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THE INFLUENCE OF THE GEOMORPHOLOGIC HERITAGE ON PRESENT SLOPE DYNAMICS. THE GREDOS CIRQUE, SPAIN

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ABSTRACT.- Sierra de Gredos is the highest mountain range in the Sistema Central which crosses the Iberian Peninsula from west to east at a latitude of 40° N. Research was carried out at the valley head of an area of glacial origin -Gredos Cirque-, situated on the northern side of this range, below its highest peak -Almanzor, which is 2,592 m in height.

This work analyzes the different landforms, and infers from them the geomorphologic history of the Cirque. In addition, it studies the accumulation and permanence of the nival slope cover, as the fundamental source of water, the main present agent of erosion . The conclusions show the relationship between old sediment and weathered mantle distribution and the effective capacity of present erosive activity on slopes.

As a result of this work, a model of slope dynamics for glaciated areas in the Iberian peninsula has been proposed. According to this model, the Pleistocene glaciers accentuated a significant geomorphologic asymmetry between eastern and western slopes of valley heads. The present snow distribution patterns mirror those during the Pleistocene. Although snow amounts are obviously significantly lower, it is the present principal agent erosion and is accentuating this contrast. This is because, with the exception of the higher average temperatures, especially in summer, the same Pleistocene system of snow accumulation is continuing. This model will enable research work to be initiated in present dynamic Gredos Cirque, where it has never been carried out before.

RESUMEN: La investigación se llevó a cabo en la cabecera de un valle en un área de origen glaciar: Circo de Gredos, situado en la cara Norte de la Sierra de Gredos (Sistema Central) a 40 ° de latitud Norte, bajo su pico más alto (Almanzor, 2592 m de altitud).

Este trabajo analiza los diferentes paisajes y deduce a partir de ello la historia geomorfológica del Circo. Además, se estudia la acumulación y permanencia de la cubierta nival, como fuente fundamental de agua, principal agente actualmente de la erosión. Las conclusiones muestran la relación entre sedimentos antiguos y la distribución del manto meteorizado y la capacidad efectiva de la actividad erosiva actual en las laderas.

Como resultado de este trabajo se propuso un modelo de dinámica de vertientes para áreas glaciadas en la península Ibérica. De acuerdo con este *modelo, los glaciares pleistocenos acentuaron una significativa asimetría geomorfológica entre las laderas al Este y al Oeste de la cabecera del valle. El modelo actual de distribución de la nieve asemeja esta situación durante el Pleistoceno. Aunque las cantidades de nieve son significativamente menores, éste es actualmente el principal agente de erosión y está acentuando este contraste. Esto es debido a que con la excepción de las altas temperaturas medias, especialmente en verano, continúa el mismo sistema de acumulación de nieve que durante el Pleistoceno. Este modelo permitirá que sean inciados trabajos de investigación sobre la dinámica actual del Circo de Gredos, donde nunca habían sido llevados a cabo anteriormente.*

Key Words: *geomorphology, slope dynamics, Sierra de Gredos*

1. Introduction

The aim of the geomorphologic research in this area was to study the interaction between the present slope activity and the preglacial sediment and weathered mantle distribution. The research hypothesis was formed on the idea that present slope processes are driven by water derived from snowfall. Consequently, topoclimate (the interaction of climate and topography) is a controlling influence on local geomorphology. In addition, existing landforms, particularly deposits and weathered mantle, play an essential role in limiting geomorphic processes.

This paper presents a detail discussion of three representative sectors that contain examples of the range of the landforms and contemporany processes in this area. Afterwards the whole range of erosive landforms, deposits and weathered mantle of the Gredos Cirque was determined. On the basis of this typology, the geomorphologic evolution during periods before, during and after glacial activity was reconstructed. Subsequently, the snow cover distribution was analyzed. The slope relief, snow cover and erosion distributions were contrasted in order to study the relationship between them.

2. Geomorphological background

The study area is situated in the Sierra de Gredos, the highest section of the Central System (Fig. 1), which crosses the Iberian Peninsula from the SW to the NE. It consists of tectonic Paleozoic blocks raised during the Alpine tectonic activity. Although the highest peaks of this range were altered considerably by glaciation during the late Pleistocene, most summits areas tend to be flat and very broad, reflecting remnants of the pre-Alpine erosion surface.

The Sierra de Gredos is composed, principally, of granites that form tectonic blocks inclined towards the north and are separated by a network

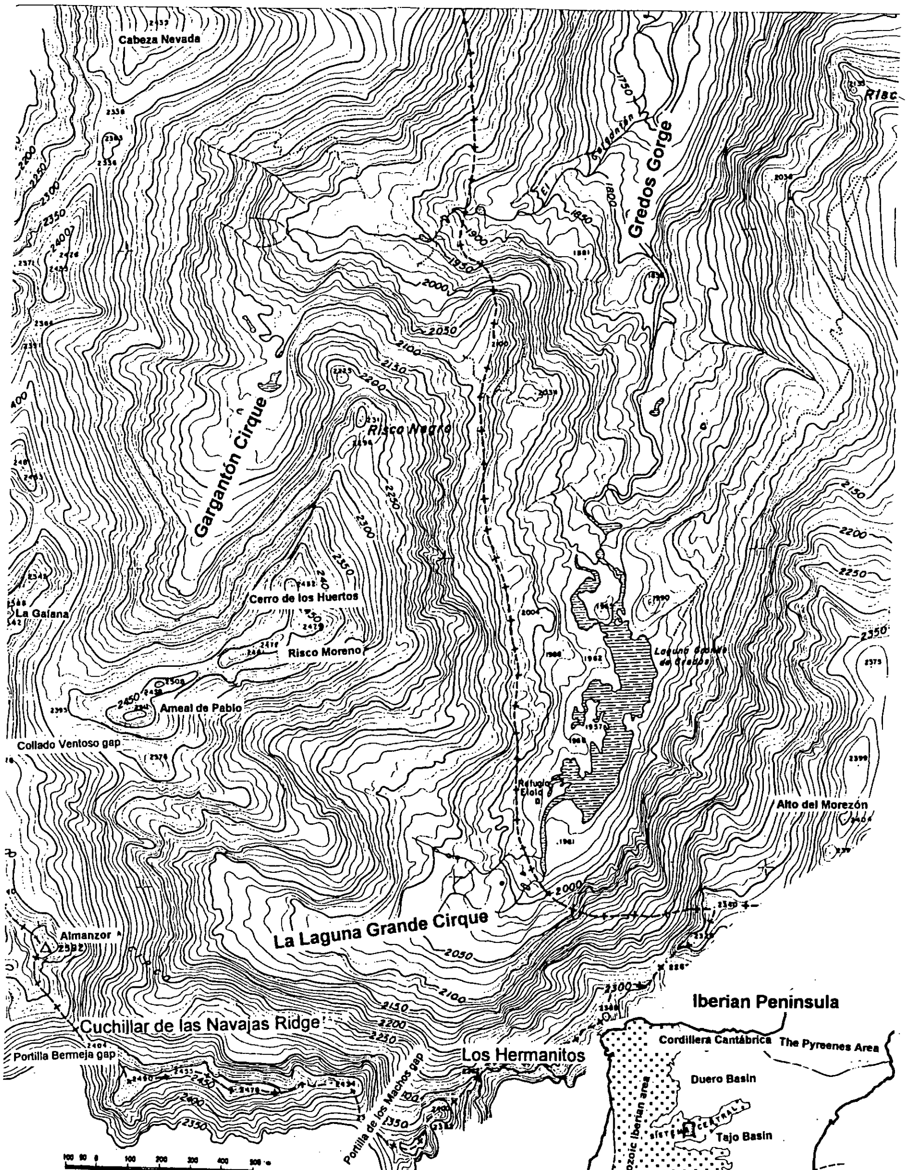


Fig.1. Location map.

of fault lines, running in N-S and E-W directions. This tectonic history determines the most important geomorphologic characteristic of the Sierra: a steep southern wall incised only by short ravines and a more gently inclined northern slope, and broken by longer and deeper valleys. In the late Pleistocene, glaciers were located at the heads of these northern valleys and attained a length of 9 km. In contrast, the glaciers on the southern slope were much shorter, rarely exceeding a length of 2 km.

The study of glaciation in the Sierra de Gredos area began in the second half of the last century and focused upon the identification and description of the main areas of glacial activity during the Pleistocene. Between 1862 and 1970, many studies were published which defined, delimited, described and interpreted the glacial relief of the Sierra de Gredos. Early studies (Prado 1862, Schmieder 1915, Huguet del Villar 1915, Obermaier and Carandell 1916, Vidal 1932, 1936, 1948) identified a number of important regional characteristics including: glacial features were usually restricted to gorges on the north slope of the range, multiple retreat phases identified by moraines, a regional Late Pleistocene snowline at 1,800-1,900 m, with glaciers extending down to 1,415 m. In addition, it is worth noting that only passing reference was made to glacial evidence in the incipient cirques on the southern flank of the Sierra de Gredos. The sites of former small niche glaciers were found on the south side of the Sierra in the Alardos gorge by Hernández-Pacheco (1962), with moraines situated above the 1,800 m level and Asensio (1966) recognized evidence of former hanging niche glaciers in the Santa María gorge.

During the 1970's and early 1980's a basic model of the glacial processes of the Sierra de Gredos was established. Martínez de Pisón and Muñoz (1973) defined the important lines of glaciation in Sierra de Gredos and provided an exhaustive description of the glacial forms on the northern slope. In this area glaciers were constrained by the prior form of the fluvial valleys; intense periglaciation was both contemporaneous with the glacial period and active to the present. Evidence of only one glaciation, the Würm (with only minor readvances), has been identified. Arenillas and Martínez de Pisón (1977) studied the gorges on the southern side of Gredos and concluded that the glacial forms are of two types: (I) forms which are derived from hanging glaciers on southern slopes with a very steep incline and without cirques, which are only found in the areas close to the peaks; (II) more obvious glacial forms, composed of eight well defined cirques and two nivo-glacial niches. Sanz Donaire (1977) studied glaciation on the southern side in the area immediately to the west of Gredos Cirque, describing nine glacial cirques and various snow hollows. Pedraza and Lopez (1980) made an overall analysis of the glacial forms of Gredos, establishing a typology and evolution. Rubio, Pedraza, and Carrasco (1992) established the Pleistocene glacial sequence in the Sierra de Gredos, defining two stages of glaciation, without specifying dates.

At present, there are few climatic data to evaluate the climate of the Sierra de Gredos. The only high elevation station is at Gredos Platform area

(2,200 m a.s.l.) for which records of annual precipitation totals (October 1973-September 1988, table 1). Annual totals are highly variable from year to year. The only meteorological stations are at low elevations. Those to the south show high annual precipitation totals, while those to the north record lower precipitation levels (Table 2). This contrast is rare in Spanish mountain ranges and arises from the fact that the Sierra de Gredos rises to a height of 2,000 m above the southern plains of La Fosa del Tajo basin and acts as a topographic barrier to the warm humid tropical SW winds, which prevail between autumn and spring (García Fernández 1986). This marked topographical feature gives rise to heavy showers on the southern side of the Sierra, which account for the high levels of average rainfall at the stations on that side, notwithstanding their low altitude. Hydrologic calculations suggest that rainfall precipitation in excess of 3,000 mm per annum may occur at higher levels (1,500-2,000 m) on the southern slope of Gredos (García Fernández, 1986). In contrast, although the SW winds also produce the dominant precipitation events on north faces, these take the form of snowfalls which are able to accumulate on the leeward side of the range.

Table 1. *Annual precipitations (mm) of Gredos platform area (2,200 m)*

Year	1972/73	1973/74	1974/75	1975/76	1976/77	1977/78	1978/79	1979/80
mm	1,431	1,673	945	630	1,823	1,800	1,206	697
Year	1980/81	1981/82	1982/83	1983/84	1984/85	1985/86	1986/87	1987/88
mm	990	1,137	1,578	1,549	1,676	765	1,687	2,272

Table 2. *Climatic data of Sierra de Gredos stations*

Station	Location	Altitude (m.a.s.l.)	Annual precipitation (mm)
Candeleda	South	430	1,009
Arenas de San Pedro	South	510	1,414
Guisando	South	766	2,271
Bohoyo	North	1,142	884
Hoyos del Espino	North	1,440	906
Navarredonda	North	1,525	986

The present work is focussed on the Gredos Cirque, the headwater reaches of the most important valley on the northern slopes. (longitude 5° 15' E; latitude 40° 15' N; maximum altitude: the Almanzor Peak (2,592 m).

3. Geomorphologic description of the key areas in Gredos cirques

Gredos cirque, at the head of Gredos Gorge, faces north and has an area of approximately 2.5 km^2. It is bordered to the east by Cuento Ridge which has a flat summit descending gently from the Alto de Morezón at 2,349 m. to an altitude of approximately 2,075 m. The western limit of the cirque is formed by a sharper and more uneven ridge whose highest peak is Almanzor (2,592 m) and which continues towards the north almost without losing height, having the La Galana (2,568 m.) and Cabeza Nevada (2,433 m.) peaks at that end.

The very sharp crest of the Hermanitos-Cuchillar de las Navajas (2,366-2,490 m.) forms the cirque's southern limit. This crest separates the cirque from the heads of the southern ravines of Tejea, Chilla and Blanca.

Within this area, an important ridge of peaks of a similar height to those above mentioned (Ameal de Pablo, 2,505 m.; Risco Moreno, 2,478 m.; Cerro de los Huertos, 2,472 m.) and tending in a N-S direction, divides the Gredos cirque into two separate valleys; the cirque named Laguna Grande, with the floor between 1,900 and 2,000 m and the Garganton cirque, which is a little higher (2,000 and 2,100 m). The two branches join at the northern end of the study area.

In this study, we consider three relatively small areas, where the important contrasts which define both the geomorphologic characteristics and the erosional development of the whole area can be analyzed.

a) The valley head of the Laguna Grande cirque.

This area is bordered by the ridge of Cuchillar de las Navajas and the ridge of Almanzor (Fig. 2).

The ridge of Cuchillar de las Navajas separates two very contrasting landscapes. Preglacial periglacial forms predominate on the southern side, with rock outcrops such as tors, affected by subsequent chemical weathering. Taffoni are common on the steepest walls as are pits on the flat steps. At the bases of these tors are periglacial block fields of 3-4 meters thickness, in which the blocks are angular, (35 cm to 4 m in diameter) and exhibit signs of chemical weathering. These deposits are widespread on the southern slopes, except in the Portilla de los Machos, where the northern slope above the limit of glacial erosion is also covered by this deposit. This old periglacial deposit has been removed locally by erosion in two situations: first, at the heads of the south-draining streams which are forming badlands at their lowest levels; second, where snow accumulation at the eastern side of pronounced spurs is most marked. This erosion has developed nivation niches, such as the one on the eastern side of the Portilla de los Machos gap (see Photo 1). Where the block field deposit has been removed, a zone of chemically weathered bedrock is frequently left exposed. The weathered zone has a thickness of 0.5 to 1.5 m, as can be observed in many gullies.

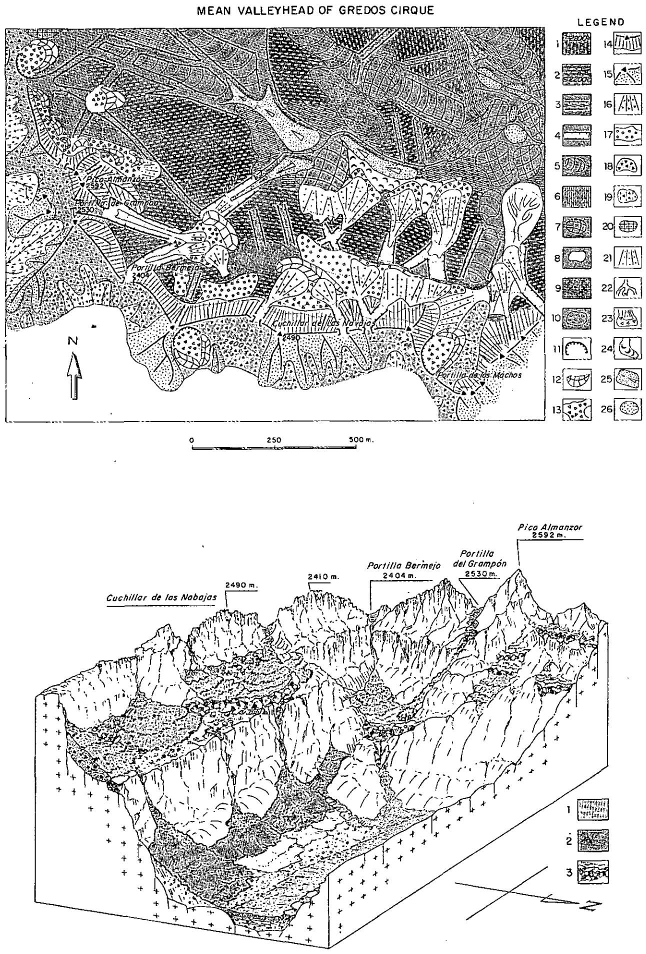


Fig. 2. Valleyhead of Gredos cirque: **2.A.** Geomorphologic scheme. *Forms caused by glacial erosion:* 1. Glacially smoothed valley walls (with smoothing in slope direction). 2. Glacially smoothed valley walls (with smoothing in perpendicular direction of the slope). 3. Channels of deep incision along fault lines where chemical weathering has extended. 4. Channels of shallow glacial incision also along major fault lines. 5. Glacially smoothed spurs, on the valley sides. 6. Glacial valley floor. 7. Glaciated valley steps 8. Glacial depressions. 9. Glacial shoulders. *Forms caused by glacial sedimentation:* 10. Till deposits associated with valley steps. *Nivation forms:* 11. Snow hollows. 12. Protalus ramparts. 13. Other deposits removed by nivation. *Unglaciated rocky slopes:* 14. Walls affected by recent intense gelifraction. 15. Walls affected earlier by gelifraction, gullying and chemical weathering. *Deposits of non-glacial origin.* Deposits arising directly from recent gelifraction: 16. Talus cones. 17. Scattered blocks. *Block deposits caused by the earlier gelifraction and affected by chemical weathering:* 18. Autochthonous. 19. Removed. 20. Periglacial patterned ground. *Gravity deposits:* 21. Rockfall talus 22. Alluvial talus 23. Scattered blocks. 24. Gelifluction deposits. 25. Alluvial fans. 26. Bogs. **2.B.** Block Diagram. 1. Gelifraction deposits in situ. 2. Rockfall talus. 3. Protalus ramparts.

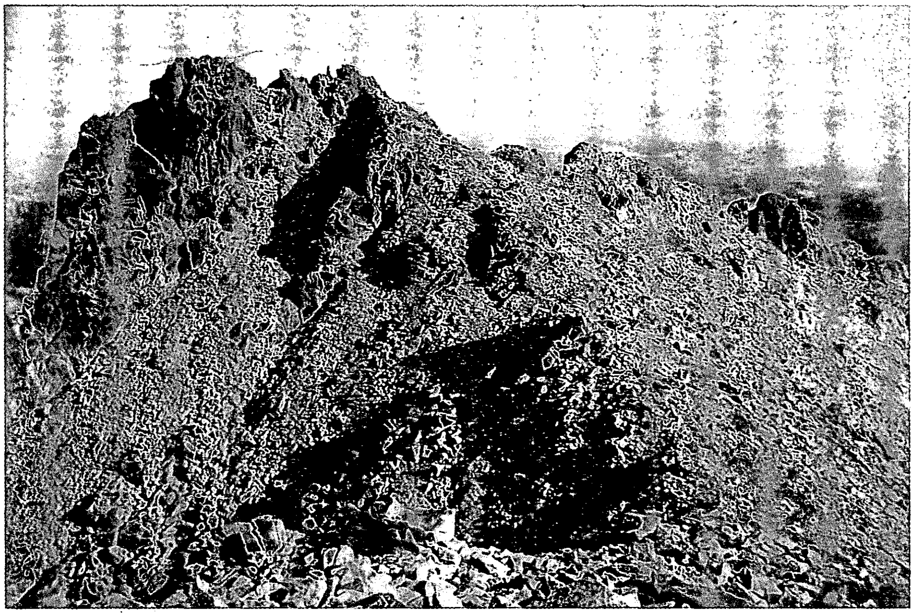


Photo 1. Portilla de las Mulas gap. The gap is cover by old periglacial blockfield. The blockfield is removed by a snow hollow at the bottom of the photograph.

On the northern side of the Portilla, three clearly differentiated landscape units can be distinguished. The upper level is a vertical rock-wall (about 85° inclination) with a rectilinear profile. It is modified by frost action (lichenometry evidence), and shows no signs of chemical weathering. The only weathering features on this side are in some deep channels cut along fault lines in which deep-weathering has penetrated to considerable depth, as can be observed in Almanzor north channel (see Photo 2).

Below the main rock-wall, there is a marked glacial shoulder ("alp") at 2,400 to 2,300 m in altitude. On it lie a series of cones of periglacial deposits which came from the channels mentioned above. The blocks of these deposits vary greatly in size (from 20 cm to 3 m in diameter). They exhibit no traces of chemical weathering, and have only a slight lichen cover. The deposits are crudely stratified. In places the cones have been modified by the action of permanent snow patches, which according to oral sources were particularly important in the last century. Because of this, east-facing nivation hollows and protalus ramparts have been formed.

The lower section of the valley side (2,250 to 2,050 meters in altitude) has been clearly modeled by glacial flow. It remains steep (75° on average)

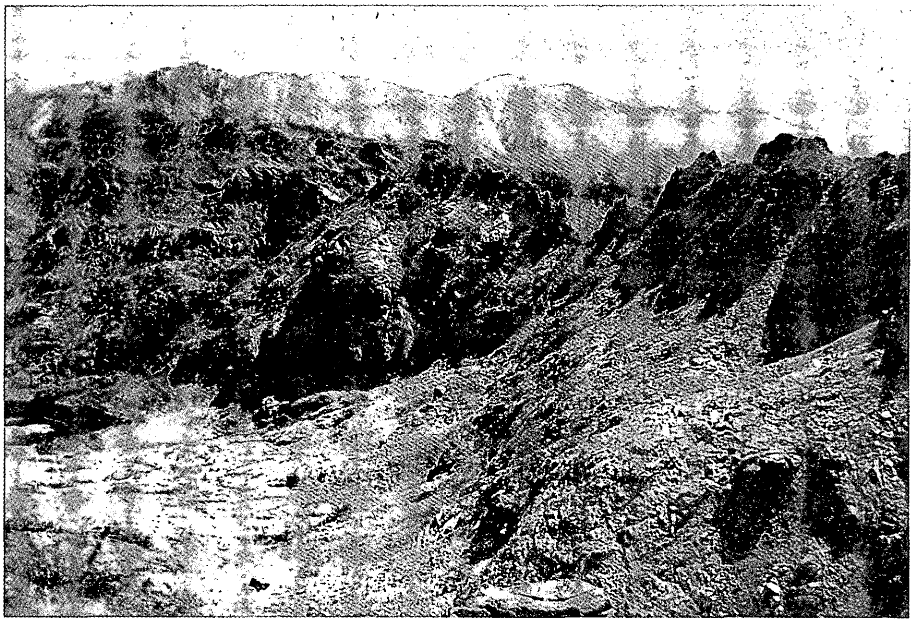


Photo 2. Northern slope of Cuchillar de las Navajas Ridge and western slope of Los Hermanitos Ridge in background. The glacial shoulder covered by gelifract deposits is visible in the foreground, with gravity cones situated at the foot of the wall.

and is frequently striated and grooved across the slope. There are also a series of channels, continuations of those which have been formed in the upper level and following the same fracture lines. At the inner part of these channels there is a significant level of chemical weathering which hasn't been removed by the ice. In winter and spring, snow avalanches, which accumulate on the upper shoulder, descend these channels. Quantities of blocks are also transported, by avalanches or rockfall, through the channels to accumulate as talus at the base of this wall. The finest materials are deposited at the highest part of the talus and the large blocks are deposited at the base. The debris cones have advanced onto the valley floor, sometimes covering gelifluction lobes formed at their outer edge. Stream action from melting snow forms extensive alluvial fans at the foot of most cones. When the channels have a wide head and the flow of water is therefore considerable, there are frequent debris flow processes over these cones.

The western side of the Almanzor ridge is similar to the southern side of the Cuchillar de las Navajas ridge. On the other hand, the eastern side of Almanzor is quite different from the northern side of the Cuchillar de las

Navajas. The glacial action here reached higher altitudes (over 2,500 m). With the exception of the peak of Almanzor there is a very small supraglacial wall here (20 meters in height being the average with absence of striae). The small quantity of deposits which accumulated here have been completely removed by the action of nivation. The rest of the lower slope (85% of the whole slope) is less steep (45° on average) and has been markedly smoothed by the action of the ice. Frequent striae and grooves run in the slope direction and the channels which follow the fracture lines have been intensely excavated by the ice. Here, the level of weathering which exists at the Cuchillar de las Navajas wall has disappeared completely. As there are no deposits at either the higher or lower levels and the wall is almost completely free of sediments.

b) Garganton cirque.

The characteristics of the Laguna Grande cirque are repeated in an similar form at the Garganton cirque (see Fig. 3). This valley head is narrower and is bordered by a ridge running in a N-S direction, whose most important peak is La Galana (2,542 m) and by another ridge running in a SW-NE direction, whose principal peaks are Ameal de Pablo (2,511 m), Risco Moreno (2,481 m) and Cerro de los Huertos (2,478 m). A gap known as Collado Ventoso (2,478 m) separates these ridges.

The northwestern side of the Risco Moreno ridge displays all of the features evident on the northern side of the Cuchillar de las Navajas ridge. The slope is divided into three clearly defined sections; an upper vertical section, a glacial shoulder with recent periglacial deposits, and a lower glacial section with plentiful coarse deposits at its base.

The eastern sides of Galana and Almanzor also share this similarity. The only difference between them is that, as Galana is lower in altitude, the upper periglacial level is absent. Elsewhere, the same characteristics repeat themselves. The slope is in the form of a long but not very steeply inclined surface and markedly polished by the action of the ice (always in the same direction as that of the slope). There is a complete absence of deposits. The cirque is also noticeably asymmetrical (See Photo 3 and Fig. 4).

c) Cabeza Nevada.

As has been explained, some of the summits areas surrounding the cirque are formed by broad plateaus, which form a contrast with the sharp peaks described earlier. To analyze this type of landscape as well, we chose the area of peaks known as Cabeza Nevada (2,435 m) (see Fig.4 and Photo 4).

The summit of the Cabeza Nevada is a gently sloping old periglacial block field with very similar characteristics to those of the deposits on the southern side of the Cuchillar de las Navajas ridge and the western side

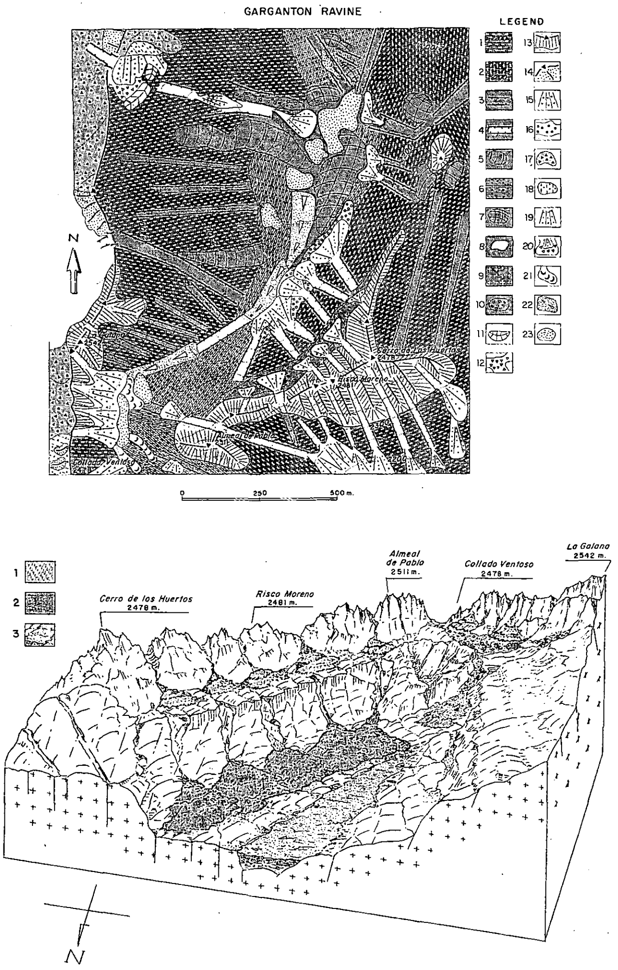


Fig. 3. Garganton ravine. **3.A.** Geomorphologic scheme. *Forms caused by glacial erosion*: 1. Glacially smoothed valley walls (with smoothing in slope direction). 2. Glacially smoothed valley walls (with smoothing in perpendicular direction of the slope). 3. Channels of deep incision along fault lines where chemical weathering has extended. 4. Channels of shallow incision also along major fault lines. 5. Glacially smoothed spurs, on the valley sides. 6. Glacial valley floor. 7. Glaciated valley steps 8. Glacial depressions. 9. Glacial shoulders. *Forms caused by glacial sedimentation:* 10. Till deposits associated with valley steps. *Nivation forms:* 11. Protalus ramparts. 12. Other deposits removed nivation. *Unglaciated rocky slopes:* 13. Walls affected by recent gelifraction. 14. Walls affected earlier by gelifraction, gullying and chemical weathering. *Deposits of non-glacial origin. Deposits arising directly from recent gelifraction:* 15. Talus Cone. 16. Scattered blocks. *Block deposits caused by the earlier gelifraction and affected by chemical weathering:* 17. Autochthonous. 18. Removed. *Gravity deposits:* 19. Rockfall talus. 20. Scattered blocks. 21. Gelifluction deposits. 22. Alluvial fans. 23. Bogs. **3.B.** Block Diagram. 1. Gelifraction deposits in situ. 2. Rockfall talus. 3. Alluvial fans.

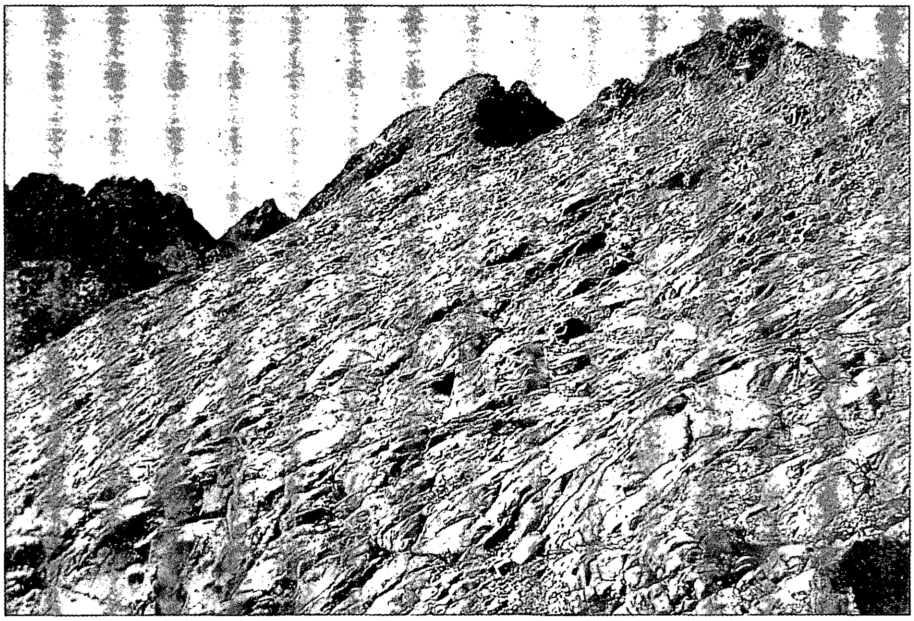


Photo 3. La Galana east-facing slope. The slope is formed by a glacial ramp without deposits.

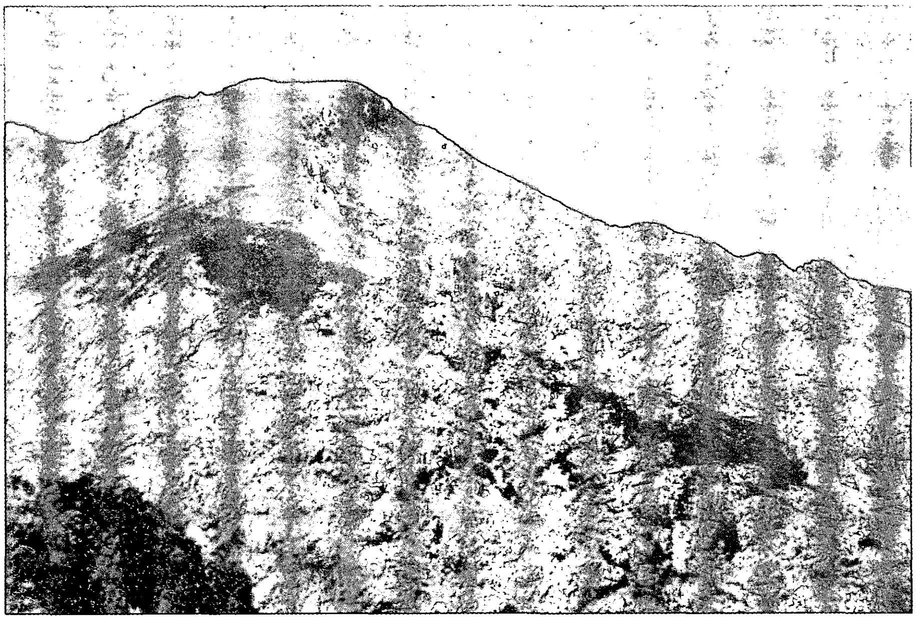
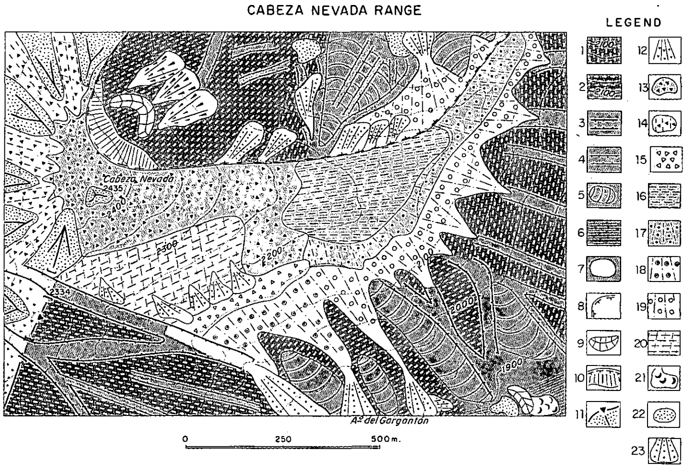


Photo 4. East slope of Cabeza Nevada Peak (See block diagram of Fig. 4.B).



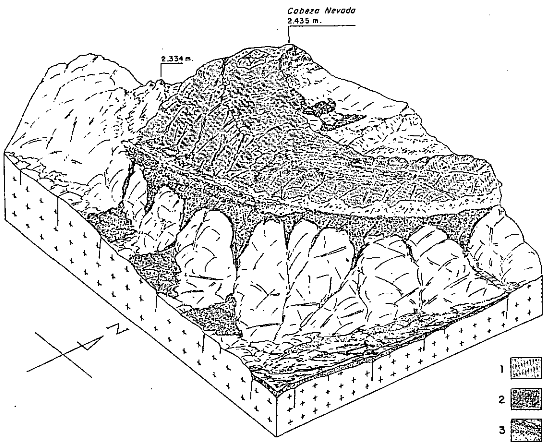


Fig. 4. Cabeza Nevada Range **4.A.** Geomorphologic scheme. *Forms caused by glacial erosion:* 1. Glacially smoothed valley walls (with smoothing in slope direction). 2. Glacially smoothed valley walls (with smoothing in perpendicular direction of the slope). 3. Channels of deep glacial incision along fault lines where chemical weathering has extended. 4. Channels of shallow glacial incision also along major fault lines. 5. Glacially smoothed spurs, on the valley sides. 6. Glacial valley floor. 7. Glacial depressions. *Landforms of non-glacial origin:* 8. Wallheads of the snow niche. 9. Protalus ramparts. 10. Walls affected by a recent gelifraction. 11. Walls affected earlier by gelifraction, gullying and chemical weathering. 12. Gelifraction deposits forming cone blocks. *Block deposits caused by the earlier gelifraction and affected by chemical weathering:* 13. Autochthonous. 14. Removed. 15. Kame-terrace deposits 16. Autochthonous boulder field from chemical weathered mantle. 17. Badlands over weathered mantle. 18. Rockfall and rillwashing deposits from kame-terrace. 19. Rockfall, rillwashing and gelifluction deposits from weathered mantle. 20. Rock chemical weathered outcrops. 21. Gelifluction lobes. 22. Bogs. 23. Cone talus. **4.B.** Block Diagram. 1. Chemical weathering and earlier periglacial landforms. 2. Rockfall talus. 3. Kame-terrace

of Almanzor ridge. Here too, the blocks have been notably affected by chemical weathering. This peak is in the form of a triangle, with three contrasting sides. The western side faces the Cinco Lagunas cirque, the valley head of Pinar Gorge. On this slope, the deposits have been largely removed by stream action. On sectors within these ravines a mantle of weathering can be seen below the block field.

The north-eastern side bears a small glacial cirque. At its highest level there is a wall which has been affected by recent gelifraction. Below this, some of the deposits which have accumulated from this activity have been remodeled by snow action and have formed protalus ramparts. The rest of the slope, which has a morphology very similar to that of the eastern slopes described earlier, descends in a relatively gentle incline (40°). It has been notably smoothed by the ice in the direction of the slope.

The south-western side is very varied. At the upper levels of the slope (between 2,400 and 2,200 m. in altitude) the ancient block fields of the summit are again to be seen, but bedrock also outcrops in places. Where this happens it has been strongly affected by chemical weathering and has abundant taffoni. This morphology forms a contrast with that of the nearby eastern side of La Galana ridge, which is only separated by a narrow channel, and where the glacial forms have developed to their fullest possible extent.

At lower levels the block field disappears and the layer of chemically weathered rock, dotted with boulders and core stones, forms the surface level. This chemical weathering unit has been destabilized by the glacial action at the base of the slope and by the subsequent gravitational action. Below 2,150 m, the classic forms of glacial abrasion on the slope have developed. At times this line is indicated by small ice-contact deposits, but there are now no remains of any glacial moraine. The glacially eroded surface of the slope is often hidden below coarse sediments, plus fluvioglacial deposits, and materials emanating from the chemical weathering unit. The latter are easily recognizable on account of the abundance of sand and rounded boulders.

4. Geomorphologic units at the cirque of Gredos

Throughout the cirque of Gredos, because of the presence of the geomorphologic elements described above, the following geomorphologic units may be distinguished there (Fig. 5):

a) *Flat summits.*- These are remains from the old pre-Alpine surface. This old surface is quite in evidence on Cuento, Morezon and Cabeza Nevada ridge summits. The morphology of these summits is one of gentle plateaus which are free of any rough sections protruding above the general level of the relief. All of this area is

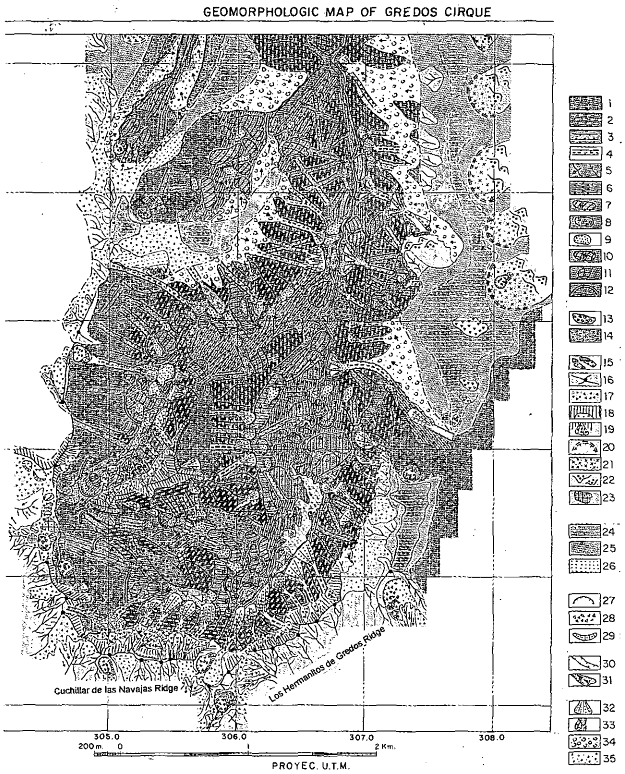


Fig. 5.- Geomorphologic map of the Gredos cirque. *1. Landforms of the glacial period. 1.a) Erosion Glacial Landforms:* 1. Glacially smoothed valley walls (with smoothing in slope direction). 2. Glacially smoothed valley walls (with smoothing in perpendicular direction of the slope). 3. Channels of deep glacial incision along fault lines where chemical weathering has extended. 4. Channels of shallow glacial incision also along major fault lines. 5. Glacially smoothed spurs, on the valley sides. 5.a. Cross-spur forms 5.b. Along-spur forms. 6. Glacial valley floor. 7. Glaciated valley floor steps 8. Plucking faces of the glaciated steps. 9. Glacial depressions 10. Glaciated outcrops. 11. Glaciated valley side steps. 12. Upper limit of important glaciated steps. *1.b) Sedimentary Glacial Landforms.* 13. Till deposits associated with valley steps. 14. Lateral moraines. *1.c) Other Landforms which were formed during the glacial period.* 15. Kame-terraces. 16. Periglacial ridges. 17. Periglacial blockfields. 18. Supraglacial walls and shoulders. 19. Periglacial deposits on the glacial shoulders. *Snow niches.* 20. Wallhead upper limit. 21. Wallhead of the niche. 22. Floor niche deposits. 23. Periglacial patterned ground. *2. Pre-glacial Landforms. Uplands formed by old erosion surfaces.* 24. Flat higher surfaces (remnants of the old erosion surface with a 1-0,5m thick weathered layer, which is covered by blockfields of periglacial origin) 25. Debris-mantled slopes (preglacial slopes covered by a deep-weathered layer under relict periglacial blockfields) 26. Bedrock slopes (Stripped bedrock slopes formed by preglacial weathering front) *3. Post-glacial Landforms. 3.a) Nivation landforms Snow hollows in superficial debris.* 27. Hollow upper limit. 28. Hollow wall 29. Protalus ramparts. *3.b) Fluvial landforms* 30. Stream incision channels 31. Alluvial fans. *3.c) Combination landforms.* 32. Rockfall cone talus. 33. Alluvial talus. 34. Rockfall, gelifluction and rillwashing deposits from weathered layer. 35. Rockfall, gelifluction and rillwashing deposits from lateral moraines.

covered by old blockfields. Below this periglacial layer, there is a chemically weathered mantle between 0,3 and 1,7 meters thick. The periglacial deposits have also been quite affected by chemical weathering and so are presumed to be relatively old.

b) *Sharp Crests.-* The crests of Los Hermanitos, Cuchillar de las Navajas and Almanzor ridges form ridges between the Cirque and the southern ravines. The crests of La Galana and Risco Moreno ridges form the divide between Pinar Gorge and Garganton cirque on the one hand, and Garganton cirque and Laguna Grande cirque on the other.

These crests are always asymmetrical. The southern slopes are very uneven, with deep stream incisions and sharp spurs and needles. The slopes are covered by a deep periglacial blockfield. On the eastern slopes the glacial smoothed ramps reach high levels on the peaks. The northern and western slopes of the peaks are vertical rock walls above glacial shoulders.

c) *Slopes formed in former ice accumulation areas.-* These were formed by intense glacial smoothening in the direction of the slope. The channels which follow the fracture lines have been re-excavated and now reach to a great depth and are free from deposits and weathered mantle. They always face towards the east or north east slopes of the Laguna Grande Cirque and Garganton Cirque.

d) *Slopes which have been modeled in their lower sections by the abrasive lateral action of glaciers.-* Three units are distinguishable on these slopes: The wall above the glacial level, the glacial shoulder and the wall affected by abrasive action. The glacial shoulder is clearly marked. Onto the surface of the glacial shoulder, debris cones are built from the slope behind. Below the shoulder is the surface which has been smoothed by glacial action, where there is an abundance of striae aligned across the slope. Large gravitational talus cones are situated below the shoulder, beneath couloirs developed along lines of weakness along faults. They are growing actively today by debris produced by gelifraction.

This geomorphologic unit is always situated on the northern and western slopes, ie. on the northern slope of Cuchillar de las Navajas-Hermanitos ridge and the western slope of Morezon and Risco Moreno ridges.

e) *The valley floor.-* On the valley floor, the characteristic glacial morphology of alternating basins and valley-steps has developed. The subglacial waters excavated deep incisions. The materials of the talus situated at the foot of the northern and western walls were washed downslope to form new alluvial fans. Till remnants are found only in the lee of certain valley steps.

f) *Nivation niches.-* Two kinds may be distinguished:

The first occur at low elevations, e. g. the hollows on the eastern side of Cuento ridge or Cabeza Nevada. Here, the snow has removed the chemical weathering layer and accumulated the resultant deposits at the base in a disordered manner. These deposits are being worn away along the valley heads of the present day by streams or gelifluction flows.

The second kind of hollow are small snow hollows, which deserve attention from the point of view of climatic and geomorphologic dynamics. They are located over unstable blockfields on the eastern side of the ridges. Typical examples are to be found at the following locations: at the eastern slopes of spurs on the southern side of Cuchillar de las Navajas-Hermanitos; at the eastern slopes of a particular spur, above the northern shoulder of the same ridge; and on the eastern sides of the Cirque, but only where there exists an earlier addition of deposits emanating either from gelifraction or from the weathered mantle.

5. The characteristics of weathering formations and sediment deposits

On the basis of the description of the geomorphologic units and an analysis of each formation, it is possible to distinguish the following deposits and chemical weathering units.

a) *In situ chemical wathered residues.*- Such a mantle is located on the flat surfaces of certain peaks and is covered by blockfields. This weathered mantle is relatively thick (0,3-1 m) and reaches its maximum depth (1-1,7 m) only on the flattest surfaces, independent of the altitude. It shelters important core stones. Where protected from glacial abrasion, it is also visible in the channels in the area.

b) *Coluvial Deposits generated by chemically weathered materials and the lateral moraines.*- Instability of the weathered deposits and lateral moraines is associated with the melting of the snow and ice on high steeper slopes. Gelifluction acts on these materials, leading to the development of lobes and steps similar to those noted in other mountain areas (e. g. Smith, 1988). Flooding action during snowmelt removes the finest materials, allowing core stone to fall and accumulate on the valley floor, where they may be moved further by streams.

c) *Moraine and nival deposits.*- There are no moraine deposits in any part of the valley head, but only under the shelter of large valley steps. There remain certain deposits with the following characteristics: they vary texturally with a fine sand matrix, they are quite rounded and are occasionally striated. Given these characteristics and their location, they seem to be till deposits.

Small cirque glacier left frontal moraines which, though not very important, are relatively well formed. The best formed are in the Cabeza Nevada cirque which has two well defined arcs which are presently being eroded. The Los Barrerones cirque almost formed a link with the principal glacial valley but later become separated, creating kame deposits which are being removed by stream action. Other cirques, dating from the same period as the large glacier, are smaller with poorly defined moraines on the cirque floor.

At the valley head of the Gredos cirque, there are different types of nivation hollows, which, judging from their situation on glacial features, postdate the period of glaciation. These deposits frequently display the characteristics of the protalus ramparts of nival accumulation origin (Francou, 1983; Perez, 1988).

The formation of transverse nivation hollows is sometimes due to displacement of blocks over the nival surface. At other times transverse nivation hollows are caused by wash slope, associated with melt water, i.e. by processes very similar to those recorded on the eastern slopes of the Scandinavian mountains (Rackawska, 1990). In contrast, the accumulation and ablation of snow on the western slopes is more uniform and doesn't generate the same diversity of geomorphologic forms. Something similar occurs in the Japanese Alps, where similar processes have been noted, again only on the eastern slopes, where perennial snow patches, which originate from snow blown accumulation, are formed (Watanabe, 1988).

d) *Periglacial deposits.*- On unglaciated peaks, there is a layer of block field, made up of large angular blocks (30-300 cm), without sediment matrix. This layer occurs independently of the orientation of the peaks and is related to outcrops of bedrock. This blockfield extends as far as the foot of the rocky outcrops. In so doing it fills in old fluvial incisions in a uniform manner and covers the high mountain gaps. Its fabric is similar to other blockfields and blockstreams cited by Caine (1968). The blockfields always cover a weathered mantle, as happens in other areas (see for example Caine and Jennings, 1968). These matrix free blocks imply intersticial ice when they were active and moving. At present they are being displaced and destabilized by stream and snow action. This action on the relict blockfields brings about important rockslides (very similar to those cited in the Scandinavian mountains by Rapp, 1960 and in the Alps e.g. Julian, 1991). When snow action is persistent in a given area nivation hollows are formed.

Polygons, sorted nets, patterned ground and stone circles exist in very high and flat areas (above 2,400 m). These formations could have developed in the preglacial period and been preserved by permafrost (see a reference to the same morphology and a theory as to its origin in Coxon, 1988), which would account for the degree to which they have been chemical weathered.

The postglacial deposits, are located chiefly on the northern and western slopes of the glacial valley. The debris cones which are located on the glacial shoulder could have been added to in the postglacial period. An interruption during the Little Ice Age in the formation of these rockfall cones, caused by permanent snow patch, and which created protalus ramparts can be observed. Since the end of that period, these cones have continued to form and have covered the protalus ramparts.

These cones are being continually destabilized at their base. In most cases the destabilization at the base is greater than the degree of augmentation at the head of the cone.

The second type of debris cone is situated at the foot of these same slopes. These cones are principally fed by the higher ones. Some of the lower cones are completely unconnected with the higher ones and are fed from materials derived from the channels which cut into the wall. These deposits may be defined as of the gravitational rock fall variety (Rapp, 1960): they have finer deposits at the higher part of the talus, large blocks at the base and the block surfaces often show impact scars. Most of the accumulation on these cones occurs in mid-winter, on account of the avalanches, or in spring during snowmelt. On some of them, debris flow channels are formed and facilitate the stratification of the deposits (see other examples in Van Steijn, 1988). Their chronology is currently being investigated by means of lichenometric dating and lacustrine sediment analysis. For the present, their morphology suggests that debris flow activity was greatest during the Little Ice Age as in the Alps (Strunk, 1991) and the Tatra Mts. (Kotarba, 1988, 1991).

Locally, normally in areas close to basins covered with peat bogs, there are gelifluction deposits and some debris cones have suffered mass wasting when they have covered peat bogs and have become flooded in the process, acquiring a lobe-like morphology at their front.

e) Alluvial fans.- They may be classified according to the degree of intensity of flooding. Some alluvial fans descend laterally towards the valley and gravity and avalanches continue to play an important role in their development. In these cases, as has been noted by Krainer (1988) in the Alps, sieve deposition processes are common. These deposits cover the foot of the wall, forming an alluvial talus (according to the terminology used by Kotarba, 1984). Other fans extend along the valley having a morphology more properly described as alluvial fans.

6. Recent geomorphologic evolution

The origins of the geomorphic features of Gredos Cirque may be ascribed to various periods of activity:

1º. Preglacial development

The Pleistocene glaciers developed in previous fluvial valley heads. The landforms of these valley heads were determined by fault lines. These valleys, initially modeled by fluvial stream action, were cut out in the highest surface of a tectonic horst. This surface is made up of an old erosion surface which is slightly tilted towards the north. As a result, the fluvial forms are situated on the northern side of the horst and are surrounded by peaks which are either flat or very gently inclined, towards the north. Both at these higher flattened levels and at the sides and floors of these same valleys, the granite rock has a continuous level of weathering which is normally about one meter thick. However, along fracture lines, the granite may be decomposed to a depth of several dozen meters.

2º. Glaciation

During the late Pleistocene, the eastern lee slopes of the fluvial valley heads accumulated great depths of snow. Furthermore, the summits are situated at an altitude in excess of 2,000 m and are dominated by raised levels of between 2,300 and 2,600 m in height which, on account of their flatness are particularly prone to collecting snow. The convergence of these factors allowed glacial cirques oriented towards E-NE to develop, as in other mountain systems in the northern hemisphere, e.g. in Scandinavia (see for example Vilborg , 1984) or on the eastern slope of Front Range in the Rocky Mountains (Richmond, 1960).

These glacial cirques always cause their ice to move along the east side towards the two principal valleys which face towards the north. The floors of these valleys vary between 1,800 and 2,000 m. The movement of the ice assists the formation of tongues of ice in each valley which form tributaries to a major 9 km-long valley glacier that formerly terminated at 1,400 m.

The valley head of the Gredos gorge as a whole, does not have the character of an area of great ice accumulation. In fact, the accumulation of ice is almost exclusively restricted to the eastern ramps and channels on the east facing slopes which are the only ones which can be considered as active in terms of accumulation. In contrast, the floors of the two principal valleys and their west-facing walls may be considered passive in that they do no more than constrain the ice flow received from the opposite slopes and channel it towards the north.

In the glaciated areas, the weathered layer was quickly removed and landscape typical of glacial cirques and valleys developed. Nevertheless, important remnants remain outside the glaciated area. Thus, in the high flat areas, the weathered granite may have been protected by a permanent snow and ice cover and so, has survived without significant transformation of the relief.

In the highest parts of the west-facing slopes, above the level of glaciation, processes of fragmentation and periglacial slope activity have been powerful and effective. The jointed granite has been affected by gelifraction, breaking down to large blocks which were added to the glacial debris. The combination of fragmentation, slope dynamic and mass wasting causes these high areas to retreat significantly, leaving them with the form of a vertical slope over a characteristic shoulder above the glaciated part of the slope.

3°. Deglaciation

The increase in the length of runoff season and the magnitude, duration and frequency of snow and ice melt and the major summer rain storms favoured rapid erosion during "paraglacial" period (Church and Ryder, 1972). At Gredos Cirque, the direct result of this was an extension of the area subjected to an increase in the effectiveness of the periglacial processes, as has been noticed in other high mountain areas (see for example Thorn and Loewenherz, 1987). The gelifraction particularly affected the high west facing slopes, where the rock was most susceptible to being fractured. The masses of gelifracts formed continuous talus, The debris accumulated on the shoulders of these west facing slopes, became destabilized and fell to the valley floors.

The ice retreated to the east facing slopes, protecting them from periglacial processes. When the ice finally disappeared, the lack of glacial sediments, and weathered mantle protected these east slopes from paraglacial erosion, in spite of the increase in supply of melt water.

At the cirque, lower areas dominated by weathered mantle and lateral moraines, which reached a position of relative stability in the glacial environment, were significantly affected by slope processes, probably very soon after deglaciation as Church and Ryder suggested (1972).

4°. The post-glacial

Almost all of the winter snow which accumulates in the Gredos cirque today melts in the following year. As a consequence, snowmelt runoff is a most important slope process. This overland flow occurs either extensively or in ephemeral rills which are not well defined and transport the finer sediments towards the valley floors. As a result, core stones and other coarse fragments in the surface deposits and the moraines become loose and exposed.

On the valley sides, the fault lineations which have facilitated chemical weathering also channel the seasonal flows of water and form drainage lines wherever their direction coincides with that of the slope. At the valley floors they form alluvial fans which overlie the glacially scoured bedrock.

The debris dislocated by gullying and stream action or displaced by the force of gravity, encounter difficulties in reaching the valley floors of the high part of Gredos on account of the topography. This topography is characterized by an alternation of depressions with lakes and steps which does not favor continuous transport of sediment. Most of the sediment is retained in the lake basins which have infilled to swamp or bog areas across which there are numerous meandering channels. Only one lake, La Laguna Grande, has survived as a water body.

The effects of other processes related to cold and snow may be observed at Gredos Cirque where gelifluction continues to model lobes and small terraces in snow accumulation areas. Snow action has also continued until recently to remove and organize blocks into protalus ramparts. There is evidence that this activity occurred more readily during the Little Ice Age. Some of the protalus ramparts date from the last century, when, as has been orally testified by many people from local areas, the snow used to remain in these hollows throughout the whole summer. The processes of debris flow and gelifraction also seem to have been more intense during the last century. In the absence of conclusive data, all of the available evidence would indicate that the erosive processes in the area were more intense in the early part of the Holocene than in the middle and late Holocene, as has also been claimed in respect of other mountain areas (Jonasson, 1991).

7. The relationship between snow cover distribution and slope processes

The snow cover has been analyzed by means of five sets of aerial photographs taken in different years (winter or spring of 1956, 1979, 1983, 1986 and 1989), consulting 1980-1993 series of D.M.S.P. satellite System of LF band, and by direct observation during the winters from 1991-93. As a result of this work, a first attempt to map the snow cover in the area has been made (Fig. 6).

At the height of the cold season the snow covers a large area of Gredos cirque, but as can be seen in Fig. 6, it becomes rapidly confined to the areas with the most favourable local topographic conditions -such as big slopes facing towards the east, corridors facing towards the north or the north-east; slopes of spurs facing to leeward in an easterly or north-easterly direction; and below the highly defined scarps of the highest crests. According to the experimental studies undertaken by Föhn and

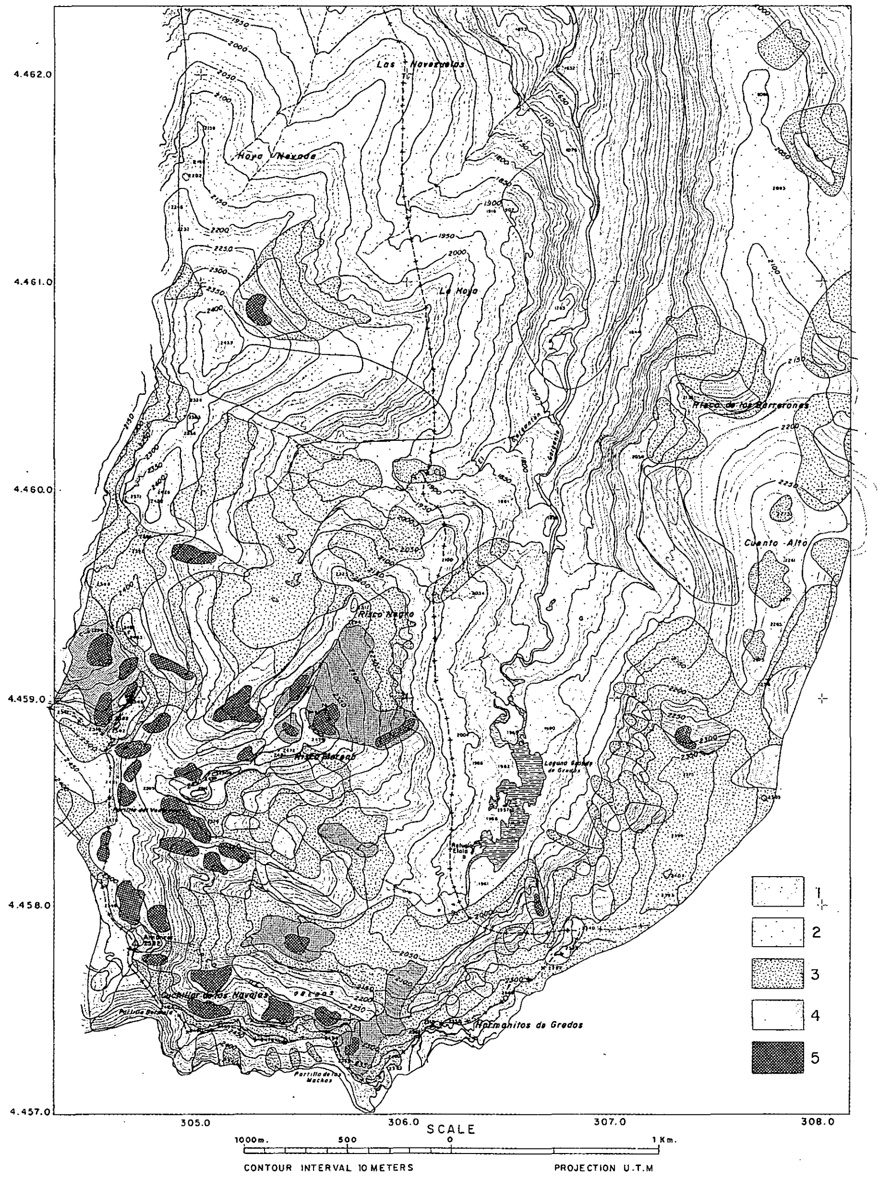


Fig. 6. Duration of snow cover at present. 1. Less than 60 days a year. 2. Between 60 and 120 days a year. 3. Between 120 and 150 days a year. 4. Between 150 and 180 days a year. 5. More than 180 days a year.

All of the indications point to the fact that the present snow distribution patterns is quite similar to that which was predominant in the cirque during glaciation, as well as during the Little Ice Age. For example, at the end of the summer, snow patches can only be found at very specific and high points just where the nivation niches from L.I.A. occur.

The relationship between this snow distribution and the present erosive activity can be compared in the maps of Fig. 6 (snow distribution) and Fig. 7 (erosion distribution).

On the western and northern sides of the valley-head of Gredos cirque, in spite of accumulating lesser quantity of snow, the periglacial activity on the wall above the glaciated slope is important. Weathered material remains in the fissures there and is still affected with great ease by gelifraction. In addition, the glacial shoulder retains the rockfall debris from this wall as talus cones. Only at the east face of some spurs of this wall do almost permanent snow patches remain. This causes the remodelling of the debris cones as nivation hollows.

On the glaciated northern and western slopes, three elements come together: - (a) channels little affected by ice erosion, (b) a high supraglacial wall, and (c) an accumulation of deposits on the shoulder. The convergence of these factors leads to the existence of extensive areas, facing towards the north or west, affected both by rock fall and dirty snow avalanches. The coincidence of these processes on glaciated slopes has been noted in many mountain systems (Rapp, 1960).

On the other hand, the east facing sides, where the old glacier used to extend, and where the deeper snow cover now accumulates, and where several snow patches remain until the end of the summer, are practically inactive. This is due to the fact that the glacial erosion was along the channels and so, cut into the pre-existing surface more deeply. This contrast in slope processes, between those which were completely covered by a glacier and those having a supraglacial wall where avalanche processes were active has frequently been noted in the context of mountain systems which remain glaciated (see for example André, 1988).

Other areas affected by active processes are also related to the mutual influence between old deposits and snow accumulation and are of three main types:

a) The old periglacial block fields in the valleyheads of the southern gorges are being affected by snowmelt stream action and by snow patches at the east face of the abundant rock spurs. Most of the frequent present-day rock mobility in the old block field result from the combination of both of these processes (see other Dumas & Raffy, 1991 and Julian, 1991).
b) The level of chemical weathering which occurs at slightly lower altitudes and which generates large quantities of fine materials. This in turn facilitates gelifluction and other mass wasting processes

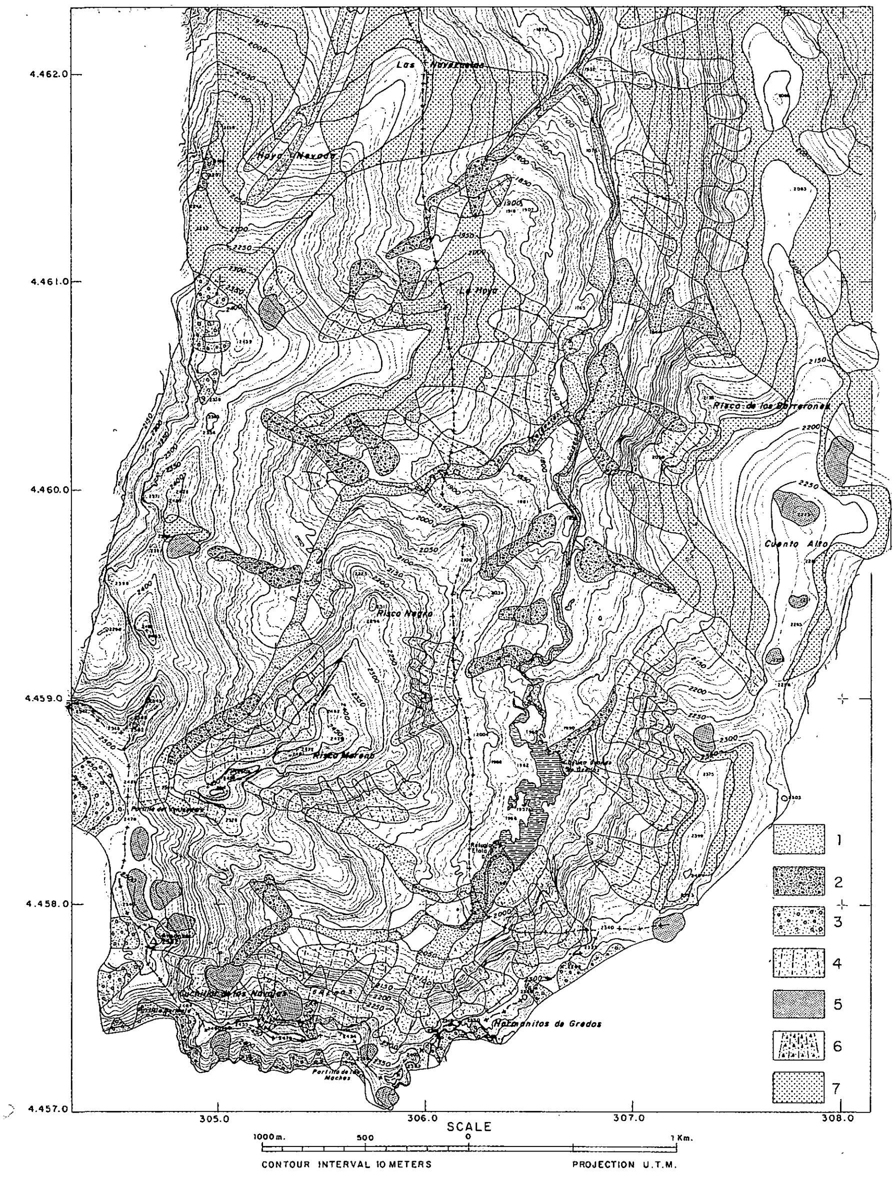


Fig. 7. Contemporary erosion types. 1. Areas dominated by permanent stream action. 2. Areas where irregular stream action predominates. 3. Areas dominated by rockslides. 4. Areas dominated by rockfalls. 5. Areas directly dominated by snow action. 6. Areas dominated by gelifraction. 7. Areas dominated by gelifluction and rillwashing.

just where the high snow accumulation areas provide more snowmelt water. Over large parts of this chemically weathered formation, diffuse surface runoff is very important in removing fine sediments and leaving core-stones, characteristically isolated. This process is at times so intense that the slope acquires a badland aspect. The resulting morphology is very similar to that described in other mountain areas where deep weathering profiles have persisted on the slopes (see for example Pech, 1986).

c) Something similar occurs on the lateral moraine hanging above the higher levels of the valley. Here, the removal of large blocks is more common. In any event, a great variety of processes act upon these moraine materials: -debris slide, debris flow, mudflow, rockfall and creeping, but always the intensity of the process is determined by the distribution of snow cover which acts as a water supply. This typology of processes, acting upon these same materials, has been noted, though in a more intense form in higher mountain systems (see for example Owen 1991).

The convergence of processes which act on both weathered materials and lateral moraines is very complex. In general, these processes may (according to Rapp, 1960) be considered as responses to heavy water saturation and runoff over unconsolidated materials.

8. Conclusions

The dynamic activity derived from snow accumulation at Gredos Cirque is not intense today. In fact, at Gredos Cirque snow and snowmelt only affect weak materials such as are found only at the highest elevations where block fields, weathered mantle or lateral moraines survive. On these surfaces, nivation facilitated the development of snow hollows during the Little Ice Age, but at present slight activity related to gelifraction, gelifluction and slope wash processes associated with snow patches is observed. Stream erosion is now rare at Gredos cirque. It is only capable of reorganizing slope deposits, not of removing them from the system

The reasons for this limited slope activity at Gredos Cirque are both climatic and historical: the sites where ice would have accumulated during glaciation are those where snow drifts formed during the Holocene. Nivation is recognized as a process of modification and not initiation (Thorn 1988). Thus its erosive capacity is significantly restricted by the fact that snow accumulation is more important where the deposits and weathered level are less abundant, on east-facing slopes.

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