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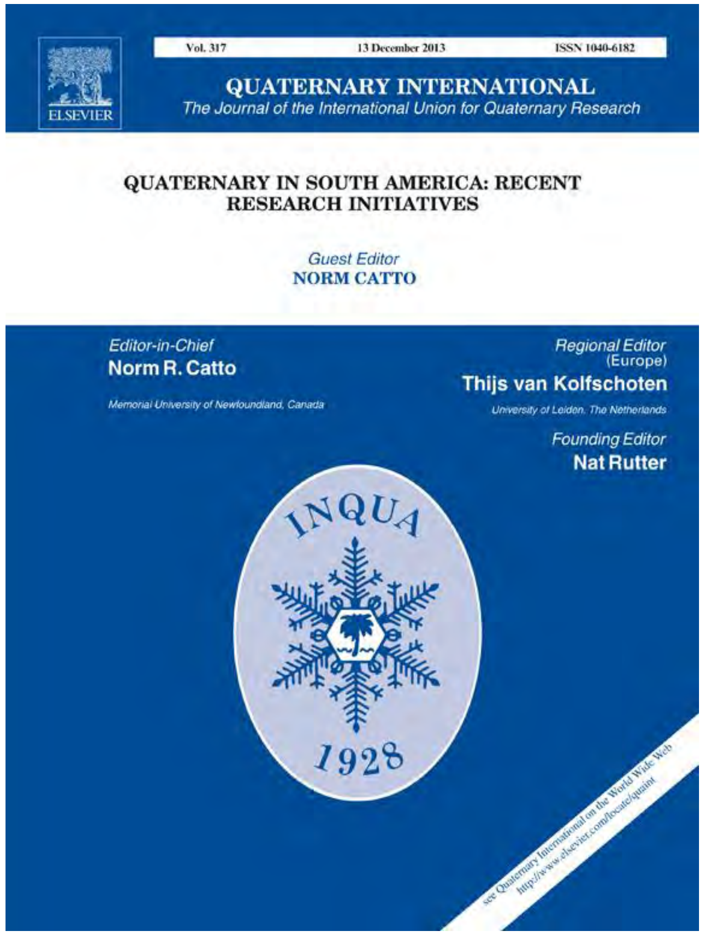

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Landform analysis of the Pueyrredón Lake area in northwestern Santa Cruz, Argentina

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ABSTRACT

The aim of this research was to analyze the landforms around Pueyrredón Lake (NW Santa Cruz in Argentina) to contribute to the understanding of the paleoenvironmental evolution of Patagonia during the Late Pleistocene–Early Holocene. The Pueyrredón Lake area belongs to the Patagonian shield, northwest of the Santa Cruz Province (47°22′28″ S–71°55′34″ W). Characteristic landforms were identified through satellite images (Landsat 7 ETM) and field work. These landforms include glacial troughs, glacier striations and groove casts, three fan deltas on the south margin of Pueyrredón Lake, lacustrine and glacio-lacustrine sediment, and till deposits. In addition, short detailed stratigraphic logs were measured for paleoenvironmental analysis, and several sedimentary deposits were sampled to characterize grain size variations. All of the information is displayed on a geomorphological map. The modern and ancient landforms were also analyzed based on their topographic characteristics, which were determined by a digital elevation model (DEM). Geomorphological conditions of the erosional and depositional processes in the paleoglacial environment were analyzed using longitudinal- and cross-sections. The results shed light on the climatic variability during the most recent geological period. Major changes in the landscape morphology were associated with glacier evolution and the development and division of the great lakes in the eastern Andes, in Central Patagonia.

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1. Introduction

Cenozoic glaciation deposits in the area were studied by Hatcher (1903), but Caldenius (1932) provided the first stratigraphic framework of the moraine and fluvioglacial deposits. Caldenius postulated that four main glacial stages occurred in Patagonia, the initial, dani-, goti-, and fini-glacial stages, and explained that the first advance (initial glacial) was the longest and oldest and that the other three advances were minor and correspond to the last glaciation. Although neither the number of glaciations nor the correlation established by him are correct, it is important to emphasize the accuracy with which he mapped the boundaries of the various glacial advances (Rabassa and Coronato, 2002).

A progressive increase in the mean annual temperature caused the melting and crenulation of the ice, producing changes in the base level and subsequently modifying the direction of the lake drainage from the Atlantic to the Pacific drainage basin (Coronato et al., 1999; McCulloch and Morello, 2009). The geomorphological study of the Quaternary deposits around Pueyrredón Lake (Fig. 1) has clarified the paleogeographic evolution of this area in northwestern Santa Cruz (Río Chico, Argentina).

During the Late Pleistocene to the Early Holocene, glacier erosion and deposition modeled the landscape and the geometry of many lakes in the Patagonian Andes (Hatcher, 1903; Ramos, 1982; Sylwan et al., 1991; Clapperton, 1993; Ton-That et al., 1999; Aschero et al., 2005; Rabassa et al., 2011). Studies regarding the evolution of these glaciers and lakes have led to a regional approximation of the climatic and paleogeographic patterns of this region (Caldenius, 1932; Mercer and Sutter, 1982; Turner et al., 2005; Glasser et al., 2008). For this region, the glaciation chronology from Pleistocene to Early Holocene was established by Hein et al. (2009, 2010, 2011). Hein et al. (2009, 2011) determined the existence of 4 moraine arcs that were dated by cosmogenic isotopes (^{10}Be): Río Blanco (25–27 ka, corresponding to the Last Glacial Maximum, LGM), the Hatcher ice limit (260.6 ± 6.5 ka), the Caracoles ice limit (~315–760 ka), and the Gorra de Poivre (~760–1100 ka, corresponding to the Greatest Patagonian Glaciations,

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Fig. 1. Map of South America is indicated in gray sector corresponding to Patagonia. Study area, Santa Cruz, Argentina. The shaded area represents the drainage basin of Pueyrredón Lake (modified from De Nigris et al., 2004).

GPG), considered by Caldenius (1932). In the current study, the moraines were considered as possible natural dams that enclosed the natural drainage towards the Atlantic Ocean and generated proglacial lakes, which controlled prehispanic settlements in the region, due to the presence of fine grain lake deposits. Deglaciation and moraine arc deposits promoted lake formation, so aborigines of the region developed settlements nearby the ancient paleolake levels. Hein et al. (2010) stated that the maximum extension of the latest glacial maximum (LGM) took place between 27 and 25 ka in the area studied and had later advance between 23 and 22 ka, 20–18 ka and approximately 18–17 ka. They also concluded that the initial deglaciation began after approximately 18–17 ka.

The nature of the landforms and deposits allows to understand the sedimentary processes and the resulting paleogeomorphology of the region (Coronato et al., 2002), which is important for determining the sedimentary geological processes that are most relevant to paleogeomorphological modeling (Ercolano et al., 2004). Pleistocene glacial processes produced landscape modeling on different scales: hanging valleys or glacial troughs, striations and groove casts on Jurassic ignimbrites, glaciolacustrine deposits with fossils, erratic blocks, frontal moraines, and fan deltas. Later, the great lakes of Patagonia formed as a result of the recession of the large glaciers (Tatur et al., 2002; Del Valle et al., 2007). The current fluvial and lacustrine system was a result of this ice recession. The purpose of this study is to analyze the current landforms and their evolution over time to better understand the paleoenvironmental development of this region of Patagonia. To this end, the stages of the lacustrine system and the paleolandforms that evolved in this landscape due to climatic changes during the Late Pleistocene–Early Holocene are described and interpreted.

The Paleogene–Neogene–Quaternary Andean Orogeny (2.5 Ma) initiated a cycle of mountain building that produced the uplifting of the South American Andes, which continues to this day, and has been recorded by neo-tectonic geo-indicators (Lara, 2009). This tectogenesis promoted the uplifting of the meridian, or north–south oriented mountain front, raising an orographic climatic barrier for the Atlantic and Pacific anticyclones, which produced summit snow fall during the Quaternary glaciations. Consequently, ancient glacier tongues, as alpine or valley glaciers, were oriented west to east (at 90° the Andes front) and had an Atlantic drainage. Due to the impressive ice thickness that accumulated during glaciations, ice recession caused substrate vertical erosion that, in turn, produced a drainage inversion towards the Pacific Ocean.

2. Study area

2.1. Location

Pueyrredón Lake is located in the northwestern region of the Province of Santa Cruz, Argentina (47° 22′ 28″ S; 71° 55′ 34″ W). Pueyrredón Lake spans two countries, with one part of the lake in Argentina (Pueyrredón) and one part in Chile (Cochrane Lake). The Argentinian portion of the catchment basin for Pueyrredón Lake covers 2875 km^2 and is limited by the San Lorenzo Massif (3706 m asl) to the southeast and Cochrane Lake and Principio Hill (1278 m) to the northwest (Fig. 1). The region is located in a transitional zone between two ecosystems, with the shrubs on the steppe to the east and the forest westward on the border with Chile (Markgraf, 1983; Mancini, 1998), an ecotone (Solomon et al., 1998). The average height of this basin ranges between 300 and 400 m.

2.2. Climate

Climate is controlled by the South Pacific Anticyclone, with 500 mm precipitation per year in the Oro River Valley westward, decreasing to 200 mm precipitation in the east. The mean annual temperature is 7–8 °C, decreasing to between 0 and 1 °C during July. According to Daniele and Natenzon (1988), the region belongs to the Patagonian Forest Ecoregion and has developed on the Argentine slopes of the hills in the Patagonian Andes. In this region, deep lakes promote microclimate conditions, regulating temperatures. Lenga trees (*Nothofagus pumilio*) are a typical deciduous species, as well as Ñire (*Nothofagus antarctica*), a smaller tree linked to more unstable ecological environments. Mires of sedges and grasses (high mountain peat bog) are located at the bottom of the valleys and are essential for livestock activities in the region (Sarafian, 2009).

2.3. Geology

There are outcrops of Paleozoic metasedimentary rocks (Río Lácteo Formation) towards the South (Fig. 2) (Fossa Mancini et al.,

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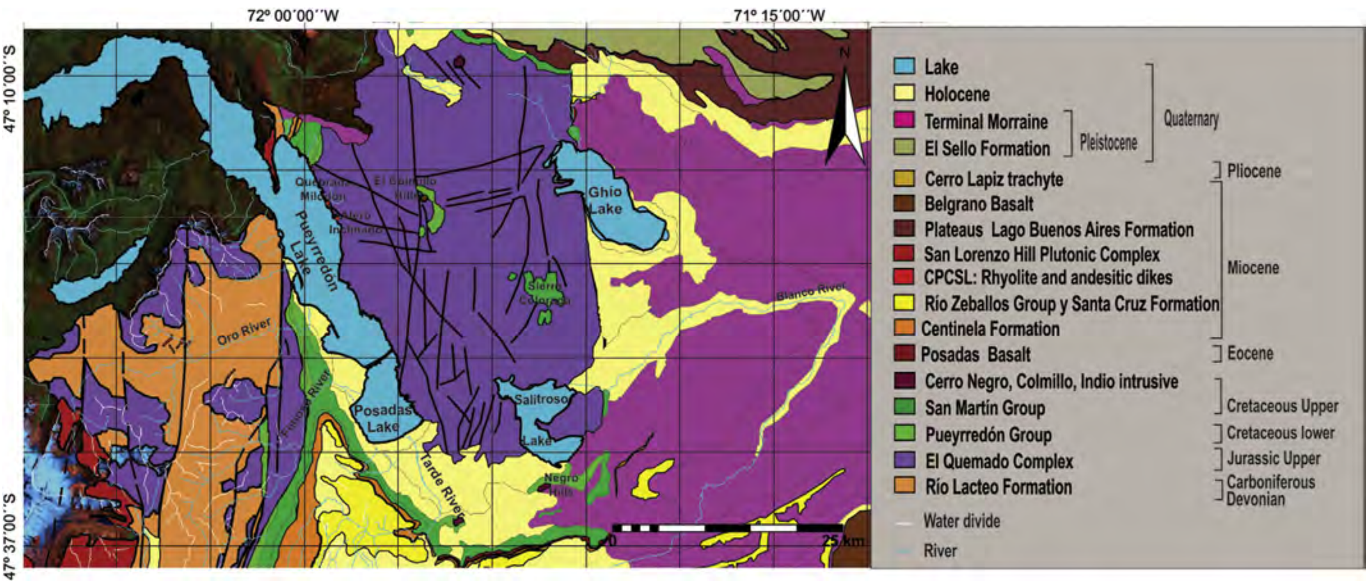

Fig. 2. Geological map.

1938; Bianchi, 1967 y Leanza, 1972), which are overlain by extensive Jurassic rhyolitic ignimbrites (El Quemado Complex). Marine clastic deposits, from the early to late Cretaceous, are covered by continental strata from the Pueyrredón Group (Hatcher, 1900; Riggi, 1957; Ramos, 1979) and clastic continental deposits with pyroclastic material from the San Martin group (Hatcher, 1900; Ramos, 1979). There are Cretaceous andesitic–dioritic hypabyssal rock outcrops in the core of the Negro, el Colmillo and Indio hills, among other peaks. Basalt Posadas spread during the Eocene (Riggi, 1957), and the sediments of the Centinella Formation were overlain by an erosive discordance (Furque and Camacho, 1972) during the Patagonian marine transgression. Later, according to Ugarte (1956), Miocene continental sediments of Río Zeballos Group covered the Santa Cruz Formation (Ramos, 1982; De Barrio, 1984; De Barrio et al., 1984), which is comprised of rocks that are linked to the tectonic uplift of the Andes Cordillera. San Lorenzo hill is the most distinctive

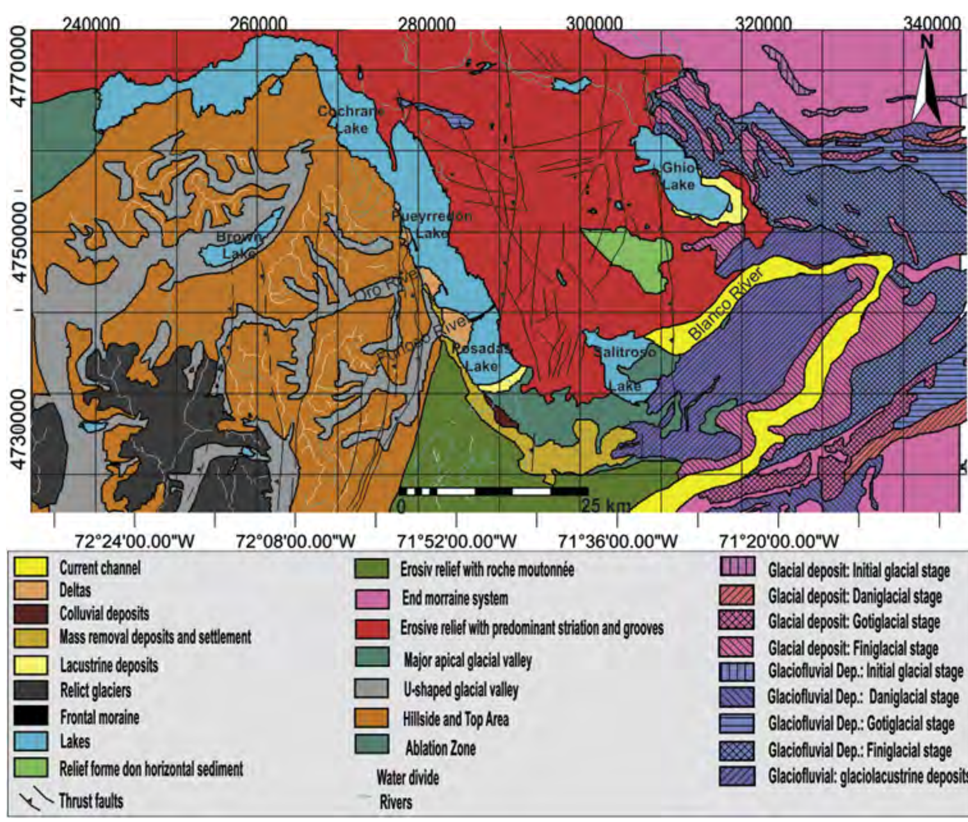

Fig. 3. Landforms map. The predominant landforms are glacial and glaciofluvial landforms to the west; slopes and summits, Glacial troughs, and glacier ice to the southwest; and erosional relief with notable striations and grooves to the north. The locations of the cross sections and of the Alero Inclinado deposit are shown.

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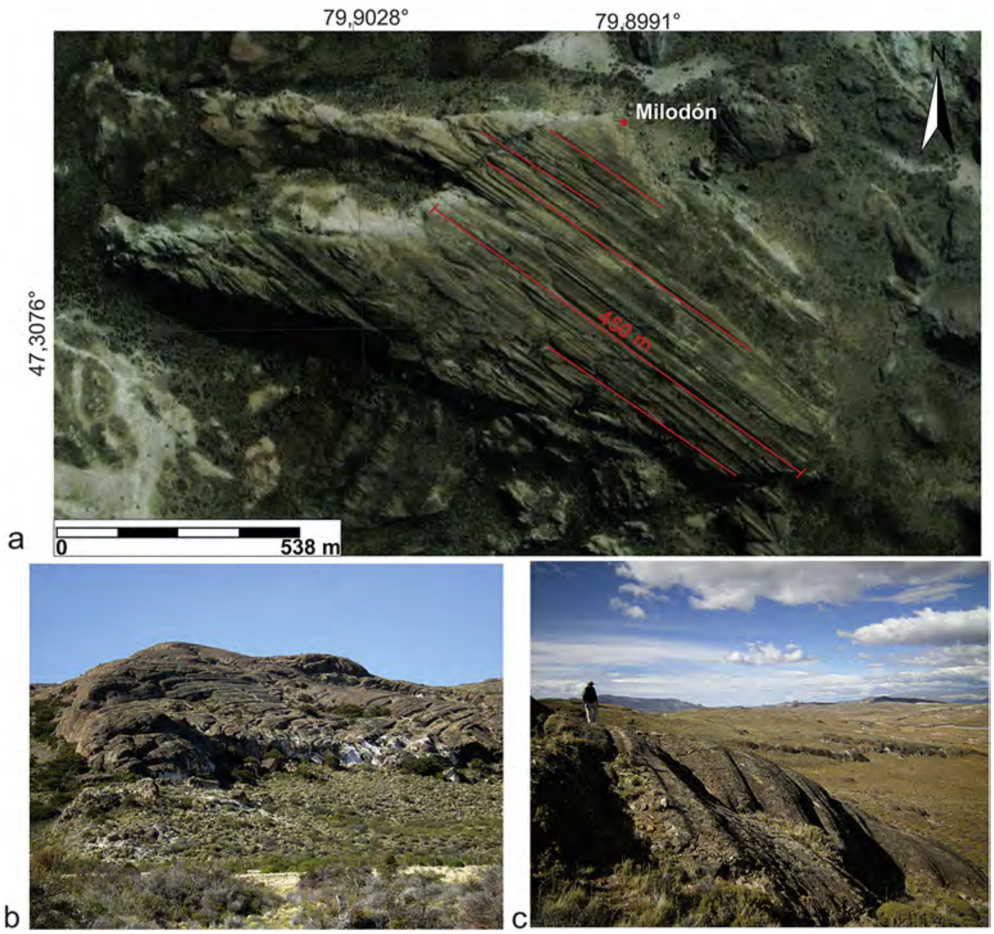

Fig. 4. a) Glacial grooves in the ignimbrite outcrop on the north margin of Pueyrredón Lake, mapped from a satellite image from Google Earth; b) view north-west of the ignimbrite outcrop, where parallel grooved structures can be observed; and c) view southward of a roche moutonnée produced by basal erosion due to the glacial front advance.

element of the mountain front and is composed of Cretaceous and Miocene plutonic rock (San Lorenzo Hill Plutonic Complex; Riggi, 1957; Ramos, 1982). Olivine basalts were erupted at the end of the Miocene, developing extended plateaus surrounding the Buenos Aires and Belgrano lakes. New volcanic episodes occurred during the Pliocene and lasted until the Pleistocene, producing trachytic rock peaks, which are acute sharp hills that are differentiated from the surrounding area and are located above the level of the plateau.

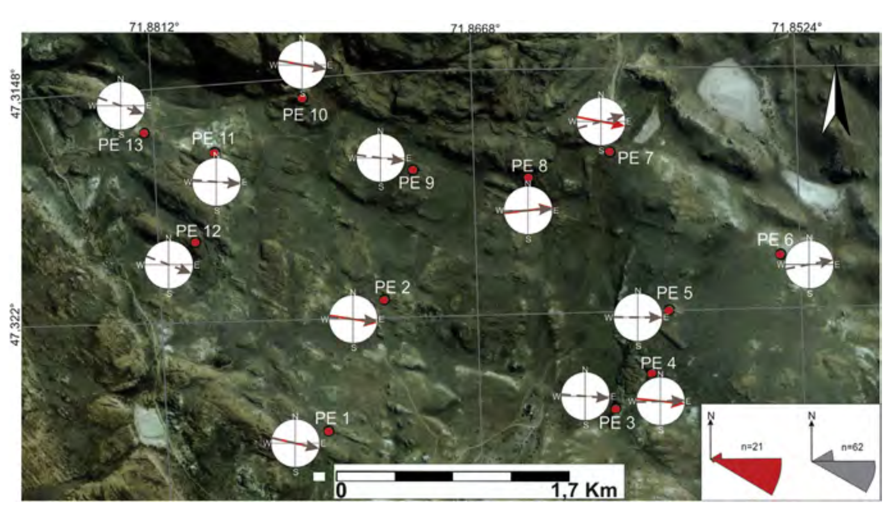

Fig. 5. Satellite image, taken from Google Earth, indicating the measuring stations and the directions of striations and grooves. At the bottom right, the total number of measurements, expressed as a percentage, and main orientation is shown. The direction pattern is defined and the ice movement is inferred to have been eastwards.

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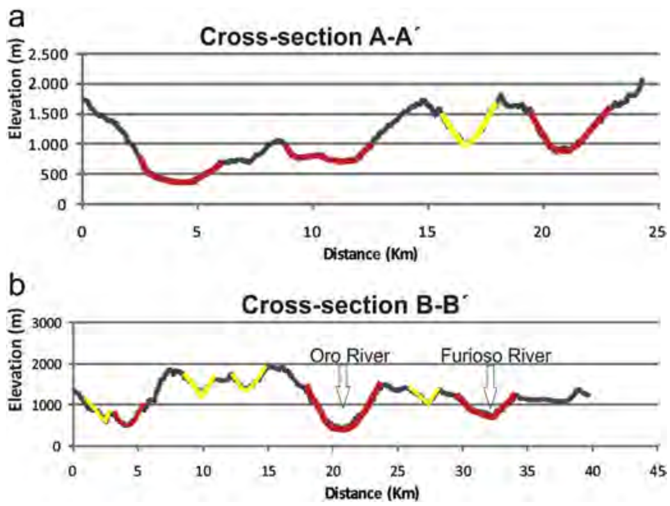

Fig. 6. a: NW–SE topographic cross-section in the SW of the study area; Glacial troughs are highlighted in red, and V-shaped valleys are highlighted. 6 b: NW–SE topographic cross-section in the center of the study area. Glacial troughs are highlighted in red, and V-shaped valleys are highlighted in yellow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Materials and methods

The geomorphological map of the area was obtained following the morphogenetic criteria of Van Zuidam and Van Zuidam Cancelado (1986), which used satellite image interpretation (Landsat 7 ETM: 01/15/2001) and the GIS software ILWIS (Integrated Land and Water Information System), developed by the International Institute for Geoinformation and Earth Observation (ITC) in The Netherlands. The best satellite view was the 741 band in the RGB channels to generate the thematic maps because this combination clearly identifies the difference between vegetation, ice cover, lithologies with different reflections, and, therefore, delineates the landform boundaries. The landscape was analyzed, taking into account the topographic characteristics determined using digital elevation models (DEM) that were taken from SRTM (Shuttle Radar Topography Mission, 2000), which consisted of raster data with 90 m pixel resolution. The DEM was corrected using a mathematical algorithm for the interpolation of GPS points, and more than 1000 points, with ±10 m height error, were used. The geomorphological map was confirmed and georeferenced with GPS (Garmin MAP). The field measurements, stratigraphic cross-section descriptions, sediment samples, and most of the representative landforms that were mapped were referenced to geographic coordinates, as well as a Gauss–Krugger (WGS84) Transverse Mercator Projection and an Ellipsoid and Datum (WGS84), corresponding to the third strip of Gauss-Krugger System, as stated by the National Geography Institute of Argentina. In the stratigraphic log (1:20 scale), grain size, sedimentary structures, paleoflow directions, and fossils were described, and the lateral contact correlations were developed on color photographic mosaics.

Landforms were determined through the topographical analysis of a slope map obtained from DEM data and from detailed maps from Google Earth Images (age 2010 Spot 5 and GeoEye), which were useful for highlighting the landforms based on topography. Google Earth (2010) images were also used as a complement for more detailed mapping.

The striations and groove casts identified exclusively in the ignimbrites were measured with a geological compass, recognized in the satellite images, and referenced with GPS. Cross- and longitudinal-sections of the land were also performed (and checked by field confirmations) to analyze the resulting topography of the erosional and depositional processes in the paleoglacial environment.

4. Geomorphological cartography

Landforms were mapped using satellite image processing of Landsat 7 ETM products (Fig. 3). The area is dominated by a recessional glacial landscape and a periglacial environment with glacial relicts in the southwest, glacial lakes, glacial and glaciofluvial deposits, Glacial troughs, a predominant relief with roches moutonnées in the central-southern area of the map, and erosional relief with striations and groove casts to the north. At the eastern end, there are terminal moraine systems, which were first mapped by Caldenius (1932), followed by Mercer and Sutter (1982), Turner et al. (2005), Glasser et al. (2008), and Hein et al. (2009, 2010 and 2011).

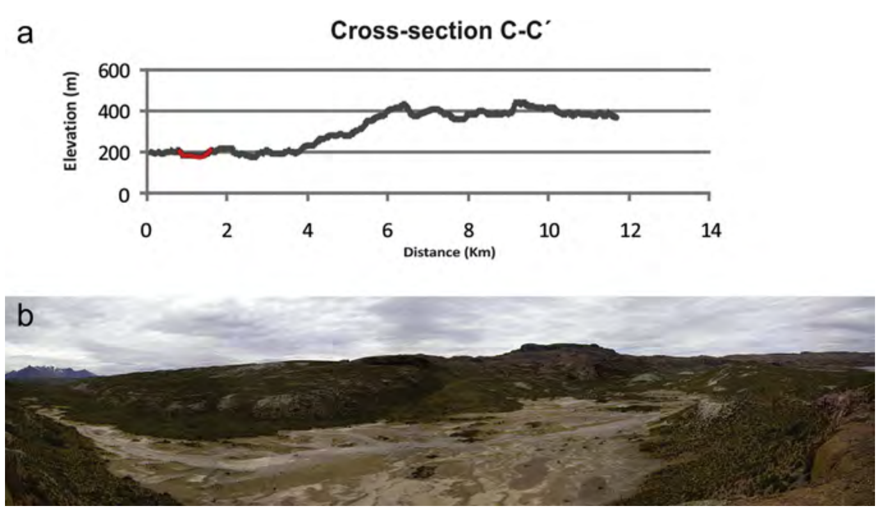

Fig. 7. a) NW–SE topographic cross-section on the NE margin of Pueyrredón Lake. The glacial trough valley, corresponding to the Alero Inclinado area, is highlighted. b) Panoramic photo of the glacial trough valley highlighted in the topographic cross-section.

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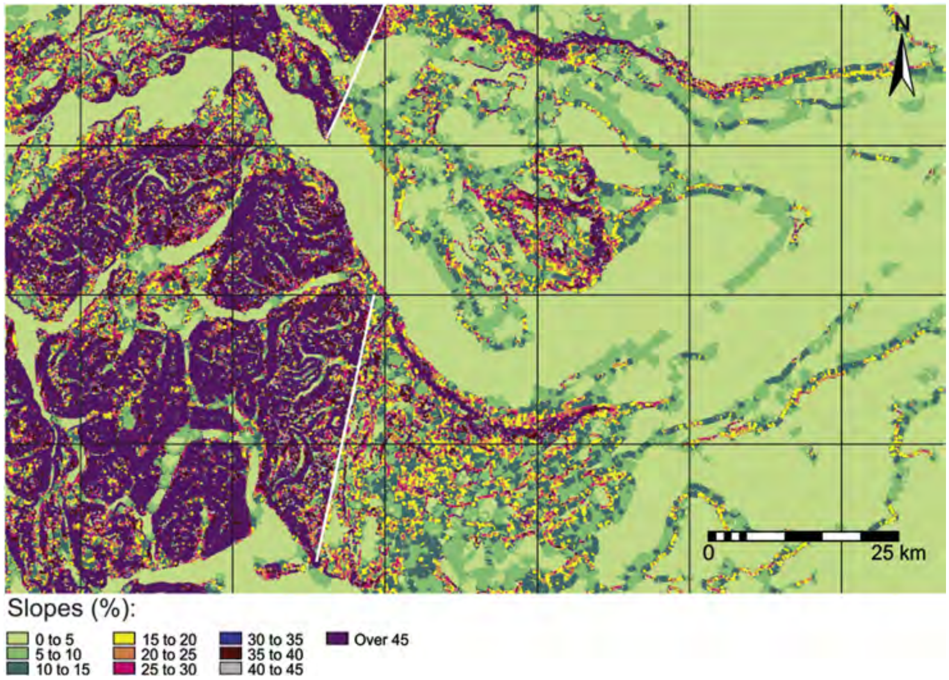

Fig. 8. Slope map gradient classification. The white line separates areas with steeper slopes to the west, which underwent intensive compressional distortion.

5. Landforms

5.1. Glacial paleoforms

5.1.1. Erosional landforms

5.1.1.1. Striations and grooves. The abrasive action of glaciers shaped the substrate, generating landscapes with roches moutonnées. Glacial erosion also produces a polish in the rocky substrate and leads to rectilinear striations that are typically aligned parallel to the direction of the ice flow. If the striations are a number of centimeters wide, they are called grooves. The geomechanical characteristics of the ignimbrite plateau of Complejo El Quemado (upper Jurassic) were favorable for the preservation of these features, and remarkable grooves more than 420 m long, 0.75 m wide, and 0.40 m deep have been preserved (Fig. 4a, b and c). This site lies on the north margin of Pueyrredón Lake, an area classified in landform mapping as an erosional relief with predominant striations and grooves.

In this area of erosional landscape, 21 striations and 62 grooves were measured and grouped, according to their location, into 13 stations (Fig. 5). The grooves and striations are mainly oriented between 120° and 90°, with extreme values between 68° and 132°,

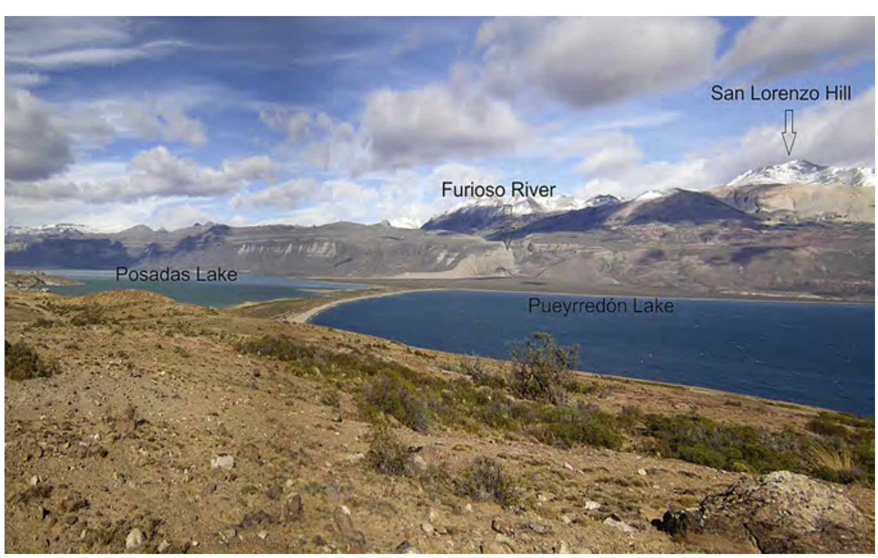

Fig. 9. View of the SE of the isthmus (terminal moraine) that separates Pueyrredón from Posadas Lake.

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Fig. 10. Detail of the tillite, with abundant fine-grained matrix and subangular volcanic clasts.

indicating that the direction of ice advance was predominantly west to east. For the striations, 14% of the measured azimuths are between 60° and 90°, 81% are between 90° and 120°, and 5% are between 120° and 150°. For the grooves, 27% are between 60° and 90°, 71% are between 60° and 90°, and 2% are between 120° and 150°.

5.1.1.2. Glacial troughs. These valleys form due to the widening and deepening of old fluvial valleys through glacial erosion. These valleys were mapped and cross sections were drawn to highlight their characteristics and differentiate them from the V-shaped valleys (Fig. 3). Glacial troughs are located mainly in the SW area (Figs. 3, 6a and 6b) and those in the north are smaller (Fig. 7).

5.1.1.3. Denudational hillsides and summit surfaces. The slope map was obtained from the digital elevation model (DEM) and processed in ILWIS using directional filters and a specific algorithm. The resulting slope map represents the degree values of the slopes extracted from the DEM. The classification of slope gradients (Fig. 8) shows that the western area is characterized by a steep slope due to the uplift of Paleozoic metasediments, which underwent intensive compressional distortion as part of the accretion process to the Paleozoic sedimentary prism (Giacosa and Franchi, 2001). On San Lorenzo hill, minor glaciers are observed as relict shapes. The steeper slopes in the region, together with the Glacial troughs of the Oro and Furioso Rivers (Fig. 6b), are mainly concentrated in the area termed hillsides slopes and summits on the landform map (Fig. 3).

5.2. Depositional landforms

5.2.1. Moraines: till

The main morainic deposits are in the eastern area and have been studied previously by Caldenius (1932), Hein et al. (2009, 2010 and 2011), and some other scientists (Fig. 3). The initial glacial moraines are located above 950 m asl and, in some areas, such as at the southern border of the plateau of Buenos Aires Lake and in the higher part of Sierra Colorada, reach elevations of over 1250 m asl. The daniglacial and gotiglacial stages are located approximately between 750 and 950 m asl, and the finiglacial stage is found between 500 and 650 m asl (Giacosa and Franchi, 2001).

The Pueyrredón and Posadas Lakes are separated by an isthmus (Fig. 9), which corresponds to relict terminal moraine deposits. A channel at the NE end of the isthmus connects Posadas Lake to Pueyrredón Lake.

The most recent morainic deposits correspond to small outcrops in the area of Alero Inclinado (Horta et al., 2009). This 1.8 m thick till deposit (Figs. 3 and 10) was formed by a matrix-supported conglomerate. The matrix is fine-grained silt to sand, with abundant subangular clasts. The clasts are composed of volcanic ignimbrites and subordinate metamorphic rocks and clast size varies from 0.5 to 30 cm.

These deposits are located in a glaciated valley on the NE margin of Pueyrredón Lake, in Alero Inclinado (43.317291° S, 71.902986° W), and correspond to lateral morainic relicts that were preserved from later erosional processes (Fig. 11a and b).

5.2.2. Dropstones and erratic blocks

5.2.2.1. Dropstones. Dropstones are found in Late Pleistocene–Holocene lacustrine deposits and in many small dry lakes. These deposits suggest that the rafting of blocks in ice flows was a process of active transportation. In Fig. 12(a, b, and c), a small dry lake, at 311 m asl, contains exposed fragments of cobble-sized rocks.

The deposits described in the cross-section of Quebrada del Milodón include the glaciolacustrine strata of silt, with dropstones ranging in size from 0.3 to 5 cm (Fig. 13a and b) at the base of the cross-section. Above this layer there is a sequence of coarse- to fine-grained sand moving upward in the cross-section. The upper half of the cross-section contains gastropods, *Succinea* (pers comm Ovando X., 2011). The glaciolacustrine deposits are known to be older than 5000 BP, based on molluscs that were found above it that date to 5208 ± 38 BP (Horta et al., 2011).

5.2.2.2. Erratic blocks. Erratic blocks are mainly found northeast of Pueyrredón Lake (Fig. 12a, 14a and b); these blocks are granitic and range in size from 1 m^3 to 75 m^3. Given the absence of granite outcrops in the direct area, the direction of the measured striations and grooves indicates that the blocks could have been transported up to 15 km. The blocks were carried from an area near the peninsula to the north, which juts into Chile, where the granitic outcrops are part of the plutonic complex of San Lorenzo Hill (upper Miocene).

6. Current landforms

6.1. Glacier ice

These ice bodies are located in the southeastern area of the study region and are relicts of the more extensive alpine glaciers that existed during the last glaciation. The most important glaciers are those in the area of San Lorenzo Hill (Fig. 15), which has a maximum elevation of 3706 m asl (47° 35′ S, 72° 19′ W) and is the highest peak in the province of Santa Cruz, on the border between Argentina and Chile. The South San Lorenzo glacier is the most significant body of ice on this hill.

6.2. Proglacial lakes

Deposits corresponding to old lacustrine levels were found in a number of areas. These old flooding levels were reconstructed through a study of points where paleobathymetric indicators could be found. Four main areas, corresponding to older flood zones, were classified based on the different elevations (Fig. 16): (1) the area occupied by current lakes covering 491.62 km^2, (2) the flooded area for a paleo-elevation at 200 m asl covering 736.76 km^2, (3) the flooded area for a paleo-elevation at 297 m asl covering 1061 km^2, and (4) the flooded area for a paleo-benchmark at 400 m asl covering 1525.32 km^2. Two radiometric ages were obtained from the ^{14}C

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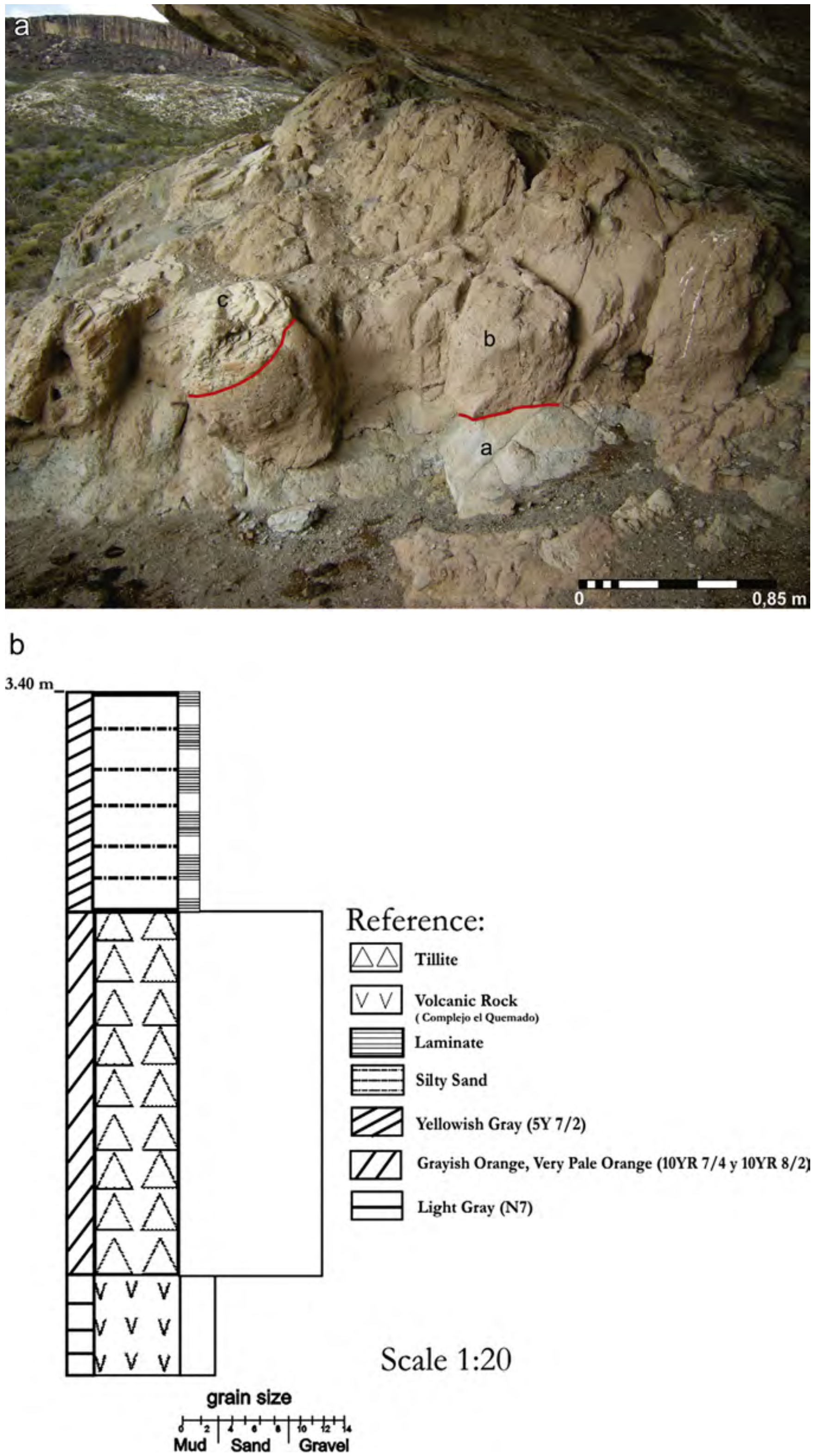

Fig. 11. a) View of the SE; details of the cross-section in Alero Inclinado. The red lines separate the volcanites (a) from the diamictitic deposits (b) and the clay-silt sediments (c). (b) Stratigraphic log of Alero Inclinado. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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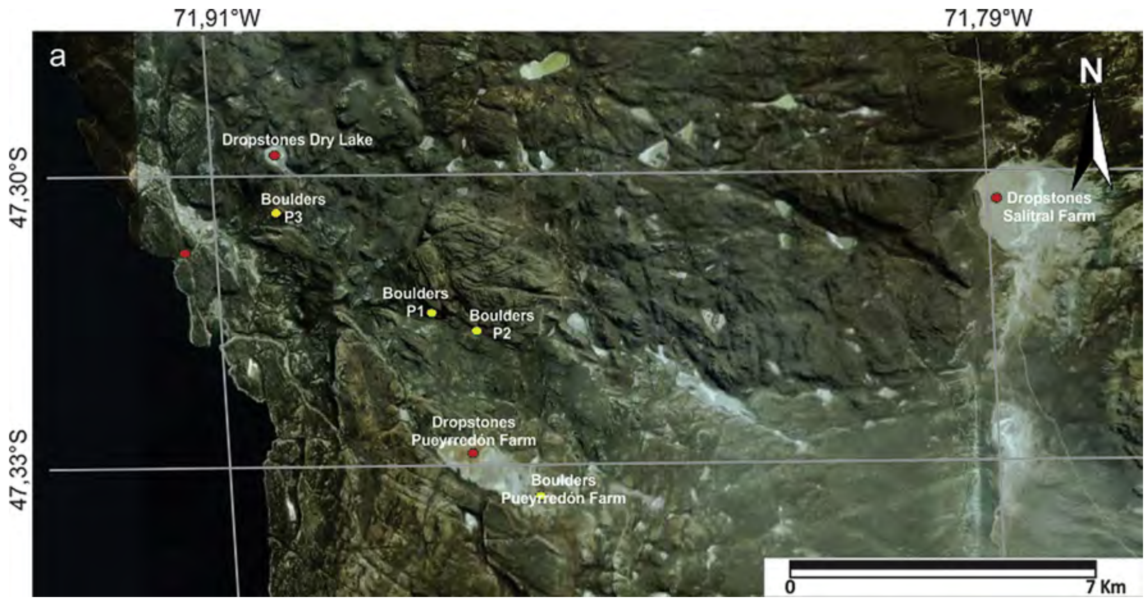

Fig. 12. a) Image indicating the location of the small dry lakes where dropstones (red circles) and erratic blocks (yellow circles) were found; b) block-sized dropstones found on Salitral Farm (47.30° S, 71.79° W); and c) Pueyrredón Lake with dropstones 1.2 by 1.4 meters large (47.32° S, 71.87° W). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

dating of organic matter in lacustrine sediments, 19,910 ± 310 BP and 18,050 ± 350 BP for an outcrop located at 190 m asl and 7070 ± 120 BP for an outcrop at 300 m asl. A date of 5208 ± 38 BP was obtained using the AMS dating of mollusc shells in glaciolacustrine deposits located at 190–200 m asl (Horta et al., 2011).

The lacustrine system occupies an old glacial valley, as indicated by the shape of the valley in cross-sections (Fig. 17). This geometry is observed in topographic cross-sections transverse to the Pueyrredón–Posadas–Salitroso lacustrine system (Fig. 16). The morainic deposits and the fall of the lake level fragmented the old system into the three lakes present today (Del Valle et al., 2007; Horta et al., 2011).

6.3. Fan deltas

Several fan deltas on the south coast of the Pueyrredón–Cochrane Lakes were mapped. The three largest deltas are located to the north of Pueyrredón Lake (Fig. 16). The Oro and Suyai Farm River mouth bars in the fan deltas were repeatedly worked by waves to form spurs or bars parallel to the coast (1.3 and 1.7 km long, respectively). The elevation of the fan delta areas decreases from east to west (Horta et al., 2009), 14 km^2 and 400 m asl in the Furioso River, 6.27 km^2 (Fig. 18) and 300 m asl in the Oro River, and only 2.28 km^2 in the Suyai Farm River (Fig. 3). The apices of the fan deltas (Fig. 16) coincide with the old paleocoast levels (Horta et al., 2010) and may be indicators of the glacial recession. In the other two fan deltas, the development of spurs towards the southeast is characteristic, which is indicative of waves controlled by westerly winds (Fig. 19).

6.4. Current drainage system

The Posadas and Pueyrredón Lakes lie in a lacustrine depression aligned southeast to northwest and are predominantly fed by the mountain range area. Pueyrredón Lake continues into Chilean territory (where it is named Cochrane Lake) and drains to the Pacific Ocean through the Baker River. The two lakes are separated by a thin frontal morainic deposit that forms a 2 km long isthmus, and a channel allows drainage into Posadas Lake. This lake is the catchment for the high plateaus south of the basin, where the Tarde and Furioso Rivers are the major tributaries. The Tarde River begins in the north drainage area of Belgrano Hill, at more than 2000 m asl, and enters Posadas Lake in the south. The Furioso River, which begins on the mountainside to the east of the San Lorenzo and Belgrano Rivers, is a meltwater river with a more developed dendritic system. Over almost its entire range, the Furioso River drains into a narrow valley, with steep slopes and a high-volume capacity. Pueyrredón Lake is fed from both sides but only the waters from the western side of the mountain are significant. The Oro River flows from the southwest into Pueyrredón Lake; its drainage basin includes the northern face of San Lorenzo Hill (glacier ice and a proglacier lake) and mountains along the western border with Chile.

The drainage basin of Ghío Lake includes the Ghío River and permanent streams from Principio Hill to the north. In the central southern area, Salitroso Lake is fed by the Blanco River from Belgrano Hill. The changes in current direction of this river are controlled by moraines dating to the Pleistocene.

Although the main rivers drain into the Atlantic, as observed in Fig. 1, the Pueyrredón (Cochrane)-Posadas system drains into the Pacific. During the glaciations, this lacustrine system formed a basin draining towards the Atlantic, but as a result of the deepening of glaciers and the later deglaciation, the drainage switched direction.

7. Discussion and conclusions

The importance of this research is that it contributes significantly to the understanding of paleoglacial geomorphology, which is linked to the generation of ancient periglacial–proglacial lakes and the human settlement around the study area. This study is useful for further research regarding the paleoglacial deglaciation landscape of Patagonia and other archaeological investigations. The area is characterized by a recessive glacial environment with its own unique landforms, including receding glacial relicts in the summit areas.

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Fig. 12. (*continued*).

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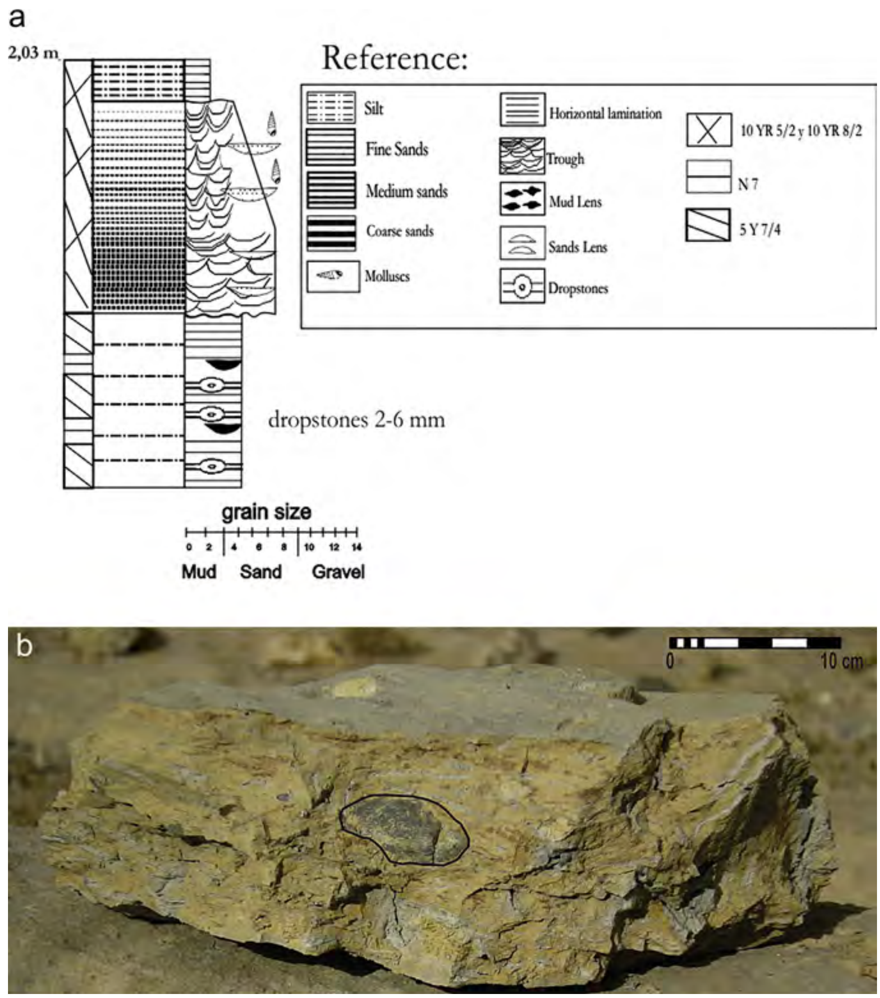

Fig. 13. a) Quebrada Milodón stratigraphic log. b) Glaciolacustrine strata of silt with dropstones found at the base of the cross-section. In this figure, one of the dropstones (approximately 6 cm long) is outlined.

The position of the Pueyrredón–Posadas–Salitroso lacustrine system is controlled by faults that are oriented north to south, which are controlled by the Patagonian ranges. The Pueyrredón-Posadas system lies between the Principio Hill-Oro River strike-slip fault and the El Salitral fault; whereas Salitroso Lake is delimited by the El Salitral and Sierra Colorada faults (Giacosa and Franchi, 2001). These structures dip to the east, which may explain the elevation difference between the Pueyrredón–Posadas Lakes (150 m asl) and Salitroso Lake (130 m asl). The NW–SE orientation of the Pueyrredón–Posadas lacustrine system, referred to as the Pueyrredón Alignment by Giacosa and Franchi (2001), has been attributed to possible dextral strike-slip faults, which developed as a consequence of slip in the region.

Grooves and striations show variations in the direction of ice paleomovement. The different patterns evident in the satellite images (Glasser and Jansson, 2005) are likely conditioned by structural relief (Sierra Colorado), secondary NW–SE faults, and, locally, by faults oriented W–E (Fig. 3).

The decrease in the area of the fan deltas to the west is most likely related to the progressive decline of the lake level during the glacial recession. This hypothesis may also explain the decrease in elevation observed in the apical deposits of the Furioso and Oro Rivers and the formation of two hanging valleys at 850 and 700 m asl, which were identified in the Oro River basin.

The evolution of the Pueyrredón–Posadas–Salitroso lacustrine system is similar to that observed in other lakes in the Patagonia Andes (Clapperton, 1993; Tatur et al., 2002; Aschero et al., 2005; Del Valle et al., 2007; Glasser et al., 2008; McCulloch and Morello, 2009; Rabassa et al., 2011), where rising temperatures caused ice recession and the formation of paleolakes, which extend beyond the boundaries of the present lakes. According to Hein et al. (2010), ca. 17 ka glaciers filled the basin of Pueyrredón Lake. However, Horta et al. (2011) mentioned a dating of 18.05 ka in lacustrine sediment near to the north shore of Posadas Lake. The paleolake *ca.* 18.05 ka covered the region corresponding to the present Pueyrredón–Posadas–Salitroso Lakes, which represents a flood area of approximately 736 km^2, reaching 1061 km^2 with a height of 300 m asl around 7 ka (Fig. 16).

The glacial recession also altered the drainage direction of lakes at the foot of the mountain, shifting the drainage from the Atlantic Ocean to the Pacific Ocean, by the time the ice disappeared (Quensel, 1910; Caldenius, 1932; Isla and Cortizo, 2005). The isthmus that separates Pueyrredón Lake from Posadas Lake is defined by frontal moraine relicts, which also are connected to the Furioso River fan delta.

The till deposits of Alero Inclinado site correspond to remnants of a lateral moraine in the northern area of the glaciated valley (shown in Figs. 7 and 10). The changes in the direction of ice paleomovement, at different scales, were controlled by local geological structures as lineaments and thrust faults. The relicts of drainage towards the Atlantic can be explained by the hydrological system because the current predominant drainage towards the Pacific Ocean was generated after the Last Glacial Maximum.

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Fig. 14. Erratic granite blocks. (a) A 1 x 1 x 2 m block found at point 3, and (b) a 4 x 6 x 3 m block found near the small lake on Pueyrredón Farm (47.333977° S, 71.861561° W).

Fig. 15. Looking south towards San Lorenzo Hill.

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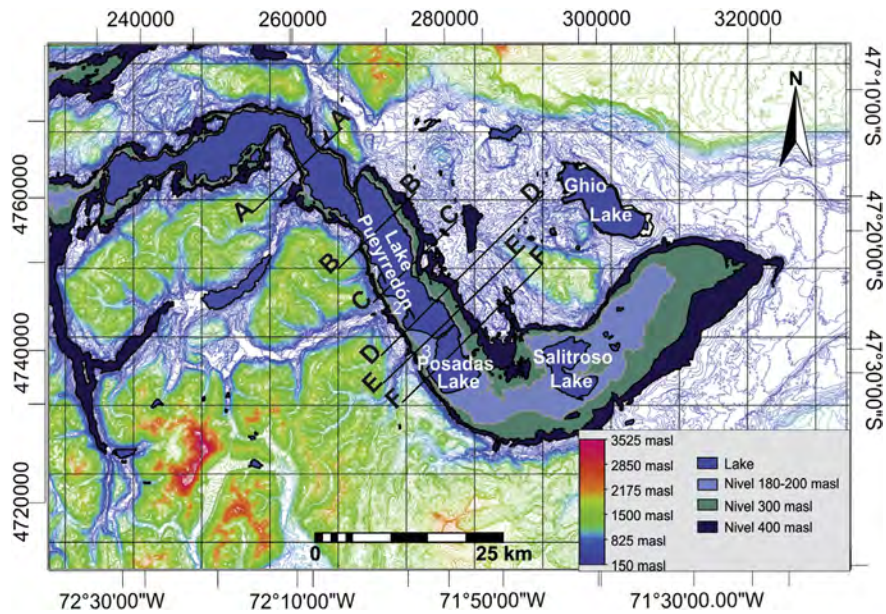

Fig. 16. The DEM shows the cross-sections (see Fig. 17) transverse to the lacustrine system. Additionally, the different flooding levels of this system are represented in the figure. Ghío Lake is located at a higher altitude than Pueyrredón, Posadas, and Salitroso Lakes, but it is represented with the same color because it is a current lake. Number 1 corresponds to the fan delta in the river of Suyai Farm, number 2 is the fan delta of the Oro River, and number 3 is the fan delta of the Furioso River. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

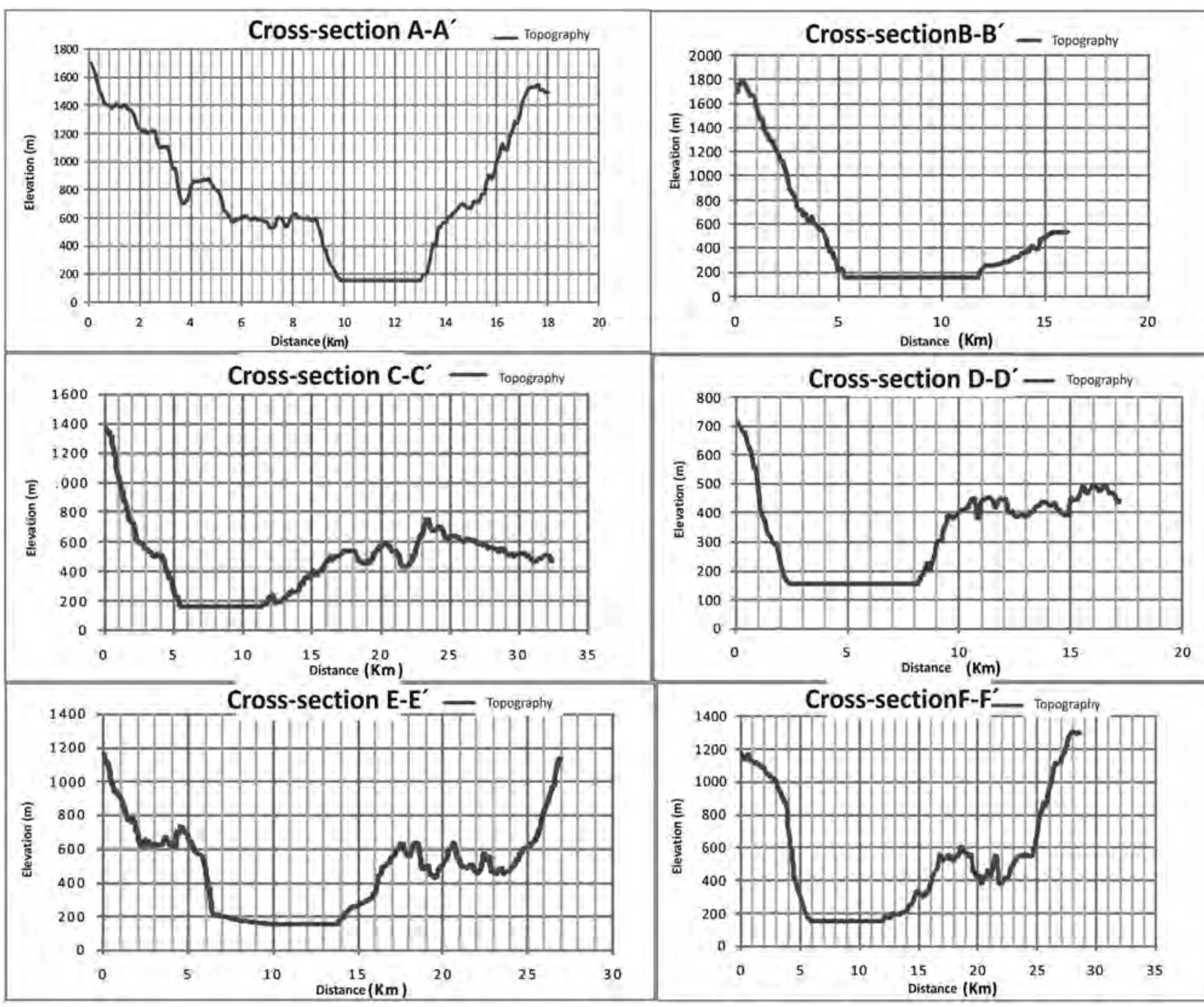

Fig. 17. Cross-sections transverse to the lacustrine system displayed on the map in Fig. 16.

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Fig. 18. Southern view of the Furioso River fan delta.

Fig. 19. View towards the NW of the spur of the fan delta in the mouth of the Suyai Farm River.

The main glaciated valley is occupied by the Pueyrredón, Posadas, and Salitroso Lakes; similar valleys, currently inhabited by the Oro and Furioso Rivers, correspond to former glacial fronts flowing from the primary glacial tongue. A minimum elevation of 190 m asl would have been required for the Pueyrredón, Posadas and Salitroso lacustrine systems to have formed a single paleolake covering 669.28 km^2.

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