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GLACIAL EVOLUTION OF SIERRA NEVADA (SPAIN) AND THE ORIGIN OF ROCK GLACIARES

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I. INTRODUCTION

In spite of considerable advances in the knowledge and understanding of the glacial chronology of southern Europe, some very significant mountains still have to be studied. These include the Sierra Nevada, the highest mountain range in the Iberian Peninsula, located in the extreme south-east, only 170 km from Africa, where the last glaciers disappeared last century. The aim of this paper is to present a chronology of deglaciation from the Sierra Nevada based on geomorphological analysis of glacial and periglacial landforms and on ^{36}Cl surface exposure dating, then to relate it to the historical Little Ice Age (LIA) deglaciation process reconstructed from field data and historical documentary sources.

II. METHODS

First, a detailed geomorphologic survey was carried out of the glacial forms and rock glaciers in three of the main glacial valleys with contrasting orientations around the summit of the Sierra Nevada: the head of the Poqueira valley, on the south slopes of the Pico Mulhacén, and the Dílar and Monachil valleys on the western slopes of the Pico del Veleta. The resulting map helped in identifying the most stable and suitable sites to sample for ^{36}Cl dating.

Samples were collected using hammer and chisel from moraine and rock glacier boulders >1 m-high standing on stable, gently sloping surfaces. Samples were also taken from well-preserved glacial polish on bedrock steps, aiming at spots with a protrusive morphology (to reduce the possibility of a sediment cover and to minimize the effect of snow cover); a clear glacial polish (to ensure that the rock has not been eroded since deglaciation); and located where the former glacier was thick (thus maximizing erosion of the pre-glacial surface and minimizing the chances of ^{36}Cl inheritance).

The $^{36}Cl/Cl$ and $^{37}Cl/^{35}Cl$ ratios were measured on AgCl targets by AMS at PRIME Laboratory (Purdue University). Aliquots of rocks were powdered and analysed for major elements by fusion inductively coupled plasma, trace elements by mass spectrometry, and boron by PGNAA, at Activation Laboratories (Ancaster, Canada). Exposure ages were calculated assuming erosion rates of the rock surface of 0 (no erosion), 3 and 5 mm/kyr.

III. RESULTS

The relief of the Sierra Nevada, like most other glaciated mountains in Europe, shows signs of significant glaciation during the late Pleistocene. The phase, which produced well-defined and large-scale moraines, is called Last Local Glacial Maximum Advance (LLGM) in this paper. However, the geomorphologic study carried out recently in the Sierra Nevada shows that remains of moraine formations older than the LLGM exist in some valleys, although poorly preserved and of limited use for cosmogenic dating.

Our results do not provide conclusive information on the age of the LLGM. In the three valleys sampled some boulders from LLGM moraines (SECO-M-1; MONA-M-1) yield ages which seem too young, in particular when compared to ages from glacial polish located near the headwalls (SECO-BR-4; DILAR-BR-5). However, other moraine boulders from LLGM moraines (MONA-M-2; SECO-M-3) yield ages close to the LGM. This is a common problem in cosmogenic dating of moraine boulders (Zreda and Phillips, 1994; Putkonen and Swanson, 2003), not surprising considering the intense postglacial hillslope dynamics on the Sierra Nevada.

The ages of samples MONA-M-2 (19.0 ka), SECO-M-3 (19.3 ka) and MUL-M-2 (30.0 ka), belonging to three moraine segments from different valleys, suggest that the LLGM of the Sierra Nevada can be considered as proximal to the Global Last Glacial Maximum.

In the Sierra Nevada, between the LLGM moraines and the highest bedrock steps, there are younger moraines, highly dispersed and not easy to correlate between different valleys. Chronological data for these is not yet available. The results from five glacially polished bedrock steps indicate deglaciation reaching the headwalls of different valleys between 15.4 and 12.0 ka.

Once deglaciated, the Sierra Nevada valleys still retained small ice masses or large snow fields inside the highest cirques, such as the one which occupied what is now Laguna de la Caldera lake, at the head of the Mulhacén valley. However, the most significant feature of these cirques was the development of rock glaciers. Their formation was contemporary with the deglaciation process, as the oldest and largest rock glacier (DILAR-RG-1) became relict more than 12 ka ago, i.e. ~2 ka after the disappearance of the Dílar glacier. In general, these rock glaciers formed lobate bodies. The fronts of these lobes stabilized between 12.0 ka (lowest lobe, 2635 m) and 7.5 ka (highest lobe, 2837 m). Rock glaciers in the Sierra Nevada probably survived until 7.5 – 7.5 ka, i.e. well into the Holocene (DILAR-RG-3). The oldest lobes reached a distance of more than 1500 m from the valley head, e.g. in the Dílar valley, and were cut off from their supply source. Subsequently, new lobes formed from the headwall slope and may have been superimposed on the older ones, within the same climatic cycle.

IV. CONCLUSIONS

The existence of glacial vestiges older than the LGM is evident in the Sierra Nevada, although their precise age still to be determined, a difficult task considering the poor state of preservation of most of the moraines. There are well-preserved lateral moraines similar to moraines identified as originating from the LGM in other European mountains. Although a few ^{36}Cl exposure ages from such moraines have been obtained, their chronological results are not yet conclusive. Samples from moraine boulders that we consider reliable yield ages ranging from 30.0 ka (MULH-M-2, valle de Mulhacén) to 19.0 ka (SECO-M-3, valle de Monachil), although some boulders from the same moraines yield substantially younger apparent ages. Moraine formations younger than the LGM can also be found in all the valleys of the Sierra Nevada, but these have not been dated so far.

The retreat of glaciers from the valleys to the headwalls must have taken place rapidly, as the samples obtained from bedrock steps near the cirques show very similar ages in all the valleys, which also indicates that deglaciation was widespread. Deglaciation was in progress around 15.4 ka (DILAR-BR-5), and by 14.6 ka (MULH-BR-4) the process had reached the cirques. Only at the base of cirque headwalls did small glaciers or permanent snowfields continue to exist, which promoted the formation of rock glaciers. The dates obtained from them indicate that they were active between 12.0 ka and 7.5 ka (DILAR-RG-1; DILAR-RG-3).

The rock glaciers of Sierra Nevada were formed immediately after the deglaciation of the valleys, as a result of climatic conditions which favoured the development of cryoclastic rock fragmentation processes. They are 'glacier-derived' rock glaciers. They are always found at the foot of walls well-supplied with snow. These factors reduce the relevance of climatic criteria in relation to the ground temperature distribution. For this reason, the existence of different generations of rock glaciers is not a solid argument for delimiting cold wet phases in this mountain, as might have been expected. In general terms, the last rock glaciers in Sierra Nevada may have become relict by 7.5 ka ago. At present, there is only one rock glacier still active, in the Corral del Veleta, although it is in an advanced process of stabilization. Its origin is linked to the disappearance of the last glacier from the Sierra Nevada at the end of the LIA.