Geomorphology of the Aran Valley (Upper Garonne Basin, Central Pyrenees)

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ABSTRACT

Geomorphological mapping in mountain regions is key for a better understanding of past and present environmental dynamics. Here, we present a 1:25000 scale geomorphological map covering 553 km² of the Aran Valley, Upper Garonne Basin (Central Pyrenees). The map identifies 44 different geomorphological units classified under glacial, periglacial, nival, karst, slope, alluvial, and fluvial categories. The area includes geomorphic evidence of past Quaternary glaciations reconstructed based on the distribution of moraines from the valley floor to the highest cirques. Following deglaciation of the valley, the landscape was mainly reshaped by periglacial, slope, alluvial and fluvial processes. In addition to paleoenvironmental reconstruction, the map can also be used to promote geoheritage and geoconservation, as well as for planning. As such, it is of relevance for areas exposed to natural hazards, since present-day slope failures and debris flows frequently impact the villages and infrastructures across the valley floor.

1. Introduction

Geomorphological mapping in mountains has significantly advanced over the last decades in parallel to the development of survey techniques and availability of aerial and satellite images (Chandler et al., 2018), as well as of airborne LiDAR surveys (Oguchi et al., 2012). A better understanding of present-day geomorphological processes allows improved territorial management in areas exposed to natural hazards (Paron & Claessens, 2011). Accurate geomorphological maps of alpine regions can be used to reconstruct their past environmental histories and to promote the inventorying and classification of geoheritage (Coratza & de Waele, 2012). As such, geomorphological maps are important tools, leading to the implementation of geoconservation measures that may be applied to promote regional development policies.

Geomorphological maps have been used as a scientific tool since the 1960s, developing into more complex maps on glaciated landscapes of mountains, piedmonts, and glacial forefields at the beginning of the twenty-first century (Knight et al., 2011). Several geomorphological maps have been recently published for mid-latitude mountains, such as the Iberian mountains (González-Gutiérrez et al., 2017; Pellitero, 2014) and the Alps (Coratza et al., 2019; Lambiel et al., 2016), or for areas such as the Tibetan Plateau (Lindholm & Heyman, 2016; Schneider et al., 2021). In the Pyrenees, besides the geomorphological maps by the ‘Instituto Geológico y Minero de España’ at 1:50000, detailed geomorphological mapping has mostly focused on (i) National Parks, such as Ordesa-Monte Perdido (García-Ruiz & Martí-Bono, 2001) and Aigüestortes Estany de Sant Maurici (Martínez-Rius, 2010), (ii) some large valleys, such as Benasque (García-Ruiz et al., 1992) or Andorra (Copons, 2005), (iii) singular landscape features for all valleys of the southern part of the range, such as glacial landforms (Martí-Bono & García-Ruiz, 1994), or (iv) in small valleys and glacial cirques, where geomorphological sketches and maps supported various research topics, mainly on glacial, periglacial or slope dynamics (e.g. André et al., 2018; Fernandes et al., 2017; Jarman et al., 2014; Serrano et al., 2020).

To date, a detailed map including the wide range of geomorphological features existing in the Aran Valley is still missing. This work focuses on the Aran Valley, one of the longest glacial valleys in the Pyrenees, which showed a ca. 80 km long valley glacier at the maximum ice extent of the last glacial cycle (Fernandes et al., 2017). The geomorphological and paleogeographical richness of the area has resulted in several publications (Fernandes et al., 2021b, 2021a, 2018, 2017; Lopes et al., 2018; Oliva et al., 2021). The valley has ca.
10,000 inhabitants distributed in 33 settlements and infrastructures are widespread both in the valley floor and mountain slopes. Hence, an accurate identification and analysis of the geomorphological features become important for a better spatial planning, for the mitigation of natural hazards and for the implementation of geoconservation measures and promoting geoconservation. To present, the existing geomorphological coverage of the Aran Valley is incomplete and not systematic, consisting of: (i) a low-resolution map from the early 1990s focussing on the main glacial features (Serrat et al., 1994), (ii) a geomorphological map of the northern part of the Aran Valley including only the Toran, Varradòs and Unhòla tributaries (Martí-Soler, 1988), (iii) a map of glacial and postglacial features of the SW area of Aran, namely the Joëu and Nère valleys (Bordonau, 1985), and (iv) the geomorphological map of the Ruda Valley (Fernandes et al., 2017).

The objectives of this work are to: (i) improve the existing geomorphological maps, which covered only 200 km² and expand the survey to the entire 553 km² of the Aran Valley, and (ii) offer the local authorities a high-resolution geomorphological map, that may be used as a tool for spatial planning purposes.

2. Study area

The Aran Valley is the northwesternmost district of Catalonia within Spanish administrative territory (Figure 1). The headwaters are on the central axis of the Pyrenees, with elevations above 3000 m a.s.l. (Molières Peak, 3009 m asl; Besiberri Nord Peak, 3007 m), whereas the valley floor, near the French border, is at ca. 600 m. The Aran Valley constitutes the headwaters of the Upper Garonne Basin at its easternmost flank (Figure 1).

The current climate in the Aran Valley is dominated by wet and cool Atlantic air masses. Annual precipitation in the valley floor is ca. 900 mm at Vielha village (980 m), and increases to 1232 mm at the Port de la Bonaigua water divide (2266 m). Annual air temperatures (MAAT) at these two sites are 9.6°C and 2.7°C, respectively. The regional 0°C isotherm is at 2950 m asl in the Central Pyrenees (López-Moreno et al., 2016), with only the highest summits recording negative MAATs. The Aran Valley shows typical Euro-Siberian vegetation, with flat-leaf, deciduous forests in the lower elevations and conifers up to ca. 2200–2300 m asl, where they are replaced by alpine meadows (Bolòs & Vigo, 1984).

The Aran Valley is part of the Paleozoic basement of the Central Pyrenees that was uplifted during the Alpine orogeny (García-Sansegundo et al., 2013; Quesada & Oliveira, 2019). The rise of the Pyrenees formed several thrusts organized in two structural domains: the first is mainly located in the northern part of the Aran Valley with E-W direction subhorizontal structures, and the second constitutes the central part of the valley and mainly includes E-W subvertical folds (Sitter & Zwart, 1962; Zwart, 1979). Both were intruded by granitoids, such as the Malàta Batholith and the Dome of Bossóst (García-Sansegundo, 2004). Bedrock in the north and central valley slopes is composed of metamorphic (slates, schists and marbles) and sedimentary rocks (limestones, lutites, conglomerates and sandstones) from the Cambrian to the Devonian periods (Geològic de Catalunya, 2017). The highest areas are mostly composed of igneous rocks (granites) that intruded during the Carboniferous period (Martínez et al., 2016; Mezger & Gerdes, 2016). Quaternary deposits are located along the narrow valley bottoms, floors and footslopes of the glacial cirques and in parts of the slopes.

Similar to other areas of the Pyrenees, the Aran Valley was extensively glaciated during Quaternary glacial cycles (Oliva et al., 2019). A ca. 80-km long glacier descended along the main Garonne Valley until the glacial basin near Montrejeau at 400–500 m asl, where it formed a series of frontal moraine ridges, both at ca. 130 ka and prior to 24–21 ka (Fernandes et al., 2021b). At those periods, the equilibrium line altitude (ELA) was located at ca. 1500 m (Fernandes et al., 2017).

The Aran Valley presents a U-shaped cross-section and a prevailing S-N direction, turning E-W between the villages of Baquèira and Vielha (Figure 1). The relief may be divided into three major units: (i) interfluves (peaks, ridges and summit plateaus) and glacial cirques, (ii) mountain slopes, and (iii) gently sloping floors of the Garonne Valley and its tributaries (Aiguamòg, Valarties, Nère, etc.). The landscape was extensively shaped by Quaternary glaciers, although the chronological framework of glacial oscillations in the northern slope of the Central Pyrenees is yet to be established (Fernandes et al., 2021a; Oliva et al., 2019). Postglacial dynamics has been mainly driven by periglacial and nival processes in the highest areas, with the occurrence of frequent permafrost-related features, such as rock glaciers and protalus lobes (Fernandes et al., 2018), as well as by hillslope and alluvial processes across the slopes and valley floor (Fernandes et al., 2020). Warmer temperatures during the Holocene promoted soil development, slope stabilization and forest expansion (González-Sampériz et al., 2017; Tejedor-Rodríguez et al., 2021). Since the Neolithic/Chalcolithic periods, and particularly since 4 ka cal BP, humans have significantly modified the landscape. Initially the impacts were associated with forest clearing to expand transhumance practices, that triggered hydrologic and erosion changes (García-Ruiz et al., 2020; Tejedor-Rodríguez et al., 2021). Over the last millennium, particularly since 1.1 ka cal BP, human settlements grew and agriculture and grazing expanded across the valley floor (Garcés-Pastor et al., 2017). Since the latest twentieth century, a tourism-
driven economy has dramatically changed the landscape, with the construction of infrastructures and the expansion of settlements, mainly across the valley floor.

3. Methodology

The elaboration of the geomorphological map of the Aran Valley at 1:25000 scale was based on:

(i) extensive bibliographical and cartographic review, including georeferencing of existing geomorphological maps by Bordonau (1985), Martí-Soler (1988) and Serrat et al. (1994),

(ii) remote sensing data interpretation, including the analysis of LiDAR-derived terrain models (digital elevation model, hillshade and slope), digital orthophotomaps and very high-resolution Google Earth imagery (Table 1),

(iii) systematic field surveys during the summers of 2015, 2019, 2020 and 2021 for reconnaissance, landform identification and validation (Figure 2(C)), and

(iv) editing in GIS environment (ArcGIS) and the final map layout (Illustrator).

The geomorphological map main focus is on landforms and processes, with Table 2 synthesizing the criteria used for their mapping. They were outlined and symbolized according to Joly (1997) and Lambiel et al. (2013) and grouped following criteria on glacial, periglacial, slope, alluvial, fluvial, nival and karst features. The symbolization uses lines for the linear landforms (e.g. moraine crests), points for the isolated landforms or deposits (e.g. erratics), and polygons for larger non-linear features (e.g. fluvial plain). Additional information includes the main faults (Geològic de Catalunya, 2017), pre-Quaternary geology (1:50000; Geològic de
Catalunya, 2017), rivers and lakes (Institut Cartogràfic i Geològic de Catalunya ICGC), 100 m contours (derived from the Advanced Spaceborne Thermal Emission and Reflection Radiometer – ASTER DEM), main peaks (Instituto Geográfico Nacional de España; IGN), and main infrastructures (ICGC).

All landforms were validated during the summer when the snow-free landscape allowed for the identification of geomorphological features. Most landforms were identified in LiDAR-derived models, online anaglyph map viewer (https://www.ign.es/iberpix2/visor/), satellite imagery, and orthophotomaps, with only the small-size features having been identified in the field.

4. Results

4.1 Glacial landforms

Abundant erosional and depositional glacial landforms occur from the highest areas to the Aran Valley floor. The highest areas show glacial cirques (Figure 3(D)), where ice accumulated before filling the valleys with a maximum thickness of ca. 800 m (Fernandes et al., 2017). The main valley as well as its tributaries display well-preserved U-shaped sections. Glacial erosion shaped overdeepened basins along the valley bottoms (e.g. Valarties Valley), that are occupied by lakes, peatlands (e.g. Ruda Valley; Figure 3(C)) and fluvial plains.

| Table 1. Attributes of the remote sensing products used for the geomorphological map. |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Product                        | Source                          | Characteristics and spatial resolution | Information                        |
| Orthophotomaps                 | Institut Cartogràfic i Geològic de Catalunya (ICGC) (http://www.icc.cat/appdownloads/index.html?c=fmeof25c) | RGB, 25 cm/pixel                | Terrain characteristics (e.g. vegetation cover, outcrops, deposits, etc) |
| Lidar data                     | ICGC (http://www.icc.cat/appdownloads/?c=dfh3lidar) | Collected in 2011. Point cloud density of 0.5-2.7 m² | Ground surface characteristics (e.g. flat surfaces, furrows, crests, etc) and delimitation of landforms |
| Stereoscopic viewer            | Instituto Geográfico Nacional (IGN; http://www.ign.es/3d-stereo/) | Photograms of the Plan Nacional de Ortofotografía Aérea. Variable resolution (22-45 cm/pixel) | Characteristics of the ground surface morphology |
| 3D models satellite images     | Browser of Google Earth (https://earth.google.com/web/) | IGN imagery (large scale) and Landsat imagery (small scale). NASA SRTM Digital Elevation dataset (30 m) with the IGN imagery (25x25 cm) and Landsat imagery (30x30 m) | Validation of the ground and terrain characteristics and a broader framework of geomorphological features |

Figure 2. Steps followed during the elaboration of the geomorphological map; (A) combination of hillshade (40% transparent) with orthophotomaps; (B) first draft of the geomorphological map; (C) field validation of the first geomorphological draft with pictures, such as till cover (C₁), superficial deformation of till cover at the plateau (C₂), peat area (C₃), and alluvial fan (C₄). (D) final geomorphological map respecting the Main map legend.
### Table 2. Location and morphological characteristics of the landforms and processes drew in the Main map.

| Categories | Landforms and processes | Geomorphological setting | Morphological criteria | Mapping identification criteria | Reference |
|------------|-------------------------|--------------------------|------------------------|--------------------------------|-----------|
| Glacial    | Headwaters of the valleys | Amphitheatre-like basin surrounded by steep walls | Steep walls displaying a concave area with a (semi)elliptical morphology | Joly (1997); Lambiel et al. (2013) |
| Ridge (or arêtes) | Water divide between glacial cirques/valleys | Truncated spur dividing adjacent glacial cirques or valleys | Sharp and narrow rock alignments | Giles et al. (2017) |
| U-shaped valley | Trunk and tributary valleys shaped by glaciers | U-shaped transverse valley section with concave slopes | Parabolic cross-profile (steep-sided and flat bottom) | Evans (2013) |
| Rock step (>50°) | Polished surface in glacial cirques/valleys | Slope rupture with a rounded shape and asymmetric up/down valley faces | Higher slope degrees in lee’s bare rocks | Joly (1997); Giles et al. (2017) |
| Watershed breach | Headwaters of the valleys (cols | Concave water divide eroded by past glacial diffi uly | Lower areas within an elevated alignment, able to connect two opposite valleys containing bare rocks and/or boulders | Joly (1997); Giles et al. (2017) |
| Overdeepened basin | Depressed area in glacial cirques/valleys | (Sem)circular depression surrounded by polished surfaces or glacial deposits | Current flat areas frequently include lakes or peatlands | Joly (1997); Lambiel et al. (2013) |
| Hanging valley | Lateral glacial valley hanging above the main glacial valley floor | Glaciously eroded valley floor standing above the adjacent valley | Different base levels between lateral valleys and the tributary/main valley | Joly (1997); Giles et al. (2017) |
| Riegel | Bottom of glacial cirques/valleys | Upstanding transverse ridge with polished surfaces | Rock barrier across the bottom of the glaciated valley/cirque with or without a narrow exit | Lambiel et al. (2013); Giles et al. (2017) |
| Roche moutonnée | Bottom of glacial cirques/valleys | Convex surfaces showing polished surfaces upstream and quarrying downstream | Bare surfaces with a smooth up-facing slope and steep down-facing slope | Lambiel et al. (2013); Giles et al. (2017) |
| Polished surface | Slope or bottom of glacial cirques/valleys | Relatively horizontal glacially abraded bedrock | Bare rocks with a smooth surface | Giles et al. (2017); Lambiel et al. (2013); Giles et al. (2017) |
| Striation | Polished rock surface in glacial cirques/valleys | Millimetric to metric long scratches or grooves commonly on stoss side of the polished rock surfaces | Only identifiable in field observations | Lambiel et al. (2013); Giles et al. (2017) |
| Debris-free glacier moraine | Bottom and slopes of glacial cirques/plateaus/valleys | One or several crests with subangular to subrounded boulders and with a depression upvalley | Elongated ridges with smooth surfaces | Joly (1997); Lambiel et al. (2013) |
| Debris-covered glacier moraine | Bottom and slopes of glacial cirques | Supraglacial till with angular boulders showing frequent longitudinal furrows and crests | Parallel ridges with supraglacial boulders on top or surfaces with collapses (minor-closed depressions) and debris thickness increasing towards the glacier front | Evans (2005) |
| Till | Wide range of settings affected by past glaciations (summit surfaces, slopes, plateaus, valley bottoms) | Unsorted glacial sediment | Soft surfaces covered with unsorted sediments and embedded boulders where commonly vegetation colonized the fine fraction of the deposit | Lambiel et al. (2013); Benn and Evans (2010) |
| Till collapse | Till deposits Sides of glacial valleys | Depression on till cover Relatively horizontal deposit generated by meltwater streams along the side of a glacial valley | Closed depressions Smooth and flat (table-like) surfaces | Joly (1997); Lambiel et al. (2013) |
| Erratic boulder | Widespread deposit across formerly glaciated areas Isolated boulder lying on the surface | Large boulders needing of field validation | – | Joly (1997); Lambiel et al. (2013) |
| Periglacial | At the foot slope and bottom of glacial cirques | Large accumulation of boulders displaying perpendicular ridges and furrows and a steep front | Large boulders with different vegetation maturity and morphological changes ridge-like | Joly (1997); Kääb (2013) |
| Protalus lobe | At the foot of talus slopes in glacial cirques/valleys | Accumulation of boulders with one lobate ridge at the front | Large boulders with different vegetation maturity and morphological changes ridge-like | French (2007); Kääb (2013) |
| Block stream | Slopes of glacial cirque/valleys | Linear accumulation of coarse angular boulders | Angular boulders with scarce vegetation flowing downslope | French (2007); Knight and Harrison (2009) |
| Patterned ground | Relatively flat surfaces or gentle slopes, generally at high altitudes | Geometric landforms composed of sorted/non-sorted circles (flat | Only identifiable in field observations | Joly (1997); French (2007) |

(Continued)
| Categories                          | Landforms and processes                                                                 | Geomorphological setting                                                                 | Morphological criteria                                                                 | Mapping identification criteria | Reference                     |
|------------------------------------|----------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|--------------------------------|--------------------------------|
| Block field                        | Relatively flat surfaces or gentle slopes at the summit level                           | Accumulation of in-situ boulders on the mountaintops                                      | Only identifiable in field observations                                                |                               | Giles et al. (2017)           |
| Solifluction lobe                  | Slopes of glacial cirques/valleys                                                     | Tongue-shaped landforms or terrasses occurring in vegetation and sediments                | Only the biggest lobated structures are identified on vegetation and sediments         |                               | Joly (1997); Giles et al. (2017) |
| Ploughing boulder                  | Gentle slope of glacial valleys                                                      | Boulder showing downslope displacement with a linear depression upslope                   | Boulder’s pathway is recorded in vegetation and topography                           |                               | Joly (1997)                   |
| Nival                              | Late-lying snow patch                                                                 | Hollows of glacial cirques                                                               | Semi-permanent snow field                                                             | Snow patches                   | Joly (1997); Lambiel et al. (2013) |
| Avalanche corridor                 | Steep slope of glacial cirques/valleys                                               | Corridor of frequent avalanche occurrence                                                | Linear patches with no arboreal strata along the slope                                 |                               | Joly (1997)                   |
| Protalus rampart                   | At the foot of slopes in glacial cirques/valleys                                      | Accumulation of well-sorted sediments transversal to slope and at the foot of late-lying snow patches | Difficult to identify with remote sensing products                                      |                               | Joly (1997); Lambiel et al. (2013) |
| Karst                              | Doline                                                                                 | Outcrop of limestones                                                                     | Isolated closed depression                                                            | Dots identified as topographic depressions                                              | Joly (1997)                   |
| Karst                              | Uvala                                                                                  | Outcrop of limestones                                                                     | Set of coalescent dolines next to each other                                           | Set of dots connected with each other identified as one topographic depression           | Joly (1997)                   |
| Karst                              | Karst window                                                                           | Contact between limestone and silt-grained bedrock                                       | Depression where a stream falls into a karst aquifer                                  | Only identifiable in field observations                                                | –                             |
| Slope                              | External scar                                                                          | Slopes or interfluves of glacial cirques/valleys                                         | Delineation of the slope failure origin/valleys                                        | Steep areas of downslope ruptures                                                     | Lambiel et al. (2013)         |
| Karst                              | Internal scar/antiscar                                                                 | Surface of rock slope failures in glacial cirques/valleys                                | Downslope or upslope scar                                                             | Steep areas of perpendicular and linear ruptures on the mass movement. The position of the highest degrees on the rupture defines if is downslope or upslope | –                             |
| Talus slope                        | At the foot of rock walls in glacial cirques/valleys                                  | Irregular and angular rock debris covering the valley sides                              | Large boulders forming a talus or cone morphology                                       |                               | Joly (1997); Giles et al. (2017) |
| Rock slope failure                 | Slopes of glacial cirques/valleys                                                     | Break of slope caused by mass movements                                                   | Steep downslope scars with irregular displaced body surface and steep front           |                               | Joly (1997); Giles et al. (2017) |
| Rock fall                          | At the foot of the rock wall of glacial cirques/valleys                                | Non-sorted deposit of large angular boulders                                            | Large boulders showing a chaotic distribution on foot slopes                          |                               | Lambiel et al. (2013)         |
| Gully/Ravine                       | Slopes of glacial cirques/valleys                                                     | Narrow runoff channels eroding the bedrock/soil                                         | Abrupt channels directly affecting the bedrock                                       |                               | Rapp (1960); Lambiel et al. (2013) |
| Debris flow                        | Slopes of glacial cirques/valleys                                                     | Channel, leée margin and sometimes lobate feature on the terminal areas of talus slopes | Narrow channels on sediments                                                          |                               | Joly (1997); Lambiel et al. (2013) |
| Alluvial                           | Foot slopes of glacial cirques/valleys                                                | Prominent toe of the rock slope failures                                                 | Arched morphologies facing downslope                                                   |                               | –                             |
| Alluvial                           | Alluvial fan                                                                           | Foot slopes of glacial valleys                                                           | Triangular-shape morphologies                                                          |                               | Joly (1997)                   |
| Alluvium                           | Flat area on the slopes of glacial valley                                             | Alluvium defined by a relatively horizontal surface                                     | Soft and flat surfaces covered with herbs                                              |                               | Parry (2011)                  |
| Mudflow                            | Slope of glacial cirques/valleys                                                     | Silty-rich deposit with lobate morphology in the distal section                         | Poorly defined morphologies with fan-shaped and lobate terminus                       |                               | Matsuoka et al. (2005)        |
| Peatland/wetland                   | Depressed area of glacial cirques/valleys                                             | Dense vegetation cover with poor drainage within overdeepened basins                     | Relatively horizontal surfaces covered with peat sediments                             |                               | Joly (1997)                   |
| Fluvial                            | Bottom of glacial valleys                                                              | Deep fluvial incision on bedrock                                                        | Longitudinal deeply incised bedrock                                                   |                               | Joly (1997); Lambiel et al. (2013) |
| Plain                              | Bottom of glacial valleys                                                              | Relatively horizontal surface formed by fluvial sediments                                | Relatively soft and flat surface parallel to the riverbed                            |                               | Joly (1997)                   |
| Terrace                            | Bottom of glacial valleys                                                              | Lateral staggered level of fluvial sediments                                              | Staggered flat levels constrained by steep slopes, parallel to the main axis of the river |                               | Joly (1997); Lambiel et al. (2013) |
| Hydrology                          | River/stream                                                                           | Bottom of glacial cirques/valleys                                                       | Linear water bodies                                                                   |                               |                               |

(Continued)
(e.g. main Garonne Valley). Intense glacial erosion is also shown in smaller landforms, such as roches moutonnées and glacially polished surfaces – including striations – along the valleys (e.g. next to the Maubèrme Peak). A significant part of the glacially eroded material was transported downvalley and accumulated as terminal and lateral moraines (e.g. Nère Valley; Figure 3(A)), till or scattered erratics (e.g. main Garonne Valley; Figure 3(B)). Moraines accumulated during different periods of advance or standstills during glacial retreat and are distributed in a wide elevation range: from the highest cirques at 2400 to 2600 m asl (e.g. Aigua-mòg Valley) to the valley floors at 1300 m asl (e.g. Nère Valley), or even on the marginal and elevated plateaus including deposits located 500 m above the riverbed (e.g. between Ruda and Aiguamòg valleys).

### Table 2. Continued.

| Categories | Landforms and processes | Geomorphological setting | Morphological criteria | Mapping identification criteria | Reference |
|------------|------------------------|--------------------------|------------------------|-------------------------------|-----------|
| Lake       | Bottom of glacial cirques/valleys | Linear water body that is permanent (river) or ephemeral (stream) | Permanent water body with irregular shape | Water bodies from natural origin, coinciding with overdeepened basins or landslide obstructions/scars | Joly (1997); Lambiel et al. (2013) |

#### 4.2 Periglacial landforms

The frozen ground has promoted the development of numerous landforms, some of which are still active under current climate conditions. Rock glaciers (Figure 4(A)) and protalus lobes (Figure 4(B)) provide evidence for the past occurrence of permafrost (Fernandes et al., 2018), with only one active rock glacier having been identified in the area (Serrano et al., 2011). Above ca. 2300 m asl, smaller landforms associated with seasonal frost show traces of activity. In relatively flat summit surfaces, there are block fields (e.g. between Joèu and Nère valleys) and patterned ground features (e.g. next to the Maubèrme Peak; Figure 4(D)), while in gentle slopes, there are block streams (e.g. Ruda Valley; Figure 4(C)) and solifluction lobes (e.g. Salient Valley).

![Figure 3. Examples of the different glacial landforms identified in the area: (A) lateral moraine around 1600 m at the Nère Valley; (B) E-W perspective of the main Garonne Valley with an erratic boulder of granite distributed on a slate outcrop above Salardú village; (C) glacial lake distributed in an overdeepened basin at the Unhòla Valley; (D) glacial cirque of the Montardo Peak at the Valarties Valley.](image-url)
4.3 Nival landforms

Under current climate conditions, snow remains for 6–8 months/year above 2000–2200 m asl with nival dynamics affecting upper slopes. Snow avalanches are relevant on steep slopes (e.g. Valarties Valley) and in shady areas of the cirques and high valleys, snow-patches can persist during most of the year (Figure 5(A)), triggering the formation of protalus ramparts (e.g. Nère Valley).

4.4 Karst landforms

Karst morphologies occur in limestone terrain, especially at the Unhòla valley, between the Armeròs and Maubèrme peaks. In these sectors, glaciers and dissolution have originated a glacio-karst landscape (Figure 5(B)) with dolines, uvalas and karst windows.

4.5 Slope landforms and processes

The elevation difference of ca. 2500 m from the highest peaks to the lowest valley floors in the Aran results in very active slope processes, particularly in slopes between 25 and 35°. Past slope dynamics occurred mostly during the paraglacial stage consisted of catastrophic rock slope failures, rock slope deformations, rockfalls and landslides (Figure 5(C)) (Fernandes et al., 2020). Postglacial gravitational processes generated thick debris mantles covering the slopes (e.g. main Garonne Valley). Talus cones and talus slopes, particularly those located at lower elevations (e.g. Nère Valley), have gradually become inactive, allowing for soil development and forest expansion. Some of them show traces of deep incision, following debris flows and gully erosion (e.g. Varradòs Valley). These processes also occur on fine-grained sedimentary rocks, such as lutites or shales.

4.6 Alluvial landforms and processes

Alluvial fans (Figure 5(D)) are found at the contact between steep slopes and the valley floors, forming triangular-shaped features of fine sediments of variable sizes (e.g. main Garonne Valley). Depending on the prevailing lithology, alluvial fans can be also reshaped by debris flows, mudflows or rockfalls (e.g. main Garonne Valley). These are particularly intense during heavy rainfall or snow-melt episodes. Sediments can also accumulate in overdeepened basins in the valley heads (e.g. Ruda Valley), infilling ancient lakes and promoting the development of peatlands (e.g. Unhòla Valley).

4.7 Fluvial landforms

Rivers and streams flowing to the Garonne River show a high capacity to mobilize sediments, particularly during the snow-melting period. Whereas in some
Figure 5. Examples of other geomorphological landforms identified in the area: (A) long-lying snow patch at 2350 m, in the north face of the Arméros Peak; Unhòla Valley; (B) dolines located in the Sascorjada glacial cirque, Toran Valley; (C) Rock slope deformation at the Varradòs Valley; (D) alluvial fan connected with the fluvial plain at the Joèu Valley.

Figure 6. Sequence of environmental phases shaping the landscape of the Aran Valley: (A) maximum ice extent of the last glacial cycle; (B) glacial tongues flowing downvalleys during a glacial advance/standstill (Oldest Dryas) within the long-term glacial retreat of the Garonne paleoglacier that favored also intense slope readjustment; (C) alpine and cirque glaciers (Younger Dryas) with very intense postglacial slopes dynamics, and the occurrence of permafrost that promoted the formation of rock glaciers; (D) deglaciated cirques with periglacial processes prevailing at higher elevations (inactive rock glaciers), and slope, alluvial and fluvial processes at lower elevations.
areas the rivers flow through gorges (e.g. Unhòla Valley), in others the valley presents a large floodplain that is used for agriculture and grazing purposes (e.g. Nère Valley). In the Aran Valley, there are more than 700 lakes of glacial origin distributed between 1566 and 2711 m asl with a 0.5 m² ha mean size (Main map). In the Aran Valley, 80% of the lakes are located above 2000 m asl, mostly in overdeepened basins in the granitic bedrock. At lower areas, the lakes are smaller and show infill of peat and pro-glacial sediments.

5. Discussion

The geomorphological map of the Aran Valley shows evidence that almost the entire valley was glaciated during the last glacial cycle, and only the peaks and rock ridges (<8% of the area) protruded above the ice as nunataks (Main map). Given the prevalence of glacial erosional landforms supporting basal sliding, the broad spectrum of periglacial, slope and alluvial phenomena existing in the area must have followed deglaciation of the valley.

The chronology of the maximum ice extent of the last glacial cycle is still not well-known in the Central Pyrenees (Oliva et al., 2019). However, recent studies shed light on the chronological frame of the terminal basins. Glacial features associated with the Garonne paleoglaciers in the Lourès-Barousse-Barbazán basin at 470–680 m asl show an advance during the marine isotope stage (MIS)-6 and retreat during MIS-2 (Fernandes et al., 2021a). The presence of discontinuous morainic steps on the slopes above the main Garonne Valley suggests that glaciers reached an ice thickness of ca. 600–800 m during the maximum Pleistocene ice expansion (Figure 6). The intensity of postglacial slope, alluvial and fluvial dynamics must have destroyed glacial evidence in the lowest areas of the Aran Valley, where no terminal moraines are preserved. Erosional (e.g. polished surfaces) and accumulation glacial landforms (e.g. moraines) are widespread in the upper parts of the valley. Indeed, exposure ages from polished surfaces showed glacier recession at 15–14 and at 12.7 ka. Moraines located in glacial cirques at 2080–2190 m and 2430–2470 m asl show ages of 13.5–13.0 and 12.9–12.6 ka, respectively. These relate to glacial advances or standstills in the Bolling-Allerød, as well as in the Bolling-Allerød to Younger Dryas transition (Fernandes et al., 2021b; Oliva et al., 2021). Such glacial landforms are a legacy from past processes and environments. The wide range of glacial landforms, its degree of preservation, as well as its singularity within southern Europe constitute key elements of the natural heritage and geodiversity of the Aran Valley.

As glaciers disappeared from glacial cirques, periglacial morphogenesis became the prevailing process shaping the highest landsurfaces. Indeed, rock glaciers and protalus lobes present in most cirques show evidence of permafrost in formerly glaciated cirques (Fernandes et al., 2018). In the Pyrenees, these periglacial features developed following glacial retreat at the end of both the Oldest and Younger Dryas cold events under paraglacial debuttressing of cirque slopes (Andrés et al., 2018; García-Ruiz et al., 2016; Palacios et al., 2017). The readjustment to new glacier-free conditions favored widespread slope failure events affecting both the bedrock and unconsolidated glacial sediments. Fernandes et al. (2020) show that more than 90% of the 135 large slope failures identified in the Aran Valley occurred within the glaciated domain of the last glacial cycle (Figures 5(C) and 6).

Since the onset of the Holocene, climate variability ranged within ± 2°C compared to present conditions in mid-latitude regions (Mayewski et al., 2004; Wanner et al., 2015). The current periglacial zone in the Aran Valley is located above ca. 2300 m asl (Fernandes et al., 2017) and thus seasonal frost processes should have affected elevations between ca. 2000 and 2500 m asl, with permafrost existing at the summit levels only during the coldest phases (Oliva et al., 2018). Holocene periglacial processes have reshaped slopes with widespread development of talus cones and slopes, as well as solifluction landforms, whereas patterned ground and block fields formed in flat or low gradient hillsides (e.g. Nère and Unhòla valleys – Main map). Climatic changes during the Holocene together with transhumance practices during the Mid-Late Holocene promoted vegetation shifts in the periglacial environment that enhanced or diminished hydrological and geomorphic dynamics (García-Ruiz et al., 2020).

Frequent high-intensity events, such as snow avalanches (e.g. Valarties Valley), debris flows (e.g. Varra-dòs Valley) or mudflows (e.g. Bargadera Valley), dominate the glacial landscape from the cirques and valley heads to the valley floors, where they contributed to the development of several generations of alluvial fans (e.g. Unhòla; Victoriano et al., 2016). These are the major natural hazards currently affecting the Aran Valley, particularly debris flows that cause annual infrastructure damage, such as in the road network. An example occurred in the Valarties Valley, where a debris flow in May 2018 mobilized 50,000 m³ of sediments, destroying the local road (Perdices Cos, 2019). Intense rainfall and snow-melting episodes lead to frequent flood events that trigger intense fluvial erosion in the highest sectors and accumulation of sediments in the flood plains of the lowest areas, such as in June 2013 where a flash flood in the Upper Garonne Basin caused damage to infrastructure exceeding 100 million euros (Balasch et al., 2019; Victoriano et al., 2016). Therefore, this high-resolution geomorphological map identifying landforms
6. Conclusions

Accurate mapping of geomorphological processes and landforms of the Aran Valley at 1:25000 scale allows a better understanding of the processes that have shaped the alpine landscape of this valley. The glacial landforms are diverse and widespread from the summits to the Garonne riverbed, and reveal that glacial, periglacial, nival, karst, slope, alluvial and fluvial processes have played a role in shaping the landscape of the entire valley. Once glaciers started retreating and thinning following the Last Glacial Maximum, periglacial processes dominated in the exposed ice-free terrain, accompanied by intense slope, alluvial and fluvial dynamics. In specific areas, nival and karstic processes also contributed to reshape the formerly glaciated environment.

Today, the steep slopes surrounding the main valley floor favor the occurrence of slope failures and frequent snow avalanches. In addition, sudden snow-melting episodes and torrential rains trigger also floods. Mapping these processes at a high-resolution improves the precision of the available tools and consequently enhances spatial planning, such as by validating susceptibility maps of geohazards or by promote geoheritage protection and assess geosite management.

Software

The geomorphological map was developed using ArcGIS 10.7.1 (ESRI) software. The final map was improved with Illustrator 16.3.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The data described in this article are openly available at the ZENODO data repository (https://doi.org/10.5281/zenodo.4644265).

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