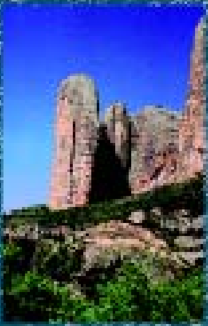
GEOMORPHOLOGY
GEOMORPHOLOGIE

SEG

SIXTH INTERNATIONAL CONFERENCE ON GEOMORPHOLOGY
ZARAGOZA 2005

CENTRAL SPANISH PYRENEES: GLACIAL AND PERIGLACIAL LANDFORMS

J.M. Garcia Ruiz; C. Marti Bono; B. Valero Garcés and P. González Samperiz



FIELD TRIP GUIDE

A-8

SIXTH INTERNATIONAL CONFERENCE ON GEOMORPHOLOGY

CENTRAL SPANISH PYRENEES: GLACIAL AND PERIGLACIAL LANDFORMS

J.M. García Ruiz, C. Martí Bono, B. Valero Garcés and P. González Samperiz

FIELD TRIP GUIDE - A8

CENTRAL SPANISH PYRENEES: GLACIAL AND PERIGLACIAL LANDFORMS

José M. García-Ruiz, Carlos Martí-Bono, Blas Valero-Garcés and Penélope González-Sampériz
Instituto Pirenaico de Ecología, CSIC, Campus de Aula Dei, Apartado 202, 50080-Zaragoza, Spain
E-mail: humberto@ipe.csic.es Phone: 976 716026; Fax: 976 716019

1. Introduction to the geology and geomorphology of the Central Spanish Pyrenees

The Pyrenees have undergone a complex tectonic evolution that began during the Paleozoic Age and the Hercinian orogeny, followed by a long erosive period accompanied by continental and marine sedimentation, a new Alpine orogeny, and, finally, another erosive period with mostly continental sedimentation that led to the current relief. Therefore, the Pyrenees includes materials of different features and ages, affected by different tectonic styles. The result is a very contrasted succession of morphogenetic processes and landforms.

Geographycally, the Pyrenees comprises the regions from the Biscay Gulf to the Creus Cape, along 440 km. The highest peaks are located in the central part of the range (Aneto Peak, 3404 m asl; Posets, 3375 m; Monte Perdido, 3355 m), decreasing toward the west and the east, as well as the Aquitania and Ebro depressions (north and south respectively). Both in the French and in the Spanish slopes, the rivers cut perpendicularly the structure, resulting in valleys of different shape and width, according to the resistance and erodibility of the lithology.

The oldest materials appear in the axis of the range, forming the so-called Axial Pyrenees (Fig. 1), composed of Paleozoic rocks affected by regional and contact metamorphism: quartzites, shales, schistes and limestones. These materials were folded during the Hercinian orogeny (Carboniferous). Today they show a very heterogeneous relief, in which calcareous and quartzitic cliffs alternate with smoother landforms in the shale dominated areas. The Axial Pyrenees do not crop out along the whole Pyrenees, since the Paleozoic materials were covered in most of the range by continental (Permian and Triassic) and marine (Jurassic, Cretacic, Eocene) sedimentary formations.

Several pre-Stephanian granodioritic intrusions are located within the Axial Pyrenees (Panticosa-Cauterets, Posets, Eriste, Perdiguero, Maladeta, Andorra, Albera), which result in relief characterised by sharp divides and strong topographic gradients, as well as remains of older erosion surfaces. Some remains of volcanic activity at the end of the Hercinian orogeny appear in the Upper Gállego Valley (Anayet, Campo de Troya, Midi d´Ossau).

To the south of the Axial Pyrenees, the Pre-Pyrenees also follow the main W-E trend of the main Range. They are composed of the sedimentary formations that covered the Paleozoic materials after the Hercinian tectonics until the end of the Alpine uplift, between the Upper Eocene and Oligocene. The Prepyrenees are composed of Mesozoic and Tertiary materials, displaced toward the south by several overthrusting structures during the Alpine orogeny (i.e., Monte Perdido-Gavarnie and Cotiella-Montsec mantles).

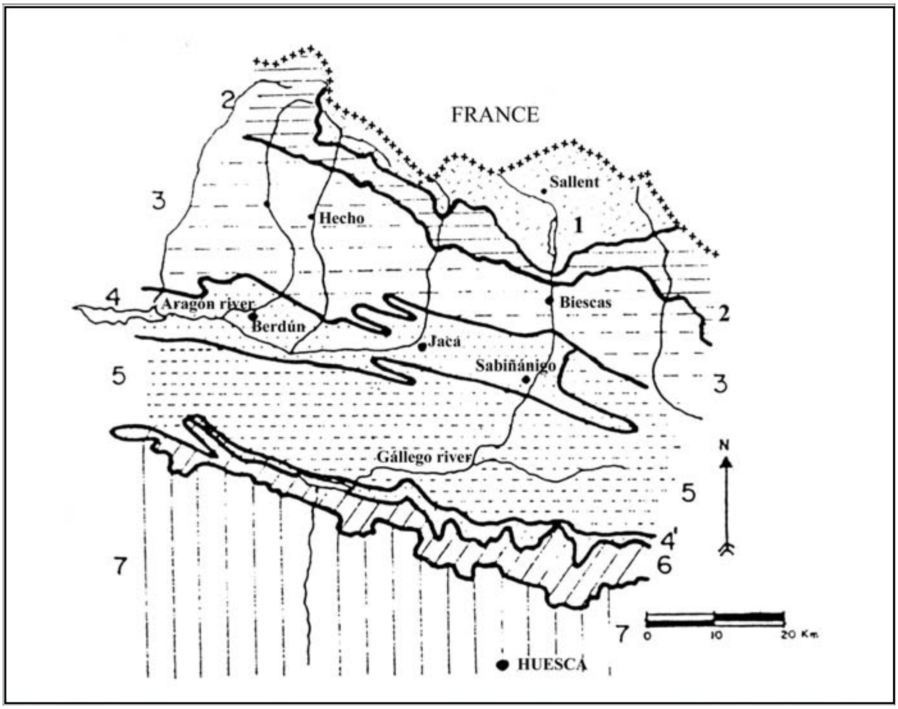


Figure 1. Geomorphological Units in the Western Aragonese Pyrenees: **1** Axial Zone; **2** Inner Sierras; **3** Flysch Sector; **4** Inner Depresion; **4'**Arguis-La Peña Depresion; **5** Oligocene molassic area; **6** Outer Sierras; **7** Ebro Depresion

The sedimentary formations were continental at the base of the stratigraphic sequence (Triassic), with conglomerates, sandstones and clays of a typical wine-red colour, and, later, marine, with limestones (Jurassic and Cretacic an d Eocene), marls and sandstones (Cretacic and Eocene). Several units can be distinguished from north to south: The Inner Sierras, the Flysch Sector, the Inner Depression (including the molassic area) and the Outer Sierras.

The Inner Sierras are a large W-E trending overthrusting anticlinorium, relatively narrow in the western part and wider in the central-eastern part, especially between the Cinca and Segre Rivers. The occurrence of limestones and sandstones results in an abrupt relief in which the vertical cliffs alternate with small platforms intensively karstified (Larra, Aspe. Tendeñera and Monte Perdido massifs, among others). The highest peaks are located in Monte Perdido Peak (3355 m), Collarada Peak (2886 m), Telera (2764 m) and Tendeñera (2853 m). The rivers have cut down deep and narrow canyons in this unit (i.e., Boca del Infierno in the Hecho Valley, Canfranc-Villanúa in the Aragón Valley, Santa Elena in the Gállego Valley, Ordesa, Añisclo and Escuaín in the Ordesa National Park, Ventamillo in the Ésera Valley, etc.). In general, the relief is controlled by the geological structure: from the highest divides to 2000 m asl the verticality of the cliffs is only interrupted by small marly outcrops or by large debris taluses (screes). The importance of the structure can be deduced not only by the presence of the cliffs but also by the continuity of *cuestas* and perched synclines (i.e., Castillo de Acher, "floating" over the Permian in the Upper Hecho Valley, and Castillo Mayor, near the Añisclo Canyon).

The Flysch Sector is especially developed in Navarra and Aragón, and it is composed of thin layers of alternating sandstones and marls. It is characterised by a smooth relief, with rounded divides that decrease regularly from around 2000 m to 1000 m, showing the remains of Tertiary and Quaternary erosion levels. The hillslopes, covered by a coarse, matrix-supported colluvium, are regularized, with a gradient of around 40%. The flysch was intensively folded and faulted during the Alpine tectonics, thus favouring the triggering of both deep and shallow landslides (debris flows) that contribute to the torrentiality of rivers and ravines (García-Ruiz and Puigdefábregas, 1982; Lorente et al., 2002). The relief shows few contrasts due to the lithological homogeneity, except where isolated beds of limestone intercalate within the flysch. Some of the best terminal areas of the Pyrenean glaciers develop within the Flysch Sector, leaving lateral, well-preserved deposits, whereas the frontal moraines only occur in the basins of Castiello (Aragón Valley) and Senegüé-Sabiñánigo (Gállego Valley). The contact with the Inner Depression is an overthrusting fault.

The Inner Depression is a long valley oriented from west to east, between the Pamplona Basin and the Tremp basin (Conca de Tremp), although some N-S structures (i.e., the Boltaña anticline) break its continuity. This depressed area is related to a large outcrop of Eocene marls, where the fluvial network has “voided” the original relief, due to the erodibility of the marls. Pediments (“glacis”) and fluvial terraces prevail in the bottom of the Depression, whose borders easily evolve into badlands.

The southernmost part of the Inner Depression is covered by Oligocene continental deposits (molasses) of deltaic and fluvial origin (conglomerates, sandstones, clays and marls), lodged in a synclinorium developed after the main phase of the Alpine tectonics. A new posterior uplift folded slightly this area, which has evolved into very regular *cuestas*. The Peña Oroel, San Juan de la Peña and Canciás massifs, composed of conglomerates, are its more dramatic relieves.

The Outer Sierras constitute the front of the overthrusting mantles of Gavarnie and Cotiella-Montsec. They form a big anticlinorium laid toward the south and faulted in the contact with the Ebro Depression. The materials are similar to those of the Inner Sierras, although the upper crests usually are around 1500-1600 m (except in the case of the Tozal de Guara (2077 m). Nevertheless, the relief is very craggy, with cliffs (especially in the south facing versant), *cuestas* and very deep and narrow canyons. Karstification has been also very intense (Guara and Montsec sierras).

2. 2. Glacial features in the Southern Pyrenees: Landforms, deposits and chronology

Landforms in the Central Spanish Pyrenees mainly depend on lithological contrasts and on the structural organisation (folds and faults). Nevertheless, a very important part of the landscape features is related to the relatively recent activity of glaciers, which excavated cirques close to the divides and eroded U-shaped valleys. Besides, their morainic deposits were the responsible for many glaciolacustrine deposits. For this reason, the Pyrenean valleys show the effect of the lithological resistance and structure (with successively wide and narrow stretches) and the consequences of erosion and sedimentation by large ice tongues during thousands of years.

The altitude of the Pyrenean range enabled the development of large glaciers in both the French (north) and the Spanish (south) versant, although they reached a bigger size in the northern one, where the front of the tongues reached around 400 m asl. In the south versant the most important ice tongues reached about 30 km in length, melting as much at about 850 m (Castiello de Jaca, in the Aragón Valley) or 800 m (Sabiñánigo, in the Gállego Valley). The thickness of the ice tongues varied according to the topography, but in some cases reached 500 m (immediately after the pass through the Inner Sierras), with a maximum of near 900 m in the overdeepened basin of Benasque (Ésera

Valley) (Bordonau, 1992). In any case the best examples o glacial valleys and deposits correspond to the central part of the Pyrenees, where the peaks usually exceed 2500 m asl and even 3000 m in the upper Gállego, Ara, Cinca, Ésera, Noguera Ribagorzana and Noguera Pallaresa valleys.

The study of the Spanish Pleistocene Pyrenean glaciers begins at the middle of the 19th century (Penck, 1883) and continued along the 20th century with a description of the main valleys, including information on the length of the glaciers and different deposits, preliminary interpretation of the chronological evolution. (Panzer, 1926; Vidal Box, 1933; García Sáinz, 1935, 1942; Llopis Lladó, 1947; Fontboté, 1948; Nussbaum, 1949, 1956).

Modern studies were initiated by Barrère (1952, 1963), which identified the different internal and external morainic arcs as corresponding to pulses or stages of a single glaciation. Barrère (1966, 1971) is also the author of a very good geomorphic mapping of a large part of the Central Spanish Pyrenees, with an excellent delimitation of the Pleistocene glaciers.

During the last decades, new papers have been focused in studying different detailed aspects of the glaciers, like the sedimentology of morainic, fluvioglacial and glaciolacustrine deposits, as well as the palinology of lake deposits. These studies allowed the dating of moraines and related-terraces and the establishment of the paleoenvironmental evolution since the Late Glacial Maximum (Vilaplana, 1983; Serrano, 1998; Martínez de Pisón, 1989, 1991; Bordonau, 1992; Chueca, 1992; Montserrat, 1992; Martí-Bono and García-Ruiz, 1993, 1994; García-Ruiz and Martí-Bono, 1994, 2001; Serrano and Martínez de Pisón, 1994; Lampre et al., 1998; Martínez de Pisón and Serrano, 1998; Peña et al., 1998, 2004; García-Ruiz et al., 2001, 2003).

2.2.1. Glacial landforms

The Central Spanish Pyrenees contain good examples of glacial cirques in different lithological environments, as well as of detailed erosion landforms such as *roches moutonnées* and polished rocks especially in granodiorites, above 1500 m asl. These landforms are difficult see in sandstones or limestones due to weathering processes (above all, dissolution of carbonates). The best locations are the Maladeta massif, where the glaciers reached a relatively important extent until recent times, and also the Panticosa massif. Striations are frequent in rockwalls providing that the rock has been protected later by sediments; if not, they have been easily eroded.

The maximum presence of glacial cirques is concentrated around 2500-2700 m, although in some cases they can appear at more than 3000 m asl. The minimum altitude at which the bottom of a cirque appears is around 1700 m, thus coinciding with the limit of permanent snow in the southern versant of the Pyrenees. North and south aspects are the prevailing in the location of the cirques, with 22 and 16% respectively. The rest of the 8 classes each represent around 10% (García-Ruiz et al., 2000). This distribution suggests that, in the Pyrenees, glacial cirques could develop in any aspect. The relatively greater presence of cirques on north and south aspects is related to the Pyrenean structure, with dominant ridges from west to east, notably the Inner Sierras and the main divide between France and Spain.

The Pyrenean cirques show a large morphometric variability. Width concentrates between 200 and 1000 m, with a mean value of 653 m. Length has a mean value of 503 m. This means that cirques are of moderate size, with a mean area of 34 ha. The most typical form of glacial cirques in the Pyrenees is rounded and deep. Other types of cirques are: very wide and deep cirques, long and narrow cirques and rounded cirques, with gentle gradient and without over-deepening.

Altitude affects the length of the cirques and the Length/Width (L/W) relation. At lower altitudes glacial cirques are clearly wider than they are long, while in the highest areas both the length and width tend to be equal. This trend suggests that the increase in length is a sign of maturity or of a long evolution of the cirques. It seems that, as time passes, the length tends to increase more than the width of the cirques (García-Ruiz et al., 2000).

As for the effect of lithology, cirques on granite are the largest and longest, while on flysch they are small and short, and have a low L/W index. In general, rounded or arcuate, over-deepened cirques prevail on granite, favouring the existence of many lakes of glacial origin. At similar altitudes, limestone, quartzite or Permo-Triassic sandstone include only a few examples of well developed glacial cirques.

The glacial valleys show frequent topographic gradient breakings, representing glacial thresholds (“verrous”), usually related to lithological changes. In the headwater, these thresholds delimit glacial lakes or over-deepened basins, some of which have been already infilled with sediment. U-shaped forms prevail along the glacial valleys, although the areas with the most resistant rocks (i.e., the limestones of the Inner Sierras) result in narrower valleys, sometimes incissed by short, fluvial-originated canyons. Even in the case of the best examples of U-shaped valleys, the structure plays a very important role: Thus, in the Ordesa, Añisclo and Pineta (Cinca) valleys, the valley walls are characterized by alternating vertical cliffs and taluses, representing changes in the resistance of the substratum. There, the gradient of the valley bottom is also affected by lithological contrasts. This is the case of the Ordesa Valley, where the outcrop of subhorizontal beds of sandstones and limestones results in a dramatic succession of steps, or the Estrecho and Abanico waterfalls, representing the pass through very resistant limestone layers. Tributary glacial valleys appear usually perched in relation to main valleys, and the contact is marked by an abrupt gradient breaking and waterfalls, as in the Aragón, Ésera and Cinca valleys.

2.2.2. The glacial phases in the Spanish Pyrenees

At present, two main facts are known in the glacial evolution of the southern Pyrenees:

(i) The existence of remains of at least two different glaciations, Riss and Würm, according to Alpine terminology. The outermost moraine at the end basin of the Aragón glacier corresponds clearly to the Riss glaciation, as well as the 60 m fluvial terrace in different Pyrenean valleys (Peña et al., 2004). Dates between 150,000 and 200,000 years B.P. have been obtained by OLS.

(ii) The earlier maximum glacial advance in the Pyrenees than in North Europe during the last glaciation (García-Ruiz et al., 2003). Several studies (Vilaplana, 1983; Bordonau, 1992; Montserrat, 1992) suggested that the maximum extent of Pyrenean glaciers occurred before 38,000 years B.P., long before the Last Glacial Maximum. An early maximum and deglaciation has been suggested for several valleys in the northern Pyrenean slopes (Andrieu et al., 1988) and other European mountain ranges, such as the French Vosgues (Seret et al., 1990) and the Alps (Guiter et al., 2005). New dates in the Pyrenees confirm that the maximum extent of the glaciers occurred at about 60,000-65,000 years B.P., according to OLS dates in the Aragón and Gállego valleys. Besides, new 14C dates in the Gállego Valley confirm that during the Late Glacial Maximum the Pyrenean glaciers had much shortened sizes than thousands of years ago (García-Ruiz et al., 2003).

According to the available 14C and OLS dates, and to the topographical position of different glacial deposits, the following chronology has been proposed for the Spanish Pyrenees (García-Ruiz et al., 2003):

(i) The maximum expansion of the glacier occurred most probably at around 60,000-65,000 years B.P. Later, the tongues retreated very much, though there are no evidences of the location of the glacier fronts for thousands of years.

(ii) Around 20,000-25,000 years B.P., coinciding with the coldest period of the Upper Pleistocene (Late Glacial Maximum) a new readvance occurred, but the length to the ice tongues was much smaller than before. Most of the main tributaries did not connect with the main glacial tongues (Martínez de Pisón, 1989; Serrano, 1998; Chueca et al., 1998).

(iii) Several frontal arcs and their lateral ridges evidence a short readvance during the Oldest Dryas. This is the “Upper Valley Glacier Phase” defined by Bordonau (1992), and dated between 16,000 and 15,000 years B.P. (end of the last pleniglacial)

(iv) Rock glaciers and debris-covered glaciers confirm the occurrence of a short period with cold temperatures and a high activity of gelifraction in the cirque backwalls with a large debris input (14,000-13,000 years B.P.?) (Bordonau, 1992; Copons and Bordonau, 1997).

(vi) Many cirques have a final morainic arc close to the cirque backwall, that represents the last stage of glaciation, attributed to the Younger Dryas.

2.3. Periglacial deposits and landforms and their environmental implications

Most of the Pyrenees, especially to the north of the Inner Depression, is located above 1700 m, that is, above the 0ºC winter isotherm. This has important geomorphic consequences: though gelifraction and cryoturbation are possible below this threshold, the number of frozen days per year clearly increases from that altitude. At lower altitude, all of the periglacial phenomena can be considered as fossil, as is the case of many screes in the Outer Sierras and in the Flysch Sector.

Almost all of the limestone, sandstone, quartzitic or granitic scarps developed a debris talus at the foot of the hillslope. They are a consequence of the breaking of the rock due to freeze-thaw processes. Clasts and blocks fall and accumulate after a very short transport. As a result, debris cones of different size develop, sometimes connecting one to the others and forming a continuous, dramatic talus. In the uppermost part of the Pyrenees they show a fresh look, with loose clasts and blocks and only a few very adapted plants, especially in the border of the taluses. They tend to occur in glacial cirques and adjacent to tors and cliffs. They are close to the highest divides on all aspects, though preferably in shady exposures (Serrano, 1998). Below 2000 m, screes use to be a consequence of a past colder climate, and are stabilised and even covered by other deposits or even soils and paleosoils. Most of them are colonised by shrubs and trees (García-Ruiz and Ruiz-Budría, 1977).

Fossil screes supply much information on paleoclimate-associated processes. A particular type of debris taluses is the stratified screes, composed of alternating matrix-supported beds and openwork layers. They have been attributed to debris flow activity, creep and even sheet wash erosion, although recent detailed sedimentological studies attribute their genesis to the alternating activity of cohesive debris flows, grain flows, sheet wash processes and slushflows. In the Pyrenees they can be found everywhere, from lowlands close to the Ebro Depression (below 500 m asl) to high elevations up to

3000 m asl (Peña et al., 1998). Fossil stratified screes are relatively frequent in the Ésera, Cinqueta and Cinca valleys, though good examples can be also be found in the Gállego and Hecho valleys.

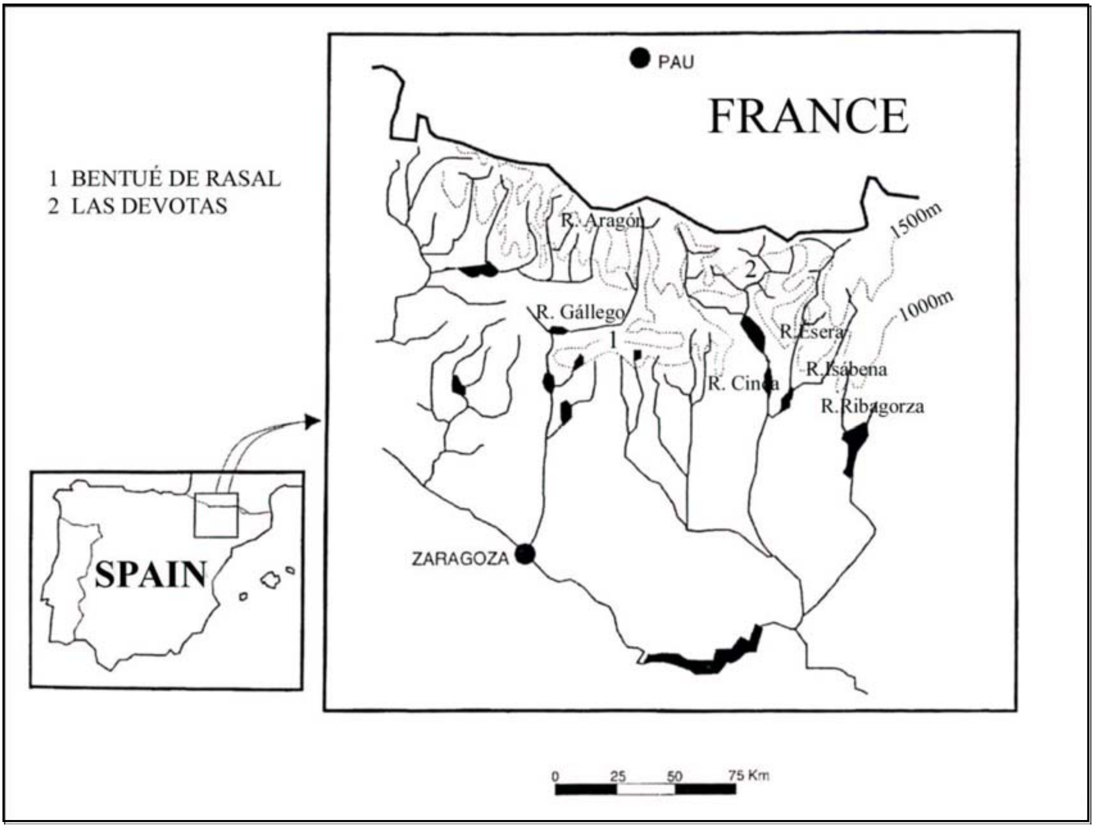


Figure 2. Location of some periglacial scree deposits.

Some stratified screes have ben studied in detail in the Central Pyrenees and dated (García-Ruiz et al., 2001) (Fig. 2). This is the case for (i) the Bentué de Rasal scree, located at the northern side of the Outer Sierras, at 1000 m asl; and (ii) The Devotas Canyon, a north-south reach of the Cinca River, with the bottom of the gorge at 690-730 m asl, and no geomorphological or sedimentological evidence to support the passage of glacial ice (García-Ruiz and Martí Bono, 2001).

Fig. 3 shows the existence of four units in the Bentué de Rasal deposit: the main, basal unit, with a visible thickness of 4 m, consists of crudely stratified alternating coarse and fine layers, each up to 20 cm thick. Coarse layers show an openwork (clast supported) structure, with a heterogeneous clast size distribution and many clasts over 10 cm in the *a* axis. The fine layers are composed of clasts up to 5 cm long, with a matrix supported structure. The contact between layers is blurred, with many irregularities. In a frontal exposure the layers show little continuity, being affected by short-wave sinuosities. Above this unit, a 40-cm thick, dark-brown unit containing charcoal remains is interpreted as a paleosoil, overlained by a 50-cm thick unit composed of loose blocks, interpreted as a massive openwork scree. The exposure is topped by a 50-cm thick unit of loose, small clasts, interpreted as a massive openwork scree developed by single-particle rockfall.

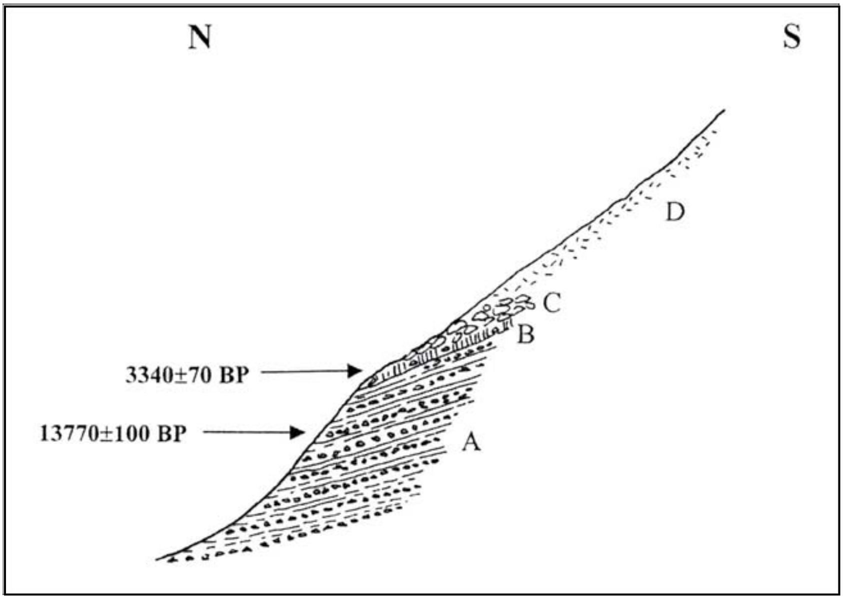


Figure 3. Stratified scree of Bentue de Rasal: **A** Stratified scree; **B** Palaeosoil with clasts and charcoal; **C** Clasts and blocks in an openwork structure; **D** Semi-active, recent scree, with small clasts.

Pollen from the basal unit provided an age of 13,370 ± 100 years 14C BP, whereas charcoal from the paleosoil was dated as 3340 ± 70 years 14C BP. The pollen spectrum shows that during the deposition of the stratified scree the most representative species was *Juniperus*, a colonizing, pioneering plant. Some pine is also present, but graminea and other herbaceous plants are scarce. The pollen spectrum from the paleosoil suggests a Mediterranean landscape dominated by thermophylous and heliophylous species. *Asphodelus* reveals the occurrence of periodic fires and the presence of eggshells of parasites characteristic of domestic animals suggests livestock activity. Thus, the environment corresponding to the paleosoil is a deforested Mediterranean landscape, where the presence of fire and livestock suggests an anthropogenic origin for this deforestation.

Two screes were studied in the Devotas Canyon (Devotas 1 and 2). In Devotas 1 a small cave is located at the foot of the rockwall. Some clasts from the cliff had accumulated in the cave, in an ordered stratified sequence. This unit is fossilized by a calcitic speleothem deposit that covers the bottom of the cave (Fig. 4). The U/Th ages obtained indicate that the stalagmite formed between 10,910 ± 55 U/Th years BP and 9040 ± 100 U/Th years BP (García-Ruiz et al., 2001). The age of pollen from the stratified scree in Devotas 2 is 22,800 ± 200 14C years BP. Also a paleosoil covers the scree in Devotas 2, with abundant charcoal indicating the occurrence of fires.

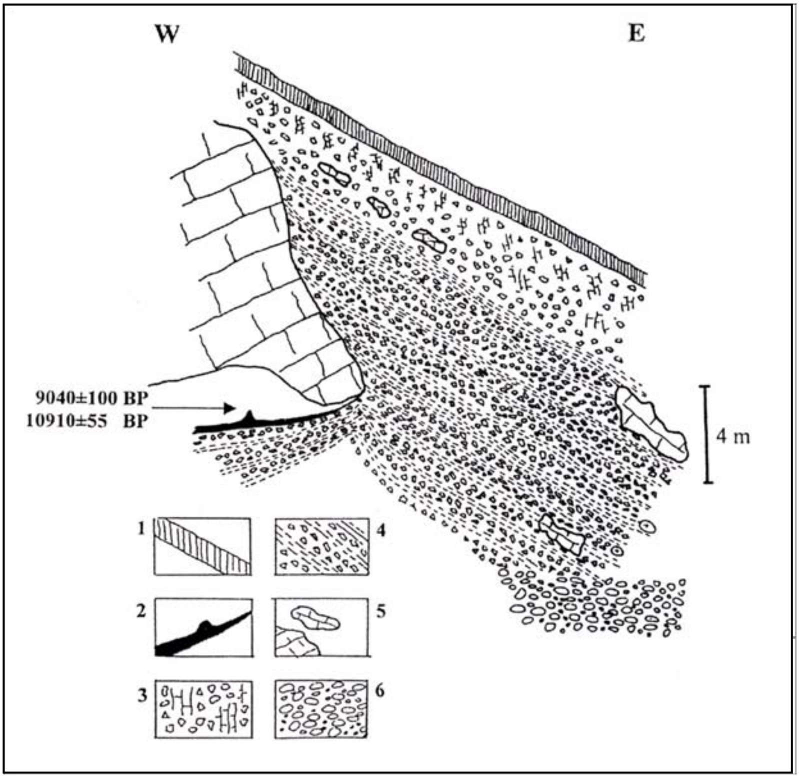


Figure 4. Stratified scree of Devotas 1, in the Devotas Canyon, Cinca Valley: **1** Paleosoil; **2** Stalagmitic layer; **3** Scree with some carbonatic cementation; **4** Stratified scree; **5** Limestone blocks; **6** Fluvioglacial terrace (15 m).

These screes reveal the following paleoenvironmental sequence:

(i) The stratified bodies were formed during two main periods: the coldest stage of the Upper Pleistocene and the Tardiglacial (especially the Oldest Dryas), when stone-banked solifluction lobes, debris flows and frost-coated clast flows developed stratified layers.

(ii) Speleothemes were formed in the time period between the Youngest Dryas and the Pre-Boreal, coinciding with an amelioration of climate and greater humidity.

(iii) Soil developed during the Holocene, both in the Devotas Canyon and in Bentué de Rasal.

(iv) Forest fires occurred in the Late Holocene, around 3,300 years BP, coinciding with the presence of livestock. This is consistent with other palynological and archaeological data from the Central Spanish Pyrenees. Thus, Montserrat (1992) identifies a detritic layer with charcoal, dated 3980 ± 50 years BP, followed by a rapid forest recovery.

(v) The recent supply of clasts from the rockwalls, initially very coarse and finally very fine, has an ambiguous climatic meaning, not necessarily linked to a cold spell. In both study areas, fire could have facilitated sediment transfer from the cliffs to the screes, until then restricted by the presence of trees. The finer clasts could be related to the Little Ice Age.

At present, periglacial activity in the Central Spanish Pyrenees is limited to the uppermost parts of the range. Höllermann (1985) underlined that, after deforestation of the upper forest level, the solifluction belt lowered some hundreds of metres. In fact, this deforested level (attributed by Montserrat, 1992, to generalized forest fires during the 11 and 12th centuries) support the presence of stone banked lobes, ploughing blocks, solifluction and gelifluction lobes and terracettes, that increase their activity close to the divides of the Flysch Sector (García-Ruiz et al., 1990). But the best examples of periglacial activity can be found between 2500 and 3000 m asl in the Inner Sierras (especially in the Monte Perdido massif). There, in the Marboré cirque, at the foot of the Monte Perdido glacier, active examples of patterned ground can be found. Actual glaciers create a permanent *tundra* environment, with generalized stone fields.

Poligonal soils are the most typical figures of patterned ground. They are located very close to the Marboré lake, in very flat areas with poor drainage, on sandy, poor in organic matter soils, where fine material prevail together with some angular clasts that have been displaced by cryoturbation processes (Barrère, 1952; García-Ruiz and Martí-Bono, 2001).

Besides, many examples of striated soils occur in steeper areas, where the soil contains a higher proportion of stones, accompanied exceptionally by stone roses.

* * *

During the A-8 Pre-Conference Field Trip several stops will show examples of morainic deposits, different glacial phases, and the relationships between glacial, periglacial and fluvial phenomena.

Stop 1: The Hecho glacier terminal basin

The Hecho glacier (Aragón Subordán Valley) ended at the Hecho basin, very close to the locality of the same name, at around 830 m asl, within the Flysch Sector. In this area the glacier greatly enlarged its width and left abundant lateral tills that caused the sedimentation of several glaciolacustrine deposits in both sides of the valley (Fig. 5).

The most important lateral deposits are located almost immediately after the glacier passes across the Inner Sierras (Boca del Infierno): On the left margin a large morainic deposit appears in the junction with the Agüerri ravine, 470 m above the valley bottom. The internal part of the deposit was carried by the Hecho glacier, but the inner ridges correspond to the Agüerri glacier, since they only contain Cretaceous limestones and sandstones. This deposit suggests that during the maximum expansion of both glaciers they were connected and that the Agüerri glacier provided a main contribution to explain the low altitude reached by the front of the Hecho glacier.

On the right margin an excellent remain of the lateral moraine locates its ridge 230 m above the valley bottom. This moraine dammed the Hospital ravine at the moment of maximum extent of the glacier. The consequent lake was infilled with glaciolacustrine and torrential deposits.

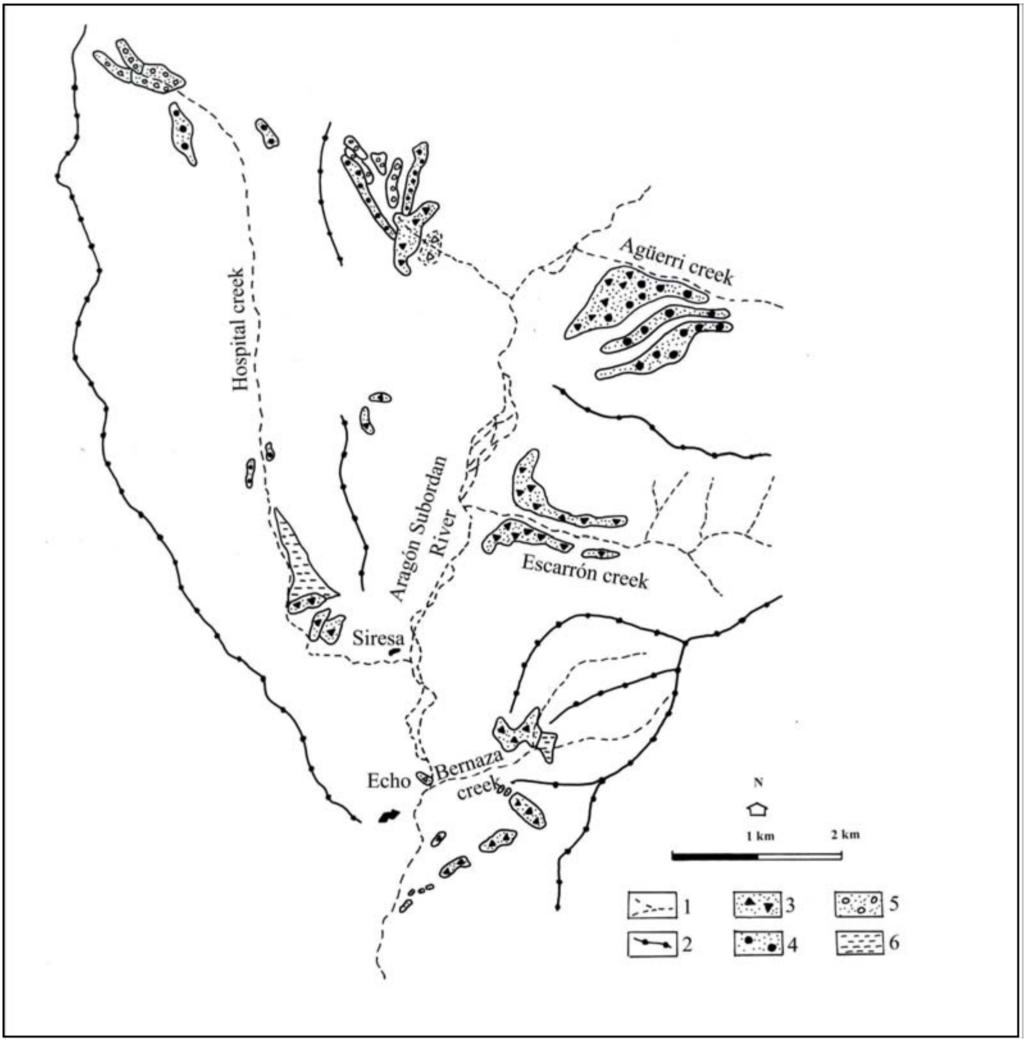


Figure 5. Geomorphological scheme of the terminal morainic complex in the Hecho Valley (Aragón Subordán river): **1** River and creeks; **2** Smooth divides; **3** Moraines of the main glacier deposited during the Maximum Extent Phase; **4** Moraines of tributary glaciers deposited during the Maximum Extent Phase; **5** Moraines of tributary glaciers deposited after a recession; **6** Lateral obturation deposits.

The outermost tills in the Hecho Valley are located about 800 m downstream of the village of Hecho. The left lateral moraine changes laterally to a greater accumulation of loose blocks crossed by the San Juan ravine. Complex relationships between tills, outwash terrace and torrential (cold-climate) deposits can be seen in a few hundred of metres.

Stop 2: The Boca del Infierno Canyon and periglacial breccias

In the Inner Sierras, the Aragón Subordán River shows an U-shaped valley over the fluvial canyon. It seems that the glacier enlarged the pre-glacial valley, resulting in a typical U-shaped valley, and at the same time the subglacial melting waters excavated a subglacial gorge, very deep and narrow in some stretches (The Boca del Infierno Canyon). The evolution of the gorge has continued after the retreat of the glacier by simple fluvial erosion. The end of the pass through the Inner Sierras produces a clear topographic threshold, due to the easier erodibility of the Flysch Sector.

Within the Boca del Infierno Canyon a scree is lodged in a small cave of the subglacial gorge, at the foot of the valley wall. This scree varies from a typical stratified scree and a breccia of heterogeneous clasts. The layers of the stratified scree show in general an openwork structure later infilled with a non-coherent calcareous dust. Martí-Bono (1996) suggestes the formation of this scree at around 20,000-25,000 years B.P.

Stop 3: The Upper Hecho glacier Valley and the lateral moraine

Upstream of the Inner Sierras, the Aragón Subordán valley passes through a large outcrop of Permo-Triassic sandstones and clays, clearly less resistant than the sandstones and limestones of the Inner Sierras. As a consequence, the valley enlarges (Selva de Oza) and it is dominated by the heights by the perched sinclyne of Castillo de Acher and the rough relieves of the north face of Peña Forca. Toward the headwater the river crosses some quartzitic outcrops and finally the Upper Hecho Valley shows a typical U-shaped section.

At the junction between the Aragón Subordán and the Acherito rivers, just when the valley changes from a west-east direction to a north-south one, several morainic ridges are located in the right margin of the valley. From the valley bottom, at 1220 m asl,, a first lateral ridge appears at 1320-1330 m, that is, with only 100 to 110 m of topographic difference. This deposit, mainly composed of Paleozoic sandstones that dominate in the right margin of the valley, comes clearly from the main valley, since it does not contain Cretaceous limestones that prevail in the headwater of the Acherito Valley. This means that both glacier tongues (Aragón Subordán and Acherito) were already disconnected at the moment of deposition of this lateral ridge. According to similar situations in other Pyrenean valleys, this moraine would correspond to the glacial reactivation stage of around 20,000-25,000 years BP.

A second morainic deposit locates at 1485 m asl, forming two small parallel ridges that culminate at 1525 m. This till contains Cretaceous limestones from the Acherito Valley, indicating that it corresponds to a lateral moraine of this valley, probably belonging to the maximum extent of the tributary valley.

Stop 4: The Aragón glacier end basin: End moraines complex and fluvioglacial terraces

The Aragón glacier end basin is probably the best developed and most interesting in the Spanish Pyrenees, due to the large variety of lateral and frontal moraines, together with some glaciolacustrine deposits (Fig. 6). After the glacier passed across the Inner Sierras (Villanúa gorge) it was flanked by lateral moraines that progressively decreased in height, thus indicating the altitudinal decrease of the ice tongue toward the south, connecting with the frontal deposits. In the right margin three lateral ridges can be clearly identified in Aratorés. In the left margin the three ridges are more voluminous and continuous. The most important one develops an elongated hill toward the south-southwest, and culminates at 1082 m asl, that is, 160 m above the valley bottom.

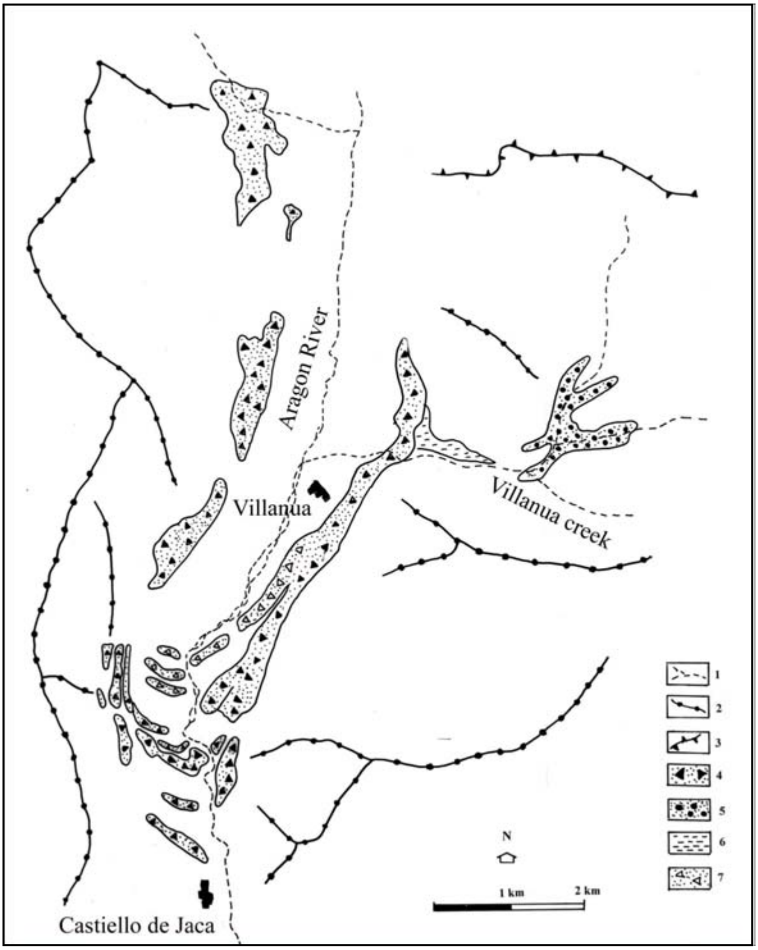


Figure 6. Geomorphological scheme of the terminal morainic complex in the Aragón Valley (Castiello de Jaca-Villanúa basin): **1** Rivers and creeks; **2** Smooth divides; **3** Sharp divides; **4** External frontal and lateral moraines of the main valley; **5** Moraines of local origin; **6** Glaciolacustrine sediments; **7** Internal moraines of the main valley.

At the bottom of the basin six end morainic arcs can be found, with different topographic and depositional significance. The outermost arc connects with the 60 m fluvial terrace of the Aragón River. This moraine is at above 80 m over the valley bottom and develops a powerful hill perpendicular to the valley direction. According to the Llopis Lladó's (1947) terminology, this moraine is called M1. 500 m upstream a second arc is located, but it only raises 10 m over the valley bottom. It is the so-called m1 arc.

The third arc is of similar importance than M1. Its ridge also is at 80 m above the valley bottom. It has a transversal position and closes almost totally the Aragón Valley except for the fluvial channel. This arc was called M2 and connects with the 15-20 m terrace of the Aragón River.

Almost 1 km upstream, three new end moraines develop transversal, small size arcs. They were named m2, m3 and m4.

Since the beginning of the study of the Pleistocene glaciers in the Pyrenees, the Aragón basin has been used to discuss the number of glacial stages and even their chronology. Panzer (1926) considered that the moraines of the Aragón basin belonged to two different glaciations, represented by M1 and M2, with their respective fluvial terraces. Barrère (1963) argued that these moraines only represent one stage, since the M1 moraine would not be connected with the terrace but it was deposited *against* the pre-existing terrace. In any case, Martí-Bono (1973) confirmed the fluvioglacial character of the 60 m terrace, and hence, even if M1 does nor connect with the terrace, it could be argued that two different stages are represented in the Aragón basin. New OLS, still no published dates demonstrate that the first Panzer's idea was in the good way.

Stop 5: The Senegüé end moraine and the maximum stages of the Gállego glacier
The Gállego glacier developed one of the most important ice tongues in the Spanish Pyrenees, with more than 30 km length until its terminous at the Sabiñánigo-Senegüé basin. This valley has many morainic deposits in the headwater, as well as excellent glacial erosion forms in both granodiorites and limestones. However, the best examples of deposits (both lateral and frontal) appear, as in other valleys, in the Flysch Sector, after the pass across the Inner Sierras. There, the glacier ice was at least 400 m thick, leaving powerful lateral moraines in the junction with its tributaries, that remained dammed at the moment of maximum glacial extent. For that reason, most of the tributaries lodge glaciolacustrine deposits, perched some hundred of metres above the valley bottom.

Two are the end moraines located in this basin (Fig. 7). The most important one is the Senegüé moraine, that forms a large transverse hill up 35 m over the Gállego River. The south facing slope of the moraine connects with a large proglacial plain that corresponds to the 20 m terrace. A trench within the moraine shows the typical matrix-supported structure, with sub-rounded blocks of granite, sandstones and limestones. Likewise, there is a small void infilled by a lacustrine deposit (rhythmites), most probably caused by the melting of an internal ice block (kettle).

About 2 km downstream, close to the Aurín River (a tributary of the Gállego River), small morainic remains scarcely raise up over the alluvial plain. They have been eroded by the Gállego River, mostly by the melting waters during the Senegüé stage. These are the outermost morainic resmains in the Gállego Valley. Nevertheless, Peña et al. (2004) underline the existence of a polished sandstone outcrop at Sabiñanigo, although its glacial attribution is uncertain. Most of the city of Sabiñánigo has been built over an ambiguous deposit with large sub-rounded, glacial-origin blocks, though the deposit would be carried for some hundred of metres by the Gállego River from the end moraine.

In the Sabiñánigo-Senegüé basin, the oldest dates has been obtained from a fluvioglacial terrace of the Gállego River, located 60 m above the present channel (155,800 years B.P.) (Peña et al., 2004), which would correspond to the stage M1 in the Aragón Valley. The proglacial outwash of the Aurín moraine has been dated in 69,000 ± 8,000 years B.P. (Peña et al., 2004), an age relatively similar to that of M2. Finally, the Senegüé moraine has an OLS age of 35,700 years, that is a clear retreat stage. Here, as in the case of the end Aragón Valley basin, the Isotope Stage 2, corresponding to the Late Glacial M aximum, is absent. Its deposits have been found several kilometres upstream, confirming that the maximum extent of the Pyrenean glaciers occurred earlier than in the north of Europe (García-Ruiz et al., 2003).

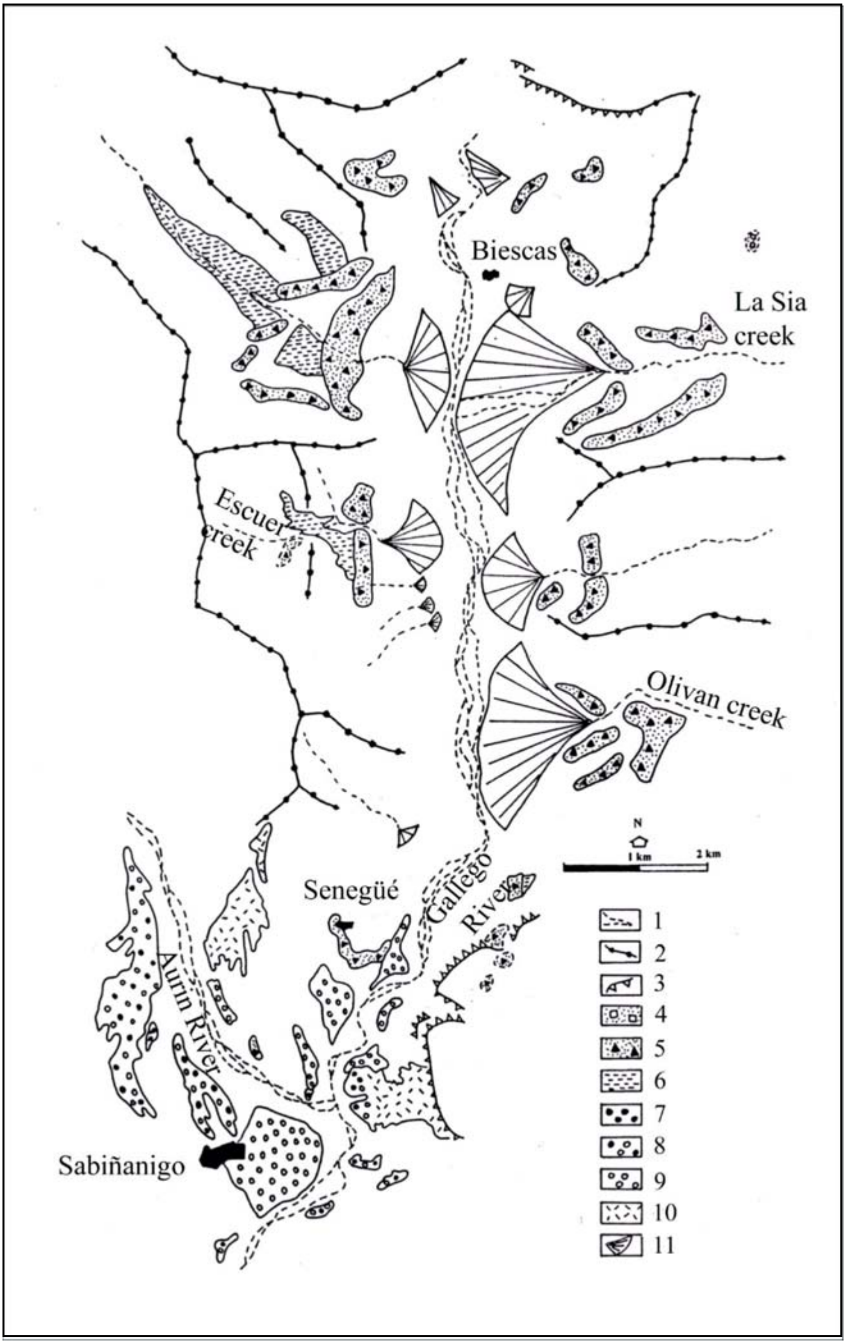


Figure 7. Geomorphological scheme of the terminal morainic complex in the Gállego Valley (Sabiñánigo-Biescas basin): **1** Rivers and creeks; **2** Smooth divides; **3** Cuesta front; **4** Glacial deposits previous to the Phase of Maximum; **5** Moraines deposited by the Gállego glacier; **6** Lateral obturation glaciolacustrine deposits; **7** Terrace of 100-110 m; **8** Main level of terraces (50-60 m); **9** Terraces of 15-20 m; **10** Main level of glacis; **11** Alluvial fans.

Stop 6: The Santa Elena subglacial gorge (Gállego Valley): glacial lee-side deposits and periglacial scree.

The Santa Elena subglacial gorge shows a particular evolution (Fig. 8). It is located in the Gállego Valley, when the Gállego River passes across the Inner Sierras. It is a very short incised stretch in which the Gállego Valley maintains the U-shape, somewhat masked by an alluvial fan coming from the dismantlement of a lateral moraine.

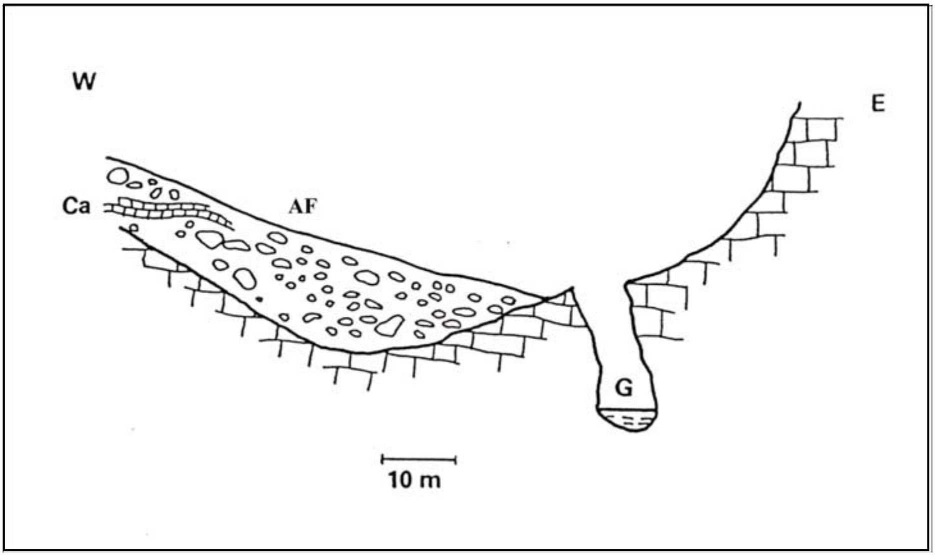


Figure 8. Santa Elena subglacial gorge: **G** Gállego river; **AF** Alluvial fan; **Ca** Carbonatic levels.

It is interesting to note that the gorge does not occupy the bottom of the valley, but it has been excavated on the left versant. This situation could be explained if the valley had been occupied by a powerful ice tongue (at least 400 m in depth) that would have forced the subglacial torrent to flow dissymmetrically with respect to the natural valley axis. The incision would be relatively fast due to dissolution processes in the limestones, that would continue after the glacial retreat.

Very close to the Santa Elena gorge, on the left side, a typical stratified scree covers the foot of a big calcareous cliff. It consists of alternating clast-supported layers with openwork structure and matrix-supported layers, partially cemented. It is 10 m thick in total, with small clasts (3-5 cm of *a* axis), decreasing upward in size. The average gradient is between 25 and 30º, decreasing in the upper layers.

This deposit fossilizes a morainic deposit with a low percentage of fine material: less than 30%, when similar deposits in this areas contain around 60% of fine material. Taking into account its location, in a place where the ice was not able to adapt to the topography, it has been interpreted as a lee side till. It was deposited in a void between the ice and the rockwall, falling directly from the base of the ice. The presence of an incipient paleosoil between the glacial deposit and the stratified scree suggests that the development of the latter did not occur immediately after the ice retreat. Martí-Bono (1996) notes that the position and age of the scree would be more or less the same than that of the Boca del

Infierno Canyon (Hecho Valley), that is, probably during the coldest stage around 20,000-25,000 years BP.

Stop 7: The Tramacastilla lake: Paleoenvironmental interpretation and glacial inner stages.

One of the right-margin tributaries of the Gállego glacier in its headwater is the Escarra Valley, where a complete sequence of glacial stages can be found, since the maximum expansion of the glaciers until the Younger Dryas. A field trip through the valley allows to observe deposits corresponding to different glacial, Würmien stages.

A sediment core was retrieved by Montserrat (1002) in a glacial-origin lake (Tramacastilla lake) located in the divide between the Escarra and the Lana-Mayor valleys. The basal date of the lacustrine sediments is 29,400 ± 600 years B.P., suggesting once again that the maximum extent of the glaciers in the Southern Pyrenees was reached earlier than the LGM. The Escarra glacier would have diminished very much in size at about 30,000 years B.P., since tills belonging to the maximum extent are located at least 100 m above the Tramacastilla lake.

The sediment core of the Tramacastilla lake has been also used to study the landscape and paleoclimate evolution of the last 30,000 years. Until the beginning of the Holocene, the sediment sequence is characterized by the presence of massive fine silts ("Blue Clays" facies) with low organic matter, relatively low quartz and feldspars, anf high carbonate content. Nevertheless, an abrupt change in the local hydrology occurred between 18,000 and 20,000 years B.P., due to a change in the size of the valley that drained toward the lake, caused by a large mass movement. As a consequence, the area source sanged, a slight increase in the grain size occurred and carbonates were absent in the sediments. An expansion of forest after the Bolling period greatly reduced watershed erosion, and sedimentation in the lake became dominated by organic material during the Holocene. Coarser sands were deposited during a short interval at about 4,000 years B.P. and correlate with a short opening of the vegetation (maybe a first man-induced fires due to livestock management?). During the last 1000 years sedimentation has become coarser, organic-poor and clastic, with a much higher rate of sediment accumulation. This last stage begins with a charcoal-rich-ash layer, that represents a generalized period of fires and deforestation provoked to enlarge the subalpine grasslands. The consequence was an increase of soil erosion and sedimentation rate (García-Ruiz and Valero-Garcés, 1998).

Stop 8: The Gavín-Cotefablo morainic deposits

The Sía Valley is a tributary of the Gállego River within the Flysch Sector. It poses very interesting glaciological problems because the Gállego glacier penetrated laterally several kilometres, leaving morainic ridges and loose granitic blocks. The outermost blocks are located more than 6 km away from the Gállego Valley, what lead to interpret them as a result of an ancient glacial stage (Fontboté, 1948; Serrano, 1992).

On a lower topographic position very well defined morainic arcs appear, with a similar aspect than the rest of lateral deposits of the Gállego glacier. The most important one shows a coarse grain size distribution, with continuity in both sides of the Sía ravine. It is a subglacial deposit, with abundant granites and limestones, overlain by a highly heterometric supraglacial deposit, with palaeochannels infilled with sands with evidence of currents (ripples). This latter deposit has been interpreted as a kame deposit. The moraine culminates at 1290 m, thus indicating an ice thickness of 450 m in the Gállego glacier.

There is another morainic ridge at 1100 m, of lower size than the previous one. Between them there are other scarcely defined lateral tills with small glaciolacustrine deposits.

Stop 9: The Linás de Broto glacio-lacustrine deposit

Toward the east, after the Cotefablo mountain pass, a large flat area occupies the valley bottom of the Sorrosal valley, a tributary of the Ara River. During the Last Glacial Maximum the Ara Valley was occupied by an ice tongue coming from the southern cirques of the Monte Perdido massif (Ordesa Valley), the western face of the Vignemale massif (Bujaruelo Valley) and the north face of the Tendeñera Sierra. At the junction with the Sorrosal Valley, the ice tongue had 400 m in depth, melting finally around Sarvisé, where the lateral moraines quickly decrease in height. In the headwater of the Sorrosal ravine a small glacier developed, though it did not reach to contact with the Ara glacier.

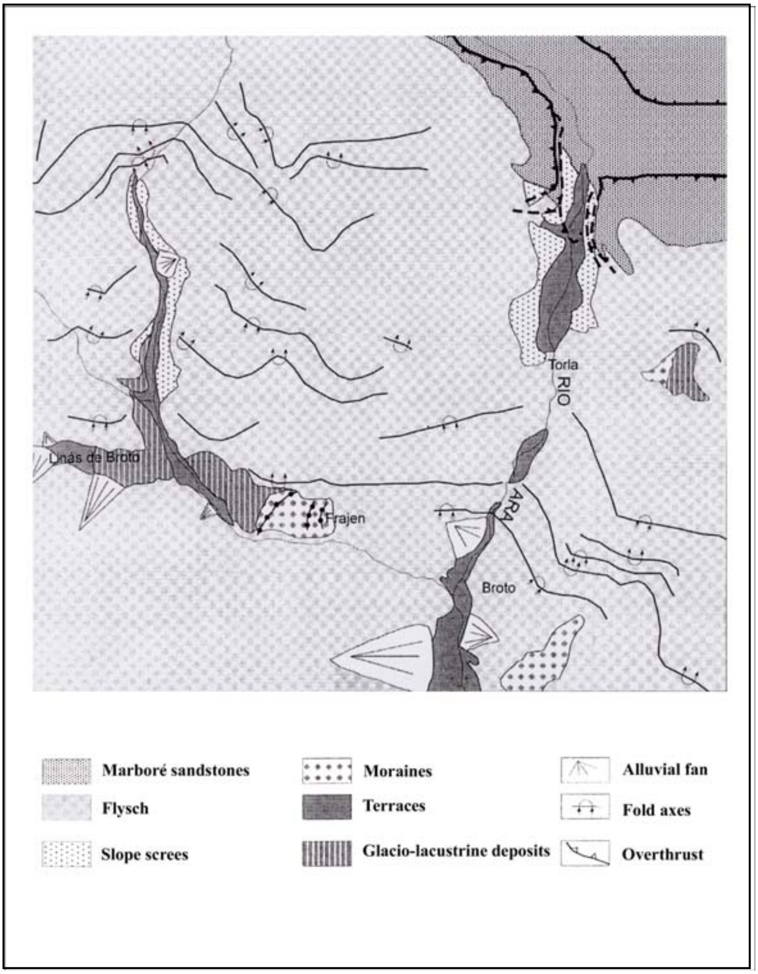


Figure 9. Location of Linas de Broto glaciolacustrine deposits.

In the Flysch Sector, the lateral moraines of the Ara glacier dammed the tributaries, resulting in the development of lakes that were infilled by sediments supplied by both yuxtaglacial torrents (flowing in the contact between the ice, moraine and the valley wall) and the tributary (Martí-Bono and García-Ruiz, 1993). This was the case of the Sorrosal ravine (as well as the Diazas and Buesa ravines). A clear lateral moraine occurs close to the village of Viu, corresponding to the maximum extent of the Ara glacier (Fig. 9). This moraine is the responsible of the formation of a lake of 2 km in length and 500 m width. Other lateral moraines appear at Frajén, 150 m below, showing different retreat stages. The incision of the Sorrosal ravine into the glaciolacustrine deposits allowed the exposure of a 60 m height trench (Serrat et al., 1982).
Fig. 10 shows two stratigraphic columns of the Linás de Broto deposit. The characteristics of the base of the deposit are unknown, since the incision made by the Sorrosal ravine does not affect to the whole deposit. In the case of the column A the base is composed of fluvial or fluviotorrential gravels. In the case of the Column B, there is a layer of sands and deltaic foresets layers under the gravels.

Over the gravels the presence of lacustrine clays with some striated gravels and blocks, laminated clays and sands reflects a lacustrine environments, dominated by fine sedimentation. This layer is 26 m thick, with frequent alternation between different facies. The clayey layers show sinsedimentary, normal and inverse faults, sometimes of glaciotectonic origin, but mainly as a consequence of sinsedimentary slumps.

A 24 m thick unit, mostly composed of fluvial gravels, with some thin clayey layers, deposited over the lacustrine clays.

The alternance of facies from the base to the upper part of the deposit is interpreted as the result of sedimentation in a lacustrine environment, subject to important fluctuations of the water depth and even with subaereal exposure phases. The two stratigraphic profiles show that (at least in the visible section) a first phase was dominated by fluvial sedimentation. Late, a lacustrine sedimentation occurred, sometimes with deep waters (massive and laminated clays) and sometimes with shallow waters (sands and even gravels, like deltaic facies). The short advances of the Ara tongue toward the Sorrosal Valley that occurred from time to time, explained the glaciotectonic activity. The occurrence of striated clasts and boulders in the clayey levels is due to the presence of floating ice on the lake, including tose boulders (dropstones).

The final stage is mainly fluvial, probably caused by the retreat of the ice and the consequent voiding of the lake, followed by gravel sedimentation. Nevertheless, new short dammings occurred, with the restoration of lacustrine conditions, especially visible in profile B. The upper level of sediment in the profile connect directly with the fluviotorrential deposits of the Sorrosal ravine.

A clayey bed located 22 m above the base of the deposit was dated by AMS (concentrated pollen) in 30,380 ± 400 years BP (Martí-Bono et al., 2002). This date is coherent with the results obtained in different Pyrenean sites, confirming the early age of the maximum extent of the Pyrenean glaciers (Montserrat, 1992; García-Ruiz et al., 2003).

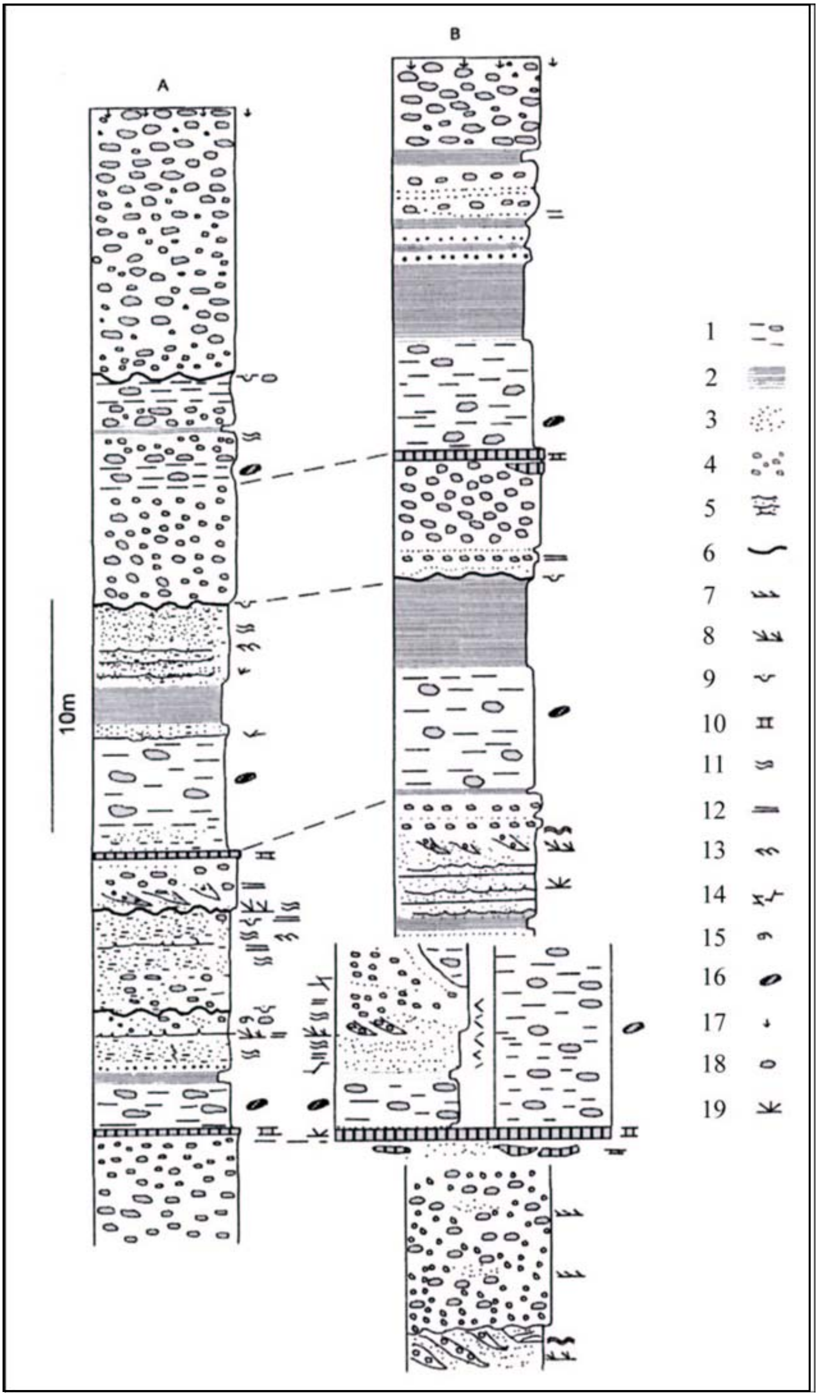


Figure 10. Stratigraphic logs in the glaciofluviolacustrine deposits of Linás de Broto.

Stop 10: The Ordesa-Monte Perdido National Park U-shaped valley

The Ordesa Valley is a tributary of the Ara Valley. During the Upper Pleistocene glaciation it had a powerful ice tonge coming from the south versant of the Monte Perdido massif. From the cirques, at about 3000 m asl, the ice masses went down toward the Ordesa valley by different ways, following the Cotatuero and Salarons small tributary valleys or, directly, from the Cilindro Cirque. Also, small ice tongues arrived from Tobacor and Custodia Sierras, throughout dramatic icefalls.

For thousands of years the ice eroded the pre-glacial valley, developing one of the most interesting U-shaped valleys in the Pyrenees. The whole valley was excavated in the Inner Sierras, on limestones, with some sandstone (Maestrichtien) layers, with a thickness of about 1000 m. The canyon shows vertical walls, with different scarps corresponding to horizontal outcrops. Several perched tributary valleys can be seen on the right versant. The very steep gradient of the hillslopes did not enable the preservation of lateral moraines. The valley bottom, flat and wide, shows frequent nick points that correspond to the pass by more resistant outcrops. This results in waterfalls (Estrecho, Cola de Caballo) or in rapids, like the Gradas de Soaso.

References

Andrieu, V., Hubschman, J., Jalut, G. and Herail, G. (1988). Chronologie de la deglaciation des Pyrénées françaises. Dynamique de sedimentation et contenu pollinique des paleolacs: application à l'interpretation du retrait glaciaire. *Bull. Assoc. Fran. pour l'Étude du Quaternaire*, 2/3, 55-67.

Barrère, P. (1952). Evolution mécanique et nivation sur les versants calcaiues de la haute montagne pyrenéenne. *Pirineos*, 24, 201-213.

Barrère, P. (1963). La période glaciaire dans l'Ouest des Pyrénées Centrales Franco-Espagnoles. *Bull. Soc. Géol. France*, 7 (5), 516-525.

Barrère, P. (1966). La morphologie quaternaire dans la region de Biescas et de Sabiñánigo (Haut Aragón). *Bull. Assoc. Fran. pour l'Étude du Quat.*, 1966 (2), 83-93.

Barrère, P. (1971): *Le relief des Pyrénées centrals franco-espagnoles. Cartes géomorphologiques*. Instutut de Géographie, Université de Bordeaux.

Bordonau, J. (1992). *Els complexos glacio-lacustres relacionats amb el darrer cicle glacial als Pirineus.* Geoforma Ediciones, Logroño, 251 pp.

Chueca, J. (1992). *Análisis geomorfológico de la fenomenología glaciar y periglaciar en el Macizo del Turbón-Sierra de Ballabriga (Pirineo oscense).* Instituto de Estudios Altoaragoneses, Huesca, 212 pp.

Chueca, J., Peña, J.L., Lampre, F., García-Ruiz, J.M. and Martí-Bono, C. (1998). *Los glaciares del Pirineo aragonés: estudio de su evolución y extension actual.* Departamento de Geografía, Universidad de Zaragoza, Zaragoza, 104 pp.

Copons, R. and Bordonau, J. (1997). El ultimo ciclo glacial (Pleistoceno Superior-Holoceno) en el macizo de la Maladeta (Pirineos centrales). *Revista de la Sociedad Geológica Española,* 10, 55-66.

Fontboté, J.M. (1948). La Ribera de Biescas. *Pirineos*, 7, 39-88.

García-Ruiz, J.M. and Ruiz-Budría, E. (1977). Sobre unos depósitos de ladera al sur de San Juan de la Peña (Prepirineo aragonés). *Trabajos sobre Neógeno-Cuaternario*, 6.

García-Ruiz, J.M. and Puigdefábregas, J. (1982). Formas de erosión en el flysch eoceno surpirenaico. *Cuadernos de Investigación Geográfica*, 8, 85-130.

García-Ruiz, J.M. and Martí Bono, C. (1994). Rasgos fundamentals del glaciarismo cuaternario en el Pirineo aragonés. In C. Martí-Bono and J.M. García-Ruiz, eds., *El glaciarismo surpirenaico: nuevas aportaciones*, Geoforma Ediciones, Logroño, 17-31 pp.

García-Ruiz, J.M. and Martí-Bono, C. (2001). *Mapa geomorfológico del Parque Nacional de Ordesa y Monte Perdido*. Ministerio de Medio Ambiente, Madrid, 106 pp.

García-Ruiz, J.M. and Valero-Garcés, B. (1998). Historical geomorphic processes and human activities in the Central Spanish Pyrenees. *Mountain Research and Development*, 18, 309-320.

García-Ruiz, J.M., Alvera, B., Del Barrio, G. and Puigdefábregas, J. (1990). Geomorphic processes above timberline in the Spanish Pyrenees. *Mountain Research and Development*, 10, 201-214.

García-Ruiz, J.M., Gómez-Villar, A., Ortigosa, L. and Martí-Bono, C. (2000). Morphometry of glacial cirques in the Central Spanish Pyrenees. *Geografiska Annaler*, 82A, 433-442.

García-Ruiz, J.M., Valero-Garcés, B., González-Sampériz, P., Lorente, A., Martí-Bono, C., Beguería, S. and Edwards, L. (2001). Stratified scree in the Central Spanish Pyrenees: Palaeoenvironmental implications. *Permafrost and Periglacial Processes*, 12, 233-242.

García-Ruiz, J.M., Valero-Garcés, B., Martí-Bono and González-Sampériz, P. (2003). Asynchroneity of maximum glacier advances in the central Spanish Pyrenees. *Journal of Quaternary Science*, 18, 61-72.

García Sáinz, L. (1935). Morfología glaciar y periglaciar de la región de la Noguera (C. Cinca-Segre). *Bol. Soc. Geogr. Nac.,* 54, 64-110.

García Sáinz, L. (1942). Evolución morfológica del valle del Aragón. *Estudios Geográficos*, 6, 5-31.

Guiter, F., Triganon, A., Andrieu-Ponel, V., Ponel, P., Hébrard, J.P., Nicoud, G., De Beaulieu, J.L., Brewer, S. and Guibal, F. (2005). First evidence of “in situ” Eemian sediments on the high plateau of Evian (Northern Alps, France): Implications for the chronology of the last glaciation. *Quaternary Science Reviews*, 24, 35-47.

Höllermann, P. (1985). The periglacial belt of mid-latitude mountains from a geoecological point of view. *Erdkunde,* 39, 259-270.

Lampre, F., Peña, J.L. and Chueca, J. (1998). Aproximación al conocimiento de los glaciares rocosos en la vertiente meridional del Pirineo oriental y central. In A. Gómez Ortiz and A. Pérez Alberti, eds., *Las huellas glaciares de las montañas españolas*, Universidad de Santiago de Compostela, pp. 291-306.

Llopis Lladó, N. (1947). El relieve del Alto valle del Aragón. *Pirineos*, 5, 81-166.

Lorente, A., García-Ruiz, J.M., Beguería, S. and Arnáez, J. (2002). Factors explaining the spatial distribution of hillslope debris flows. A case study in the Flysch Sector of the Central Spanish Pyrenees. *Mountain Research and Development*, 22, 32-39.

Martí-Bono, C. (1973). Nota sobre los sedimentos morenicos del Alto Aragón. *Pirineos*, 107, 39-46.

Martí-Bono, C. (2000). *El glaciarismo cuaternario en el Alto Aragón Occidental*. Collecció de Tesis Doctorals Microfitxadas, Universidad de Barcelona, 254 pp.

Martí-Bono, C. and García-Ruiz, J.M. (1993). Complejos morrénicos laterales en la vertiente surpirenaica aragonesa. *Tercera Reunión del Cuaternario Ibérico*, AEQUA, Coimbra, 149-156 pp.

Martí-Bono, C. and García-Ruiz, J.M., eds.(1994). *El glaciarismo surpirenaico: nuevas aportaciones.* Geoforma Ediciones, Logroño, 142 pp.

Martí-Bono, C., González-Sampériz, P., Valero-Garcés, B. and García-Ruiz, J.M. (2002). El depósito glaciolacustre de Linás de Broto (Pirineo aragonés) y su implicación paleoambiental. In A. Pérez-González, J. Vegas and M.J. Machado, eds., *Aportaciones a la Geomorfología de España en el inicio del Tercer Milenio,* IGME, Madrid, pp. 77-83.

Martínez de Pisón, E, (1989). Morfología glaciar del valle de Benasque (Pirineo aragonés). *Ería,* 18, 51-64.

Martínez de Pisón, E. (1991*). El valle de Benasque. Estudio geomorfológico*. Instituto de Estudios Altoaragoneses, Huesca, 196 pp.

Martínez de Pisón, E. and Serrano, E. (1998). Morfología glaciar del valle de Tena (Pirineo aragonés). In A. Gómez Ortiz and A. Pérez Alberti, eds., *Las huellas glaciares de las montañas españolas*, Universidad de Santiago de Compostela, 239-261 pp.

Montserrat, J. (1992). *Evolución glaciar y postglaciar del clima y la vegetación en la vertiente sur del Pirineo: Estudio palinológico.* Instituto Pirenaico de Ecología, Zaragoza, 147 pp.

Nussbaum, F. (1949). Sur les traces des glaciers quaternaries dans la region de l'Aragón. *Pirineos*, 13-14, 497-518.

Nussbaum, F. (1956). Observations morphologiques dans la region de la Noguera Pallaresa. *Pirineos*, 39-42, 57-97.

Panzer, W. (1926). Talentwicklung und Eiszeitkilma in nordöstlichen Spanien. *Abh. Senckenbg. Nat. Ges*., 39: 141-153. (Trad. En *Estudios Geográficos*, 30, 79-130, 1948).

Penck, A. (1883). Die Eiszeit in den Pyrenaen. Mitt. Ver. Erdk. Leipzig. (Translated to French: La période glaciaire dans les Pyrénées". *Bulletin de la Société d'Histoire Naturelle de Toulouse,* 19, 105-200.

Peña, J.L., Chueca, J. and Lampre, F. (1998). Estado actual del conocimiento del glaciarismo pleistoceno de la vertiente meridional del Pirineo central. In A. Gómez Ortiz and A. Pérez Alberti, eds., *Las huellas glaciares de las montañas españolas,* Universidad de Santiago de Compostela, pp. 211-238.

Peña, J.L., Sancho, C., Lewis, C., McDonald, E and Rhodes, E. (2004). Datos cronológicos de las morrenas terminales del glaciar del Gállego y su relación con las terrazas fluvioglaciares (Pirineo de Huesca). In J.L. Peña, L.A. Longares and M. Sánchez, eds., *Geografía Física de Aragón. Aspectos generales y temáticos*. Universidad de Zaragoza e Institución Férnando El Católico, Zaragoza, pp. 71-84.

Seret, G., Dricot, E. and Wansard, G. (1990). Evidence for an early glacial maximum in the French Vosgues during the last glacial cycle. *Nature*, 346, 453-456.

Serrano, E. (1992). Huellas de una glaciación pre-pleniglaciar en la Ribera de Biescas (cuenca del Gállego, Pirineo aragonés). *Cuadernos de Sección Historia*, 20, 213-227.

Serrano, E. (1998). *Geomorfología del Alto Gállego. Pirineo aragonés.* Institución Fernando El Católico, Zaragoza, 501 pp.

Serrano, E. and Martínez de Pisón, E. (1994). Geomorfología y evolución glaciar en el Pirineo aragonés. In C. Martí-Bono and J.M. García-Ruiz, eds., *El glaciarismo surpirenaico: nuevas aportaciones. Geoforma Ediciones*, Logroño, pp. 33-64.

Serrat, D., Vilaplana, J.M. and Martí-Bono, C. (1982). Some depositional models in glaciolacustrine environments (southern Pyrenees). In E.B. Evenson, Ch. Schlüchter and J. Rabassa (eds.*), Tills and related deposits*, Balkema, Rotterdam, 231-244 pp.

Vidal Box, C. (1933). Nota sobre la glaciología pirenaica. *Bol. R. Soc. Esp. Hist. Nat.*, 33, 273-285.

Vilaplana, J.M. (1983). *Estudi del glaciarisme quaternary de les altes valls de la Ribagorça*. Unpublished PhD, Universidad de Barcelona, 322 pp.

ROAD LOG:

First day (4th September 2005). Zaragoza- Aragón Valley-Biescas.

Departure from the Conference Hall at 8,30 a.m.

Road N-330 (75 Km), Zaragoza-Huesca.

Road A-132, **Coffee stop** at Murillo de Gállego (10-10,30 a.m.).

Road A-132, Pte la Reina (11,15 a.m.).

Road A-176 (37 Km), upstream along the Aragón Subordán River. **Stop 1**, the Hecho glacier terminal basin**. Stop 2**, Boca del Infierno gorge and periglacial screes. **Stop 3**, Upper Hecho glacial valley, and lateral moraines (Stop 3 is optional, according to time availability).

Road A-176 (37 Km). Return to Pte la Reina (14,15 h).

Road N-240 (20 Km). Pte la Reina-Jaca (upstream along the Aragon River).

Road N-330 (12 Km), (upstream along the Aragon River). Castiello de Jaca, lunch (15 h). **Stop 4** Aragón glacier terminal basin (lateral and frontal moraines, terraces).

Road N-330 (32 Km). Return to Jaca-Sabiñánigo.

Road N-260 (13 Km). Sabiñánigo-Biescas. Night at Biescas (Hotel Ruba) (20 h).

Second day (5th September 2005). Biescas- Portalet-Biescas.

Departure from the Hotel Ruba (9 a.m.).

Road N-260 (12 Km), Sabiñánigo direction, **Stop 5** Senegüé. Frontal moraine of the Gállego valley, and glacial landscape. Walk of about 30 minutes (9,30-11,45 a.m.).

Roads N-260 and A-131(17 Km), (upstream Gállego Valley). **Stop 6**, Sta Elena. Lee-side glacial deposits, periglacial scree and subglacial gorge. Ten minutes walk (12-13 h).

Road A-131, Escarrilla. Stop for lunch, at Restaurante Mingo (13,30-15,30 h).

Road A-131 and track (19 Km). **Stop 7**, Tramacastilla lake (moraines of the glacial inner stages). If the road conditions were not suitable for coach traffic in the dates of the field trip, this stop would be changed for another near the French border (Portalet).

Road A-131 (Return to Biescas (20 h). Night at Biescas (Hotel Ruba).

Third day (6th September 2005). Biescas-Ordesa-Zaragoza.

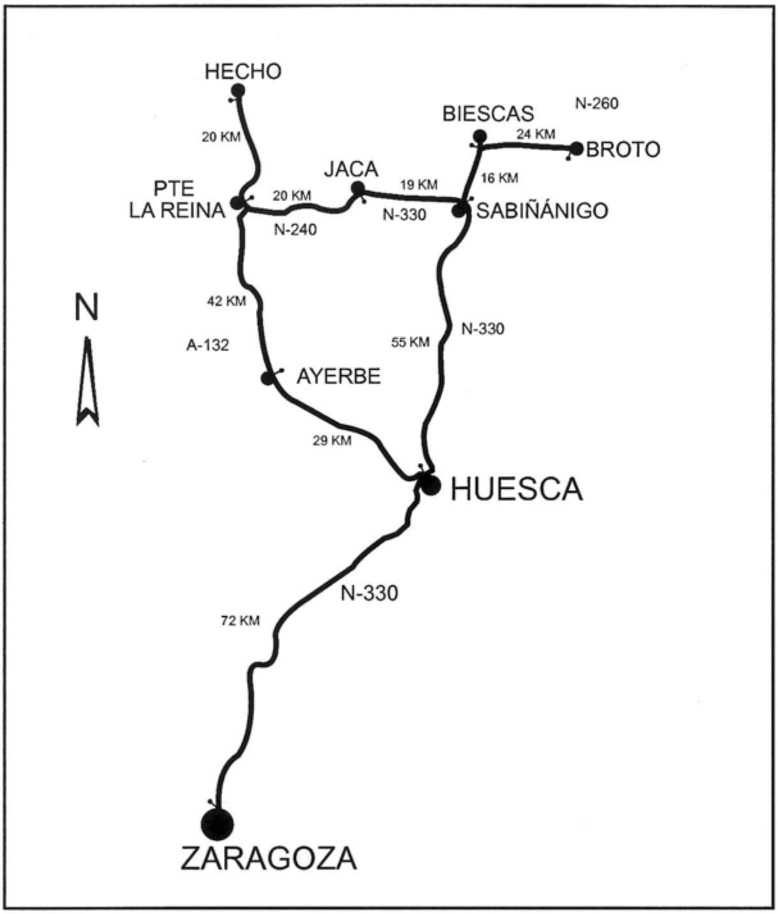
Departure from the Hotel Ruba (9 a.m.).

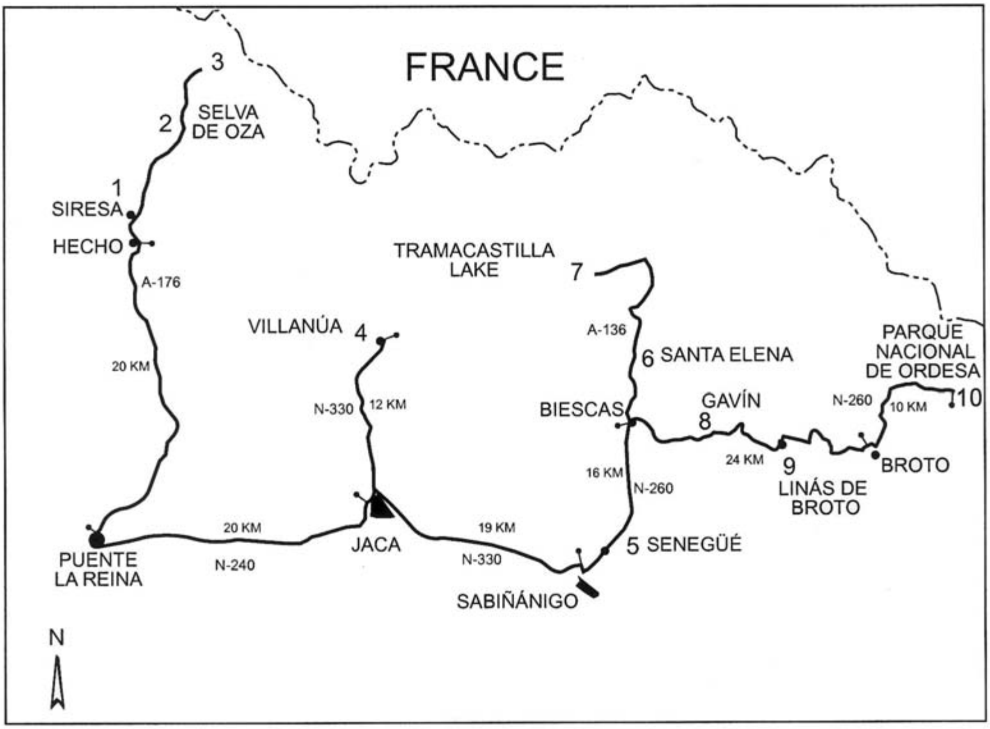
Road N-260, Ordesa direction, **Stop 8**, Gavin-Cotefablo lateral moraines.(9,15-9,45 a.m.).

Road N-260, Linás de Broto, **Stop 9**, Glacilacustrine deposits. Thirty minutes walk (boots or field shoes are advisable), (10-11,30 a.m.).

Road N-260, **Stop 10**, Ordesa National Park. Glacial valley with limestone cliffs. Two hours walk. Lunch. (12-16 h).

Return to Zaragoza (16-18,30 h).




FRANCE
3
2
SELVA DE OZA
1
SIRESA
HECHO
A-176
20 KM
PUENTE LA REINA
20 KM
N-240
JACA
VILLANÚA
4
N-330
12 KM
19 KM
N-330
SABIÑÁNIGO
TRAMACASTILLA LAKE
7
A-136
6
SANTA ELENA
BIESCAS
16 KM
N-260
5
SENEGÜÉ
GAVÍN
8
24 KM
9
LINÁS DE BROTO
N-260
10 KM
10
BROTO
PARQUE NACIONAL DE ORDESA
N