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PrePub Article

Evolution of the Eastern flank of the North Patagonian Ice Field: The deactivation of the Deseado River (Argentina) and the activation of the Baker River (Chile)

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with 6 figures and 1 table

Summary. Patagonia had significant morphological changes when moraines at the foot of the Andes caused reversals in the drainage of rivers that crossed flat plateaus. Several examples of such basins are known from evidences of misfit valleys and the activation of short watersheds with rapids. The Deseado River drained the second largest lake of South America (Buenos Aires-General Carrera) and another glacial-valley system. The Deseado-Pinturas system conducted large amounts of water that satisfied herds of guanacos; paleoindians established to take advantage of such a quantity of proteins favored by the configuration of gorges at the upper valley (Cueva de las Manos site). However, during the shrinking of the North Patagonian Ice Field, the Baker River activated capturing the drainage of both basins towards the Pacific Ocean. The deactivation of the Pinturas and Deseado systems caused the lowering of progressive younger fluvial terraces, a record of hanging tidal flats at the inlet, and a progressive abandonment of the Las Manos site. The Baker River today supplies large amounts of water for planned hydroelectric dams. However, the watershed has not arrived into morphological equilibrium and recently suffered several Glacial-lake outbursts floods (GLOFs).

Key words: drainage reversals, glacial-lake outbursts floods, North Patagonian Ice Field, subduction of active ridge

Introduction

During the Pleistocene water from the Eastern flank of the North Patagonian ice field flowed towards the Atlantic Ocean via the Deseado River. The western flank was drained directly via short glaciers to the Pacific Ocean. The Eastern drainage was performed by two valleys today occupied by chain lakes; the northern valley comprises the Bertrand-Carrera Buenos Aires system toward the Fénix and Deseado rivers.The southern valley, today occupied by the Cochrane-Pueyrredon-Posadas and other smaller lakes, was drained by the Pinturas canyon towards the Deseado watershed (Fig. 1). Such a quantity of water caused the incision of Jurassic volcanic rocks into deep valleys extending from the foot of the mountains to the Atlantic coast.

The end of the Pleistocene Glaciation caused the deposition of terminal moraines that helped by some basaltic lava deposits to block the Atlantic outflow (Ton-That et al. 1999). There was a moment when the ice retreat permitted water to drain to the Pacific Ocean via the Cochrane and Baker rives. Much of the Deseado

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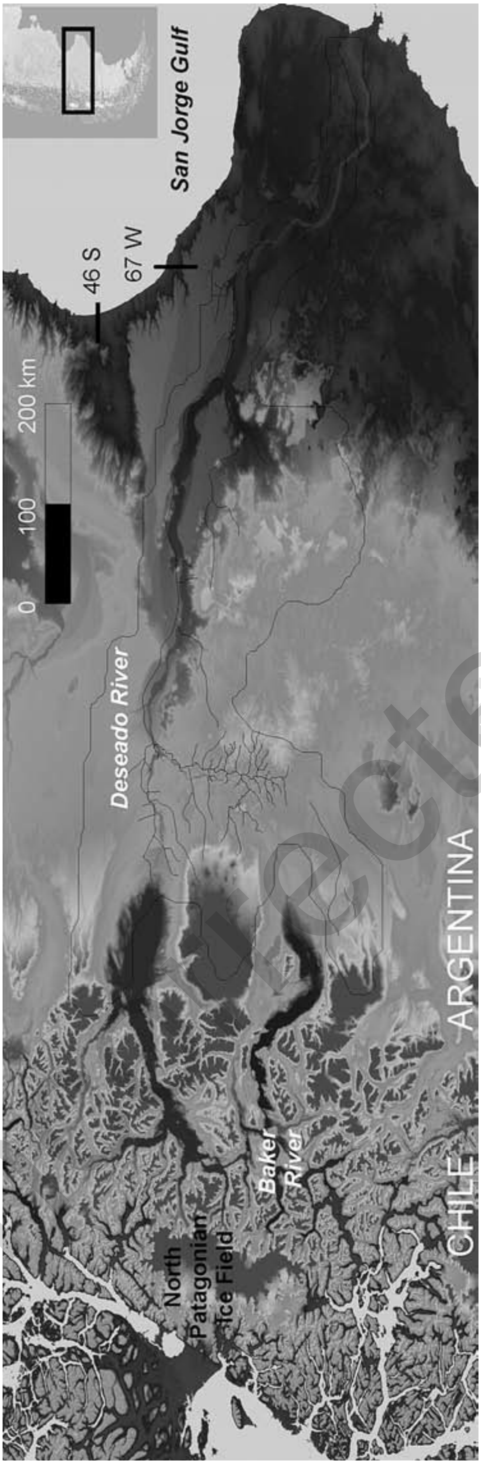


Fig. 1. Present Deseado watershed within the limits of the Pleistocene watershed overlying on a DEM.

River watershed was diminished, and gorges close to the inlet became infilled (Iantanos 2004).

Significant differences were detected between both flanks of the North Patagonian Ice Field. These differences were assigned to second-order controls of the glacier behaviour (Glasser et al. 2005).

Although some of these changes in the drainage of the Andes were reported by the first explorers during the beginning of the XX century, the purpose of this paper is to resume in details the morphological evidences that led to the reversal in the direction of flow. One of the main purposes of this manuscript is to analyse together the geomorphological evidences from both countries: Argentina and Chile, in order to explain the evolution of both watersheds.

Methods

DEMs were downloaded from the website http://srtm.csi.cgiar.com, with a spatial resolution of 90 m. They were handled with the Global Mapper v.7.04 (www.globalmapper.com). Drainage networks were digitised on a GIS environment (Arc View 3.1). At the lower valley of the Deseado River, Holocene sequences were described from non-operative tidal flats during the thesis work of one of the authors (NI). Vibracores were collected from intertidal areas of the same tidal flats.

The puzzle about the Tehuelche Gravels

This region of Patagonia has been studied specifically in relation to the origin of the Tehuelche Gravels (Shingle Formation in the sense of Darwin, 1842), assumed to be of Lower Pleistocene age. In the past, several authors considered them of glacial origin (Nordenskjold 1907, Caldenius 1932, Feruglio 1950, Frenguelli 1957), or fluvial (Keidel 1919, Groeber 1936), while others accepted a marine origin (Darwin 1842, Bonarelli & Nágera 1921). A specific study about their origin at the north-western extreme of Santa Cruz Province, Fidalgo & Riggi (1965) stated that:

1. The Tehuelche Gravels is a generic name for gravel deposits of different ages and origins,
2. Regarding the most ancient deposits, at Meseta Guenguel (fig. 1), there are two pediment formations with gravel accumulated before the Glacial deposits that characterise the Lago Buenos Aires region, and
3. The fluvial effects should be discarded at least for that region.

Pediments and volcanic plateaus

Patagonia history is also characterised by relief reversals. Gravels deposited on valleys are today covering plateaus armouring Tertiary sediments (Césari et al. 1986). During the Pliocene the oldest deposits of the Tehuelche Gravels were dipping towards the NE. Remains of these pediments are today located on top of Meseta de Guenguel and other plateaus close to the Atlantic coast (Castillo, Salamanca and Montemayor), and a small relict at Cerro Cuadrado (Césari et al. 1986). However,

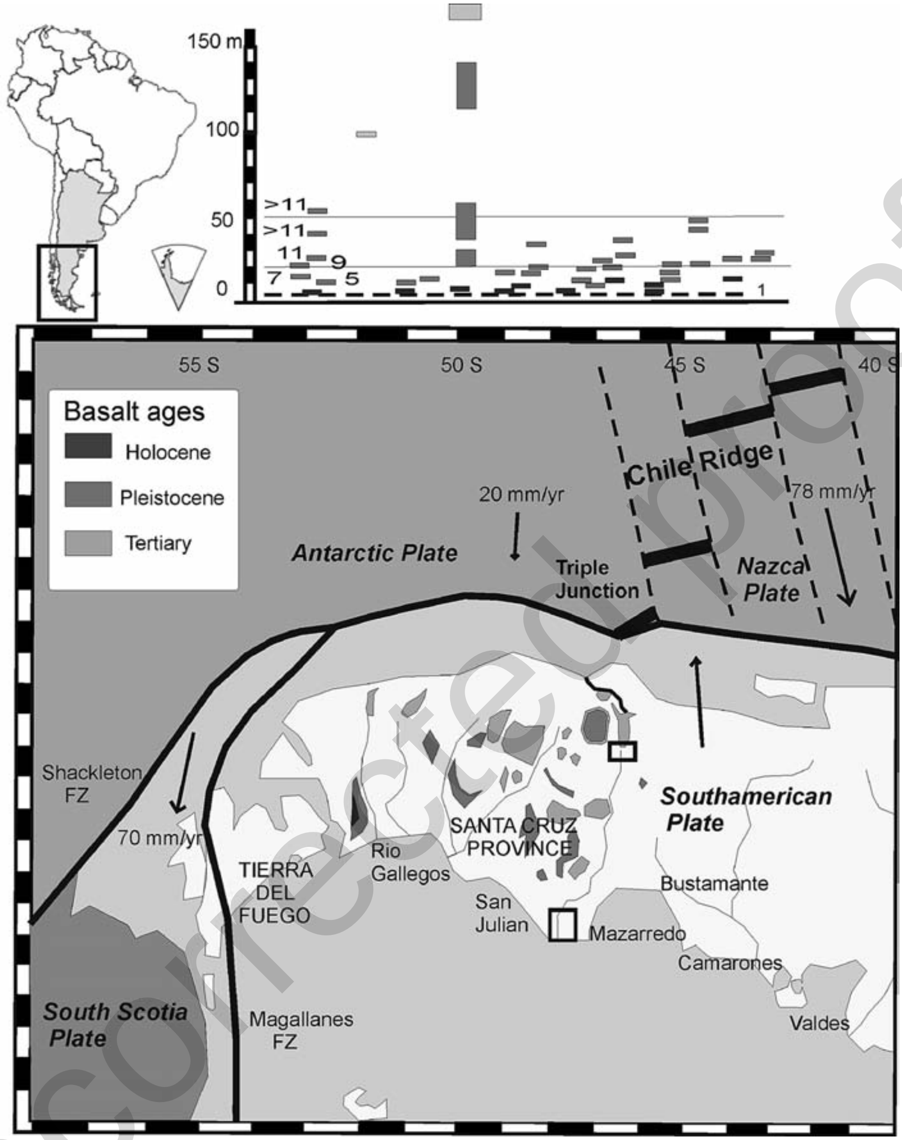
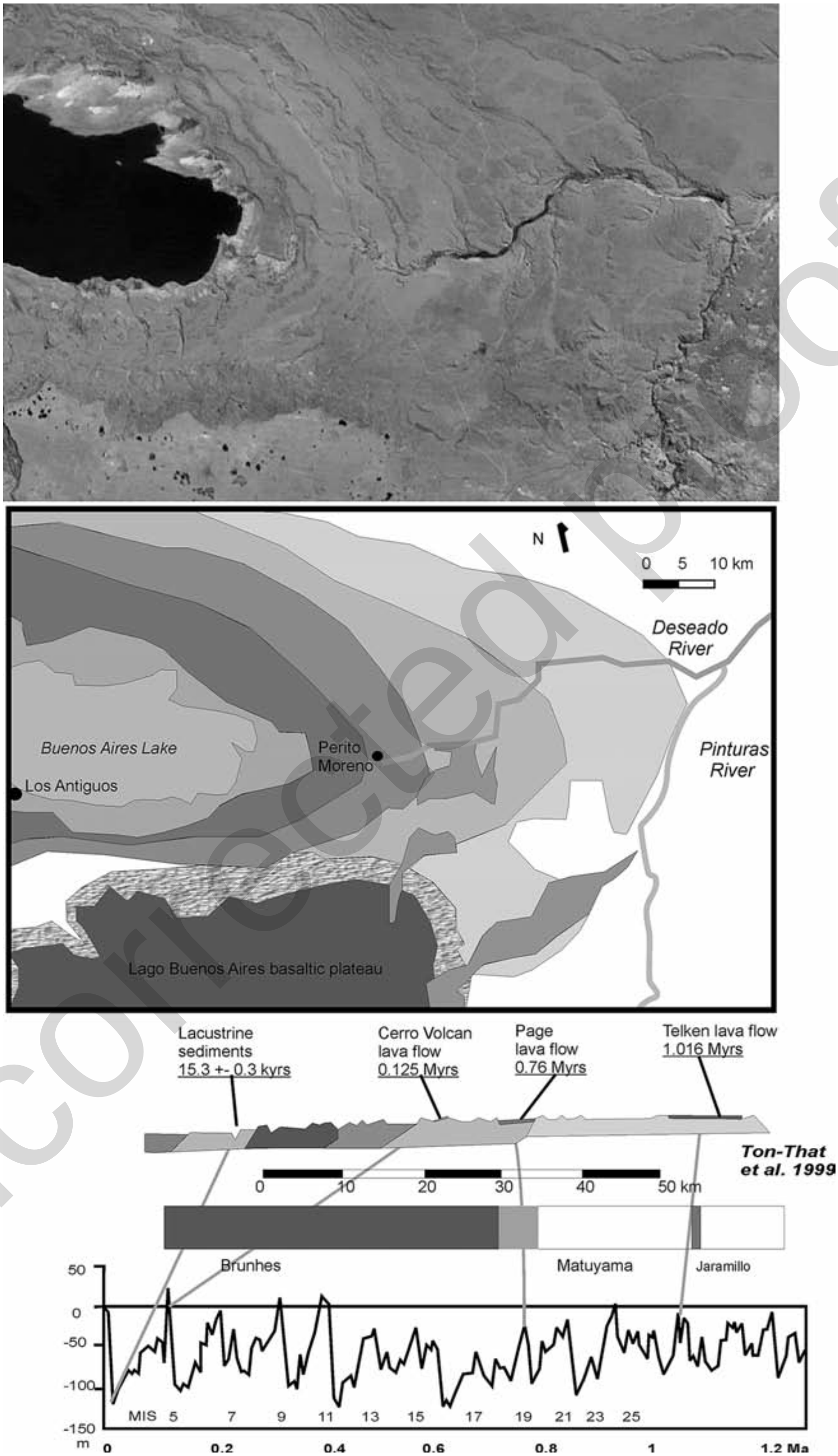


Fig. 2. Tectonic relationships of the four plates interacting in Patagonia, particularly in relation to the subduction of the Chile Ridge. A) The highest Upper Quaternary marine terraces are associated to the subduction of the active ridge. B) Rectangles locate the eastern area of Buenos Aires Lake, and the outlet of the Deseado River, that contain evidences of changes in the discharge of the watershed.

Fig. 3. Moraine arcs and lava-flows interlayered at the eastern coast of Buenos Aires Lake (modified from Ton-That et al. 1999). The ages of the lava flows were related to the sea-level variations during the last 1.2 Myrs.


N
0 5 10 km
Deseado River
Pinturas River
Buenos Aires Lake
Perito Moreno
Los Antiguos
Lago Buenos Aires basaltic plateau
Lacustrine sediments 15.3 +- 0.3 kyrs
Cerro Volcan lava flow 0.125 Myrs
Page lava flow 0.76 Myrs
Telken lava flow 1.016 Myrs
Ton-That et al. 1999
0 10 20 30 40 50 km
Brunhes
Matuyama
Jaramillo
50
0
-50
-100
-150
m
MIS 5 7 9 11 13 15 17 19 21 23 25
0 0.2 0.4 0.6 0.8 1 1.2 Ma

there are certain sedimentary differences between these deposits on top of gentle-sloping plateaus that lead to discriminate the age of these plateaus. The gravels on top of Pampa del Castillo are sloping eastwards (N 83°), those on Pampa de Malaspina are dipping towards the NE (N 18°), and the Montemayor gravels are sloping towards the NNE (N 06°). Based on these differences, it was stated that the gravels of Pampa del Castillo were older, and that those on top of the remaining plateaus were caused by the recycling of the former and material provided from Cretacic and Tertiary deposits (Beltramone & Meister 1992).

Tectonic uplift was responsible for pedimentation cycles. Basaltic deposits were covering Patagonian plains (fig. 2). Some extruded during the Miocene and Pliocene, while others were as modern as Pleistocene and even Holocene (Servicio Geológico Nacional 1994, Mazzoni & Rabassa 2010). This volcanic activity, in conjunction with the uplift trends represented by coastal terraces, should be assigned to the subduction of the active Chile Ridge (fig. 2). Due to the assymetric growth of the Chile Ridge, the triple junction has migrated from S to N in the last 14 Myrs as was analysed in detail at the Taitao Ridge (Guivel et al. 1999).

Pleistocene glaciogenic record

Several moraine systems were described attached to the Andes Cordillera (Caldenius 1932, Rabassa et al. 2000). The Lake Buenos Aires (called General Carrera Lake in Chile) has four moraine systems spanning around the eastern flank of the lake (fig. 3). Originally recognised by Caldenius, theyr were called as *initio*, *dani*, *goti* and *finiglacial* assuming that they were partly coeval to the Swedish glaciations. Detailed field works at the eastern end of the lake permitted to map several lava-flow deposits interlayered to the moraine systems (Ton-That et al. 1999). Datings of three of these basaltic deposits recognised ages of 1.016 ± 0.005 Myrs (Telken lava flow), 0.76 ± 0.007 Myrs (Page lava flow) and 125 ± 0.005 kyrs for the Cerro Volcán lava flow (Ton-That et al. 1999, Rabassa 2008). The ages of the moraines corresponding to Last Glacial Maximum also spanned into four systems dated between 23.0–22.7 ka (Fénix V) to 15.6–15.3 ka (Fénix I, Rabassa 2008).

Deglaciation

During the maximum of Last Glaciation the ice extended easterly from the Andes piedmonts. At Lago Buenos Aires valley, a large glacier extended to the present confluence of the Deseado and Pinturas rivers (Ton-That et al. 1999). The valley of the Pueyrredon Lake was also more extended to the NE, reaching Bajo Caracoles (Sylwan et al. 1991, Horta et al. 2011, fig. 4a).

The deglaciation caused large lakes occupying the former glacial valleys climbing down from the Patagonian Ice Shield. During the first centuries of the deglaciation the Deseado and Pinturas rivers have a maximum discharge capable of eroding their present canyons (fig. 4b).

Deglaciation continued until a fault oriented N-S and located beneath the ice began to collect the subglacial flows towards the Pacific Ocean. This new flow direction caused either the drop of the level of piedmont-lakes and the sudden vanishing of some small glaciers (jokulhaulps). It is assumed that the Pueyrredon-Posadas basin

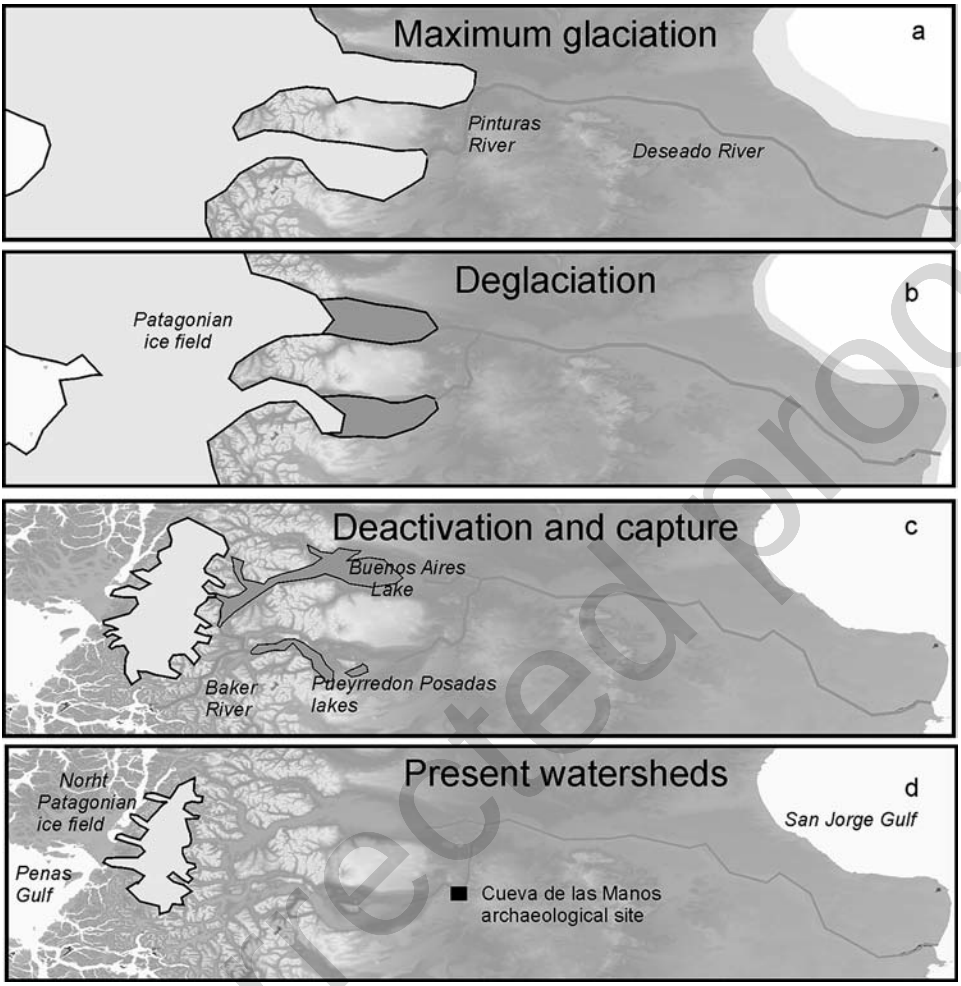


Fig. 4. Evolution of the Patagonian Ice shield and its drainage during the Upper Quaternary.

was captured at the beginning of the deglaciation (via the Cochrane River) and that a significant outburst flood was caused when the Baker River connected to the great Buenos Aires-General Carrera and the Bertrand lakes (fig. 4c). The calving induced by this river would have caused the division of the Patagonian Ice Field into the present two fields (Hielo Patagónico Norte and Hielo Patagónico Sur). There are several outcrops indicating a rapid decrease in the level of these lakes. Glaciolacustrine deposits were studied at the Eastern shore of Lago Buenos Aires (Caldenius 1932) although other deposits were detected at Paso Jeinimeni and Fachinal, and to the East of Lago Pueyrredon at the other watershed.

Based on the satellite mapping of some terminal moraines, some changes of the glaciers were considered to occur during the Holocene (Glasser et al. 2005). More modern changes were detected for the last 60 years (Fernandez Rivera et al. 2006,

Fig. 5. Fluvial valleys of the North Patgonian Ice Field. a) The Baker River initiates at the southern end of the Bertand Lake and is today draining the General Carrera-Buenos Aires Lake. b) The Pinturas River cut a plateau composed of Jurassic volcanic rocks (the white circle locates the Cueva de las Manos archaeological site).

Table 1. Radiocarbon ages of different beds of the Cueva de las Manos site, with depth of bed and number of specimens of Lama guanicoe (modified after Gradin et al. 1976, Mengoni Gonalons & Silveira 1976).

Bed	Prof (m)	Age ^{14}C	Lab number	Specimens of Lama guanicoe
3b	0.3	430 ± 50	CSIC 137	
4c	0.6	1610 ± 60	NOVA 115	11
5	0.7	3380 ± 90	NOVA 116	3
6 top	1.10	7280 ± 60	NOVA 117	2
6 middle	1.25	9320 ± 90	CSIC 138	2

fig. 4d). Ashes from the eruption of the Hudson Volcano (1991) are still covering some ponds (former lakes) along the way between Hipólito Irigoyen and Los Antiguos (route 41).

The archaeological record

Part of the Holocene evolution is known from archaeological evidences collected along the Pinturas River gorges. The well-known archaeological site of Cueva de las Manos (Fig. 4 and 5) has provided radiocarbon dates supporting significant changes at that human settlement (table 1). The canyon of the Pinturas River was carved into Jurassic volcanic rocks when the river had a discharge greater than today. However, the archaeological history indicates a period between 6,000 and 4,000 years (Pinturas 2 period) when there was a decrease in the hunting success (Gradin et al. 1976). Although this period was attributed to a climatic change, it can be more easily explained by a diminution in the discharge of the river caused by the significant changes in the watershed explained here.

The sea level record at the Deseado estuary

The estuary of the Deseado River has a record of the deactivation of its watershed, although it is masked by the Quaternary sea-level fluctuations. Feruglio (1950) discriminate between Pleistocene fluvial and marine terraces. The altitude of these terraces permitted to calculate a uniform uplifting trend of 0.12–0.16 m/yr (Pedoja et al. 2011). The Holocene sea-level fluctuation is recorded at the beach-ridge plains close to the inlet (Iantanos 2004, Schellmann & Radtke 2010). Non-operating tidal flats were described at the gorges of the northern shore of the estuary and explained exclusively by the Mid-Holocene sea-level drop (Iantanos et al. 2002). However, the deactivation of the watershed can explain very abrupt changes of the base levels. Tidal-flat deposits of more than 2 m were measured within the gorges composed of volcanic rocks close to the estuary (Iantanos 2004, fig. 6).

The activation of the Baker River

There is little information about the discharge of the Baker River in the Past. The valley is thought to have been buried under ice during the maximum glaciation. In recent years, this watershed has been matter of great concern in relation to hydroelectric projects planned (HidroAysén Project). Several gauge stations have been operating at the discharge of the Bertrand Lake (since 1963), Angostura Chacabuco (since 1976) and at the Colonia River juncture (1963–1990). Mean discharges vary between 300 and 1,000 m^3/s at Angostura Chacabuco (Barria Sandoval 2010). By mean of principal components the variations of discharges were estimated, distinguishing between rainy and dry years. However, there are doubts about the validity of some data, and the methods for estimating the glacier shrinking should be improved (Barria Sandoval 2010). Sudden outbursts of glacial lakes into the Baker River have been described caused by the Colonia Glacier during the years 2008 and 2009, with peaks of 3,000–4,000 m^3/s (Dusaillant et al. 2009). Outbursts floods of the Cachet 2 Lake and the downstream river network caused discussions about the interrelationships between the Baker and Colonia rivers (Ingendesa 2009). However, the large sediment loads confirmed by the outbursts floods recorded in the watershed indicated an aspect that was not considered in the estimated of life expectancy of the hydroelectric dam complex (Dusaillant et al. 2009).

Discussion

Drainage reversals were repeatedly reported in connection with volcanism or tectonism (Reheis et al. 2002). The uplift of the Southern Alps of New Zealand during the Quaternary, for instance, caused several changes in the discharge area a direction of flow of several rivers with implying the setting of barriers and corridors for fish distribution (Craw et al. 2008). The evolution of the Clutha River progressively increased its watershed with implications on the evolution of the galaxiid fishes (Craw et al. 2012). The divergence between mitochondrial DNA of fish population of several catchments of southernmost South Island of New Zealand was used to approximate the Holocene changes in these populations assigned to outwash moraines (Craw et al. 2007).

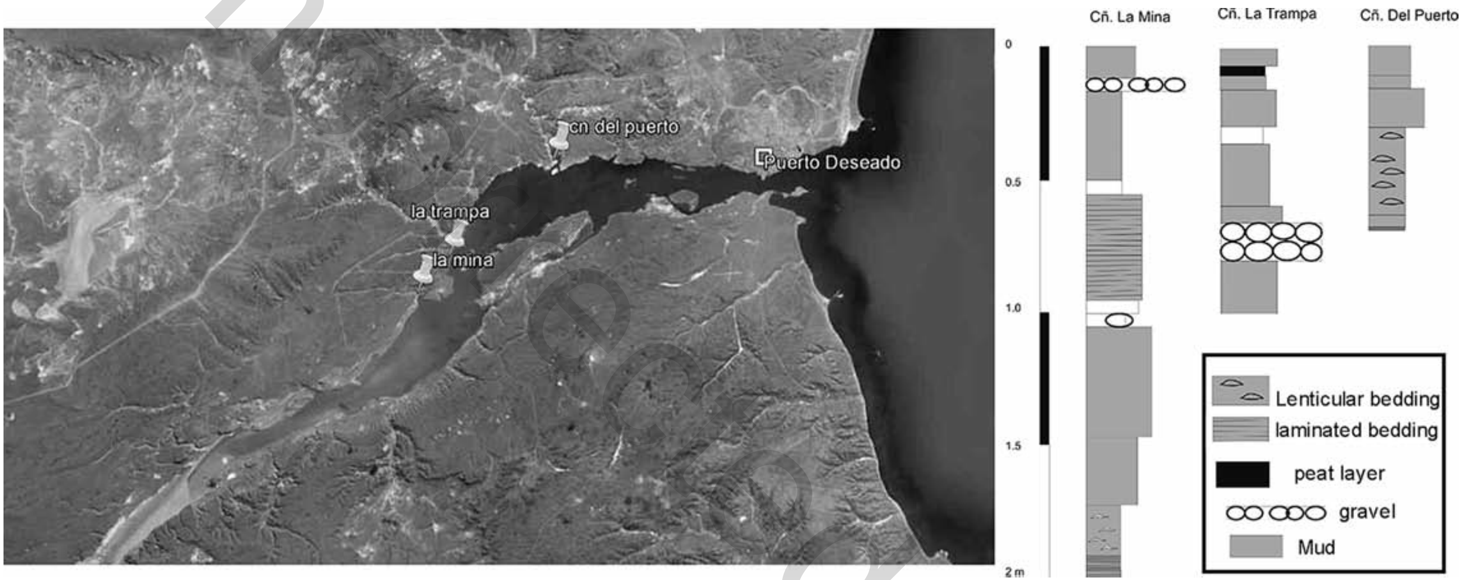


Fig. 6. Deseado River estuary. Non-operating tidal flats are recorded within the gorges on the northern shore of the estuary. b) Vibracorings obtained from the outlet of three gorges ("cañadones").

Deglaciation caused significant changes in the drainage of the Andes Cordillera where the humidity of the Pacific Ocean concentrates snow and rain. Although some of these changes occurred during the uppermost Pleistocene when terminal moraines were deposited as water divides, the changes of the drainage of the eastern flank of the North Patagonian Ice Field occurred during the Holocene.

Based on a scheme of glacier advances and retreats and pollen analyses, a speculative age of 11,500 radiocarbon years BP (13,500 calibrated years) was proposed for the reversal of the drainage of the eastern flank of the North Patagonian Ice Field (Mc Culloch et al. 2000). Considering that this reversal is recorded at the archeological site of Las Manos, the capture of the Deseado River by the Baker River is assigned to the mid-Holocene. In this sense, it is necessary to discriminate geomorphological evidences caused by climatic changes and local changes assigned exclusively to river captures that affect significantly piedmont valleys.

Conclusions

1. Significant geomorphological changes in this region of Patagonia caused a reversal in the direction of the water flow. During the Holocene, the Atlantic watershed diminished while the Pacific watershed became dominant.
2. In this particular case, the blocking of the terminal moraines is not the only cause. Basaltic deposits related to the subduction of the Chile Ridge are interfingered to these moraines.
3. The archaeological record is also suggesting changes in the discharge of the Pinturas River.
4. There are still significant changes in the high altitude watersheds with retreats and advances in the glacier fronts and sudden jökulhlaups.

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