Equilibrium line altitude estimation by the AAR method in eight massifs for each stage established (Serrano et al., 2013). (iii) Chronologies based either on absolute dating by ^{14}C, AMS, U/Th and OSL (Table 1). The different dating techniques imply chronological uncertainty about the maximum ice extent and the LGM in Iberian mountains. Although the dating procedures AMS, 14C, and OSL pose different limitations and problems –such as possible contamination of samples of aquatic organic matter affected by old carbon, evolution of complexes or fine deposits undetected during field work- and the results can be questionable, the coherence of the datings obtained by AMS and OSL techniques increases the consistency of glacial chronologies. (iv) Sedimentological archives and a sequence of Loss of Ignition (LOI) in the Picos de Europa (Serrano et al., 2012) used as evidence of environmental changes directly related to glacial evolution. (v) Information on environmental changes and human population in the eastern Cantabrian Mountains has been obtained from natural deposits and archaeological research (Baena et al., 2004; Cabrera et al., 2004; Rasilla and Straus, 2004; Garralda, 2005; Strauss, 2005; Iriarte et al.,, 2005; Sánchez-Goñi and d'Errico, 2005; Uzquiano, 2005; Gutiérrez and Serrano, 1996, 2006; Uzquiano et al., 2008, 2012; Alvárez and García, 2011; Maroto et al., 2010; Sepulcre et al., 2004; Hoftfechner, 2009; García Garriga, 2012). Several parameters such as open-air or cave sites, mountain or coastal emplacement and altitude have been considered in order to differentiate environmental conditions.

4. Pleistocene glaciations and chronology

In the Cantabrian Mountain Pleistocene glaciations were limited to the highest massifs and all glaciers were of small size (Table 2) compared with those of the Pyrenees or the Alps. Nevertheless, the Cantabrian Mountains hosted the lowest glaciarized massif in the Iberian Peninsula. Two groups of glacial massif can be differentiated in the eastern Cantabrian Mountains in terms of altitude, longitude and distance from the sea (Figure 2). In the easternmost area, glaciers developed in very low mountains; on the Pas Mountain, Gorbeia and Aralar, where cirque, alpine and ice domes were emplaced below summits of 1700 and 1300 m a.s.l. A strong longitudinal gradient and an increase in precipitation from west to east in the Pleistocene lowered the

ELAs to less than 1300 m a.s.l. in the east. The western area is characterised by massifs glaciated above 2000 m a.s.l. with ELAs of between 1600 and 1800 m a.s.l.

Recent studies with a regional focus centring on Cantabrian Mountain massifs have provided optically stimulated luminescence (OSL) and radiocarbon datings for the glaciolacustrine, proglacial, peat bog deposits and moraines. Datings obtained by radiocarbon (^{14}C, AMS) of discrete organic matter fragments or concentrated pollen to minimize a possible hard-water effect (Jalut et al., 2010; Moreno et al., 2010; Serrano et al., 2011, 2012) have been obtained in Sil Valley, Picos de Europa and Pas Mountains, and are consistent with U/Th and OSL datings (Pellitero, 2011, Serrano et al., 2012; Frochoso et al., 2013) from the Palentina and Pas Mountains.

In the Picos de Europa a slope deposit on an erosional feature on limestone have been dated as prior to MIS7 (Frochoso and Castañón, 1996) and in 396.47±240,8 ka (MIS11), inferring an age prior to 478 ka (MIS12 glacial period) to the first glacial features (Villa et al., 2013). This is an indirect dating, and an unclear glacial feature below the slope deposit requires more data to confirm an ancient glaciation prior to the slope deposits. Ancient glacial deposits have been described (Serrano, 1991) and dated in the Pyrenees (Peña et al., 2004; Lewis et al., 2009; Sancho et al., 2003, 2011; Delmas et al., 2011) and have provided the most extensive glaciations with an age during MIS6 (190–130 ka BP). Datings have also been obtained in the NW Iberian Peninsula of around MIS8 and MIS6 (Fernández-Mosquera et al., 2000). Pre-Würm glaciations in the Cantabrian and Pyrenean Mountains, located between MIS12 and MIS6, have highly uncertain chronologies depending on the different dating techniques used, and morphostratrigraphic sequences and more deposits, landforms or datings are required.

The morphostratigraphic correlation of the glacial landforms (Table 3) and datings of different moraine complexes have facilitated a first approximation to the Late Pleistocene glacial chronology. During this period three main Pleistocene phases have been detected (Serrano et al., 2013; Jiménez et al., 2013; Rodríguez et al., 2014).

4.1. Stage of maximum expansion (S-I)

Glaciers occupied the maximum extent during S-I, when the ELAs were located at an average altitude between 1580 and 1700 in the western massif, and 1190 in the Castro Valnera icefield (Figure 2).

During S-I in Campoo, Valdecebollas, Fuentes Carrionas and Cebolleda Cebolleda massifs were developed alpine and cirque glaciers, in which the mean altitudes of the ELAs increased the further from the sea they were. Cebolleda and Fuentes Carrionas massif have a sharp N-S dissymmetry and the ELAs are very low to the north. Alpine glaciers have large cirques and tongues (between 3.7 and 14.9 km length) reaching 1200 m a.s.l., where the moraine complexes are well preserved. On the southern side only cirque glaciers without tongues were generated. Alpine glaciers developed in Alto Campoo and Valdecebollas, whose fronts were situated at around 1300 m with the ELA at 1700 m a.s.l. In Peña Sagra, a massif located only 26 km from the sea, alpine glaciers oriented to the north (87%) were dominant. Similar processes took place in Gorbeia, where only three small cirques oriented to the north and generated by leeward spindrift accumulation were shaped by ice (Figure 3B).

In the northernmost massifs, with greater Atlantic influence (Pas, the Picos de Europa and Aralar), lesser distance from the sea and no physiographic barriers, ice domes developed. Glaciers of the Picos de Europa were short, but their fronts reached very low altitudes, 450 and 600 m a.s.l. in the north side and 800 m in the south (Figures 2 and 3). The maximum expansion of glaciers was defined by summit icefields with outlets reaching 7 km in the Duje, 4 km in the Deva and 4.2 km in Valdiezmo. The Pas Mountain developed two glaciated sectors, the Castro Valnera massif (1718), where a

icefield developed with an outlet dropping to the north (Miera tongue of 5 km length) and the south (Trueba tongue of 15 km length) and the Veinte-Pizarras massif (1472 m), at the north of the watershed, where cirques and troughs of moderate size developed. The icefield shows net dissymmetry with the main ice accumulations to the east of the dividing line, low altitudes of glacial fronts (400-600 m a.s.l. to the north and 760 m a.s.l. in the south side) and the ELA at 1190 m a.s.l. (Figure 2). It was a large glacier born as low as 1700 m and reaching front altitudes analogous to the western massifs or Pyrenean glaciers. The Aralar Range (Ugarte, 1992; Rico, 2012) was occupied by a small ice dome around 3.9 km^2 with several tongues reaching the 850 m a.s.l. The low altitude and eastern longitude of glacial processes does not provide an explanation of the existence of colder conditions than in the westernmost Pyrenean massifs. Distance from the sea, physiography and the longitudinal gradient of snowfall from west to east explain the development of glaciers at unusually low altitudes in the context of a hyperhumid climate characterised by strong winter snowfall and a cold summer.
The threshold of the lowest glaciated peak was at 1800 m a.s.l. in the Picos de Europa and Campoo, and around 1400 m a.s.l. in the Pas Mountains. Campoo, Cebolleda, Peña Sagra, Valdecebollas, Gorbeia and Aralar denoted a topoclimate influence in the location of cirque and alpine glaciers, dominating in the northern ones. In the Valdecebollas and Fuentes Carrionas massifs, located to the south of the watershed, due to their windward position and moderate altitude only a SW flowing atmospheric circulation can explain the oceanic character of the glaciated massif, confirmed by a pattern of lower ELAs in the north and northeast glaciers.
Results of dating (Table 1) in the Picos de Europa place the glacial maximum prior to 40 ka ago in Enol (Moreno et al., 2010); 40,480±820 a BP in Comeya (Jiménez and Farias, 2002); and 35,700-34,850 cal a BP in el Duje (Serrano et al., 2012). In the Fuentes Carrionas the minimum age is of 36,028±2,350 a BP for the glacial maximum (Pellitero, 2011; Serrano et al. 2012). The Trueba Valley (Pas Mountains) yields an age prior to 29,149-28,572 cal a BP (Serrano et al., 2012, 2013) and on the north side an age of 44,980±2,3 ka (Frochoso et al., 2012). Further west, datings point to ages of 28,990±230 a BP in Redes (Jiménez et al., 2002; 2013), around 44 ka in the Sil Valley (Jalut et al., 2010) and prior to 25.6 ka in Sanabria (Rodríguez et al., 2011). All datings, made on different deposits (lacustrine, peat bog and till) and using different techniques (AMS and OSL) confirm the maximum extent of glaciers during MIS3, before the LGM of N and NW Europe.
It must be pointed out that if all massifs have homogeneous thermal behaviour the differences between massifs are determined by changes in snowfall conditions (Serrano et al., 2013). Therefore, snowfall intensity and origin (NW, N and SW) would be the determinant factor in the types of glaciations during Pleistocene glacial stages. Limitations deriving from distance from the sea, barrier effects and altitude, are compensated by SW flows feeding snowfall towards the southern massifs. This different behaviour could only be explained by a more southerly circulation of the atmospheric currents, with SW fronts reaching the southern massifs (Florineth and Schluter, 2000).

4.2. Stage of alpine glaciers (S.II)

This stage was characterised by a small reduction in the extent of glaciers and a moderate ascent of the ELA, between 1200 and 1775 m in the western mountains and 1200 m in the Castro Valnera icefield (Figure 2). The glaciers were of similar proportions in extension to the previous phase but with an increase in volume in the frontal portions.

The glacial retreat and re-advance to positions very close to the previous phase have been revealed by changing directions of glacial flows in the Picos de Europa, two different infill deposits in the Trueba Valley and the different lithology of the moraines at Vega del Naranco in Fuentes Carrionas (Turú et al., 2007a; Serrano et al., 2012, 2013; Pellitero, 2011). A period of glacial equilibrium has been dated by minimum LOI in the lacustrine sediments of Áliva at between 21,500-21,390 cal a BP, a second stage of deglaciation in Enol between 20-18 ka ago (Moreno et al., 2010) and 20,640$\pm$300 a BP in the Alto Nalón (Jiménez et al., 2002). A glacial advance has been established between 32-18 ka ago (Jalut et al., 2010) in the Pyrenees and the Cantabrian Mountains. It could belong to MIS2 cold stage, or to the transition from MIS3 to MIS2 (H2), possibly prior to the LGM of the N and NW of Europe or very close to it. The explanations of this cooling and glacial stage may be the altitudinal decrease of the frozen sea that led to the prevalence of cold but rather dry air masses, generating intense cold conditions, dry winters, absence of air masses from the SW and a relative decline in the snowfall from the N and NW (Serrano et al., 2013).

4.3. High mountain advance, Stage of cirque glaciers (S-III).

Northern oriented glacial cirques over 1800-2000 m, especially those protected by walls 200 to 250 metres high in shaded and high sites, present well conserved moraine complexes that reveal a cirque glacier stage. These landforms belong to a period of equilibrium and minor advance with ELAs at 2050-2130 m a.s.l. Ice fields and ice domes disappeared during this moderate cooling period, no glaciers remained in Gorbeia and Aralar and only small alpine and cirque glaciers were left on the northern slope of the Pas Mountains. Topoclimatic factors were determinant to the development of glaciers and the cold permitted the genesis of small rock glaciers but the snowfall was not enough for the development of large glaciers.

A high degree of uncertainty remains regarding the chronology of this period because it is based on indirect data; an equilibrium in the Ca content between 14.5 and 13.5 ka in Enol (Moreno et al., 2010) and a moderate minimum LOI in the lacustrine sediments of Áliva circa 13.9 ka (Serrano et al., 2012) are interpreted as cooling.

5. Human occupation

There is discussion between authors who think of a local technological and cultural transition between Middle and Upper Palaeolithic techno-complexes, with Aurignacian emerging as a local evolution from the Mousterian (Cabrera and Bernaldo de Quirós, 1990; Cabrera et al., 2001; Sáenz de Buruaga, 1991, 2004) and authors who think that there is no reliable evidence suggesting this continuity (Maroto et al., 2012). So, the coexistence of Neanderthals and AMH in Iberian Peninsula sites can currently be dismissed due to problems related to dating, cultural attribution, or a lack of reliable radiocarbon datings and the supposed survival of Neanderthals in other European regions is not supported by recent radiocarbon datings (Maroto et al., 2012).

Neanderthal groups are documented in the Iberian Peninsula from ~170 ka B.P. to ~30 ka B.P., which reflects inter- and intra-population variability, and although the most Neanderthal remains were found with Mousterian industries, a few appeared with the so-called 'transitional cultures' between Middle and Upper palaeolithic (Garralda, 2005). The main Neanderthal findings of the Iberian Peninsula very often have chronostratigraphical problems, not only those found a long time ago but also remains recently discovered. Only in six sites of the Cantabrian Mountains and the coast have remains been found of Neanderthals (Table 4), all of them dated between 45.7 and 38.5 ka (Garralda, 2005).

Human occupation of the Cantabrian region in the study period was characterised by important changes in population density (Finlayson and Giles, 2000; Finlayson, 2004; Strauss, 2005). The maps of sites (Baena et al., 2004, Cabrera et al., 2004; Rasilla and Straus, 2004; Gutiérrez and Serrano, 2006; Straus, 2005) reveal high Mousterian density and a greater proliferation of sites in mountain regions (Maroto et al., 2012; García-Garriga, 2012). In this sense, the Mousterian occupation reached the high valleys, with sites in Nestares or Mave in Campoo (Alonso and Serrano, 2006; Diaz et al., 2011; Yravedra et al., 2013), a natural connection between the Cantabrian coast and the Duero, and the inner mountain at low altitudes in Picos de Europa or Pas Valley. The moderate density of Neanderthals in the Cantabrian region 39 ka ago (Finlayson, 2004) coincides with the combination of Mousterian and Gravettian cultures and the change in conditions from forest landscapes with closed woods of dominant Mousterian culture to open Gravettian-dominant ones (Finlayson, 2004) and also a moderate presence of AMH.

In the north of the Iberian Peninsula Maroto et al. (2012) described the first Upper Palaeolithic assemblages appearing mainly in lowland areas linked to natural corridors and thick Middle Palaeolithic sequences where Middle Palaeolithic populations were replaced by Upper Palaeolithic ones. This is probably the case of the El Castillo and Lezetxiki fossils, all of them very near the passages to or from southwestern European regions (Garralda, 2005). After 40 ka BP these assemblages tend to appear at higher altitudes, in mountain landscapes with clearly diverse ecological conditions characterised by environments with contrasting features in terms of their biological potential to support humans, with long occupational hiatus, where there was no cultural replacement and the extinction of the Neanderthals cannot be explained by the pressure of Upper Palaeolithic populations (Maroto et al., 2012; García-Garriga, 2012). Although the most Neanderthal finds are related to Mousterian cultures, in El Castillo and Lezetxiki there are documented remains of 'Transitional Aurignacian' or 'Transitional Mousterian' techno-complexes (Garralda, 2005; García-Garriga, 2012). Two key sequences, El Castillo and El Esquilleu show the survival of Middle Palaeolithic communities in inland areas, while in coastal areas the Aurignacian was in early development (García-Garriga, 2012). But doubts remain about the exact chronology of fossils, dated between 45.7 ka and 38.5 ka, and Mousterian cultures. The archaic Aurignacian of El Castillo Cave would be, at ~40 ka BP, among the most recent in Europe, but the context of Level 18 (see Table 4) is questioned by some authors. They consider a mixture of two technologically differentiated assemblages, with Aurignacian occupation in the upper part and a Mousterian presence in the lower part of the sequence (García-Garriga, 2012). The most accurate dating of a Neanderthal fossil by AMS in the Sidrón Cave, 43,129$\pm$129 cal a BP (Garralda, 2005; Lalueza et al., 2005) is included in the glacial period S-I. Finally, the geographical distribution of sites shows the latest Neanderthals inhabiting the harshest, but also the most diverse environments, and not in the temperate conditions of the southern areas (Maroto et al., 2012).

d'Errico and Sánchez (2003) and Finlayson et al. (2008) consider climatic deterioration during H4 to be the main cause of the contraction and disappearance of the Neanderthals, together with MIS2 climatic deterioration and the development of open landscapes, perhaps more suitable for AMH, and competing with each other (d'Errico and Sánchez 2003; Banks et al., 2008). But conditions were probably not extreme and other authors sustain that with great diversity in geography and ecosystems between 40 and 30 ka BP in MIS3, the key historical event was the expansion of AMH and Upper Palaeolithic technology (García-Garriga et al., 2012), not climatic variability. Therefore, some archaeologists are in agreement on one explanation of the extinction or assimilation of the Neanderthals in the northern Iberian Peninsula, based on the relations between neighbouring communities and the alteration of the equilibrium (García-Garriga, 2012). They argue that if Neanderthal withdrawal was the response to climate change, flows of cultural groups over time should be detected. But archaeologists have observed that when Neanderthals or Middle Palaeolithic levels disappeared from a particular region, it was forever. García-Garriga et al. (2012) point to an agreement with a model of competition among groups rather than climate adaptation.

In the Aurignacian, a fall in population density took place in contrast with the stability of the Acheulean and Mousterian, as well as a fall in the number of sites and a distancing from the mountain, though this also occurred on the coast (Strauss et al., 2007). It was not only a fall in resources and migration towards lower areas, but a generalized depopulation in which the possible emigration to the north of the AMH would not be substituted by the Neanderthal. Around 33 ka ago the Neanderthals disappeared from the Cantabrian region, coinciding with a high density of AMH in the north of the Iberian Peninsula.

The mapping of the Gravettian shows a moderate increase in sites, mainly at low altitudes on the Cantabrian slope near the high mountain, with the re-occupation of inland valleys. In the Solutrean there was a sharp population increase attributable to the 'refuge effect' (Straus, 2000) deriving from southward migrations resulting from cooling and glacial expansion in the north. This phase coincides with the complete extinction of the Neanderthals to the south and a sharp fall in population in the north and northwest of Europe. Again in the Magdalenian, density increased in the north of Europe and north of Iberia, mountain areas becoming occupied at the end of the LGM.

The premises adopted by Maroto et al. (2012), first the consideration that the Middle Palaeolithic techno-complexes were produced by Neanderthals and second, that the Upper Palaeolithic was the product of AMH, have been adopted by us to consider the disappearance of the Neanderthals. Both premises consider that MIS3 is characterised by wide climatic variability with a highly changing environment in which there were glaciers at the summits forcing humans to readjust their behaviour and develop new adaptive strategies to occupy and exploit the territory.

6. Discussion:

Climatic and glacial evolution, geographical location and physiography in the eastern Cantabrian Mountains have given rise to a wide variety of ecosystems and landscapes over the last 70 ka. The differing environments arose because of the oceanic climate and existence of Pleistocene glaciers during S-I, S-II and S-III. Glaciers were relegated to the interior of the mountains, at low altitudes in the north (400-600 m) where they shared territories with humans, and higher ones in the south (700-1000 m).

The S-I glaciation is dated at 42-31 ka ago, a period coinciding with MIS3 with the presence of dated Neanderthal fossils (40-38 ka) and Mousterian cultures in the north of the Iberian Peninsula. Glacial chronological results are similar to the Pyrenees, where datings indicate that the glacial maximum occurred during MIS4 and MIS3, earlier than in central and northern Europe (MIS2) (Peña et al., 2004; Lewis et al., 2009; Sancho et al., 2003, 2011; García-Ruiz et al., 2010, 2013). The LGM was restricted to the headwater (García-Ruiz et al., 2003) and although evidence of the LGM is scarce (Lewis et al. 2009; García-Ruiz et al., 2003, 2010), the landforms related to LGM valleys occur several kilometres upstream of the maximum ice extent features (García Ruiz et al., 2012). Studies in the Mediterranean mountains based on ^{14}C and OSL dating techniques led to similar conclusions (Mardones and Jalut, 1983; Andrieu et al., 1988;

Jalut et al., 1992, 2010; Hughes et al., 2006; Hughes and Woodward, 2008) and cosmogenic surface exposure ages have provided ages coherent with an early maximum ice extent in the Pyrenees (Pallàs et al., 2010; Delmas et al., 2011, 2012). All of this leads to the conclusion that a maximum ice extent occurred in the Pyrenees much earlier than the global LGM. Nevertheless, not all datings show a maximum advance in MIS3. Studies based on 10Be exposure in the Pyrenees indicate an ice advance maximum in the LGM (MIS 2). All cases are obtained in the eastern Pyrenees, but the debate regarding the chronology of the maximum ice extent in the Pyrenees remains open (Pallàs et al., 2006, 2010; Delmas et al., 2008; García-Ruiz et al., 2010; Calvet et al., 2011).

The presence of glaciers during MIS3 implied geographical variations (latitudinal and altitudinal) on the distribution of glaciers and environments. The important latitudinal changes and glaciers at lower altitudes in the easternmost area would be reflected in geographical variations in vegetation landscapes. Therefore, the altitudinal differences between the glaciation threshold altitude, ELAs and front altitudes can be considered as being dependant on changes between precipitations and wetness. Changes between glacial stages SI and SII also derive from changes in moisture linked to variations in the atmospheric dynamic, mainly of the latitude of NW flows. Between 65 ka and the LGM short cold water stages (Heinrich events) have been reported, one of which between 39-40 ka was of similar intensity to that of the LGM.

The regional responses to climate variability have been pointed to as causes of different glacial periods in the south of Europe (Hughes et al., 2006; Delmas et al., 2008; Serrano et al., 2012; García Ruiz et al., 2013). Small glaciers characterising the Cantabrian Mountains react more rapidly than large glaciers, with almost immediate expansion or contraction of the ice mass as a consequence of changes in precipitation or temperature. In the Pyrenees (García Ruiz et al., 2013) it has been pointed out that if, during some of the abrupt changes (Dansgaard et al., 1993) the Scandinavian ice cap and valley glaciers had undergone sustained growth during MIS3 due to the greater inertia, with stabilization or slower growth of the ice mass, other small Mediterranean glaciers would have retreated during the warm periods because of their greater sensitivity to climate fluctuations. In the Cantabrian Mountains we must add the hyperhumid climate and the reception of SW cold and wet air masses to explain the regional responses of glaciers depending on cooling or moisture increase (Serrano et al., 2012, 2013). The location of the Polar Front during the MIS4 and 3, at approximately 46°N favoured meridian circulation (Florineth and Schlüchter, 2000), which explains the different response to the Polar Front. Variations in the growth of glaciers have been recognized not only in the Cantabrian Mountains, but also in the Pyrenees, the Vosges, and the northern and western Alps (Seret et al., 1990; Ivy-Ochs et al., 2008; Preusser et al., 2007). Changes in the Polar Front and the dry conditions after 30 ka were a limiting factor to glacial expansion in humid or Mediterranean environments of the southernmost latitudes of Europe and glaciers did not reach the positions they did during MIS3.

In the eastern Cantabrian Mountains the more intense snowfall supplied by cold and partially humid air masses from the N and NW, as well as less cold but more humid ones from the SW, may have been the cause of a more extensive S-I glacial advance, between 42 and 30 ka ago, than the LGM. The MIS3 period has been characterised in the Esquilleu Cave by open landscapes with arboreal taxa (Pinus, Betula, Juniperus) discontinuously distributed. The morphological features and dominant humid conditions favoured the survival of mesophilous and hygrophilous taxa (Uzquiano, 2008) and provided enough vegetable biomass and housed related fauna to support periodic seasonal human occupations (Uzquiano et al., 2012). A mild and moist period has been detected in the Atlantic during 38.6-36.5 cal ka BP (GI8) with the development of a weak deciduous forest (Banks et al., 2008), and a favourable moisture period has been detected in the Esquilleu Cave (Phase III, layers XIII-V) by a decrease in Pinus taxa and an increase in mesophilous taxa between 39 and 34.3 ka BP (Uzquiano et al., 2012), a fact which may be more pronounced due to the regional climate between the sea and the mountains in the easternmost Cantabrian Mountains. The vegetation in the Cantabrian area during MIS3 is an open forest on poorly developed soils with Pinus on dry subtracts, Betula with Sorbus on humid ones, and occasionally hygrophilous taxa such as Salix and Agnus, with Corylus, Quercus and Castanea (Iriarte et al., 2005, Sánchez-Goñi and d'Errico, 2005; Uzquiano, 2005; Uzquiano et al., 2008, 2012). Between 39 and 36 Ka ago there was a pre-forest vegetation cover characterised by colonizing species such as Pinus, Sorbus and Betula (Uzquiano, 2005).

During the S-I, posterior to 38.5 ka, Neanderthals were living in the Cantabrian Mountains following an isolation period or migration to the south, but they disappeared from the Cantabrian area coinciding with environmental changes (Figure 4) from closed to open landscapes (Uzquiano, 2005; Sánchez-Goñi and d´Errico, 2005; Iriarte et al., 2005). Corridors passing toward the Duero basin had been used during previous periods (Gutiérrez and Serrano, 2006; Díaz et al., 2008). AMH reached the area during a wet and cold period using the Cantabrian coast and mountains as a refuge prior to 37 ka BP. The early arrival of the Aurignacians has been interpreted as a relatively rapid substitution of the Neanderthals by AMH in the north of the Iberian Peninsula (Maroto et al., 2012, García-Garriga et al., 2012), but the co-existence of AMH and Neanderthals in the same region may span from the initial S-I until the warming period at the end of the S-I. During the S-I, climatic instability, fragmentation of the remnant Neanderthal population and the existence of environment non-analogues with modern ones (Finlayson et al., 2004; Stewart, 2005) may have generated intense environmental stress on Neanderthal populations, leading to southward migrations. If the Neanderthals were able to remain in the Iberian Peninsula by adapting to environmental changes such as the steppe environment between 200 and 100 ka ago as described by some authors, the cold events in MIS4 earlier than 70 ka ago, H6 and MIS3 (H5), some of which were abrupt changes between warm phases with swift environmental changes, it is difficult to reach the conclusion that they could not adapt to cold and wet events (H4, H3). It has been pointed out that changes in the ecosystems the Neanderthals belonged to would generate an absence of resources culminating in their demise, partially coinciding with the extinction of associated fauna (Finlayson, 2004, Stewart, 2005; Finlayson et al., 2008). Nevertheless, we have seen how orographic characteristics and the longitudinal gradient cause a wide variety of ecotones between the steppe and forest environments in a cold and wet Atlantic climate. Neanderthals failed to adapt to the new environmental conditions, although they had, no doubt, been considerably more flexible in the past (Straus, 2005). Conditions to the south of the Cantabrian Mountains were possibly less rich, made up of extensive steppes occupied by cold-adapted mammal species that remained in the north of the Iberian Peninsula until 10 ka (Álvarez and García, 2011). But to the north the wide variety of ecosystems and the location of the glaciers, at the top of mountains with a natural passage free of ice, would not necessarily appear to be a limiting factor.

The only new and very different event during the MIS3 was AMH taking refuge in the north of the Iberian Peninsula (Figure 4). The hypothesis of 'competitive exclusion' (Banks et al., 2008) seems possible, though other authors do not consider the evidence to be compelling (Stewart, 2005). Relationships between often obscure environmental and cultural changes (Straus, 2005) are, therefore, one possible explanation for the demise of the Neanderthal population. On a regional scale we can consider the inability to adapt culturally to the new environment and abrupt conditions (climate variability, AMH population, faunal migration and extinctions), overcome in the recent past but now collapsed.

The glaciers retreated and partially abandoned the mountain valleys until the new glacial stage S-II, a glacial advance at the transition to MIS2. The cooling of the LGM coincided with a period of intense cold and glacial advance in all massifs studied. The intense cold was accompanied by a decrease in altitude of the frozen sea that led to the prevalence of cold but very dry air masses from N and NW during the winter and a relative decline in snowfall and air masses from the SW (Ruddiman and McIntire, 1981; Florineth and Schluchter, 2000). During that period the glaciers were less extents but thicker, reflecting a more stable cold period characterised by cold and dry conditions, with stepped landscape reaching the lower part of mountain valleys. The lowest and most continental massifs evolved towards marginal glaciation immediately after the glacial maximum. Glacial advance is coetaneous to an open landscape occupied by AMH and cold-adapted mammal species, which sheltered in the Cantabrian area until 17.5 cal ka BP (Alvarez and García, 2011).

The last Pleistocene glacial stage (S-III) extended only over the highest ranges, whereas the easternmost massifs and low altitude ranges were free of ice during this phase. The presence of cirque glaciers and rock glaciers appears to be a general feature in the Cantabrian Mountains. Glaciers developed in Campoo, Fuentes Carrionas, Cebolleda and the Picos de Europa. The cooling meant the landscape was dominated by herbaceous vegetation but with little representation of cryoxeric taxons. The oceanic environment remained and open landscapes with little forestation were dominant (Iriarte et al., 2005). During the Late Glacial in the north of the Iberian Peninsula the 'Magdalenian Boom' (Strauss et al., 2002) took place, with an increase of human occupation favoured by the moderately wet and cold climatic conditions. Glaciers, located up in the mountains, would no longer constrain human activities.

The environmental changes in N and NW Europe explain the increase in population during cold phases in the Cantabrian Mountains, as AMH flowed south as a relatively cold and dry optimal refuge. This did not happen to the Neanderthals, which disappeared from the Cantabrian region at the time of the S-I glacial advance (Figure 5), a cold, wet period at the end of the MIS3. If, during previous periods (MIS4, MIS5) they had adapted to environmental changes, including abrupt cold events (H6, H5) with important environmental consequences, the inability to adapt to the changes that took place in H4 in the Cantabrian Mountain, with the intensification of cold but, above all, the increase in humidity, it may have been down to two factors, the competitive exclusion imposed by AMH, who migrated to the south in search of better conditions, or to the cultural limitations of a human group incapable of adapting with innovative responses to the new environmental and cultural conditions, and to the presence of AMH. The weight of one of these hypotheses, primarily cultural, seems more likely in view of the environmental changes, glacial evolution and the continuity of oceanic climates. More environmental and cultural records are needed to be more accurate in the chronologies and possible human responses to cultural or environmental changes in northern Iberian Peninsula. Following the territorial occupation by AMH during the cold and dry S-II, the AMH population increased in response to the advance of the glaciers in northern Europe and migrations thereafter. Finally, the last glacial advance, S-III, had no regional influence and coincided with the population and cultural expansion of the Magdalenian.

7. Conclusion

In the Late Pleistocene in the Cantabrian Mountains during MIS3 and MIS2, three glacial stages have been established. The reconstruction of glacial advances and retreats and climatic variations are not in accordance with responses in Palaeolithic population density. Glacial stages coincide with population increases at the end of the Mousterian culture, in the Gravettian and Solutrean, and in the Magdalenian.

Glacial advances and equilibriums behave differently with regard to northern Europe: S-I takes place during MIS3 in a cold and wet environment associated with snowfall coming from cold, humid masses from the N, NW and SW, and open landscapes in inner and coastal sites. The accentuated gradient of longitudinal precipitations meant that in the easternmost mountains glaciers were generated at very low altitudes in favour of snowfall. Available datings situate S-I at 42-31 ka ago, coinciding with the permanence and expansion of Mousterian and Aurignacian cultures. Adaptation to new environmental conditions could not be very different to what occurred during the previous phases of MIS3 and MIS4 (H5 and H6 events), when Neanderthals still occupied the territories, mainly on the coast.

Later, during S-II, characterised by shorter, thicker glaciers denoting a cold, dry and more stable climate with glaciers fed by snowfall from cold, dry air masses from the N and NW, the Neanderthal and Middle Palaeolithic cultures withdrew. The climate was colder and dryer than S-I, but glaciers occupied only the high mountain. There were no environmental conditions different to S-I that would cause further difficulty to the Neanderthal occupation. S-II is coetaneous with the European LGM and AMH travelled from north and northwest Europe to the south, increasing the population on the Cantabrian coast. Finally, S-III was a brief period attributed to the LGM, which is still poorly dated but related to the Younger Dryas when AMH population once more expanded throughout the north of the Iberian Peninsula. The cold period in the North of Europe may possibly have led to human flow to the south in search of favourable ecosystems in the wetter and warmer coasts and mountains compared with central and northern Europe. In this period the glaciers, small in size, were housed at altitude and disappeared from the lower mountains.

The reasons behind this lack of harmony between environmental cooling and population may have come in response to environmental changes in N and NW Europe, since on the Cantabrian coast the climate would have been relatively harsh with respect to that of the north. It would, thus, constitute an optimal refuge for AMH in spite of its relative cold or dryness. This did not happen to the Neanderthals, which disappeared from the Cantabrian region at the time of the S-I glacial advance (Figure 5), a cold, wet period at the end of the MIS3.

If, during previous periods (MIS4, MIS5) they could adapt to cold and abrupt environmental changes, why did they fail to adapt to changes of H4, characterised by cold and increased humidity? This may be explained either by competition with AMH, migrating southwards from Europe, or by the cultural limitations of a human group incapable of adapting with innovative responses to the new environmental and cultural conditions. The expansion of AMH during the cold and dry S-II and S-III shows the relationships between glacier advance and human flows from northern Europe during the Late-Pleistocene.

We must get a better chronological and environmental knowledge on glacial evolution, because at present our only reliable knowledge relates to the extension of glaciers. It is necessary to establish links between glaciers and cultural records as well as achieving a more accurate chronology between glacial and cultural changes. Effort must be made to develop an accurate glacial chronostratigraphy.

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Tables.

Table 1. Dating for the glacial related deposits in the Cantabrian Mountains.
Table 2. Glaciated massifs in the eastern Cantabrian Mountains.
Table 3. Glacial stages and correlation between massifs in the eastern Cantabrian Mountains.
Table 4. Neanderthal remains located in the North of Spain (Garralda, 2005).

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Figure 1, Location of study area and distribution of studied glaciers by massifs. 1, the Picos de Europa. 2, Cebolleda. 3, Fuentes Carrionas. 4, Peña Sagra. 5, Alto Campoo and Valdecebollas. 6, Pas. 7, Gorbeia. 8, Aralar.

Figure 2. Distribution of main glacial parameters of glaciated massifs.

Figure 3. Glacial extent and evolution in the larger (A, The Picos de Europa) and smaller (B, Gorbeia) glaciated massifs.

Figure 4. Cultural and climate events in the Cantabrian region (Synthesized from Finlayson and Giles, 2000; Finlayson, 2004; Straus, 2005; Sepulcre et al., 2004; Serrano et al., 2012, 2013).

Figure 5. Glacial, landscape and human evolution in the study area. (1), Moreno et al. 2010. (2), Serrano et al. 2012, 2013. (3), Uzquiano, 2005, Uzquiano et al., 2011; 2012. (4), Finlayson, 2004; Garralda, 2005. (5) Hoffecker, 2009. (6) Chronology of dated Neanderthal remains in Cantabrian Region. 1 and 2, El Castillo Cave. 3, Axlor Shelter. 4, El Sidrón Cave. 5, Arrillor Cave.

Figure1

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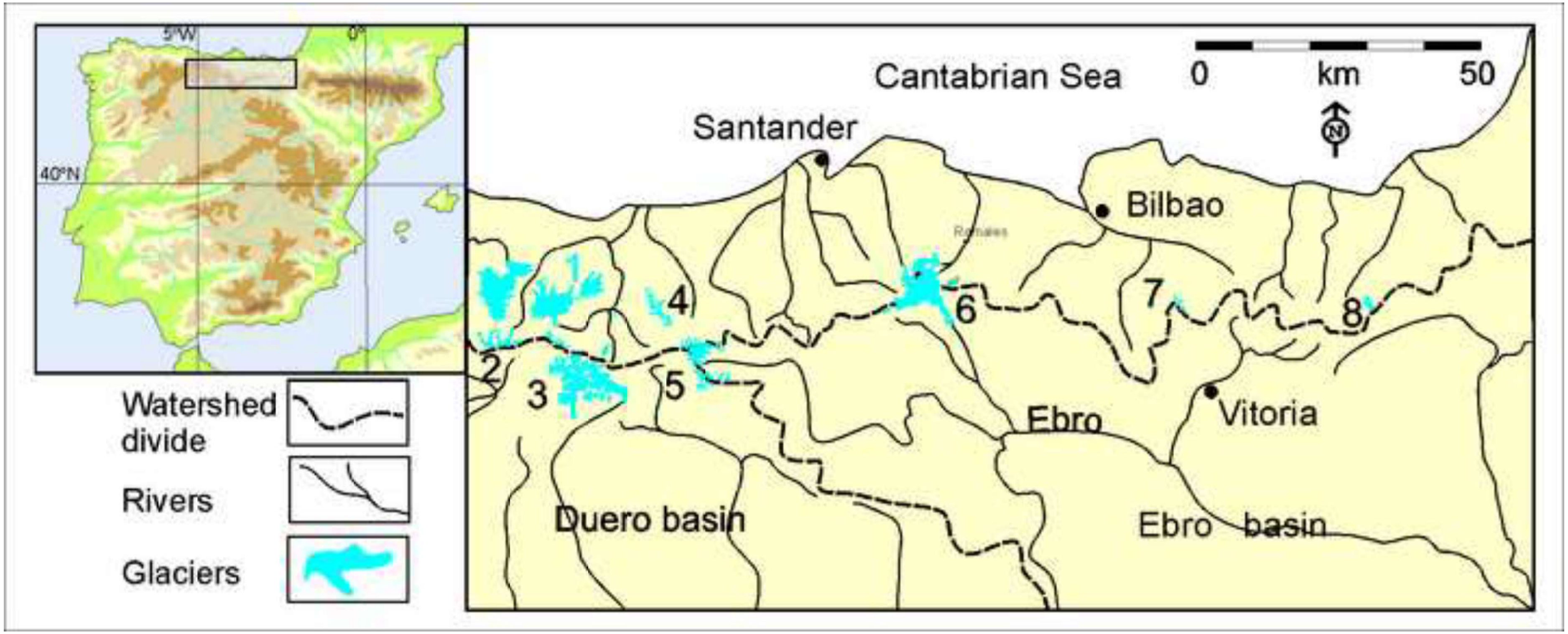
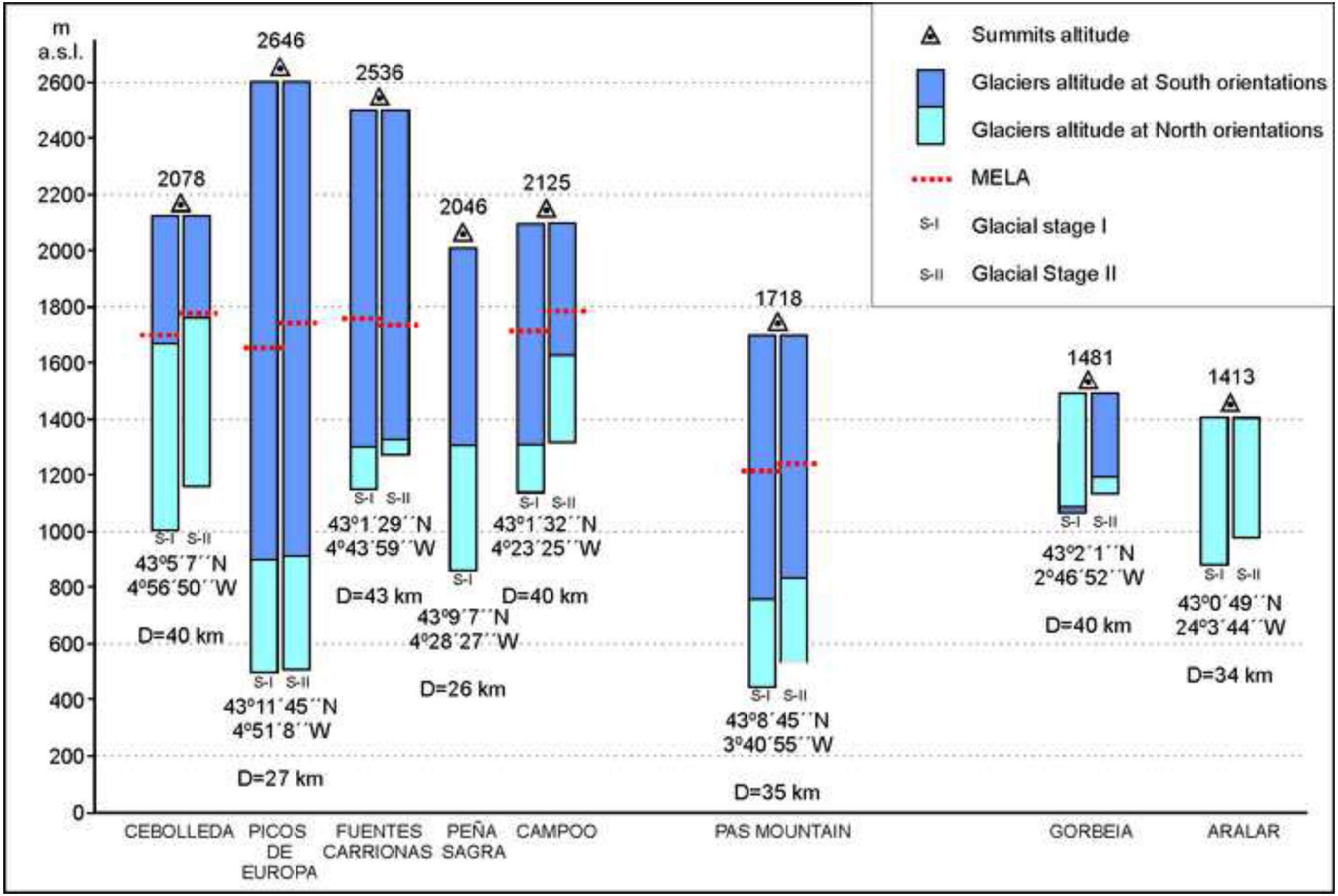


Figure2



m a.s.l.
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Summits altitude
Glaciers altitude at South orientations
Glaciers altitude at North orientations
MELA
S-I Glacial stage I
S-II Glacial Stage II
2078
43º5´7´´N
4º56´50´´W
D=40 km
2646
43º11´45´´N
4º51´8´´W
D=27 km
2536
43º1´29´´N
4º43´59´´W
D=43 km
2046
43º9´7´´N
4º28´27´´W
D=26 km
2125
43º1´32´´N
4º23´25´´W
D=40 km
1718
43º8´45´´N
3º40´55´´W
D=35 km
1481
43º2´1´´N
2º46´52´´W
D=40 km
1413
43º0´49´´N
24º3´44´´W
D=34 km
S-I S-II
CEBOLLEDA
PICOS DE EUROPA
FUENTES CARRIONAS
PEÑA SAGRA
CAMPOO
PAS MOUNTAIN
GORBEIA
ARALAR

Figure3
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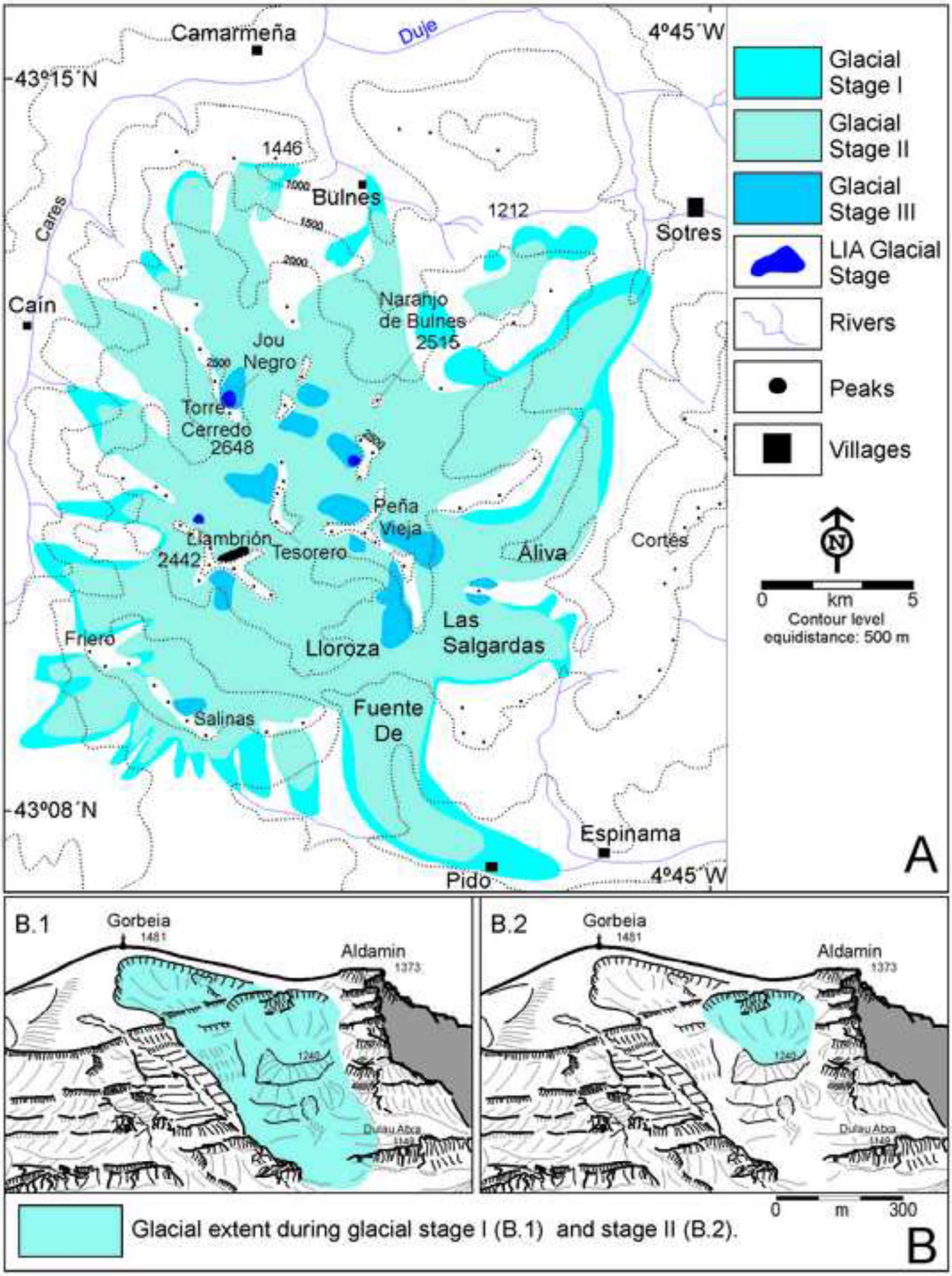

Figure4

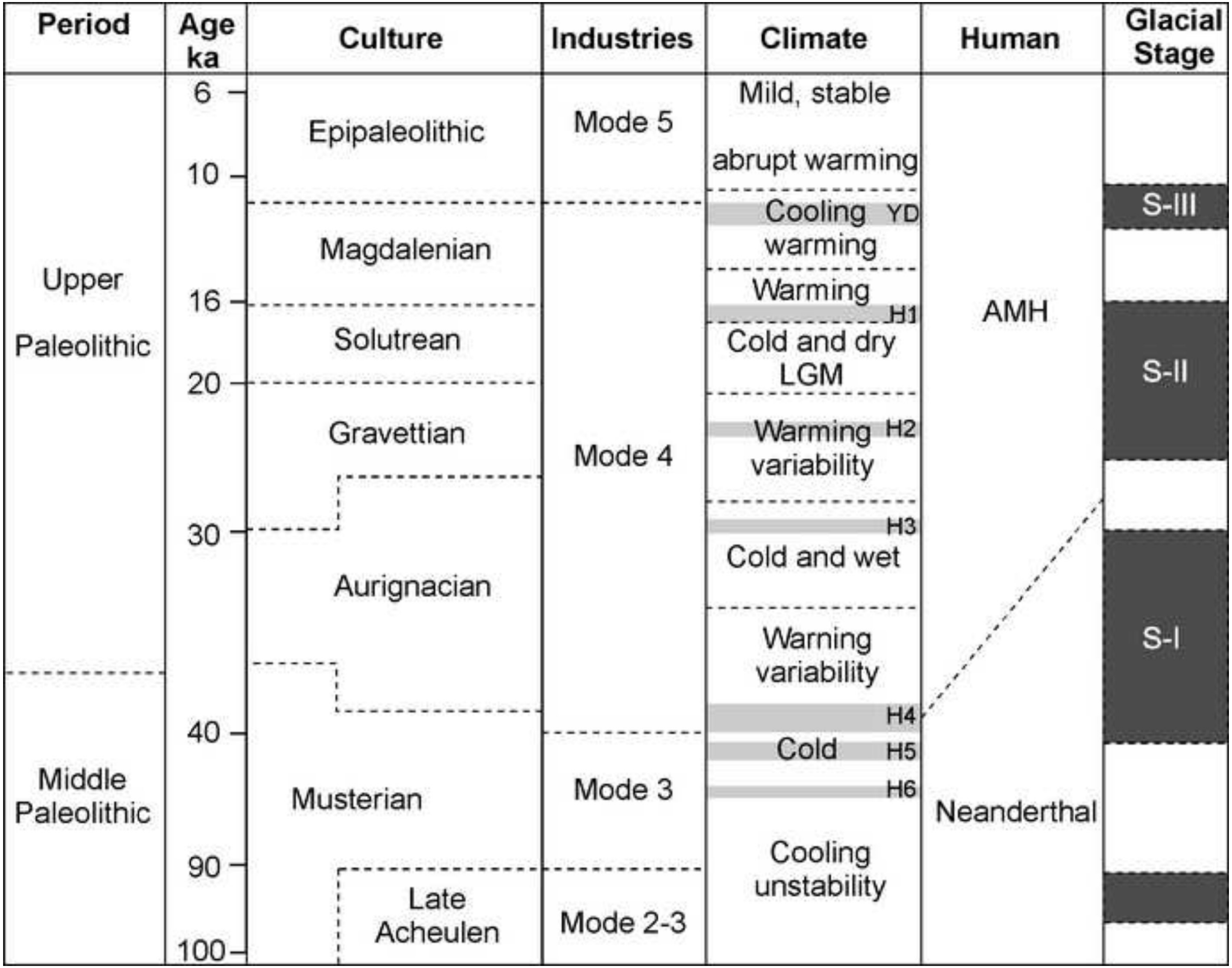
Period
Age ka
Culture
Industries
Climate
Human
Glacial Stage
Upper Paleolithic
Middle Paleolithic
6
10
16
20
30
40
90
100
Epipaleolithic
Magdalenian
Solutrean
Gravettian
Aurignacian
Musterian
Late Acheulen
Mode 5
Mode 4
Mode 3
Mode 2-3
Mild, stable
abrupt warming
Cooling
YD
warming
Warming
H1
Cold and dry
LGM
Warming
H2
variability
H3
Cold and wet
Warning
variability
H4
Cold
H5
H6
Cooling
unstability
AMH
Neanderthal
S-III
S-II
S-I

Figure5
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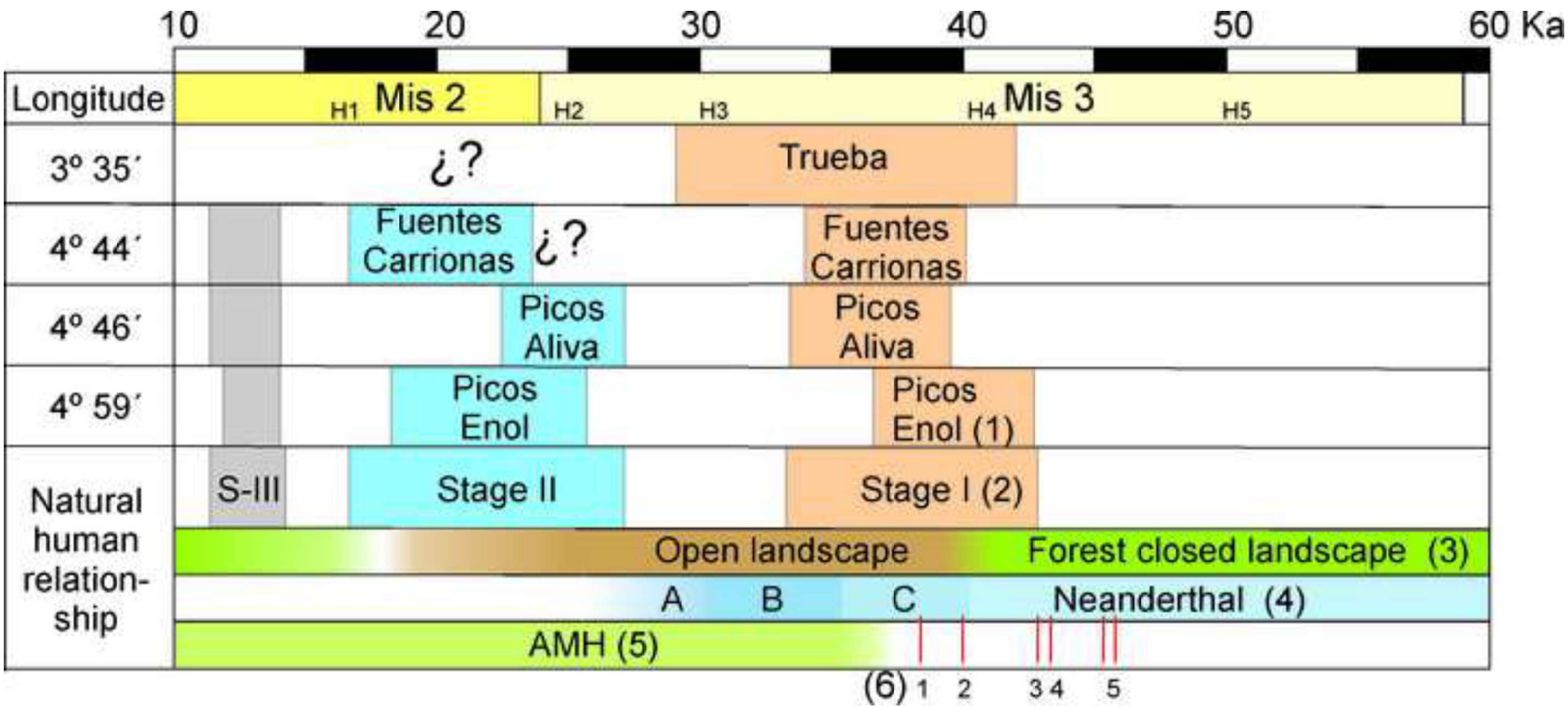

Table1

Table 1. Dating for the glacial related deposits in the Cantabrian Mountains.

Place	Site	Tecnique	Sediment	Depth (m)	Age a BP	Ages cal a BP	Reference
Picos de Europa	Aliva	U/Th	Debris slope	--	396470±24083	--	Villa et al., 2013
	Duje	U7Th	Debris slope	--	192700 +3190/-2330	--	Castañón Frochoso, 1996
	Áliva	AMS	Lacustrine	1	6660+/-40	6720-6640	Serrano et al., 2012
	Áliva	AMS	Lacustrine	1,33	8310 +/- 50	9400-9300	
	Áliva	AMS	Lacustrine	3	17300+/-100	17400-17300	
	Áliva	AMS	Lacustrine	5,50	21390+/-100	21500-21390	
	Áliva	AMS	Lacustrine	7,80	27570+/-320	32580-31900	
	Áliva	AMS	Lacustrine	10,55	26090+/-240	30660-31400	
	Áliva	AMS	Lacustrine	14,10	27460+/-300	31850-32426	
	Áliva	AMS	Lacustrine	15,50	31200+/-440	35700-34850	
	Comeya	AMS	lacustrine	35.5	40,480±820	44118±885	Jimenez and Farias, 2002
	Enol	AMS	Lacustrine	6 m	---	9109±74	Jiménez et al., 2013
		AMS	Lacustrine	10	---	14734±326	
		OSL	cemented sand and silt	42.7	44,966±3337	--	
Pas Mountain	Trueba valley	AMS	Peat	1	26082+/-118	29149-28572	Serrano et al., 2013
		AMS	Peat	0,50	8768+/-42	7968-7633	
		AMS	Peat	1,40	8186+/-35	7310-7077	
		AMS	Peat	1,60	10467+/-42	10623-10420	
	Soba valley	OSL	Till	--	44,98±2,3	--	Frochoso et al., 2012.
		OSL)	Till	--	41,56±2,4	--	
		OSL	Till	--	44,53±2,45	--	
	Altos Asón	OSL	till	--	40,43±5,14	--	
	Zucia	OSL	till	--	13,42±1,25	--	
Fuentes Carrionas	Vega de Naranco	OSL	Proglacial/Supraglacial	0,50	36028±2350	----	Pellitero, 2011
		AMS	Lacustrine	5,50	15614±21	16950-16695	
		AMS	Lacustrine (sands)	3	25591±23	28673-28300	
		AMS	Lacustrine	0,33	6831±50	5750-5660	
		AMS	Lacustrine	19	14275±49	15570-15240	
Sanabria	Pías	OSL	Lacustrine		27000±200	---	Pérez-Alberti et al., 2011
		OSL	Lacustrine		3100±300	---	
		OSL	Lacustrine		33000±300	---	
	Sanabria lake	AMS	basal clastic unit			25584±374	Rodríguez et al., 2011
			Top of clastic unit			14494±347	
			Clastic unit			13100	
			Coastic unit			12300	
	San Martin	AMS	Lacustrine			21833±358	
Redes Natural Park	Monasterio	C14	lacustrine clastic	35.6–35.5	28990±230	33485±362	Jiménez et al., 2013
	Tarna Valley	OSL	Till		23967±1841	---	
		OSL	till		23967±1841	---	
		OSL	Landslide		22983 ±2321	---	
		OSL	Lacustrine	42	44966 ± 3337	---	
		AMS	peat bog		20,640±300	24579±421	
Ancares		Radiocarbon dates	peat bog		17400		Muñoz-Sobrino et al., 2001
Sil Valley	Villaseca	AMS	glaciolacustrine		---	41150	Jalut et al., 2010

Table2

Table 2. Glaciated massifs in the eastern Cantabrian Mountains.

Massif		Altitude m a.s.l.	Glaciers Nº	Ice surface		Orientations %	
				Km^2	%	N	S
Picos de Europa	Urrielles	2648	24	68.55	20	55	45
	Andara	2444	15	30.5	9	57	43
Cebolleda		2078	11	16.75	5	77	23
Fuentes Carrionas		2536	20	105	30.7	45	55
Peña Sagra		2046	15	11.4	3	87	13
Campoo		2125	10	20	6	15	85
Valdecebollas		2143	4	5.8	2	25	75
Pas		1718	8	76.5	22.5	67	33
Gorbeia		1481	3	1.15	0.3	100	--
Aralar		1413	2	5.35	1.5	100	--
Total		---	112	341	100	67	33

Table3

Table 3. Glacial stages and correlation between massifs in the eastern Cantabrian Mountains.

Massifs	Pleistocene glacial stages		
	S-I	**S-II**	**S-III**
Picos de Europa, Urrielles	I	II	III
Picos de Europa, Ándara	I	II	IIIa IIIb
Cebolleda	I	II	IIIa IIIb
Fuentes Carrionas	I Ib	II	III
Campoo	I	II	III
Valdecebollas	I	II	IIIa IIIb
Pas Mountains	Ia	IIa-IIb	III IV
Gorbeia	I	II	--
Aralar	I	II	--
AGE	MIS3	MIS2	MIS2

Table4

Table 4. Neanderthal remains located in the North of Spain (Garralda, 2005).

Site	Province	Dating	Material	Culture	MIS	Reference
Lezetxiki	Gipuzcoa	--	Bones Teeth	Pre Mousterian	MIS4 MIS3	Baldeón, 1993
Arrillor Cave	Álava	45,700+1200 a BP	Teeth	Mousterian	MIS3	Bermúdez de Castro and Saenz de Buruaga, 1999
		45,400+1800 a BP	Teeth	Mousterian	MIS3	
Axlor Shelter	Biscaye	42,010+1280 a BP	Bones Teeth	Mousterian	MIS3	Basabé, 1973 González et al., 2005
El Castillo Cave	Cantabria	--	Bones Teeth	Mousterian	MIS3	Cabrera et al., 2001 Maillo et al., 2004
		40 ka 38,5 ka	Bones Teeth	Transitional Aurignacien[1]	MIS3	
Sidrón Cave	Asturias	43,129+129 cal a BP	Bones Teeth	Mousterian	MIS3	Lalueza et al., 2005

1, Level 18 El Castillo cave, in Cabrera et al. 2001.