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Multiproxy reconstruction of Holocene glaciers in Sierra Nevada (south Spain)

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Abstract:	<p>Pleistocene glaciers shaped the highest lands of the National Park of Sierra Nevada, South Spain. Alpine glaciers filled with hundreds of meters of ice the western valleys of the massif. Surface exposure dating show evidence of glacial expansion during the Younger Dryas and the subsequent disappearance of glaciers of the massif during the Early Holocene. Since then, glacial records and lake sediments reveal that the massif has been ice-free most part of the Holocene, with the development of small glaciers during the coldest phases inside the highest northern cirques. This occurred at 2.8-2.7, 1.4-1.2 cal. ka BP, and during the Little Ice Age (1300-1850 CE), when documentary sources confirm also the existence of some glaciers at the foot of the highest summits. This historical period was probably the coldest and wettest phase of the Holocene in the massif, and recorded the largest glaciers of the current interglacial. Those glaciers finally melted away during the mid-20th century.</p>								
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Dear Editors,

The manuscript "Multiproxy reconstruction of Holocene glaciers in Sierra Nevada (south Spain)" submitted to the new journal *Mediterranean Geoscience Reviews* constitutes a review paper focusing on the evolution of glacial processes in Sierra Nevada during the Holocene.

This manuscript comes from the joint effort of several experts that have conducted research on these topics since the early 1990s. We have used three complementing sources of paleoenvironmental information: a wide range of landforms and deposits of glacial origin, lake sediments and historical sources. The analysis of these sources shows evidence of the occurrence of several glacial advances during the Holocene in Sierra Nevada, but also suggest that the massif has been ice-free during most part of the Holocene.

The manuscript includes 5 figures, 2 tables, tens of references, and 6500 words. It has been written following the guidelines of the journal and all authors agree to the publication. It has not been published nor is under consideration for publication elsewhere. Although we are convinced of the value of this manuscript, we are also sure that the comments and suggestions of the referees will add scientific rigor to the research presented here.

Yours sincerely,

Dr Marc Oliva, on behalf of the co-authors

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1- Introduction

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4 As in other mid-latitude mountain regions, Quaternary glaciations shaped the highest lands of
5 the major mountain ranges in the Mediterranean region. The last glacial cycle favoured the
6 development of large mountain glaciers filling the valleys with hundreds of metres of ice. In
7 the Mediterranean region, the deglaciation started at 20-19 ka promoting the shrinking of those
8 glaciers (Clark et al. 2009), which only reappeared during the coldest periods (i.e. Oldest and
9 Younger Dryas) (García-Ruiz et al. 2016; Hughes and Woodward 2016; Palacios et al. 2017;
10 Ribolini et al. 2017). In Sierra Nevada, south Spain, glacial activity followed a similar pattern:
11 glaciers covered 105 km² during the maximum ice extent of the Last Glaciation with several
12 km-long ice tongues flowing down valleys (Palma et al. 2017), but shrank dramatically at 20-
13 19 ka and only expanded during the coldest phases of Termination-1 (Oliva et al. 2014a;
14 Palacios et al. 2016).

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25 The onset of the Holocene was driven by a temperature increase of ca. 10 °C in Greenland and
26 4 °C in western Europe (Clark et al. 2012), in response to higher summer insolation in the
27 Northern Hemisphere (Renssen et al. 2009, 2018), which favoured the melting of most glaciers
28 in southern Europe (Oliva et al. 2019). Periglacial conditions have prevailed in the highest
29 massifs of the Mediterranean region during the Holocene, with permafrost occurrence near the
30 summits during the coldest phases (Oliva et al. 2018b). However, although the Holocene has
31 been traditionally considered as a relatively stable climate period, there is increasing evidence
32 that there have been substantial climate changes (Wanner et al. 2014) that also led to the
33 collapse of some civilisations (DeMenocal 2001; Fagan 2003). Some of these climate shifts
34 brought colder regimes than present (Wanner et al. 2011), which must have conditioned an
35 expansion of cold-climate geomorphological processes in Mediterranean mountains (Oliva et
36 al. 2018), including the reappearance and expansion of glaciers.

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49 In the Iberian Peninsula, the existence of glaciers during the Holocene has been mostly
50 described for the Little Ice Age (LIA), that lasted from 1300 to 1850 CE (Oliva et al. 2018a).
51 Based on geomorphic evidence and historical sources, LIA glaciers were described in the
52 Pyrenees (González-Trueba et al. 2005, 2008), Sierra Nevada (Gómez-Ortiz and Plana-
53 Castellví 2006; Oliva et al. 2014b, a, 2018a; Gómez-Ortiz et al. 2015, 2018) and the Cantabrian
54 Mountains (González-Trueba 2006). However, the occurrence of older glacial phases during
55 the Holocene has been also reported in the Troumouse Cirque (Central French Pyrenees) using
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1 radiocarbon dating on organic fragments (Gellatly et al. 1992), in the closeby Marboré cirque
2 (Central Spanish Pyrenes) with surface exposure dating techniques (García-Ruiz et al. 2014)
3 and in the Mulhacén cirque (Sierra Nevada) based on radiocarbon dating of lake sediment
4 records (Oliva and Gómez-Ortiz 2012).
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9 The objective of this paper is to review our present-day understanding of the impact of
10 Holocene glaciers in the present-day landscape of the highest lands of Sierra Nevada by
11 responding the following questions:
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- 14 - Is the current ice-free situation an unusual pattern during the present-day interglacial in
15 Sierra Nevada?
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- 17 - Did other cold-climate phases detected in the North Atlantic region (e.g. 8.2 ka event,
18 Neoglaciation, Dark Ages) promote the development of glaciers in Sierra Nevada?
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- 20 - What was the magnitude of LIA glaciers when compared to previous Holocene glaciers
21 in Sierra Nevada?
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27 **2- Study area**

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29 Sierra Nevada is the mountain range hosting the highest peaks of the Iberian Peninsula
30 (Mulhacén, 3478 m asl; Veleta, 3398 m; Alcazaba, 3371 m, etc). It is located in its SE corner
31 next to the Mediterranean Sea (37° 03' N / 3° 22' W), and forms part of the Betic Range (Figure
32 1). The landscape of the massif is composed of Paleozoic mica schists strongly affected by the
33 alpine orogeny (Puga et al. 2007). The southernmost Quaternary glaciers in Europe shaped the
34 highest lands of the massif during successive glacial cycles. Glacial activity, typical of mid-
35 latitude semiarid mountain environments, mainly affected the western fringe of Sierra Nevada.
36 The headwaters of ravines and cirques stretching between the Mulhacén and Veleta peaks above
37 1900-2000 m include a great diversity of erosive and depositional features of glacial origin (eg
38 valleys of Lanjarón, Poqueira, Trevélez, Valdeinfierno, Guarnón, Dílar, etc.) that formed
39 between the penultimate glacial cycle and the LIA (Palacios et al. 2019).
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51 **Figure 1**

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55 Currently, there are no glaciers in Sierra Nevada and periglacial dynamics prevail between 2600
56 m and the mountaintops above 3400 m (Gómez-Ortiz et al. 2019). Mean annual air temperatures
57 at 2500 m average 4.4 °C with an annual precipitation of 710 mm, in the form of snow between
58 October and May (Oliva et al. 2014c, b). At the summit plateaus at 3300-3400 m, the mean
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1 annual ground temperature is ~ 0 °C (Oliva et al. 2016a), with negative values in LIA glaciated
2 environments, such as in the Veleta cirque (Gómez-Ortiz et al. 2014). Cold-climate conditions
3 determine ecological dynamics in the highest lands, with poorly developed soils and scarce
4 vegetation cover.
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7 8 9 **3- Methodology**

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12 Following a multiproxy approach using different natural records (glacial features, lake
13 sediments) and documentary sources, we have constrained the spatio-temporal pattern of
14 Holocene glaciation in Sierra Nevada (Figure 2). Natural records include glacial features of
15 sedimentological (moraine, erratic boulders) and erosional origin (polished surfaces). By
16 combining these three sources of palaeoenvironmental information, we have built up the
17 chronological sequence of glacial events that have taken place in Sierra Nevada during the
18 Holocene. Data processing and interpretation has been examined independently for each of the
19 sources.
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29 Figure 2
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32 33 **3.1 Surface exposure dating**

34 Tens of Cosmic-Ray Exposure (CRE) dates have revealed the age of glacial landforms using
35 the isotopes ^{10}Be (Palacios et al. 2019, *in preparation*) and ^{36}Cl (Gómez-Ortiz et al. 2015;
36 Palacios et al. 2016). In this paper, we include some pre-Holocene dates that are useful to
37 constrain the area affected by Holocene glaciations (Table 1). All ages have been recalculated,
38 so that the data treatment is homogenous and ages are thus comparable.
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45 Table 1
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49 The ^{36}Cl ages have been obtained for analysis in whole rock (Phillips 2003) using the
50 spreadsheet for in-situ ^{36}Cl exposure age calculations proposed by Schimmelfennig (2009)
51 and Schimmelfennig et al. (2009), and the production rates for spallation of Ca, K, Ti and Fe
52 described in Schimmelfennig et al. (2011, 2014), Fink et al. (2000) and Stone et al. (2005),
53 respectively. A value of 696 ± 185 neutrons $(\text{g air})^{-1} \text{yr}^{-1}$ was applied as the production rate of
54 the epithermal neutrons from fast neutrons in the land/atmosphere interface (Marrero et al.
55 2016). The elevation-latitude scaling factors for nucleonic and muonic production followed the
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1 scaling model proposed by Stone (2000). The topographic Shielding Factor was re-calculated
2 in the “Topographic Shielding Calculator v.2” belonging to the “CRONUS-Earth” Program
3 (Marrero et al. 2016).
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7 The ^{10}Be ages have been obtained following the beryllium extraction protocol proposed by
8 Merchel and Herpers (1999). The ages have been calculated with the online exposure age
9 calculator (Martin et al., 2017; <http://crep.cirp.cnr.fr>), using the LSD scaling model
10 proposed by Lifton et al. (2014), the ERA40 atmosphere model (Uppala et al., 2005) and LSD
11 geomagnetic database framework (Lifton et al. 2014).
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17 **3.2 Lake sediments**

18 Radiocarbon dating, together with geochemical and grain size properties of sediment records
19 from La Mosca lake, have been also used to infer the temporal patterns of Late Holocene
20 glaciation in the Mulhacén cirque. Further details about the procedures followed for the datings
21 and analysis shown in this paper can be found in Oliva and Gómez-Ortiz (2012).
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28 **3.3 Historical sources**

29 Since the first half of the 12th century until 1947 we have tens of descriptions, sketches, maps,
30 etc. from travellers and naturalists that described that landscape of the highest lands of the
31 massif. A cautious approach to some of these descriptions allows interpreting past geomorphic
32 events occurred in the massif, namely the presence of late-lying snow patches and small glaciers
33 in the highest northern cirques (Gómez-Ortiz and Castellví, 2006; Gómez-Ortiz et al. 2009,
34 2015, 2018; Oliva and Gómez-Ortiz 2012).
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43 **4- Results**

44 A variety of natural archives provide insights about the environmental evolution in Sierra
45 Nevada during the Holocene, including landforms and deposits of glacial origin and lake
46 sediments. In addition, the interpretation of historical documents is also useful to document past
47 geomorphic events occurred in the highest lands of the massif over the last centuries.
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56 **4.1. Surface exposure dating**

57 We have homogenized and recalculated the CRE ages of the landforms existing in the highest
58 cirques of Sierra Nevada (Table 1). These ages suggest that the deglaciation was complete at
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1 the onset of this period. In the lowest cirques, with summits around 2600 m, as in the Hoya de
2 la Mora cirque (Figure 3), the last glaciers formed moraines that stabilized at 11.0 ± 1.0 ka (n
3 = 2), and the CRE age of the polished bedrock located just below the cirque rock wall indicates
4 that ice disappeared shortly afterwards, at 10.7 ± 0.9 ka ($n = 2$). In the headwaters of San Juan
5 valley, with summits around 2900 m, glaciers also melted completely at 10.8 ± 1.0 ka ($n = 3$)
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7 (Palacios et al. 2016).
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10 11 12 Figure 3

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15 A similar pattern was detected in higher cirques located above 3000 m in the southern slope of
16 Sierra Nevada (Figure 4). This is the case of the SW cirque of the Lanjarón valley, where
17 glaciers definitively disappeared at 10.6 ± 0.9 ka ($n = 2$) or in the south-exposed cirque of La
18 Caldera, where the last glaciers melted away at 11.6 ± 0.7 ka ($n = 2$) (Palacios et al. 2016).
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28 In the case of the Mulhacén cirque, the moraines located near the La Mosca lake report an age
29 of stabilization slightly younger than in the other cirques 9.0 ± 0.6 ka ($n = 2$) (Palacios et al. *in*
30 *preparation*). However, the existence of several undated moraine ridges up valleys (at less than
31 300 m from the rock wall), is indicative of other phases during the Holocene with the
32 development of small glaciers across the Mulhacén cirque floor.
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40 The shrinking of glaciers favoured paraglacial activity in the recently deglaciated environments,
41 which led to the development of rock glaciers. These permafrost-related features of glacial origin
42 became inactive between the Early Holocene and the Holocene Thermal Maximum
43 (Palacios et al., 2016). This was the case of the rock glacier existing in the Dílar cirque, which
44 showed different phases of stabilization between 11.4 ± 1.0 ka and 6.4 ± 0.6 ka. In the southern
45 slope, such as in the Río Seco cirque, a rock glacier stabilized at 9.0 ± 0.8 ka, whereas in La
46 Caldera cirque, the same pattern occurred at 6.3 ± 0.5 ka (Table 1).
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54 Therefore, according to the available cosmogenic dates, the only site where neoglacial advances
55 have been detected corresponds to the Veleta cirque. Here, the moraine was built during
56 successive glacier advances during the LIA between the 14th and 17th centuries (Palacios et al.
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2019), though future studies in the Mulhacén cirque may also confirm the presence of a small glacier in the cirque during the Mid-Late Holocene.

4.2 Lake sediments

La Mosca lake, located in the lowest part of the Mulhacén cirque, occupies an overdeepened basin dammed by a moraine. Two boulders of this moraine have yielded ages of 16 to 12 ka (Palacios et al. *in preparation*), suggesting that the lake must, at least, contain paleoenvironmental data covering the entire Holocene. A recent study has dated the basal organic fragments of a sedimentary sequence collected from this lake at 8.4 cal ka BP (Manzano et al. 2019). However, the diamicton was not recovered, and thus this age represents a minimum age of deglaciation at this site.

The biogeochemical properties of the sediments of this lake have been examined to infer the paleoecological evolution of the regional area (Manzano et al. 2019) as well as the past geomorphological processes prevailing in the catchment (Oliva and Gómez-Ortiz 2012). Whereas the first study encompasses the last 8.4 cal ka BP, the second one only includes the last 2.8 cal ka BP. Manzano et al. (2019) described a sequence of vegetation changes driven by both climatic and anthropogenic factors, but did not report the existence of glaciers in the catchment during the last millennia. By contrast, based on geochemical and grain size properties, Oliva and Gómez-Ortiz (2012) clearly detected three events with increased coarse-grained particles, decreased lake productivity as well as lower vegetation cover in the catchment suggesting the existence of a glacier (Figure 5). A colder and wetter climate regime must have favoured the development of a small glacier upstream the lake, at the foot of the north wall of the Mulhacén peak, together with more abundant snow-patches that would trigger more surface runoff, enhanced erosion and sediment remobilization delivering coarser particles into the lake (Oliva and Gómez-Ortiz 2012). These phases were recorded at 2.8-2.7 (G₁), 1.4-1.2 cal ka BP (G₂) and 510 and 240 cal yr BP (G₃) (Figure 5). The magnitude of grain size and organic matter changes in the sediments from La Mosca lake suggest that the last of these phases corresponded to the LIA, which included the largest glacier that has existed at the foot of the highest peak in the Iberian Peninsula over the last three millennia.

Figure 5

4.3 Historical sources

1 A wide range of documentary sources provide information about the cold geomorphological
2 processes prevailing in the summit area of Sierra Nevada since the first half of the 12th century
3 ([Gómez-Ortiz et al. 2009](#)). The character and objectives of such texts varied considerably over
4 time. Whereas the first Arabic manuscripts were basic geographical descriptions of the massif
5 ([Torres-Palomo 1968](#)), the texts from the 18th century were strongly influenced by the Biblical
6 flood theory, and the descriptions of the 19th and early 20th centuries incorporated a clear
7 scientific background (Table 2). These centuries include some of the coldest periods of the LIA,
8 thus the interpretation of those descriptions allows tracing the landscape evolution of the highest
9 lands during the coldest period of the last several millennia in Iberian mountains ([Oliva et al.](#)
10 [2018a](#)).

19 Table 2

23 A common pattern in all documentary sources is the reference to the persistent snow and ice in
24 Sierra Nevada. Some accurate descriptions allow inferring the elevation limits of the periglacial
25 environment as well as reconstructing the evolution of small glaciers located in northern cirques
26 stretching from the Mulhacén to the Veleta peaks during the LIA ([Gómez-Ortiz et al. 2018](#)).
27 The first account revealing the existence of glacial ice was provided by [Ponz \(1797\)](#), who in
28 1754 described perpetual ice and snow in the Veleta cirque. However, it was [Boissier \(1839\)](#)
29 who described these frozen masses as glaciers; he provided a detailed picture of the Veleta
30 glacier, noting that it was the only one existing in the massif and the southernmost in Europe,
31 and stating that it included the same features than those observed in the Alps. Throughout the
32 19th century there are several references to the permanent presence of snow and ice in Sierra
33 Nevada. Some of these descriptions are very precise, providing details about its dimensions,
34 morphometry and ice properties, as well as about its shrinking trend ([Willkomm 1882](#); [Bide](#)
35 [1893](#)) (Figure 6).

49 Figure 6

53 During the 20th century, early geoscientists left written evidence of the accelerated reduction of
54 the glacial ice preserved in the Veleta cirque. Some relates, such as that of [Quelle \(1908\)](#),
55 provided detailed descriptions of the role of topography in the preservation of the glaciers
56 (Table 2). Subsequent accounts documented the gradual decline in extent of the glacier that
57 became progressively buried under layers of debris generated by frost shattering from the
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Veleta peak north wall (Obermaier 1916; García Sainz 1947). Two decades later, Messerli (1965) referring to the Veleta glacier wrote “today we can no longer speak of glacier, however we do not doubt about its existence at the beginning of the 20th century”.

5- Discussion

The National Park of Sierra Nevada encompasses unique cultural and scientific values in the context of Mediterranean semiarid mountains (Gómez-Ortiz et al. 2013a). One of its major attractions is the landscape of the highest lands that was strongly shaped by Quaternary glaciations. During the Last Glaciation, ice extended across 105 km² and flowed down valleys until elevations ranging between 2000 m (north) and 2500 m (south), with the southern valleys including ice tongues up to 10 km-long (Gómez-Ortiz 2002; Palma et al. 2017). After the major deglaciation occurred at 20-19 ka, the coldest phases of Termination-1 saw glacier reappearance in the massif, with ice masses reoccupying the valley floors in northern valleys (Palacios et al. 2016). Glacial advances during the transition towards the Holocene were also detected in other Iberian massifs (Palacios et al. 2011, 2012, 2015, 2017; García-Ruiz et al. 2016), with a similar timing as in other Mediterranean mountains (Akçar et al. 2014; Hughes and Woodward 2016; Ribolini et al. 2017; Sarıkaya et al. 2017).

The global temperature increase recorded during the Early Holocene led to the massive shrinking of mountain glaciers (Clark et al. 2012) as well as to the complete melting of the huge Pleistocene ice sheets that existed in Fenno-Scandinavia (Stroeven et al. 2016) and North America (Stokes 2017). In the Iberian Peninsula, small remnants of Pleistocene glaciers persisted a few millennia sheltered in northern cirques, namely in the Central Range, Iberian Range, Central Pyrenees and Sierra Nevada (Oliva et al. 2019). In the latter case, CRE dating indicates that the highest cirques hosted glaciers until 11.5-10.5 ka (Table 1). As temperatures warmed during the Holocene Thermal Maximum (Renssen et al. 2009), those glaciers disappeared and paraglacial dynamics occupied the formerly glaciated environments, favouring the development of rock glaciers (Gómez-Ortiz et al. 2013b; Oliva et al. 2016b; Andrés et al. 2018).

During the Mid-Late Holocene temperatures have oscillated on the order of ± 2 °C in the North Atlantic region (Mayewski et al. 2004). However, the long-term trend towards decreasing solar insolation in the Northern Hemisphere promoted cooler summers that favoured several episodes of glacial advance in mid-latitude mountains (Solomina et al. 2015). These oscillations are not

1 clearly preserved in the glacial record of Iberian mountains, where, to date, they have been only
2 detected in two ranges. In the Pyrenees, in the still currently glaciated Monte Perdido massif,
3 [García-Ruiz et al. \(2014\)](#) dated Neoglacial advances at 5.1 ± 0.1 , $< 3.4 \pm 0.2$ and 1.4-1.2 ^{36}Cl
4 ka, and in the Troumouse cirque, [Gellatly et al. \(1992\)](#) reported a neoglacial advance at 5 cal
5 ka BP. In Sierra Nevada, Neoglacial glaciation has been inferred using different
6 paleoenvironmental sources (Figure 1), which provide a better overall picture of the sequence
7 of glacial and environmental events occurred during the Late Holocene. Lake sediments
8 confirm the existence of a glacier at the northern cirque of the Mulhacén peak at 2.8-2.7, 1.4-
9 1.2 cal ka BP and 510 and 240 cal yr BP ([Oliva and Gómez-Ortiz 2012](#)) although it has not
10 been yet confirmed by surface exposure dates. The presence of a glacier during the Late
11 Holocene must have been driven by colder and wetter conditions than present, despite the long-
12 term aridity trend detected in other lacustrine records of the massif ([Oliva 2009](#); [Oliva et al.](#)
13 [2010](#); [García-Alix et al. 2017](#)). Based on La Mosca lake record, the cirque has been ice-free
14 during most of the Late Holocene, with a glacier existing in the catchment only less than 20
15 percent of the time of the last three millennia. Late Holocene glacial phases in Sierra Nevada
16 coincided with cold periods in western Europe driven by large armadas of icebergs discharged
17 in the North Atlantic region known as Bond events ([Bond et al. 1997, 2001](#)).

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Despite the chronology of Neoglaciation in many European mountain ranges is still poorly
known ([Matthews 2013](#); [Solomina et al. 2015, 2016](#)), the last two glacial episodes recorded
during the Holocene in the Central Pyrenees and Sierra Nevada were synchronous and took
place during the Dark Ages and the LIA. A recent review on the Dark Ages cold period using
different sources of paleoclimate information across various regions suggests that cold climate
conditions prevailed between 400 and 765 CE ([Helama et al. 2017](#)), which was concurrent with
the glacial advance detected in these two Iberian massifs at 1.4-1.2 ka. In other European
mountains, such as in the Alps, evidence of glacial expansion was also detected during the Dark
Ages ([Wanner et al. 2011](#); [Solomina et al. 2015](#)).

Following the warm episode recorded during the Medieval Climate Anomaly in the Iberian
Peninsula ([Moreno et al. 2012](#)), there was a period of glacial expansion in Sierra Nevada
starting at the end of the 13th century. The construction of the outermost ridge of the moraine
of the Veleta cirque has been dated at 1295 ± 270 CE ([Palacios et al. 2019](#)), which suggests that
climate conditions were then much colder and wetter than during the preceding medieval
period. This moment coincides with the onset of the LIA in Iberian mountains at ca. 1300 CE,

1 as revealed by robust geomorphic and biological evidence (Oliva et al. 2018a). Historical
2 sources confirm the existence of a glacier in the Veleta cirque during the LIA centuries, as well
3 as in the Mulhacén cirque. The comparison of sketches and maps made by naturalists and
4 travellers during those centuries allows tracing the evolution of Sierra Nevada's glaciers (Figure
5 6). Those southernmost glaciers in Europe finally melted during the mid-20th century (Gómez-
7 Ortiz and Castellví 2006; Gómez-Ortiz et al. 2009, 2018), when the last reference to glacial ice
8 in the Veleta cirque was reported (García-Sainz 1947). Their disappearance was determined by
9 the temperature increase recorded in Sierra Nevada since 1850 that has been quantified in ca. 1
10 °C (Oliva and Gómez-Ortiz 2012), comparable to the magnitude of post-LIA warming inferred
11 in other Iberian mountains (González-Trueba; González Trueba et al. 2008; Oliva et al. 2018a).
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20 Although to date no evidence has been reported from other Iberian mountains, it is certainly
21 likely that other high massifs encompassed glaciers during the Holocene: whereas in some areas
22 geomorphic evidence may have not been dated yet, in others it may be difficult to differentiate
23 it from previous Holocene glacial advances (Crest et al. 2017). The absence of moraines
24 between Younger Dryas and LIA complexes may suggest that the terminal moraines developed
25 during the glacial expansion of the last centuries constitute polygenic moraine systems that
26 include sediments deposited by successive Holocene glacial advances. A similar pattern has
27 been described in other mountain environments of the Alps and Norway (Matthews 2013).
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36 The LIA glaciated environments in Iberian mountains are undergoing a rapid process of
37 paraglacial readjustment following their deglaciation (Serrano et al. 2018). In Sierra Nevada,
38 the remnants of LIA glaciers are preserved in the form of ice bodies and permafrost patches
39 buried under a thick debris cover (Gómez-Ortiz et al. 2014). Some permafrost-related
40 landforms, such as protalus lobes and rock glaciers, developed above those subsurface frozen
41 masses, though their degradation in response to warming is accelerating their stabilization and
42 generating subsidence and collapses on the surface debris cover (Gómez-Ortiz et al. 2019). If
43 the present-day warming trend continues, it is expected that the fossil relict ice and permafrost
44 will disappear in the next decades, with the stabilization of the permafrost-related features
45 sitting on them.
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56 **6- Conclusions**

57 Sierra Nevada is one of the best studied massifs with regards to its past glacial history. A wide
58 range of documentary sources and natural records have provided a detailed picture of the past
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1 environmental evolution since the last glacial cycle until nowadays. The landscape of the
2 National Park of Sierra Nevada has been intensely shaped by Pleistocene glaciations, and the
3 last glaciers disappeared in the mid-20th century. Based on cosmogenic dating, lake records and
4 historical sources, we have inferred that: (i) the disappearance of the large Pleistocene glaciers
5 occurred during the Early Holocene, and (ii) the presence of glaciers has been rare during the
6 Holocene, with small features only occasionally reappearing in the highest northern cirques
7 during the coldest phases of the present interglacial, such as the Neoglacial (2.8-2.7 cal ka BP),
8 the Dark Ages cold period (1.4-1.2 cal ka BP) and the LIA (1300-1850 CE). This period has
9 been shown to be the coldest and wettest period of the last millennia and probably of the entire
10 Holocene in the massif. Prevailing climate conditions favoured the development of glaciers in
11 the highest northern cirques stretching from Veleta to Mulhacén peaks. Today, the remnants of
12 those glaciers are buried under the debris cover of the cirques undergoing a rapid process of
13 degradation and are likely to disappear in the near future.
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42 **Conflict of interest**

43 On behalf of all authors, the corresponding author states that there is no conflict of interest.
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Figure captions

1
2 Figure 1. (A) Location of Sierra Nevada in the Iberian Peninsula, and (B), and the distribution of sites
3 reporting glacial activity during the Holocene in the massif based on the recent compilation by (Oliva
4 et al. 2019).
5

6 Figure 2. Examples of the three paleoenvironmental sources used in this research to reconstruct past
7 glacial phases in Sierra Nevada.
8

9 Figure 3. Main glacial features of the highest valleys in Sierra Nevada suggesting glacial activity in
10 Sierra Nevada during the Holocene.
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12 Figure 4. Examples from single valleys.
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14 Figure 5. Phases with presence of a small glacier in the Mulhacén catchment inferred from La Mosca
15 lake sediment properties (modified from Oliva and Gómez-Ortiz 2012).
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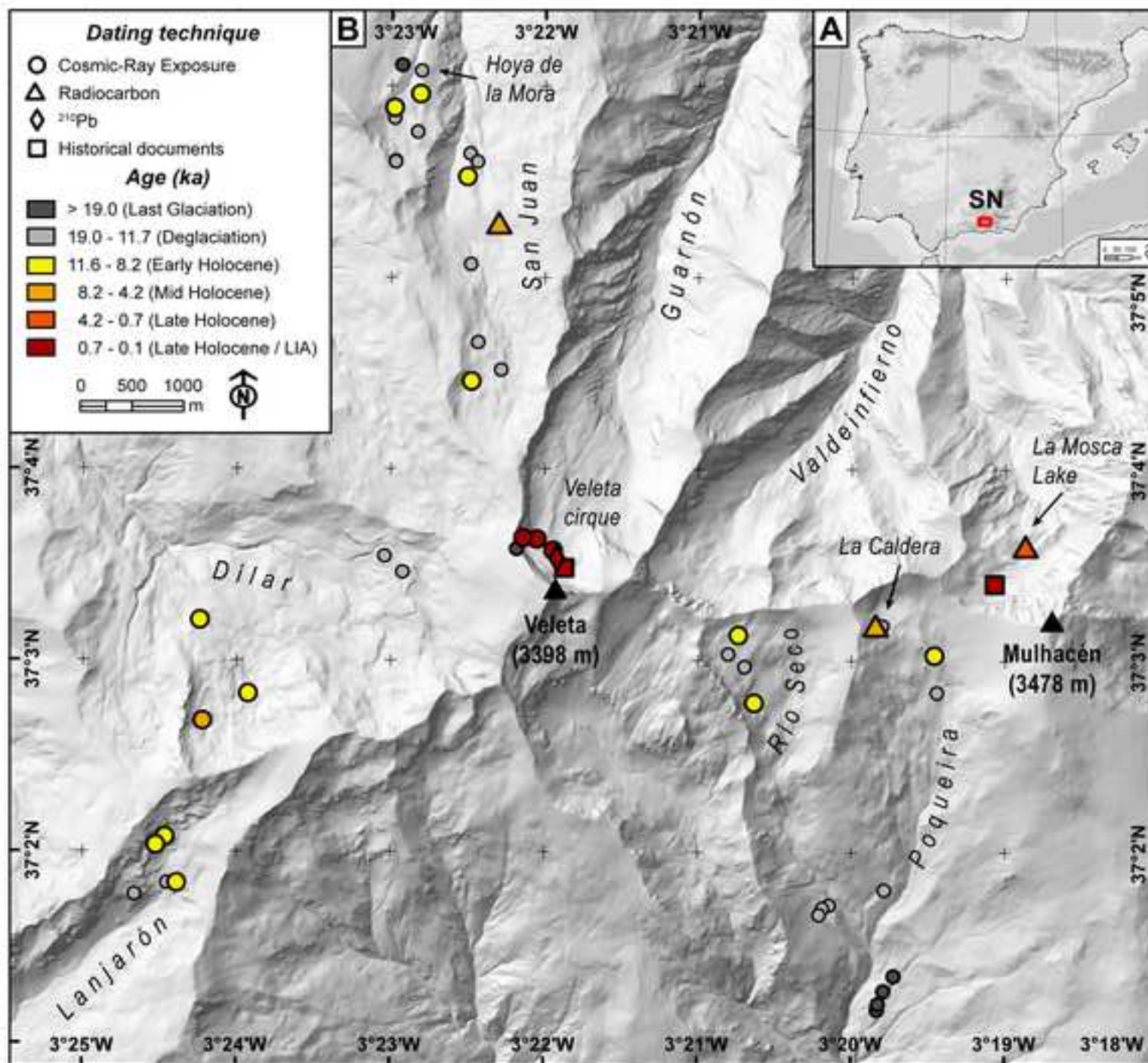
17 Figure 6. Sequence of historical sources allowing tracing the glacial history of the LIA in the highest
18 lands of Sierra Nevada: based on these sources, the glacier located in the Mulhacén cirque must have
19 disappeared during the second half of the 19th century.
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Table 1. CRE ages obtained for Holocene glaciations in Sierra Nevada. These ages have been recalculated following the methodology described in section 3.1.

Sample	Landform	Distance to headwall (m)	Latitude (DD)	Longitude (DD)	Elevation (m a.s.l.)	Aspect	Isotope	Age (ka)	Reference
DILAR-RG-1	Rock glacier boulder	1600	37.0535	-3.4040	2583	NW	³⁶ Cl	11.4 ± 1.0	Palacios et al. (2016)
DILAR-RG-2	Rock glacier boulder	970	37.0471	-3.3987	2784	NW	³⁶ Cl	8.6 ± 0.9	Palacios et al. (2016)
DILAR-RG-3	Rock glacier boulder	600	37.0447	-3.4037	2870	NW	³⁶ Cl	6.4 ± 0.6	Palacios et al. (2016)
SECO-RG-5	Rock glacier boulder	1020	37.0463	-3.3438	2895	S	³⁶ Cl	9.0 ± 0.8	Palacios et al. (2016)
SJ-2*	Moraine boulder	950	37.0743	-3.3746	2834	N	³⁶ Cl	11.1 ± 0.9	Palacios et al. (2016)
SJ-8*	Moraine boulder	2900	37.0921	-3.3751	2391	N	³⁶ Cl	11.6 ± 1.0	Palacios et al. (2016)
SN11- 6	Moraine boulder	1000	37.0993	-3.3802	2341	N	³⁶ Cl	10.9 ± 1.0	Palacios et al. (2016)
SN11- 9	Moraine boulder	820	37.0981	-3.3830	2371	N	³⁶ Cl	10.7 ± 1.0	Palacios et al. (2016)
SN11- 10	Polished bedrock	360	37.0935	-3.3829	2495	N	³⁶ Cl	10.7 ± 1.0	Palacios et al. (2016)
SN11- 11	Polished bedrock	300	37.0934	-3.3829	2499	N	³⁶ Cl	12.0 ± 1.0	Palacios et al. (2016)
MULH-M-1	Moraine boulder	2760	37.0300	-3.3297	2461	S	³⁶ Cl	11.6 ± 0.5 / 11.7 ± 1.0	Palacios et al. (2016)
MULH-BR-3	Polished bedrock	1200	37.0472	-3.3240	2912	S	³⁶ Cl	12.0 ± 0.6 / 12.7 ± 1.2	Palacios et al. (2016)
MULH-M-6	Rock glacier	310	37.0529	-3.3307	3090	S	³⁶ Cl	8.7 ± 0.4 / 6.3 ± 0.5	Palacios et al. (2016)
LAN-1	Polished bedrock	1750	37.0346	-3.4077	2926	SW	³⁶ Cl	10.8 ± 0.9	Palacios et al. (2016)
LAN-2	Rock glacier boulder	1870	37.0339	-3.4087	2931	SW	³⁶ Cl	10.5 ± 0.9	Palacios et al. (2016)
LAN-5	Polished bedrock	1920	37.0306	-3.4064	2872	SW	³⁶ Cl	9.5 ± 0.8	Palacios et al. (2016)
SN-11-1	Moraine boulder	160	37.0596	-3.3657	3076	N	¹⁰ Be	0.32 ± 0.13	Palacios et al. (2019)
SN-11-2	Moraine boulder	265	37.0606	-3.3675	3061	N	¹⁰ Be	0.71 ± 0.22	Palacios et al. (2019)
SN-11-3	Moraine boulder	130	37.0607	-3.3690	3095	N	¹⁰ Be	0.38 ± 0.12	Palacios et al. (2019)
MOSCA-4	Moraine boulder	330	37.0589	-3.3153	2946	N	¹⁰ Be	9.5 ± 0.5	Palacios et al. (<i>submitted</i>)
MOSCA-8	Moraine boulder	360	37.0575	-3.3175	2984	¿Orientación?	¹⁰ Be	10.2 ± 0.3	Palacios et al. (<i>submitted</i>)

Table 2. Some examples about the texts and geomorphological meaning of these relates (adapted from [Oliva and Gómez-Ortiz 2012](#)).

Author (year)	Text	Geomorphological interpretation
Abi Baku al-Zuhri (1137), mentioned in Torres-Palomo (1968)	<i>“There can be found the snow of past years, which, darkened and solid, looks like black stone, but when it is broken open white snow is to be found on the inside. Plants do not grow at the summits of the mountain, nor can animals live there”</i>	Presence of glaciers and abundant snow-patches
Ponz (1754)	<i>“In the Veleta cirque, ..., a gulley filled with snow, considered the first snow that fell after the Flood, turned to stone; as it lies open to the North, here there is ice where in other places there is only snow; and it never melts but for the surface of it, which the Sun discovers”</i>	Presence of a glacier in the Veleta cirque and abundant snow-patches
Boissier (1839)	<i>“The glacier has a very steep slope, and a perpendicular height of 200 or 300 feet, and a width of some 600 paces. The peculiarity of it is that this is the only one in the Sierra and the most southerly in Europe: due to its formation and its position in the depths of a sheltered cirque and dominated in every part by the high peaks where the storms sweep away the snow in the winter. It presents in miniature all the characteristics of the alpine glaciers, clefts, impure ice and muddy moraines. This region (referring to the snowy area) includes all the upper parts of the Sierra Nevada, above 8000 feet. In the Alps at this altitude there may already be perpetual snow, but here nothing similar; however, the snow characterizes our region, although only in the form of patches or drifts that accumulate in the depths and folds of the land...”</i>	Presence of a glacier in the Veleta cirque and abundant snow-patches
Madoz (1849)	<i>“These two lofty mountains, Mulhacén and Veleta, are covered with eternal and hardened snows, with layers or stratifications which can be counted easily. The snow, blown by the wind, which can be found collected in the great repository of these cirques, is petrified to such an extent that it has the consistency of the hardest marble”</i>	Glaciers in Mulhacén and Veleta cirques
Willkomm (1882)	<i>“...I could make out the clear silhouette of the Veleta ice field. Above the Veleta glacier could be seen an enormous and even steeper snowdrift, reaching a very rugged wall almost 500 meters high”</i>	Presence of a glacier in the Veleta cirque and abundant snow-patches
Quelle (1908)	<i>“The Veleta glacier owes its existence solely and exclusively to the fact that it faces north, protected by high walls. The lower edge of the glacier is at an altitude of 2850 m; according to Hellmann, 2845 m; according to Boissier, 2850 m; while I myself set it at 2835 m. It is clear that we cannot use the Veleta glacier to determine the climatic limit of perpetual snow, because it owes its existence only to its extremely favourable location. Only ice fields can provide us with a starting point. On the south face, the average altitude of the lower limit of these ice fields is approximately 3000 m, but on the north face 2850 m”</i>	Presence of a glacier in the Veleta cirque and abundant snow-patches above 2850 m in northern valleys and 3000 m in southern cirques
Obermaier (1916)	<i>“The ice field of Veleta is a mass of dead ice, without movements or fluctuations”</i>	Degradation of the glacier of the Veleta cirque
García-Sainz (1947)	<i>“It presents the same stratigraphic superimposition of layers of snow and bluish ice as can be observed in the glaciers of the Pyrenees”</i>	Last reference to the glacier that existed in the Veleta cirque

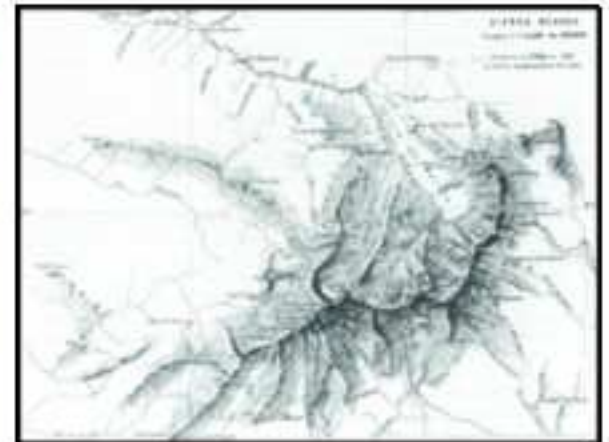




**Boulder sampled for cosmogenic dating
(moraine, Volcán cirque)**

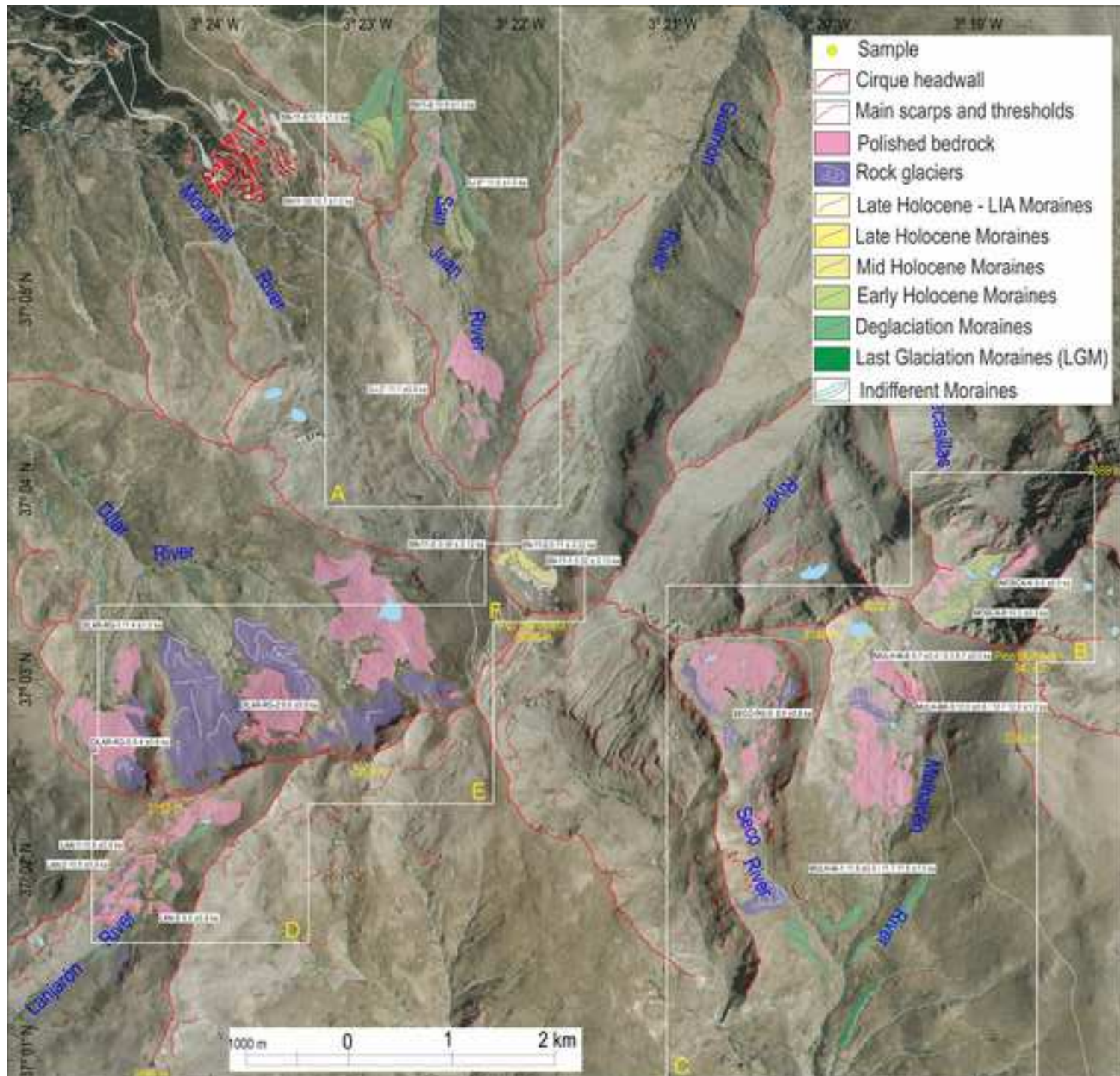


Lake Micocha (La Micocha, Milihuacán cirque)



Historical documents (Bida, 1932)

Figure 3



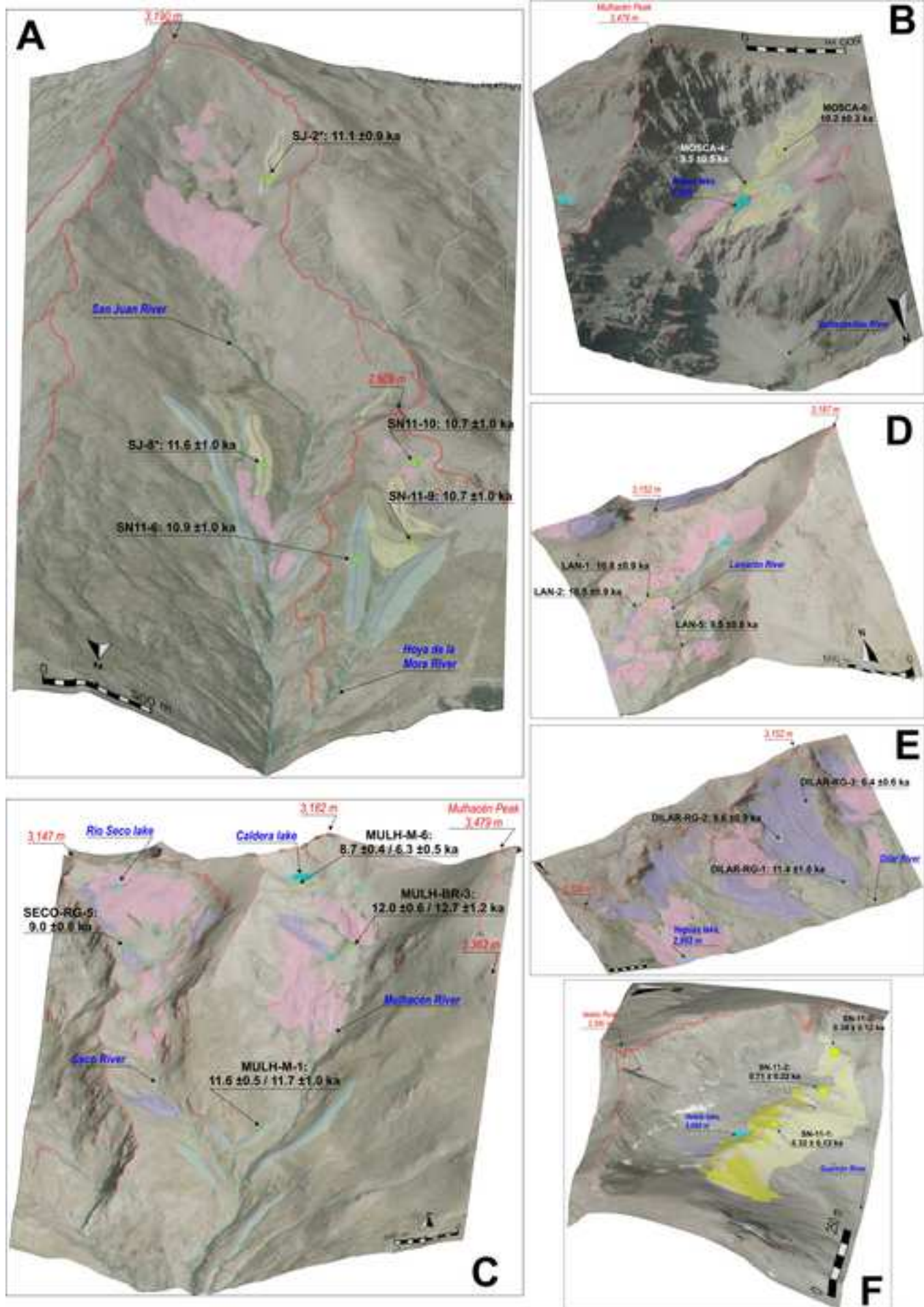
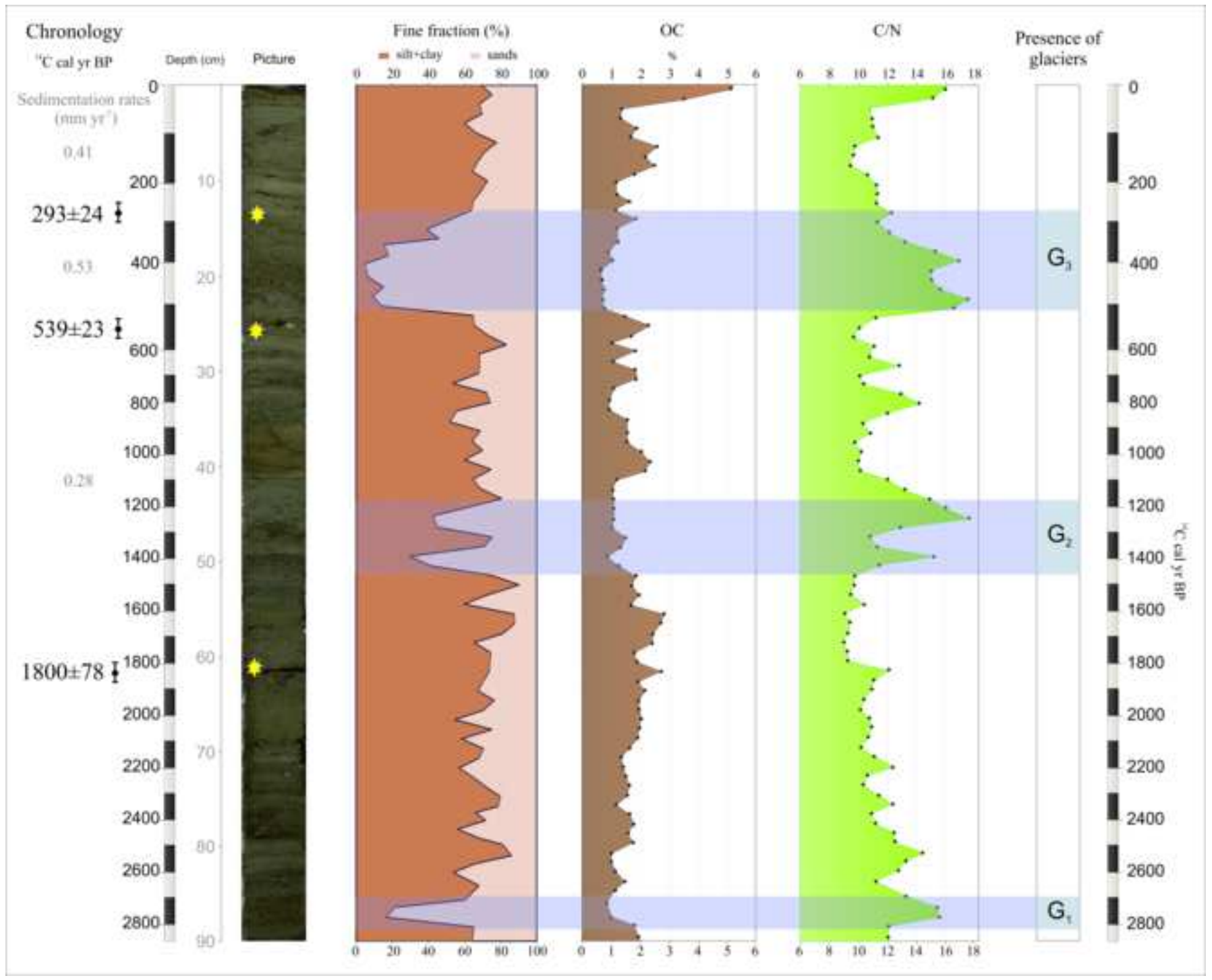


Figure 5

[Click here to access/download;Figure;Figure 5.tif](#)





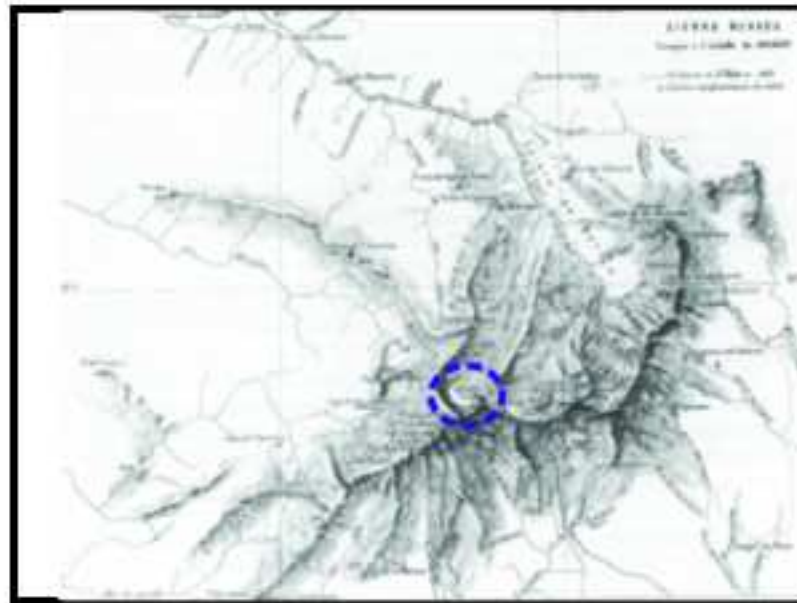
Fernández-Navarrete (1732)



Boissier (1845)



**Glacier in the
Volata cirque**



Bide (1892)



**Glacier in the
Malbacón cirque**