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Glacial morphology and evolution in the Arritzaga valley (Aralar range, Gipuzkoa)

Morfología y evolución glaciar en el valle de Arritzaga (Sierra de Aralar, Gipuzkoa)

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Abstract

Interpretation of glacial processes during the late Quaternary in the Basque Mountains has been a polemic issue over the last decades. Discussions have been mainly (but not exclusively) focused on the Aralar range (1421m) providing contrasted interpretations. This work presents the results of the analysis of the landforms and deposits of the valley confirming the existence of glacial processes in the Arritzaga valley during the last glaciation generating a glacial body with a front at 800 m, a longitude of 5 Km and 70-100 m of thickness. Glacial processes at such moderate altitudes were linked to particular conditions: snow overfeeding and leeward effect in a cold and very humid climatic context, and an appropriate relief for snow retention.

Keywords: Glacial Geomorphology, Last Glacial Maximum, Basque Mountains, Aralar range.

Resumen

La cuestión del glaciarismo en los Montes Vascos ha sido objeto de diferentes interpretaciones durante las últimas décadas. Las discusiones han estado fundamentadas en la moderada altitud y la ausencia de huellas claras de origen glaciar, centrando la polémica principalmente (aunque no exclusivamente) en la sierra de Aralar (1421 m). El análisis de las formas y depósitos del valle de Arritzaga confirma la existencia de procesos glaciares durante la última glaciación generando un cuerpo glaciar con un frente a 800 m, una longitud de 5 Km y un espesor de entre 70-100 m. Los procesos glaciares a tan moderada altitud estuvieron ligados a unas condiciones particulares que lo favorecieron: Sobrealimentación nival y efecto ventisca en un contexto climático frío y muy húmedo junto con un relieve apto para la retención nival fueron factores clave.

Palabras clave: Geomorfología Glaciar, Último Máximo Glaciar, Montes Vascos, Sierra de Aralar.

1. Introduction

The growing body of research and studies with regard to the Quaternary glaciation across the Atlantic region[1] of the Iberian Peninsula has enabled to reach a rather precise knowledge of its characteristics, magnitude and chronology. In general terms, is accepted that the glaciation was affected by the oceanic influence allowing the development of glacial processes below lower mountain ranges and descending up to lower altitudes than the inland glaciers. These processes were developed largely below summits between 2600 and 2000 m, occasionally below 2000 and 1600 m and exceptionally below summits of 1600 m (Frochoso and Castañón, 1998; Gómez Ortíz et al, 2001).

From the Saioa massif in the Pyreneean margin up to the Castro Valnera-Asón massif in Cantabria, the Basque Mountains extent from E to W making up a mountainous region of moderate altitudes not higher than 1600 m. In spite of the relatively high amount of studies aiming to understand the effects of glacial processes within this region, the interpretation of its magnitude, intensity and chronology remains still unsolved. Most of discussions revolve around the Aralar range, particularly the Arritzaga Valley whilst in the rest of massifs, both lack of research and geomorphological evidence leave the question open to new interpretations.

The modest altitude of the Aralar Massif (Irumugarrieta 1421m) together with the shortage of landforms and deposits related with the glacial phenomena in the Arritzaga valley has complicated its geomorphologic interpretation.

Even though the majority of the authors support the interpretation of late Pleistocene glacial processes in the Arritzaga valley (Gomez de Llarena, 1948; Koop, 1965; Duvernois et al, 1972; Ugarte, 1985, 1992; Galvadón et al, 1986), backed up by the landforms and deposits found in the valley and more definitely by the sediment analysis evidence (Bordonau et al, 1992b), some other researchers have raised serious doubts and demanded further research in order to confirm their presence (Martínez de Pisón et al, 1984, 1992).

Moreover, the limited presence of periglacial features and deposits in the Atlantic side of the Basque Mountains has brought more doubts about the mentioned glacial processes. According to some authors (Gonzalez Martin, 1986) the climatic conditions required for the occurrence of glacial processes should be theoretically translated into the territory through more extended and stronger periglacial phenomena that haven't been reported so far.

2. Objectives and methodology

This work has aimed to move forward in the knowledge of the morphogenetic evolution of the Basque Mountains region. In short the objectives have been to comprehend the geo-

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[1] Terms such as "Atlantic", "Atlantic region" and "Atlantic glaciation" will be used to point out the region located between the Galician ranges and the foremost limit of the western Pyrenees (Saioa Range).

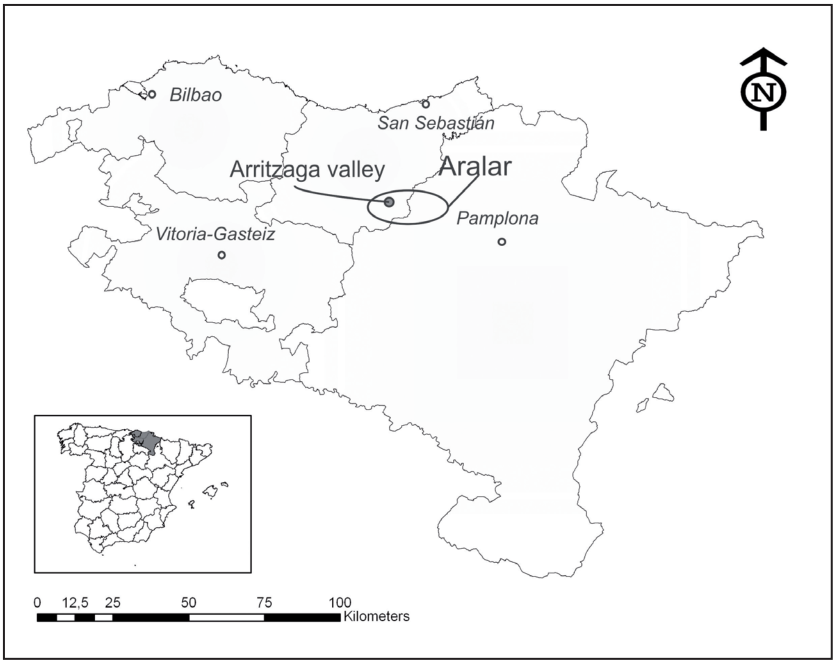

Figure 1. Location of the Aralar mountain range and the Arritzaga valley within the Basque Autonomous Community and Navarra (CNIG BCN200).

Figura 1.Situación de la sierra de Aralar y el Valle de Arritzaga dentro de la comunidad Autónoma del País Vasco y Navarra (CNIG BCN200).

morphologic evolution of the Arritzaga valley during the Late Quaternary, assessing the existence of glacial processes and their intensity, magnitude and characteristics. This study has also aimed to present a chronology of the glacial and postglacial phases based on the morpho-stratigraphy and its comparison with the chronology of other southeuropean mountain massifs affected by the quaternary glaciations.

The methodology has been based on; bibliographic analysis, field-work (identification of deposits and landforms), laboratory work (sediment analysis), morpho-stratigraphy, aerial photography interpretation and geomorphological mapping.

3. Geographical setting

The Aralar mountain range lies in the eastern end of the Basque Mountains. These mountains comprise a range of 150 Km long and 50 Km wide with four main massifs of moderate altitudes (Aizkorri 1544 m, Gorbea 1475 m, Aralar 1421 m, Anboto 1311 m). The alpine orogeny was responsible of the lifting and bending of the mesozoic and cretacic limestone materials that characterise the mentioned range. During the Quaternary, fluvial and karstic processes have modelled its relief and the current landscape.

The geology of the Aralar range is characterised by a thick limestone layer in form of anticline towards the North, while the South side jumps over the North side through a ENE-WSW inverse fault. It forms a 12 Km wide and 25 long massif with a average altitude of 800-1000 m in the East and 1000-1300 m in the North West with a maximum altitude of 1421m on the Iru-

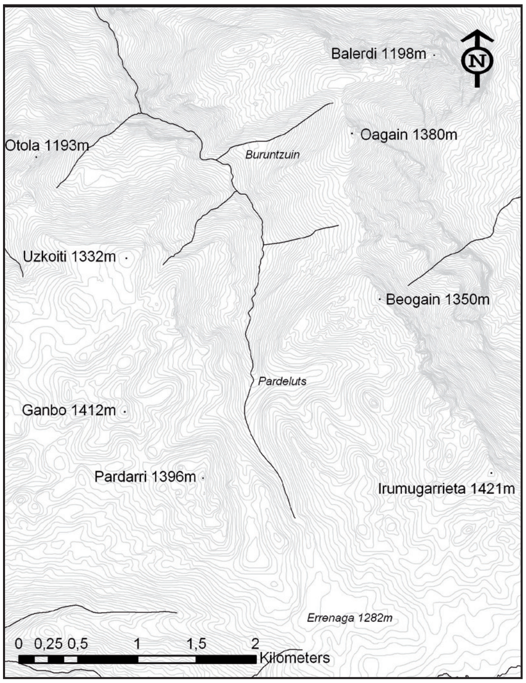

Figure 2. Main summits and topography of Arritzaga valley (CNIG BTN25).
Figura 2. Topografía y principales cumbres del valle de Arritzaga (CNIG BTN25).

mugarrieta peak. Main fault system runs in NE-SO direction but there is also an alternative fault system in NO-SE direction forming the Arritzaga and Muitze Valleys in the NO of the massif (Galvadón et al, 1986).

Arritzaga valley lies in the NW of the range, with its watershed in Errenaga at 1282 m and coming down to 200 m in the village of Amezketa. Highest peak in the area is Irumugarrieta (1421 m) but is mainly surrounded by other peaks between 1300 and 1400 m high such as the Ganbo (1412 m). The relief is directed by high structural control through a NO-SE fault and by the thrust fault of Jurasic materials coming over the newer Cretacic layers.

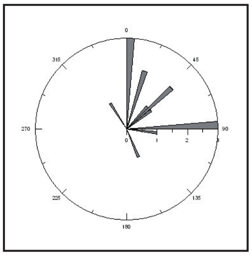

Figure 3. Orientation of cirques (15).
Figura 3. Orientación de circos (15).

Due to its closeness to the Cantabric Sea (31 Km), the altitude, massivity, latitude and the current Western General circulation patterns, the climate in the Arritzaga valley is characterised by temperate and very humid conditions reflected in high annual precipitations (1740 mm at 1000 m, Ugarte 1985). The annual average temperature is 11ºC, being 17ºC de average of maximum temperatures and 7ºC the average of minimum temperatures (IKT, 1999). Absolute minimum and maximum temperatures are -12 ºC in winter and 35ºC in the summer respectively (Uriarte, 1996). Eventually, vegetation above 800 m in the valley is nowadays affected by extensive grazing; the potential European Beech (*Fagus sylvatica*) forest is scarce and the landscape is dominated by pastures and remains of rock vegetation (Iparragirre, 1991).

4. Glacial landforms and deposits in the Arritzaga valley

Landforms and deposits in Arritzaga valley have been studied since the mid 20th century. First mention to glacial processes comes from Gómez de Llarena (1948) followed later by Koop (1965) who produces a detailed study defending glacial processes in the valley and Duvernois et al (1972) who also supported the same idea. A decade later, in a new study (Martinez de Pisón et al, 1984) glacial processes are questioned due to their moderate altitude, and are related to periglacial processes. Following studies (Ugarte, 1985; Galvadón et al, 1986) again raise the theory of glacial processes in the Arritzaga valley. In 1986 another study (González Martín, 1986) questions the supposed glacial remains in Aralar. However, later works based on landform and sediment analysis (Ugarte, 1992; Bordonau et al, 1992b) classify the Buruntzuin deposit as a subglacial till. Nevertheless, in the same year another work (Martinez de Pisón et al, 1992) states that supposed glacial evidences in Aralar are not clear and numerous enough and relates them to periglacial or snow-karstic dynamics. Eventually, in another study (González Amuchástegui, 2000) glacial processes in Aralar are again supported. In short, even though the majority of the studies support the "pro-glacial" view based on morphological and sediment evidence some other researchers have raised doubts and demanded further research in order to confirm their presence.

It should be highlighted that in a limestone relief such as in the Arritzaga valley, description, analysis and interpretation of landforms and deposits becomes problematic due to the karstic erosion that has taken place during the Holocene. Below, landforms and deposits studied in the Arritzaga valley are described and analysed. Results of the sediment analysis are also shown.

4.1 *Glacial plucking and abrasion landforms*

4.1.1 Cirques

These forms appear below the summits ridges and show different morphologies depending on their orientation, lithology, and structural characteristics. Most of them show an eroded and attenuated morphology by the post-glacial processes.

From the 15 cirques identified in the valley, 13 are in the western summits alineation whilst only two remain in the eastern side (See Fig. 3

Figure 4. Glacier cirque in Zotaleta.
Figura 4. Circo glaciar en Zotaleta.

Table 1. Characteristics of the analysed deposits.
Tabla 1. Características de los depósitos analizados.

Nº of deposit	**Laboratory Analysis**	**Visible thickness**	**Situation**	**Morphogenetic Interpretation**	**Geomorphological Context**
A1	-	30m	962 m. North slope of Uzkuiti	Multiple processes related deposit. - *Maximum Advance*	Frontal moraine afterwards re-activated by periglacial processes
A2	√	1m	1020 m. W slope of Egurtegi. 60m over the talweg.	Subglacial Till *Equilibrium Phase*	Boulder. Lateral retreat moraine
A3	-	2m	890 m. Attached to "Roche moutonée" S of Buruntzuin. 10m over talweg.	Sorted slope deposit *Periglacial Phase*	Regularized slope
A4	√	15m	970 m. W slope of Zotaleta 10m over talweg.	Subglacial Till *Maximum Advance*	Ground moraine.
A5	-	3m	1100 m. 200m E of Pardeluts.	Subglacial Till *Maximum Advance*	Lateral moraine.
A6	-	1m	970 m. Below Zotaleta cirque.20m over talweg.	Subglacial Till *Maximum Advance*	Ground moraine.
A7	√	15m	900 m. Over Buruntzuin mine	Subglacial Till *Maximum Advance*	Ground moraine.
A10	√	5m	1020 m. By Pardeluts spring right over talweg.	Subglacial Till *Equilibrium Phase*	Lateral moraine
A11	√	15m	900-950 m. By Buruntzuin "Roche moutonée".	Subglacial Till *Maximum Advance*	Ground moraine.

and Fig. 12). Eighty percent of the cirques have an N or NE orientation; this could be explained in relation with two factors: their orientation leeward to the snow storms coming from the W (Spindrift effect) and their favourable orientation for snow accumulation and retention.

All the cirques are located below summits between 1300 and 1421 m of altitude, being 1300 m then the limit of summits altitude below which cirques were not developed. Altitudes of cirque bottoms are mostly (80%) between 1170 and 1200 m.

4.1.2 Roches moutonées and rock basins

These two forms are found in several places across the valley (see Fig. 12). Despite of the post-glacial erosion is possible to identify

Table 2. Sedimentary characteristics of the analysed samples.
Tabla 2. Características sedimentarias de los depósitos analizados.

COBBLES				SANDS						
Sample	*Median (cm.)*	*Centile.Long of largest boulder (cm.)*	*Roundness median*	*>2.00 mm. (%)*	*Munsell Colour*	*2.000-500µ*	*500-200 µ (%)*	*200-50 µ (%)*	*<50 µ (%)*	*Organic Matter*
A2	5.5	270	71.45	64	2.5Y 3V/2C	28.24	11.79	11.45	48.6	**
A4	7	140	81.63	8.5	2.5Y V4/ C2	26.96	19.2	19.76	33.9	***
A7	4.5	170	80.88	10	2.5Y V4/ C1	33.33	18.58	15.84	32.2	***
A10	4.5	210	72.72	49	2.5Y V4/ C1	21.63	7	12.76	58.61	***
A11	4.5	165	73.40	25	2.5Y V6/ C2	20.06	12.76	13.39	53.79	***

such forms across the Arritzaga valley. Roches moutonées and rock basins are found in Buruntzuin, Zotaleta, Uzkuiti, Pardeluts, Ganbo, Pardarri and Errenaga. In the Errenaga area, a great rock basin was formed due to the permanent presence of ice.

4.1.3 Valley shape

The valley shape along the Arritzaga shows different profiles (Fig. 7); whilst the higher section its clearly an "U" shaped valley, below the fountain of Pardeluts (1020 m) the profile becomes sharper and closer to a "V" shape. In the lower part, the river cuts deeply into the bedrock showing an almost gorge profile. Several factors have driven the formation of such valley shape: On the one hand, lithology in the upper part of the valley has probably shown a higher resistance (Massive limestone with silex) to fluvial post-glacial erosion. On the other hand, the existence of a stream from Pardeluts may have implied higher erosion in the mid section of the valley (Loams). Moreover, a temperate glacier such as the one developed in Arritzaga likely maintained a relatively high sub-glacial melting in the lower parts of the glacier, helping the maintenance of a "V" valley shape in the section from Pardeluts (1020 m) to Buruntzuin (850 m). Finally, post-glacial slope regularization on the western slopes of Beogain and Oagain might have contributed to the disappearance of glacial valley shape.

4.1.4 Other minor landforms

Despite the post-glacial erosion over the limestone materials and the appearance of newer karstic landforms, some other minor glacial landforms are also found in the Arritzaga valley. At the Buruntzuin glacial threshold, where glacial melting must have reached its maximum, a sub-glacial stream morphology appears at the limestone bedrock in a deep cut. Also in the same threshold, polished surfaces are observed on the limestone bedrock despite the fluvial erosion has rubbed and unshaped this morphology.

4.2 *Glacial deposition landforms and deposits*

Analysis and interpretation of deposition landforms and deposits in the Arritzaga valley has also involved some handicaps due to the post-glacial erosion effects on the deposits and the difficulty of finding cut sections in the identified deposits because of soil and vegetation colonization. Description, geomorphological interpretation, results and morpho-stratigraphy of the identified deposits are synthesised in tables 1 and 2 and cumulative curves shown in figure 9.

Results from sediment analysis (both in situ and laboratory work) and field observations allowed to classify A2, A4, A5, A6, A7, A10 and A11 from glacial origin. In general terms, all this samples show the usual glacial till characteristics defined by Bennet and Glasser (1996): non-sorted or very poorly sorted unconsolidated sediment containing a very wide range of particle sizes, consisting on large pebbles, cobbles or boulders set within a fine-grained matrix of silt and clay (Table 2., Fig. 9.).

Deposit A11 is confirmed to be a subglacial till as pointed out by Bordonau et al (1992b) and together with A7, A4 and A6 are ascribed to a maximum advance stage due to their situation in the valley, morphology and context with the rest of deposits. However, A10 is classified as deposit formed by subglacial till materials in lateral moraine morphology. From its morphology it could be classified as fluted moraine of the sub-glacial materials; however the absence of a large boulder or a collection of large boulders necessary to create the *fluted moraine* (Bennett and Glasser, 1996) dismisses such possibility. The orientation of the alienation suggests that it could be a lateral moraine of a later equilibrium phase. A2 deposit is formed by a large boulder comprising a subgalcial till characteristics materials. Major axis orientation of the boulder points 315º whilst slope orientation points 255º, suggesting an influence of the ice flow. Its position and characteristics allow linking it to a secondary equilibrium boulder deposit. Eventually A5 deposit is interpreted as a lateral moraine of the main valley glacier at its maximum extent stage.

In Eitzegi area, a large semicircular deposit is observed. Interpretation is difficult due to the extensive vegetation cover, but its position, shape and volume suggest that it could be a frontal moraine originated by a small cirque glacier. However, the excellent conservation

Figure 5. Roches moutonées below Ganbo.
Figura 5. Umbrales glaciares bajo el pico Ganbo.

Figure 6. Glacial rock basin in Errenaga.
Figura 6. Cubeta glaciar en la zona de Errenaga.

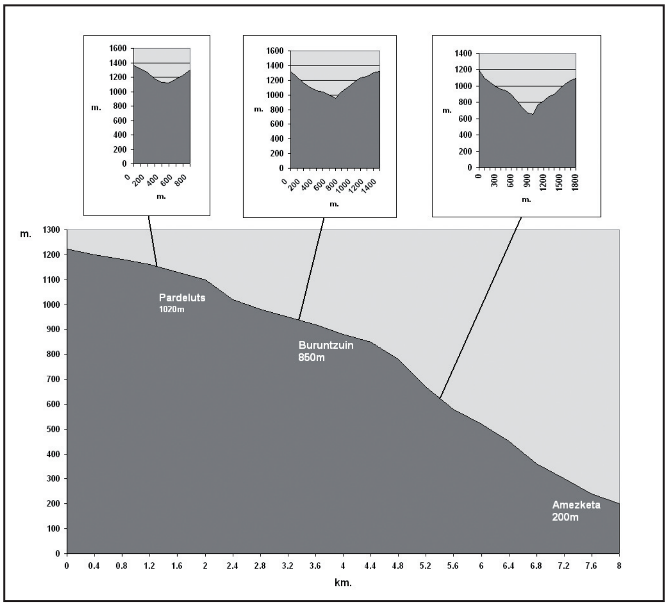

Figure 7. Longitudinal profile and cross-cuts of the Arritzaga valley (Rico Lozano, 2008)
Figura 7. Perfil longitudinal y cortes transversales del valle de Arritzaga (Rico Lozano, 2008).

of this landform and its elongated shape also suggests a posterior re-activation through periglacial processes such as *protalus rampart* dynamic, gelifraction, gelifluxion and frost creep.

On the other hand, A3 deposit materials classification and sorting on a 25º slope and over the A7 deposit enables to be classified as a *sorted slope deposit* during

Figure 8. "U" valley shape in the higher part of the valley.
Figura 8. Artesa glaciar en forma de "U" en la parte superior del valle.

a last cold period characterised by periglacial activity.

Taking into account the results of the analysed samples and their morpho-stratigraphy, is possible to distinguish three kinds of deposits outlining a primary glacial evolution sequence for the Arritzaga valley:

1. External deposits; A11, A7, A6, A5, A4. Maximum advance phase
2. Inner deposits; A10, A2. Equilibrium phase
3. Periglacial deposits; A1, A3. Periglacial phase

5. Interpretation: Glacial evolution and oceanic influence

5.1. *Interpretation*

The analysis of the landforms and deposits in the Arritzaga valley and the examination of the previous studies have enabled a more precise interpretation of the effects of the ice in this massif.

Sediment analysis and laboratory work have confirmed the existence of glacial deposition landforms and deposits (A2, A4, A5, A6, A7, A10) and corroborated the previous analysis (Bordonau et al, 1992b) in the Arritzaga valley. On the other hand glacial abrasion and plucking landforms have been identified across the valley such as cirques, valley shape, *roches moutonées* and rock basins and some smaller landforms such as sub-glacial streams and polished surfaces. These landforms show a preferential glacial development on the N and NE slopes of the western ridge (Pardarri-Ganbo-Uzkuiti) clearly opposed to the eastern ridge (Oagain-Beogain-Aldaon) with almost no glacial landforms and deposits. Taking into account the altitude of cirque bottoms (80%, 1020-1200 m) and the situation of the lateral moraines over the valley (A11 100 m, A5 80 m) it's estimated that the thickness of the glacial body would be between 70 and 100m depending on several factors such as the bed-rock relief and the ice deformation at the rock basins.

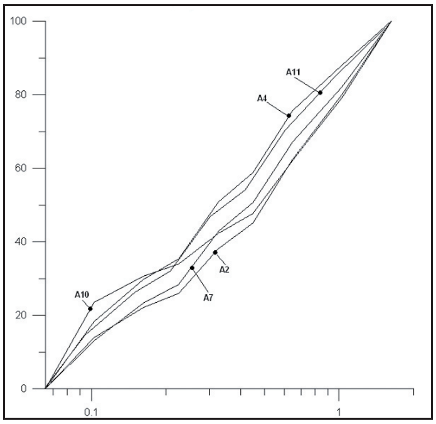

Figure 9. Cumulative percent plotted against grain size for the A2, A4, A7, A10 and A11 samples.
Figura 9. Curva acumulativa granulométrica para las muestras A2, A4, A7, A10 y A11.

In consequence, and based on the geomophological evidences it's possible to interpret the existence of a glacial body of 70-100 m thick and 5 Km long from the watersheds at Errenaga (1271m) to the front at Buruntzuin (800 m) during the late Pleistocene. Main ice feeding was made by the accumulation rock basin of Errenaga and the cirques of Pardarri (1396 m), Ganbo (1412 m) and Uzkoiti (1332 m).

In the area of Urgute, the possibility of glacial development is dismissed due to the lack of favourable conditions for the snow accumulation and retention (orientation and exposition) and also due to the absence of related deposits (A5 deposit is interpreted as a lateral moraine from the main glacier). Morphology of this area is more related with karstic and snow-karstic dynamic due to the presence of snow and the snow-patch formation below the summits of Aldaon and Urgute.

In the area of Eitzegi (Deposit A1) is possible to infer a reduced glacial activity physically independent to that developed in the main valley and linked to very favourable conditions of orientation and lithology. This produced a small cirque glacier below the N slopes of Uzkuiti and that it was in a later period re-activated by periglacial processes. However, how can be such glacial processes at moderate altitudes (around 1400 m) explained in the context of the quaternary glaciations in the Iberian Peninsula? Is therefore necessary to consider the climatic, topographic and structural factors.

The oceanic influence was one of the key factors; the high exposition to the oceanic humid winds provided significant snow overfeeding besides an elevated cloudiness that would reduce insolation. Nevertheless, oceanic influence itself wasn't the triggering factor of the glacial processes in Aralar. The pre-existent relief and the local topography where also crucial. On the one hand, with a surface of 35 km² over 1100m, Aralar stands out with the rest of the Basque massifs for having the best conditions for snow accumulation (Ugarte 1992). On the other hand the N-S orientation of the Pardarri-Uzkuiti ridge, together with the SO-NE fault lines and a relatively smooth relief provided the optimal conditions for the development of cirques with N-NE orientation. These cirques where developed leeward of the main humid wind direction from the W (Florineth et al, 2000), producing important snow accumulations due to the spindrift effect and the reduced insolation. In short all this factors would enable the snow accumulation, retention and further transformation and flow as glacial ice,

However, is not possible to generalize such processes to the rest of the massif neither to the rest of the Basque Mountains. Even within the Aralar range there are areas with peaks with similar altitudes to those in Arritzaga valley such as Muitze (1300 m), Araitz (1200-1350 m) or Urgute-Aldaon (1411 m) without glacial traces. The lack of aproppiate conditions (orientation, relief, structure)

Figure 10. 1. General view of Buruntzuin deposit (A11, A7); 2. Detail of cut section in A11; 3. View of the moraine morphology from the top of the same deposit; 4. and 5. A10 deposit; 6. General view of pardeluts area; 7. A5 deposit; 8. A3 deposit; 9. A4 deposit.

Figura 10. 1. Vista general del depósito de Buruntzuin (A11, A7); 2. Detalle de corte en A11; 3. Vista de la morfología de morrena desde la parte superior del mismo depósito; 4. y 5. Depósito A10; 6. Vista general de la zona de Pardeluts; 7. Depósito A5; 8. Depósito A3; 9. Depósito A4.

could explain the absence of such traces. At a wider level, the research undertaken by Ugarte (1992) pointed out that the rest of the Basque massifs did not present such good characteristics for glacial development. Given the lack of research in the rest of Basque massifs, glaciation in Aralar must be so far classified as exceptional within the Basque Mountain context. The limited action of periglacial processes in the Atlantic side of the Basque Mountains also reflects moderate cold conditions for the period when glacial processes took place. Other authors (González Amuchástegui, 2000) have also pointed out the attenuating effect of the snow overfeeding in the periglacial phenomena.

All this aspects highlight the unusual character of the glacial processes in Aralar, undoubtedly intertwined with particular climatic, but overall structural and topographic conditions. Nevertheless, in the context of the Peninsular Atlantic region and the westernmost limit of the Pyrenees this glaciation does have similar cases of glacial development at very low altitudes such as in the massifs of: Jures (1556 m) (Pérez Alberti and Covelo Abeleira, 1996), Xistral (1062 m) (Vidal Romaní, 1989; Pérez Alberti and Valcárcel Díaz, 1998; Pérez Alberti et al, 2004), Queixa-Invernadoiro (1778 m) (Vidal Romaní et al, 1990a, 1990b; Brum Ferreira et al., 1992; Vidal Romani and Santos Fidalgo,

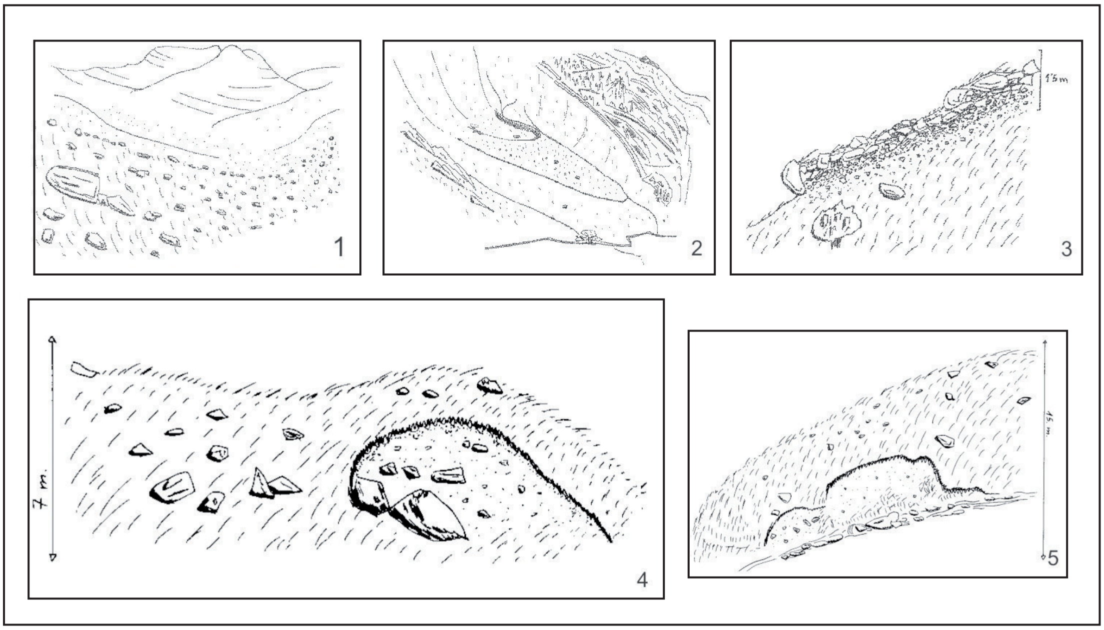

Figure 11. Sketches of deposits: 1. A5 Deposit; 2. A1 Deposit; 3. A3 Deposit; , 4. A11 Deposit and 5. A4 Deposit (Rico Lozano, 2008).

Figura 11. Dibujos de los depósitos: 1. Depósito A5; 2. Depósito A1; Depósito A3; 4. Depósito A11 y 5. Depósito A4 (Rico Lozano, 2008).

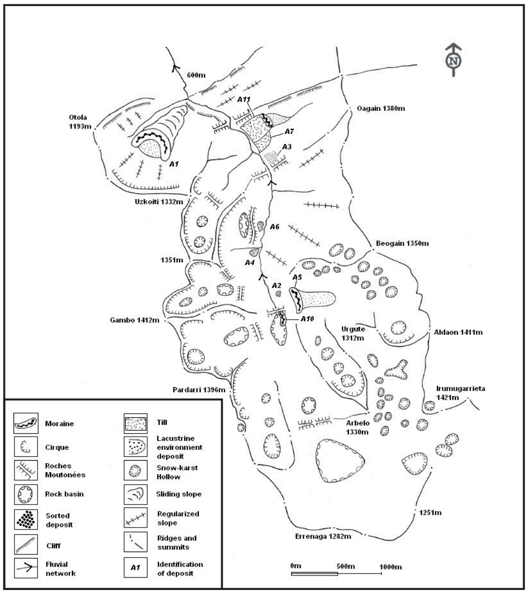

Figure 12. Geomorphological sketch and location of deposits of the Arritzaga valley. Extended from González Amuchástegui (2000).

Figura 12. Esquema geomorfológico y situación de los depósitos del valle de Arritzaga. Ampliado de González Amuchástegui (2000).

1993, 1994), Castro Valnera (1707 m) and Alto Asón (1637 m) mountains (Lotze, 1963; Moñino et al, 1988; Serrano, 1996; Frochoso and Castañón, 1998; Serrano y Gutiérrez, 2002), Saioa (1419 m) and Adi (1459 m) (Viers, 1992). In other higher massifs above 2000m, glacial processes have also been reported below some of their lower summits: 1650 m in San Isidro massif, 1670 m in Ten-Pozua massif, 1611 m in Picos de Europa massif, 1640 m in Peña Sagra massif and 1710 in Reinosa massif (Frochoso and Castañón, 1998).

5.2. *Glacial Evolution*

Through the interpretation of the landforms and deposits found across the Arritzaga valley and their morpho-stratigraphy is possible to distinguish four glacial phases for the Arritzaga valley (See three main phases in Figure 13). The glacial evolution stages have

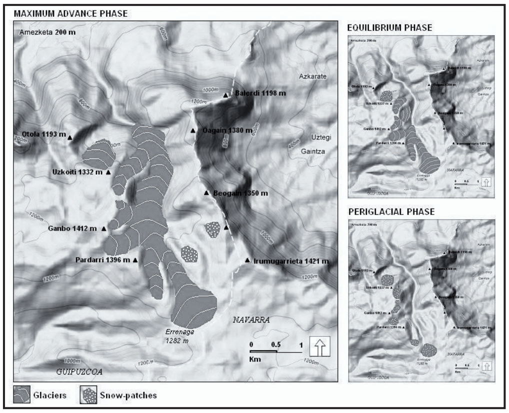

Figure 13. Main glacial phases in Arritzaga Valley. (Modified from Google.Earth).

Figura 13. Principales fases glaciares en el valle de Arritzaga (Modificado sobre Google.Earth).

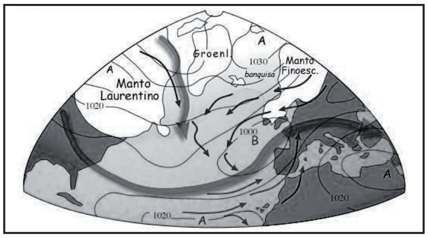

Figure 14. Atmospheric situation during the LGM; Jet stream current moved south bringing SO and S winds over the Iberian Peninsula. The current Icelandic low pressures were located by the Cantabric coast (Uriarte, 2003).

Figura 14. Situación atmosférica durante el Último Máximo Glaciar; La corriente Jet Stream se desplazaba hacia el sur, generando vientos del SO y S sobre la Península Ibérica. La actual borrasca de Islandia se situaba cerca de la costa cantábrica (Uriarte, 2003).

been extended to the Holocene period and up to the present in order to provide a more integrated view of the geomorphological evolution in the Arritzaga valley. Post-glacial morphogenetic stages have been inferred on the basis of regional and local works (Refereed below) based on the results from pollen and vegetation studies.

1. Maximum Advance Phase
2. Equilibrium Phase
3. Retreat and Deglaciation Phase
4. Periglacial Phase
5. Holocene-Postglacial Phase
6. Antropization and Sub-actual dynamics Phase

Maximum Advance Phase: Constitutes the maximum glacial advance in the Aralar range. The lateral moraines of Buruntzuin (950 m, A11) and Antziriko-Ordeka (1100 m, A5) and the ground moraines of Zotaleta area A7, A4, and A6 (970 m) together with the landforms related to the action of the ice made up the tracks of a 5km long and 70-100m thick glacier fed by the N and NE cirques of the western ridge of the valley and linked to the spindrift effect of the W winds. It's estimated that the glacier front reached the 800 m altitude at it maximum extension. During this phase the Eitzegi cirque housed a small cirque glacier independent of that of the main valley producing a small push moraine (A1) at 962 m. In short, despite of the moderate altitude, during this period climatic conditions of permanent cloudiness, low summer insolation and snow overfeeding together with the topographic and structural factors, enabled the maximum extension of the glacial processes in the Arritzaga valley (See Fig. 13).

Glacial Equilibrium Phase: Morphology and situation of *Pardeluts* lateral moraine deposits (A2, A10 1020 m) suggest that they belong to a retreat and equilibrium phase that had less morphogenetic power than the previous one (See Fig. 13) with a glacial front now at 1020 m. Decreased snow precipitations could have limited glacial processes reducing the dynamism and erosion capacity of the glacier. In Eitzegi, favourable lithology and orientation could maintain an ice body in transition between glacier and snow-patch supporting material mobilization and *protalus rampart* formation.

Retreat and deglaciation Phase: During this phase, complete deglaciation of the cirques would happen, with vegetation stabilization probably developing in the lower parts of the valley.

Lateglacial Phase: Excellent conservation of detritic accumulations in Eitzegi (A1) and slope regularization in Uakorri and Beogain (A3) reflect a vegetation stability break down on the slopes and a turn back to cold and arid conditions that translated into activation of periglacial phenomena where weaker lithology and orientation allowed it. In Eitzegi, the outstanding conservation of the deposit suggests that during this phase a *protalus rampart* or a *protalus lobe* was developed. Besides, is very likely that in the N-NE cirques from Pardarri to Uzkoiti, snow-patches were developed. In the most favourable slopes gelifraction enabled some slope regularization with *sorted slope deposits* (Deposit A3). Afterwards, external agents started to erode landforms and glacial deposits.

Holocene-Postglacial: Transition into a mild and humid climate with similar characteristics with the current climate in the NW of the Iberian Peninsula and the Cantabric-Basque mountains was reflected into a general expansion of forests and arboreal vegetation. (Peñalba, 1989, 1984; Ramil-Rego et al 2001). In Aralar this must have supposed an extensive vegetation stabilization of the slopes. However, in some spots with favourable lithology, low intensity gelifraction processes were maintained (Sub-actual slope deposits in the lower part of the valley). External agents proceeded to an intense erosion of most of glacial deposits and landforms through karstic and snow-karstic dynamics and the fluvial erosion of the valley below Pardeluts area. In the higher parts of the valley an extensive snow-karst was developed (Fig. 12).

Anthropization and sub-actual dynamics: Since the appearance of the Neolithic culture and practices in the Basque Mountains (Armendariz, 1997) forest clearance and over-grazing roughly affected the Aralar range (Iriarte, 1999), removing part of its vegetal cover, disturbing the vegetal species composition as well as the ecosystem of the area, and activating the slope dynamics; humid solifluxion and soil erosion processes. Such processes can currently be seen in the surroundings of Pardeluts (1020 m) (Ugarte, 1985) as well as on the W slopes of Uakorri (970 m). Currently, geomorphologic processes occurring in Aralar and the Arritzaga valley are karstic and snow-karstic but also fluvial. Only in few limited spots controlled by lithology and structure is possible to observe gelifraction dinamics of very low intensity and linked to gravity processes producing accumulations of certain entity (Zotaleta cirque, Eitzegi and Aitzerlo).

6. Climatic context and chronology proposal

It could be argued that only during the coldest momentum of the Late Pleistocene glacial development at the Arritzaga valley would reach its maximum. However, there are several reasons suggesting that maximum ice advance occurred before the Last Glacial Maximum (LGM).

According to the model proposed by Duplessy et al (1981) and Adams (2002), between 25.000 and 18.000 BP continental glaciers (Laurentide and Scandinavian Icefields) reached their maximum development (Figure 14), the ocean lowered 120 m below the current level (Valcárcel Díaz and Pérez Alberti, 2002) and the World's average temperature was 7 Cº cooler than nowadays (Uriarte, 2003). However, the Oceanic Polar Front during this period came to 44º N maintaining a very cold Atlantic Ocean temperature with a low salinity percentage. This fact had critical consequences in the humidity levels reaching the continent;

Table 3. Proposed correspondence and chronology of the morpho-stratigraphic phases in the Arritzaga valley.
Tabla 3. Propuesta de correspondencia y cronología para las fases morfoestratigráficas en el valle de Arritzaga.

Morpho-stratigrapic Phase	Proposed Correspondence
Maximum Advance Phase	*50.000-30.000 BP (OIS 3)*
Equilibrium Phase	*30.000-18.000 BP (LGM)*
Retreat and Deglaciation Phase	*18.000-14.000 BP*
Periglacial Phase	*14.000-10.000 BP Old/Younger Dryas*
Holocene-Postglacial Phase	*10.000 BP- Neolitic*
Antropization and Sub-actual dynamics	*Neolitic-Present*

continentalization effect due to the ocean level decrease, humidity reduction due to the aridification and severe reduction of the hidrogeological cycle (Valcárcel Díaz and Pérez Alberti, 2002). Nevertheless, the most remarkable change occurred linked to the General Atmospheric Circulation; the marine ice and the low temperatures generated a high pressure area in the North Atlantic whilst the current low pressure area located over Iceland moved south (Valcárcel Díaz and Pérez Alberti, 2002). This process was supported by a strong anticyclone circulation over the Scandinavian Icefield (Uriarte, 1996). Eventually, *Jet Stream* moved also south due to the disturbances created by the sea-ice and the European ice-fields and thus before reaching Europe turned NE producing SO and E winds over Spain and south of France (Uriarte, 1996; Florineth et al, 2000) (See Fig. 14).

In short the climate during the LGM in this region of Europe was characterised by cold and dry-arctic climate with an atmospheric circulation with winds from S and SO (Florineth et al, 2000). In the Basque Mountains, Uriarte (1992) points out that during LGM the transfer to the south of low pressure areas and the influence of the Scandinavian Icefield could imply a higher frequency of Southerly and Easterly winds.

Despite is accepted that the coldest momentum of the last glaciation took place globally around the 18.000 BP (LGM) it seems arguable that the dynamic of the great icefields and the mountain glaciers was parallel. Even though the processes in both cases are conditioned by the climatic conditions allowing a positive balance between accumulation and melting, the ice volume resulting from the mountain glaciers is far smaller than the one generated by the icefield, and therefore these smaller glaciers are more exposed to climatic oscillations (Valcárcel Díaz and Pérez Alberti, 2002). According to Faibridge (1972), alpine mountain ranges in mid latitudes would be the first to react to a global cooling enabling the development of glacial processes much faster than the continental icefields.

A premature development of mountain glaciers could have occurred with a high humidity and precipitation context but not so severely cold conditions as in the LGM. The Oxygen Isotopic Stage (OIS) 3 comprised between 59.000 and 24.000 BP (Florineth et al, 2000; Adams, 2002) shows high precipitation context with winds from the W. Since the Atlantic was free of ice and sea level was not so low, winds were more humid. The polar front was at this time as high as 63º N (Florineth et al, 2000) and General Atmospheric Circulation provided western winds that in mid latitude mountains exposed to those winds developed glacial processes on leeward slopes faster than continental icefields. Snow accumulation and retention was also enhanced by the fact that during this period astronomic factors reduced summer insolation (Valcárcel Díaz and Pérez Alberti, 2002).

There is considerable agreement about when the maximum advance of glaciers took place in southern Europe. Many authors point out that in the Pyrenees, Cantabrian Mountains and some parts of the Alps maximum development of the glaciers occurred previous to the LGM. Absolute datations in the Pyrenees (Sancho et al, in press; Jalut et al*,* 1988; Montjuvent and Nicoud, 1988; Bordonau et al*,* 1992, a; García-Ruiz et al, 2003; Lewis et al*,* 2009) place the maximum extension of ice around the OIS 3. In the El Portalet sequence (Central-Western Spanish Pyrenees) González-Sampériz et al (2006) state that *"the basal age of the sequence (ca. 33,000 calBP) confirms that the last deglaciation occurred earlier in the Pyrenees than in northern latitudes in Europe".* In the Cantabrian Mountains similar conclusions have been drawn by setting the maximum advance previous to 30.000 BP (Ruiz Zapata et al, 2000; Jiménez-Sánchez and Farias, 2002). Other absolute datations carried out in the Vosgues (Seret et al 1990) and the Alps (Hannss 1980; Chapron, 1999; Guiter et al, 2005) also set the maximum ice development between 50.000-30.000 BP and 58.000-48.000 BP respectively.

This chronology backed up by absolute datations concords with other studies based on extrapolations and relative datations: According to Florineth et al (2000) in the W of Norway, Vosgues, Central Massiff of the Alps maximum glacial advance occurred generally before 38.000 BP In the Cantabrian range and the Pyrenees several studies (Vilaplana, 1983; Andrieu et al, 1988; Serrano & González Trueba 2001, 2002; Serrano et al, 2002; Serrano y Gutíerrez, 2002; Valcárcel Díaz & Pérez Alberti, 2002; Calvet, 2004; González Trueba, 2006) coincide to place the phase of major glacial advance previous to the LGM.

However, these positions have been recently challenged by Pallas et al, 2006 and Delmas et al, 2008. The results of their absolute datations based on Be10 analysis appear to reflect that the maximum advance of ice in the Pyrenees was synchronous with the LGM during the OIS 2. Some other authors (Hughes et al, 2008) have also suggested the possibility that both periods of maximum advance could have coexisted in different southeuropean massifs: Some massifs having the maximum ice advance previous to the LGM and some others reaching their maximum positions coetaneous with the LGM. Nevertheless, he also highlights that such possibility is difficult to have happened within a certain massif or region.

Therefore, despite this is still an unsolved issue and under constant revision, currently most authors defend the chronology of an early maximum advance of glaciers for the southeuropean massifs, placing this advance generally within a period between 50.000 and 30.000 BP.

The palaeoclimatic conditions during that period concord with the conditions required to develop glacial processes at low altitudes in several massifs in the Atlantic area of Spain (Snow overfeeding from W winds and permanent cloudiness). Taking into account the most accepted chronology of phases (Based on absolute datations) for the Cantabrian range, the Pyrenees and Alps it seems logical to think that glacial processes in Aritzaga valley where fully developed between 50.000 and 30.000 years BP (within OIS 3) and not during the LGM. During the OIS 3, despite not having very severe temperatures, westerly winds would provide the conditions for snow overfeeding on leeward faces in the Arritzaga valley, enabling the maximum advance of glaciers.

During the LGM climatic conditions for snow accumulation would not be so ideal. In spite of the temperature decrease, aridity would reduce precipitations and cloudiness and thus snow accumulation. Winds would be dry and cold with less snow precipitations and coming from the East (Uriarte, 1992). Besides, the little spindrift effect would fall onto O and NO slopes of the valley; these slopes hadn't been excavated previously by the ice and thus would not have the topographic conditions for snow accumulation and retention. Eventually, summer insolation increase would not help snow retention so in general glacial processes would face a retreat and stabilization phase until reaching a new equilibrium level at higher altitude than the previous phase.

Therefore, assuming an early maximum glacial development for the Aralar range, the *Maximum Advance Phase* identified in the Arritzaga valley could be ascribed to the OIS 3 period whilst the *Equilibrium Phase* would be linked to the LGM period during the OIS 2. Following this chronology, the phase identified as *Periglacial Phase*, that took place in a later stage could be tentatively ascribed to a Lategalacial period of cooling that took place during the Oldest or Younger Dryas, leading to periglacial activity in cold but especially drier conditions.

To sum up, the above paleoclimatic considerations and the review of the current state of the question about the chronology of the glacial stages in the Pyrenees, Cantabrian Mountains and other southeuropean massifs has allowed a preliminary chronology proposal for the glacial phases identified through morpho-stratigraphy analysis in the Arritzgaga valley (Table 3.). Ascription of the two post-glacial phases has been estimated based on the palinonogical and vegetation studies referred in the previous section.

7. Final remarks

In the light of the results from the analysis of landforms and deposits and their interpretation within the palaeoclimatic context is possible to confirm the existence of glacial processes in the Arritzaga valley during the Last Glaciation. Such processes generated a glacial body through the valley from its watershed at Errenaga (1270 m) up to its front close to Buruntzuin (800 m), with a longitude of 5 Km and 70-100 m of thickness. Glacial processes had a marginal character and were linked to climatic, structural and topographic particular conditions: The appropriate relief, oceanic influence, leeward topography from westerly winds, N-NE orientation of the cirques, permanent cloudiness, snow overfeeding and retention and the low insolation summers created the optimal conditions for the development of a glacial body below moderate altitudes (between 1300 and 1421 m). Glacial processes were housed in a pre-existent relief, prone to snow retention, and mainly managed to retouch the landforms previous to the glaciation, following the structural organization and lithology.

The apparent lack of glacial features in the rest of the Basque mountain massifs makes only possible to speak about glacial processes in the Aralar range so far. Further research would provide new perspectives about the incidence of glacial phenomena in these mountains. Nevertheless, the processes occurred in Aralar do have homologous cases at moderate altitudes in the Cantabrian Mountains and the westernmost end of the Pyrenees (Saioa massif).

The interpretation of the results of the analysis of the landforms and deposits allows discerning six morphogenetic phases in the Arritzaga valley; four first phases for the glacial evolution and two for the post-glacial dynamic. The analysis of the paleoclimatic considerations and the extrapolation with the absolute datations in other mountain massifs such as the Pyrenees, Alps and the Cantabrian Mountains suggests that maximum advance of ice in Arritzaga valley must have taken place in a moment previous to the LGM, probably around the OIS 3 and between 50.000-30.000 BP.

Further advances in the palaeoclimatic field and the environmental reconstruction, together with new data from absolute datations in the Basque Mountains and other southeuropean massifs will be crucial for the establishment of a rigorous chronology that characterised the morphogenetic evolution of this mountain region during the late Quaternary.

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