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Bathymetric level fluctuations of laguna turquesa and laguna del peinado (Antofalla, Catamarca) during the late Pleistocene – Holocene

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Resumen: *FLUCTUACIONES DEL NIVEL BATIMÉTRICO DE LA LAGUNA TURQUESA Y LA LAGUNA DEL PEINADO (ANTOFALLA, CATAMARCA) DURANTE EL PLEISTOCENO TARDÍO – HOLOCENO.* Este trabajo examina las fluctuaciones batimétricas de los lagos Turquesa y Peinado (Catamarca) durante el Pleistoceno Tardío-Holoceno, mediante el análisis de depósitos microbialíticos y paleocostas. Con el mapeo de elevación basado en SIG y la datación de los niveles microbialiticos, reconstruimos los cambios hidrológicos pasados y sus determinantes climáticos. Los resultados indican una tendencia de desecación a largo plazo, con tres niveles microbialíticos (M1, M2, M3) en el lago Turquesa y dos en el lago Peinado, lo que sugiere una conectividad lacustre pasada. El nivel microbialítico más antiguo (M1) se formó hace unos 11.830 años. La evaporación se identifica como el principal factor de control de los niveles lacustres, se ha acelerado en las últimas décadas, con tasas de desecación modernas que superan los promedios del Holoceno. Las microbialitas registran tanto cambios climáticos a gran escala como cambios hidrológicos localizados, lo que refuerza su papel como indicadores paleoambientales en ambientes áridos andinos.

Abstract: This study examines the bathymetric fluctuations of Turquesa and Peinado lakes (Catamarca) during the Late Pleistocene – Holocene by analyzing microbialitic depositsand paleoshorelines. Using GIS-based elevation mapping and microbialite dating, we reconstruct past hydrological changes and their climatic drivers. Results indicate a long-term desiccation trend, with three microbialitic levels (M1, M2, M3) in Turquesa lake and two in Peinado lake, suggesting past lake connectivity. The oldest microbialitic level (M1) formed at ~11,830 years BP. Evaporation, identified as the primary control on lake levels, has accelerated in recent decades, with modern desiccation rates exceeding Holocene averages. Microbialites record both large-scale climatic shifts and localized hydrological changes, reinforcing their role as paleoenvironmental indicators in arid Andean environments.

Palabras clave: Microbialitas. Cambio climático. Lagos Andinos. Paleohidrología. Puna.

Key words: Microbialites. Climate. Andean lakes. Paleolakes. Puna.

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Introduction

The Central Andes region, encompassing areas of Bolivia, Argentina, and Chile, hosts high-altitude Andean salt flats and lakes, as well as active volcanoes, creating ideal environments for evaporitic deposits and polyextremophilic microbial communities (Farías, 2020).

Since their discovery, studies on microbialites in the Puna have primarily focused on genetic and microbiological diversity perspectives (Farías *et al.*, 2013; Farías *et al.*, 2014; Rascovan *et al.*, 2016, among others). More recently, microbialites have also been investigated as tools for paleoenvironmental reconstructions (Gómez *et al.*, 2014; Gómez *et al.*, 2018) and for the conservation of microbial ecosystems (Farías, 2017; Vignale *et al.*, 2021).

Microbialites are organo-sedimentary structures formed through the interaction between benthic microbial communities and chemical or detrital sediments, via both trapping and binding of sediments and mineralization resulting from the metabolic activities of microbes or eukaryotic microorganisms (Kennard & James, 1986; Burne & Moore, 1987; Riding, 2011). Lithification occurs when mineral precipitation (commonly calcium carbonate) exceeds dissolution, promoting the preservation of these deposits in the geological record (Dupraz & Visscher, 2005; Dupraz *et al.*, 2009).

The Argentine Puna (Catamarca) has experienced a hydrological crisis in recent decades, as documented in previous literature (Valero-Garcés *et al.*, 2000, 2001). In the study area, these crises have caused fluctuations in lake levels, leading to episodes of connection and disconnection between Turquesa lake and Peinado lake, thereby altering the physicochemical conditions of the environment (Villafañe *et al.*, 2021) while Peinado lake remains partially fed by hydrothermal springs, contributing to a relatively stable water input, Turquesa lake is now isolated and relies solely on limited precipitation (Della Vedova *et al*; 2022; 2025). This disconnection leads to a higher evaporation rate in Turquesa, resulting in increased salinity, conductivity, and concentration of dissolved solids. Such physicochemical stressors not only influence lake hydrology but also affect microbialite development, favoring structures adapted to more extreme, evaporitic conditions (Villafañe *et al.,* 2021; Della Vedova *et al.*, 2022).

In the stratigraphic record of Turquesa lake, Villafañe *et al.* (2021) and Della Vedova *et al.* (2022) identified three Holocene microbialite accumulations along its shore and paleoshoreline (MI, MII, and MIII). Two of these (MI and MII) were observed as paleoshoreline deposits, with individual structures displaying similar external morphologies and internal oncoid-like structures (with diameters of up to 20 cm and 12 cm, respectively). The third accumulation is currently submerged at depths of up to 50 cm, exhibiting a biostromal morphology with an internal structure characterized by alternating parallel laminae. Although Villafañe *et al.* (2021) proposed that each microbialite accumulation represents a different environmental stage of the lake, their hypothesis has yet to be confirmed by a detailed microstructural study.

In addition to the three previously documented levels in Turquesa lake (referred to in this study as MT1, MT2, and MT3), two microbialite levels (MP1 and MP2) were identified in Peinado lake, also exhibiting oncoid morphology and resembling MT1 and MT2.

This study aims to conduct a detailed microstructural analysis of the microbialites from the stratigraphic record of both lakes to assess the extent to which past episodes of lake connection and disconnection influenced microbial colonization. Identifying the primary components of each microstructure and the growth mechanisms that formed them will provide insight into the resilience of microbialite-producing microorganisms in response to environmental and climatic changes. This perspective is crucial for understanding analogous processes throughout Earth's history and even for recognizing potential fossil record reservoirs. The interaction between microbial metabolism, extracellular polymeric substances (EPS) secreted by microorganisms, and the surrounding physicochemical conditions influences the early attributes of carbonate deposits, including macrostructure, depositional texture, and porosity (Dupraz *et al.*, 2006; Harwood & Sumner, 2012; Mata & Bottjer, 2012; Chafetz, 2013; Rezende & Pope 2015; Hickman-Lewis *et al.*, 2019).

Geological setting

The El Peinado lacustrine basin, located in the Antofalla community, Antofagasta department, Catamarca province, Argentina (Figura 1a), contains two water bodies: Peinado and Turquesa lake. Peinado Lake (Figura 1b), the larger of the two, covers approximately 2.12 km², while Turquesa Lake has an area of about 0.1 km² (Figura 1b). Both are situated south of the Antofalla Salar and north of El Peinado volcano (26° 28' 44.33" S, 68° 5' 51.46" W), which formed during the Andean tectonic cycle, with an age ranging from 42,000 to 7,000 years and eruptive events in the last 12,000 years (Grosse *et al.*, 2017).

The study area belongs to the Puna geological province (Turner, 1972), a morphotectonic unit of the Central Andes rising to ~3,700 m.a.s.l. This region features rugged topography shaped by contractive basins and ranges, as well as volcanic activity (Kraemer *et al.*, 1999; Alonso & Rojas, 2020 in Farias *et al.* 2020; Ramos, 1999). The Puna province is divided into the Austral and Septentrional Puna (Turner, 1972), covering ~10,000 km² in northwestern Argentina. It is bounded by the Volcanic Cordillera and the Eastern Cordillera and is characterized by block faulting and isolated and chain volcanoes (Alonso & Rojas, 2020).

The Peinado basin, formed by tectonic and volcanic activity during the Plio-Pleistocene (Valero-Garcés *et al.*, 2001), is part of the Ojos del Salado volcanic region within the Central Volcanic Zone (CVZ) of the Andes (Grosse *et al.*, 2017). This zone contains major volcanic structures, including calderas, stratovolcanoes, ignimbrites, composite volcanoes, and alkaline volcanic rocks. The geology surrounding the lake mainly consists of lacustrine deposits, ignimbrites, and volcanic flows, some forming basaltic lava fields with volcanic cones (Grosse *et al.*, 2017; Maro *et al.*, 2017 and Petrinovic *et al.*, 2017) (Figura 1c).

The Central Andes (15°S–27°S) lie within a high-pressure subtropical region and exhibit extreme aridity, comparable to deserts in western Africa and Australia. The Atacama Desert receives ~20 mm of annual precipitation and has some of the world's lowest erosion rates (Houston & Hartley, 2003 in Strecker *et al.*, 2007). The western flank experiences hyperaridity, while the Puna plateau and intermontane basins to the east receive <200 mm annually (Garleff & Stingl, 1983; Bianchi & Yañez, 1992 in Strecker *et al.*, 2007). This arid climate enables the formation of evaporitic environments in the endorheic Peinado basin, including lake, salars, and wetlands (Alonso *et al.*, 2006; Jordan & Mpodozis, 2006; Alonso & Rojas, 2020).

Peinado and Turquesa Lake, separated by only 250 m, have distinct hydrochemical characteristics. Turquesa lake (26°39'14" S, 68°10'42" W) covers 0.1 km², with an average depth of 6 m, pH of 7.58, conductivity >100 mS, total dissolved solids >60 mg/L, and an average temperature of 9.15°C (Villafañe *et al.*, 2021). Peinado lake has an area of 1.6 km², ~8 m depth, pH of 7.91, conductivity of 65.20 mS, total dissolved solids of 39.10 mg/L, and a similar temperature (Villafañe *et al.*, 2021). South of Peinado lake, hydrothermal springs reach temperatures of 33.13°C (Valero-Garcés *et al.*, 2001; Villafañe *et al.*, 2021).

Puna microbial ecosystems have gained attention due to their adaptation to extreme conditions, including high salinity (125 mS), low oxygen pressure, volcanic activity, arsenic content, large temperature fluctuations, and extreme aridity (Villafañe *et al.*, 2021; Farías *et al.*, 2011, 2013, 2014; Saona *et al.*, 2020). Temperature varies from 20°C to -10°C in summer and 10°C to -40°C in winter.

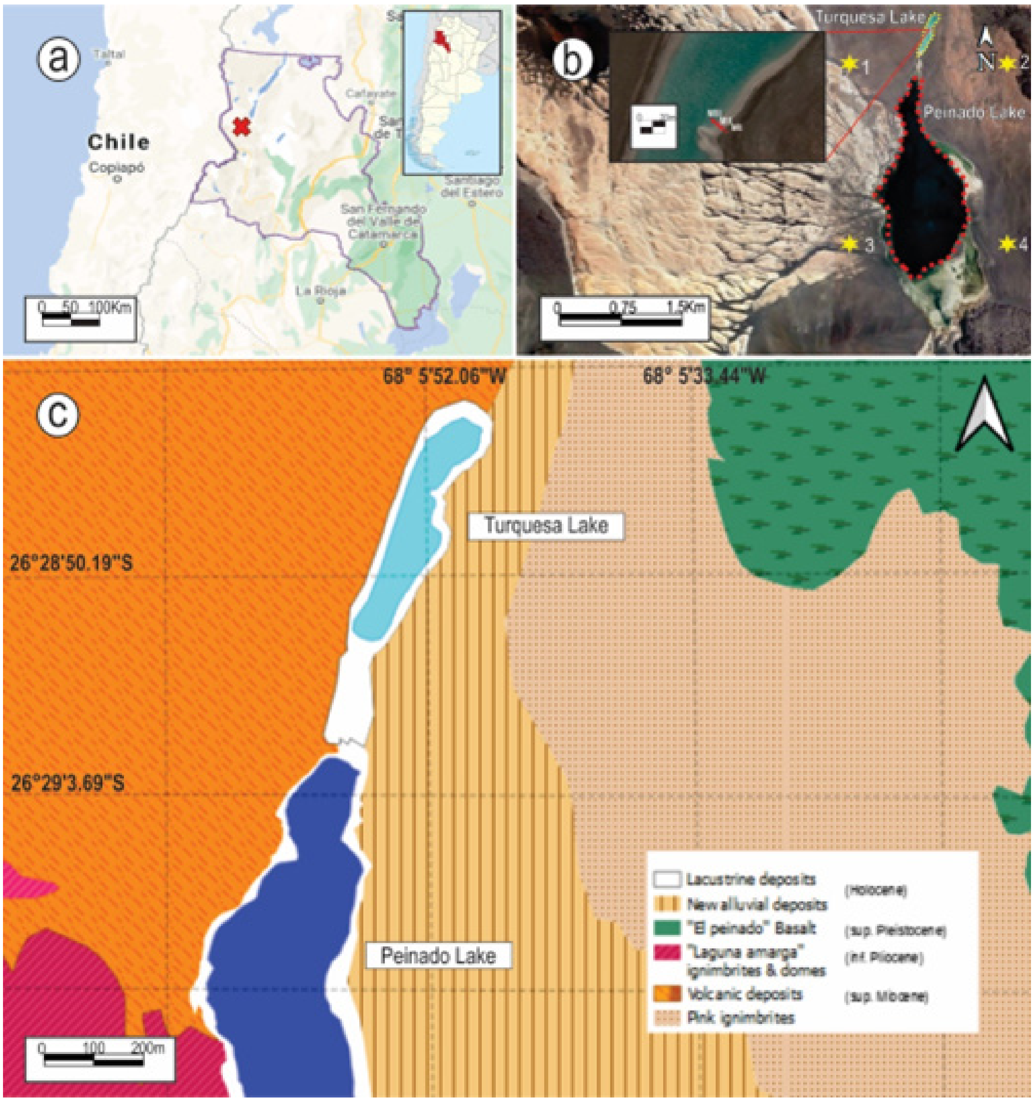

Figure 1. Adapted from Della Vedova *et al.* (2022). **a)** Location of the study area in Catamarca, Argentina. **b)** Satellite image showing both lakes (Turquesa lake to the north and Peinado lake to the south), with the positions of the microbialite levels in the former. **c)** Geological map of the area. Coordinates: 1: 26°29'10.08"S, 68°6'29.37"O; 2: 26°29'10.08"S, 68°5'8.95"O; 3: 26°30'31.32"S, 68°6'29.37"O; 4: 26°30'31.32"S, 68°5'8.95"O./**Figura 1.** *Adaptado de Della Vedova* et al. *(2022).* **a)** *Ubicación del área de estudio en Catamarca, Argentina.* **b)** *Imagen satelital que muestra ambos lagos (lago Turquesa al norte y lago Peinado al sur), con la posición de los niveles de microbialita en el primero.* **c)** *Mapa geológico del área. Coordenadas: 1: 26°29'10.08"S, 68°6'29.37"O; 2: 26°29'10.08"S, 68°5'8.95"O; 3: 26°30'31.32"S, 68°6'29.37"O; 4: 26°30'31.32"S, 68°5'8.95"O.*

Water input from precipitation is very low (<120 mm/year), while evaporation is extremely high (>1500 mm/year) (Vignone *et al.,* 2024). The Andean valleys receive some of the highest solar radiation levels worldwide, averaging 6.6 kWh m^{-2} d^{-1}. These extreme conditions make the region a challenging environment for life and microbial ecosystem development.

Paleoclimate setting

The climate of the Puna region in Argentina is primarily governed by the South American Summer Monsoon (SASM) and the interaction between the Bolivian High and the Chaco Low (Lenters & Cook, 1997). During the austral summer, moisture advection from the Amazon Basin and the Atlantic Ocean drives orographic precipitation along the eastern Andean slopes (Bookhagen and Strecker, 2008). However, as air masses ascend and traverse the orogen, progressive moisture depletion occurs, generating a pronounced east-west precipitation gradient that transitions from semi-arid conditions on the eastern flanks to hyper-arid environments in the western Puna (Hartley, 2003). This orographic rain shadow, combined with the influence of the Southeastern Pacific Anticyclone, establishes the Puna as one of the driest regions in South America, where hydrological availability is primarily controlled by seasonal precipitation variability and multi-millennial climatic cycles (Pingel *et al.*, 2016).

The extreme aridity of the Central Andes, particularly in the Puna region, has profoundly influenced geomorphological and sedimentary processes. The combination of minimal precipitation (<200 mm/year) and high evaporation rates (>1500 mm/year) has led to the formation of extensive evaporitic deposits and the development of endorheic lacustrine systems (Alonso *et al.*, 2006; Jordan & Mpodozis, 2006). These arid conditions have facilitated the preservation of playa lake environments, saline flats, and microbialite-bearing carbonate deposits, which provide a valuable record of hydrological fluctuations over geological timescales. The Peinado Basin, for instance, exhibits a stratigraphic archive of cyclic lake-level changes, hydrological crises, and long-term aridification trends that can be linked to both climatic shifts and structural controls imposed by Andean tectonics (Valero-Garcés *et al.*, 2001; Strecker *et al.*, 2007).

The persistence of evaporitic deposits in the Argentine Puna reflects a long-term trend of increasing aridity since the Pleistocene, which has significantly impacted sedimentary dynamics and the evolution of lacustrine environments. The progressive drying of the region has led to the accumulation of evaporites and the alternation of wetter and drier phases, modifying the hydrological regime of the basin (Alonso *et al.*, 2006; Jordan and Mpodozis, 2006). These processes have contributed to the episodic expansion and contraction of lakes, influencing the deposition of carbonates and other lacustrine facies indicative of hydrological variability.

Recent investigations have documented these climatic fluctuations in Laguna Turquesa and Peinado lake, where stratigraphic sequences preserve evaporitic horizons and carbonate deposits formed during the Pleistocene-Holocene transition (Della Vedova *et al.*, 2022; Valero-Garcés *et al.*, 2001). These lake records provide valuable evidence for reconstructing past environmental changes in the Puna and offer new insights into the interplay between tectonic activity, climate shifts, and sedimentary processes in this high-altitude arid environment (Trauth *et al.*, 2003).

Methodology

In Turquesa lake, three microbialitic levels (M1, M2 and M3) were identified based on previous studies (Valero-Garcés *et al.*, 2001; Villafañe *et al.*, 2021; Della Vedova *et al.*, 2022) and subsequently sampled. Additionally, two distinct paleolake terraces located above these levels were also sampled.

During fieldwork, we measured the altitude of the lake and the paleoshoreline to extrapolate their positions within a GIS system.

The digital elevation model (SRTM 1 Arc-Second Global) was obtained through the USGS Earth Explorer, while the satellite imagery was sourced from SASPlanet. Using ArcMap 10.4.1, we extracted the contour lines corresponding to the elevations of the microbialitic levels and the paleolake terraces. Additionally, using Google Earth, we made an elevation profile (NE – SW), between Turquesa lake and Peinado lake in order to observe the elevation at which both lakes connect. Finally, their respective areas were calculated, and a detailed map was generated.

To estimate long-term and modern desiccation rates of Turquesa Lake, we compared the elevation and surface area of microbialitic levels and paleoshorelines. The altitude of each level was measured in the field using GPS, and paleoshoreline positions were extracted using a digital elevation model (SRTM 1 Arc-Second Global) and analyzed in ArcMap 10.4.1.

We calculated surface area changes between each level based on elevation contours.

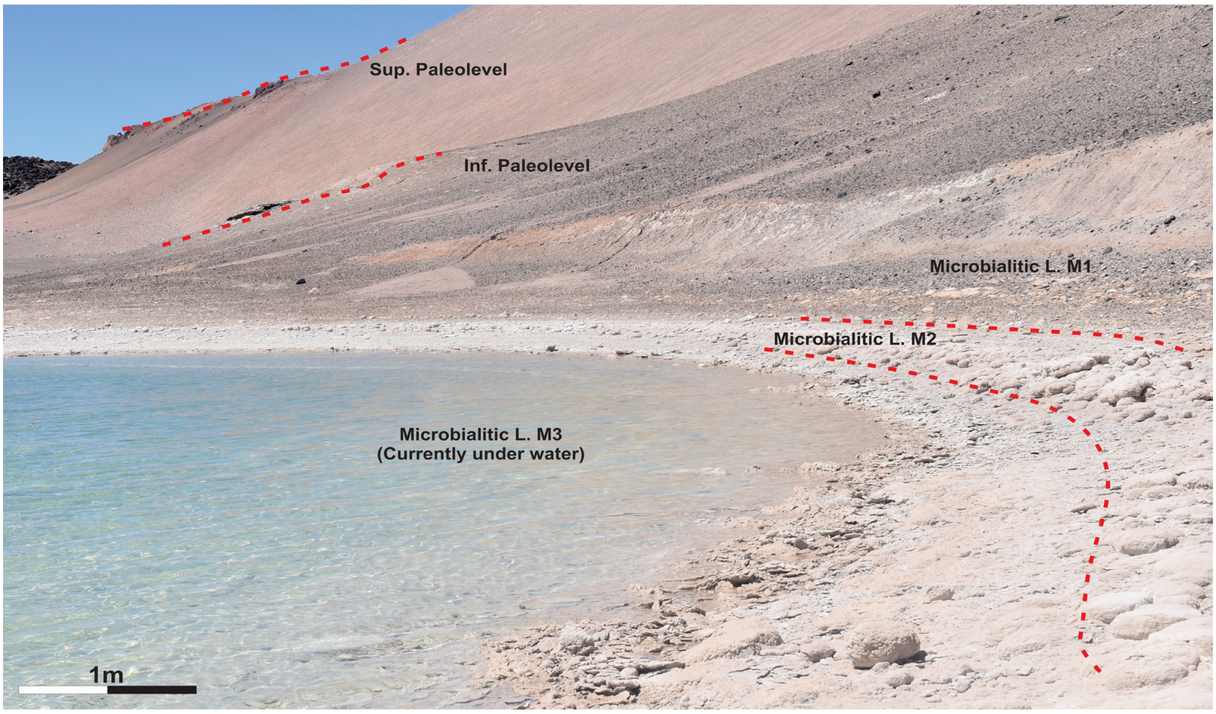

Figure 2. Current water level (M3), microbialitic level M1 and M2 and both paleo lake terraces./**Figura 2.** *Nivel de agua actual (M3), nivel microbialítico M1 y M2 y ambas terrazas paleolacustres.*

Figure 3. Field photographs. (a, b, d) Paleolake levels. (c) Microbialitic levels M1, M2, and M3, along with the shoreline of Turquesa Lake. /**Figura 3.** *Fotografías de campo. (a, b, d) Niveles del paleolago. (c) Niveles microbialíticos M1, M2 y M3, a lo largo de la línea de costa del lago Turquesa.*

The difference in lake area between the dated microbialitic level M1 (~11,830 ± 170 years BP at 3,763 m a.s.l.) and the current lake level (~3,753 m a.s.l. in 2023–2024) was used to estimate the long-term average desiccation rate (in m^2/year). The same calculation was performed for short-term change, comparing satellite imagery from 2007 and 2024 to estimate the modern desiccation rate.

The desiccation rate was obtained by divi-

Point Measured	Description	Contour line height	Area covered by this contour line/ Area of the lakes	Area difference and desiccation rates	
1	Paleo Lake Sediments	3,775 m a.s.l	5.25 Km^2 (Both Lakes)		
2	Paleo Lake Sediments	3,770 m a.s.l	4.82 Km^2 (Both Lakes)	Area difference between 1 and 2= 0.43 Km^2	
3	Microbialitic Level M1→11,830 ± 170 years BP	3,763 m a.s.l.	4.25 Km^2 (Both Lakes)	Area difference between 2 and 3= 0.57 Km^2	
4	The area of Turquesa lake, using the M1 level as a reference, was	3,763 m.a.s.l. Only Tuquesa Lake	48.46 m^2	Area difference between M1 level: 48.46 m^2 (11,830 years) 38.50 m^2 (present)=	9.96 m^2 over approximately 11,830 years → 0.00084 m^2 per year
5	Current Area of Turquesa Lake (2024)	3,763 m.a.s.l. (Only Turquesa Lake)	38.50 m^2		
6	Area of Turquesa Lake in 2007.	3,763 m.a.s.l. (Only Turquesa Lake)	40.03 m^2	Difference in areas from 2024 to 2007 = 1.53 m^2	In 17 years → 0.09 m^2 per year

Table 1. Summary of bathymetric levels, elevation contours, and corresponding lake areas used to estimate past and present desiccation rates in the Peinado–Turquesa lake system (Figura 4). Elevation data were obtained via GPS measurements and digital elevation models. Surface areas were derived from contour lines in GIS. Area differences were used to calculate long-term and modern desiccation rates, based on the temporal gap between dated levels and satellite imagery. /**Tabla 1.** *Resumen de los niveles batimétricos, las curvas de nivel y las áreas lacustres correspondientes, utilizados para estimar las tasas de desecación pasadas y presentes en el sistema lacustre Peinado-Turquesa (Figura 4). Los datos de elevación se obtuvieron mediante mediciones GPS y modelos digitales de elevación. Las áreas superficiales se derivaron de las curvas de nivel en SIG. Las diferencias de área se utilizaron para calcular las tasas de desecación a largo plazo y actuales, basándose en la diferencia temporal entre los niveles datados y las imágenes satelitales.*

ding the area loss by the time interval:
Desiccation rate = (Area difference) / (Time interval in years).

The three microbialitic levels identified in the field were approximately 1 m apart from each other (Figura 2), with M1 being the oldest, dated at 11,830 ± 170 years BP in the outer zone of the oncolite (Della Vedova et al., 2022). The microbialites (Figura 3c) were located at approximately 3,763 m a.s.l., and M3 is currently forming underwater. We measured the paleo-levels above (Figura 2; 3a, b;d) at elevations of 3,770 and 3,775 m a.s.l.

The contour lines at each respective elevation encompass both lakes, supporting previous findings that they were once united (Vi-

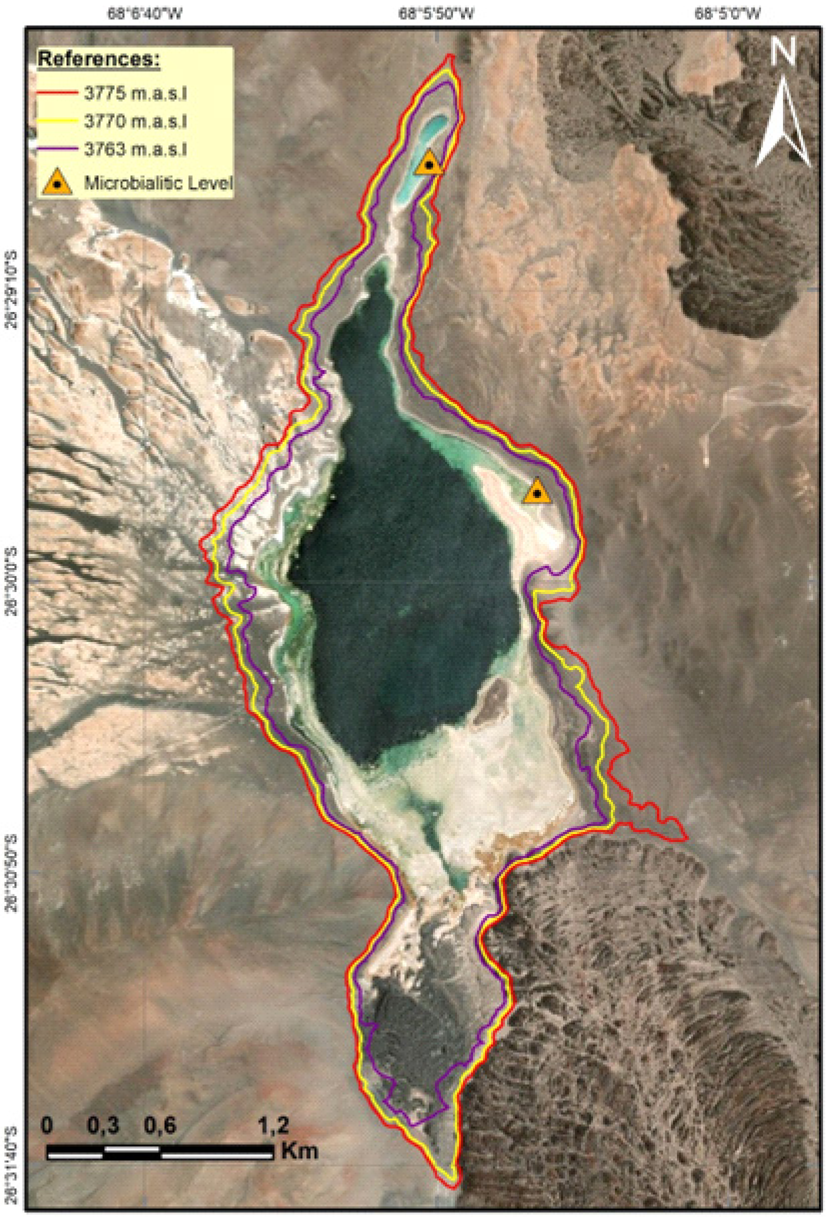

Figure 4. Extracted curves of the different altitudes of the paleolevels (3770 and 3775 m.a.s.l) and from the M1, the oldest microbialitic level (3763 m.a.s.l). /**Figura 4.** *Curvas extraídas de las diferentes altitudes de los paleoniveles (3770 y 3775 m.s.n.m.) y del M1, el nivel microbialítico más antiguo (3763 m.s.n.m.).*

llafañe *et al.*, 2021; Della Vedova *et al.*, 2022). Based on area measurements, we estimated that at 3,763 m a.s.l., the lake covered approximately 4.25 km², increasing to 4.82 km² at 3,770 m a.s.l. and 5.25 km² at 3,775 m a.s.l. (Figura 4).

From the first paleo-level (3,775 m a.s.l.) to the second (3,770 m a.s.l.), the lake lost an estimated surface area of 0.43 km², while from the second paleo-level to the onset of microbialite formation (M1 at 3,763 m a.s.l.), it lost an additional 0.57 km² (Figura 4).

In images of the Google Erath, it was also possible to observe that on 12/31/2023, the level of the lake was at 3,753 meters above sea level and on 09/27/2007 at 3,757 meters above sea level (Figura 5). The area of Turquesa lake, using the M1 level as a reference, was 48.46 m², while the current area is 38.50 m². Considering that the dated level is 11,830 ± 170 years BP, the area difference amounts to 9.96 m² over

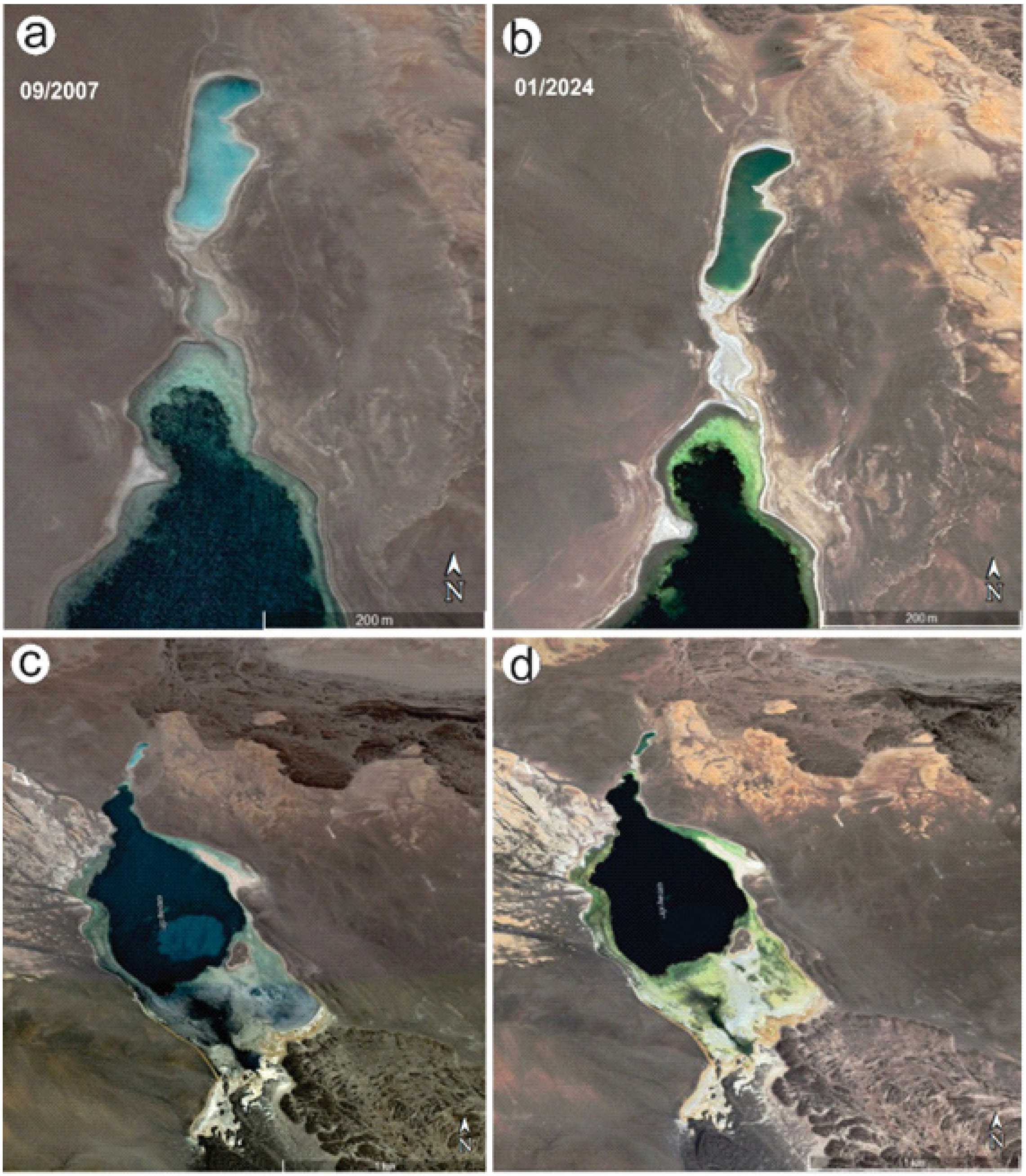

Figure 5. a,b) Satellite images of Turquesa Lake from 2007 and 2024, sourced from Google Earth. **c,d)** Satellite images of Peinado and Turquesa lakes from 2007 and 2024, sourced from Google Earth. /**Figura 5. a,b)** *Imágenes satelitales del Lago Turquesa de 2007 y 2024, provenientes de Google Earth.* **c,d)** *Imágenes satelitales de los lagos Peinado y Turquesa de 2007 y 2024, provenientes de Google Earth.*

approximately 11,830 years, with a desiccation rate of 0.00084 m² per year. On the other hand, in some images, water is seen connecting both lakes. Specifically, for Turquesa lake, the surface area of the water body was 40.03 m² in 2007 (Figura 5 a;c) and 38.50 m² in 2024 (Fig. 5 b,d), reflecting a decrease of 1.53 m² over 17 years, with a desiccation rate of 0.09 m² per year, indicating a higher evaporation rate compared to the past.

Furthermore, by carrying out an elevation profile where it was possible to see that both some of them connect to 3,755 m a.s.l, and that Turquesa lake drains towards Peinado lake (Figura 6).

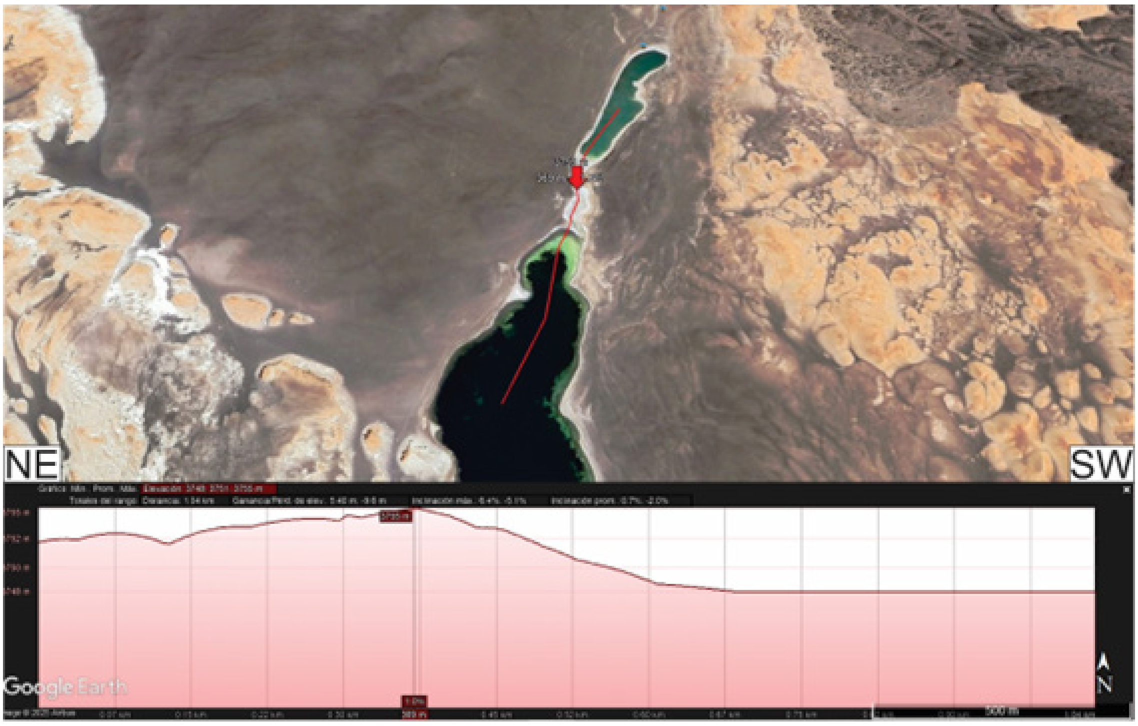

Figure 6. Elevation profile with NE - SW orientation that connects Turquesa and Peinado lakes. /**Figura 6.** *aPerfil de elevación con orientación NE – SO que conecta los lagos Turquesa y Peinado.*

Discusion

Valero-Garcés *et al.* (2001) identified four lacustrine terraces on the northern shore of the lake, indicating past fluctuations in water levels. During lowstand periods, macrophytic travertines formed in areas with thermal spring discharge, while stromatolites developed along shallow margins when the lake's water level was higher. The correlation between stable isotopes ($\delta^{13}C$ and $\delta^{1}O$) and salinity proxies suggests that evaporation played a key role in lowering the lake level (Della Vedova *et al.,* 2025; Vignoni *et al.* 2024).

The high evaporation rates in El Peinado Lake are primarily attributed to the disconnection between the two lakes (Villafañe *et al.*, 2021; Della Vedova *et al.*, 2022). However, in the present study, a reduction in the lake's area is observed, as evidenced by contour lines at different elevations that delineate the former extent of the lakes. Additionally, the region has a negative water balance, meaning evaporation exceeds precipitation, which contributes to the continuous decline in water levels (Vignoni *et al.*, 2023; 2024).

Initially, the lakes reached their highest paleo-level at 3775 m a.s.l., then receded to 3770 m a.s.l., and finally dropped to 3763 m a.s.l., a stage that favored the formation of the oldest microbialitic level (M1). At this level, microbial activity initiated the development of these organo-sedimentary structures. The water level subsequently dropped by approximately one meter, stabilized, and allowed for the formation of microbialitic level M2. These two microbialitic levels are believed to have formed when Turquesa and Peinado lakes were still connected, as suggested by their similarities. In contrast, M3 is distinct from the other two; it is currently forming underwater, with Turquesa lake now isolated from Peinado lake (Villafañe *et al.*, 2021; Della Vedova *et al.*, 2022).

As noted by Vignoni *et al.* (2023), Peinado lake is fed by hydrothermal springs located on its southern and western shores. In contrast, Turquesa Lake is disconnected from this source and relies solely on limited precipitation, resulting in a higher evaporation rate.

Considering the lake's elevation when the M1 level formed 11,830 years ago and its present elevation, the desiccation rate was significantly slower in the past compared to the period between 2007 and 2024.

Some researchers have described microbialites as "disaster forms" that thrive in stressed, post-extinction environments (Ezaki *et al.*, 2003; Mata & Bottjer, 2012). However, as also noted by previous studies, microbialites respond not only to large-scale environmental disturbances but also to more localized changes, such as fluctuations in water levels or desiccation events (Della Vedova *et al.*, 2022).

Conclusion

This study highlights the significant bathymetric fluctuations of Turquesa lake and Peinado lake during the Late Pleistocene–Holocene, driven primarily by climate variability and hydrological dynamics. The identification of microbialitic levels and paleoshorelines provides valuable evidence of past lake-level changes and their impact on microbialite formation.

The results indicate that the Peinado–Turquesa system has undergone a long-term trend of desiccation, punctuated by wetter intervals that temporarily reconnected both lakes. The correlation between microbialite distribution, isotope dating, and salinity proxies suggests that evaporation has played a dominant role in regulating lake levels. Additionally, the increasing desiccation rate observed in recent decades underscores the influence of modern climatic conditions on these high-altitude lacustrine environments.

Microbialites, often considered indicators of extreme environmental stress, have recorded not only large-scale climatic shifts but also smaller-scale hydrological fluctuations, reinforcing their significance in paleoenvironmental reconstructions. The findings of this study contribute to a better understanding of microbialite resilience, lake evolution in arid environments, and the broader implications for interpreting past climate variability in the Central Andes.

References

Alonso, R. N., y Rojas, W. (2020). Origin and evolution of the Central Andes: deserts, salars, lakes, and volcanoes. *Microbial ecosystems in Central Andes extreme environments: biofilms, microbial mats, microbialites and endoevaporites*, 3-19.

Alonso, R. N., Bookhagen, B., Carrapa, B., Coutand, I., Haschke, M., Hilley, G. E., ... y Villanueva, A. (2006). Tectonics, climate, and landscape evolution of the southern central Andes: the Argentine Puna Plateau and adjacent regions between 22 and 30 S. *The Andes: Active Subduction Orogeny,* 265-283.

Bianchi, A. R., Yañez, C. E., y Acuña, L. R. (2005). Base de datos mensuales de precipitaciones del Noroeste Argentino. *Informe del Proyecto Riesgo Agropecuario. INTA-SAGPYA.*

Bookhagen, B., y Strecker, M. R. (2008). Orographic barriers, high-resolution TRMM rainfall, and relief variations along the eastern Andes. *Geophysical Research Letters*, 35(6).

Burne, R. V., y Moore, L. S. (1987). Microbialites: organosedimentary deposits of benthic microbial communities. *Palaios*, 241-254. https://doi.org/10.2307/3514674.

Chafetz, H. S. (2013). Porosity in bacterially induced carbonates: Focus on micropores. *AAPG bulletin*, 97(11), 2103-2111. https://doi.org/10.1306/04231312173

Della Vedova, M., Villafañe, P. G., Cónsole Gonella, C., Bahniuk Rumbelsperger, A., Fadel Cury, L., Horta, L. R., y Farías, M. E. (2023). Disentangling microstructure and environmental conditions in high-altitude Andean microbialite systems (Catamarca, Argentine Puna). *Environmental Microbiology Reports*, 15(2), 92-108. https://doi.org/10.1111/1758-2229.13128.

Della Vedova, M., Alonso, G. E., Villafañe, P. G., Horta, L. R., y Cury, L. F. (2025). Isotopic composition and growth rate of microbialites in Laguna Turquesa, a high-altitude lake in the Central Andes. *Quaternary Science Reviews*, 361, 109386.

Dupraz, C., y Visscher, P. T. (2005). Microbial lithification in marine stromatolites and hypersaline mats. *Trends in microbiology*, 13(9), 429-438. https://doi.org/10.1016/j.tim.2005.07.008.

Dupraz, C., Pattisina, R., y Verrecchia, E. P. (2006). Translation of energy into morphology: simulation of stromatolite morphospace using a stochastic model. *Sedimentary Geology*, 185(3-4), 185-203. https://doi.org/10.1016/j.sedgeo.2005.12.012

Dupraz, C., Reid, R. P., Braissant, O., Decho, A. W., Norman, R. S., y Visscher, P. T. (2009). Processes of carbonate precipitation in modern microbial mats. *Earth-Science Reviews,* 96(3), 141-162. https://doi.org/10.1016/j.earscirev.2008.10.005.

Ezaki, Y., Liu, J., Nagano, T., y Adachi, N. (2008). Geobiological aspects of the earliest Triassic microbialites along the southern periphery of the tropical Yangtze Platform: initiation and cessation of a microbial regime. *Palaios*, 23(6), 356-369.

Farías, M. E., Rascovan, N., Toneatti, D. M., Albarracín, V. H., Flores, M. R., Poiré, D. G., ... y Polerecky, L. (2013). The discovery of stromatolites developing at 3570 m above sea level in a high-altitude volcanic lake Socompa, Argentinean Andes. PloS one, 8(1), e53497. https://doi.org/10.1371/journal.pone.0053497

Farías, M. E., Contreras, M., Rasuk, M. C., Kurth, D., Flores, M. R., Poire, D. G., ... y Visscher, P. T. (2014). Characterization of bacterial diversity associated with microbial mats, gypsum evaporites and carbonate microbialites in thalassic wetlands: Tebenquiche and La Brava, Salar de Atacama, Chile. *Extremophiles*, 18, 311-329. https://doi.org/10.1007/s00792-013-0617-6

Farías, M. E., Rasuk, M. C., Gallagher, K. L., Contreras, M., Kurth, D., Fernandez, A. B., ... y Visscher, P. T. (2017). Prokaryotic diversity and biogeochemical characteristics of benthic microbial ecosystems at La Brava, a hypersaline lake at Salar de Atacama, Chile. PLoS One, 12(11), e0186867. https://doi.org/10.1371/journal.pone.0186867.

Farías, M. E., Villafañe, P. G., y Lencina, A. I. (2020). Integral prospection of Andean microbial ecosystem project. *Microbial ecosystems in Central Andes extreme environments: Biofilms, microbial mats, microbialites and endoevaporites*, 245-260.

Garleff, K., y Stingl, H. (1983). Hangformen und Hangformung in der periglazialen Höhenstufe der argentinischen Anden zwischen 27° und 55° Südlicher Breite. In H. Poser & E. Schunke (Eds.), *Mesoformen des Reliefs im heutigen Periglazialraum* (pp. 155–170). E. Schweizerbart'sche Verlagsbuchhandlung.

Gómez, F. J., Kah, L. C., Bartley, J. K., y Astini, R. A. (2014). Microbialites in a high-altitude Andean lake: multiple controls on carbonate precipitation and lamina accretion. Palaios, 29(6), 233-249. https://doi.org/10.2110/palo.2014.049.

Gómez, F. J., Mlewski, C., Boidi, F. J., Farías, M. E., y Gérard, E. (2018). Calcium carbonate precipitation in diatom-rich microbial mats: the Laguna Negra hypersaline lake, Catamarca, Argentina. Journal of Sedimentary Research, 88(6), 727-742. https://doi.org/10.2110/jsr.2018.43.

Grosse, P., Guzmán, S., & Petrinovic, I. (2017). Volcanes compuestos cenozoicos del noroeste argentino. *Ciencias de la Tierra y Recursos Naturales del NOA (Muruaga, C.; Grosse, P,* 484-517.

Hartley, A. (2003). Andean uplift and climate change. *Journal of the Geological Society*, 160(1), 7-10.

Harwood, C. L., y Sumner, D. Y. (2012). Origins of microbial microstructures in the Neoproterozoic Beck Spring Dolomite: variations in microbial community and timing of lithification. *Journal of Sedimentary Research*, 82(9), 709-722. https://doi.org/10.2110/jsr.2012.65

Hickman-Lewis, K., Gautret, P., Arbaret, L., Sorieul, S., De Wit, R., Foucher, F., ... y Westall, F. (2019). Mechanistic morphogenesis of organo-sedimentary structures growing under geochemically stressed conditions: keystone to proving the biogenicity of some Archaean stromatolites?. *Geosciences*, 9(8), 359. https://doi.org/10.3390/geosciences9080359

Jordan, T. E., y Mpodozis, C. (2006). Estratigrafía y evolución tectónica de la cuenca Paleógena Arizaro-Pocitos, Puna Occiden tal (24–25). In *Actas of XI Congreso Geologico Chileno* (Vol. 2, pp. 57-60).

Kennard, J. M., y James, N. P. (1986). Thrombolites and stromatolites: two distinct types of microbial structures. *Palaios*, 492-503. https://doi.org/10.2307/3514631.

Kraemer, B., Adelmann, D., Alten, M., Schnurr, W., Erpenstein, K., Kiefer, E., ... y Görler, K. (1999). Incorporation of the Paleogene foreland into the Neogene Puna plateau: The Salar de Antofalla area, NW Argentina. *Journal of South American Earth Sciences*, 12(2), 157-182. https://doi.org/10.1016/S0895-9811(99)00012-7.

Lenters, J. D., y Cook, K. H. (1997). On the origin of the Bolivian high and related circulation features of the South American climate. *Journal of the Atmospheric Sciences*, 54(5), 656-678.

Maro, G., Caffe, P. J., y Báez, W. (2017). Volcanismo monogenético máfico cenozoico de la Puna. In *Ciencias de la Tierra y Recursos Naturales del NOA. Relatorio del XX Congreso Geológico Argentino, San Miguel de Tucumán* (Vol. 2017, pp. 548-577). Asociación Geológica Argentina.

Mata, S. A., y Bottjer, D. J. (2012). Microbes and mass extinctions: paleoenvironmental distribution of microbialites during times of biotic crisis. *Geobiology*, 10(1), 3-24. https://doi.org/10.1111/j.1472-4669.2011.00305.x

Pingel, H., Mulch, A., Alonso, R. N., Cottle, J., Hynek, S. A., Poletti, J., ... y Strecker, M. R. (2016). Surface uplift and convective rainfall along the southern Central Andes (Angastaco Basin, NW Argentina). *Earth and Planetary Science Letters*, 440, 33-42.

Ramos, V. A. (1999). Rasgos estructurales del territorio argentino. *Geología Argentina*, 29(24), 15-75.

Rascovan, N., Maldonado, J., Vazquez, M. P., y Eugenia Farías, M. (2016). Metagenomic study of red biofilms from Diamante Lake reveals ancient arsenic bioenergetics in haloarchaea. *The ISME journal,* 10(2), 299-309. https://doi.org/10.1038/ismej.2015.116

Petrinovic, I. A., Grosse, P., Guzmán, S., y Caffe, P. J. (2017). Evolución del volcanismo Cenozoico en la Puna Argentina.

Rezende, M. F., y Pope, M. C. (2015). Importance of depositional texture in pore characterization of subsalt microbialite carbonates, offshore Brazil. *Geological Society, London, Special Publications*, 418(1), 193-207. https://doi.org/10.1144/SP418.2

Riding, R. (2011). The Nature of Stromatolites: 3,500 Million Years of History and a Century of Research. In: Advances in Stromatolite Geobiology. Lecture Notes in Earth Sciences, vol 131. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-10415-2_3.

Strecker, M. R., Alonso, R. N., Bookhagen, B., Carrapa, B., Hilley, G. E., Sobel, E. R., y Trauth, M. H. (2007). Tectonics and climate of the southern central Andes. *Annu. Rev. Earth Planet. Sci.,* 35(1), 747-787. https://doi.org/10.1146/annurev.earth.35.031306.140158

Trauth, M. H., Deino, A. L., Bergner, A. G., y Strecker, M. R. (2003). East African climate change and orbital forcing during the last 175 kyr BP. *Earth and Planetary Science Letters*, 206(3-4), 297-313.

Turner, J.C.M. (1972). Puna. Cordillera Oriental. Leanza, A. F. (ed.), Geología Regional Argentina, 91-142.

Valero-Garcés, B. L., Arenas, C., y Delgado-Huertas, A. (2001). Depositional environments of Quaternary lacustrine travertines and stromatolites from high-altitude Andean lakes, northwestern Argentina. Canadian Journal of Earth Sciences, 38(8), 1263-1283. https://doi.org/10.1139/e01-029.

Valero-Garcés, B., Delgado-Huertas, A., Ratto, N., Navas, A., y Edwards, L. (2000). Paleohydrology of Andean saline lakes from sedimentological and isotopic records, Northwestern Argentina. Journal of Paleolimnology, 24, 343-359. https://doi.org/10.1023/A:1008109507580.

Vignale, F. A., Lencina, A. I., Stepanenko, T. M., Soria, M. N., Saona, L. A., Kurth, D., ... y Farías, M. E. (2021). Lithifying and non-lithifying microbial ecosystems in the wetlands and salt flats of the Central Andes. Microbial ecology, 1-17. https://doi.org/10.1007/s00248-021-01674-7.

Vignoni, P. A., Córdoba, F. E., Tjallingii, R., Santamans, C., Lupo, L. C., y Brauer, A. (2023). Spatial variability of the modern radiocarbon reservoir effect in the high-altitude lake Laguna del Peinado (southern Puna Plateau, Argentina). *Geochronology*, 5(2), 333-344.https://doi.org/10.5194/gchron-5-333-2023.

Vignoni, P. A., Jurikova, H., Schröder, B., Tjallingii, R., Córdoba, F. E., Lecomte, K. L., ... y Brauer, A. (2024). On the origin and processes controlling the elemental and isotopic composition of carbonates in hypersaline Andean lakes. *Geochimica et Cosmochimica Acta, 366*, 65-83. https://doi.org/10.1016/j.gca.2023.11.032.

Villafañe, P. G., Cónsole Gonella, C., Cury, L. F., y Farías, M. E. (2021). Short-term microbialite resurgence as indicator of ecological resilience against crises (Catamarca, Argentine Puna). Environmental Microbiology Reports, 13(5), 65 667. https://doi.org/10.1111/1758-2229.12977.

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