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Chronological and geomorphological investigation of fossil debris-covered glaciers in relation to deglaciation processes: A case study in the Sierra de La Demanda, northern Spain

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A B S T R A C T

In this study, fossil debris-covered glaciers are investigated and dated in the Sierra de la Demanda, northern Spain. They are located in glacial valleys of approximately 1 km in length, where several moraines represent distinct phases of the deglaciation period. Several boulders in the moraines and fossil debris-covered glaciers were selected for analysis of ^{10}Be surface exposure dating. A minimum age of 17.8 ± 2.2 ka was obtained for the outermost moraine in the San Lorenzo cirque, and was attributed to the global Last Glacial Maximum (LGM) or earlier glacial stages, based on deglaciation dates determined in other mountain areas of northern Spain. The youngest moraines were dated to approximately 16.7 ± 1.4 ka, and hence correspond to the GS-2a stadial (Oldest Dryas). Given that the debris-covered glaciers fossilize intermediate moraines, it was deduced that they developed between the LGM and the Oldest Dryas, coinciding with a period of extensive deglaciation. During this deglaciation phase, the cirque headwalls likely discharged large quantities of boulders and blocks that covered the residual ice masses. The resulting debris-covered glaciers evolved slowly because the debris mantle preserved the ice core from rapid ablation, and consequently they remained active until the end of the Late Glacial or the beginning of the Holocene (for the San Lorenzo cirque) and the Holocene Thermal Maximum (for the Mencilla cirque). The north-facing part of the Mencilla cirque ensured longer preservation of the ice core.

1. Introduction

A debris-free glacier becomes a debris-covered glacier when supraglacial debris, delivered by a combination of mechanisms such as avalanching and rock fall, cover 50% or more of the ablation zone (Kirkbride, 2000, 2011; Brenning, 2005; Azócar and Brenning, 2010), and the thickness of supraglacial debris layer, which normally increases towards the glacier snout, is more than 0.5 m (Whalley, 2004; Hambrey et al., 2008; Monnier and Kinnard, 2015). Despite this definition, the separation between debris-free and debris-covered glaciers is typically not clear, and the genetic processes that trigger the transition from debris-free to debris-covered glaciers is still debated (Berthling, 2011; Janke et al., 2015). Differentiating debris-covered and rock glaciers is also difficult because there is no agreed definition of a rock glacier (Hamilton and Whalley, 1995a,b; Berthling, 2011; Janke et al., 2015). Rock glaciers are considered to have a thicker surface rock layer compared

Abbreviations: LGM, Last Glacial Maximum; OD, Oldest Dryas; YD, Younger Dryas; CED, Cosmogenic Exposure Dating; ELA, Equilibrium Line Altitude; HTM, Holocene Thermal Maximum; AAR, Accumulation Area Ratio; AABR, Area Altitude Balance Ratio; AWMA, Area-Weighted Mean Altitude.

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with debris-covered glaciers, for which the ice content is estimated to be 40–70% of the total mass (Haeberli et al., 2006). However, in some cases rock glaciers develop at the front of debris-covered glaciers (Janke et al., 2015; Monnier and Kinnard, 2015; Andrés et al., 2016), as the environment shifts from glacial to periglacial. Berthling (2011) noted that some authors use the terms "debris-covered glacier" and "rock glacier" interchangeably (e.g. Konrad and Clark, 1998), and that it is difficult to "draw the line" between these two glacier types if there is a continuum between a glacial and a periglacial origin of rock glaciers.

The difficulties in distinguishing rock glaciers from debris-covered glaciers increase markedly when they become fossil, i.e. the inner ice has melted, and they tend to evolve into convergent landforms involving large accumulations of coarse material arranged chaotically. It is almost impossible to determine the initial ratios of ice and debris when studying fossil debris-covered and/or rock glaciers. One approach is to assess differences in surface morphology. For instance, ridges of debris-covered glaciers tend to be more longitudinal, and lateral and central moraines are evident and do not show viscous flow morphology (Clark et al., 1994). Also, thermokarst morphology is common in debris-covered glaciers, which favors the development of great depressions and lakes (Richardson and Reynolds, 2000; Hambrey et al., 2008), whereas spoon-shaped depressions commonly occur associated with rock glaciers (Janke et al., 2013).

Rock glacier morphology is defined by the occurrence of pronounced transverse ridges and furrows perpendicular to the flow direction (Capps, 1910; Wahrhaftig and Cox, 1959; Martin and Whalley, 1987; Vitek and Giardino, 1987; Barsch, 1992, 1996; Whalley and Martin, 1992; Hamilton and Whalley, 1995a, 1995b; Haeberli et al., 2006; Berthling, 2011; Janke et al., 2013). The transverse ridges originate from over-thrusting of internal shear planes, differential movement of distinct layers, or changes in debris supply, while lateral ridges originate by resistance to flow, or from remaining moraines, and meandering furrows are also common (Wahrhaftig and Cox, 1959; Potter, 1972; Barsch, 1987, 1996; Whalley and Martin, 1992; Degenhardt, 2009; Janke et al., 2013). A steep front is also common in advancing rock glaciers (Wahrhaftig and Cox, 1959; Martin and Whalley, 1987; Hamilton and Whalley, 1995b; Janke et al., 2013, 2015).

Janke et al. (2015) recently proposed a classification scheme for various types of debris-covered and rock glaciers, based on surface morphology and measurements of ice content. In this scheme the glacier types (uncovered, debris-covered and rock glaciers) are considered to be stages in a continuum of landforms derived from the degradation of valley glaciers, following a model proposed by Johnson (1980) and Giardino and Vitek (1988), among others. The evolution of a glacier into a debris-covered glacier and to a rock glacier is characterized by a reduction in the proportion of internal ice in relation to the volume of the supraglacial and englacial deposits, and a reduction in the flow (Janke et al., 2015). This transformation is accompanied by a clear change in the surface morphology and the ice crystallography from sedimentary and super-saturating permafrost ice (Janke et al., 2015).

A continuum in the transformation of glaciers to debris-covered and rock glaciers has only rarely been directly observed in the field, but cases exist in the Himalayas (Shroeder et al., 2000), the Andes (Emmer et al., 2015; Monnier and Kinnard, 2015), and the Alps (Seppi et al., 2015). All these cases confirm the hypothesis of Ackert (1998), i.e. the transformation from debris-covered to rock glacier occurs in the context of glacial recession, when the Equilibrium Line Altitude (ELA) is rising.

Furthermore, the usually complex evolution of rock glaciers and debris-covered glaciers makes it difficult to determine the point of stabilization (Barsch, 1996; Haeberli et al., 2006), particularly because of the slow ablation and flow of the inner ice (Juen et al., 2014; Krainer et al., 2014; Collier et al., 2015). Haeberli et al. (2003) synthesized the most useful methods for dating fossil rock glaciers, including: (i) dating of lacustrine sediment overlapped by rock glaciers (Paasche et al., 2007); (ii) direct traditional methods, including the Schmidt hammer, which are supposed to provide minimum ages for stabilization of the rock formations (Matthews et al., 2013); (iii) lichenometry, which is appropriate for determining the age of stabilization of rock glaciers that were active until relatively recent times (Rosenwinkel et al., 2015); (iv) luminescence methods, which are also applicable to alpine rock glaciers (Fuchs et al., 2013); and (v) cosmogenic exposure dating (CED), which has in recent years been used to date rock glacier stabilization, e.g. in Scotland (Ballantyne et al., 2009) and the Alps (Hippolyte et al., 2009). CED methods have also been useful in dating rock avalanches that occurred on active debris-covered glaciers (Deline et al., 2015; Mackay and Marchant, 2016), particularly as the ice in rock glaciers and debris-covered glaciers can be 10 ka to > 1 million years old (Krainer et al., 2014; Bibby et al., 2016). This fact can explain that boulders over stable ice receive cosmic radiation before the definitive fossilization of rock glaciers and debris-covered glaciers (Mackay and Marchant, 2016). No or very limited information is available on the age of fossil debris-covered glaciers.

Only few studies exist so far on the origin and development of fossil rock and debris-covered glaciers in the Iberian Peninsula and their significance in relation to the processes of the last deglaciation period. While the global Last Glacial Maximum (LGM) (26–20 ka; Hughes et al., 2013), corresponds to the timing of greatest extent of both the Northern Hemisphere ice-sheets and the mountain glaciers (e.g. Ivy-Ochs et al., 2009; Federeici et al., 2011; Hippe et al., 2014; Giraudi, 2015; Ivy-Ochs, 2015), studies in most Mediterranean mountains have revealed that a maximum glacial expansion occurred before the global LGM, probably coinciding with marine isotope stage (MIS) 4 (approximately 65–60 ka) or MIS 3 (approximately 35–30 ka). This could be explained by their position further south compared to Northern Hemisphere Ice-Sheets and the Alps, the latitudinal migration of the Intertropical Convergence Zone (Tzedakis et al., 2009; Fletcher et al., 2010), and the prevailing negative North Atlantic Oscillation conditions (Alves Martins et al., 2015). Studies in the Iberian Peninsula have shown that glaciers did not reach their maximum extent during the LGM in the Pyrenees (García-Ruiz et al., 2003, 2013; González-Sampériz et al., 2006, 2017; Delmas, 2015) and the Cantabrian Mountains (Jiménez-Sánchez and Farias Arquer, 2002; Jiménez-Sánchez et al., 2013; Rodríguez-Rodríguez et al., 2016). Nevertheless, there is direct and indirect evidence of glacier growth during the LGM in most Iberian mountains (e.g. Andrés and Palacios, 2014; Oliva et al., 2014; Carrasco et al., 2015; Delmas, 2015; Gómez-Ortiz et al., 2015).

The formation of the Iberian rock glaciers is associated with the rapid and intense deglaciation processes following the Late Glacial advances, as occurred in the eastern Alps (Kellerer-Pirklbauer et al., 2012). The Older and the Younger Dryas (YD) stadials represented the occurrence of short periods of glacier expansion in the Iberian mountains (García-Ruiz et al., 2016a; Palacios et al., 2016a). During the Oldest Dryas (OD, GS-2a; 17.5–14.5 ka) glaciers reoccupied valley floors, although the glacier lengths were considerably shorter than those during the LGM (Palacios et al., 2016a). The use of CED methods has recently shown that a number of rock glaciers developed at the end of the OD and the beginning of the Bølling/Allerød interstadial (15–13.5 ka) in deglaciated cirques, particularly in the Cantabrian Mountains (Rodríguez-Rodríguez et al., 2016), the Pyrenees (Palacios et al., 2015a, 2015b), and the Sierra Nevada (Oliva et al., 2016; Palacios et al., 2016a, 2016b). Similar