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GLACIAL GEOMORPHOLOGY OF THE SANCENAS KARST MASSIF (CANTABRIAN MOUNTAINS, NORTHERN SPAIN)

Abstract: González-Gutiérrez R.B., Santos-González J., Santos J.A., Cano M., Irwin J.R., Gómez-Villar A. & Redondo-Vega J.M., *Glacial geomorphology of the Sancenas karst massif (Cantabrian Mountains, northern Spain).* (IT ISSN 0391-9838, 2019).

With an extensive and high elevation surface (1800-1900 m a.s.l.), the Sancenas karst massif (Cantabrian Mountains) was home to a small icefield developed during late Pleistocene times. Glacial and karst processes are dominant in this region, generating many glaciokarst landforms which are uncommon in the glaciated mountains of Spain. Well-preserved moraines from outlet glaciers developed from the icefield are present. In several moraines outcrops, grain size and macro-fabric analyses were conducted to determine sediment origin and the extent of the glacial ice. An estimation of ice thickness and the position of the equilibrium line of altitude during the last glaciation were also accomplished. Three main glacial stages were identified. (IT ISSN 0391-9838, 2019).

Key words: Glacial geomorphology; Till macro-fabric; Grain size; Equilibrium line altitude; Sancenas Massif, Cantabrian Mountains.

Resumen: González-Gutiérrez R.B., Santos-González J., Santos J.A., Martín Cano, Irwin J.R., Gómez-Villar A. & Redondo-Vega J.M., *Geomorfología glacial del macizo kárstico de Sancenas (Cordillera Cantábrica, norte de España).* (IT ISSN 0391-9838, 2019).

La existencia de una amplia y elevada superficie en el Macizo kárstico de Sancenas ha favorecido la presencia del hielo y el desarrollo de formas de modelado glaciar durante el Pleistoceno reciente. Además, los importantes afloramientos de calizas en la zona han permitido la superposición del modelado glaciar a un relieve kárstico preexistente, generándose formas glaciokársticas, ausentes en otros macizos no calcáreos cercanos que también estuvieron ocupados por el hielo. Se ha analizado la localización de morrenas y bloques erráticos existentes en la zona de estudio y, mediante técnicas de granulometría y macrofábrica, se ha determinado el origen glaciar de los sedimentos. Igualmente, se ha realizado una estimación del espesor del hielo y posición de la línea de equilibrio glaciar durante la última glaciación, constatándose la presencia de un pequeño *icefield* durante el Último Máximo Glaciar. Se han identificaron tres fases glaciares. (IT ISSN 0391-9838, 2019).

Palabras clave: Geomorfología Glaciar, Macro-fábrica de Till, Análisis Granulométrico, Línea de Equilibrio Glaciar, Macizo de Sancenas, Cordillera Cantábrica.

INTRODUCTION

In the Cantabrian Mountains the interest in glacial landforms started in the late nineteenth and early twentieth centuries when authors such as Casiano de Prado, Hernández Pacheco, Obermaier or Stickel (Frochoso Sánchez & Castañón Álvarez, 1997) recognized these landforms. Since then the glacial dynamics have been intensely studied on the range´s main massifs, both on its N and S sides (Jiménez-Sánchez & *alii*, 2013; Rodríguez-Rodríguez & *alii*, 2015; Santos-González & *alii*, 2013b, 2018; Serrano & *alii*, 2013, 2017). Studies have mostly focused on the well-known higher sectors, in valleys next to watersheds or even where the erosive-sedimentary footprint is unquestionable and does not interact with other geomorphological processes that difficult its identification and interpretation.

However, the small glaciated valleys in the Cantabrian Mountains have been poorly studied. They are marginal locations, outside the drainage divide and with modest elevations (around 1900 m). In these sectors, large erosional landforms such as cirques and glacial valleys are scarce, but some present well-preserved small to medium glacial landforms. In addition, some areas display other processes interacting with the glacial dynamic, as it occurs in the

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karst massifs. In these areas careful field work is required to recognize medium and small landforms such as sheepbacks, polished and fluted surfaces, erratics or protected deposits between rocky outcrops.

An example of a singular and poorly known glaciated area is the Sancenas karst massif, which is part of the southernmost massifs in the central sector of the Cantabrian Mountains, next to the Duero Cenozoic Basin. It is located away from the watershed summits and displays modest elevations around 1750-1850 m a.s.l. with a few peaks ≥1900 m. This massif displays a platform at 1750 to 1900 m a.s.l. with limestone rocks being the dominant lithology and therefore karst processes are widespread. During the last glacial period, ice covered the plateau and glaciokarst landforms were formed, as it happens in other sectors of the Cantabrian Mountains (Alonso, 1994; Frochoso Sánchez & Castañón Álvarez, 1997; González-Gutiérrez & *alii*, 2017c; Ruiz-Fernández & *alii*, 2016; Serrano & *alii*, 2012; Smart, 1986).

The influence of karst processes in glacial dynamics has been poorly studied with only a few examples from other mid-latitude mountains (Kunaver, 1983; Stepišnik & *alii*, 2009; Žebre & Stepišnik, 2015a; 2015b). In the Sancenas massif, well-preserved moraines where the internal structure is visible are present but overall, glacial deposits the Cantabrian Mountains are still poorly studied (Santos-González & *alii*, 2013a).

The first reference to glaciation in the Sancenas massif is a map by Rodríguez Fernández (1984), presenting two small glacial deposits located inside poljes and uvalas without mentioning the presence of glacial dynamics. Subsequently, a detailed study by Castañón Álvarez (1989) on the glacial geomorphology of the Cantabrian Mountains mentions glacial deposits in the area and the possible existence of a small icefield in the Peña del Sumidero sector that could have emitted outlet glaciers towards the North and, also the Bucioso valley ice tongue in the westernmost zone.

Later studies describe the same landforms, highlighting marginal glaciation in the massif in relation to other parts of the range (Frochoso Sánchez & Castañón Álvarez, 1997). References to the spatial convergence of karst and glacial processes in Sancenas are the geomorphic studies of González Gutiérrez (2002a; 2002b), where glaciokarst depressions are mentioned with ice overflow towards the head-valleys located in the north hillside (González Gutiérrez, 2002), or the geomorphic cartography of these landforms (González Gutiérrez, 2002c).

In 2008 abundant siliceous pebbles and erratic boulders were discovered in the Sancenas main polje, away from its source area (Fernández-Martínez & *alii*, 2009). That indicated more extensive and intense glacial dynamics in the massif of what had previously been thought. New detailed observations have been included in a geomorphological map (1:25,000 scale) of this zone (González-Gutiérrez & *alii*, 2017b).

The main objectives of this work are: 1) to analyze the nature, development and size of the glacial dynamics in the Sancenas karst massif by confirming the existence of a small icefield during the local Last Glacial Maximum (LGM) that overfed outlet glaciers northwards; 2) to highlight the importance of a preexisting karst relief in the formation of the icefield, standing out the spatial convergence between glacial and karst landforms as a geomorphological singularity in this mountain; 3) to characterize the sediments by grain size and fabric analyses in order to establish their origin.

THE STUDY AREA

The Sancenas karst massif (42°55-56′ N / 5°25-31′ W) is located north of the province of León, in the southern side of the Cantabrian Mountains, between the Torío and Curueño rivers (Douro basin, fig. 1 (A and B). It extends 11 km in a direction W-E and its altitudes are around 1900 m (Bucioso 1961 m, Cueto Calvo 1912 m, or La Carva 1917 m). The massif is limited in the north and in the south by streams which run towards the Torío and the Curueño rivers, with elevations around 1300-1140 m a.s.l.

The climate is influenced by altitude and the dominant exposure. It is a transitional zone between the Oceanic and Mediterranean climates, with an average annual temperature of 5-7.9 °C and an annual precipitation ≥1200 mm (AEMET-IM, 2011). However, in the higher sectors winters are severe, with an average temperature in January of ≤ 0 °C and summers short and cool (average values in July ≤ 14 °C). The massif´s main orientation W-E and its nearby valleys generate dissymmetries in the hillsides, with summer droughts on the sunny slopes and maximum average thermal values of ≥ 25 °C (Nafría-García & *alii*, 2013).

From a geological point of view, the Sancenas massif is a part of the Folds and Thrust Unit which belongs to the Cantabrian Zone. The main geological structures are thrusts and this zone is situated between Correcillas and Gayo Nappes (Alonso & *alii*, 2009; Rodríguez Fernández, 1984). These structures were created during the Variscan Orogeny, generating a structural repetition in the lithologic formations (fig. 1C). That allowed a great lithological diversity, with more than 17 geological formations in less than 5 km. The rocks are Paleozoic in age with limestones being the main lithology -Láncara, Coladilla, Santa Lucia, Baleas, Alba-Genicera, Barcaliente and Valdeteja Fms- (Wagner & *alii*, 1971). Other lithologies are the siliceous rocks such as sandstones (San Pedro, Nocedo and Ermita Fms), shales (Oville, Formigoso, Huergas, Fueyo, Vegamián and San Emiliano Fms) and quartzite (Barrios Fm).

These structural features changed during the Alpine Orogeny when the Sancenas massif and the rest of Cantabrian Mountains, were uplifted with respect to the Cenozoic sedimentary basin. This modified the drainage direction to N-S, from the watershed line to the Douro River, the main river in the Cenozoic basin. The main rivers follow this direction (Torío and Curueño) by cutting the old structures. The secondary network uses incohesive rocks and digs transverse valleys while resistant rocks generated crests (Redondo Vega & *alii*, 2002).

The Sancenas massif is limited to the north and south by thrusts and whose central portion is higher than nearby furrows due to its resistant calcareous rocks. The furrow is a valley carved in shales facies, and extends between the Valverdín and Valdeteja villages. Between both units there is a 600 meters gradient, and this gives the calcareous massif the feature of a high mountain relief, especially in its northern slope.

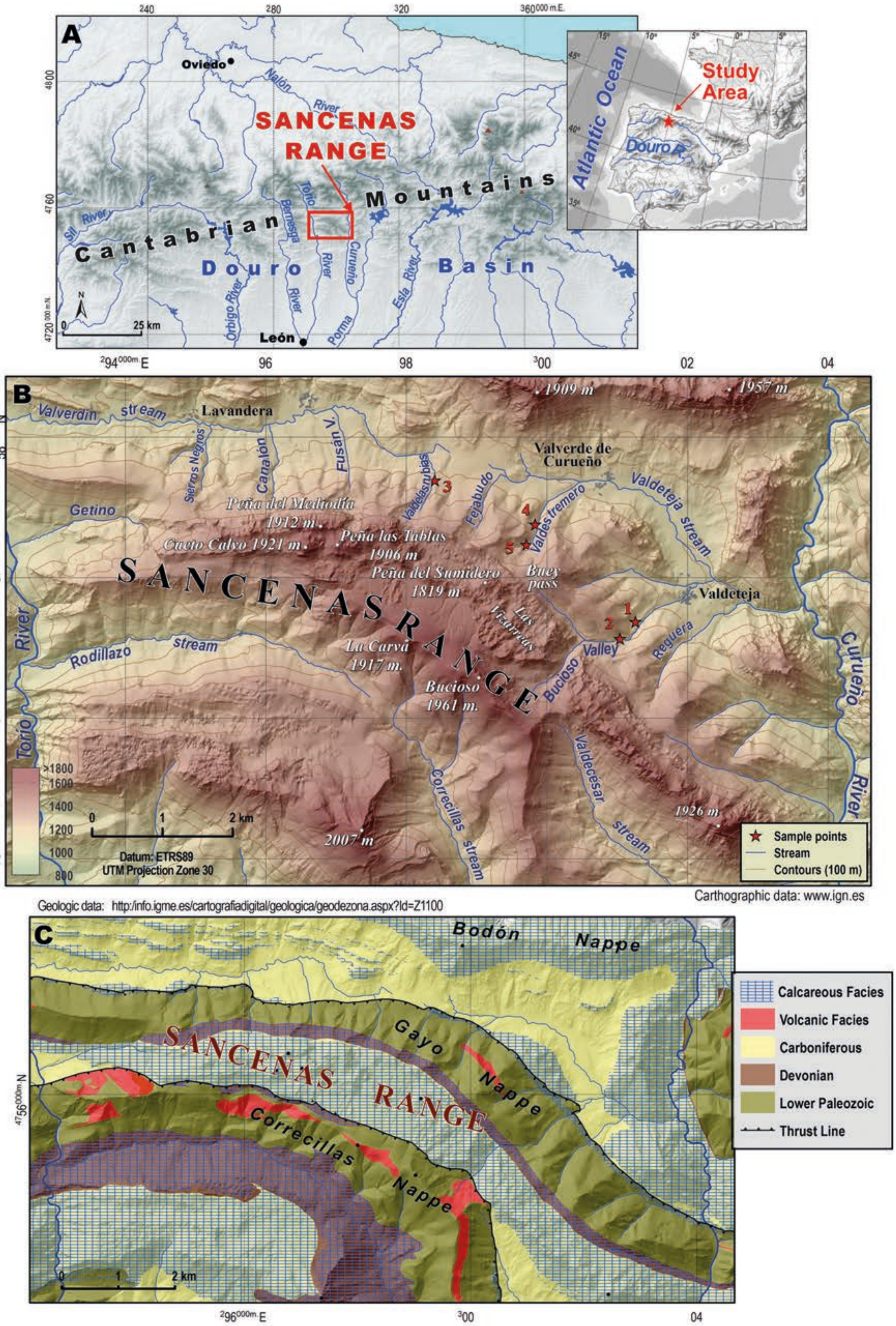
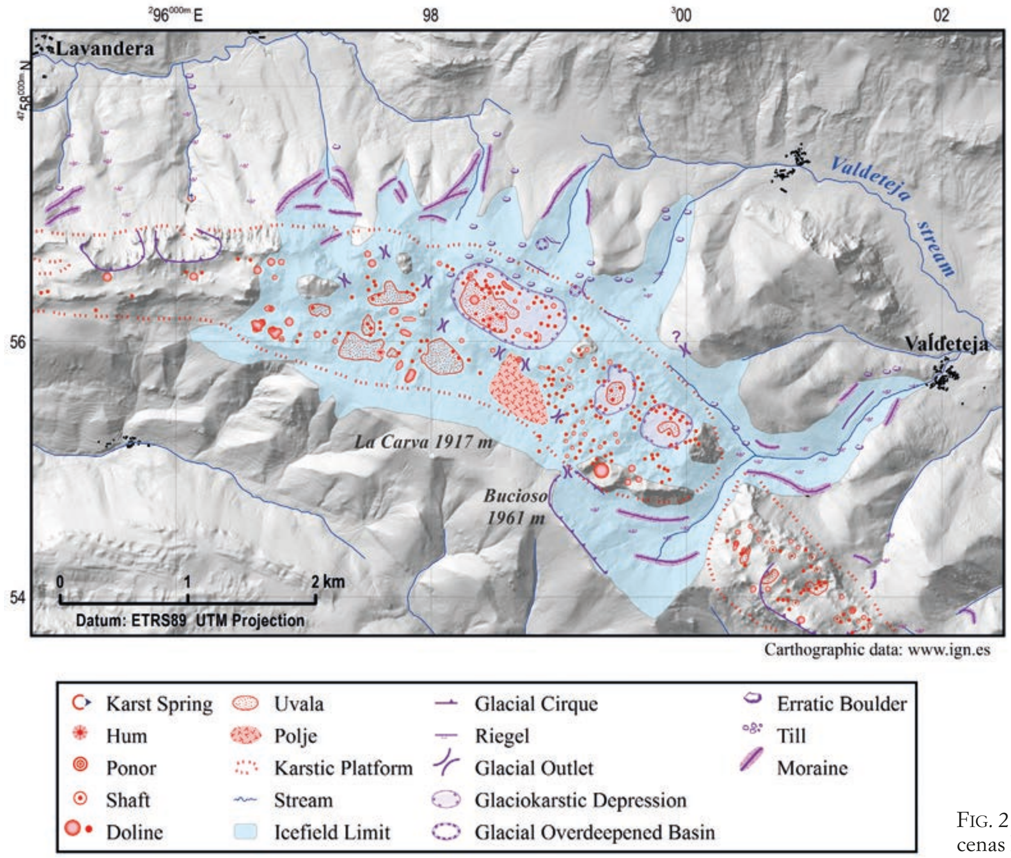


FIG. 1 - A) Location map of Sancenas massif within the Cantabrian Mountains. B) The main physiographic features with the sampled sites and C) the main litho-structural elements of the study zone.



Carthographic data: www.ign.es

FIG. 2 - Geomorphological map of the Sancenas karst massif with the icefield extent.

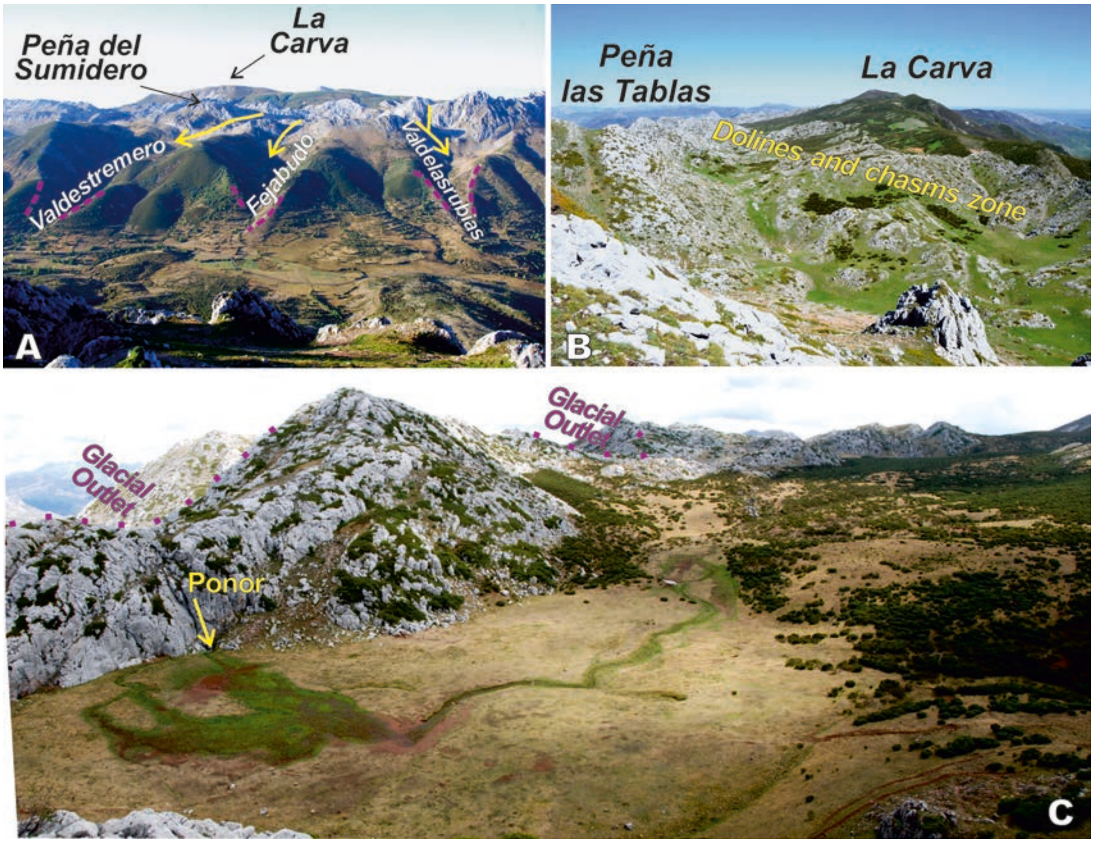


FIG. 3 - A) - The northern side of the Sancenas karst massif with the morainic arcs sited in the Valdeteja-Valvedín´s shale furrow. B) The dolines and shafts zone with the siliceous zone in the background, source area of the clasts present in glacial deposits. C) Sancenas small polje mall seen from the glacial outlet sited to the NW; to the left, the polje ponor, at the bottom of the limestone scarp.

Due to the prevalence of limestone rocks, karst processes define this massif's relief. Small poljes, uvalas, dolines, shafts and ponor landforms appear in a generally flat area but surrounded by rocky ridges. This means that favorable conditions exist where a pre-existing relief favors the accumulation and conservation of snow and, at the time, for the progressive appearance of glacial ice.

On the other hand, the external fluvial incision of the massif has been more intense and effective than the dissolution processes inside of it; due to that, polje elevation is around 1750 m a.s.l., while the main valleys are at 1200 m. This high elevation of the karstic zones ensures a greater rain amount and often snow. Moreover, the karst processes have been favored by structural factors, such as the high density of diaclases network and the frequent lithological contacts between facies of different ages and behavior towards dissolution.

The complex and diverse mountain landscape of the Sancenas massif led to its inclusion since 2015 in the Los Argüellos Biosphere Reserve, and due to its geomorphic interest it has been included in the Inventory of Geological Interest Sites of the Province of León as a natural heritage to preserve (Fernández-Martínez & *alii*, 2009).

METHODOLOGY

Glacial landforms have been identified, located and mapped through field work in order to reconstruct the palaeoglacier extension. Till macro-fabric and grain-size analyses have been performed in 5 sections, in the Valdelasrubias, Valdestremero and Bucioso valleys (fig. 1B).

The methodology applied for macro-fabric analysis is the same used in other mountains of the Northwestern portion of the Iberian Peninsula (Redondo Vega & *alii*, 2010; Santos & *alii*, 2015, 2017; Santos-González & *alii*, 2103a). From each sampling point and according to the deposit availability, the orientation and dip of 25-50 clasts was measured. Only elongated clasts were considered, particularly those in which the ratio between the major axis and intermediate is ≥ 1.5, following the A/B plane (Kjaer & Krüger, 1998; Li & *alii*, 2006). The data were represented in an equiareal stereogram (Schmidt net), contoured by areas of equal density. For that the StereoPro program (Version 3.0) developed by Martin Walters was used. Fabric shape (isotropic, girdle and cluster), the main eigenvectors (V_1, V_2 and V_3) and their eigenvalues (S_1, S_2 and S_3) were calculated and represented in two diagrams: the Benn's ternary diagram (Benn, 1994; 2004) and the Dowdeswell & Sharp's (1986) biaxial diagram.

For the grain size analysis, 200 grs were taken in each sampling point, using the Udden-Wentworth classification (Udden, 1914; Wentworth, 1922) and the Krummbein's phi scale (Krumbein, 1934) as a criterion. The grain size estimate was made by mechanical analysis, placing the sediment for 15 minutes in a sieve shaker. The content of each sieve was weighed and represented in a trigon diagram (Blott & Pye, 2012), which shows the percentage of fine (clay and silt), medium (sand) and coarse (gravels) material for each sample.

A new geomorphological map was designed from pre-existing maps, recent orthophotographs, and new elements identified on the field (fig. 2). It highlights major glacial landforms such as glacial cirques, moraines and karst landforms (poljes, uvalas, dolines, ponor). Moraines, glacial outlets, and the erratic boulders were the main elements used to delimit the icefield. In sectors where these landforms are absent other geomorphological elements (polished surfaces, sheepback) were considered to estimate palaeoglacier extension. The precision of the reconstruction is greater in the valleys due to the existence of well-preserved moraines, but is lesser in the upper area where glacial deposits are unusual. In this case we infer ice thickness using erratics in nearby areas. The uppermost southern area does not show signs of glaciation, so we consider that the icefield did not cover the summits.

The geomorphological map was designed with cartographic data and Digital Elevation Models (DEM, 5-25 m spatial resolution) obtained from the Spanish National Geographic Institute (IGN, http://www.ign.es). Likewise, the orthoimages used for photo-interpretation were obtained from the National Plan of Aerial Orthophotograph (PNOA) in several years. They are available in the IGN and Junta de Castilla y León Agricultural Technology Institute (ITACYL, http: //www.itacyl.es) digital serves.

The palaeoglacier Equilibrium Line of Altitude (ELA) was calculated using two methods: 1) the AAR method -Relation of the Area of Accumulation- (Meier & Post, 1962; Torsnes & *alii*, 1993), which assumes that a glacier has a fixed surface over the ELA, so its position can be estimated if all glacier surface is known and, 2) the AABR method that considers the hypsometry of the ice body. This method considers that the accumulation zone of glaciers in mid latitudes represents 67% of the total and it can vary between 50-80% (Furbish & Andrews, 1984; Rea, 2009). The estimate was automated performed based using an ArcGIS ELA calculation tool developed by Pellitero & *alii*, (2015).

The contour lines of the paleo-icefield were drawn. For that purpose, an equidistance of 50 m was considered, starting from the intersection points between the ice body contour and the topographic contour lines. The new curves values were interpolated using ArcGIS, v. 15.4, and an MDE was generated, by expressing the paleo-surface altitude in the icefield at each point. It was then possible to calculate the first glaciological parameters (location, extension and thickness). During the recessional phase, the ice extension limits (especially in the ancient icefield area) are not clear, so we do not estimate palaeo-ELA.

RESULTS

Karst landforms

The study area displays two differentiated sectors. The western sector is a mature karst zone with intense karst processes. The main landform is a small polje developed on Devonian limestones (Santa Lucia Fm) with two levels: the eastern which is currently functional and presents a small brook around 1 km long sinking in a ponor (fig. 3C); the second level where the polje widens and forms a paleo-valley 30 m higher and disconnected from the current surface circulation. The polje is covered by a decalcified clays mantle, in some places mixed with siliceous gravels and pebbles, whose origin is allochthonous to the karst from the southern and higher siliceous reliefs (La Carva). These deposits accumulated on the bottom of the polje.

In the eastern sector there is a dolines succession, with an irregular edge, flat bottom and semi-covered by decalcified clays. Some of them have joined in irregular, narrow and elongated uvalas which present an NNE-SSW orientation according to structural weakness lines, perpendicular to the Paleozoic structures direction. All uvalas and dolines are settled on a high surface around 1770-1810 m from which only some ridges stand out (hums). This sector is lower than the Carboniferous calcareous ridges located northwards and also than the siliceous summits line situated to the south.

Further north from the polje and uvalas appears a vertical ridges succession ≥1900 m a.s.l. and closed depressions. These reliefs are more irregular than those in the southern sector, with funnel dolines, and vertical shafts (Cueto Clavo zone, fig. 3B), usually without decalcified clays cover.

Glacial landforms

The major glacial landforms in the study area are large moraines situated in the shale furrow which delimits the Sancenas massif in the North. They are placed at the bottom of the main escarpment (fig. 3A) and are a succession of arcs representing three phases of ice recession. The external moraines are placed in the confluence of the Sancenas valleys (Sierros Negros, Canalón, Fusán, Valdelasrubias, Fejabudo, Valdestremero, Bucioso and Reguera) with the Valverdín and the Valdeteja streams with the latter ones being just to the bottom of that scarp. Quartzite and ferruginous sandstone pebbles and boulders (some with polished and striated surfaces) are also positioned in the glacial outlets (figs 7D and 7E) and over calcareous rocks. These materials came from outcrops located 4-5 km to the south, in the southern line divide. Sometimes they appear inside the decalcified red clay mantle of karstic origin. Also polished calcareous zones appear in the funnel dolines and shafts area, and large calcareous erratic boulders rest unstably on the sinkholes edge or in another non-calcareous facies (fig. 6 (B and C).

There are also large limestone erratics from the Valdeteja Fm. overlaying the limestones from the Barcaliente Fm. (fig. 6B) around the central pass located in the Fejabudo valley head. They are located on a glacial outlet pass during the LMG. In addition, other similar erratics (size ≥ 3.0 x 2.5 m size) appear between the indicated ridges and those located to the west in the Valdelasrubias valley head. Erosional landforms are mainly glaciokarst depressions in the ancient icefield area. Glacial cirques only are present to the west (Sierros-Negros and Canalón head-valleys) and to the east (Bucioso head-valley). From glacial cirques and from the icefield, some short (1-3 km) U shaped glacial valleys developed.

Glacial sediments

Till sections in the Bucioso, Valdelasrubias and Valdestremero valleys where analyzed. In the other valleys (Getino, Sierros Negros, Canalón, Fusán, Fejabudo and Reguera) glacial landforms have been identified (moraines, erratics), but exposures are absent or show poorly preserved deposits. Therefore, five samples were taken, and analyzed.

In the Bucioso valley, the samples were taken at two points from the left lateral moraines. Sample 1 (42° 55′ 28″ N / 5° 26′ 90″ W) was collected from a deposit 1.5 m thick at 1350 m a.s.l. located in a recessional moraine overlaying Ordovician quartzite (fig. 6A). It is a massive deposit, not compacted, matrix-supported with abundant gravel and sand (93%, graphic mean 0.73). It is dark brown and poorly sorted (standard deviation: 2.12). It presents great lithologic variety with angular and sub-angular clasts dominate (70% of clast sampled). Only a few clasts (~20%) show polished and striated surfaces. The clasts do not have a dominant orientation, and the fabric is polymodal with several orientations (Hicock & *alii*, 1996). The main vector (V_1) presents a direction subparallel to the flow orientation in this part of the valley, but only agglutinates 52.5% of sampled clasts (S_1: 0.525). This value is slightly higher than the intermediate vector (V_2), which eigenvalue (S_2) is 0.425 and perpendicular to the ice flow direction. This diamicton is interpreted as a supraglacial melt-out till.

Valley	Sample	N	Local direction of glacier flow (°)	Eigenvector V_1		Eigenvalue			Isotropy (S_3/S_1)	Elongation 1-(S2-S1)
				Azimuth	Plunge	S_1	S_2	S_3		
Bucioso Valley	1	50	040-050	253.32	2.06	0.525	0.425	0.049	0.113	0.189
	2	50	090-100	332.59	8.35	0.661	0.289	0.050	0.076	0.561
Valdelasrubias V.	3	50	000-010	166.26	12.96	0.591	0.326	0.083	0.136	0.441
Valdestremero V.	4	24	005-015	150.42	8.58	0.593	0.348	0.059	0.103	0.407
	5	50	075-090	132.70	2.33	0.573	0.375	0.052	0.088	0.333

Note: the locations of the samples are showed in fig.1

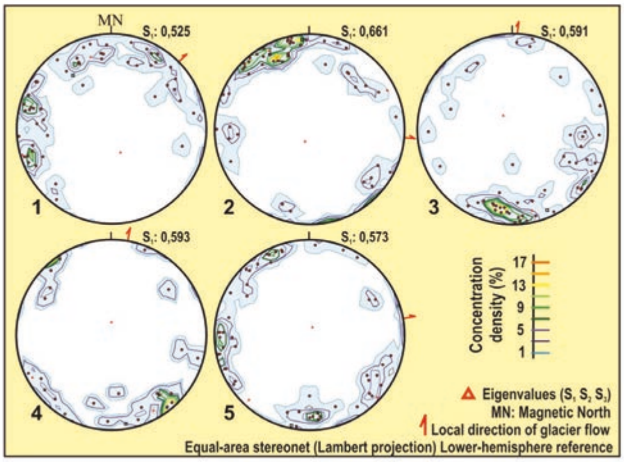


FIG. 4 - Macro-fabric data of Sancenas massif sediments and stereo-diagrams showing the fabric data plotted.

Sample 2 (42° 55′ 22″ N / 5° 26′ 80″ W) was collected from a deposit 3 m thick at 1410 m a.s.l. in the left slope of the Bucioso valley, placed on the Ordovician quartzite (fig. 6B). It is quite compacted, brown in color, matrix-supported, poorly sorted (standard deviation: 2.23) and showing great lithological diversity. It contains sub-angular boulders

(~65% of the clasts) of Carboniferous limestones and Ordovician quartzite and boulders and pebbles of Devonian limestones, and Silurian and Devonian sandstones. Around 50% of the clasts have the flat-iron shape, with its rounded edges and polished and striated surfaces The fabric presents clasts orientations, perpendicular to the valley direction in this sector. It is a moderate grouped fabric (Hicock & *alii*, 1996) with a clear main vector (V_1) whose eigenvalue (S_1) is 0.661. The diamicton is interpreted to be a subglacial lodgment till.

Sample 3 (42° 56′ 32″ N / 5° 28′ 49″ W) was collected from a deposit in the Valdelasrubias valley at 1430 m a.s.l. overlaying Lower Paleozoic formations. The deposit, part of the terminal moraine, is light brown in color, not compacted, and is poorly sorted (standard deviation of 2.16, tab. 1). The coarse fraction contains limestone, sandstone and quartzite clasts, with few polished surfaces, striated and micro-fractures on the sandy facies (25% of clast sampled). The fabric presents around a 45% of the clasts oriented to the paleo ice flow direction in this valley with the A/B plane imbricated up glacier (fig. 6C). However, the main vector (V_1: 166.26 and 12.96) concentrates less than 60% of the sample (S_1 value of 0.591), with another sub-perpendicular direction concentrating clasts. The diamicton is interpreted as a supraglacial melt-out till.

Sample 4 was collected in the left slope of the Valdestremero valley (42° 56′ 13″ N / 5° 27′ 11″ W) from a 1.30 m thick deposit overlaying Ordovician quartzite at 1430 m a.s.l. It is light brown, matrix-supported, not compacted, with large quarzitic boulders (20% of clasts sampled). The clasts are mainly angular (~60%) and only the 15% show rounded edges. It is poorly sorted (average standard deviation of 2.21, tab. 1) with abundant sandy matrix (70.9%, graphic mean of 1.72). The fabric displays a main vector (V_1: 150.42 and 8.58) opposite to the local ice flow and concentrates 59% of the clasts (S_1 value of 0.593). Although it shows cluster fabric shape, its intensity is low and very widespread (Hicock & *alii*, 1996), with concentration contours in the 3% deep indents (fig. 5). This is also reflected in the intermediate vector value (V_2: 241.3 and 5.8) which gathers around 35% of the sample. This diamicton is interpreted to be a supraglacial melt-out till.

Sample 5 (42° 56′ 41″ N / 5° 27′ 48″ W) was also collected from a deposit located the left side of the Valdestremero valley at 1480 m a.s.l. overlaying the Formigoso and San Pedro Fms. The deposit is 2.30 m thick, dark brown, matrix-supported with abundant fine matrix (7.4%), highlighting the silt-clay fraction (16.8%). The deposit is poorly sorted (average standard deviation of 2.48, tab. 1), with ~40% of Carboniferous limestone sub-rounded clasts (Alba, Barcaliente and Valdeteja Fms) and ~25% of sandstone-quartzite subangular clasts (San Pedro, Ermita and Barrios Fms). The fabric shape is polymodal (Hicock & *alii*, 1996) with clasts grouped both parallel and transverse to the ice direction in this portion of the valley (fig. 4). The main vector (V_1: 132.7 and 2.33) only joins 57% of the sample (S_1 value of 0.573), showing other stereonet sectors contours around 10% and clasts with the dip inclination ≤ 10°. This diamicton is interpreted to be a supraglacial melt-out till.

Glacial dynamic

The icefield covered more than 5 km from W-E and 2 km from N-S during the local LGM (Local Maximum Glacier), reaching 750 ha and a volume of 420 hm^3. In the central portion the ice thickness exceeded 140 m with its surface next to the highest altitudes, around 1960 m a.s.l (fig. 5). Undoubtedly this size is modest for an icefield but was decisive for the glacial dynamic development.

The ice thickness in the Sancenas polje exceeded 100 m, being its height around 1820 m a.s.l. From this surface some ridges not occupied by ice would stand out as small nunataks and the ice could flow between them towards the North, to the Las Vizarreas zone.

The lower elevation in the karst area (1740 m a.s.l.) allowed ice to escape from the icefield towards the Valdestremero, Fejabudo and Valdelasrubias valleys headwaters (fig. 3A), as well as overfeeding the Bucioso valley head, in the easternmost area, converging with the ice from a glacial cirque formed in its siliceous head-valley. Through these valleys during the local LMG the ice reached the center of the shale furrow near the local road which nowadays connects the Valdeteja and Valverdín villages (fig. 3A). The Valdelasrubias glacier reached the 1380 m a.s.l.,

TABLE 1 - Grain size data of deposits from Sancenas karst massif.

		Grain size %			Sorting (phi)	
Valley	Sample	Gravel[a]	Sand	Mud[b]	Graphic Mean	Standard Deviation
Bucioso Valley Lower Moraine	1	25.8	67.1	7.1	0.73	2.12
Bucioso Valley Upper Moraine	2	26.3	63.7	10.0	0.77	2.23
Bucioso Average		26.1	65.4	8.6	0.75	2.18
Valdelasrubias Terminal Moraine	3	25.0	66.7	8.3	0.78	2.16
Valdestremero Valley Lower	4	15.1	70.9	14.0	1.72	2.21
Valdestremero Valley Upper	5	24.6	58.6	16.8	1.08	2.48
Valdestremero Average		19.9	64.8	15.4	1.40	2.35

Gravel[a] = pebbles + granules Mud[b] = silt + clay
*Averages are taken from all clast in each site.
Note: the locations of the samples are showed in fig. 1

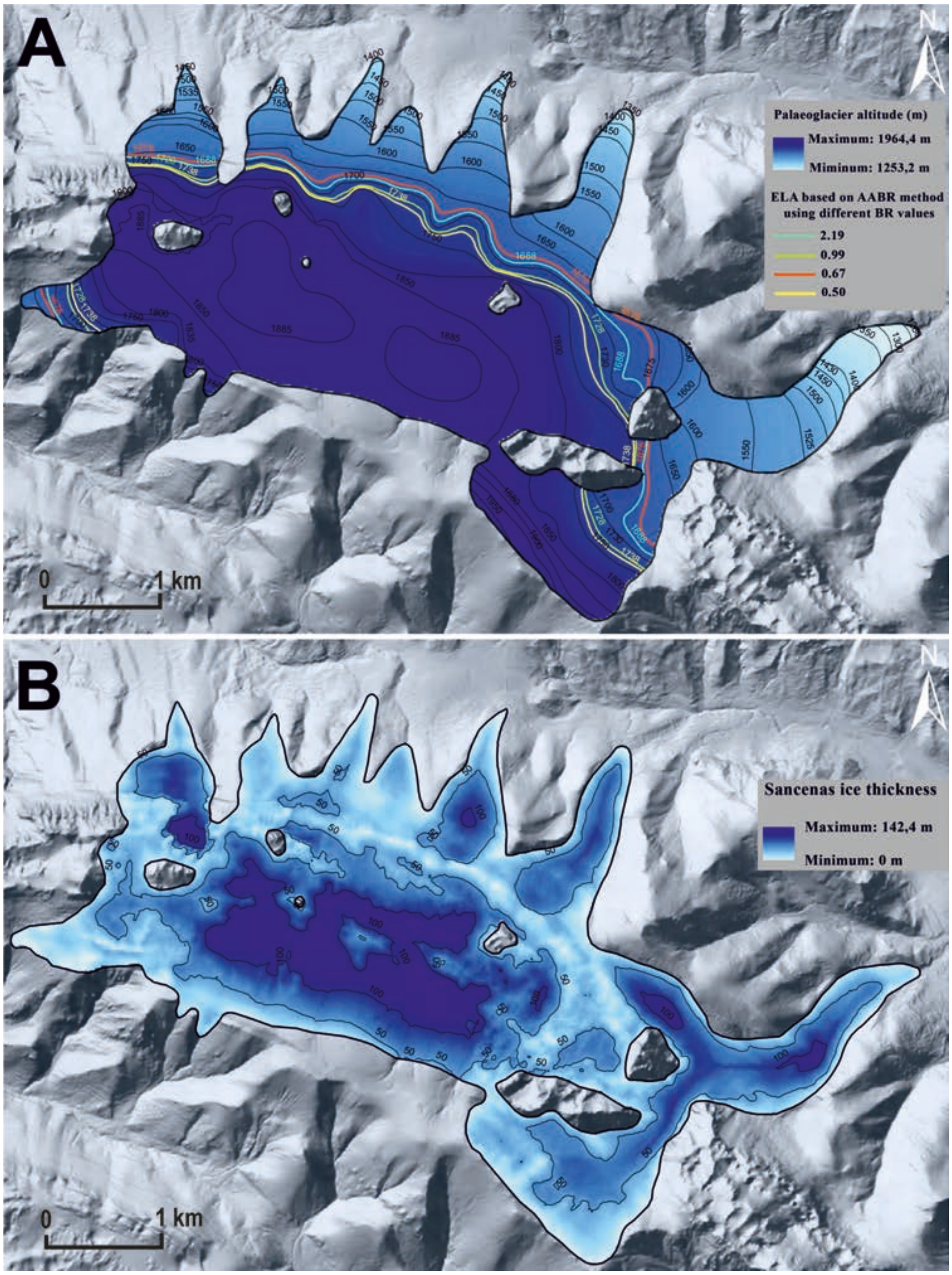


FIG. 5 - A) The Sancenas icefield model showing the paleo-glacier elevation and its contour lines (50 m). The ELA has been calculated using both the AAR and AABR methods. B) The reconstruction of Sancenas icefield thickness with sections around 140 m.

Fejabudo glacier reached 1370 m a.s.l., and Valdestremero 1375 m a.s.l. Although in the last valley the moraines from the maximum advance are eroded due to agrarian use and their remains hidden inside a dense broom scrub, except for the upper part of the terminal moraine which is still well-preserved (fig. 6A). The Bucioso glacier reached 1250 m a.s.l., near the Valdeteja village, being the largest glacier in the study area (3.5 km) due to glacial cirque accumulation and icefield overfed. The ELA values obtained were 1688 m (±40 m) according to the AAR method, and 1728 m (±20 m) using the AABR method (figs 6A and 6B).

A second glacial phase, indicated by the internal moraines evidences that the paleo-glaciers stabilized at 1480 m a.s.l. (left lateral internal moraine of Valdelasrubias at 1485 m, internal moraine on the right side of the Fejabudo valley at 1475 m). In the Valdestremero valley no moraines were founded at that elevation although there is abundant morainic material from the valley head (sandstones belonging to San Pedro Fm), with large erratic sandstone and quartzite boulders. In any case, the altitude of the ice front was raised with thinner ice outlets coming from the main accumulation zone, the Sancenas icefield. It would have thinner ice than during the local LMG, but enough to transfer ice through the glacial outlets. In the Bucioso valley the ice front reached 1450 m a.s.l., near the current valley bottom. In this phase there is not enough morphological evidences to reconstruct the glacial extension of the icefield, but probably similar in size with less thickness.

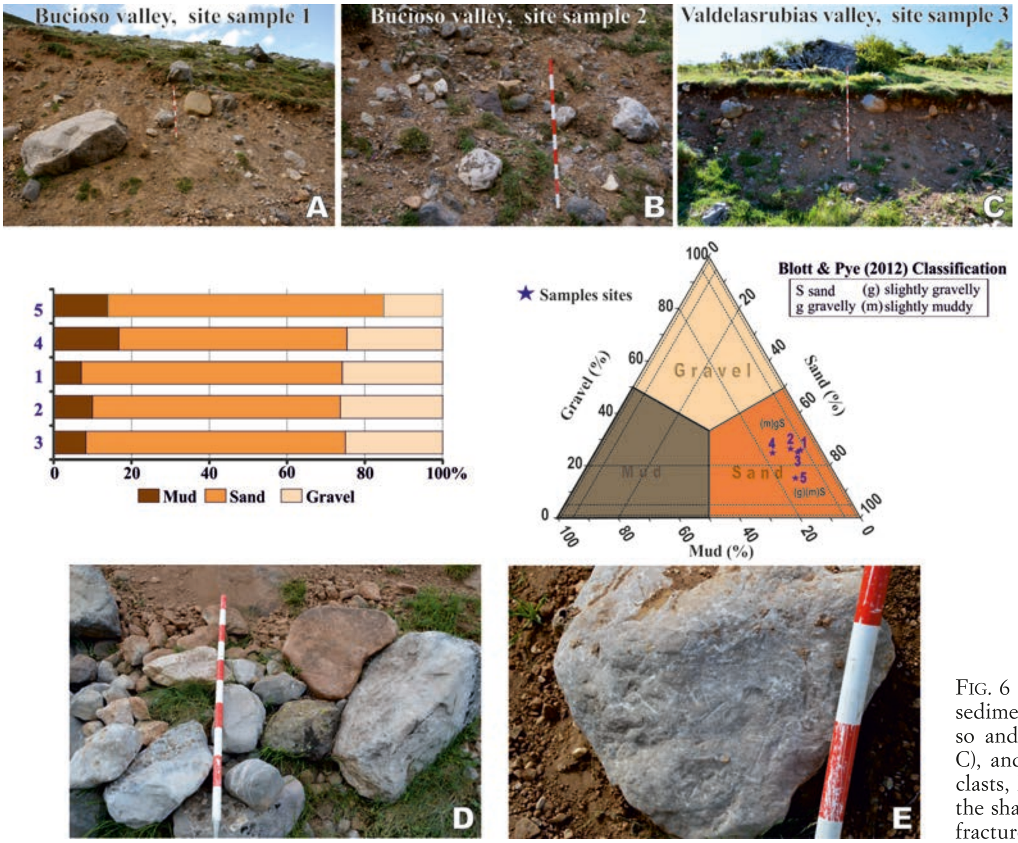


FIG. 6 - Grain size analysis of the studied sediments showing the sites on the Bucioso and the Valdelasrubias valleys (A, B, C), and the representative aspects of the clasts, like the lithologic diversity (D), or the shape and surface features -striations, fractures- in a limestone pebble (E).

The outlet glaciers show two minor recessional phases associated to a reduction in ice thickness. Ice probably disappear progressively remaining only in head-valleys and karstic depressions.

Only in the Bucioso valley, where a cirque exits, a glacier developed in a recessional phase. This was a very small alpine glacier (850 m long) located NE from the Bucioso peak (1961 m), reaching 1660 m. The ELA of this glacier is estimated at 1800 m, and probably is related to Younger Dryas phase. A small moraine in the Valdelasrubias head-valley, composed of limestone at the foot of the NE face of an escarpment is probably from the same glacial stage.

DISCUSSION

The Sancenas massif was a privileged location for ice accumulation because of special structural features such as the presence of a karstic platform (Rodríguez-Pérez, 2009) at 1750 m. a.s.l., with an extension of 5.6 km^2, and tilted northwards. Karst dynamics in limestone outcrops and structural features were determining elements to define the main relief. The glacial dynamic was superimposed on a karstic relief and a spatial convergence of landforms and processes were generated, which is typical in others sectors of the high Cantabrian Mountains such as in the Picos de Europa (Serrano Cañadas & González Trueba, 2002; González Trueba, 2007) and other smaller massifs (González -Gutiérrez & *alii*, 2017b).

The karst processes developed a high karstic platform, with poljes, uvalas and dolines closes to the accumulation area of the paleo-icefield. Other zones such as the Las Vizarreas were also favorable to conserve ice because sinkholes and shafts worked as traps for ice retention and conservation. To the west and the east, where siliceous rocks are important and the calcareous outcrops are smaller, the ice field was not formed. In their place ice tongues with cirques were formed (Bucioso valley).

In the Sancenas karst massif Paleozoic siliceous gravels, pebbles and boulders are frequent inside dissolution landforms, and over the calcareous outcrops. Undoubtedly these materials are not part of the karst dynamics; their origin is allochthonous to it. These materials are from the southern and highest zone (La Carva, 1917 m a.s.l.) which also is the watershed line (fig. 3B). These siliceous allochthonous clasts are also present in the slopes which connect the Sancenas polje with the Las Vizarreas sector, lying on the Valdeteja massive limestones (fig. 3C). They also appear northernmost in three outlets connecting the dolines zone with the Valdelasrubias, Valdestremero and Fejabudo headwaters valleys, settled them on Barcaliente limestones (fig. 6E). Between the source area and the location of the materials, a karstification area exists (polje, dolines, sinkholes, shafts). In addition, some sandstone pebbles present glacial striations produced during their transport (fig. 4D). Therefore, only glacial dynamics could explain the distribution of siliceous sediments inside the karst Sancenas massif (fig. 6D).

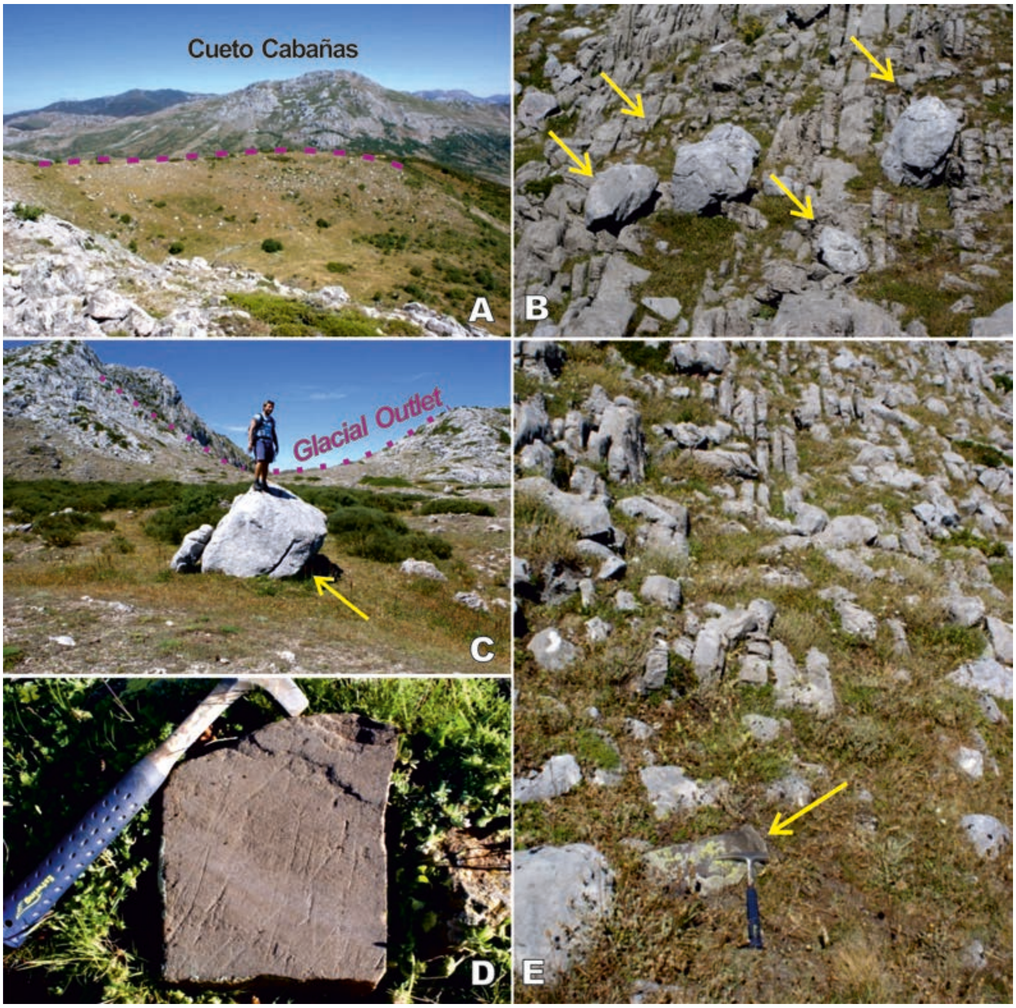


FIG. 7 - Moraines and deposits in the Sancenas karst massif. A) Lateral moraine in Valdestremero valley with limestone, sandstone and quartzite boulders visible between the grasslands. B) Massive Carboniferous limestone erratics (Valdeteja Fm) over the laminate limestones (Barcaliente Fm) near the Fejabudo pass which functioned as glacial outlets. C) Limestone erratic boulder over dolomitic facies and the Valdelasrubias glacial outlet in the background. D) A broken ferruginous sandstone clast, near the Sancenas polje pass with its surface polished, scratched and striated. E) Ferruginous sandstone pebble lodged on the Carboniferous limestones in the Fejabudo pass.

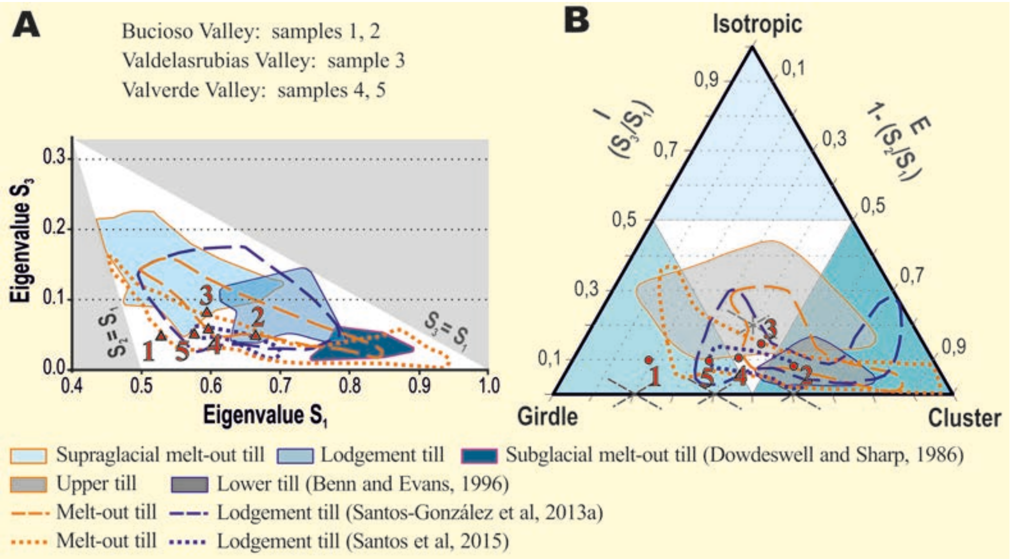


FIG. 8 - A) Eigenvalues S_1 and S_3 plotted in the biaxial diagram of Dowdeswell and Sharp (1986). B) Isotropy and elongation indexes, I: S_3/S_1 and E: $1-(S_2/S_1)$, plotted according the ternary diagram of Benn (1994). The results in each graphic are compared with data from Dowdeswell & Sharp (1986), Santos-González & *alii*, (2013a) and Santos & *alii*, (2015).

TABLE 2 - Clast fabric strength (S_1 eigenvalue) for tills from different field case studies, including data from Sancenas karstic massif.

Case study (reference)	Till type	S_1 eigenvalue range	S_1 eigenvalue mean
Dowdeswell & Sharp, 1986	Supraglacial melt-out till	0.54-0.56	0.55
	Subglacial melt-out till	0.78-0.86	0.82
	Lodgement till	0.57-0.66	0.62
Benn, 1994	Subglacial till	0.65-0.79	0.72
Benn & Evans, 1996	Upper till	0.49-0.65	0.58
	Lower till	0.40-0.50	0.45
Lawson, 1979	Melt-out till	0.87-0.90	0.88
Santos-González & *alii*, 2013a	Melt-out till	0.51-0.57	0.54
	Lodgement till	0.63-0.71	0.67
Santos & *alii*, 2015	Supraglacial Melt-out till	0.44-0.92	0.64
	Subglacial melt-out till	0.86-0.92	0.89
	Lodgement till	0.57-0.69	0.63
Santos & *alii*, 2017	Melt-out till	0.46-0.73	0.57
	Lodgement till	0.62-0.78	0.69
Sancenas massif	Melt-out till	0.53-0.59	0.57
	Lodgement till	0.66	0.66

The moraines in these valleys are composed with the same pebbles and boulders, including also limestone. However they are placed over siliceous material, so it is difficult to distinguish if they come from the southern Sancenas zone or if their origin is more local. However, with sedimentological analysis, we observed that clasts show polished surfaces, sub-rounded edges or oval shapes (fig. 7 (D and E), indicating a long-term transport.

Some Valdeteja Fm limestone boulders were also deposited over the same substrate (fig. 7C), but some features indicate glacial transport: 1) their dolomitic facies, light beige color and showing different dissolution, more irregular (alveolar) than the substrate, and 2) the presence of funnel sinkholes and shafts between those boulders emplacement and their respective source area.

The grain size analysis displays variations no significant between both the lower levels moraines and the upper ones (fig. 6). In general samples show a low classification with a dominant sandy fraction with percentages around 65%. The main difference appears in the Valdestremero samples (samples 4 and 5), which present a higher fines percentage (15.4%), almost doubling the values of the other samples (8.3% in Valdelasrubias and 8.6% in Bucioso). Probably, the higher percentage of fine material is related with the more extensive Lower Paleozoic shale outcrops present in the head valley, which would constitute the source area for the sediment matrix.

The fabric analysis displays differences in the shape and in the strength (fig. 8). In the Benn's diagram the data indicate a low isotropy index (< 0.2); but the fabric shape of the upper section of the Bucioso Valley (sample 2) is cluster. Its eigenvalue (S_1) of 66.1% presents many clasts oriented perpendicularly to the ice flow in this sector (N 95° E). The dominant fabric shape is girdle, being the samples 1 and 5 (Bucioso and Valverde valleys) the most polymodal. The clasts are clustered in different sectors without a net direction and concentration densities ≤ 10%. In both samples the main vector value (V_1) is the lowest, with eigenvalues (S_1) of 0.52 and 0.57. The Dowdeswell and Sharp's biaxial diagram also reflects a unimodal fabric in the Bucioso valley (sample 2) and more random fabrics for the other samples. This last one show the two main values (S_1 and S_2) close to each other with a $S_1 < 60\%$, being this data proper to polymodal fabrics, with several clasts orientations. In addition, these directions, except sample 3 (Valdelasrubias valley), are not parallel to the ice direction in this portion of the valley. In the Valdelasrubias fabric, most clasts follow the direction of ice flow in this sector (N 3°E), with imbricated clasts pointing towards the valley head (South), with values of dip inclination ≥ 15°-20°. In fact, the main vector dip inclination (V_1: 12.96°) is the highest of the analyzed samples.

Grain size and fabric analysis describe the sample 2 deposit (Bucioso Valley) as a subglacial lodgment till. The deposit is compacted, poorly sorted, the clasts are subangular but with the typical flat-iron shape and showing surface striations and fractures. Its fabric shape is cluster and there is a main direction in the major axis of clasts. In contrast, the other samples have been characterized as supraglacial melt-out tills because the materials show a lower sorting, not compacted, angular and subangular clasts with very few surface marks, and polymodal fabric shapes with eigenvalues very low (S1).

The sediments analyzed in the valleys present similar values to those collected in other areas of the Iberian Peninsula northwest such as the Sil valley, in Spain (Santos-González & *alii*, 2013a) and the Peneda and Gerês ranges, in Portugal (Santos & *alii*, 2015 and 2017). The subglacial lodgment till identified in the Bucioso valley (sample 2) is a unimodal cluster fabric with certain intensity (S_1: 0.66), being in the range of other zones with fabric studies (figs 9 and 10). This fabric strength occurs both in the ancient deposits (Karlstrom & Barendregt, 2001; Santos-González & *alii*, 2013a) and those recently abandoned (Benn, 1994, 1995; Dowdeswell & Sharp, 1986; Evans & *alii*, 2016; Li & *alii*, 2006). This deposit indicates an advance phase of the ice tongue, with clasts oriented in a main direction.

The other samples also show similar values to the supraglacial melt-out till studies in other zones: the fabric shape is girdle, without a clear orientation of the clasts, the fabric shape show a low strain and uneven values between the analyzed samples. These glacial materials were deposited in retreat or stabilization phases with many processes operating during their sedimentation such as the fusion of the ice itself, the melting water dynamic, mass movements and sediments readjustments, the final stabilization or, even post-depositional processes. These processes unable the occurrence of unimodal cluster fabrics, typical of environments where the ice flows and its pressure condition a main direction (Hicock, 1990; Evans, 2018). Consequently, supraglacial melt-out till values show wider ranges, from moderate-low to high strain fabrics, according to the main process that emplaced and stabilized the sediment and, the post-depositional processes that could have modified it (tab. 2). For this reason, some studies show intense fabric shape for the supraglacial melt-out till, with $S_1 \geq 0.8$ (Lawson, 1979; Larson & *alii*, 2016) and others a low strain fabric, ≤ 0.5 (Fitzsimons, 1990).

In addition to the sedimentological data, other geomorphic evidence indicates the existence of an icefield in Sancenas with outlet glaciers spreading to the northern valleys during the local LGM. In the Valdestremero, Fejabudo and Valdelasrubias valleys there is great contrast between the large moraines and the small glacial head-valleys located above (fig. 3A). The head-valleys show asymmetric and irregular walls, corresponding to a fault-block ridge. However, through these dropped sectors the ice flowed from the icefield to the cirques and their respective glacial valleys. The head-valleys were overfed and consequently the lateral moraines became larger than expected if cirques where formed in its head-valleys.

With respect to the Bucioso valley, part of the ice come from a glacial cirque formed in the siliceous and highest peak of the range (Bucioso, 1961 m), immediately to the east of the icefield. But this valley was also overfed from the Sancenas icefield through the Buey pass and sinkholes of the Peña del Sumidero. The evidence of this outlet is scarce, but some erratics show glacial action in this area. The overfed from the icefield explain the great ice thickness (100 m) the paleo-glacier reached in this valley, which was the largest of the massif.

Glacial sediments and landforms allow the reconstruction of glacial dynamic in the Sancenas massif during the last glacial cycle. During the maximum advance the elevated area of the massif was home to an icefield around 750 ha. From this icefield eight glacial tongues flowed to north and one to west. Some tongues reached the Valverdín-Valdeteja shale furrow (Bucioso, Valdestremero, Fejabudo, Valdelasrubias and Fusán) at 1380-1250 m a.s.l. This phase is followed by recession, with stabilized tongues at 1450-1600 m a.s.l. The icefield was still emitting ice through the outlets but in a smaller thickness fashion. In a later phase, stagnated ice probably remained in karst depressions and some head-valleys, but no morphological evidences persist. Only in the Bucioso valley, where a cirque developed, moraines at 1650 m indicate a last phase with a short (800 m) glacier oriented to NE. In the Valdelasrubias head-valley, a very small moraine at 1650 m is probably related with this last glacial phase, with a very small ice body located in the NE face of the Fuenfría peak (1891 m).

ELA rounded 1728 ± 20 m during the maximum advance. This value is consistent with previously published data in the Cantabrian Mountains, where great differences between areas has been observed. In the southern slope, where the Sancenas massif is located, ELA rounded 1700 m in the central and eastern part of the range, as occurs in the Curueño head-valley (González-Gutiérrez, 2002a), Peña Labra and Peña Prieta (Serrano & *alii*, 2013), Valdecebollas (Serrano Cañadas & González Trueba, 2004) or the Cardaño valley (Redondo Vega & Santos González, 2013). Lower ELA values occurred only in the more humid massifs of the range. In the Sierra de Ancares area rounded 1350 m (Valcárcel Díaz & Pérez Alberti, 2002), 1500 m in the Alto Sil area (Santos-González & *alii*, 2013b), and only 1100 to 1200 m in the Castro Valnera massif (Santos-González & *alii*, 2013b; Serrano & *alii*, 2013). In general, ELA position was related to precipitation, showing a similar pattern than present-day precipitation distribution, with values descending to the easternmost, northernmost and westernmost, and ascending to the southern and central part of the range (Santos-González & *alii*, 2013b).

Local topoclimatic factors influenced the ELA position of different glaciers, and great differences in altitude occur in some massifs. Santos-González & *alii* (2013b) highlights that ELA values were approximately 100-150 m lower in accumulation areas oriented to the north and east than those in south and west oriented areas in the same region. In the Picos de Europa, due to more extreme topoclimatic controls Serrano & *alii* (2013) observed paleoELAs range from 1215 to 2320 m depending on topography and orientation. In the case of Sancenas, the icefield was located to the north, so ELA value is restricted to this orientation. In the southern slope of this massif, any glacial evidence has been founded, so ELA probably was over 1950-2000. So, Sancenas icefield was formed in a limit conditions and was local topographic conditions favored snow accumulation and a low ELA position in relation to its location.

At the moment, no chronological data exits for the Sancenas glacial deposits, but they show similar state of conservation than other glacial landforms in the Cantabrian Mountains and the Iberian Peninsula northwest. Therefore, the works carried out in the nearby Porma valley (Rodríguez-Rodríguez & *alii*, 2016) establish an age for the Local LGM of 58-59 ± 1.9 ka BP, in glacial deposits with ^{10}Be. In the Redes Natural Park, near the Porma headwater valley on the northern side of the Cantabrian Mountains, absolute dating by means of OSL (optically stimulated luminescence) indicate ages before 33.5 ± 0.360 ka for the local LGM in the Monasterio and Tarna valleys (Jiménez-Sánchez & *alii*, 2013).

In the Picos de Europa region, radiocarbon dating has yield ages before 35.7-34.8 ka in the Duje valley (Serrano & *alii*, 2012) and, 43-45 ka BP in the Comeya-Enol area (Moreno & *alii*, 2010). In the nearby Fuentes Carrionas massif using OSL techniques, the Local LGM was established before 36 ± 2.35 ka BP in glacial deposits (Serrano & *alii*, 2013). Further west in the Sil valley, near the village of Villaseca de Laciana, Jalut & *alii* (2010) obtained ages of 35-60 ka from glaciolacustrine deposits using AMS dating. To the east in the Castro-Valnera/Asón area Frochoso & *alii* (2013) have dated morainic sediments in the Collados by means of OSL, indicating a Local LGM of 40.4-78.5 ka.

This data indicates a maximum ice extension in most of the Cantabrian Mountains valleys during the last glacial stage earlier than 30 ka BP. During the LGM, glaciers covered less extension, but reach similar positions, receding until the Younger Dryas, when ice was probably present in the main massifs (Serrano & *alii*, 2017). In this phase, ice probably was restricted to Bucioso cirque and Valdelasrubias head-valley, while the icefield was probably completely melted. After the Younger Dryas glacial ice was absent in the study area due to the lower elevations than other Cantabrian massifs.

CONCLUSIONS

The spatial convergence of karst and glacial landforms in the Sancenas massif make it a singular example to understand the interrelations of glaciokarst landforms and their processes.

The glacial development on the Sancenas massif was influenced by the Paleozoic structures disposition and the existing karst processes. It is a massif composed by an upper cohesive siliceous rocks watershed line in the south. It constitutes an inclined ramp towards the north that connects with the Sancenas polje and uvalas zone. This structural feature and its elevation (average 1750 m a.s.l.) favored the accumulation of glacial ice. Thus, when the karst depressions (whose closed form is a trap for ice retention) were filled by ice it began to flow northward through the outlets. The outlets developed large moraines that reached the central and bottom part of the Valverdín-Valdeteja shale furrow.

Moraines and karst landforms include siliceous pebbles and boulders from the upper watershed area, attesting the glacial dynamics in the Sancenas massif. In addition, ice flow polished large surfaces in the calcareous ridges, especially in Fejabudo and Valdestremero. They are well visible because the vertical limestones dip is sharply cut. In detail the intense dissolution has eroded part of that polished original surface, but the general shape is still preserved.

The landforms and sediments identified allow to establish a glacial evolution in three phases: i / the phase of maximum advance where glacial outlets fed by the icefield reach elevations of 1380-1250 m and the ELA was located at ~1700 m, ii / a retreat phase with tongues around to 1470-1580 m; iii / a final phase with ice restricted to a cirque and a head-valley in the northeastern slopes of the highest areas. Likewise, the sedimentological analysis allows the identification of a subglacial lodgement till in the Bucioso valley, with cluster fabric that would indicate the maximum advance phase. The other sections show four supraglacial melt-out tills with polymodal girdle fabrics that would indicate a phase of stability followed by an overall recessional phase.

Overall this work has allowed knowing in more detail the glacial dynamics in this region. A small icefield with outlets spreading to the north existed. The glacial dynamics in the Sancenas massif have been considered until now as marginal, however this study indicate a remarkable sized icefield during the local LGM with a length of more than 5 km from W-E, 2 km from N-S with almost 750 ha and 420 hm^3 of volume. The ice thickness exceeded 140 m in the central portion and its surface could reach 1960 m a.s.l.

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