

Late Pleistocene to Middle Holocene paleoenvironmental changes based on diatom record in Salina del Bebedero (San Luis, Argentina).

Cambios paleoambientales desde el Pleistoceno tardío hasta el Holoceno medio basados en el registro de diatomeas en la Salina del Bebedero (San Luis, Argentina).

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ABSTRACT

This study analyzes the environmental changes that occurred in the western sector of the San Luis province (Argentina) during the Late Pleistocene to Middle Holocene period (approximately 12,600 to 3,600 years BP). The information provided by diatoms as paleobiological indicators is used for this analysis. We examined the lower 5 meters of the 10-meter-long SBIII core, which was recovered from the endorheic and hypersaline shallow lake known as Salina del Bebedero (33°20'S-66°45'W, 380 m a.s.l.).

The observed peaks of relative abundance of the planktonic diatom *Cyclotella choctawhatcheeana* suggest episodes of substantial water supply to the shallow lake from the Andes mountains via the Desaguadero river. These episodes were interspersed with periods of low water levels, resulting in very shallow to marsh environments characterized by the presence of epiphytic and benthic diatoms.

Furthermore, we discuss and integrate the inferred paleoenvironmental information obtained from the diatom records, along with data from other proxies such as pollen and sedimentology. This integration aims to enhance the previously developed paleoenvironmental model for the region, covering the period between approximately 12,600 and 3,600 years BP.

Overall, this research significantly contributes to the understanding of diatom assemblages in hypersaline lacustrine systems of the eastern Andes throughout the studied period, revealing the importance of certain taxa as indicators of wetter conditions during the early Holocene and in more recent stages within this timeframe. Additionally, this study aims to expand our existing knowledge of diatoms biodiversity in this province.

Keywords: Bacillariophyceae; hypersaline; shallow lake; palaeolimnology; bioproxy; Argentina; Late Quaternary.

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RESUMEN

Este trabajo aporta herramientas de análisis para la comprensión de los cambios ambientales ocurridos en el sector occidental de la provincia de San Luis (Argentina) entre el periodo del Pleistoceno tardío y el Holoceno medio (ca. 12.600 a ca. 3.600 años AP), utilizando la información provista por diatomeas, como indicadores paleobiológicos. Se analizó la mitad inferior del testigo SBIII (10 a 5 m) obtenido en la cuenca endorreica salino-lacustre Salina del Bebedero (33° 20' S; 66° 45' O; 380 (m s.n.m.).

Los picos de mayor abundancia relativa de la especie planctónica *Cyclotella choctawhatcheeana* sugieren episodios de gran aporte de agua a la laguna, procedente de la Cordillera de los Andes a través del río Desaguadero.

Estos episodios estuvieron intercalados por periodos con bajos niveles lacustres (ambientes someros o palustres) caracterizados por la presencia de diatomeas epifíticas y bentónicas y se identificaron intervalos donde no se encontraron diatomeas.

También discutimos y articulamos la información paleoambiental inferida para el período comprendido entre ca. 12.600 y 3.600 años AP, a partir de los registros de diatomeas, con la información disponible de otros *proxies* (polen y sedimentología), con el fin de mejorar el modelo paleoambiental generado previamente para la región.

Este trabajo amplía el conocimiento de ensamblajes de diatomeas en sistemas lacustres hipersalinos de los Andes orientales durante el periodo estudiado, revelando la importancia de algunos taxones como indicadores de condiciones más húmedas durante el inicio del Holoceno y en etapas más recientes dentro de este periodo y, además, este estudio, profundiza los conocimientos existentes sobre la biodiversidad diatomológica en esta provincia.

Palabras clave: Bacillariophyceae; laguna hipersalina; paleolimnología; paleobiocindicador; Argentina; Cuaternario reciente.

Introduction

Diatoms (Bacillariophyceae) are highly valuable indicators for paleolimnological studies due to their abundant and well-preserved siliceous cell covers (frustules) deposited in lacustrine sediments (Smol & Cumming, 2000). Due to their short life cycle, diatoms are able to respond quickly to changes in their environment by using a wide range of adaptive strategies. The relationship between some groups of aquatic organisms, usually common in the lacustrine sediments, and the characteristics of their habitat have been quantified and used to characterize these environments. When reconstructing paleoenvironments using *bioproxies*, it is assumed that the ecological preferences of the species used as indicators have remained unchanged over time, at least from the Late Quaternary to the present (Birks, 2005). Therefore, by examining the autoecological information of present-day species, valuable inferences can be made about past environments.

The understanding of Late Quaternary paleoenvironmental conditions in the central-western region of Argentina remains limited, mainly due to the scarcity of paleoecological and paleoclimatic archives with continuous records of high temporal resolution. The difficulty for finding this type of archives can be attributed to the arid and semi-arid conditions pre-

vailing in the region, which show significant variability in the deposition rates of clastic materials in sedimentary environments. In addition, the development of a vegetation with a low cover and a low pollen production must be taken into account. (Paez et al., 2010).

When studying the diatom phycoflora of a specific region, it is crucial to have access to specialized literature available to compare the specimens found with those described in specific works (Díaz Pardo et al., 2008). As highlighted by Maidana and Seeligmann (2006), most of the research published in Argentina until the end of the 20th century relied on identifications using monographs predominantly focused on European flora, with a smaller proportion referring to North American species. Seeligmann and Maidana (2013) further suggest that the high percentage of European and North American species reported in earlier works on diatoms from Argentina was likely the result of forcing the identifications to assign names of taxa known from the Northern Hemisphere. Only in the past two decades have several South American monographs been published (Metzeltin & Lange-Bertalot, 1998, 2007; Metzeltin et al., 2005). This limited knowledge of regional floras significantly hampers the identification of diatom species in the region.

Salina del Bebedero is a hypersaline endorheic basin located in the arid-semiarid region of central-western Argentina (Fig. 1). The basin's bottom contains a sedimentary accumulation that spans at least the last ca. 20,000 ^{14}C years BP (González, 1994), and has garnered attention for its potential as a paleoenvironmental archive. The first paleoenvironmental studies took place in the final decades of the 20th century when paleoshore lines associated with former lake levels were identified (González, 1981). Within these basins, geological and micropaleontological studies have been carried out by Maidana (1994), González & Maidana (1998), García (1999), and others. In these studies, samples from an exposed profile of the Bebedero stream, located near the saline area, were analysed (Fig. 1). Their strata can be correlated by considering the numerical ages and sediment characteristics, such as texture and color, the latter suggesting the dominant depositional environment. Those studies have helped to interpret the fluctuations in lake level as a consequence of variations in the fluvial input of meltwater originating from the Andes Mountain Range.

In the 1990s, the Patagonian Lake Drilling Project (PATO), an international and multidisciplinary initiative, aimed to analyze the paleoclimatic records of

extra-Andean lakes in Argentina. The project sought to improve our understanding of interhemispheric climate dynamics of climate changes in America on glacial-interglacial scales. As part of this project, four drillings were conducted in the saline depression (SBI to IV, Fig. 1). Initial results from core SB-IV, which included mineralogical analysis of sediments, pollen, and diatoms (González et al., 1998), indicated changes in water levels. However, precise chronological calibration was challenging due to the lack of accurate dates. The subsequent core examined (SB-III) spans the past 12,600 years (radiocarbon dates) and focused on pollen and carbon analysis (Rojo, 2003; Rojo et al., 2012).

In the context of understanding environmental changes in the area of San Luis, Argentina over the past 12,600 years BP, this study aims to provide analytical tools using diatoms as biological indicators. Additionally, it aims to deepen our existing knowledge of biodiversity in this region. The present paper qualitatively and quantitatively analyzes diatom assemblages recovered from the lower half of a sedimentary core obtained from the endorheic shallow lake Salina del Bebedero. It compares the dominant assemblages in each sample to infer the environmental evolution during the considered period.

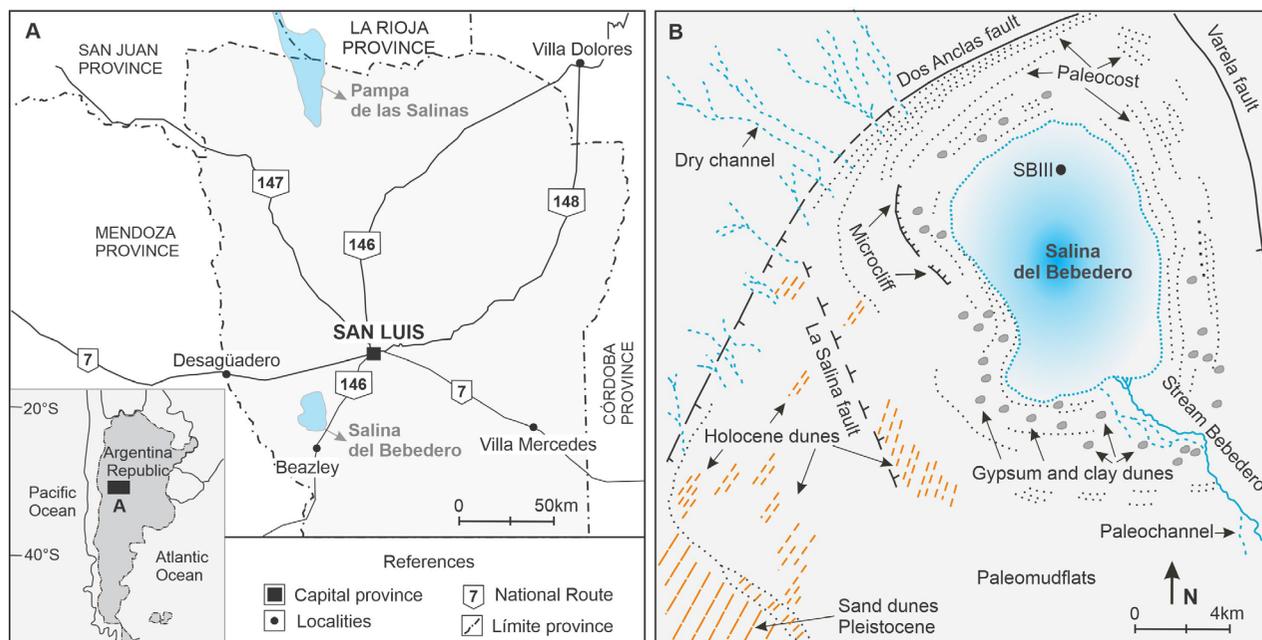


Figure 1.— Geographic location and subenvironments of Salina del Bebedero, with the location of SBIII (study code) (Modified from González, 1994 and Chiesa et al., 2015).

Study Area

Salina del Bebedero is a saline-shallow lake situated within an endorheic basin consisting of a network of ephemeral tributaries (33°20'S-66°45'W, 380 m a.s.l.) located in the western sector of the San Luis province (Fig. 1). The lake receives water from the Desaguadero River, which flows into it through the Bebedero Stream (González, 1981). During the summer rainy season, the basin becomes flooded, reaching depths of approximately 20 cm. During the period of highest evaporation, the salts concentrate and precipitate within the depression. According to Deletang (1929) and Cordini (1962) sodium chloride (halite) is the predominant salt. The surface of the salt mirror covers an area of 72 km² and consists mainly of clastic sediments, including clay, silt, and fine sand (Chiesa et al., 2015). Presently, the lake is exploited commercially for salt production.

The lake has a sub-circular shape and is surrounded by eolian sediments, such as mantles, dunes, and even loessial deposits (Fig. 1). Towards the east and south, there is a gradual transition from distal foothills to alluvial fine-grained materials and salts accumulations, with sodium chloride being predominant in the lacustrine sector. On the western and northern sides, fluvial processes are evident through the deposition of fine sands and gravels during the Late Pleistocene. In these areas, the lake features elevated and sloping margins, which have been interpreted as ancient shorelines formed during the Last Glacial Maximum (González, 1994). Despite fluctuations in lake level, the basin under study has consistently remained a saline environment throughout the period under study.

The region experiences a predominant semi-arid climate (Burgos & Vidal, 1951), with an average annual temperature of 17.5 °C and an average annual precipitation of 738.5 mm (data from the San Luis meteorological station, 2000-2009 period, as reported by the National Meteorological Service). The area, influenced by the dynamic effects of the South Atlantic anticyclone (winds from the east or *easterlies*), is characterized by a subtropical climate (Prohaska, 1976). Precipitation ranges from approximately 800 mm y⁻¹ in the eastern area, near the border between the provinces of San Luis and Córdoba,

to less than 300 mm y⁻¹ in the western area, adjacent to the province of Mendoza. In the study area, the average annual precipitation values for the second half of the last century (1950-2000) were 475 mm and 350 mm in the eastern and western areas, respectively.

The South American Arid Diagonal is a dry belt characterized by the lowest moisture contribution from both Atlantic and Pacific air masses (Bruniard, 1982). It stretches northwest-southeast to the west of the lake. On the western side of this belt, humidity is mainly due to Pacific anticyclonic air masses and westerly winds from mid-latitudes. On the eastern side, humidity is influenced by air masses from the Atlantic Ocean, facilitated by the Chaco low-pressure system, which forms mainly during summer and allows moisture to enter from southern Brazil and Bolivia (Prohaska, 1976). As a result, Salina del Bebedero currently receives its moisture mainly from summer rainfall from the Atlantic Ocean.

However, during the Late Pleistocene and Holocene, the basin probably received contributions of Pacific water when the snow accumulated in the glaciers of the Cordillera de los Andes melted, and the runoff was collected by the Desaguadero-Salado fluvial system and the Bebedero Stream (González, 1994). At the present, this fluvial system is partially disconnected from the lake. Despite fluctuations in lake levels, the basin has remained saline throughout the Holocene.

Materials and Methods

The 10 m long SB-III core was extracted in 1998, as part of the PATO project (<http://lrc.geo.umn.edu/PATO/index.html>). It was extracted using a percussion drilling system, situated approximately 2 km from the northern edge of Salina del Bebedero shallow lake. Subsampling of the core was carried out at the Universidad Nacional de San Luis. The pollen and sedimentological analyses, as well as the radiocarbon dates, have already been published by Rojo (2003) and Rojo et al. (2012).

In this study, we analyzed 43 subsamples obtained at intervals of approximately 8 cm from the lower half of the core (from 10 to 5 meters depth). These subsamples cover a chronological period between

12,600 and 3,600 years BP Rojo et al. (2012) (Tab. 1).

The subsamples were processed using standard techniques for qualitative and quantitative diatom analysis, following the methods described by Battacharjee (1986). In this process, 1 gram of dry sediments from each subsample was oxidized with H₂O₂ (100 Vol.) at 80°C to remove any organic matter residues that could interfere with the accurate observation of the material. The resulting suspension was then neutralized through successive washes with distilled water, and permanent slides were prepared using Naphrax® (ni=1.73).

To identify the dominant assemblages in each subsample, relative abundances (%) were estimated by counting a minimum of 200 valves per slide. Diatom concentration was expressed as the number of valves per gram of dry sediment. The slides used in this study have been deposited in the collection of the Laboratorio de Diatomeas continentales, Departamento de Biodiversidad y Biología Experimental, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires (UBA).

The slides were observed with a Polyvar Reichert-Jung binocular light microscope (LM), with PlanApo 100X, NA 1.32 immersion objective, DIC optics, and a Canon EOS 600D digital automatic camera.

For the observation of very small specimens or those with diagnostic features that cannot be distinguished using a light microscope (LM), a Carl Zeiss SUPRA 40 scanning electron microscope was utilized. To prepare the samples for SEM analysis, a drop of the final cleaned suspension was allowed to dry on a metallic stub. The sample was then coated with a thin layer of gold at the Centro de Microscopías Avanzadas (CMA), Facultad de Ciencias Exactas y Naturales (UBA).

Valve counts from each slide were converted to percentages and plotted using Tilia v1.7.16 software (Grimm, 1991). Only species with relative abundances greater than 3% in at least one sample were included in the plot. A dendrogram was constructed using CONISS (Constrained Incremental Sum of Squares program, Grimm, 2004), grouping samples according to their similarity in the stratigraphic sequence with respect to the upper or lower sample.

The identification of diatoms was mainly based on the monographs by Rumrich et al. (2000), Krammer & Lange-Bertalot (1986, 1988, 1991), Levkov (2009), Levkov et al. (2013), as well as other specific works. Autoecological information for the identified taxa was obtained from the literature consulted for each species and from sources such as Van Dam et al. (1994) and Lowe (1974), among others.

During the counting process, it was difficult to differentiate between species of *Denticula* Kützing and *Epithemia* Kützing because their frustules often appeared in girdle view. Therefore, they were only considered at the genus level in the analysis (Table 1).

Results

Out of the 43 subsamples analyzed, 29 were found to be sterile. In the remaining 14 subsamples, a total of 32 genera were identified, with 61 infrageneric taxa. However, due to poor preservation of the valves, 23 of these taxa could not be identified at the species level. Additionally, there were other valves that could not be recognized even at the genus level.

The sedimentological characteristics of the Salina del Bebedero III (SB III) drilling (Fig. 2) in the sequence spanning from 10 to 5 meters depth, generally show an alternation of clastic facies deposits (sands, silts, clays) and evaporites (carbonates, sulfates, chlorides). The studied sequence is clearly bounded by two numerical ages (Tab. 2) and represents lacustrine conditions during the lower and middle Holocene in the central-western region of the Western Depression, and its association with the Mid-Holocene Climatic Optimum event. From a stratigraphic point of view, it corresponds to the Arco del Desaguadero Formation and the Río Desaguadero Member (Chiesa et al., 2015).

As expressed by Rojo et al. (2012) and Chiesa et al. (2015), within this stratigraphic interval, there is a marked dominance of insoluble materials (clastics and carbonates) compared to soluble materials (sulfates and chlorides) (Table 3 and 4). This characteristic is noteworthy because in the basal and uppermost levels, the volume percentage of clastics ranges between 60% and 80%, while in the intermediate levels, the values of sulfates and chlorides slight-

Table 1. Infrageneric taxa identified along the lower 5 m of core SBIII

<i>Amphora copulata</i> (Kützing) Schoeman & Archibald	569	570	612	628	772	778	794	800	808	824	838	856	866	916
	0,3	0,16	0,69	0,10		0,4	0,1	0,08			0,17	1,0	0,20	
<i>Caloneis westii</i> (W. Smith) Hendey	0,5	0,05			0,29		0,3	0,16	0,2		0,11	1,2		0,5
<i>Campylodiscus</i> aff. <i>bicostatus</i> W. Smith	2,9	0,11	0,69			0,4					0,22	2,2	2,45	
<i>Cocconeis</i> aff. <i>euglypta</i> (Ehrenberg) Van Heurck	0,8	0,98	2,78	0,20				82,65	5,9		0,44			
<i>Cocconeis</i> sp.											0,06			
<i>Cyclotella choctawhatcheeana</i> A.K.S. Prasad	53,1	89,62	24,31	0,20	35,88	91,0	90,4	0,0	82,3	86,07	87,47	76,7	51,12	70,7
<i>Cymbella</i> sp.													0,20	
<i>Denticula</i> spp.	20,4	0,16	43,75	8,62	3,82		0,6	0,6	1,6	5,22	0,66	0,8	2,04	9,0
<i>Diatomella balfouriana</i> (Greville) W. Smith											1,38	0,1		
<i>Diploneis chilensis</i> (Hustedt) Lange-Bertalot	0,3					0,7	3,4	3,91			2,65	5,6	3,07	3,6
<i>D. smithii</i> (Brébisson) Cleve 1894 var. <i>smithii</i>						0,1					0,50			
<i>D. smithii</i> var. <i>rhombica</i> Mereschkowsky			0,69											
<i>Diploneis</i> sp.	3,4	0,05	4,17	0,20	0,29	1,4	3,9	10,59	0,2	0,75	0,33	3,3	9,41	9,3
<i>Encyonema</i> sp.		0,05		0,10										
<i>Ephitemia</i> spp.	1,6	0,27	3,47	0,71	0,59	0,1	0,9	1,55	0,2	0,25	1,99	0,4	23,52	0,8
<i>Fragilaria</i> sp1.	0,3			9,33										
<i>Fragilaria</i> sp2.			0,69											
<i>Gyrosigma</i> sp.	1,6	0,82							0,3			0,1	0,20	2,8
<i>Halamphora atacamana</i> (Patrick) Levkov									2,3					
<i>H. aff. coffeiformis</i> Agardh									0,3					
<i>Halamphora</i> sp.					0,59									
<i>Hantzschia amphyoaxis</i> (Ehrenberg) Grunow in Cleve & Grunow	0,5	0,38			0,59	0,1			0,2	0,50	0,06		0,20	
<i>Karayevia submarina</i> (Hustedt) Bukhtiyarova											0,11	0,1		
<i>Luitcola paramutica</i> D. G Mann		0,27			0,29									
<i>Mastogloia atacamae</i> Hustedt											0,44	0,2		
<i>M. braunii</i> Grunow	5,0	1,37	1,39	0,30	0,29	5,7		1,6	0,25					
<i>M. aff. harrissonii</i> Cholnoky		0,05									0,06			
<i>M. lanceolata</i> Twaites	0,5	0,16	1,39					0,5						
<i>M. pumila</i> (Grunow) Cleve		0,49												
<i>Mastogloia</i> sp.	0,5	0,11	1,39	0,51	15,59					0,25				
<i>Melosira moniliformis</i> Müll	0,3	3,01									1,49	5,3	3,07	0,5
<i>Microcostatus</i> sp.				7,00										
<i>Navicula</i> aff. <i>radiosa</i> Kützing														
<i>Navicula</i> aff. <i>salmicola</i> Hustedt	0,5			11,16					0,2					
<i>Navicula</i> sp.				0,20					0,3				0,20	
<i>Navicymbula pusilla</i> Krammer			1,39	0,20							0,11			

	569	570	612	628	772	778	794	800	808	824	838	856	866	916
<i>Nitzschia</i> aff. <i>fonticola</i> Grunow in Cleve & Moller.		1,09		39,15			0,1		0,0	3,48				0,5
<i>N. hustedtiana</i> Salah	5,3	0,38	4,86	0,20				0,24	2,1		0,50	0,6	0,20	1,8
<i>N. aff. pusilla</i> Grunow emend. Lange- Bertalot					0,59									
<i>N. aff. sigma</i> (Kützing) W. Smith				0,30										
<i>N. sinuata</i> (Thwaites) Grunow var. sinuata	0,3													
<i>Nitzschia</i> sp1.				0,10										
<i>Nitzschia</i> sp2.				19,78						2,24				
<i>Nitzschia</i> sp3.														
<i>Nitzschia</i> sp4.				0,41										
<i>Nitzschia</i> sp5.				0,10										
<i>Nitzschia</i> sp6.					0,29									
<i>Nitzschia</i> sp7.				0,51										
<i>Pinnularia borealis</i> Ehrenberg var. borealis							0,1					0,2		
<i>Pleurosigma</i> sp.		0,05	5,56	0,10	0,29				1,5				0,20	
<i>Pseudostaurosira brevisiriata</i> (Grunow) Williams & Round			0,69								0,06			
<i>Rhopalodia gibberula</i> (Ehrenberg) O. Müller		0,05							0,3					
<i>Staurosira venter</i> (Ehrenberg) Cleve & J.D. Moller											0,17		0,41	0,3
<i>Staurosirella pinnata</i> (Ehrenberg) Hustedt					40,29									
<i>Staurosirella</i> sp.												0,55	0,1	0,20
<i>Surirella striatula</i> Turpin		0,11					0,1	0,16		0,25	0,28	1,7	2,45	
<i>Tabularia</i> sp.	0,3	0,05	0,69	0,10		0,1			0,2	0,25	0,06	0,2	0,41	0,3
<i>Ulnaria</i> sp.	0,5		0,69											
Taxones no identificados	1,1	0,11	0,69	0,41	0,29			0,08		0,50	0,17		0,41	

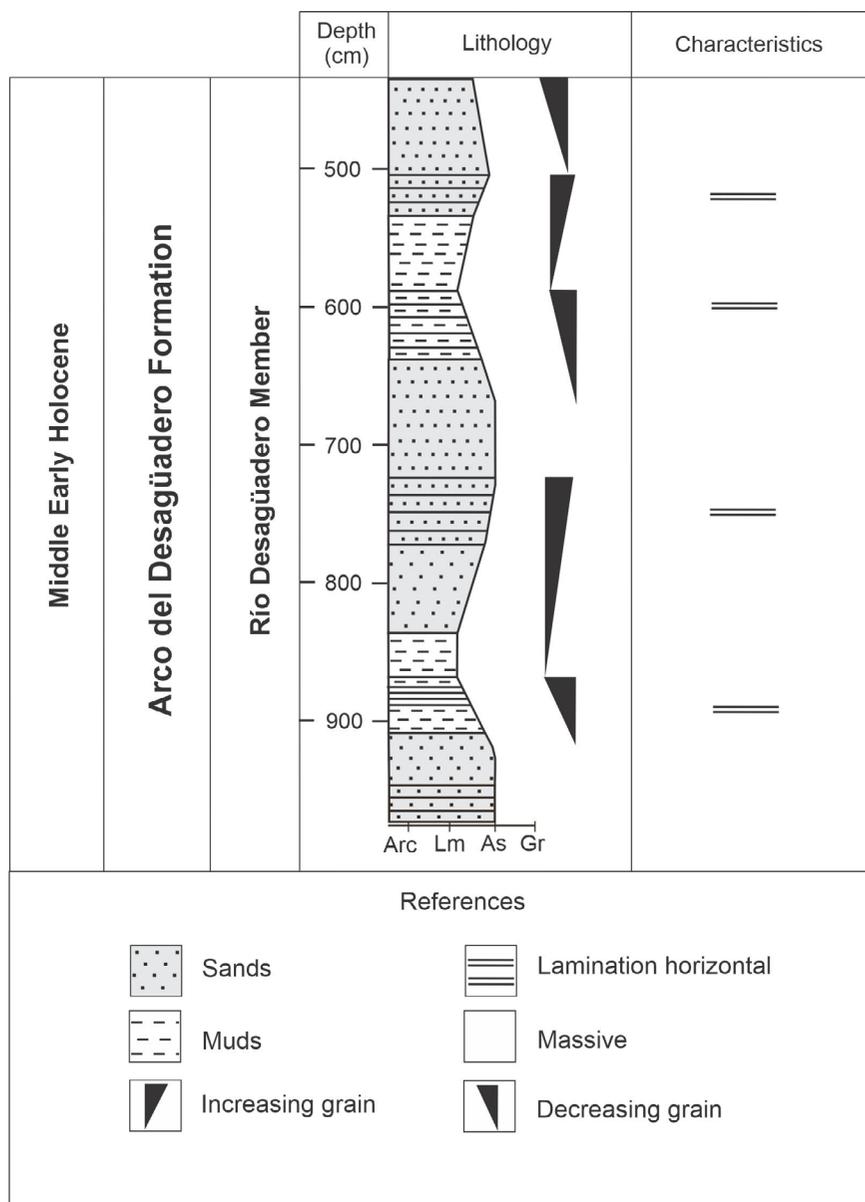


Figure 2.— Stratigraphic column.

Table 2: Radiocarbon numerical ages (Taken from Rojo et al., 2012).

Sequence	Radiocarbon age (years ^{14}C AP)	Calibrated radiocarbon age (cal AP) with 2 sigma	Median (cal AP)	d^{13}C (‰)	Depth (m)	Dated Material /Technique	Lab number
SBIII	3444 ± 54	(3476-3826)*	3633	-18,5	5,56	Sediment/AMS	AA81414
	10700 ± 170	(12103-13055)**	12603	-17,6	9,43	Sediment/AMS	AA81413

* OxCal 4.1, SHCal 04; **OxCal 4.1, IntCal 09

Table 3: Percentage values (%) of the main sedimentary components

Material	Sand	Silt	Clay	Carbonates	Sulfates	Chlorides	Clastics volume	Precipitated volume
Depth 10 to 5 m	47	42	11	3	12	27	58	42

Table 4: Percentage values (%) of the clastic components (Taken from Rojo et al., 2012).

Sedimentary Periods		Depth (cm)	Clay (0-3,9 μm)		Silt (3,9-62,5 μm)		Sand (62,5-2000 μm)				
Core SB III	1.3	590	10,81	10,81	48,05	48,05	41,13	41,13	47,12		
		685	4,81	7,47						29,05	36,27
	1.2	785	10,13		11,03	43,49	41,85	46,37			
		890	29,79	13,487						67,46	43,51
	1.1	930	5,54		41,85	31,27	43,51	63,18			
		975	5,13	31,8						63,06	
	The values of clays, silts, and sands are expressed as percentages of the clastic fraction										

ly exceed 50%. Limited to the dimensions of the core, it is observed that the strata vary in thickness between 10 and 50 cm, and their dominant color is grayish-brown to yellowish-brown, while markedly saline levels appear white.

The intense temporary summer rains also generate variability in the energy of these fluvial channels, as evidenced by the erosion of the basin slopes, the influx of sands, and the presence of fine gravels in the Pleistocene paleoshores.

The radioisotope ages, obtained in the core of the background (Rojo et al., 2012) enable us to propose a chronostratigraphic scale. Despite potential stratigraphic discontinuities, the deposition rate in the lacustrine environment is estimated to be approximately 0.8 mm per year.

Most of the observed specimens were poorly preserved, highly abraded and/or fragmented. In several cases, they could be assigned to a recognized genus, but identification to species level proved very difficult. The genera with the most complete valves were *Cymbella*, *Encyonema*, *Diploneis*, *Cyclotella* and *Melosira*, while those with more fragmented valves were *Tabularia*, *Ulnaria*, *Surirella* and *Campylo-discus*; in these cases, it was possible to identify the species

The absolute abundance of diatoms ranged be-

tween 68,600 and 14,800,000 valves gr^{-1} of dry sediment. Samples with less than 100,000 valves g^{-1} were considered unsuitable for paleoenvironmental inferences, (Bradbury, 1988).

Throughout the analyzed sequence, three peaks of absolute abundance were observed, coinciding with a higher frequency of *Cyclotella choctawhatcheeana* Prasad (Fig. 3). This species dominated in practically all the fertile samples, with a relative abundance of 70% or more, except in the sample at 800 cm depth where it was absent, as well as in the sample at 628 cm depth where it occurred at a very low frequency (2%). The first of these samples was dominated by *Cocconeis* aff. *euglypta*, possibly an epiphytic species. In the last sample, the dominant forms (*Nitzschia* aff. *fonticola* and *Nitzschia* sp2) could be considered benthic, as is the case with most species of the genus (Lowe, 2003).

Most of the identified species have cosmopolitan distributions or have wide geographic ranges. For instance, *Cyclotella choctawhatcheeana* has been recorded in Croatia, Germany, the United States, Mexico, and Argentina (Prasad et al., 1990; Maidana & Romero, 1995; Burić et al., 2007; Oliva et al., 2008; Malešević et al., 2015, among others). *Mastogloia lanceolata* is mentioned in Europe, Africa, and Argentina, while *Nitzschia hustedtiana* is known in

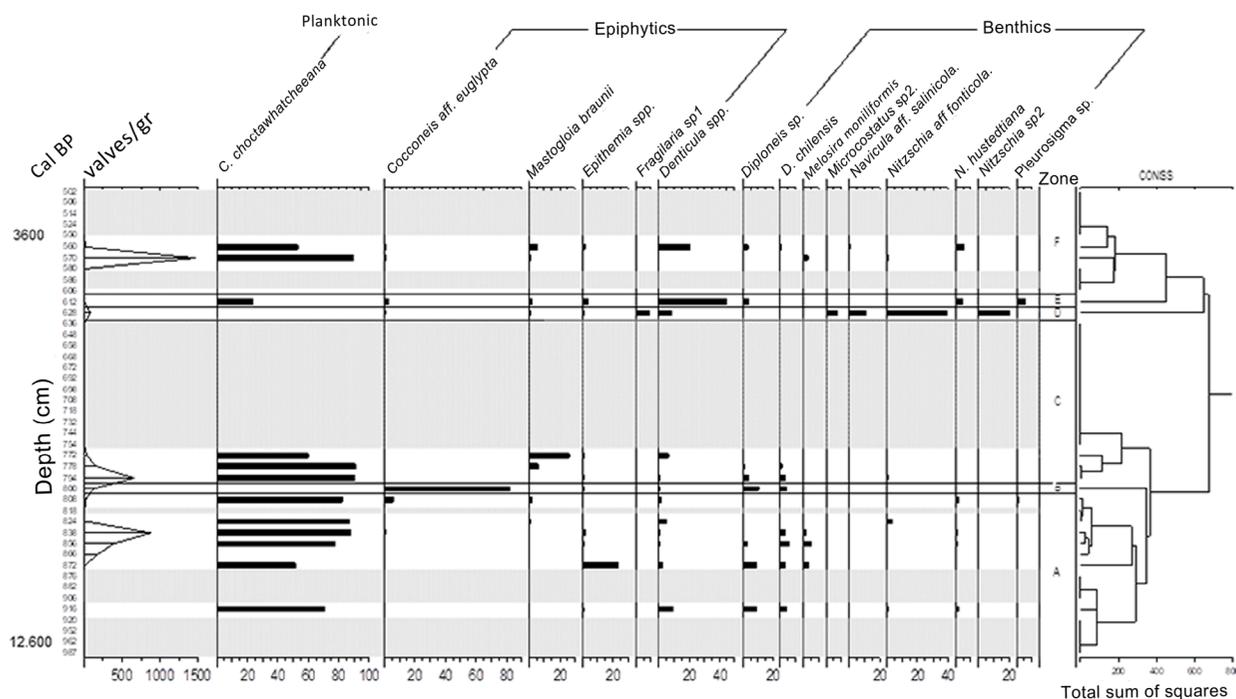


Figure 3.— Comparison of variations in absolute abundance (leaflets for gram of dry sediment) of diatom species with relative abundances greater than 3%. The gray zone represents sterile samples.

Africa, Israel, and Argentina. Almost all of the identified species have been previously reported in other aquatic environments in Argentina, with the exception of *Karayevia submarina* (Hustedt) Bukhtiyarova, which is known in Venezuela and Europe, *Mastogloia harrisonii* Cholnoky, previously mentioned only in South Africa, and *Luticula paramutica* Mann, mentioned in Europe, Israel, and the United States.

The most abundant species described in the sedimentary sequence are broadly tolerant to salinity (Tab. 1).

Only one of the identified species is planktonic (*C. choctawhatcheeana*), while the rest are mostly benthic (or presumably benthic), either periphytic, epiphytic or aerophytic.

Based on the results of the cluster analysis using the relative abundance of taxa present at > 3% in at least one sample (Tab. 1), the sedimentary sequence analyzed in core SB-III can be divided into six zones (Fig. 3):

Zone A (1000 cm to approximately 801 cm): Samples from 1000 to 920 cm, 906 to 876 cm, and 818 cm depth were sterile. The higher abundance of valves is found in the upper part of the zone. In the non-ster-

ile samples, *C. choctawhatcheeana* predominates (45-85%), along with epiphytic species such as *Epithemia*, and benthic species like *Diploneis chilensis*, *Diploneis* sp.1, and *Melosira moniliformis* in a lower proportion. The absolute abundance is high in this zone (8,700,000 valves gr^{-1}).

Zone B (800 cm): In this zone, the absolute abundance is low (1,300,000 valves gr^{-1}). In the single fertile sample, *C. choctawhatcheeana* disappears, and *Cocconeis* aff. *euglypta* dominates (80%), likely an epiphytic species, along with smaller proportions of benthic forms such as *Diploneis* sp. and *D. chilensis*.

Zone C (approximately 799 cm to 638 cm): Samples located between 754 and 638 cm were sterile, with a peak of diatom abundance only in the first centimeters of the zone. *C. choctawhatcheeana* reappears as the dominant species (over 80% relative abundance), and, to a lesser extent, epiphytic forms like *Mastogloia braunii*, and benthic forms such as *Diploneis chilensis* and *Diploneis* sp. The absolute abundance increases again reaching 6,500,000 valves gr^{-1} .

Zone D (approximately 638 cm to 613 cm): The absolute abundance in this sample is very low,

700,000 gr⁻¹ valves of dry sediment. In the single fertile sample (628 cm), epiphytic forms dominate, such as *Fragilaria* sp. 1 (10%) and *Denticula* spp. (10%), along with benthic species like *Nitzschia* aff. *fonticola* (40%), *Nitzschia* sp. 2 (20%). *Navicula* aff. *salinicola* (10%) and *Microcostatus* sp. 2 (5%) occur in lower abundance, while *C. choctawhatcheeana* is present in very low proportions.

Zone E (612 cm): In this sample, *Denticula* spp. dominates (40%), followed by *C. choctawhatcheeana* (20%). *Nitzschia hustediana* and *Pleurosigma* sp. appear in low proportions (5%).

Zone F (approximately 611 cm to 502 cm): Samples from 611 to 581 cm and from 559 to 502 cm were sterile. From 580 to 560 cm, the importance of *C. choctawhatcheeana* (50 to 90%) increases, and in smaller proportions, *Denticula* spp. (20%) does so. These taxa show an inverse fluctuation: when *C. choctawhatcheeana* decreases, the proportion of *Denticula* spp. increases, and vice versa. The importance of *Mastogloia braunii* increases (6%), while *Nitzschia hustediana* remains consistent. In this area, the highest concentration of diatoms (14,600,000 valves gr⁻¹) coincides with a peak of *C. choctawhatcheeana* (90%).

Discussion

The Late Quaternary sedimentary record in the province of San Luis, specifically in the Salina del Bebedero basin has received limited attention from a phycoecological perspective. This study represents the third contribution to the understanding of diatom phycoflora in this area. Maidana (1994) previously mentioned the diatom content in an exposed profile of Bebedero Stream, a tributary of the saline basin while Daruich & Martinez (2000) described algal communities in the Nogolí River basin.

In the analyzed samples, a total of 32 genera and 61 species were identified, of which 12 had not been previously recorded in the Salina del Bebedero area. Additionally, *Diploneis chilensis*, *Halamphora atacamana*, *Karayevia submarina*, *Luticula paramutica*, and *Mastogloia harrisonii* represent new mentions for Argentina.

In terms of geographic distribution, 21 of the identified species are considered cosmopolitan or have

a wide distribution, while only 3 taxa are exclusive to South America. These are *Mastogloia atacamae*, *Diploneis chilensis* (found in Chile and Argentina), and *Halamphora atacamana* (found in Bolivia, Chile, and Argentina).

Some authors have noted that in these fossil assemblages from saline environments, valves may be partially dissolved or even absent from the stratigraphic record (Battarbee et al., 2005) due to taphonomic processes that occur between the biocoenoses living in water and the thanatocoenoses preserved in sediments (Ryves et al., 2009).

The dominance of medium to fine-textured sands and mudstones (silt and clay) suggests the presence of a lacustrine body with continuous water input, mainly from the Desaguadero River in the south and the fluvial system of the San Luis River and the streams of the San Jerónimo-Balde ravine in the north.

The biota of extreme environments is exposed to climatic events that determine the characteristics of their waters. This usually leads to special adaptations (Sánchez Castillo et al., 1989) and it is common to find a high percentage of endemic species (Morales & Vis, 2007). In the analyzed samples, we did not identify any species that could be considered endemic to the study area. Most of the species identified at the species level have been previously reported in other hypersaline environments in Argentina, such as Laguna La Amarga (Maidana & Romero, 1995), and in some shallow lakes of the high mountains of Northwestern Argentina (NOA) (Seeligmann & Maidana, 2003; Maidana & Seeligmann, 2006, 2015; Seeligmann et al., 2008; Maidana et al., 2009, 2011).

The western winds (*westerlies*) that come from the Pacific Ocean and reach Argentina are blocked by the Andes mountains, which act as a barrier. As these winds pass over the mountains, they cool down and release their moisture in the form of rain and snow. On the other side of the mountains, the descending winds are dry, resulting in arid and semi-arid environments (Minetti et al., 1982). In contrast, the *easterlies* are not blocked by mountain barriers and directly reach the continent, retaining the moisture they carry from the Atlantic Ocean. This leads to precipitation in the region in the form of rain or snow (González & Maidana, 1998).

In the SB-III core of Salina del Bebedero, the most abundant species observed was *C. choctawhatcheeana*, which exhibited three significant peaks of abundance (Fig. 3). This planktonic species is thought to enter the shallow lake from the Desaguadero River, through the Bebedero Stream, where it has been found to be abundant in plankton samples (Maidana, 1994; González & Maidana, 1998). Therefore, the observed peaks in the sedimentary sequence can be attributed to an increase in water supply to the shallow lake, resulting from the melting of ice in the high mountains during spring and summer, as well as an increase in precipitation caused by the South Atlantic monsoon (Piovano et al., 2009; Chiesa & Ojeda, 2021). Consequently, winters would have experienced very low temperatures and high humidity, leading to ice formation, while summers would have been warm enough to melt a significant amount of accumulated snow and ice (González & Maidana, 1998). The only fertile sample without *C. choctawhatcheeana* (800 cm) was dominated by *Cocconeis aff. euglypta*, presumably epiphytic.

The variations in the relative abundance of the planktonic centric diatom and its replacement by benthic and/or epiphytic species provide insights into changes in the lake level. These changes are closely related to increased runoff and flow in the fluvial system. These fluctuations in the fluvial system can be associated with climatic episodes characterized by higher humidity and temperatures.

A terminal moraine located in the upper basin of the Mendoza River valley has been dated to an age older than 15,000 years (Coronato & Rabassa, 2007). Its development and subsequent thawing during the Late Pleistocene-Holocene transition, indicate the presence of cold climatic conditions and potentially high water levels in the fluvial and lacustrine systems (Chiesa et al., 2015). These conditions were likely linked to the Mendoza and Desaguadero rivers, and thus with the Salina del Bebedero depression.

Obviously, during the Holocene the climate variability and the beginning of Present Interglacial in the surrounding plain or Andean piedmont (including the Desaguadero River basin) is recognized by the predominance of arid and semi-arid conditions. In Salina del Bebedero, evidenced by the retreat of the paleocoast of the lake and the deposition of

wind-blown sediments (González, 1983; González & Weiler, 1984). As a result, high modern lake levels could be influenced by the rainfall from the Atlantic Anticyclone (Piovano et al., 2009), even though the influence of those Holocene neoglacial stages is possible (Wingenroth, 2012).

Lower peak - 7.50 to 8.70 m - approximately 8,000 to 6,000 years BP - top of Zone A to base of Zone C.

The pronounced dominance of *Cyclotella choctawhatcheeana* observed between the top of Zone A and the base of Zone C (approximately 870 cm to 750 cm) can be linked to the warm phase of the Mid-Holocene (approximately 8,000 to 6,000 years ago). González (1981) suggests that the development of what this author calls the “Minor Lacustrine Period” is related to moisture provided by the Bebedero Stream and local rainfall. González and Maidana (1998) argue that the relative abundance of other oligohalobous littoral diatoms found in Bebedero Stream profiles (e.g., *Epithemia argus*, *Fragilaria brevistriata*, *F. construens*) fluctuates inversely with *Cyclotella choctawhatcheeana*, thus linking them to the occurrence of local precipitation during warm and dry episodes with easterly winds. Various authors, such as Iriondo et al. (2009), Piovano et al. (2009), Font & Chiesa (2015) and Chiesa & Ojeda (2021), have analyzed geomorphological, sedimentological, and paleobiological evidence in the central-western region of San Luis, leading to regional implications regarding wet climatic conditions during the Mid-Holocene.

Upper peak - 5.50 to 6.20 m - at the top: 3,600 years BP - Zone E and middle section of Zone F.

On the other hand, the peak abundance of *Cyclotella choctawhatcheeana* found in Zone E and the middle section of Zone F (approximately 550 cm to 620 cm; 3,600 years BP) associates the underlying strata with the end of the event identified as the “Warm Optimum” of the Mid-Holocene. This humid climate condition has been found in Holocene deposits in the province of San Luis, both in the studied basin (Rojo et al., 2012) and in the vicinity of the Sierra de San Luis (Strasser et al., 2014; Facini et al., 2021) and the Conlara River fluvial system (Chiesa & Strasser, 2009; Coria et al., 2022), suggesting a significant influence of the South Atlantic Anticyclone during this period.

Conclusions

During this period, there were a series of lake level fluctuations, characterized by high and low events. The high lake level events, indicated by the dominance of *C. choctawhatcheeana*, are thought to correspond to glacial pulses in the Andes during the Last Glacial Maximum. These glacial pulses would have resulted in an increased water supply from the Desaguadero River to the shallow lake, flowing through the Bebedero Stream.

We suggest that the high climatic variability observed globally during the Holocene is also recorded in the deposits of the Salina del Bebedero basin as indicated by detailed analyses of microfossils such as diatoms, charophytes, and pollen, which are closely related to the sediment type corresponding to the depositional environment. The high levels in the shallow lake during the Late Pleistocene and the water level variations in the basin during the Holocene are mainly influenced by fluvial input from the Andean glaciers associated with the Desaguadero River and the Bebedero Stream. In addition, there may be a significant influence from rainfall originating from the east, associated with the South Atlantic Anticyclone and corresponding to wet periods. The vegetation changes observed in the Salina del Bebedero area during the transition from the Late Pleistocene to the Early Holocene are consistent with the evidence provided by lacustrine diatoms.

The periods of low lake level, characterized by the dominance of epiphytic or benthic forms, can be attributed to reduced fluvial input and seasonal rainfall. These conditions create shallow and vegetated aquatic environments. The phases of the lowest water levels in the shallow lake during the Holocene, characterized by the absence of diatoms, coincide with the periods of pronounced aridity that have been previously documented in this region.

Despite the fluctuations in water levels, most of the species identified throughout the study period are indicative of saline environments, which correspond to the current characteristics of this water body. However, further studies are needed to obtain a more accurate understanding of the paleoenvironmental evolution of the region. These studies should cover a larger area, include other aquatic environments, and

use additional proxies to provide a comprehensive analysis.

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