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Paleogeographic reconstruction of the Tar – San Martín lacustrine system during late Pleistocene to early Holocene: landscape availability and hunter-gatherer circulation (Santa Cruz, Argentina).

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Abstract

This paper presents the paleogeographic reconstructions of flooded areas of the Tar - San Martín lacustrine system during the late Pleistocene - Holocene. The dimensions of lacustrine and glaciolacustrine levels of this basin are higher than the current levels of the lakes. The organic matter of lake levels recorded on stratigraphic profiles was described, sampled and dated using AMS, while other paleobathymetric indicators were also identified (height of the fan-delta apex and paleo-coast levels). Deriving out of the reconstruction of flooded areas it was established that the lake system was formed before 28 ka ago and would have reached its maximum expansion around 12 ka ago. The first hunter-gatherer occupation of the basin (11 ka) corresponds to the period of initial contraction of the lake system and the composition of the current configuration of the coastlines. This scenario would have allowed the exploration of western areas and the gradual incorporation of the forest to the action range of hunter-gatherer populations. Similarly, the levels of lakes Tar and San Martín would not have hindered the movement of human populations through the steppe throughout the Holocene.

Key words: Paleogeographic reconstructions, Patagonia, Lacustrine system, Climatic changes.

1. Introduction

The Tar-San Martín lacustrine system (TSM-LS) is located on the south-central zone of the mountainous area of the province of Santa Cruz, centered at 48° 56' 9.83 "S - 72° 29'58. 65" W. The Tar Lake is located to the East of San Martín Lake, at an altitude of 269 metres above sea level, its main tributaries are

the rivers Tar and Meseta, and it is connected to the San Martín Lake through the Calafate stream. San Martín Lake is shared with Chile, where it is called O'Higgins, and drains into the Pacific Ocean. It is a proglacial lake which is in contact on its west side with the northern end of the Southern Patagonian Ice Field (Figure 1). Its current height is 252 masl, its maximum depth is 836 m and it is the fifth deepest in the world (Center for Scientific Studies CECS 2010).

In the area of the San Martín-Tar lakes, Glasser et al. (2011) used datings of erratic boulders to propose a contraction of the glacial mass in East-West direction between ca. 34 and 14 ka., albeit intermediate progresses of the glacial mass at 27 ka is shown as well. This paper provides evidence of an expansion of San Martín Lake for ca. 12 ka., which would indicate that fluctuations in the lake dynamics continued until a later age.

The first hunter-gatherer occupations in the basin of Tar and San Martín Lakes took place towards the beginning of the Holocene and occurred episodically until ca. 5500 cal yr BP. This became more frequent from the late Holocene, in concurrence with the stabilization of the environmental conditions (Bamonte and Mancini 2011, Belardi et al., 2013 and Bamonte et al. 2015).

In the Argentinian Patagonian mountain range the sedimentary sequences represented by till, glaciolacustrine, lacustrine and glaciofluvial facies show the evolution of sedimentary environments in the transition between the late Pleistocene - early Holocene (Garcia et al., 2015; Horta et al. 2015 and 2017). The interaction between fluvial, lacustrine and glaciolacustrine depositional systems in the Pleistocene - Holocene transition was also registered in stratigraphic columns in New Zealand (Marger and Ftzisimons, 2007). Darvil et al. (2016) proposed that

the advances of glaciers in mid-latitudes of the Southern hemisphere in the glacial period between 110 and 10 ka were controlled by variations in temperature and rainfall linked to oceanic and climate systems; in addition, they suggest that ice expansion in Patagonia and New Zealand was synchronous.

These changes would be directly related to the activity of glaciers and the consequent generation, expansion, sedimentation and contraction of the paleolakes that covered wider areas than the current ones (Valley et al., 2007; Hein, 2010; Horta et al. 2015 and 2017).

Variations in the levels of Patagonian lakes have been studied by different authors (Stine and Stine 1990; Tatur et al., 2002; Bell 2008, 2009; McCulloch and Morello. 2009; Ariztegui et al., 2010; Horta et al. 2015 and 2017). The integration of geological, archaeological and palynological information of the basins of Pueyrredón Lake and the Perito Moreno National Park (Santa Cruz, Argentina), of between 31 ka and 5 ka, indicates a very dynamic paleogeographic and paleoenvironmental evolution that would have conditioned the flow of hunter-gatherer populations (Horta et al., 2015, 2016 and 2017, Sacchi et al., 2016). The study of glacial geomorphology and paleogeographic reconstructions proposes advances and retreats of glaciers during the late Pleistocene in the area which includes the Buenos Aires (Argentina) - General Carrera (Chile) lake system (Glasser et al., 2004 and 2008; Bell 2008, 2009; Hein et al., 2010; Smedley et al., 2016). Bourgois et al. (2016), poses for Buenos Aires Lake a maximum flood of between 14.5 and 12.9 ka (214 m above the current level).

Particularly for the San Martín lake area, pollen analyzes in wetlands reflect variations in the availability of moisture between the 6.5 ka and nowadays (Bamonte et al., 2015).

The purpose of this work is to characterize the paleogeographic and paleoenvironmental evolution of the Tar – San Martín lacustrine system during the late Pleistocene - Holocene through the integration of stratigraphic data, facies analysis and absolute dating, and to associate them to the occupational dynamics of hunter-gatherer populations.

2. Materials and methods

The base map was made with satellite images Landsat 8, using the geographical information system Ilwis (developed by ITC-International Institute for Geo-informatics and Earth Observation, from Holland) and Arc GIS 10.1 Student Edition. A combination of bands 753 (RGB) was used for mapping.

In San Martín Lake, three lake levels (Fig. 1, Table 1) were described, sampled and geo-referenced with GPS GARMIN MAP and a barometric altimeter of the Pretel brand. Three detailed stratigraphic profiles were conducted (in scale 1:20); textures, primary sedimentary structures, types of contact and lateral continuity of deposits were described. They were drawn using Corel Draw (Fig. 2).

Additionally, the landform was analysed considering the topographical characteristics determined by digital elevation models (DEM) extracted from SRTM (Shuttle Radar Topography Mission); paleobathymetric indicators (fan-deltas and paleocoasts, Fig. 3 a) were identified through the use of Google Earth. Ancient paleocoasts levels of the lake system (Fig. 3 b, c and d), were also rebuilt through the generation of the DEM. Taking into account the granulometric characteristics of

deposits, the flooded area was recreated between 10 m (Bahía de la Lancha) and 15 m (Río Gallo and Río las Minas) above the current water level (Figs. 4 a, b and c).

Four (4) samples of lacustrine sediments were dated in NSF-Arizona AMS facility. The radiocarbon datings were calibrated using CALIB 7.1 (Stuiver and Reimer, 1993, Stuiver et al., 2018 with the southern hemisphere SHCal13 calibration curve (Hogg et al., 2013). Erratic boulders and moraine datings (Glasser et al., 2011) were used to complement the paleoenvironmental interpretation, as well as those of the archaeological context of the basin with the greatest temporal depth: Campo de Bloques 1, Oquedad (Belardi et al., 2013).

The site is located at the Southeastern margin of the San Martín Lake (Fig. 1), on a small plain with boulders due to processes of mass removal and gravitational movements. It is a narrow shelter provided by one of the biggest boulders that has a stratigraphic archaeological sequence since the Late Pleistocene-onset of the Holocene until the late Holocene. The artefactual and archaeofaunal depositional rates, the artefactual evidence and the punctuated human occupation suggest a mainly logistical use of the site (Belardi et al. 2010). Taken into account a regional scale hunter-gatherer landscape use covers the entire Tar-San Martín Lakes basin and has an important Late Holocene archaeological signal (Belardi et al. 2013).

3. Fluctuations of the lake system

On the basis of the analysis of satellite images and fieldwork, different indicators of the variations of the Tar - San Martín lake system are proposed:

3.1 Lacustrine sediments: outcrops were recorded in three areas: 1)- Río de las Minas, at 307 masl (Fig. 1 point 1 and Fig. 2), 2) - Bahía de la Lancha, at 345 masl (Fig. 1 point 2 and Fig. 2), 3) - Río Gallo, at 260 masl (Fig. 1 point 3, fig. 2).

3.2 Paleocoasts: which were identified at 340 and 310 masl, on the north-eastern coast of San Martín Lake (Fig. 1).

3.3 Fan-deltas: four of these were recognized in different areas of the lake system and with apexes at different heights (Fig. 1): Estancia El Cóndor fan-delta (point 9, fig. 1 and fig. 3 a): situated on the southwest coast of the Maipú affluent, it is composed of two fan-deltas –an ancient one which apex is at 360 masl, and a more modern one at 260 masl. Tar Lake fan-delta is located to the West of that lake (Fig. 1 point 10), its apex is at a height of 340 masl. North Coast fan (Fig. 1, point 11), whose apex is at a height of 313 masl. West Coast fan (Fig. 1, point 12), which apex is at a height of 270 masl.

4. Palaeoenvironmental analysis and paleogeographic reconstruction

The paleoenvironmental interpretation of deposits was performed considering the stratigraphic profiles described (Fig. 2) and through facies analysis and their associations. The nomenclature used in the analysis is detailed on table 2.

4.1 Río de las Minas (307 masl, Figs. 1, 2 and 3 b, table 1): from base to top, the interpretation is based on glaciofluvial deposits (facies Gt), lacustrine deposits (LSd and LAI facies), lacustrine beach deposits (SI), and glaciofluvial (Gm, SGt y Gm) deposits. Dating corresponds to the LAI facies.

4.2 Bahía la Lancha (345 masl): this sector corresponds to point 1 (Figs. 1, 2, 3 c, table 1), where a lacustrine beach environment (facies SI) with a further

deepening (facies LA I) and a shallowing represented by beach sand deposits (Sm) can be observed. Fluvial deposits (Gm) were found towards the top of the profile.

4.3 Río Gallo (260 masl): the base and top of the profile were sampled (Figs. 1, 2, 3 d, table1) and glaciolacustrine facies (LAId) were identified.

Flooded areas were reconstructed according to the heights of lacustrine and glaciolacustrine sediments (previously described in the profiles) and through the use of DEM (Table 1, Figs 2, 4 a, b and c). It was determined that for 28289 cal. yr. BP., the Tar - San Martín lake system would have already been formed. Both lakes would have been connected at a height of approximately 320 meters above sea level (Fig. 4 a). Towards the 12111 cal. yr. BP (Fig. 4b), the lake system would have reached its maximum expansion (355 masl). Finally between 9496 and 3742 cal. yr. BP. there is a decrease of the lake system (275 masl). Nevertheless, Tar and San Martín lakes continue connected by Calafate stream (Fig. 4 c).

5. Discussion and conclusions

According to Aristegui et al. (2014), in the Pleistocene - Holocene transition the seasonal variation of west winds and moisture has been widely used as an argument to explain changes in rainfall. In this respect, Boex et al. (2013) propose a regional retraction of the ice mass between 18.1 Ka and 15.5 Ka associated with a change in the atmospheric circulation and an increase in the global average temperature. Darvil et al. (2016) compare the fluctuations of glaciers in Patagonia and New Zealand and expose that the behavior of the ice masses were similar. However, Turner et al. (2004) propose for the eastern slope of the Andes a

regional drop of the lakes caused by the opening of the Ice Field after 12.8 ka associated with a catastrophic event that produced the drainage of the bodies of water into the Pacific Ocean.

This study determines that the ages of lacustrine deposits identified in the area surrounding San Martín Lake represent fluctuations in the level of up to 85m; between 28ka and 12ka a rise of 2.4 m/1000a occurred, and immediately a sharp drop at a rate of 37.4/1000yr. until ca. 9,5ka. These variations in lake levels may have been related to the balance of the ice masses that produced local advances and retreats of glaciers. For the area of Pueyrredón Lake (Horta, 2014) and Perito Moreno National Park (Horta *et al.*, 2019), propose the location of the glacial front approximately on the current border between Argentina and Chile, which extends southwards of this study area.

Approximately about 28 Ka. the Tar - San Martín lake system was formed, which corresponds with the ancient ages raised for other areas of the eastern slope of the Andes: Burmeister Lake (31 Ka., Horta *et al.*, 2017) and Pueyrredón Lake (28 Ka., Horta *et al.*, 2015).

The glacier fluctuations proposed by Glasser *et al.*, (2011) for San Martín Lake, could establish the connection between their shrinkage, and the formation and fluctuations of this lake system. This lake system could have been initially formed as a result of the thaw, subsequent to the deposition of moraine belts (37 and 34 Ka).

The biggest spreading of this lacustrine system would be coincident with the maximum expansion posed by Horta *et al.* (2017) for Belgrano Lake around approximately 12 Ka, as well as between 17 and 12 Ka for Pueyrredón Lake (Horta

et al., 2015). As regards Buenos Aires Lake, Burgois et al. (2016) propose for the high lake a level of 415 m between 14.5 and 12.9 Ka, 200 m above the current level. Lacustrine deposits described in Bahía de la Lancha (345 masl, 100 m above the present level) dated 12.1 ka, would be related to the ice mass advance that occurred during the Antarctic Cold Reversal (ACR). There are records of the glacier advance associated with the ACR in the Andes between tropical latitudes (Jomelli et al. 2014) and subantarctic ones (Graham et al., 2107). In this respect, Marger and Ftzisimons (2007) also relate the lacustrine and glaciolacustrine facies of Lake Pukaki to glacier fluctuations that occurred between 36 ka. and 12 ka in New Zealand.

In the area of study (ca. 28 ka, Figure 5 lower paleogeographic reconstruction), the front of the ice mass would have enabled the formation of the first proglacial lakes of the eastern slope of the Andes in the late Pleistocene. In general, lake deposits dated between 28 ka and 3.7 ka indicate a gradual contraction of the lakes (Fig. 5) followed by a sudden rise around 12.1 ka that can be related to the ACR.

Around 12 ka, paleogeographic reconstructions indicate the maximum lacustrine expansion and that the current peninsulas of Maipú, Chacabuco and Cancha Rayada used to be islands (lower and middle paleogeographic reconstruction, fig. 5); the first hunter-gatherer occupation (11 cal ka) would have occurred 1000 cal. years after that date (upper paleogeographic reconstruction, Fig. 5). Therefore, the settlement in the basin would have taken place during the period of contraction of the lake system (ca. 11.1 ka, Fig. 5) and the establishment of the current configuration of the coastlines. This scenario would have allowed the

exploration of the western areas and the gradual incorporation of the forest to the logistical range of hunter-gatherer populations (Belardi and Carballo Marina 2014; Espinosa et al. 2013). Similarly, the levels of Tar and San Martín Lakes would not have been an obstacle for human populations flow through the steppe during Holocene.

The different paleobathymetric indicators point to the dynamics of the lake system evolution. The registered paleocoasts (340 masl and 310 masl) could be associated with levels of stability of the lake system during the Pleistocene, where the fan-deltas of the Tar Lake (apex to 340 masl) and the North Coast fan-delta (apex 313 masl) would have begun to form. The oldest fan-delta of Estancia El Condor (apex 360 masl) would be contemporary to the lacustrine deposits of Bahía de la Lancha during the maximum expansion of the lake system.

The analysis and interpretation of stratigraphic profiles reflects the interaction of sedimentary environments during the evolution of the lake system. Paleogeographic maps set with the ages obtained from the lake levels (Fig. 5) provide a chronology of the bathymetric fluctuations of the Tar - San Martín lake system during the Late Pleistocene - Early Holocene.

It was only towards the Late Pleistocene - onset of the Early Holocene, when the levels of Tar and San Martín Lakes stabilized and thus the current landscape was shaped, that the circulation of hunter-gatherer populations to the west and between the north and south shore of these lakes became possible.

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Figure Captions

Fig. 1: Location of the basin under study (image LandSat 8). The datings are located in: 1-Rio de las Minas (307 MASL), 2- Bahía de la Lancha (345 MASL), 3- Río Gallo (261 MASL), 4- Campo de bloques 1, Oquedad (340 MASL, Belardi et al., 2010, 2013), 5- EM 02 (314 masl); 6- LSM 05 (320 MASL), 7- LSM 15 (310 masl), 8- LSM 08 (320 MASL), Glasser et al., 2011. Paleographic references: 9 Fan-delta Estancia Cóndor, 10 Fan-delta Tar Lake, 11 Fan-delta north coast and, 12 Fan-delta West coast. Paleocoasts at 340 and 310 MASL over the Chacabuco tributary are highlighted in black and yellow.

Fig. 2: Stratigraphic profiles with the indication of facies and sedimentary environments interpreted. They are located from west (left) to east (right).

Fig. 3: Paleobathymetric indicators: a) - West viewing of the fan-deltas of Estancia El Condor; the older one (apex is 340 masl) is indicated in yellow, while the younger one (apex at 310 masl) is displayed in green. b) - Rio de las Minas profile (A-B profile, highlighted in white), where the yellow symbol (*) indicates the sampling point where the dated sample was taken. c) - Lake levels in Bahía de la Lancha. d) - Details of glaciolacustrine levels in Río Gallo (point 3, Fig. 1), where the dropstones can be observed (highlighted in red).

Fig. 4: Reconstruction of flooded areas based on the heights of the lacustrine deposits of a- Rio de las Minas (320 masl) 28289 cal. yr. BP. (the estimated area covered by ice is displayed in gray to the left), b- Bahía la Lancha (355 masl) 12111 cal. yr. BP., and c- Río Gallo (275 masl) between 9496 and 3742 cal. yr. BP.

Fig. 5: Paleographic evolution over time. On the left, the relation between lake level ages with erratic boulders (Glasser et al., 2011) and the first human occupation (point 4 in the upper image, (Belardi et al., 2010, 2013)). To the left of the curve, the areas flooded, and to its right, the emerged areas. Encircled numbers correspond to references of Fig. 1

Table Captions

Table 1: Location, heights and radiocarbon ages of the analysed basin; the symbol (*) refers to the datings exposed in this paper.

Table 2: Code of facies and sedimentary environments.

Point	Locations	Elevations (MASL)	Coordinates	Age BP	Calibrate Age BP	Laboratory
1*	Río de las Minas	307	49° 1'24"S - 72°13'27"W	24300 ± 170	28289	NSF Arizona
2*	Bahía la Lancha	345	48°55'48"S - 72°14'45"W	10361 ± 34	12111	NSF Arizona
3a*	Río Gallo (Sup level)	261	49° 0'35"S - 72°33'12"W	3508 ± 23	3742	NSF Arizona
3b*	Río Gallo (Inf level)	260	49° 0'35"S - 72°33'12"W	8517 ± 31	9496	NSF Arizona
4	Campo de Bloques 1, Oquedad	340	49° 11'28.5"S - 72°15'24.4"W	9760 ± 60	11139	Belardi et al. 2010, 2013
5	EM 02	314	49° 6'36"S - 72°30'0"W		14.3	Glasser et al. 2011
6	LSM 05	320	49°13'48"S - 71°55'12"W		27.5	
7	LSM 15	310	49° 10'26"S - 72°5'33"W		34.4	
8	LSM 08	320	49° 14'24"S - 71°55'48"W		37.6	

Facies	Structures	Environment
GM	Massive clast-supported gravel with subrounded to subangular clasts.	Fluvial
Gt, Gm, SGt	Clast-supported gravel with tabular stratification, massive gravel, sand with dispersed clast gravels with tabular stratification	Glaciofluvial
LA l and LA ld	Laminated clayey silts and laminated clayey silts with dropstones.	Lacustrine and glaciolacustrine
Sm, Swl y Sl	Massive sandstones, wavy laminated sandstones and laminated sandstones.	Beach deposits

W

Rio Gallo
(260 masl)

Bahía de la Lancha
(345 masl)

E

Rio de las Minas
(307 masl)

References

LA Id

Sm

**Lacustrine
Shore**

Swl

**Lacustrine
deeper**

LA I

Sl

**Lacustrine
Shore**