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THE LAST GLACIAL CYCLE IN THE LUNA HEADWATERS, CANTABRIAN MOUNTAINS (LEÓN PROVINCE, NW SPAIN): A CONTROVERSIAL ISSUE

El último ciclo glacial en la cabecera del río Luna, cordillera Cantábrica (provincia de León, NO de España): un tema controvertido

Victoria Alonso

Departamento de Geología, Universidad de Oviedo, C/ Arias de Velasco s/n, 33005 Oviedo, Spain.
alonsovictoria.uo@uniovi.es

Abstract: *The Cantabrian Mountains (NW Spain) developed small icefields and alpine glaciers during the Last Glacial Cycle. The Luna Valley, which spreads along the southern slope of these mountains and shows both glaciation styles, has been studied by several authors, with different results concerning the position of the glacier fronts during the maximum ice extent stage. Prominent moraine complexes, in the valley bottom, have been frequently interpreted to represent the lowest glacier fronts; some studies, however, attribute these moraine complexes to a recessional phase. In this work, geomorphological mapping based on visual inspection of aerial photograph and field surveys allowed the maximum glacier extent at this catchment to be reconstructed. Throrough fieldwork made it possible to identify small till patches and glacially transported clasts that in turn allowed us to infer the position of the glacier front during the maximum ice extent (S-I) at an altitude around 1110 m. After this maximum, three recessional stages (RS-I, RS-II, and RS-III) were identified, followed by a Tardiglacial stage characterized by rock glaciers. This basin shows similarities with the Porma Valley (also in the southern slope of the Cantabrian Mountains) with regard to terminus altitudes, absence of terminal moraines, and glacier length during maximum.*

Keywords: *Glacier reconstruction, Last Glacial Cycle, Luna Valley, Cantabrian Mountains, Iberian Peninsula.*

Resumen: *Durante el último ciclo glacial, en las zonas más elevadas de la cordillera Cantábrica se desarrollaron pequeños campos de hielo y glaciares de tipo alpino que originaron un relieve glaciar característico. En diversos estudios realizados en la cabecera del río Luna, situado en la vertiente sur de esta cordillera y que muestran los dos tipos de aparatos glaciares, se han propuesto diferentes resultados en cuanto a la máxima extensión alcanzada por los hielos en esta área. El valle del Luna, fuertemente antropizado y sin morrenas terminales identificadas, presenta unos complejos morrénicos bien desarrollados en la desembocadura de los valles tributarios que han sido interpretados frecuentemente como indicadores de la posición de los frentes glaciares durante el máximo; otros estudios, sin embargo, los atribuyen a una fase de retroceso. Para tratar de resolver estas discrepancias, se ha realizado una cartografía geomorfológica basada en la fotointerpretación de fotografías aéreas y en un detallado trabajo de campo, lo que ha permitido reconocer, a altitudes bajas, numerosos clastos transportados por el hielo, pequeños afloramientos de till y afloramientos rocosos pulidos por la acción glaciar. A partir de todos ellos, e integrando datos de trabajos previos, se ha realizado una reconstrucción glaciar y deducido la posición de los frentes durante la fase de máxima extensión del hielo (S-I) a una altitud aproximada* *de 1110 m, a unos 20 km de la cabecera del valle y relativamente alejados de los complejos morrénicos antes citados. Se han identificado tres fases de retroceso (RS-I, RS-II y RS-III) definidas por la posición de morrenas laterales, complejos morrénicos y morrenas frontales situadas en zonas elevadas, y, finalmente, una fase caracterizada por el desarrollo de glaciares rocosos. Al retroceder los frentes glaciares a los valles tributarios, las corrientes proglaciares formaron grandes abanicos paraglaciares en su desembocadura y, más tarde, otros más pequeños en las laderas progresivamente deglaciadas. Las inestabilidades relacionadas con la deglaciación movilizaron los materiales depositados por el hielo y los frentes rocosos recientemente expuestos, contribuyendo parcialmente a la formación de morrenas frontales. En todos los valles se han identificado, además, diversas formas periglaciares, algunas de ellas aún activas en la actualidad. Un intento de correlación con otras zonas de la cordillera Cantábrica muestra similitudes entre los valles del Luna y del Porma: altitud de los frentes, ausencia de morrenas terminales y longitud del glaciar durante la fase de máxima expansión del hielo.*

Palabras clave: *reconstrucción glaciar, último ciclo glacial, valle del Luna, cordillera Cantábrica, península Ibérica*

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Introduction

The glacial features of the Cantabrian Mountains (CM hereafter) (N Spain, Fig. 1) are well known since the beginning of the 20th century (Carballo, 1911; Obermaier, 1914; Hernández Pacheco, 1914, 1929; Stickel, 1929; among others). Over the last four decades, the glacial development of the area has been approached from diverse perspectives, including studies on morphology, on paraglacial and post-glacial evolution, mapping, identification of glacial stages and dating. Today it is largely deglaciated, with only some localized glacier ice remnants inherited from the Little Ice Age in the Picos de Europa sector (González Suárez and Alonso, 1994, 1996; González Trueba, 2005; Ruiz Fernández *et al.*, 2022) that were identified in the 19th century (Prado, 1860; Saint Saud, 1893; Penk, 1897), close to the end of that period. The Luna Valley, one of the Pleistocene glaciated areas in the western sector of the CM, has been studied by several authors, such as Stickel (1929), Vidal Box (1943, 1958) or Nussbaum and Gigax (1952), who proposed lower levels of glaciation for the areas closer to the coast and very short ice tongues in higher and more inland zones.

Recognition of the extent of past glacial events in mountain valleys is essential to making correlations and establishing glacial chronologies (Chinn, 1979). However, the extent of the glaciers in the Luna basin during the Last Glacial Cycle (LGC) remains controversial. Some authors have considered that the main valley was not at all glaciated and that Pleistocene glaciers did not extend further from the tributary valleys (Castañón Álvarez, 1987; Castañón Álvarez and Frochoso Sánchez, 1992; Frochoso Sánchez and Castañón Álvarez, 1998; García de Celis and Martínez Fernández, 2002; Santos González, 2010; Santos González and Fernández Martínez, 2011; Rodríguez-Rodríguez *et al*., 2015; Serrano *et al*., 2017; Santos-González *et al*., 2018) while others have claimed that the frontal moraines of tributary valleys are not terminal moraines but that they formed during a recessional stage (Alonso, 1998; Alonso and Trombotto Liaudat, 2009; Jalut *et al.,* 2010; Alonso *et al.,* 2019). Alonso and Suárez Rodríguez (2004) calculated a minimum ice thickness for the main valley at the River Luna headwaters (Fig. 2). Furthermore, from the distribution of till and of glacially transported clasts in the valley bottom, in a fieldwork-based study, Alonso (2020) deduced that glacier fronts nearly reached the upper limit of the present-day Barrios de Luna Reservoir during the LGC, at an altitude of around 1110 m, which would imply a glacier length of 20 km from the valley head. In a further synthesis on the glaciers of the Leonese Cantabrian Mountains, Santos-González *et al*. (2021; see their Fig. 4.10.1A) presented a map –different from their own previous version of 2018– of the extent of the glaciers during the local Last Glacial Maximum (lLGM), with new glaciarized areas in the Luna headwaters, where some glaciers termini reached lower or upper altitudes, whereas others remained unchanged. On this new map, a glacier tongue occupies the main valley, reaching an altitude of 1200 m a.s.l.; however, till deposits are still common even beyond these new enlarged glacier margins.

Considering much lower limits for the Upper Luna Valley (Alonso, 2020) than those recently presented by Rodríguez-Rodríguez *et al.* (2015), Serrano *et al.* (2017), Santos-González *et al.* (2018), and Santos-González *et al.* (2021), it is necessary to reassess the glaciation stages of the zone since lower moraines in tributaries may have derived from stabilization of glacier termini during a recessional stage, which then would not indicate the maximum glacier extent in the area.

Therefore, the aims of this paper are: (i) to present a new geomorphological mapping showing the extent of the glaciers in the Luna Valley headwaters during different stages of the LGC; (ii) to analyze glacial, periglacial, and paraglacial landforms in order to establish the evolution stages and compare them with previously published data; (iii) to reconstruct the approximate size of the Luna glaciers during the LGM; and (iv) to highlight the importance of fieldwork in areas with a modified glacier relief where outermost/lowermost terminal moraines are not preserved.

The Luna Valley: geological and geographical setting

The CM a is an E-W trending range in northern Spain, adjacent to the Bay of Biscay. It was formed during the Alpine orogeny, as a western prolongation of the Pyrenees. Nevertheless, its structure is Variscan with little Alpine overprinting (Alonso *et al*., 1996; Pulgar *et al*., 1999; Gallastegui, 2000). It is made up of Palaeozoic sedimentary rocks, locally with a thin Mesozoic unconformable cover (Alonso *et al*., 2007), and irregularly distributed Quaternary deposits. In the study area, the Palaeozoic succession comprises both carbonate and siliciclastic units. Several Carboniferous limestone units form the high reliefs of the Ubiñas Massif and the area of Los Grajos in the north and east. These also occur in the northern tributary valleys and in the small hills in the valley bottom between Piedrafita and Rabanal. Well cemented quartzarenites and sandstones form the highest peaks in the south (Villabandín) and some other peaks in the valleys to the north. Other less resistant siliciclastics units form the lower reliefs of the region. The Mesozoic is restricted to a small outcrop of siliciclastics in the Peña Ubiña area, whereas Quaternary glacial, periglacial, slope and fluvial deposits are patchily distributed (see geological map at http://info.igme.es/visorweb; Merino-Tomé *et al*., 2014).

The study area lies in the western CM and contains the second-highest massif of the range, the 2417 m high Ubiñas Massif (Fig, 1A). In the south, peaks up to around 2000 m high are common. Overall, summits are slightly higher in the north (Somiedo to the west and Ubiñas to the east), along the main divide of the CM range.

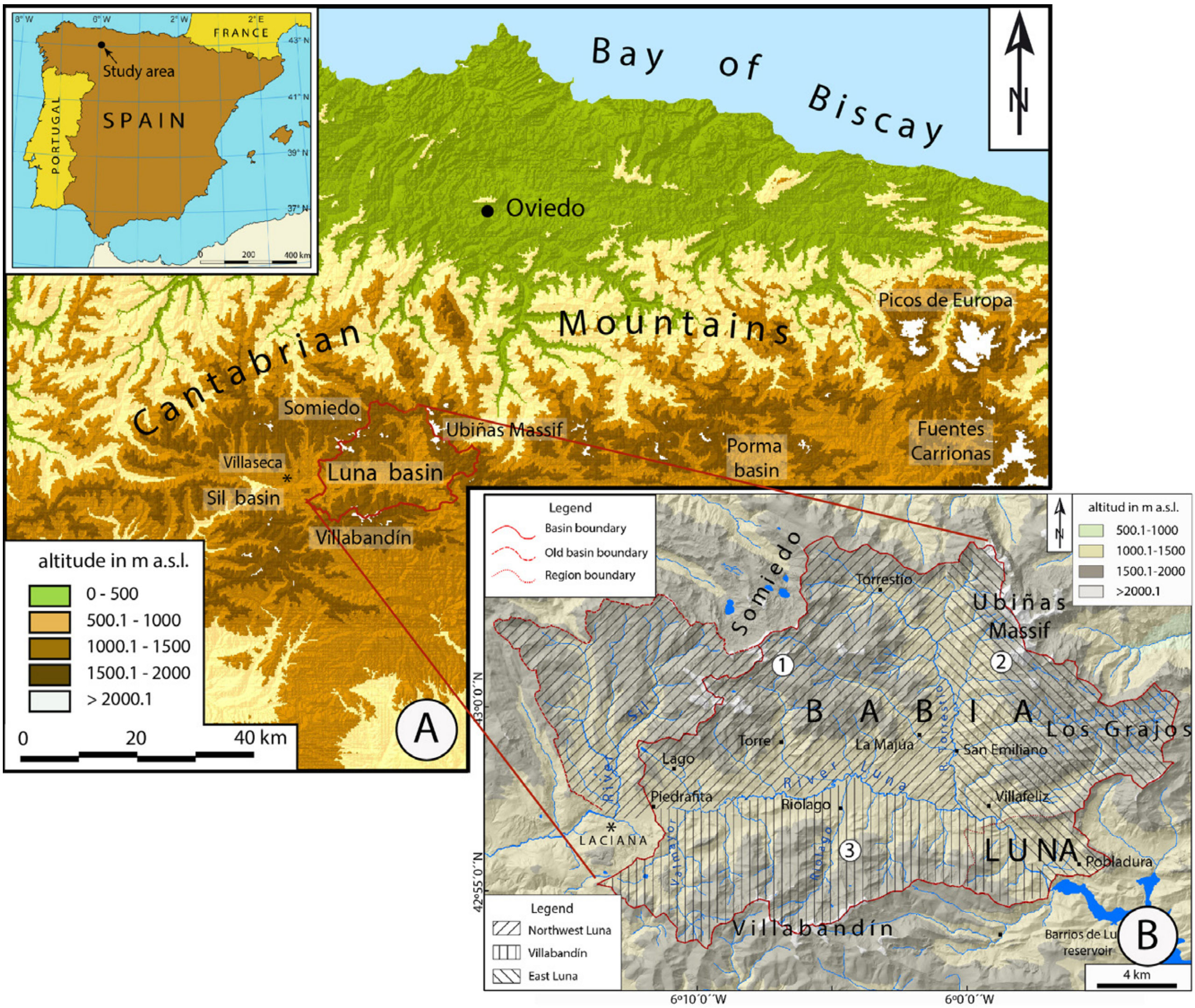

Fig. 1.- A) Location of the study area in the western domain of the Cantabrian Mountains. The upper Luna basin lies to the southwest of the Ubiñas Massif which contains the highest peaks in the area. Digital Elevation Model based on data provided by the IGN (Instituto Geográfico Nacional). B) The Luna basin, including the municipalities of Babia and Luna, has been divided into three zones: 1. northwest Luna, 2. east Luna, comprising the Ubiñas Massif and Los Grajos, and 3. Villabandín (field view in Figs. 4A, B and C). Asterisk marks the capture elbow of the River Sil.

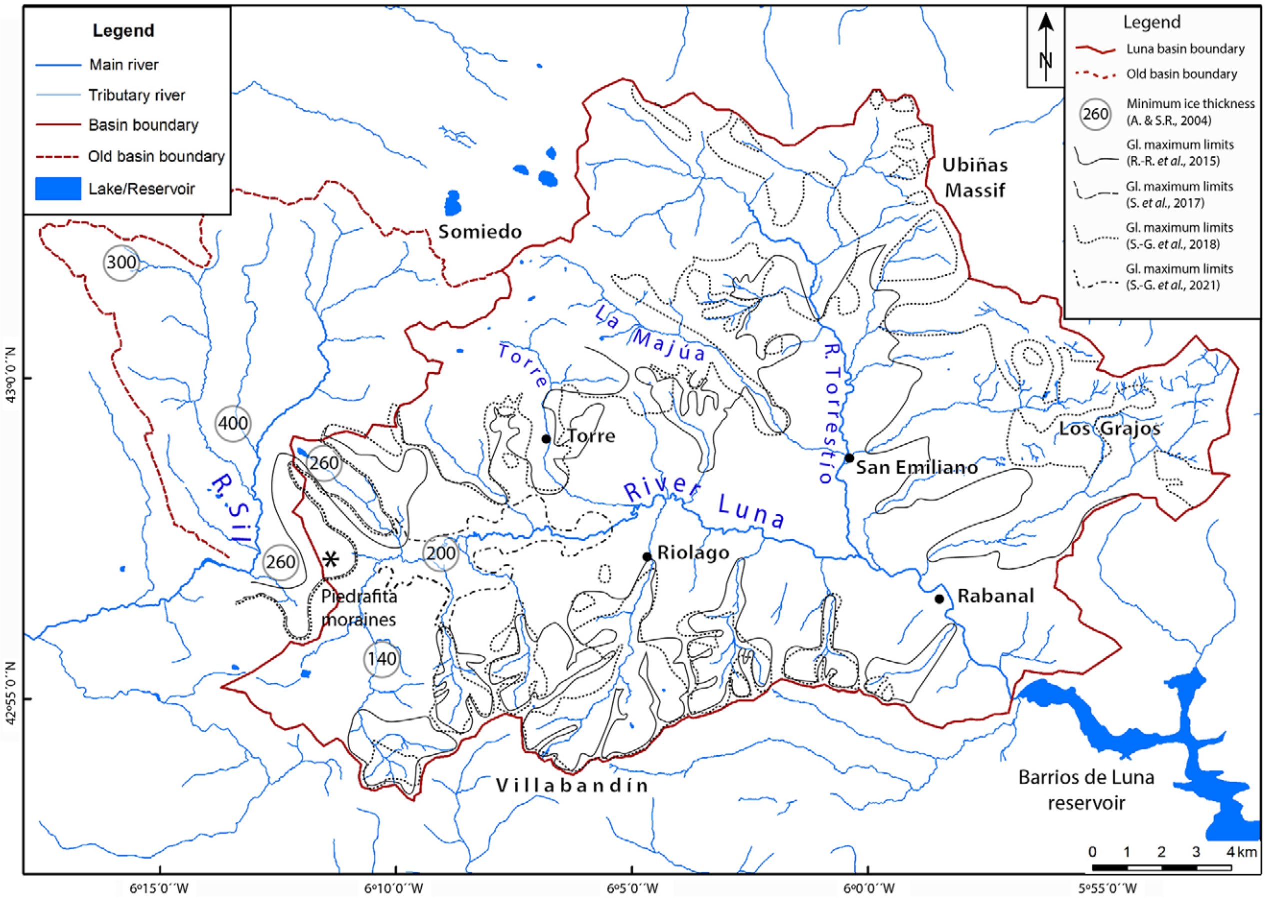

Fig. 2.- Former glacier fronts reconstructed by different authors. Numbers in circles indicate minimum ice thickness in meters (Alonso and Suárez Rodríguez, 2004; their Fig. 2). Lines, redrawn from Rodríguez-Rodríguez *et al.* (2015; their Fig. 2), Serrano *et al.* (2017; their Fig. 4), and Santos-González *et al.* (2018; their Fig. 2C), represent the maximum ice extent. Only the new fronts in the valley bottom proposed by Santos-González *et al.* (2021; their Fig. 4.10.1) are represented here. The asterisk marks the location of the Piedrafita moraine complex.

The Luna headwaters, to the south of the main divide, spread along 336 km^2, mostly in the Babia Region. This represents an areal reduction of its extent during glacial times (Fig. 1B). During that period, after draining the Somiedo Mountains in the north, the River Luna bent eastwards entering what presently is its new headwaters, a flat wetland, with poorly defined channels, in the surroundings of Piedrafita. Vidal Box (1943) related this "anomalous physiognomy" of the upper Luna Valley to the capture of the old Luna headwaters by the River Sil (the "capture elbow" is marked with an asterisk in Fig. 1B). This enlargement of the basin to the northwest is marked on our figures as "old basin boundary".

From Piedrafita, the River Luna flows to the east along an up to 3 km wide intramountainous plain, with very low gradient (< 0.8 %); the altitudinal difference between Piedrafita and the Barrios de Luna Reservoir, which are 20 km apart, is only 160 m. The river is fed by several tributaries flowing southwards from Somiedo (Torre, La Majúa, and Torrestío), northwards from Villabandín (Valmayor and Riolago), and westwards from the Ubiñas Massif and Los Grajos. The Luna, flowing eastwards, and the Torrestío, flowing southwards, are the two main rivers of the basin; their confluence occurs in the SE of the basin, 4.5 km upstream of the Barrios de Luna Reservoir. The valleys of these two rivers are highly anthropized due to a long livestock tradition (Maceda Rubio and Marcello Barriada, 1988), stemming from the Middle Ages. Long term human action has possibly contributed to destroying most of the original glacial relief, except for *roches moutonnées* at the Luna valley bottom. The glacial landscape, however, is better preserved in all the tributary valleys.

Methods

Initially, mapping glacial cirques and moraines from aerial photographs was considered the best way to determine the maximum extent of Quaternary glaciers in the area. However, without the main valleys terminal moraines and considering that most of the glacial features in this area are subtle and not detectable in aerial photographs (Alonso, 2020), thorough fieldwork was compulsory to allow recognition of glacially transported clasts and till distribution in low areas. Fieldwork was initially focused in zones with anthropic terraces, as they are usually built on till deposits (Alonso 2019), although cases of terraces made on ancient alluvial-fan or slide deposits also exist. Glacially transported materials were identified mainly based on their exotic lithology, different from the underlying bedrock. Surface abrasion degree, presence of striae, and shape (iron-flat and bullet shaped forms) were also analysed. The clasts that may have been transported by gravitational or alluvial processes were discarded. A 1:10,000 geomorphological map was made over orthophotographs with a pixel size of 25 cm by means of GIS software (ArcGis). Orthophotographs and DEMs were obtained from the Spanish CNIG (National Centre of Geographic Information; http://centrodedescargas.cnig.es/). Aerial photographs at a 1:15,000 scale and 22 cm pixel size (available at http://ftp.itacyl.es/cartografia/03_FotogramasAereos/PNOA_CYL_NW_2008/) were also used. The online 3D viewer of the Instituto Geográfico Nacional (http://www.ign.es/3d-stereo/) was consulted to complete information provided by the aerial photographs. Basin boundaries in the Piedrafita zone were determined on aerial photographs (U.S. Air Force flight from 1957) taken before extensive coal open pit mining activities changed the landscape.

Landforms mapped were grouped according to their genetic origin, i.e. glacial, periglacial, fluvial, and slope, although only the first two groups are featured in the map. Moraines were mapped as polylines, whereas patchy till deposits, not recognizable as moraines, were recorded as points. The map includes features that had not been previously reported by Alonso (2019, 2020), such as lateral moraines, till deposits, scattered erratic boulders and other allochthonous clasts, essential in order to determine glacier extent during the LGM. Medium- and small-scale periglacial features (rock glaciers and protalus ramparts) were also recorded as points. Discrepancies with previous maps, presented by other authors, regarding moraine and presence of rock glaciers were checked in the field. The final map (Fig. 3) displays the most outstanding data of till or glacially transported clasts detected in the field.

Results

The geomorphological map (Fig. 3) shows a great variety of glacial and periglacial deposits and erosional features, which are usually best preserved in quartzitic bedrock zones and at high altitudes. All the Luna tributary valleys present classical glacial erosional and depositional landforms, such as cirque basins, U-shaped valley profiles, ice-moulded bedrock, overdeepened zones, truncated spurs, trimlines, hanging valleys, and lateral and frontal moraines. In order to analyse results and based on lithology, physiographic differences and glaciation styles, the study area was divided into three zones (Fig. 1B).

- Zone 1 or northwest Luna (between the Rivers Luna and Torrestío), with alternating siliciclastic and calcareous bedrock This zone includes the old Luna headwaters, to the northwest. Here valleys were occupied during the maximum ice extent phase by outlet glaciers descending from the Somiedo icefield (Fig. 4A).

- Zone 2 or east Luna (to the east of the River Torrestío, corresponding to the Ubiñas Massif and Los Grajos), mainly formed by a calcareous bedrock, where glaciers were fed by snow avalanching from the west of the Ubiñas Massif and from a small icefield developed in the relatively flat calcareous area of Los Grajos (Fig. 4B).

- Zone 3 or Villabandín (to the south of the River Luna), mainly constituted by a siliciclastic bedrock with an alpine style of glaciation, glaciers flowing from cirques and valley heads with ice-free summits (Fig. 4C).

Glacial cirques vary from well-developed forms to small hollows on high gradient slopes. They are common in Villabandín, with well-preserved mature landforms on siliciclastics (Figs. 3 and 4C) and mainly with a N–NE aspect, although they are also frequent in northwest Luna. In both zones, a few cirques contain small lakes, occupying overdeepened depressions and occasionally dammed by frontal moraines (Fig. 5). However, cirques are almost absent in the predominantly calcareous Ubiñas Massif and Los Grajos area. In the main Luna Valley, small cirques with a N aspect occur at low altitude (with fronts at 1440-1580 m), two of them having well-preserved latero-frontal moraines. The main divide between Somiedo and Babia, in the northwest, shows glacially shaped ridges (Fig. 4A). Other transfluent or diffluent cols were identified in most of basin boundaries and within the basin (e.g. Fig. 4B). Tributary valleys in northwest Luna, and to a lesser extent in Villabandín, display U-shaped transverse profiles. The Villafeliz valley in Los Grajos area also displays a flat bottom, typical of glacial valleys. Most of the numerous small rock hills in the Luna valley bottom show similarities to *roches moutonées*, with a smooth up-ice side and a rough down-ice side, up to 120 m high. Some others occurring at the valley head are attributable to small whalebacks with a relief up to 50 m. Polished surfaces (not represented on the map of Fig. 3) are best preserved in higher areas (Fig. 4A), where subglacial channels (*nye*) were also identified in limestones. Striae on abraded bedrock are very scarce and occur on quartzites and on polished calcareous bedrock recently exposed after till removal.

Frontal moraines, either isolated or forming complexes, as well as small lateral moraines (e.g. two 35 m and 27 m long lateral moraines, close to San Emiliano) occur at low and medium altitudes in the main valleys, whereas large lateral moraines appear in tributary valleys (e.g. Fig. 4C). Main frontal moraine complexes developed in the surroundings of Piedrafita, at the head of the Luna Valley, and at the mouth of tributary valleys in northwest Luna, all of them at altitudes between 1240 and 1280 m and even higher in Los Grajos (Fig. 4B), among others in east Luna. Small frontal and lateral moraines exist in high areas at or close to cirque fronts. Relationships between aspect and altitude of frontal moraines in northwest Luna (Fig. 6) show a wider distribution for moraines above 1600 m controlled by the aspect of the feeding areas, while moraines at medium and low altitudes (<1540 m) present an E-SE aspect, delineating glacier margins within the main valleys with coincident ice flow directions.

Till deposits that do not form moraines occur mainly in low areas that had not been previously identified as glaciated. These deposits occur as a discontinuous and very thin cover (Fig. 7A) alternating with erratic boulders and allochthonous clasts of different sizes and lithology. Both till deposits and allochthonous clasts are more common at the down-ice side of the ice-moulded reliefs, al-

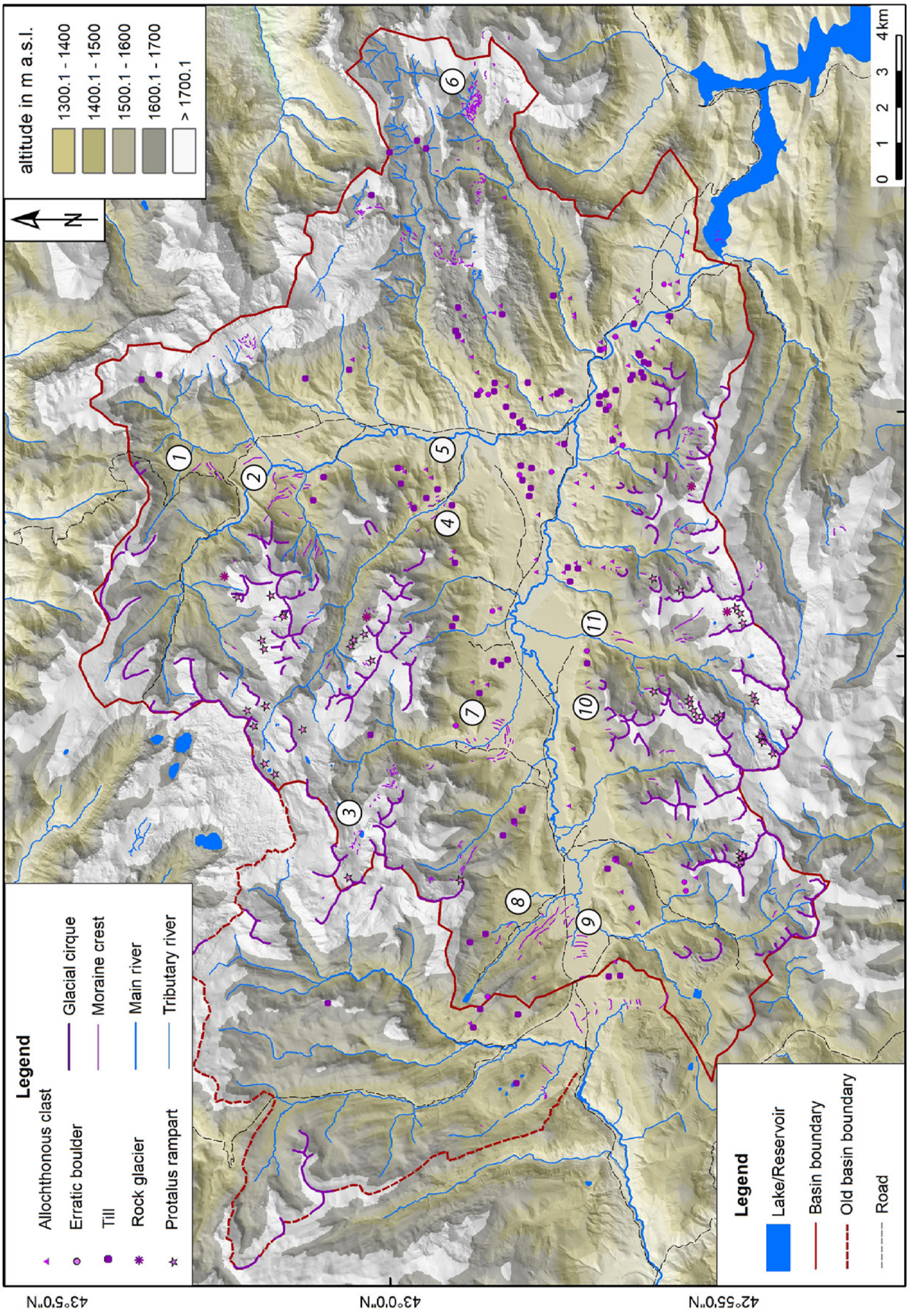

Fig. 3.- Map of the glacial and periglacial features of the Luna basin showing cirques, moraine crests and distribution of till and glacially transported clasts. Rock glaciers and protalus ramparts marked by stars. Numbers in italics correspond to zones cited in the text.

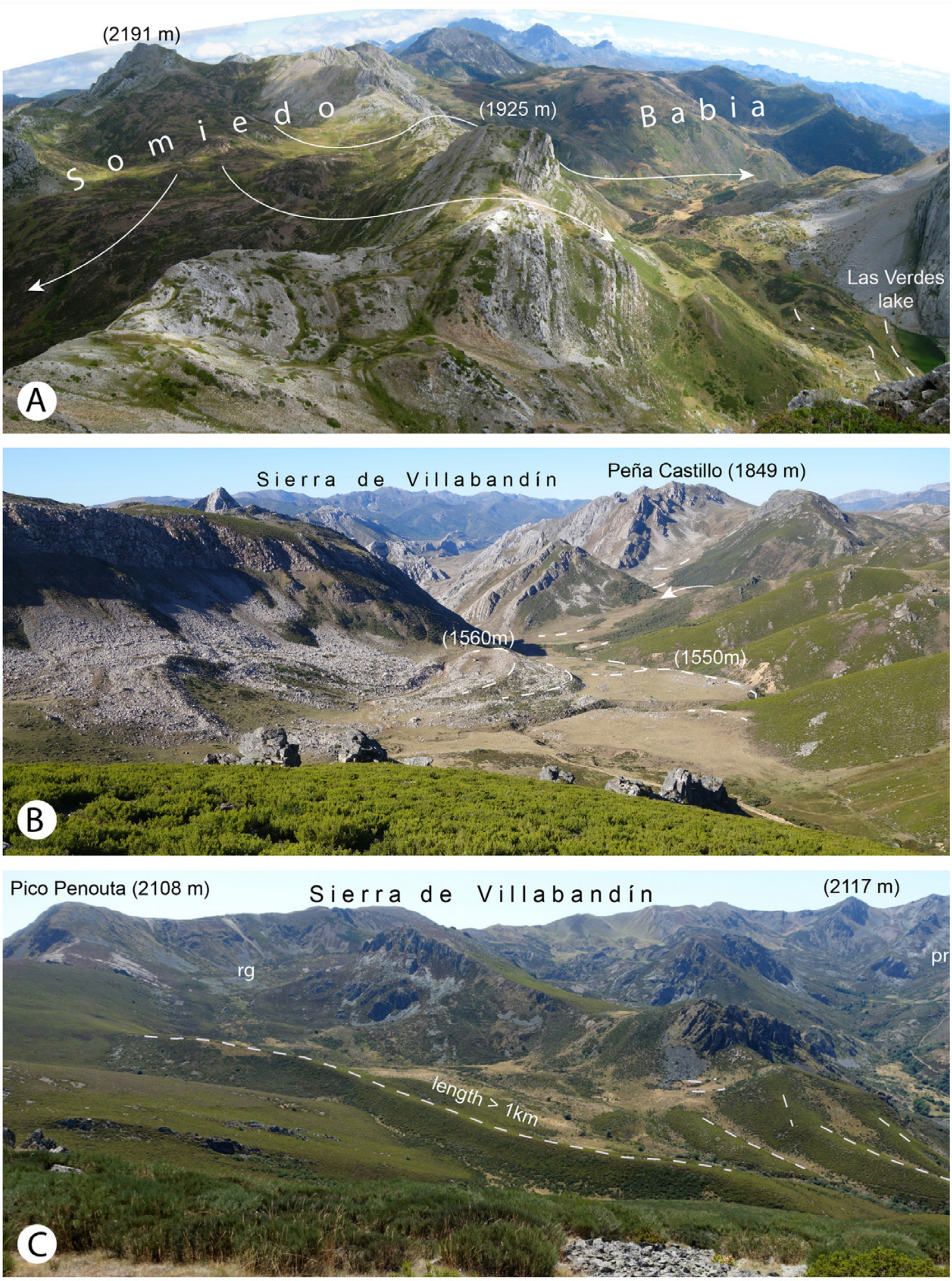

Fig. 4.- A) Accumulation area located to the northeast in Somiedo, in a relatively flat zone. The Somiedo icefield, covering and polishing the limestones of the main divide, flowed to the Babia Region and fed the glaciers in the Luna Valley. Moraine crests marked by dashed lines. Far in the background, the Ubiñas Massif. View to the east. B) The frontal moraine complex of La Cazurría in Los Grajos, partially covered by large boulders detached from a highly fragmented vertical scarp. Note the large volume of the moraine at 1560 m (altitude corresponds to the moraine ridge). Other frontal moraines to the east of Peña Castillo; arrow marks a transfluence zone. Villabandín in the background. View to the southwest. C) Villabandín, with the south divide of the Luna basin in the background. Well-preserved lateral moraines and small frontal moraines in the foreground. Frequent periglacial landforms –such as rock glaciers (rg) and protalus ramparts (pr)– occur in this siliciclastic area. View to the southwest.

though, glacially transported clasts also exist along the whole basin. These till deposits contain common well-rounded clasts and rare striated clasts (Alonso, 2020; see their Fig. 4E). Due to their importance for glacier extent reconstruction, several isolated erratic boulders, as well as most of the small till outcrops recognized by fieldwork, were recorded on the map.

Periglacial and paraglacial landforms

Periglacial landforms are widely represented in the Luna basin, where four rock glaciers (Fig. 7B), numerous protalus ramparts (Fig. 5) and several features related to solifluction processes were recognized.

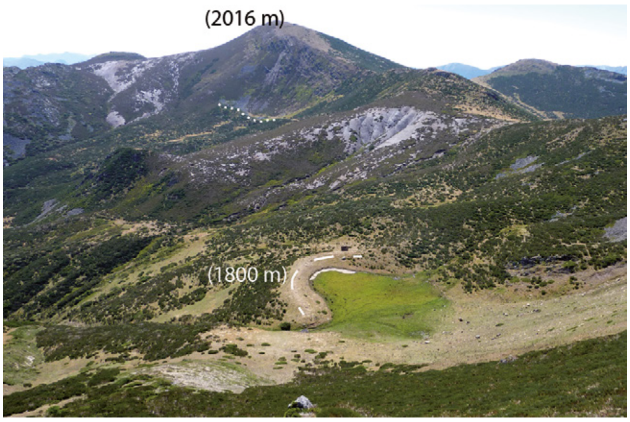

Fig. 5.- A partially infilled glacial lake closed by a frontal moraine, marked by a dashed line, with a southeast aspect attributed to the last recessional stage (RS-III) in the La Majúa Valley. The dotted line marks the crest of a protalus rampart with a north aspect at an altitude of 1830 m. View to the southeast.

Rock glaciers in the Luna headwaters are constituted by quartzite and sandstone clasts. They present a N–NE aspect, with an initiation line altitude (RILA; Humlum, 1988) at 1860–1700 m and fronts generally above 1680 m. A well-developed tongue-shaped rock glacier, located to the north in the Torrestío Valley and with a NE aspect and a long tongue-shaped appearance, flowed farther from

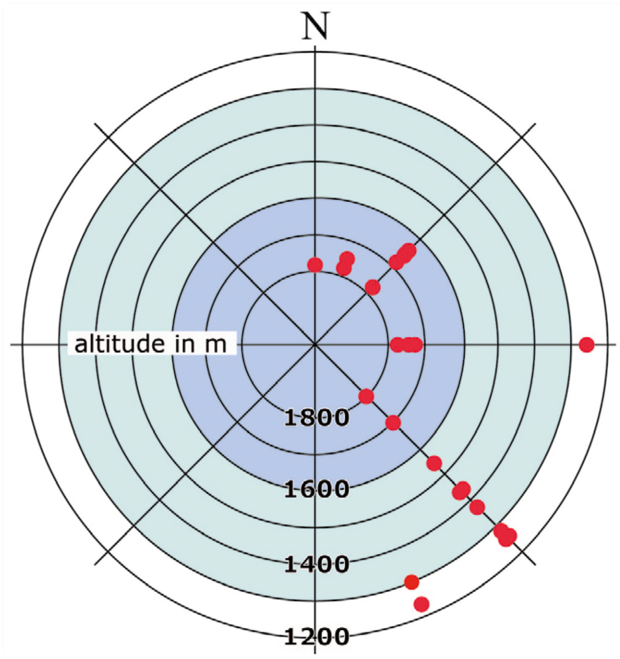

Fig. 6.- Relationship between frontal moraines aspect and altitude in northwest Luna.

its root down to an altitude of 1550 m. Protalus ramparts are widespread in northwest Luna and Villabandín massifs, but only one form has been recognized in Ubiña–Los Grajos area. They are mainly formed by siliciclastic clasts at altitudes above 1530 m, and although most of them present NW–NE aspects, some show E and SW aspects and are located at even higher altitudes (around 1900 m). At medium and small scale, several landforms related to solifluction and creep processes occur mainly on north-facing slopes, namely, stone lobes, stone-banked lobes, solifluction lobes, ploughing blocks, and terracettes (Fig. 7B). Partially buried blocks on slopes with a gentle gradient, indicating surficial solifluction, occur at low altitudes and in zones with shaly bedrock and diverse aspects.

Rock falls, flows, and other types of landslides (classification following Hungr *et al*., 2014), associated with paraglacial instabilities, are common in northwest Luna,

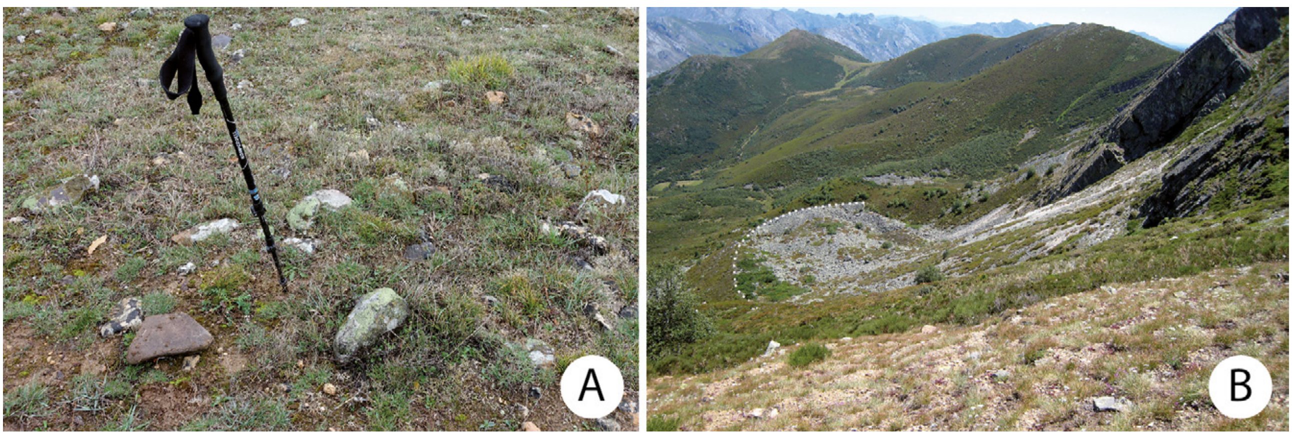

Fig. 7.- A) Discontinuous till located in the main Luna Valley at 1140 m of altitude, in a zone with no geomorphological evidence of glacial action (scale given by pole). It has been related to the maximum glacier extent. B) Peña Mala rock glacier, with a northeast aspect, at the foot of a steeply dipping quartzite outcrop. The front is at 1690 m of altitude. Terracettes in the foreground. View to the east.

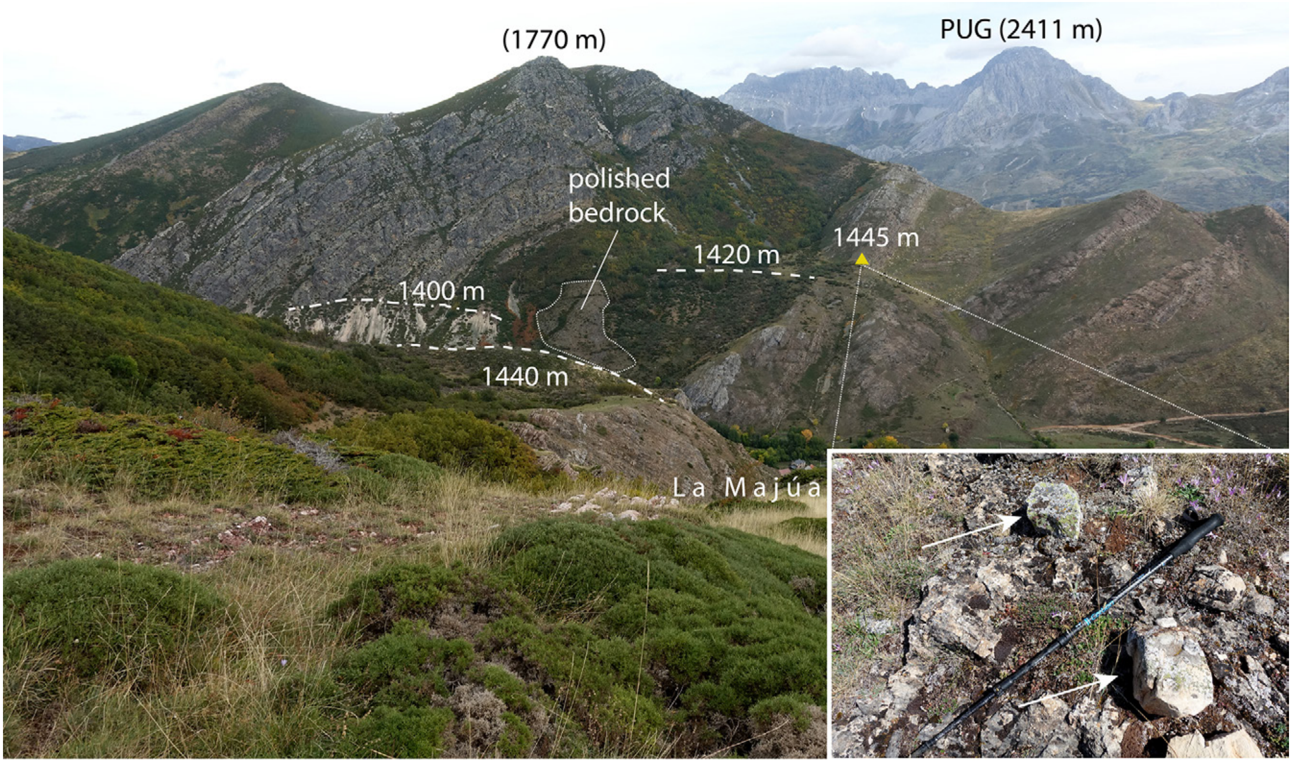

Fig.8.- Glacial features in the sourroundings of La Majúa. Glacially transported quartzitic clasts (detail in inset, pole for scale) occur at higher altitudes than lateral moraines (dashed lines), polished bedrock and the upper scree limit (dotdash line). PUG : Peña Ubiña La Grande, the highest peak in the area. View to the east.

Villabandín, and to the west of the Ubiñas Massif. Among the most significant postglacial landforms, several alluvial fans, not represented on the geomorphological map, occur all over the basin, with the largest features (e.g. Riolago fan, 3.3 km^2) at the mouth of the tributary valleys and the smallest systems at higher altitudes, built from reworked till deposits on slopes located upstream (e.g. in the La Majúa Valley).

Discussion

Analysing the position of terminal and lateral moraines is the most common method to reconstruct the past glacier extent in deglaciated regions. Since moraines are formed during ice margins stillstands they can indicate the location of the glacier limits. Nevertheless, in steep mountain zones, many of these deposits have been eroded or modified by several processes that erase or hide the glacial imprints in the landscape. Due to the difficulties to assess glacier extent in deglaciated areas, Chinn (1979) proposed a combination of fieldwork and study of aerial photographs in order to detect other features that could contribute to delimit ice margins, namely, till recognition, stream direction, and alignment of upper scree limits, among others. In addition, in areas with a faint glacial signature, moraine fragments, easily ignored because of their size, can be used to extend the limits of the glaciers (Kirkbride and Winkler, 2012). Thus, carrying out fieldwork is a fundamental step that has contributed to expanding previous glacier extents in other glaciated zones (e.g. McDougall, 2013). McDougall claims that the absence of clear moraines in an area should not be interpreted as ice-free conditions.

In this work, the ice limits were mainly established considering deposits, although erosional landforms (subglacial bedforms such as ice-moulded bedrock, *roches moutonées* and polished surfaces) were also used as indicators of glacier action. In areas devoid of lateral moraines, till patches and allochthonous clasts were used to determine the horizontal extent of the glaciation and to calculate the minimum thicknesses of the corresponding ice masses. In the two main valleys, where no terminal moraines can be detected, the most significant glacial features are the well-developed frontal moraine complexes occurring at the confluence of the tributaries with the main valleys. However, discontinuous till, erratic boulders, and allochthonous clasts are very frequent far down these complexes (Fig. 3). Ice-marginal features, commonly useful for establishing former glacier margins, are very scarce in these valleys and the two subtle and short lateral moraines to the southwest of San Emiliano would indicate ice thicknesses of 160 and 140 m respectively. However, the isolated clasts and till patches occurring nearby in higher zones suggest greater ice thicknesses (240 m above the valley bottom). Allochthonous clasts also occur at altitudes higher than moraines in other places (*7* in Fig. 3, numbers in italics correspond to location indicated on Fig. 3), pointing to glacier thicknesses greater than those suggested by the moraine complex at the mouth of this valley. Similarly, in the surroundings of La Majúa the upper scree limit, an abraded bedrock surface, and two lateral moraines would indicate an ice thickness smaller than that suggested by the relative position of glacially transported quartzite clasts (Fig. 8). Therefore,

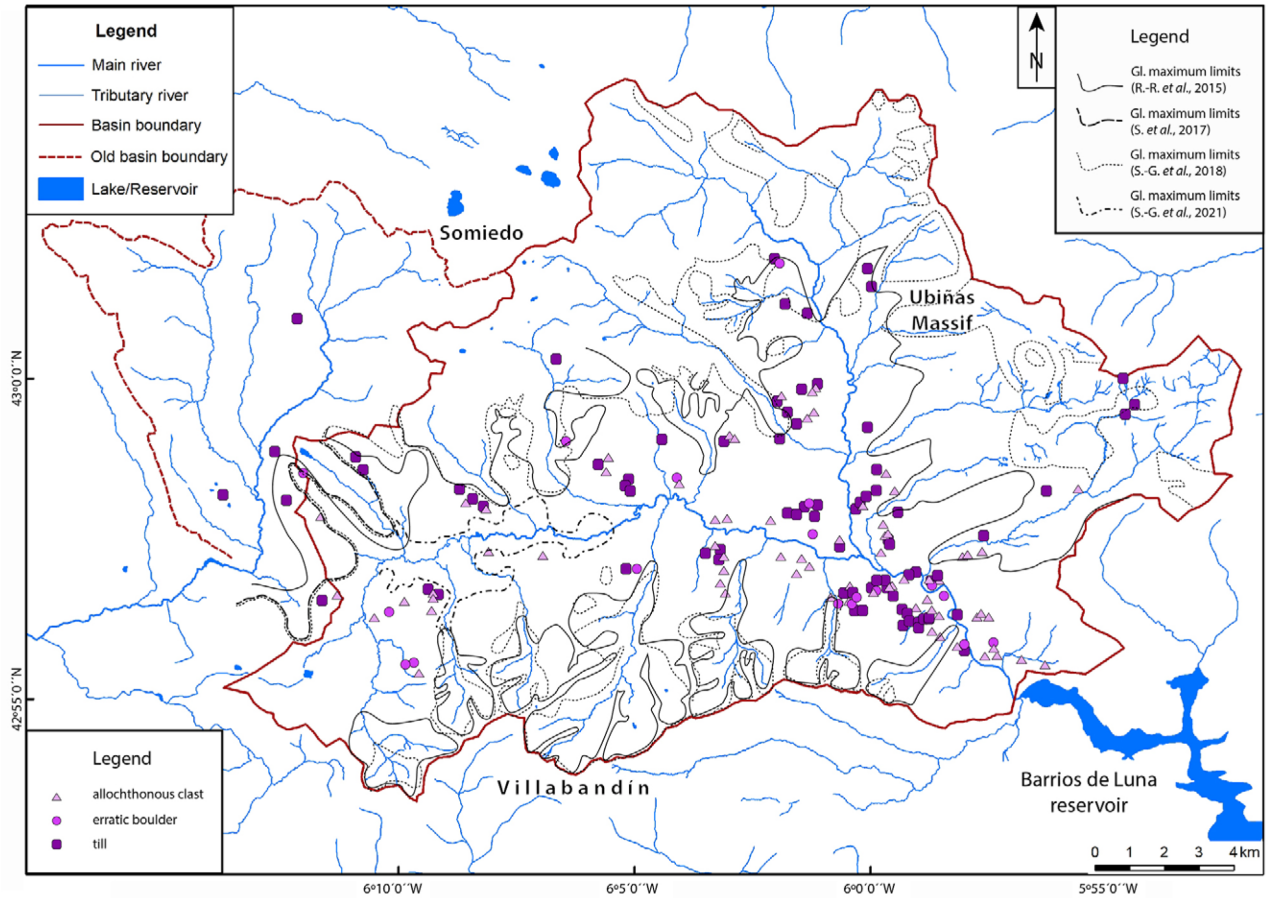

Fig. 9.- Distribution of till and glacially transported clasts identified in this work and glacier limits for the LGM proposed by Rodríguez-Rodríguez *et al*. (2015), Serrano *et al.* (2017), Santos-González *et al*. (2018), and Santos-González *et al*. (2021).

some of the criteria commonly used to determine ice limits are not valid in the study area, where the most obvious signs of glaciation do not provide evidence for the major glacier occupation.

Phases reconstruction

During the maximum ice extent phase, the northwest Luna tributary valleys were occupied by the southern outlet glaciers emitted from the Somiedo icefield, a vast accumulation area at a high altitude and with a low gradient (Menéndez Duarte and Marquínez, 1996). To the south, Villabandín, dominated by steep mountain peaks, had a better-defined divide and contained several cirques, from which ice tongues flowed to the north reaching the main valley. In east Luna, Los Grajos developed a small icefield, while glaciers to the west of Ubiña were mainly fed by snow avalanches. The interpretations for the maximum extent given by other authors (Fig. 2) seem mainly based on the location of the moraine complexes, except in the recent work of Santos-González *et al*. (2021), in which the criteria followed to stablish the glacier front around 1220 m in the Luna valley headwaters during the local Last Glacial Maximum are not explained. However, the present mapping shows a wider distribution of till and erratics far down the valleys and also at higher altitudes on slopes (Fig. 9), which can be interpreted as signs of a longer glacier and with a greater thickness than was previously thought. Based on the distribution of till, erratic boulders and frontal moraines in northwest Luna basin (Figs. 3 and 6), four glacial phases have been identified, including glacial and periglacial landforms ascribed to these phases (Table 1). The phase of maximum extent (S-I) was followed by three recessional stages (RS-I, RS-II and RS-III), and by a Tardiglacial phase, probably before the Holocene. In agreement with Barr and Lowell (2014), when comparing glaciers in plateau and nonplateau topography, glaciers in these areas could have different dimensions despite having similar climatic conditions. Thus, moraines in Villabandín and east Luna with different glaciation styles have not been considered.

S-I (Maximum extent). The maximum extent has been deduced from the distribution of till patches, disperse clasts and erratic boulders. These deposits indicate that the topography did not control the flow path since the ice tongue crossed divides even at low altitudes. The absence of glacial morphology in the low zones of the main valley points to a short phase. In order to determine the position of the glacier front, two criteria have been followed: the presence of allochthonous clasts at 1120 m, close to Pobladura, and a non-classified deposit with iron-flat shaped clasts in the Barrios de Luna Reservoir head (at around 1090 m), an area that is submerged during most of the year

Pleistocene					Holocene
Maximum ice extent S-I	**Retreat and stabilisations S-II (RS-I)**	**Stabilisations at higher positions S-III (RS-II)**	**Stabilisations at higher positions S-IV (RS-III)**	**Tardiglacial Tgl**	
- discontinuos till, isolated clasts and erratic boulders Fronts at 1110 m	- lateral moraines in main and in tibutary valleys - moraine complexes at the mouth of tributary valleys Fronts at 1240-1290 m - cirque moraines (at low altitude)	- lateral and frontal moraines in tributary valleys Fronts at 1380-1540 m - cirque moraines	- frontal moraines at altitude Fronts at >1660 m - cirque moraines	- cirque moraines	
				- rock glaciers - protalus ramparts	
		- alluvial fans (in part reworked till) - slope instabilities: rock avalanches and other landslides			
				- solifluction forms - stone lobes, stone banked lobes	

Table 1.- Glacial deposits and paraglacial and periglacial landforms ascribed to the different glacial and postglacial phases identified in the Luna Basin.

(Alonso, 2020; see their Figs. 6D and 7). Close to the front, the Luna palaeoglacier split into two small tongues, one heading northwards, reaching the location of Pobladura, and the other stretching southwards to the head of the reservoir (Fig. 10).

S-II (RS-I). From its lowest position, the recession of the glacier front took place with short periods of stabilization, before retreating later to the mouth of the tributary valleys. The two lateral moraines on the valley side, close to San Emiliano (*5* in Fig. 3 and Fig. 11A), constitute a geomorphological evidence of short still-stands of the glacier during this recession phase since moraines have a climatic significance even when they are only slightly preserved laterally (Kirkbride and Winkler, 2012). A moraine crest with an NW–SE direction (*1* in Fig. 3), located to the north of the mouth of the upper Torrestío Valley and older than the Torrestío complex indicates a later glacier stabilization. This phase finished with a sequence of still-stands registered by the well-developed moraine complex of Piedrafita in the main valley (*9* in Fig. 3) and by other complexes located at the mouth of the tributary rivers (*8, 7, 4* and *2* in Fig. 3) at heights between 1240 and 1280 m. To the south of Riolago, close to the valley mouth, three latero-frontal moraines (*11* in Fig. 3) whose fronts (calculated at 1260–1290 m) were destroyed by postglacial activity are interpreted to belong to this phase. The small latero-frontal moraines of the cirques at low altitudes in the main valley (*10* in Fig. 3) are included in this stage. Although located slightly higher (1390–1410 m) than the moraine complexes, the size and altitude of these cirques made them more sensitive to climatic changes, as observed by Chueca *et al*. (2007) in their recent study on the evolution of the small Pyrenean glaciers.

S-III (RS-II). Glacier fronts receded to higher positions, leaving the mouth of the tributary valleys behind, with short stabilizations recorded by small frontal moraines in the valley bottoms (at 1380–1540 m, to the northwest of the Luna valley). The composite inner moraines of La Cazurría complex (*6* in Fig. 3 and Fig. 4B) were produced during still-stands and readvances, suggesting a pulsating ice margin during this stage.

S-IV (RS-III). Stationary glaciers fronts, progressively located at even higher positions, were evidenced by moraines at altitudes higher than 1660 m (e.g. *3* in Fig. 3 and Fig. 4A). Finally, moraines formed in the front of glaciers confined in cirque depressions, in higher favourable areas (Figs. 5 and 11B).

Tardiglacial. This phase is characterized by the formation of rock glaciers, which coexisted with some small glaciers nested in cirques. To the west of the study area, Alonso and Trombotto Liaudat (2009) ascribed cryogenic landforms to different cryomeres (from the Tardiglacial to the LIA) and, in the adjacent Laciana Region, Rodríguez *et al*. (2020) identified two rock glacier phases, which later Santos-González *et al*. (2022) dated back to the Bølling–Allerød interstadial. To the east, in the Porma Region, the stop of the rock glacier creep has been dated in 15.7 ± 0.3 ka by Rodríguez-Rodríguez *et al*. (2016). Well-developed rock glaciers in the Luna catchment are scarce (Figs. 3 and 7B), showing a great dependence on aspect, altitude and lithology. Generally occurring at higher altitudes, protalus ramparts (Fig. 5) are in contrast less dependent on lithology than rock glaciers. Considering the low winter temperatures in the area –Rabanal thermopluviometric station, located at 1150 m a.s.l., recorded absolute minimum temperatures up to -14.10 ºC– the evolution of other periglacial landforms can seemingly reach present times. High zones experience some periglacial activity with well-developed stone lobes, solifluction tongues, terracettes and slope instabilities affecting glacial and other loose materials. Evidence of solifluction in the upper soil levels, e.g. boulders partially buried on slopes, can be recognized all over the study area.

The rare morphological evidence indicating the position of extinct glaciers, e.g. trimlines and lateral moraines, could also reflect a wide action of mechanisms operating since the deglaciation. Mainly in tributary valleys, glacier retreat left a large volume of sediments later reworked by different processes during the period defined by Church and Ryder (1972) as paraglacial time. Frontal moraine complexes, like Torre and Riolago, were partially destroyed by proglacial streams and till was mobilized by fluvial and gravitational processes. The large alluvial fans, mostly occurring at the mouth of the tributary valleys, probably started as proglacial fans during the last moments of S-II, being fed later by melting waters from retreating fronts progressively located away from the fan apex. Glaciofluvial outwash sediments also occur forming fans of smaller dimensions on tributary valleys slopes, where some are partially dissecting moraines, as in La Majúa Valley, where this reworking of till is still occurring at present. Glacial sculpturing in the tributary valleys has been partially lost due to large landslides in deglaciated slopes. Instabilities associated with glacier retreat triggered numerous gravitational deposits, including rock avalanches with a long track on limestones, described by Rodríguez *et al*. (2021) in the Torre Valley.

Chinn (1979) related large-volume moraines with landslides or rock avalanches on glaciers. These paraglacial instabilities could explain the unusual volume of a cirque moraine (Fig. 11B) that was previously interpreted as a rock glacier developed on a limestone bedrock by Alonso (2014), Santos-González *et al*. (2018), and Alonso *et al*. (2019). The cirque, located in the vicinity of the big aforementioned avalanche, presents highly fractured walls, and the deposit, with an abundant fine fraction, is now interpreted as a recessional moraine ascribed to the final recession stage RS-III, formed similarly to the large moraine at 1560 m in La Cazurría, shown in Fig. 4B.

In the Luna catchment, geomorphic evidence of earlier glaciers during the maximum ice extent phase is either absent or poorly preserved. Further data are needed for a more accurate reconstruction. Thus, glacier reconstruction carried out by empirical methods (Fig. 10) is an approach that should be refined in the future.

The LGC in other basins

Table 2 records the different glacial phases for the LGC as established by several authors in these mountains. The River Sil basin, studied by Santos González (2010) and Jalut *et al*. (2010), is included due to its proximity to the Luna basin. Rodríguez-Rodríguez *et al*. (2015) examined the Somiedo/Alto Sil/Babia mountain area and Serrano *et al*. (2017) analysed

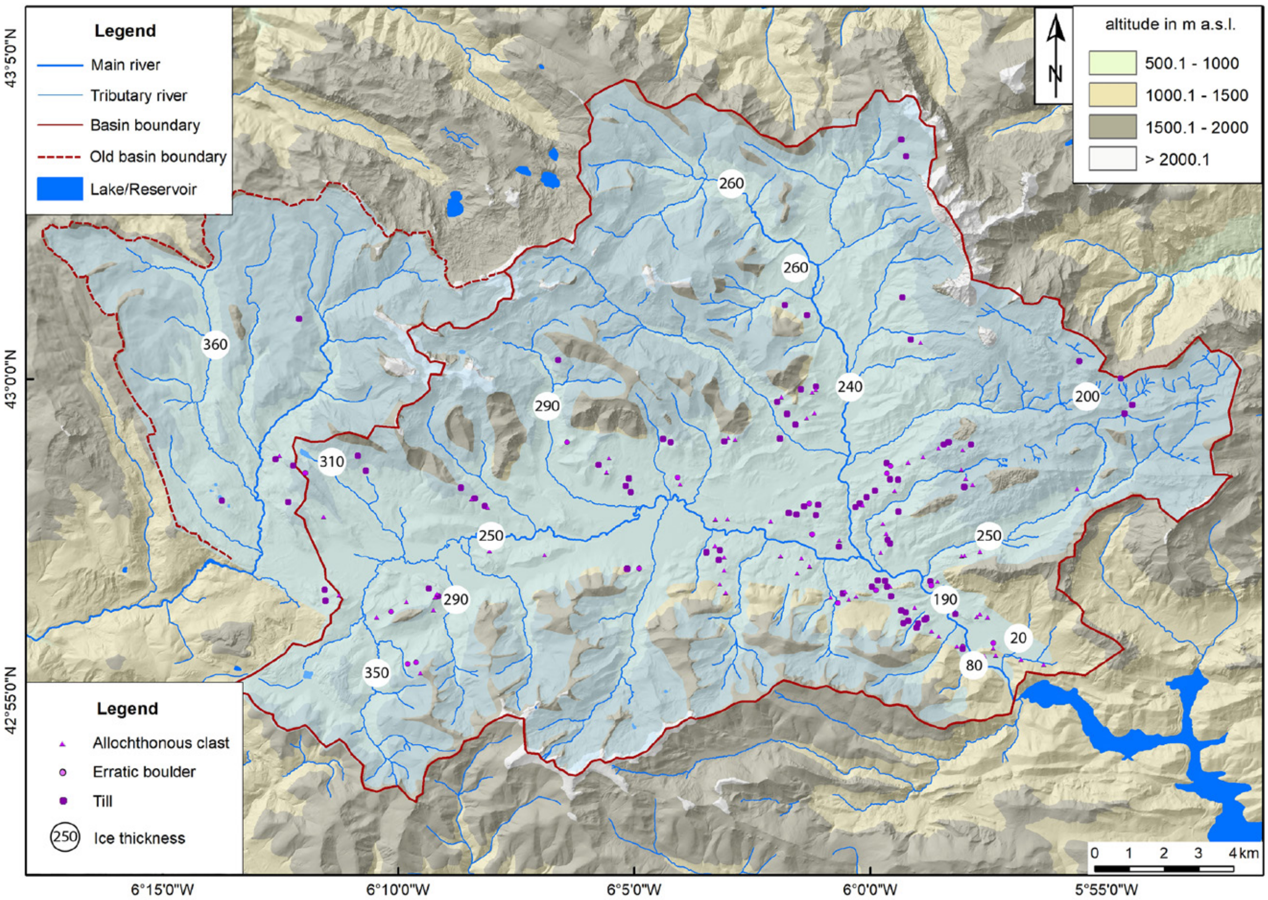

Fig. 10.- Maximum glacier extent in the Luna Valley. In circles, local minimum ice thickness, calculated from moraines and glacially transported clasts distribution, with respect to present valley bottom altitudes.

the Somiedo-Upper Sil-Babia massif. Finally, the Porma Valley (Rodríguez-Rodríguez *et al*., 2016, 2018), around 65 km to the east, is included because it shows characteristics akin to the Luna Valley. Both valleys are located on the southern slope of the CM, present similar altitudes and have bedrocks with comparable lithologies, where siliciclastics alternate with calcareous formations. Highlighted in Table 2, Piedrafita moraines refer to the moraine complex located in the valley head (indicated in Fig. 2). They were considered by Santos González (2010), Rodríguez-Rodríguez *et al*. (2015), and Serrano *et al*. (2017) as recording the maximum extent, with the main valley devoid of glaciers. For Rodríguez-Rodríguez *et al*. (2015) the local glacial maximum took place at 45–36 ka BP (MIS 3) and Serrano *et al*. (2017) propose an age of 48–35 ka (MIS 3) for the maximum glacier advance in the CM, including this area. Previously, Jalut *et al*. (2010) had dated the yuxtaglacial lake deposits of Villaseca (location indicated by an asterisk in Fig. 1A), identifying several phases and concluding that in the western CM the maximum glacier extent preceded the global LGM (26.5-19 ka; Clark *et al*., 2009). Those authors ascribe the Piedrafita moraine complex to a disjunction phase formed during a stabilization period that occurred during a general glacial retreat, at approx. 16 ka, which is in accordance with the data given by Alonso and Suárez Rodríguez (2004) for the Luna Valley and with the results obtained in the present investigation. These moraines in Piedrafita and the complexes in Lago, Torre, and La Majúa were formed at the time when glaciers were confined in tributary valleys with fronts in their confluences with the main valley, or close to the confluence as in Torrestío. For the Porma basin, Rodríguez-Rodríguez *et al*. (2016) established a local maximum, followed by four recessional phases, with fronts at 1100 m for the maximum, and at 1210 m for the recessional stage III. Front altitude at maximum is consistent with the one established for Luna, while the altitudes of the frontal moraine complexes in Luna, although a few meters higher, are comparable to fronts in Porma during RS-III. Rodríguez-Rodríguez *et al*. (2018) consider that during MIS 2, glaciers in Porma were occupying the main valleys to an altitude of 1130 m. Hence, from a chronological perspective, several questions remain to be solved; a future dating of Luna

Jalut *et al*., 2010 (Sil River headwaters)	Last Glacial Maximum Extension (LGME) 60-35 ka	Retreat phase Post-maximum stabilisation ~44 ka (48-32 ka)		Disjunction phase (valley glaciers) ~16 ka **(Piedrafita moraines) ***	Final deglaciation <16 ka	Late glacial
Santos González, 2010 (Sil River headwaters)	Maximum glacial stage >40 ky BP >60 ky BP? **(Piedrafita moraines) ***		Retreat 41 ky		Cirque phase 16 to 13 ky BP	Rock glaciers phase
Rodríguez-Rodríguez *et al*., 2015 (Sil River headwaters /Luna)		Glacial adv. 45-36 ka BP MIS 3 Local glacial max.> 43 ka BP Fronts: 1250-1300 m a.s.l. **(Piedrafita moraines) ***		Glacial advance 23-19 ka BP MIS 2 (coeval with global LGM)	Glacial retreat	
		Recessional stages				
Rodríguez-Rodríguez *et al*., 2016 (Porma Valley)	Local maximum MIS 5d Fronts: 1100 m a.s.l.	RS-I (LGM) >55.7 ka (MIS 4) Fronts: 1130-1140 m a.s.l.	RS-II Fronts: 1160 and 1190 m a.s.l.	RS-III Fronts: 1210 m a.s.l.	RS-IV (cirque glaciers) Fronts: 1750 m a.s.l.	
Serrano *et al*., 2017 (Cantabrian Mountains)	Pre-maximum phases S-0 MIS 12 MIS 22	Maximum glacial advance RGM/S-I 48-35 ka MIS 3 **(Piedrafita moraines) ***		Deglaciation and glacial equilibrium S-II 25-18 ka BP MIS 2	Altitude stage and Tardiglac. Cirque glac. and rock glaciers S-III MIS 2	Little Ice Age
Rodríguez-Rodríguez *et al*., 2018 (Porma Valley)	Local maximum ~110 ka MIS 5d	Similar positions to maximum Stage IIa ~56 ka MIS 3 Stage IIb ~33-24 ka MIS 2 (local glacier advance)		Starting glacier retreat ~21-20 ka	Rock glaciers stabilizations 15.7-13 ka	
Santos-González *et al*., 2022 (Leonese CM)	Pre maximum phase	Stage 1 local LGM 45-35 ka Fronts: 700-1300 m a.s.l.		Stage 2 26-19 ka **(Piedrafita moraines) ***	Stage 3 Cirque glac. and rock glaciers 19-11 ka Fronts: >1700 m a.s.l.	

Table 2.- Glacial phases identified by different authors in the southern slope of the central and western CM. Original terms given by these authors have been preserved. Asterisks mark the Piedrafita moraine complex, at the Luna Valley head. For locations, see Figs. 1 and 2.

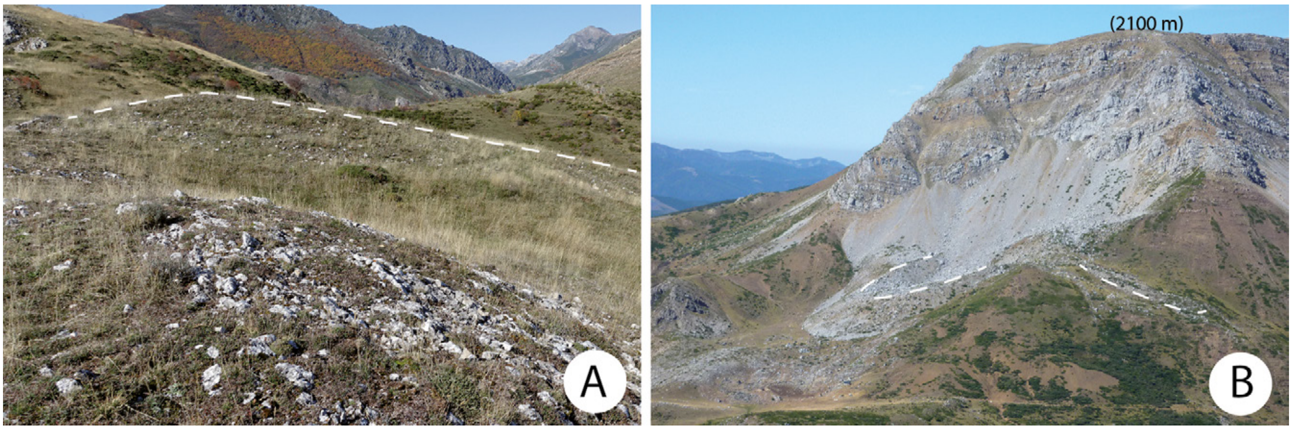

Fig. 11.- A) Lateral moraine at 1440 m in the Torrestío Valley, close to the confluence of the Rivers Torrestío and Luna. Formed during a temporary still-stand of the ice margin during glacier retreat after the maximum extent phase, the moraine indicates a minimum ice thickness of 160 m at this zone. View to the northwest. B) An avalanche supply of debris contributed to creating this unusually large cirque moraine in the Torre Valley, at an altitude of 1740 m and with an east aspect. View to the southwest.

deposits would allow a better correlation with Porma stages and with other massifs within the CM.

With respect to other mountain chains, similarly to what happened during the last glaciation in the Sierra de Béjar, located in Iberian Central System and studied by Carrasco *et al*. (2013), glacial maximum in Luna is indicated by erratic clasts and boulders while well-developed lateral moraines and posterior moraine complexes register deglaciation.

Conclusions

The distribution of glacially transported clasts, erratic boulders and till patches on apparently non-glaciated zones has allowed the position of the glacier front during the LGM in the Luna Valley to be inferred. The calculated front, at an altitude of 1110 m, indicates a glacier length of around 20 km from the valley head and a minimum ice thickness of 250 m in the main valley; values greater than those interpreted by other authors, who noticeably underestimated the extent of the Luna glacier. Although absolute chronology has not been established, position and distribution of lateral and frontal moraines indicate that after maximum (S-I) glacier retreat took place in three main recessional phases (RS-I, RS-II, and RS-III), when glaciers were gradually fragmented into independent valley glaciers and finally into cirque glaciers. These glacial phases were followed by a Tardiglacial period, characterized by rock glaciers and protalus ramparts coexisting with some cirque glaciers. Proglacial activity in progressively deglaciated zones, modifying and partially hindering the former glacial landscape, was registered by alluvial fans, both on valley sides and floors. Numerous paraglacial slope instabilities related to glaciers retreat contributed to reducing glacial imprints. Some instabilities, coeval with retreating glaciers, favoured the formation of large frontal moraines close to the accumulation zones.

Phases established for the Luna Valley are consistent with the glacial record identified in the Porma basin by Rodríguez-Rodríguez *et al*. (2018), with no terminal moraines either. However, altitudes reached by the glacier front in the different stages established in Porma differ from those found in Luna.

These conclusions suggest caution when trying to correlate glacial chronologies even within the same mountain chain, as physiography, glaciation style, altitudes distribution, aspect, and other particularities of some zones imply a different response to the same climatic conditions resulting in a diverse occupation for glaciers during a cold period. They also confirm that, before any glacier reconstruction, it is essential to produce a detailed geomorphological map (Otto and Smith, 2013) because classical criteria used to identify past glacial activity are not valid for all areas as the most prominent features cannot always reveal the full extent of the extinct glaciers.

Results obtained in this work would have not been possible without an intensive fieldwork survey, the most reliable way to identify small size moraines, till deposits and individual glacially transported clasts, essential in the interpretation of a past glacial extent.

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