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The deglaciation of the Ésera valley since the Maximum Ice Extent in the Pyrenees

La deglaciación del valle del Ésera desde la Máxima Extensión del Hielo en los Pirineos

Ixeia Vidaller[1*], Ana Moreno[1], Penélope González-Sampériz-[1], Sergi Pla-Rabés[2], Toshiyuki Fujioka[3] and Juan Ignacio López-Moreno[1]

[1] Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas (IPE-CSIC), Avda. Montañana, 1005, 50059, Zaragoza, Spain.
ixeia@ipe.csic.es, amoreno@ipe.csic.es, pgonzal@ipe.csic.es, nlopez@ipe.csic.es
[2] Unitat d'Ecologia, Department de Biologia Animal, Biología Vegetal i Ecologia, Universitat Autonoma de Barcelona, Plaça Cívica, 08193 Bellaterra, Barcelona, Spain.
sergiplarabes@gmail.com
[3] Centro Nacional de Investigación sobre la Evolución Humana (CENIEH), P.º Sierra de Atapuerca, 3, 09002, Burgos, Spain.
toshiyuki.fujioka@cenieh.es
*Corresponding author

ABSTRACT

The Ésera valley is a narrow U-shape valley located in the Central Pyrenees. It has been modelled by the glacial activity during the Last Glacial Cycle. The combination of several methods as cosmogenic exposure dating of glacial deposits and lacustrine core analyses in the Pllan d'Están proglacial lake has allowed to understand the complex dynamics of the Ésera glacier since the local glacial maximum extension (75 ka ago). After this maximum extension, the glacier retreated according with a warm interval within the Marine Isotope Stage (MIS) 3. A new glacial advance, likely corresponding with the Oldest Dryas (16 ka) was established from cosmogenic dates and subglacial sedimentation in the Pllan d'Están paleolake. From that time to nowadays, the Ésera glacier has retreated very quickly, especially during the Allerød period (13.8 ka). During the Little Ice Age, the Ésera glacier, divided in several smaller glaciers, left the thickest moraines conserved in this valley.

Key-words: *Pyrenees, geochronology, paleoclimate, last deglaciation, glaciers.*

RESUMEN

El valle del Ésera es un valle glaciar situado en los Pirineos Centrales, que fue modelado por la actividad glaciar durante el Último Ciclo Glaciar. La combinación de varios métodos como la datación por isótopos cosmogénicos de depósitos glaciares y el análisis de sondeos lacustres en el lago proglaciar de Pllan d'Están ha permitido comprender la compleja dinámica con varios avances y retrocesos del glaciar Ésera desde su última máxima extensión (75 ka). Tras este máximo, el glaciar retrocedió coincidiendo con un intervalo cálido durante el MIS (Estadio Isotópico Marino) 3. Un nuevo avance glaciar fue datado hace 16 ka por isótopos cosmogénicos, llevando al lago de Pllan d'Están a un ambiente subglaciar. Desde entonces hasta la actualidad el glaciar del Ésera retrocedió muy rápidamente, especialmente durante el periodo Allerød (13.8 ka). Durante la Pequeña Edad de Hielo ocurrió el último avance del glaciar del valle del Ésera. Este periodo se reconoce por presentar la morrenas más elevadas y mejor conservadas del valle.

Palabras clave: *Pirineos, geocronología, paleoclima, último deglaciación, glaciares.*

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Introduction

Glaciers are ice masses that change their size and shape depending on the climate, mainly temperature and precipitation, so they are very good indicators of climate changes (Braithwaite and Hughes, 2020). Although nowadays the area of Pyrenean glaciers is very small (<0.5 km^2) and they are restricted to the glacial cirques (Vidaller et al., 2021), thousands of years ago, large glaciers flowed along the Pyrenean valleys (García-Ruiz and Serrano, 2022).

The last maximum ice extension during the Last Glacial Cycle in the Pyrenees was dated at ~60-70 ka (e.g. Lewis et al., 2009), when glaciers reached elevation lower than 800 m a.s.l. (Oliva et al., 2019). After that, the deglaciation of the Pyrenees started, although some minor glacial advances have been identified (González-Sampériz et al., 2006). The Last Glacial Maximum (LGM) at a global scale was a cold period 23 ka ago, probably too dry in the Pyrenees, thus limiting the advance of the glaciers (Allard et al., 2021).

This study intends to summarize the information available of the glacial dynamics in the Ésera valley during the Last Glacial Cycle.

Study area

The Ésera valley is located in the Central Pyrenees (Spain; Figure 1). At the headwaters, the northern slope corresponds with the southern slope of the Maladeta massif, one of the highest massifs in the Pyrenees, which conserved the largest amount of glaciated area. The Ésera valley, with NNW-SSE and SSW-NNE orientation, and a clear U-shape, is mainly composed by granitic rocks modelled by glacial activity. At lower elevations the limestone and shale formations are often covered by glacial (granitic) deposits, such as erratic boulders (Figure 1).

Methods

A detailed geomorphological map of the study area was the first step to determine the succession of glacial deposits (Vidaller et al., 2024a). Once the moraines were identified, 14 samples of

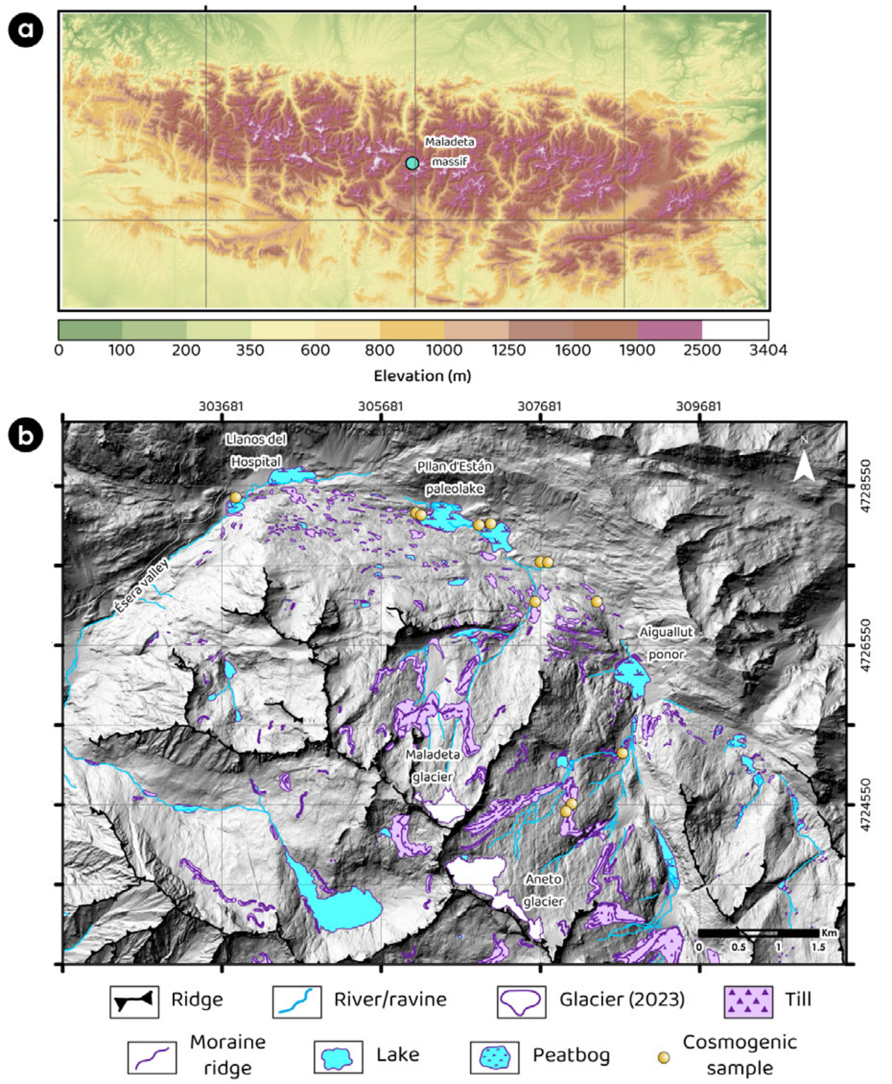

Fig. 1 (a) Location of the Maladeta massif in the Pyrenees. (b) Simplified geomorphological map of the Maladeta massif. Orange dots indicate the location of the cosmogenic samples. See color figure in the online version.

Fig. 1.- (a) Localización del macizo de Maladeta en los Pirineos. (b)Mapa geomorfológico simplificado del macizo de Maladeta. Los puntos naranjas señalan la localización de las muestras de till obtenidas para su datación mediante isótopos cosmogénicos. Ver figura en color en la versión web.

granitic boulders were dated with terrestrial ^{10}Be cosmogenic nuclide exposure dating to determine the glacial phases of the last deglaciation. Results obtained from cosmogenic dating have been combined with the multi-proxy analyses of the lacustrine sequence obtained in Pllan d'Están (1840 m a.s.l., Figure 1b). The sediments were dated with AMS ^{14}C (30 samples) calibrated with IntCall20 ^{14}C curve (Reimer et al., 2020) and OSL/IRSL (4 samples). The sedimentological and geochemical analysis carried out in the lacustrine record from Pllan d'Están include magnetic susceptibility, smear slides observation, X-ray fluorescence, total carbon, total nitrogen and total sulphur determinations, as well as the identification of paleobiological indicators such as pollen and diatoms (a total of 21 palynological and 24 diatom samples). Those results were previously published in Vidaller et al. (2024b).

Results and discussion

A till layer was founded at the bottom of the Pllan d'Están core, dated at 74.9 ka, indicating that at that time that site was covered by ice, corresponding with the time of the maximum glacial extension in other Pyrenean valleys. Therefore, the lake was not yet formed. In other Pyrenean proglacial lakes, glacier fronts were found at elevations lower than 1000 m a.s.l. at that time (Lewis et al., 2009), pointing to a particularity of the Ésera valley.

The lacustrine sedimentary sequence of Pllan d'Están paleolake started at 46.7 ka BP, coinciding with one of the largest interstadial stages within MIS 3 (Rasmussen et al., 2014). The varves and rhythmites observed in the sediment imply that the glacier front was near the lake during this period (Carrivick and Tweed, 2013), Pllan d'Están as a proglacial lake at that time (Figure 2).

The carbonate percentage in the lacustrine sediment decreases after 34.8 ka BP, likely indicating the occurrence of a cold climate (Moreno et al., 2010) and a glacial expansion. These sediments correspond with a subglacial environment, coherent with the cosmogenic dates that determined a position of the glacier front down valley. The palynological results support cold and arid conditions, being *Artemisia* the dominant taxa, matching with the climatic description inferred from lacustrine sequences (Figure 2) (González-Sampériz et al., 2006).

During the LGM there is an increase of the sedimentation rate in Pllan d'Están lake, low taxa variety and poor pollen preservation, resulting from a very cold climate. However, sedimentological characteristics do not imply a glacier advance, in coherence with other Pyrenean valleys (González-Sampériz et al., 2006).

During the Oldest Dryas (~ 17.5-15 ka), arid and cold conditions continued. *Artemisia* and steppe herbs dominated, and the first appearance of *Ranunculus* is in agreement with other regional Pyrenean sequences of high altitude (González-Sampériz et al., 2006; Vidaller et al., 2024b). During this cold period, the Ésera glacier front, as indicated by cosmogenic dating was at 1750 m a.s.l., a similar elevation to other Pyrenean valleys (Delmas, 2015; Palacios et al., 2017).

After this cold phase, a warmer interval started corresponding to the Bølling-Allerød phase (14.8-12.8 ka). Although arid conditions still remained at the beginning, this period implies an increase of temperatures as shown by the expansion of *Artemisia* and the concentration peak of *Juniperus*. Also, the dominance of the pioneering and cosmopolite diatoms indicates an organic-rich environment. The Allerød interval was characterized by warmer and moister climate, characterized by more organic matter in the sediments, higher presence of *Betula,Corylus* and deciduous *Quercus*, lower values of steppe taxa, and the development of aquatic taxa such as *Myriophyllum* (Vidaller et al., 2024b). New cosmogenic dates indicate that the Ésera glacier retreated during this warm interval, especially during the Allerød in a very fast way, from Llanos del Hospital (1750 m a.s.l.) to Aiguallut ponor (1995 m a.s.l.), a total of 5 km in 3 ka (Figure 2). These progressively warmer and moister conditions along the Bølling-Allerød period differs from the typical last deglaciation trend in other European sequences where the transition to the Bølling was abrupt with a gradual temperature decrease during the Allerød.

The Younger Dryas was the last cold stadial before the current interglacial (Rasmussen et al., 2014), but in Pllan d'Están sequence this cold period was only evident by an increase of thycoplanktonic cold-tolerant fragilaroid and post-glacial pioneering taxa (Smol, 2011; Vidaller et al., 2024b).

At the early Holocene (11.7-5 ka), the Ésera glacier was dated by cosmogenic isotopes and was located at 2046 m a.s.l. at 11 ka. The elevations of other Pyrenean glacier fronts at this age were very variable, but all of them between 1700 and 2500 m a.s.l. (Delmas et al., 2015). The Holocene Pllan d'Están sediment is an organic-rich silt deposited in a wetland environment. The vegetation was characterised by high percentages of *Pinus* and *Betula*, similar to other lakes in the Pyrenees (Leunda et al., 2017). The presence of diatoms assemblage was richer and similar to diatoms currently present in other Pyrenean lakes (Vidaller et al., 2024b).

Finally, the Little Ice Age was the last cold period at a global scale before anthropogenic climate change and it was characterized, in the Ésera Valley, with the presence of moraines located at approximately 2650 m a.s.l. Nowadays, Pyrenean glaciers are confined to the cirques and only 10% of the glaciated surface of the LIA remains. Regarding the Aneto glacier, the largest one of the Ésera valleys has lost almost 65% of its surface, and in an average thickness of 30.5 m in the last 40 years (Vidaller et al., 2023).

Conclusions

This study represents a combination of several approaches to determine the Ésera glacier evolution since its last maximum extension 75 ka ago. The combination of dating methods

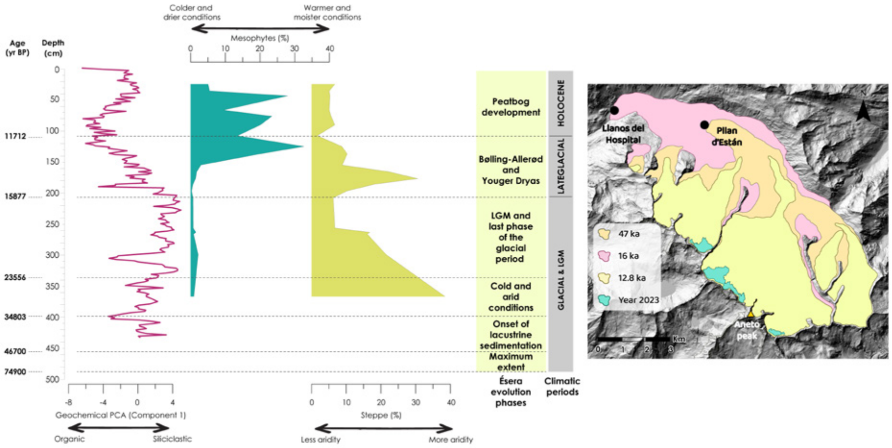

Fig. 2 Sedimentological characteristics and pollen diagram of the Pllan d'Están core. In the middle is indicated the different stages and climatic characteristics of the evolution of the Pllan d'Están lake due to the evolution of the Ésera glacier. At the right, the map shows the evolution of the Ésera glacier during the last 47 ka. See color figure in the online version.

Fig. 2 Características sedimentológicas y diagrama polínico del sondeo de Pllan d'Están. En el centro se indican las diferentes etapas y características climáticas de la evolución del lago Pllan d'Están debido a la evolución del glaciar Ésera. A la derecha, el mapa muestra la evolución del glaciar Ésera durante los últimos 47 ka. Ver figura en color en la versión web.

with sedimentological and geochemical proxies has revealed for the first time in the Pyrenees an alternation between proglacial and subglacial sediments in a lacustrine core. Thanks to the palynological study and the cosmogenic dating of glacial boulders, we have shown differences during the Bølling-Allerød with other European records. Thus, the transition from the Oldest Dryas to the Bølling was gradual in the Ésera valley, reaching the warmest phase during the Allerød.

Author contribution

Structure of the paper: IV, AM, JILM.
Methodology: IV, AM, PGS, SPR, TF.
Data acquisition: IV, AM, PGS, TF, JILM.
Original draft and figures: IV.
Manuscript review: AM, PGS, SPR, TF, JILP.
Supervision: AM, JILM.

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