Geomorphology of glaciated gorges in a granitic massif (Gredos range, central Spain)

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ABSTRACT

A detailed geomorphological map on a 1:10,000 scale is presented for a high mountain area in Gredos range (Iberian Central System). Only few detailed geomorphological maps of the range are available despite the wide diversity of landforms. The map was created with the aid of aerial photographs, satellite images, and 3D images and verified with field surveys. The landforms resulting were classified using the IGUL (Institute of Geography, University of Lausanne) legend system combined with the legend proposed by Peña et al. (1997). As a result, 40 landforms distributed over an area of 40 km² have been identified. The map shows the spatial distribution of different geomorphological processes that have modeled a wide variety of landforms. This variety of processes and landforms identified demonstrated that geomorphological cartography obtained by combining traditional image interpretation and GIS technology facilitates the production of geomorphological maps and the obtaining of valuable data for identify and understand surface processes and landforms.

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1. Introduction

Geomorphological mapping is a classical tool for representing the spatial distribution of landforms and processes (Theler, Reynard, Lambiel, & Bardou, 2010). According to Alcalá-Reygosa, Palacios, and Zamorano Orozco (2016), the development of geomorphological mapping is important because it enables us to show the type, distribution and origin of landforms and morphological processes. The result of intense high mountain processes related with deglaciation is a great diversity of landforms present in these areas (Lambiel, Maillard, Kummert, & Reynard, 2015).

The more complex the terrain is, for example, mountain areas, the greater the diversity of symbols and colors required (Verstappen, 2011). A large number of symbols and legends have been developed since the onset of geomorphological mapping in the early twentieth century (Passarge, 1914). Otto and Smith (2013) pointed that most maps, at present, are generated using GIS or graphic design software, but few symbols sets have been developed for digital application. The combination of GIS and field mapping is considered to have great potential in the analysis of complex systems and to be particularly appropriate to the study of active geomorphological systems (Gustavsson et al., 2006).

This study takes a close look at three gorges at the central massif of Gredos Range, in the center of Iberian Peninsula (Spain), specifically in La Vega gorge, Tahea-Honda small gorge and La Nava gorge. This area is located 30 km West of the Almanzor Peak, the highest peak of Iberian Central System (2596 m.a.s.l.).

The origin of Gredos range is a great cortical thin-skinn thrust, but it is delimited by normal E-W faults derived from a pop-up structure (De Vicente, 2004). The current topography is related to the tectonic evolution during the Alpine Orogeny (Cenozoic) (Pedraza, Carrasco, Dominguez-Villar, & Villa, 2013). The lithology of the whole range is uniform and consists of granites (biotitic and granodiorites) from intrusions during the Variscan orogeny (De Vicente, 2004; Palacios, Andrés, Marcos, & Vázquez-Selem, 2012).

Previous morphological studies were done in Gredos range by Vidal Box (1932), who first analyzed the quaternary glacial morphology of the eastern massif. Vidal Box (1936) also studied the Bohoyo glacial morphology in the central massif. During the 70s, Martínez de Pisón and Muñoz (1972) studied the morphology of Alto Gredos and Arenillas and Martínez de Pisón (1976) studied the glacial morphology of La Serrota. Several research studies have been carried out from the decade of the 90s, when Rubio (1990) studied the geomorphology and quaternary of Bejar and Barco ranges and analyzed primary tills of western and central sectors of Gredos range in Rubio, Pedraza, and Carrasco (1992). Muñoz, Palacios, and Marcos
(1995) analyzed the glacial geomorphology of the Gredos cirque and Martínez de Pison and Palacios (1997) summarized the glacier landforms in the whole Central System. Palacios Marcos, and Tanarro (1998) studied the geomorphology landforms of one sector of Gredos cirque, the Cuchillar de Navajas. Sancho, Palacios, De Marcos, and Valladares (2001) propose the age of pro-talus ramps in the same area. Palacios, García, Rubio, and Vigil (2003) studied the effects of debris flows formed on steep slopes covered by weathering mantle of Gredos range.

In order to improve the understanding of this zone, a geomorphological map of the area has been produced, showing in detail the geomorphologic diversity of three gorges. The Main Map was produced using a combination of the Esri ArcGIS adapted morphogenetic legend of the University of Lausanne and the legend for geomorphological maps by Peña et al. (1997).

2. Methodology

This map was created with the aid of 25 cm resolution aerial photographs provided by the Agrarian Research Institute of Castilla y León (ITACYL), the 25 cm resolution Aerial Orthophotography National Plan (PNOA), satellite image provided by National Geographic Institute (IGN), the 1:10,000 contour lines provided by ITACYL and the Iberpix online cartographic viewer 3D images provided by IGN.

The Main Map was designed using the geomorphological mapping legend of the University of Lausanne (Schoeneich, 1993). According to Lambiel et al. (2013, 2015), this legend is a morphogenetic mapping system built on the following principles:

- Colors represent process categories;
- Symbols have a genetic significance and are drawn in the color of the related processes;
- The morphodynamic differentiation between erosion and accumulation areas is achieved by white and colored surfaces, respectively;
- The morphography, slope gradient and lithology are not represented.

The Institute of Geography, University of Lausanne (IGUL) legend system was developed at the end of the 1980s by Schoeneich (1993), based upon several European legend systems and designed for a 1:10,000 scale but is usable on scales from 1:5,000 to 25,000 (Reynard, 1993). It has been used for more than 20 years for detailed mapping especially in high and middle mountain regions (Pellitero, 2009; Schoeneich, Reynard, & Pierrehumbert, 1998).

IGUL legend is combined with the Geomorphological Legend of Peña et al. (1997) in the case of some features that are not represented clearly enough. The main objective of this legend is to facilitate a flexible and coherent system, with the maximum clarity and readability (Peña, Pellicer, Chueca, & Julián, 1997).

The landforms were delimited with a stereoscope, in some areas 3D glasses has been used with Iberpix 3D and field surveys validated the outputs of aerial photos interpretation.

3. Results

This geomorphological map on a 1:10,000 scale includes 40 landforms divided into 10 morphogenetic systems: structural, hydrography, fluvial, gravitational, glacial, nival, weathering, lacustrine, periglacial and anthropic landforms. In total, the information represented corresponds to 2274 features distributed over an area of 40 km².

3.1. Structural landforms

Structural landforms are determined by the composition and tectonic arrangement of the rocks. The most prominent structural landforms on the map are rock scarp. These are rocky steeps separating ledges with steep slopes. They are located mainly on the cirque walls and upper slopes of the glacial troughs. In these areas, the erosive action of the glacial ice has remodeled these landforms, creating bedrock hills with abrupt slopes, usually higher than 45°. In addition, rock scarps of lesser importance have been distinguished, called rock steps, which differ from rock scarps as they present a height difference of less than 5 m and are mainly found on the slopes of the valley sides.

3.2. Hydrography

There are several lakes in the study area, the lakes of La Nava (1950 m a.s.l.), Cuadrada (2080 m a.s.l.) and El Barco (1788 m a.s.l.). These lakes have a glacial origin and were the result of the abrasion and over-excavation of the glaciers during Pleistocene over more tectonized areas. The first lake is in the cirque of La Nava valley and the last two lakes are located in the cirque of La Vega valley. These lakes originate several streams, which flow through the bottom of the valleys. Downstream, these streams increase their flow due to the feeding of intermittent streams that descend from the slopes, finally acquiring the character of permanent rivers.

3.3. Fluvial landforms

Fluvial accumulation landforms and fluvial erosion landforms have been distinguished (Figures 1 and 2) on the map. Some of the represented landforms were also modeled in combination with the action of glacial meltwaters.
Among these, one of the most representative forms is the glacio-fluvial plains. They are defined as broad and elongated bottoms with flat morphology, which have been formed by the accumulation of deposits of glacial melting dragging waters together with those of fluvial origin. In La Vega and La Nava valleys, the glacio-fluvial plains acquire their best development by forming the troughing bottom between the moraines of greater morphological appearance. In La Vega valley, these plains are best preserved, reaching a longitudinal development around 1.7 km and a variable width between 200 and 300 m (Figure 2).

Alluvial fans are another of the most abundant landforms in the study area. They are originated by the discharge of sediments transported by the streams that have been canalized mainly in the slopes of the valleys and that circulate sporadically. When entering a zone of low slope, the sediment load is deposited as a fan shape. This origin would explain that the mapped fans are distributed in the sides of the valleys, at the mouth of the torrents or channels associated with debris flows, depositing their load on the fluvio-glacial plain and on the riverbed. The most important fans are concentrated around El Barco lake and in the middle part of La Nava gorge.

A unique alluvial fan, of large dimensions, is located in Taheña-Honda valley, at the confluence with La Vega valley. The glacial meltwaters of this valley plus those contributed by the rivers would have dragged the sediments to form this fan in a cone shape, therefore with a fluvio-glacial origin, whose height coincides with the fluvio-glacial plain of La Vega valley.

Figure 1. Examples of fluvial landforms. (a) Alluvial fans, terrace edges and river bed deposits areas in la Nava valley. (b) Fitting of the river course over roches moutonnées in La Vega valley.

Figure 2. River bed entrenchment in the wide glacio-fluvial plain flanked by lateral moraines, in La Vega valley.
Finally, recent fluvial dynamics, mainly of a torrential nature, have modeled the river bed. There is a great development of this dynamics below the lake of El Barco, and the stream flows forming meandering channels. Also, the fluvio-glacial plain has been cut off, remaining hanging, and showing sharp edges by the lateral erosion, that reach several meters of roughness, around 10–15 m with respect to the current valley bottom (Figure 1(a)).

Among the fluvial erosive landforms, a postglacial fluvial incision has been distinguished, which is a deep and narrow cleft, with almost vertical rock walls, formed by the incision of the river after the retreat of the ice (Figure 1(b)). Only one has been distinguished in the upper part of La Nava valley, where the canyon narrows for 430 m from 1700 m a.s.l. until 1600 m a.s.l.

3.4. Gravitational landforms

We recognized and classify different types of slope-failure landforms (Figure 3). Talus slope are the dominant landforms. Active talus slope and those that are no longer active because they are covered by vegetation have been identified in the cartography. Talus slope form by the accumulation of rocky blocks coming from gelification process of rocky escarpments located on the slopes or culminating areas, creating to the typical scree slopes (Figure 3(a)). Rock fall avalanches have also been represented in this landform category, there is a great rockfall avalanche located above the lake of La Nava (Figure 3(b)). Talus slopes are concentrated in the cirque of La Vega valley and distributed by the upper half of La Nava valley, located mainly under rock scarps. Finally, the vegetation-covered talus slopes occupy around 12.8 km² and they are distributed through the slopes and cirques of both valleys.

One of the processes that most frequently occurs on the slopes of the valleys of the Gredos range is the formation of debris flows (Parrilla & Palacios, 1995). In the study area, debris flows that affect the slopes and moraines of La Nava, La Vega and Taheña-Honda valleys are very common, leaving characteristic erosive-sedimentary morphologies, such as the semicircular starting head scarp, the dragging channel and the accumulation of lobes. In particular, in La Vega valley are concentrated numerous debris flows on the slopes located around the lake of El Barco. In Taheña-Honda valley, debris flows descend from the slopes of the cirque in the vicinity of the temporary lagoon.

Figure 3. Examples of landforms of the study area. (a) Rockfall and talus deposits in La Nava valley. (b) Rockfall avalanche close to La Nava lake. (c) Recent debris flow on a slope of La Nava valley. (d) Castellated rocks area with periglacial deposits above the dashed line which indicates the limits reached by the ice.
that forms in the cirque tarn. Finally, in La Nava valley, although they are frequent on the right side slope (Figure 3(c)), the majority have formed over the morainic deposits of the west slope.

Another slope process is related to the presence of landslides that mobilize weathered material masses from the slopes into the valleys. Several deposits have been delimited, as well as the scars originated by landslides. These accumulation and erosion landforms are found in the north of the study area, affecting the slopes of La Vega and La Nava valleys just upstream of their junction. The scars appear halfway up the slope and show a concave shape, reflecting the mobilized material. Also, some landslides affect the major entity moraines, removing the morainic material towards the bottom of the valley, as it happens in La Vega valley.

Finally, boulder accumulation in slopes have been delimited, its origin is due to the physical weathering, controlled by the action of the gelification. Freeze-thaw cycles broke up the rocky outcrops resulting in a continuous block cover. These forms are found on both slopes of La Nava valley.

3.5. Glacial landforms

Glaciers have been the main modeling agent and their effects are clearly reflected in the current topographic configuration of the study area, especially in the upper parts of the valleys. Glacial erosion has developed U-shaped valleys, characteristic of mountain glaciations (Figure 4). Several glacial landforms have been found in the study area, both erosive (e.g. glacial cirques, roches moutonnées, trimlines and horns) and sedimentary, like moraines and morainic crests.

Three glacial cirques have been mapped in the study area. The cirques are located at the headwaters of the former glaciers, where the ice that slid down the valley in the form of a tongue was accumulated. The bottom of the glacial cirques is located at an altitude of 2200 m a.s.l. in La Nava valley, 2100 m a.s.l. in Taheña-Honda valley and 2260 m a.s.l. in La Vega valley, being the latter the largest, with an amplitude between walls of 2 km and being crowned by the peak of La Covacha (2395 m a.s.l.).

In cirques and valleys, the presence of roches moutonnées is very common, these erosive landforms are bedrock hills modeled by the glaciers and have their origin in the glacial abrasion on the bedrock. In the study area, these forms occupy an area of 9.2 km² and most are found in the cirque areas and on the western slopes of the valleys.

Trimlines, which represent the boundary separating glaciated and non-glaciated surfaces, have been deduced by photointerpretation, indicating the level reached by the ice. These trimlines are evident in some areas near the ridges of the cirques and especially in the east slope of La Nava valley. It is also noticeable the presence of horns, which are pyramidal peaks with steep walls, which originate from the glacial erosion, and occasionally the coalescence of the walls of several cirques. Several horns can be found in the study area in the upper parts of the cirques. The main ones are Alto del Corral del Diablo (2366 m a.s.l.), Las Azagayas (2367 m a.s.l.), El Juraco (2383 m a.s.l.) and La Covacha (2395 m a.s.l.).

On the other hand, different types of morainic deposits have been found, which have their origin in the materials transported and deposited by a glacier due to the action and retreat of the ice, producing different generations of moraines (Figure 5).

The map shows clearly the presence of lateral moraines in the valleys, defined by their sharp crests, which extend over 1.5 km, as seen in the left lateral moraine of La Vega valley, whose crest rises more than 155 m above the fluvio-glacial plain (Figure 2). They are,
overall, moraines differentiated by their greater entity and great morphological expression and conservation, which allow to reconstruct the extension of the glacial tongues, presumably, during the Last Glacial Maximum (Palacios, Marcos, & Vázquez-Selem, 2011; Pedraza et al., 2013). The crests of the moraines descend to a minimum altitude of ∼1400 m a.s.l. in La Vega valley and 1335 and 1572 m a.s.l. in La Nava and Taheña-Honda valleys, respectively.

In the outer edge of these main crests, several moraines have been found, what would attest the maximum extent of the ice and are formed by a mixture of heterometrical and fine blocks, accumulated during a phase of advance or standstill of the glacial front (Palacios et al., 2011). They have been delimited at minimum altitudes of 1323 m a.s.l. in La Nava valley, at 1368 m a.s.l. in La Vega valley and at 1552 m a.s.l. in Taheña-Honda valley. Moreover, within the moraines of greater entity, a sequence of moraines of smaller dimensions is recognized, who fronts arches rest on the fluvi-glacial plain, counting up to 14 moraines in La Vega valley. However, in La Nava valley, they have been partially blurred because of the recent fluvial incision and also have been partially covered by vegetation-covered talus slope. Some of these internal moraines are interpreted as advances and standstills of the glacier and others were deposited during the last standstill of the glacier.

During the last phases of glacier stagnation, some moraines were deposited beside the lakes of La Nava and El Barco. Finally, two moraines have been found, which probably correspond to a standstill phase in an area that was isolated from the rest of the glacier, at altitudes between 2025 and 2150 m a.s.l., on the western slope of La Nava valley.

### 3.6. Nival landforms

Nival landforms can be erosive or accumulative. In the study area, these landforms are not very common, and mainly protalus ramparts can be recognized. These are sedimentation landforms that originate from debris fall, which slips on snow patches and accumulate at their front, building a ridge of greater or lesser height depending on the persistence of the process. On the inner side, there is a depression which is only visible in the years in which the snow patch melts.

Although small protalus ramparts are recognized on the culminating steep walls of the cirques, only two protalus ramparts have been represented in the map. The first one, in the cirque of La Nava, next to the lake, at an altitude of ∼1980 m a.s.l., shows a small arch about 100 m long. The second, larger protalus rampart is located on the most eastern sector of the cirque of La Vega, facing southwest. The moraine crest is located around ∼2070 m a.s.l. and extends about 500 m. At the base of the inner side of the moraine, a depression has been modeled, which connect with the talus slopes.

### 3.7. Weathering landforms

Several weathering landforms have been delimited, such as weathered mantle and the tors. The weathered mantle consists of a layer of altered materials due to the
combination of chemical processes and the disintegration of the mineral structure of the granitic rocks, particularly medium-thick grain size granodiorites (Instituto Geológico y Minero de España [IGME], 2006), formed before the appearance of glaciers (Palacios et al., 2003). Altered rocks can exceed 4 m thickness, as it has been observed in other parts of Gredos range (Palacios et al., 2003), and they settle on the unaltered bedrock.

In the map, talus weathered mantle and summit weathered mantle have been differentiated. Two small areas of weathered mantle have been located in the upper area of the western slope of La Vega valley at ∼2000 m a.s.l. Large areas of summit weathered mantle have also been delimited, located in the interfluves and also next to a divide area in the western part of La Vega valley.

On the other hand, the rocky substrate is visible in summit areas or slopes where the weathered mantle has been eroded, which presents tors. Small areas of tors distributed in a scattered manner have been located in the summit areas of the valley divides, usually in the lower sector of the valleys, mainly surrounded by vegetation-covered talus slopes.

3.8. Lacustrine landforms

Lacustrine landforms are sedimentary landforms that come from the clogging of a lake or flooded areas. We recognized and classify several different lacustrine deposits: lacustrine deposits by glacier plugging and peatlands.

The first ones are related to the sedimentation of the moraines of the valleys, causing the valley closing and creating new lacustrine areas. Thus, several alluvial plains sealed by lateral moraines have been delimited, which are clearly observed in La Vega and La Nava valleys, where the major entity lateral moraines close alluvial fans from tributary valleys at altitudes between 1450 and 1550 m a.s.l. Narrow plains have also been recognized, they occur in the middle part of the slopes and are originated by the closing by a lateral moraine. This landform appears in La Nava valley, where it is clearly observed how the lateral moraine of the left side closes a stretch of the slope, forming a plain enclosed by lateral moraine of about 500 m in length. These plains can receive a large amount of water from the upper part of the slope, forms small lagoons and also disrupts the slopes by water infiltration, favoring the triggering of debris flows (De Marcos & Palacios, 1995). It can be observed in the map, where numerous debris flows have been formed that mainly affect the moraines of the left slope of La Nava valley.

In the study area, peatlands constitute small areas where fine sediment accumulation has filled these areas and appear as areas with abundant water and herbaceous vegetation. They are scattered in the cirques, especially in the western sector of the cirque of La Vega and in the cirque of La Nava, occupying small plains between the thresholds. They also formed in some slopes in favor of a flatter topography.

3.9. Periglacial landforms

Periglacial landforms develop in cold climates as a consequence of the presence of ice and the frequency of freeze-thaw cycles of the interstitial water inside the rocks.

Although some landforms related with these processes have been explained when dealing with slope landforms, this section is dedicated to the periglacial landforms located in the summit areas of the valleys and cirques that were not glaciated, such as the periglacial accumulation areas, generally above 2200 m a.s.l. At these altitudes, the periglacial processes affected to the granite rocks controlled by a vertical joint and fissure network, modeling castellated landforms. These castellated rocks are found near the cirque areas and in a steep area between the valleys of La Vega and La Nava.

3.10. Anthropic landforms

These landforms are the consequence of human intervention on the landscape. The most abundant anthropic works are the concrete dykes, which are artificial dams built with the aim of improving water reserves. The track that leads to El Barco dam has been delimited. Also several huts have been delimited. These huts are located at 1620 m a.s.l. in La Vega valley and 1500 m a.s.l. in La Nava valley. Finally, there are small structures intended to store livestock materials, which were abandoned last century and nowadays they remain in ruins due to the nonexistent maintenance. These structures are located close to the El Barco reservoir.

4. Conclusions

The 1:10,000 geomorphological map obtained of these three gorges of Gredos range represents clearly the distribution and characteristics of the landforms. The IGUL legend has demonstrated to be suitable for represent detailed geomorphological maps of mountain areas and their combination with the Geomorphological Legend of Peña et al. (1997) has given more consistency to the resulting map, which contributes to improve the knowledge and understanding of this zone of the Gredos range showing valuable geomorphic evaluation of the area. The Main Map reconstruct the evolution of the landscape by preglacial, glacial and postglacial landforms and set out geomorphological problems such as if some culminating surfaces were not glaciated or previous landforms survived to glacial
erosion. The map clearly reflects the importance of glacial erosive and accumulative landforms, recognizing a complete succession of moraines and showing the complex glacial evolution of the area.

**Software**

The map was produced on Esri ArcGIS 10.2 in its ArcMap and ArcScene environments and Bentley Micro-Station v8i, the final editing was carried out using Illustrator CC 2017.

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