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Geomorphological significance of lichen colonization in a present snow hollow: Hoya del Cuchillar de las Navajas, Sierra de Gredos (Spain)

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Abstract

This paper discusses the results of a lichenometrical and geomorphological study of one of the few remaining active snow hollows in the central region of the Iberian Peninsula. The study area, located on a glacial shoulder, is called Hoya del Cuchillar de las Navajas. A protalus rampart occurs at the base of the hollow. Our studies, conducted between 1992 and 1998, were designed to determine the geomorphological characteristics of Hoya, the mobility of the deposits, and the characteristics of the snow cover. These data formed the basis for a study of the lichen colonization on the blocks and on the wall surrounding the snow hollow. All of the lichen species found were analyzed according to their abundance, distribution and the extent of their surface cover. Measurements of the diameter of the thalli of the species *Rhizocarpon geographicum* were also obtained. Thalli of this species were found to require a mean snow-free growing season of at least 95 days (13.5 weeks) per year. Maximum mean thallus diameters indicate that the protalus rampart was formed during the Little Ice Age and became inactive 130 years ago.

Keywords: Lichen colonization; Lichenometry; Nivation; Protalus rampart; Little Ice Age

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1. Introduction

It is a well-known phenomenon in many regions of the world that lichens and mosses colonize surfaces that are exposed as glaciers retreat or as the thickness or duration of snow cover is reduced (Benedict, 1990, 1991; Sancho and Valladares, 1993). The slow growth rate of epilithic lichens, however, makes it impossible for colonization to take place on very unstable rocky substrates. Lichenometry takes advantage of this slow growth to measure the lichen thalli and to calculate how long the surfaces have been exposed to conditions that support lichen symbiosis (Beschel 1961, 1973; Innes, 1985a, 1988). In addition to their longevity, many species of lichen are cosmopolitan in terms of their distribution, so they served as ideal biological indicators in comparing the incidence of global climatic changes in different regions of our planet.

One of the limitations of lichenometry is that it is difficult to establish a direct and universal relationship between growth rate and size of the lichen thallus (Innes, 1985a; Gallo and Piervittori, 1993). Since many factors may be involved, it is not always easy to isolate the specific cause of a particular growth rate. Some factors are inherent to lichen biology, such as the different speeds of growth during the life span of a lichen (Armstrong, 1976). Others are related to the lichens' extraordinary sensitivity to variations in the microclimatic conditions of their habitat (Innes, 1985a; Sancho and Valladares, 1993). Also, lichen symbiosis is extremely susceptible to atmospheric pollution and to the eutrophication of the substrate (Wetmore, 1988), so it is difficult to use lichens as a tool for dating in areas affected by human activity. In fact, lichenometry is mostly used in alpine and subpolar environments where there is little human influence and where vast surface areas were exposed and plant colonization took place during periods of climate warming after the Little Ice Age.

The lichen species most widely used in these areas is *Rhizocarpon* gr. *geographicum*, whose growth rates have been recorded world wide in such areas as the Antarctic (Lindsay, 1973; Sancho and Valladares, 1993), the Arctic (Calkin and Ellis, 1980), and throughout the major mountain ranges in both hemispheres (see Locke et al., 1979; Innes, 1985a). Growth curves for *Rhizocarpon* gr. *geographicum* have recently been established on the Iberian Peninsula in certain areas of the Pyrenees (Chueca, 1994; Mateo, 1998).

Of all of Spain's Central Mountain Range, Sierra de Gredos (2596 m) was most affected by glacial and periglacial episodes during the Quaternary. Glacial activity clearly affected these mountains during the Little Ice Age, as evidenced by the existence of protalus ramparts that were formed as blocks moved over the permanent snow hollows located in old glacial shoulder. The intensification of periglacial activity and nivation are probably the most important characteristics of the Little Ice Age in the medium altitudes of these southern European mountains. The epilithic plant communities and, in particular, the lichens, probably suffered drastic disturbances caused by prolonged periods of snow cover and a greater instability of the substrate.

Currently, the bioclimate of the Gredos Cirque has been defined as crioromediterranean humid (Gavilán-García, 1999). The total precipitation is over 1600 mm m^{-2} $year^{-1}$, principally in the form of snow, and the annual average temperature is below 4°C. The summer is relatively dry, with only occasional storms.

The snow hollow and protalus rampart selected for this study, is called Hoya del Cuchillar de las Navajas, and is located in Gredos Cirque. *R. geographicum* (DC.) L. grows in the area and appears in all of its stages of colonization. We reasoned that if by using lichenometric techniques we could determine when this type of lichen began to colonize the protalus rampart, we would also be able to date when the rampart had completely formed and stabilized. Our hypothesis was that data on the development and diversity of the lichen colonies could be correlated with data on block stability and the duration of snow cover in the area. Once established, this correlation would allow us to determine if the protalus rampart had originated in the Little Ice Age. Given the geomorphology of the area which includes nearly vertical walls to the south of the hollow, we were able to establish horizontal and vertical transects to create a three-dimensional image of the snow hollow's evolution.

2. Geographical background and methods

Gredos Cirque (40°15′N, 5°18′W) is located on the northern slope of the central massif of the Gredos Mountain Range, and its highest elevation is Almanzor Peak (2596 m) (Figs. 1 and 2). The lithology of the sector is predominately granite with phenocrysts. The cirque forms the head of Gredos Gorge, which was carved by a glacier that traveled 14 km downvalley to an altitude of approximately 1450 m. The cirque is bordered on the south by a jagged ridge called Cuchillar de las Navajas (2470 m). The north side of Cuchillar de las Navajas faces the interior of the cirque and forms a wall that is nearly vertical except for a step-like glacial shoulder that appears about 150 m below the crest (Fig. 3). The basin forms a ledge that is approximately 70 m wide. The wall below the ledge has been polished smooth by glacier ice, while above the ledge it was grooved by periglacial action, which also filled the channels with rock that subsequently underwent intense chemical weathering. This rock is particularly sensitive to gelifraction. At the base of these channels, on the shoulder, there are large rock fall cones (Fig. 4).

Between two of the channels and their respective gravity cones there is an area of significant snow accumulation called Hoya del Cuchillar de las Navajas. This hollow is bordered by the headwall of Gredos Cirque to the south. Two channels and their gravity cones, Canal Oculta and Ventana del Diablo, form the eastern and western boundaries of Hoya. The hollow rests on the glacial shoulder. A protalus rampart has formed to the north of Hoya, on the edge of the glacial shoulder, and some boulders that originated in the gravity cones of the channel cover either side.

Earlier studies confirm that Hoya del Cuchillar de las Navajas has the greatest amount of snow accumulation and the longest snow cover in the area of Gredos Cirque and probably in all of the Central Mountain Range (Muñoz et al., 1995; Palacios and Marcos, 1998; Palacios et al., 1998).

Data on the geomorphological and sedimentological characteristics of the protalus rampart (Palacios et al., 1998) confirm that snow normally accumulates perpendicular to the slope with nearly horizontal dips and displays a chaotic fabric consisting of fragments of all sizes including megablocks (Fig. 5), as is characteristic of a protalus

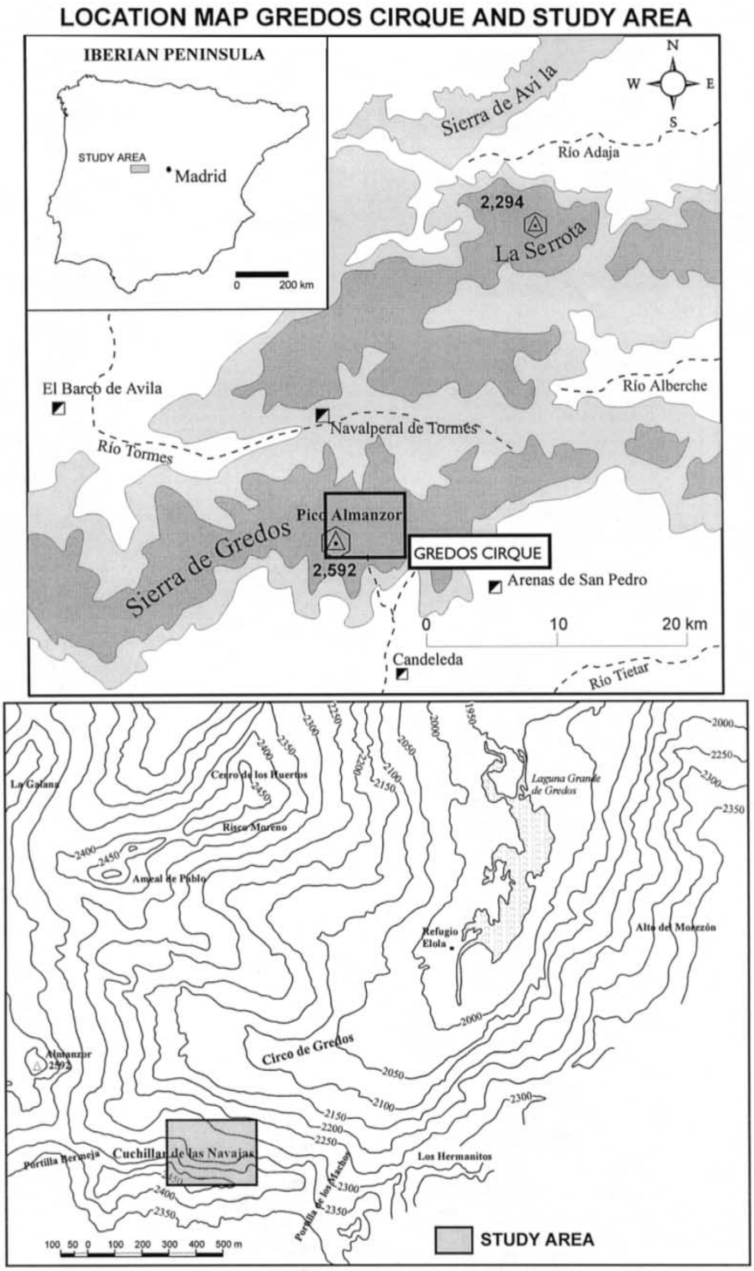

Fig. 1. Location map of Gredos Cirque and study area.

Fig. 2. Photo of Cuchillar de las Navajas from the north.

(Pérez, 1988; Shakesby, 1997). The blocks that form the ridge generally originate in the lateral channels (Ventana del Diablo and Canal Oculta). They do not accumulate and form cones below the channels, because the layer of permanent snow on the floor of the hollow causes them to slide over the surface and pile up on the protalus rampart.

In order to determine the geomorphological and nivation dynamics of the hollow, we consistently monitored the movement of the deposits and the extent of the snow cover from 1992 to 1998, according to the method proposed by Francou (1983, 1991). The protalus rampart showed no movement during this period (Palacios et al., 1998), so it was considered inactive. We also concluded that the snow hollow was permanent, since it was never without snow cover throughout the 6-year study period, except in 1992, an unusually dry year, when the snow receded to one side, exposing a large sector of the glacial shoulder.

The methodology used to study the evolution of the extension of the snow cover inside the hollow was very simple, since access to the area and winter working conditions made research difficult. Because of this, we were unable to study the evolution of the thickness of the snow. During the summer, we painted markers on reference points in key areas in Hoya and made bimonthly visits to the sites. The distance between the reference points and the top of the snow was measured, and the results were used to map the extension of the snow cover. Finally, we superimposed all of the maps made during the site visits to produce a snow cover map synthesis.

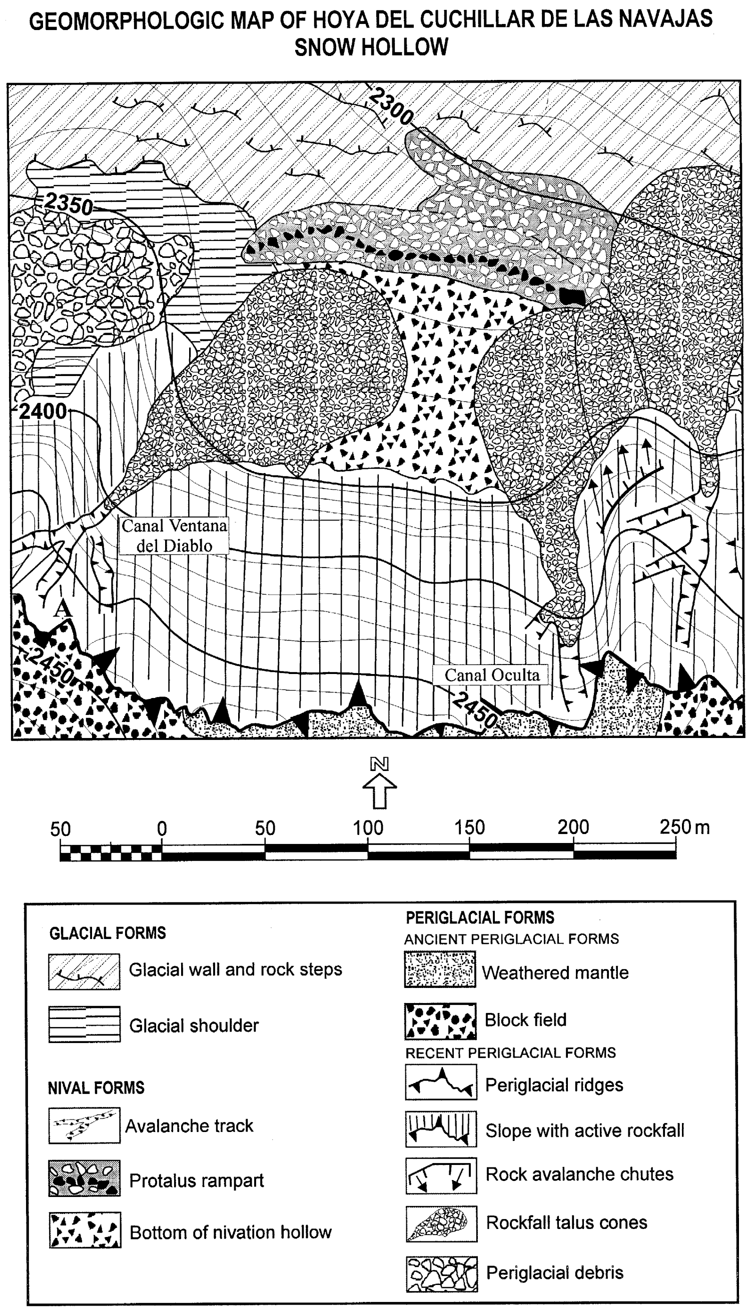

Fig. 3. Geomorphologic map of the Hoya del Cuchillar de las Navajas snow hollow.

Fig. 4. Photo of Hoya del Cuchillar de las Navajas snow hollow.

To identify the characteristics of the lichen cover, we marked two transects on the protalus rampart that crosscut the axis between the area of the most prolonged snow cover and the edges of the hollow. We also established three vertical transects on the wall of the hollow, which included one in the center and two on the edge. Three to five points were selected for lichenometrical readings in each transect. In order to avoid the effect of competition, only thalli of *R. geographicum* (DC.) L. that were completely isolated from thalli of the same species or other species were used in the lichenometric measurements.

The measurements of the maximum and minimum recognizable diameter within the same thallus were taken for the 10 largest thalli of *R. geographicum* using a callipers of an instrumental error below 0.5 mm. In accordance with the literature, (see Innes, 1986), the average of the maximum diameters of the thalli was chosen as the most suitable parameter for lichenometrical purposes.

In addition to the diameter measurements, we made complete relevées (list of species with indication of their abundance) for each sample point and estimated their total lichen cover.

For each block we recorded all of the species that were developed enough to be recognized. Table 1 contains an inventory of the lichens growing on each block and the wall and an index of the relative abundance of each species (Braun-Blanquet, 1964), adapted to lichen communities according to Wirth (1972) and Schroeter et al. (1999). Specimens were taken of all of the samples and examined at the laboratory to confirm

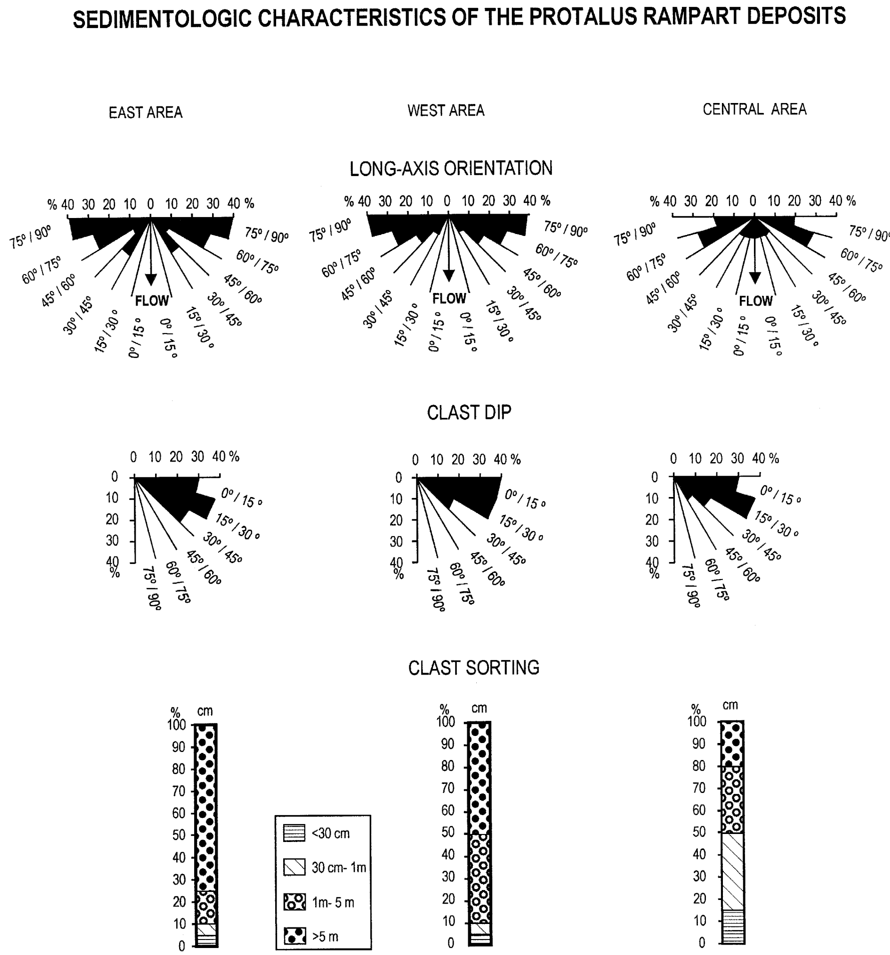

Fig. 5. Sedimentological characteristics of the protalus rampart deposits.

the identification of each species. Taxonomic criteria coincided with current literature (Santesson, 1993). Voucher specimens are kept at the MAF herbarium.

3. Results of the snow cover study

The map developed for snow cover duration revealed that the snow on the wall of the hollow and on the rocky spurs that rise above the channels was the first to disappear (Fig. 6). The steepness of these areas makes it impossible for the snow cover to remain there for more than a short time after heavy snowfalls. Occasionally, the snow would freeze on the wall and last for longer periods.

Table 1
Relevées taken in horizontal and vertical transects

Transect	Horizontal 1					Horizontal 2				Vertical 1			Vertical 2			Vertical 3		
Relevée	a	b	c	d	e	a	b	c	d	a	b	c	a	b	c	a	b	c
Distance to the snow patch (m)	13.8	21.4	24.7	27.0	29.6	9.8	16.4	23.8	26.5	1.7	3.0	5.2	0.2	1.1	1.7	0.3	1.4	2.0
Aspicilia cinerea (L.) Koerb.	–	–	1	1	2	–	–	–	2	–	–	–	–	–	–	–	–	–
A. epiglypta (Norrl. ex Nyl.) Hue	–	–	–	–	–	–	–	–	–	1	2	2	–	2	1	–	2	1
Bellmerea alpina (Sommerf.) Clauzade & Roux	–	–	2	2	2	1	2	4	3	–	–	–	–	–	–	–	–	–
Candelariella vitelina (Hoffm.) Müll. Arg.	–	–	1	1	1	–	1	1	1	–	–	–	–	–	–	–	–	–
Carbonea vorticosa (Flörke) Hertel	3	3	2	2	1	2	1	1	+	–	+	1	–	–	1	1	1	+
Lecanora intricata (Ach.) Ach.	1	1	2	3	2	–	–	–	2	–	–	2	–	1	2	1	1	2
L. polytropa (Ehrh. ex Hoffm.) Rabenh.	–	1	1	–	1	1	1	1	1	1	–	1	1	2	1	–	1	+
Lecidea atrobrunnea (Ramond ex Lam. & DC.) Schaer.	–	–	–	–	1	–	–	–	1	–	–	–	–	–	–	–	–	–
Lec. lapicida (Ach.) Ach.	–	–	1	1	1	–	1	2	1	–	–	–	–	–	–	–	–	–
Lec. praenubila Nyl.	1	–	1	2	1	–	2	1	2	–	1	1	–	–	–	–	–	–
R. geographicum (L.) DC.	2	2	3	3	3	2	2	3	3	1	1	4	2	3	4	1	3	4
Sporastatia polyspora (Nyl.) Grummann	–	–	2	2	3	–	1	1	2	–	–	1	–	–	–	–	–	–
S. testudinea (Ach.) A. Massal.	–	–	–	–	3	–	–	–	2	–	–	–	–	–	–	–	–	–
Umbilicaria cylindrica (L.) Delise ex Duby	–	–	–	1	1	–	–	–	–	–	–	–	–	–	–	–	–	–
U. polyphylla (L.) Baumg.	–	–	–	1	1	–	–	–	+	–	–	–	–	–	–	–	–	–
Unidentified mosses (af. *Grimmia*)	1	1	–	+	–	2	1	–	–	1	–	–	–	1	+	–	–	+

Indices express the relative abundance of each species in the relevée (+ = just present; 1 = very sparse; 2 = scattered; 3 = frequent; 4 = very frequent; 5 = dominant).

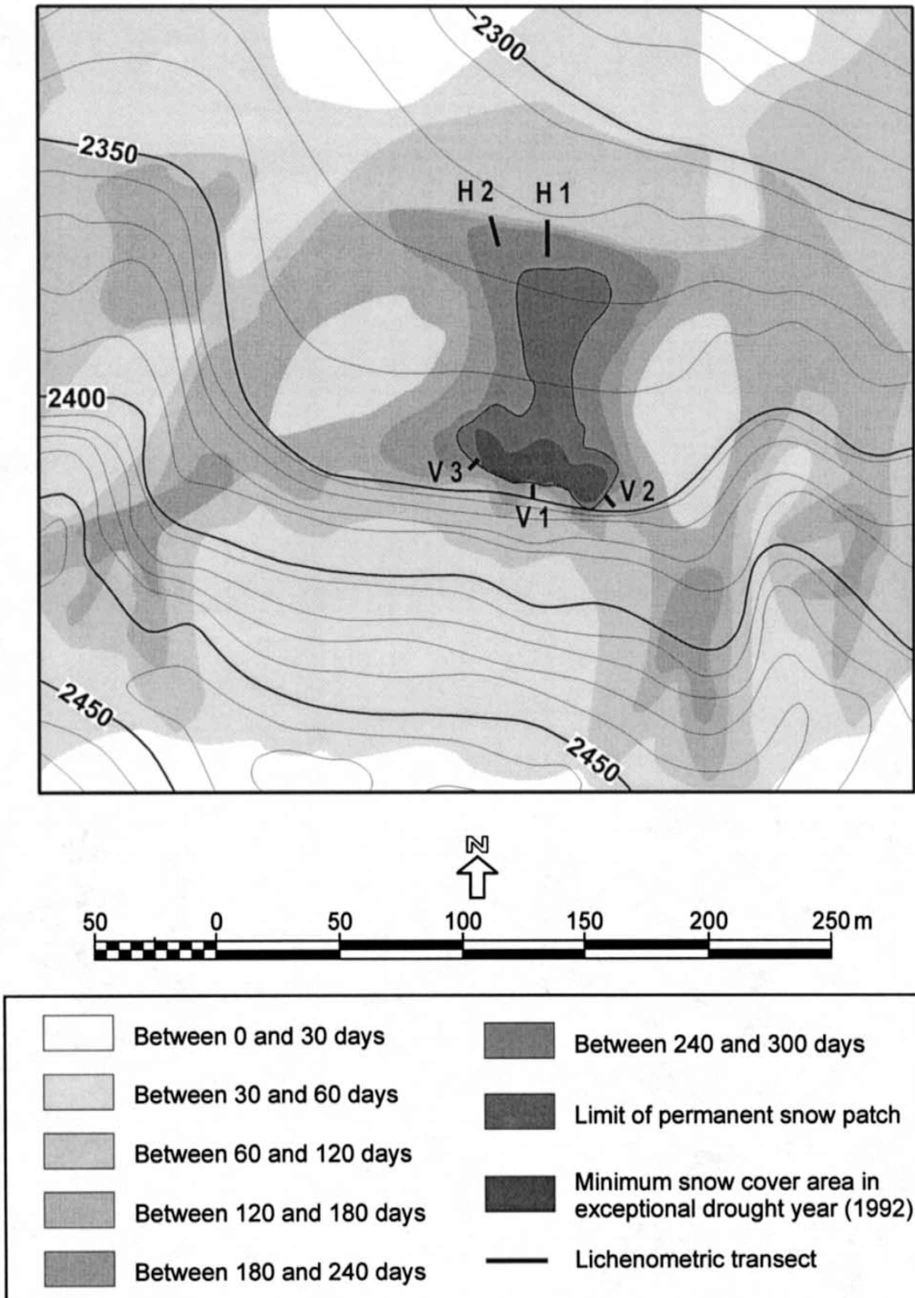

Fig. 6. Map of the permanence of snow cover.

The snow in the channels, however, lasted for nearly 6 months, and during most years, remained visible in August. The prolonged duration of the snow cover explains the importance of gelifraction in this sector. During the spring when daily freeze–thaw cycles occur, snow provides water to the rock.

The intermediate sectors of the axes of the rockfall cones had no snow cover during the entire spring, while the interior of the hollow was always covered. This situation produced instability when meltwater appeared in the spring and caused small rockslide lobes to form. These deposits contain a high content of fines, which made it easy for the blocks to be dislodged and to slide across the snow to the bottom of the hollow. Our observations confirmed that this activity occurred every year, and the average yearly volume of sediments displaced was 1.3 m^3.

The rest of Hoya had snow cover for more than 6 months of the year, which also occurs in many of the glacial shoulder that face the northern rim of Gredos Cirque. The peculiar aspect of Hoya, however, is that the snow remained on the floor of the hollow for more than 8 months. The only other places where this happens are some high-altitude niches on the cirque that face northeast. Snow accumulates on the lee side of the range and most snowfall is generated by southwest storms.

The prolonged duration of snow cover in Hoya is influenced by the presence of a great rocky spur to the west that forms the western side of the Ventana del Diablo channel. This spur and the rest of Cuchillar create an effective barrier against westerly winds and the snow-bearing southwest storms, and allows large quantities of snow to

Fig. 7. Photo of the protalus rampart of Hoya del Cuchillar de las Navajas.

accumulate. These landforms also provide protection against sun exposure. The combined effects of wind and sun protection provide Hoya with ideal conditions for prolonged snow cover.

Snow cover lasts from 2 to 6 months longer in Hoya than in any other hollow in Gredos Cirque. During the 6-year study period, we observed that the snow in the other niches disappeared completely as summer temperatures rose and the autumn rains arrived, even during the years of heavy snowfall. In Hoya, however, the snow on the floor of the hollow lasted beyond autumn, except in 1992, when it too disappeared from the floor but survived in the spaces between the blocks (Fig. 7). At that time, only a small strip of snow along the base of the wall lasted until the first winter storm. Thus, we considered that the area at the bottom of the hollow, with snow cover during 300–360 days per year, and for at least 5 years, was a permanent snow patch.

4. Results of the lichenometrical analysis

A total of 15 species of lichens and a single species of moss were found in the central area of Hoya del Cuchillar (Table 1). Most of the lichen species were distributed along the edge of the snow hollow or above a certain height on the north wall. In the two transects that covered the center of the hollow to the edge of the moraine, the number of species increased radically from 4 to 14 species in the space of 15 m (Fig. 8). Also, surface cover increased from 15% to 85%. Beginning at 85% coverage, the thalli of *R. geographicum* showed more interaction among themselves and with other species. Similar changes were reflected in the lichen thalli growing at different heights on the wall, although here the length of the transect was much longer in the center of the hollow than on the edges.

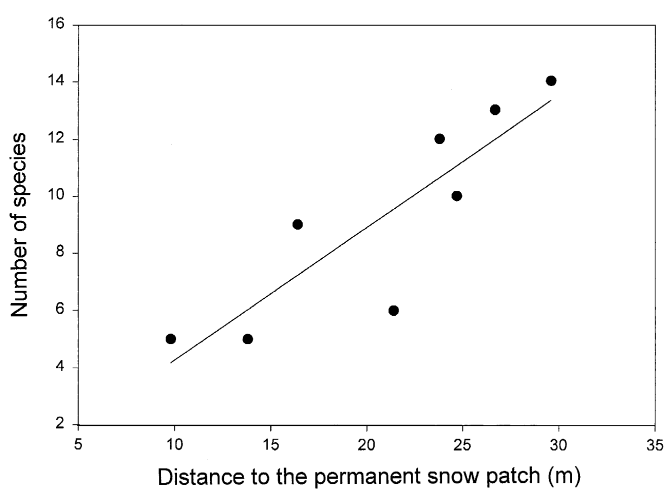

Fig. 8. Linear regression analysis of the total number of species in the relevées from the horizontal transects in relation to the distance to the permanent snow patch ($r^2 = 0.7614$).

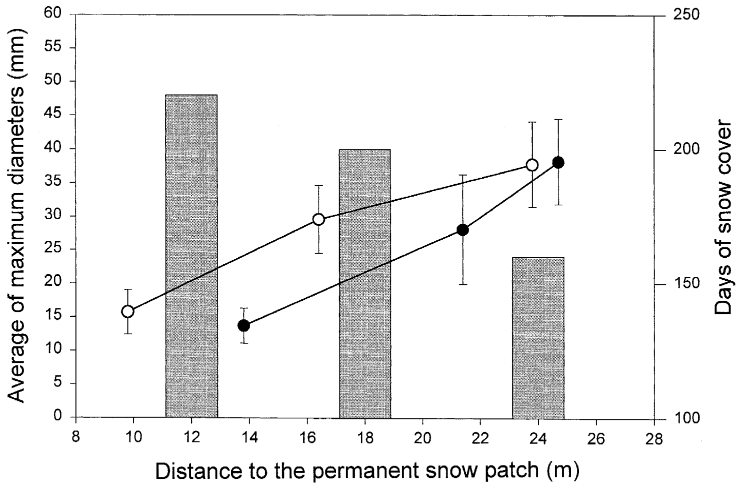

Fig. 9. Average of the maximum diameter of thalli of *R. geographicum* in the horizontal transects 1 (closed circles) and 2 (open circles) in relation to the distance to the permanent snow patch. Histograms show the days of snow cover in three different points of the transect.

R. geographicum is, without a doubt, the most abundant of lichen species in this area and one of the few that appears in zones most affected by snow cover. In the both the horizontal and vertical transects, there was a marked variation in the size of the thalli. The smallest ones were found in the center of the hollow (Fig. 9) or along the bottom of the wall (Fig. 10), while the largest ones appeared on the edge of the protalus rampart or high on the wall. Despite this, not all areas had lichen cover. After a macroscopic

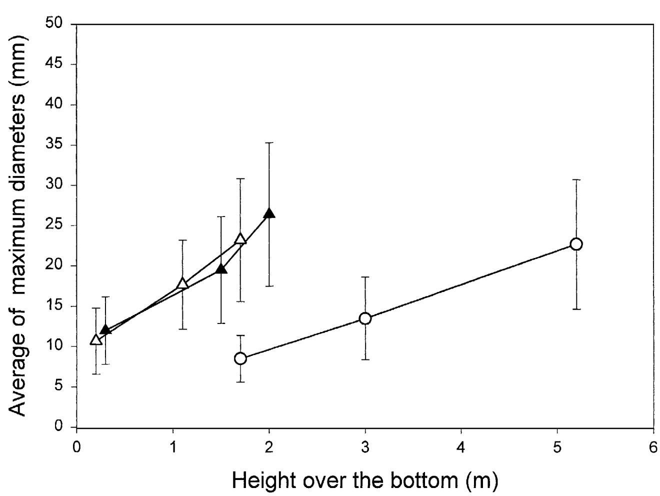

Fig. 10. Average of the maximum diameter of thalli of *R. geographicum* in the vertical transects 1 (open circles), 2 (open triangles) and 3 (closed triangles) in relation to the height to the bottom of the wall.

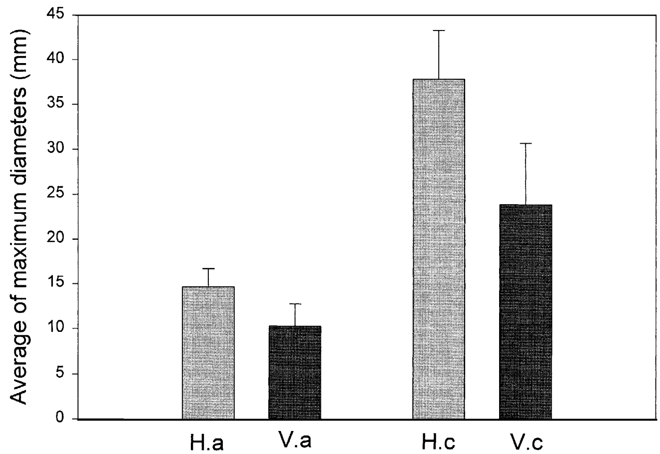

Fig. 11. Average of the maximum diameter of thalli of *R. geographicum* in the relevées "a" and "c"of the horizontal and vertical transects (see Table 1).

examination of the area (15 × magnifying glass) that was free of snow during part of the year (300–360 days of snow cover), we determined that there was no lichen or moss colonization on the floor of the hollow. This was also true for the area along the base of the wall up to a height of 1.5 m in the central zone and up to 0.2 m on the eastern and western extremes. This moss- and lichen-free zone generally coincided with the limit of the zone that had snow cover for more than 270 days. The thalli of *R. geographicum* with diameters greater than 40 mm began to show interaction among themselves or with other species on the protalus rampart at about 25 m from the line of maximum snow accumulation inside the hollow. At this location, the duration of snowcover was about 160 days per year. The diameter of the *R. geographicum* thalli on the wall of the hollow was considerably smaller than that of the specimens from the protalus rampart (Fig. 11). The wall thalli started interacting with others even before they had reached a diameter of 30 mm. Similarly, the thalli growing in the center of the hollow had larger maximum diameters (ca. 16 mm) than those at the base of the wall (ca. 11 mm).

5. Discussion and conclusions

R. geographicum has been used intensively in world-wide lichenometric investigation in comparative studies among different localities. The annual growth rate of this species is reported to be 0.25–0.3 mm year^{-1} in the Italian Alps (Beschel, 1958; Porter and Orombeli in Porter, 1981; Orombelli and Porter, 1983) and in the Pyrenees (Chueca, 1994). These rates are similar to those obtained in the maritime zones of the Antarctic (Sancho and Valladares, 1993) and in northern Sweden (Karlen and Denton, 1976), but higher than most of those from the remote areas of the Arctic (Denton and Karlen, 1973 and Miller and Andrews in Porter, 1981). All these data correspond to a linear phase of growth, although most authors suggest that the growth curve of *R. geographicum* is curvilinear (see Innes, 1985a). However, for *R. geographicum* thalli that are younger than 300 years, a linear growth curve has been reported (Innes, 1985a).

A common problem associated with the interpretation of the variation in the diameters of the lichen thalli is determining whether these represent normal phases in a chronological sequence or if they are associated with ecological variation. In terms of the Hoya study, we had to establish whether the small size of young thalli and the large size of older ones were due to the gradual recession of the snow during the Little Ice Age, or if all of the thalli were really of a similar age and their size differences were governed by ecological conditions that proved favorable for some colonies but not for others. According to the first hypothesis and using a growth scale of 0.3 mm $year^{-1}$, the snow would have started to recede from the blocks on the protalus rampart 130 years ago; from those on the crest of the ridge, 100 years ago; and from those on the slope that faces the interior of the snow hollow, 50 years ago. No lichen colonization was found on the floor of the snow hollow, so we concluded that the recession had probably remained fairly constant from that time. One should not ignore the fact, however, that the presence of snow continues to exert an influence in this locality where areas nearest the inside of the hollow are affected for more than 300 days of snow per year, but peripheral areas are covered for only 160 days of snow per year.

A regular snow cover lasting longer than 270 days per year seems sufficient to prevent lichen colonization in the study area. This concurs with results obtained by Haeberli et al. (1979) in the Alps. Benedict (1990) also found that the thalli of *R. geographicum* in the Colorado Front Range died within 5–8 years, if the average annual duration of snow cover exceeded 40.3 weeks (282 days) to 42.7 weeks (299 days).

Several authors have attributed abnormally slow growth in lichens or even mortality to the effects of long snow cover (Locke and Locke, 1977; Porter, 1981; Innes, 1985a; Benedict 1990, 1991; Valladares and Sancho, 1995). Pitman (1973) and Innes (1985b) found that the diameters of thalli increased as colonies grew farther away from the center of the snow patches, and they related this to a longer growing season. Studies in the Antarctic suggest that a prolonged snow cover can diminish the lichen growth rate to less than half (Sancho and Valladares, 1993). For the Hoya study, this means that the thalli of *R. geographicum* in the interior of the hollow would be ca. 100 years old.

If microclimatic conditions influence the size of the thalli, then an explanation for the difference in size between the smaller thalli on the wall and the larger ones on the protalus could be that the combined effects of prolonged snow cover and the lack of sunlight on the north-facing walls had reduced growth rate. The age difference between the larger and smaller thalli collected in the horizontal (protalus rampart) and vertical (wall) transects would not exceed 30 years, and the duration of the snow cover would be a major factor in regulating the growth rate. The chronological sequence of the evolution of the snow hollow could therefor be summarized as follows: approximately 130 years ago the volume and surface area of the permanent snow bank rapidly diminished and reached its current dimensions about 100 years ago. Since then, it has receded at a relatively constant rate.

Although the thalli of *R. geographicum* on the wall are smaller in diameter than those on the protalus rampart, they occupy nearly the same percentage of surface space. In fact, the wall thalli begin to interact when they reach an average diameter that is 35%

less than that of the thalli on the protalus rampart (Fig. 11). This indicates a greater number of thalli per surface unit in all of the transects on the wall, which is probably due to more successful colonization process. The mature lichen colonies on the upper portion of the wall appear to be an efficient source of the numerous propagules that grow along the base of the wall where there is abundant runoff from rainwater and meltwater. The protalus rampart is located 100 m away from these mature colonies and is separated by the permanent snow patch. Consequently, fewer propagules reach the protalus rampart, so there are fewer thalli per surface unit.

Present conditions are no longer conducive to further development of the protalus rampart since the snow patch is too small, so the rampart is now completely inactive.

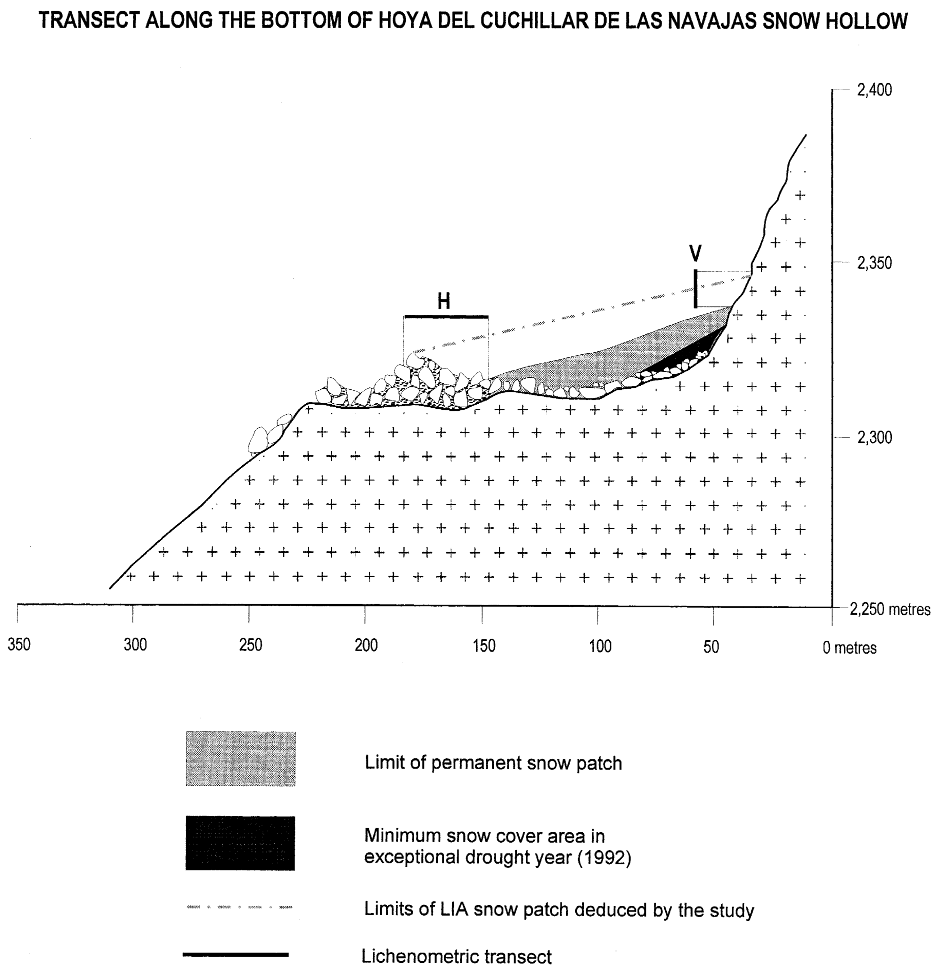

Fig. 12. Transect along the bottom of Hoya del Cuchillar de las Navajas snow hollow, with location of transects where lichenometric studies took place and the results of the LIA protalus rampart dating.

The only way to date when the protalus rampart was formed and when it became inactive is to use lichenometric analysis. The results suggest that the moraine formed 130 years ago, and subsequently, the area of almost permanent snow cover was reduced to what is now the patch on the floor of the snow hollow (Fig. 12). They also confirm the conclusions from previous studies that state that there was a substantial increase in snow cover in Sierra de Gredos during the Little Ice Age (Toro et al., 1993), which altered the geomorphological dynamics of some thalli. Finally, the present study corroborates data obtained in the Pyrenees regarding the earliest time at which protalus ramparts associated with the Little Ice Age were formed (Chueca et al., 1998).

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