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Spatial distribution and morphometry of permafrost-related landforms in the Central Pyrenees and associated paleoclimatic implications

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ABSTRACT

Present and past permafrost distribution in the Pyrenees is still under discussion. As in other mid-latitude mountain regions, rock glaciers and protalus lobes are the main indicators of permafrost conditions. In this paper we examine the distribution of these landforms in Aran and Boí valleys, formerly glaciated U-shaped valleys ranging from 600 to 3000 m in the southern and northern sides of the Central Pyrenees, respectively. The spatial distribution of these landforms and their chronostratigraphic position within the valley allow a better understanding of the climatic and environmental conditions necessary for their development. Up to 151 permafrost-related landforms were identified in the Boí valley, including 56 rock glaciers and 95 protalus lobes. In the case of the northern Aran valley, 76 rock glaciers and 89 protalus lobes were cataloged corresponding to 165 landforms. Most of the landforms (93% for rock glaciers and 95% for protalus lobes) are located inside the glacial cirques, with a few distributed in the slopes of the formerly glaciated valleys. The lowest elevation of rock glaciers is situated at 1744 m (Aran) and 2007 m (Boí), whereas the lowest protalus lobes are located at 1740 m and 2033 m, respectively. Therefore, this altitude may be indicative of the lowest level recording permafrost conditions during the period in which these landforms formed, with paleotemperatures ca. 7-8 °C lower than present-day. Between 60 and 70% of the protalus lobes and rock glaciers are located between 2300 and 2600 m in Boí valley and 2100 and 2400 m in Aran valley. The aspect shows a prevailing orientation of NW, N and NE for both cases of rock glaciers and protalus lobes, being almost absent in the S, SE and SW aspects. The average slope of both landforms lies between 11 and 27°, with a maximum of 35° for rock glaciers and 29° for protalus lobes. The amplitude/length ratio reveals that rock glaciers placed at lower altitudes are more elongated. The chronostratigraphic position of these landforms within the valley and with respect to the moraine complexes suggests the existence of three generations of permafrost-related landforms which are associated to the massive deglaciation process between the maximum glacial advance of the Last Glaciation and the Holocene.

1. Introduction

Cold geomorphological processes in the mountains of the relatively warm Mediterranean region, an area with high interannual and intraanual climate variability are limited to the highest mountains. Here, small changes in temperature and/or moisture regime may alter the spatial domain affected by permafrost conditions and the type and intensity of associated geomorphological processes. Mediterranean mountains, such as the Pyrenees where this research focuses, encompass a wide range of landforms and sedimentary records that may include valuable paleoclimatic and paleoenvironmental data that can provide information about environmental dynamics since the Last Glaciation until nowadays.

Rock glaciers and protalus lobes are common features in polar regions and alpine environments with similar characteristics

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generated by permafrost creep, such as arcuate ridges and furrows aligned, in general, perpendicular to the flow direction (Barsch, 1977; Giardino and Vitek, 1988; Serrano et al., 1999; Whalley and Azizi, 2003; Matsuoka et al., 2005; Haeberli et al., 2006; French, 2007; Tampucci et al., 2017). They constitute the main geomorphic indicators of permafrost conditions in many mid- and low-latitude mountain environments, such as in the Mediterranean region (Serrano, 1996; Gómez-Villar et al., 2011; Pellitero et al., 2011; Serrano et al., 2010, 2011). Rock glaciers are depositional landforms characterized by downslope fluxes of a permanently ice-rich debris bodies (Barsch, 1996; Benn and Evans, 1998; Owen and England, 1998). Similarly, protalus lobes are depositional landforms with ice-rich presence, with similar morphology, nonetheless occur in front of talus slopes, on valley walls, with low creep rates and are generally wider than long (Whalley and Azizi, 2003; González-García et al., 2017). An accurate analysis of the distribution of permafrost-related landforms within a mountain range allows reconstructing permafrost history and inferring past climate conditions (French, 2007; Oliva et al., 2016).

Few attempts have been made in the Central Pyrenees to map and characterize the main morphometric characteristics and spatial distribution of these landforms in the Central Pyrenees (Chueca, 1992; Serrano et al., 1999; Pérez-Sánchez et al., 2014), with more studies focus on the monitoring of these features (Chueca and Andrés, 2005, 2011; Serrano et al., 2006, 2011). Traditionally, the development of rock glaciers and protalus lobes in the Pyrenees was associated with dry climate conditions, which impeded the formation of glaciers (Vilaplana, 1983). Recently, new findings point to the key role of paraglacial processes in their development, showing that most of the currently inactive features formed following the massive deglaciation occurred during the Bølling-Allerød (14.7–12.9 ka) (Palacios et al., 2015b; Andrés et al., 2015; submitted). The identification of the type and origin of these landforms is crucial to infer paleoclimatic conditions, since as permafrost indicators their presence suggests mean annual temperatures below −1.5 °C (Whalley and Azizi, 2003; González-García, 2014). Therefore, their distribution at different environments and elevations within a mountain range may be also indicative of the succession of permafrost conditions since the deglaciation of the area (Brenning, 2005). For example, in the Pyrenees several generations of rock glaciers have been attributed from the LGM to the Little Ice Age (LIA) (Serrano, 1998; Serrano and Agudo, 2004; Serrano et al., 2011; Andrés et al., 2015).

Based on the distribution of periglacial deposits, as well as the location of rock glaciers and protalus lobes in non-glaciated mid slopes, permafrost during the Last Glaciation may have reached elevations down to 1100 m in the Pyrenees (Oliva et al., 2016). Since then, and following glacial retreat, permafrost regime has receded in extension, shifting to higher elevations between 2250 and 2490 m during the Oldest Dryas (17.5–14.7 ka) (Bordonau, 1992; Chueca et al., 1994; Hirsch and Raab, 2014) and above 2525 m during the Younger Dryas (12.9–11.7 ka) (Serrano, 1998; García-Ruiz et al., 2015; Hirsch et al., 2010). During the Holocene permafrost degradation reached higher areas and only the highest Iberian massifs included discontinuous patches of permafrost (Oliva et al., 2016). Serrano et al. (2011) suggested that the formation of rock glaciers in the Central Pyrenees above 2560 m started at 6 ka and 2.5 ka, reactivating during the LIA. At present-day, based on geomorphological observations, BTS measurements and geomatic techniques Serrano et al. (2006, 2010, 2011) established the limit of permafrost above 2630 m in north-facing areas and 2800 m in south slopes (Serrano et al., 2011; Oliva et al., 2016), with 13 active rock glaciers above 2600 m (Lugon et al., 2004).

This research focuses on Boí and Aran valleys, two formerly glaciated valleys in the Central Pyrenees. The objective of this paper is to examine the distribution and morphometric characteristics of the rock glaciers and protalus lobes existing in these valleys in order to provide insights on the past environmental conditions in the area and its subsequent evolution. This will be achieved by responding to the following specific objectives:

- Identify the main geographical factors controlling the development of permafrost-related landforms in the Central Pyrenees.
- Examine if the aspect (i.e. climate regime) influences different morphometrical and topographical characteristics of these features in the southern (Boí valley) and northern sides of the Pyrenees (Aran valley).
- Reconstruct the sequence of climatic and environmental stages favourable for the formation of rock glaciers and protalus lobes in the Central Pyrenees.

2. Study area

The Pyrenees is an extensive mountain range located at latitude 42º-43° stretching along 450 km from the Atlantic Ocean to the Mediterranean Sea. This range constitutes a geographical and climatic boundary, which condition the geoecological processes prevailing within the mountain range and the surrounding lowlands. This research focuses on two valleys in the Central Pyrenees: Boí and Aran valleys (Fig. 1).

Boí is U-shaped glacial valley drained by the Noguera de Tor river, with a prevailing NE-SO exposure, encompassing a surface of 247 km^2. Aran is also a classical U-shaped valley extending over 550 km^2 with the Garonne river flowing SE-NW to the Atlantic. Comaloforno (3029 m) and Besiberris (3023 m) constitute the highest peaks from both valleys, whereas the lowest elevations reach 850 and 600 m, respectively.

The Pyrenees act as a barrier to the atmospheric circulation, provoking N-S and E-W asymmetries. Present-day climate conditions are characteristic of Pyrenean high mountain environments, with Atlantic climatic influence in Aran valley and Mediterranean influence in Boí valley. High altitude meteorological stations recorded between 2009 and 2014 a mean annual temperature of 2.7 °C and a precipitation of 1200 mm in Aran (2266 m) and 1.7 °C and 1200 mm (2535 m) in Boí.

Geologically, Boí valley is divided in three major Paleozoic units: granites are abundant in the upper part, while most of the valley is composed of limestones and shales, with the exception of the Taüll area where there are alternating sandstones and shales. Aran valley is made of igneous intrusive outcrops (granites) surrounding the headwaters, while sedimentary rocks such as carbonated (limestones) and detrital rocks (sandstones, and conglomerates) are distributed across the plateaus and valley bottoms. There are also slates. The valley infills in both areas include deposits of glacial, periglacial and fluvial origin that have affected the study area during the Quaternary.

The landscape in both valleys is a consequence of both glacial processes as well as post-glacial environmental dynamics. During the Maximum Glacial Extent (MIE) of the Last Glaciation the glacier in Boí filled of ice its valley but did not connect with the Noguera Ribargorçana glacier; its front reached 890 m and based on several erosion and accumulation glacial landforms an estimated maximum glacier thickness of ca. 600 m was inferred (Vilaplana, 1983). Aran valley was heavily glaciated during the MIE and constituted the upper part of the Garonne glacier, with a maximum ice thickness of 835 m (Fernandes et al., 2017).

The vegetation is representative of the Eurosiberian environment, with the treeline located at ca. 2200–2300 m. Therefore,

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