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Mio-Pliocene glaciations of Central Patagonia: New evidence and tectonic implications

Yves Lagabrielle[1], Bruno Scalabrino[1], Manuel Suárez[2], Jean-François Ritz[1]

[1] *CNRS-UMR 5234, Géosciences Montpellier, Place E. Bataillon, CC 60, 34095, Montpellier Cedex 5, France*
yves.lagabrielle@gm.univ-montp2.fr; scalabri@gm.univ-montp2.fr; ritz@gm.univ-montp2.fr

[2] *Servicio Nacional de Geología y Minería, Avenida Santa María 0104, Santiago, Chile*
msuarez@sernageomin.cl

ABSTRACT. Patagonia is well known for spectacular occurrences of a variety of glacial-derived landforms and deposits and for a long history of ancient glaciations. In this paper, we first review the diverse evidence that demonstrates the development of glacial-related sedimentary units within the Central Patagonian Cordillera since 7 Ma. Well preserved glacial landforms at the top surface of mesetas on both sides of the Lago General Carrera-Buenos Aires are described: the Meseta Guenguel to the north, and the volcanic Meseta del Lago Buenos Aires to the south. The latter meseta corresponds to a 3 Ma old, morphologically inverted paleo-piedmont, based on Ar/Ar dates of the uppermost lava flows. It shows evidence of glacier advances to the NE direction. Over a distance of 20 km, glacial landforms observed by remote sensing data and digital elevation model define glacial tongues that were fed by the Cordillera reliefs to the west. These lobes are now beheaded from their westward sources along a morpho-structural corridor that bounds the Meseta del Lago Buenos Aires to the west. These remnants can be correlated with the oldest glacial landforms recognized north of Lago General Carrera-Buenos Aires, on the Meseta Guenguel that form the Chipanque moraine system. From these features it is concluded that the glacial drainage network of Central Patagonia has been strongly modified following relief inversion in response to erosion processes and to tectonic causes. Changes occurred after 3 Ma, from a smooth piedmont surface covered by an extensive ice mantle ending with ample glacial lobes, to the current series of deeply incised glacial valleys such as the Lago General Carrera-Buenos Aires depression. These new data bear important constraints on the history and development of the first glaciations in southern South America.

Keywords: Mio-Pliocene glaciations, Tectonism, Patagonia.

RESUMEN. Glaciaciones mio-pliocenas en Patagonia central: nueva evidencia e implicancias tectónicas. Patagonia es bien conocida por una espectacular geomorfología glacial y por una larga historia de antiguas glaciaciones. En este artículo primero se describe la variada evidencia que demuestra el desarrollo, desde hace 7 Ma, de unidades sedimentarias glacigénicas en la Cordillera Patagónica Central. Luego se describe una bien preservada geomorfología glacial en la cima de mesetas expuestas a ambos lados del lago General Carrera-Buenos Aires: en la Meseta Guenguel en el lado norte y en la meseta volcánica del lago Buenos Aires en el lado sur. Esta última corresponde a un paleo-piedemonte morfológicamente invertido de 3 Ma acorde a edades Ar/Ar de las lavas basálticas superiores. Exhibe evidencia del avance de glaciares hacia el NE. Observaciones hechas con sensores remotos y con modelos de elevación digital evidenciaron la presencia de formas glaciales a lo largo de una distancia de 20 km, las que fueron alimentadas desde los relieves cordilleranos ubicados al oeste. Estos lóbulos están ahora descabezados de su fuente ubicada al oeste a lo largo de un corredor morfoestructural que limita la Meseta del lago Buenos Aires por el oeste. Estos remanentes pueden ser correlacionados con las formas glaciales más antiguas reconocidas al norte del lago General Carrera-Buenos Aires en la Meseta Guenguel y que forman el sistema de morrenas Chipanque. Sobre la base de estos antecedentes se concluye que el sistema de drenaje de la Patagonia Central ha sido fuertemente modificado subsecuentemente a la inversión del relieve en respuesta a procesos erosivos y a causas tectónicas. Hubo cambios después de 3 Ma, desde una suave superficie de piedemonte cubierta por un extenso manto de hielo terminando con amplios lóbulos glaciales, hasta la actual serie de valles glaciales profundamente incididos tales como la depresión del lago General Carrera-Buenos Aires. Estos nuevos datos entregan importantes antecedentes a la historia y desarrollo de las primeras glaciaciones cenozoicas del sur de América del Sur.

Palabras clave: Glaciaciones Mio-Pliocenas, Tectonismo, Patagonia.

1. Introduction

The Patagonian Cordillera forms the southern segment of the Andes, north of the Andes of Tierra del Fuego. It was built coevally with the subduction of the southern part of the Chile Spreading Ridge during the late Cenozoic. Between latitudes 45° and 47°S the Central Patagonian Cordillera has both the highest mountains (Monte San Valentín, 4,058 m a.s.l.) and a deep transverse incision occupied by the Lago General Carrera-Buenos Aires (LGCBA). The northernmost ice-cap in South America occurs in this part of the cordillera (Campo de Hielo Norte: North Ice Cap, NIC, Fig. 1). The eastern border of the Cordillera, corresponding to the tectonic front, is marked by a rapid transition to the flat plain region of the pampa and is delineated by a N-S alignment of plateaus or mesetas, preserving perched flat surfaces that formed in response to relief inversion which occurred after 3 Ma (Lagabrielle *et al.,* 2004, 2007; Scalabrino *et al.,* 2009).

Patagonia is well known for spectacular occurrences of a variety of glacial-derived remnants and for a long history of ancient glaciations since the very first observations by Charles Darwin (Clapperton, 1993; Rabassa *et al.,* 2005; Strelin and Malagnino, 2009). Most of the previous studies which described the abundant relict landforms and deposits of glacial or fluvioglacial origin refer to glaciations which occurred during the Quaternary (Singer *et al.,* 2004; Kaplan *et al.,* 2004, 2005; Douglass *et al.,* 2005; Rabassa, 2008; Glasser *et al.,* 2008). The maximum areal extent of ice during the Quaternary Period is known as the Greatest Patagonian Glaciation (GPG) and developed between 1.168 and 1.016 Ma (OIS 30-34; Early Pleistocene) (Mercer, 1983; Singer *et al.,* 2004; Rabassa *et al.,* 2005). A minimum of eight glaciations occurred in the Middle-Late Pliocene (Oxygen Isotopic Stages 54-82). After the GPG, 14-16 cold (glacial/stadial) geoclimatic events occurred, intercalated with their corresponding warm (interglacial/interstadial) equivalents.

A major characteristic of the glacial history of Patagonia is that numerous deposits of pre-Pliocene glaciations, some as old as 7 Ma, have been observed in various places (*e.g.,* Mercer, 1983). These are not located within the present-day glacial valleys but are found as remnants preserved on perched relict surfaces, implying complex interaction between mountain building and glacial dynamics. In this paper, we first review the evidence collected so far in Central Patagonia demonstrating the development of glacial-related sedimentation over the reliefs of the Cordillera since *ca.* 7 Ma. Second, we report the existence of well-preserved glacial landforms exposed on the top surface of mesetas on both sides of the Lago General Carrera-Buenos Aires: the Meseta del Lago Buenos Aires to the south and the Meseta Guenguel to the north. These remnants have been disconnected from the main Cordillera after 3 Ma as shown by Ar/Ar ages from lava flows associated with glacial deposits. This implies important changes in the glacial drainage network of Central Patagonia which occurred around 3 Ma due to tectonic causes. At a broader scale, these findings bear important constraints on the history of the initiation and development of the very first glaciations over entire southern South America.

2. The geological framework of the Miocene-Pliocene glacial deposits of Central Patagonia

As stressed in the review of section 3 below, inception of the glacial history of Patagonia began at or before 7 Ma. Therefore, our understanding of the evolution of the Patagonian glaciations cannot be disconnected from accurate knowledge of the geological history of the Cordillera and its piedmont during the Neogene. In particular, we have to evaluate the succession of volcanic and tectonic events which affected Central Patagonia and their possible impacts on the development of the glaciations and glacial landscapes. The following section is an overview of the geological evolution of Central Patagonia pointing at the relationships between magmatic and tectonic events on one hand and glacial deposits on the other hand. These relations are examined in crucial sites such as the so-called mesetas, the large plateaus situated along the eastern front of the Cordillera, which show frequent spatial associations of magmatic products and glacial or fluvioglacial deposits.

In eastern Central Patagonia, Jurassic and Cretaceous volcanics rocks and marine sedimentary rocks unconformably overlie Late Paleozoic metamorphic rocks (Suárez *et al.,* 1996; De La Cruz and Suárez, 2006 ; De La Cruz *et al.,* 2003a, 2004). The Cenozoic stratigraphic sequence, well exposed in the area south of Lago General Carrera-Buenos Aires, includes: **1.** Oligocene marine clastic deposits

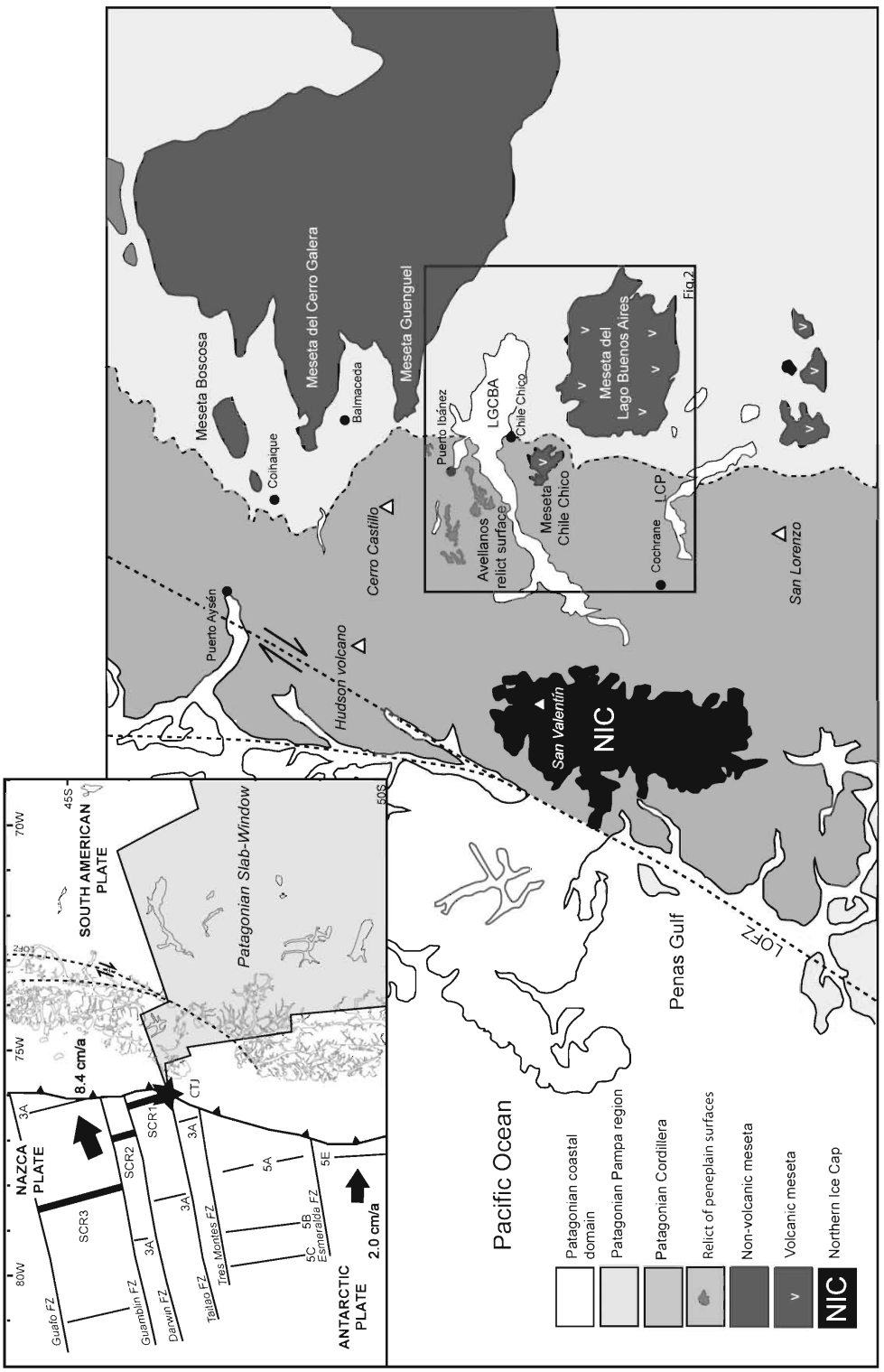

FIG. 1. Simplified map of Central Patagonia showing the type localities discussed in the text including: the pampa region, the mesetas, and the relict of flat surfaces inside the Cordillera. The contour of the Patagonian slab-window with respect to the location of the active spreading Chile Ridge (SCR) is shown in the upper cartoon (**CTJ:** Chile triple junction; **LOFZ:** Liquiñe-Ofqui Fault Zone).

(Guadal Formation); **2.** Miocene fluvial deposits, the so-called 'molasse', of the Zeballos Group (Flint *et al.,* 1994; Ray, 1996; Flynn *et al.,* 2002; De La Cruz and Suárez, 2006), **3.** Upper Miocene to Recent basalts forming the prominent flat-topped plateau of Meseta del Lago Buenos Aires (Gorring *et al.,* 2003; Lagabrielle *et al.,* 2004; Brown *et al.,* 2004; Espinoza *et al.,* 2005; Guivel *et al.,* 2006).

The orographic front of the Central Patagonian Cordillera is formed by the Jurassic to Lower Cretaceous volcanic rocks of the Ibáñez Formation, thrusted to the east over Cretaceous and Cenozoic volcanic and sedimentary rocks (Suárez and De La Cruz, 2000a; Lagabrielle *et al.,* 2004; Scalabrino *et al.,* 2009). The main Cenozoic contractional tectonism occurred during and after the deposition of the Zeballos Group (Santa Cruz Formation) and prior to the emplacement of the alkali basalts forming the large basal flows of the Meseta del Lago Buenos Aires around 14-12 Ma (Lagabrielle *et al.,* 2004, 2006; Guivel *et al.,* 2006; De La Cruz and Suárez, 2006). Therefore, the end of the major contractional event in the region of study can be correlated with the initiation of the subduction of the Chile Ridge at 15-14 Ma in southernmost Patagonia, inducing changes of stress regime in the frontal arc region and in the Cordillera domain (Lagabrielle *et al.,* 2004). Between 5 Ma and 3 Ma, renewed orogenic activity, uplift and disruption of former erosional surfaces occurred in relation with activation of strike-slip fault zones and normal inversion of older thrusts (Lagabrielle *et al.,* 2007; Scalabrino *et al.,* 2009).

The Meseta del Lago Buenos Aires (47°S-71°30'W) is one of the largest (~6,000 km^2) and most voluminous (*ca.* 2,000 km^3) basaltic plateaus in the back-arc domain of Central Patagonia (Figs. 2 and 3). It forms part of the Neogene Patagonian Plateau Lavas province (NPPL, Gorring *et al.,* 1997) known from 46°30'S to 52°S in Argentina. This province has been genetically related to the development of a series of slab windows opened as a consequence of the subduction of the South Chile Spreading Ridge (SCR) under the South American Plate since ~15 Ma (Cande and Leslie, 1986; Ramos and Kay, 1992; Gorring *et al.,* 1997; Gorring and Kay, 2001 ; Gorring *et al.,* 2003; Guivel *et al.,* 2006 ; Scalabrino *et al.,* 2009).

The Meseta del Lago Buenos Aires locally exposes spectacular successions of tills and lava flows. In addition, the boundary between the Cordillera and the Meseta is also characterized by the existence of numerous recent shallow magmatic intrusions. Both lavas and intrusions have stratigraphical relationships with the glacial deposits and represent suitable targets to build accurate chronological schemes for ancient glaciations. For all these reasons this area is of high interest.

The oldest lavas of the Meseta del Lago Buenos Aires succession are poorly exposed and are known only in one place, at Cerro Zeballos, along the Río Zeballos valley where they have been dated at 16-14 Ma (Espinoza *et al.,* 2010; Boutonnet *et al.,* 2010). These lavas were emplaced during the fluvial sedimentation of the uppermost beds of the Río Zeballos Group and show the transition from an arc related source to a more OIB-like, alkali source. The main-plateau basaltic pile determining the overall plateau morphology of the meseta comprises tabular basaltic lava flows and interbeds of fluvioglacial deposits emplaced during the Late Miocene-Pliocene (~12.2-3.3 Ma: Mercer and Sutter, 1982; Ramos and Kay, 1992; Kay *et al.,* 1993; Gorring *et al.,* 1997; Ton-That *et al.,* 1999; Guivel *et al.,* 2006) (Figs. 2, 3 and Table 1). Later, post-plateau basalts were emplaced in several volcanic pulses during the last 3.3 Ma-100 ka interval as isolated monogenetic cones and maars (Ton-That *et al.,* 1999; Gorring *et al.,* 2003; Brown *et al.,* 2004; Singer *et al.,* 2004) as well as flows filling valleys incised into the main plateau sequence (Lagabrielle *et al.,* 2007). The post-plateau lavas are volumetrically minor (~600 km^3, Gorring *et al.,* 2003) compared to the main sequence.

In the SW border of the Meseta del Lago Buenos Aires, west of Monte Zeballos, several felsic alkaline subvolcanic bodies, mostly shallow level plugs, dikes and laccoliths, are exposed at altitudes around 1,800-2,000 m a.s.l. The most prominent bodies (Pico Rojo, Mifeldi pluton and Cerro Lápiz peaks : Espinoza *et al.,* 2008; Boutonnet *et al.,* 2010) are aligned along a N160-170 trending lineament, the Zeballos Fault Zone, paralleling the western edge of the Meseta and marking the morphotectonic front of the Patagonian Cordillera (Giacosa and Franchi, 2001; Lagabrielle *et al.,* 2004; Scalabrino *et al.,* 2009). They are intrusive into the main-plateau basaltic pile of the Meseta or into the molasse of the Zeballos Group. $^{40}Ar/^{39}Ar$ and whole-rock K-Ar ages dates for the lavas and the felsic intrusions indicate that the emplacement of these rocks occurred between 3.98 and 3.08 Ma synchronously with that of the

TABLE 1. A COMPILATION OF LOCATION AND AGES OF DATED LAVA FLOWS AND DIKES THAT ALLOWED DATING GLACIAL DEPOSITS IN THE REGION OF MESETA DEL LAGO BUENOS AIRES.

Label in Fig. 2	Article Reference	Location	Sample No.	Location (UTM 19)	Dated Material	Age (Ma)	± Error (2σ)
1	a	Avellanos Surface	Q387	4,854,211/257,617	WR	4.57	0.27
2	b	MCC	PG36-38	4,836043/284,123	WR	4.63	0.13
3	b	MCC	PG138	4,836,043/284,123	WR	4.46	0.22
4	b	MCC	FE01-11	4,819,707/283,249	WR	4.50	0.30
5	b	MCC	FE01-16	4,827,408/285,508	WR	4.60	0.20
6	b	MCC	FE01-36	4,831,666/280,272	WR	4.40	0.80
7	c	Alto Río Ghío	PG65	4,783,664/288,643	WR	4.98	0.15
8	c	Alto Río Ghío	PG67	4,783,664/288,643	WR	6.95	0.24
9	c	Alto Río Ghío	PG69	4,783,664/288,643	WR	4.32	0.23
10	c	Alto Río Ghío	PG70	4,783,664/288,643	WR	2.96	0.09
11	c	Alto Río Ghío	PG72	4,783,664/288,643	WR	3.91	0.11
12	c	Alto Río Ghío	PG75	4,785,410/286,064	WR	4.81	0.32
13	d	South C. Zeballos	PA06-03	4,790,021/286,906	Bt	2.91	0.10
14	d	W-MLBA	PA06-17	4,788,816/289,717	Bt	4.48	0.14
15	d	W-MLBA	PA06-18	4,788,728/289,375	Bt	3.23	0.08
16	d	W-MLBA	PA06-19	4,789,134/288,263	Bt	6.85	0.15
17	d	Alto Río Ghío	PA06-20A	4,789,134/288,263	Bt	2.12	0.45
18	d	Alto Río Ghío	PA06-22	4,782,182/285,551	Bt	6.22	0.74
19	d	Alto Río Ghío	PA06-23	4,782,182/285,551	Bt	9.42	1.42
20	d	W-MLBA	PA06-12	4,790,274/289,079	Bt	2.76	0.07
21	d	SW-MLBA	TM-01	4,783,140/288,460	Bt	4.17	0.16
22	d	SW-MLBA	TM-02	4,783,332/289,383	Bt	6.41	0.22
23	e	SW-MLBA	PAT-12	4,778,705/292,340	WR	3.65	0.10
24	e	SW-MLBA	PAT-20	4,780,366/292,728	WR	3.08	0.13
25	e	SW-Mlba	PAT-22	4,781,845/293,488	WR	3.28	0.10
26	e	SW-Mlba	PAT-26	4,789,707/290,427	WR	4.52	0.16
27	c	NE-Mlba	PG113	4,815,765/293,768	WR	5.84	0.21
28	c	NE-Mlba	PG105	-	WR	6.53	0.25
29	c	NE-Mlba	PG108	-	WR	5.80	0.19
30	c	NE-Mlba	PG109	-	WR	5.64	0.19
31	c	S-MLBA	PG132	4,774,130/306,184	WR	3.32	0.10
32	c	S-MLBA	PG133	4,774,072/306,312	WR	3.64	0.11
33	c	S-MLBA	PG134	4,772,347/307,422	WR	3.89	0.14
34	f	NE-MLBA	8 ages of flows above and below tills			max. 7.00	-
						min. 4.6	-
35	g	NE-MLBA	-	-	Bt	5.04	0.04
36	g	NE-MLBA	-	-	Bt	7.38	0.05
37	h	NE-MLBA	-	-		6.53	0.23

a. Pelleter, 2003; **b.** Espinoza *et al.*, 2005; **c.** Guivel *et al.*, 2006; **d.** Boutonnet *et al.*, 2010; **e.** Espinoza *et al.*, 2006, 2007; **f.** Mercer and Sutter, 1982; **g.** Ton-That *et al.*, 1999; **h.** Morata *et al.*, 2002. **Bt:** biotite; **WR:** whole rocks.

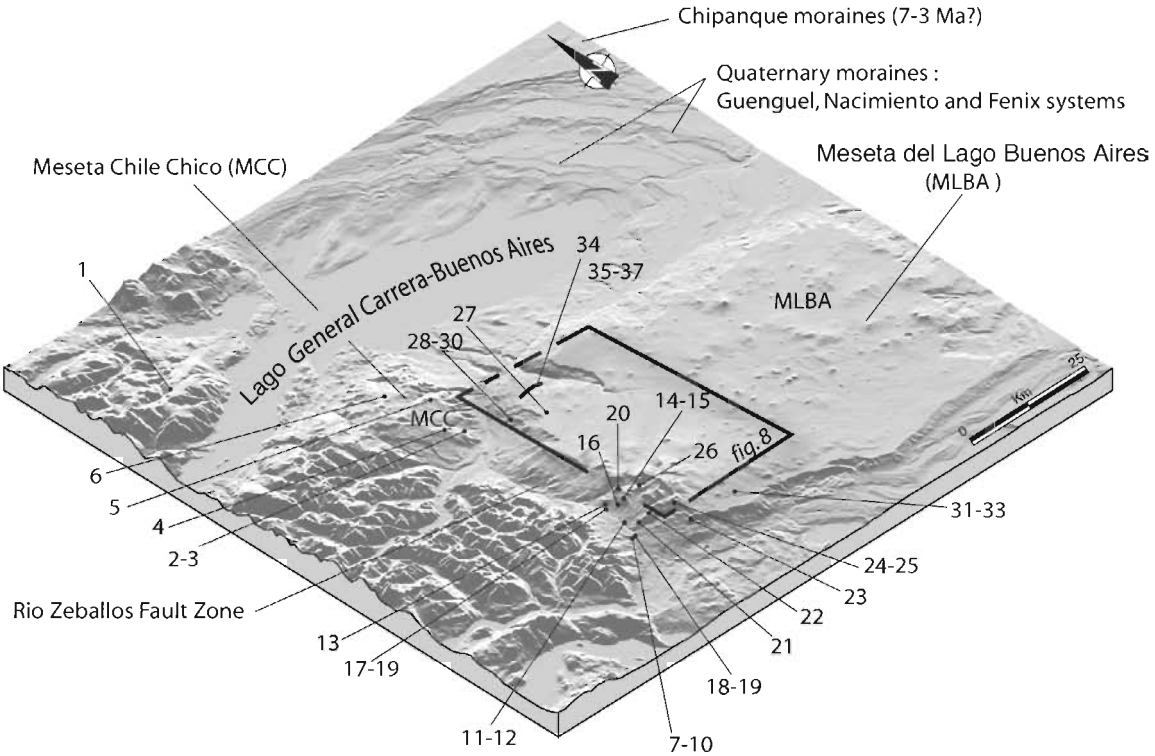

FIG. 2. A 3D view of the Meseta del Lago Buenos Aires (MLBA) and its surroundings based on a SRTM DEM (location in Fig. 1). Numbers indicate the main sites where lava flows have been dated since the first work of Mercer and Sutter in 1982, as reported in table 1.

more mafic, post-plateau basaltic sequence, during a bimodal mafic-felsic magmatic episode devoid of intermediate compositions (Brown *et al.*, 2004; Espinoza *et al.*, 2008; Boutonnet *et al.*, 2010). The exposure of these bodies along the western scarp of the meseta indicates that a major tectonic disruption occurred here, along the N160 trending Zeballos fault at 3 Ma or after. This event led to the relative uplift of the western border of the meseta with respect to the Cordillera. As shown below, this event had a major impact on the glacial network of this region.

The top surfaces of three other mesetas adjacent to Meseta del Lago Buenos Aires are composed of pre-Quaternary glacial and fluvial-glacial deposits (Fig. 1).

1. On the northern side of the Lago General Carrera-Buenos Aires, the Meseta Guenguel extends north of Rio Fenix Grande. It has a triangular shape and its maximum elevation reaches 1,200 m a.s.l. at its western tip, close to Portezuelo. The Meseta Guenguel rises by 1,000 m above the Lago General Carrera-Buenos Aires and the moraines of the Fenix system deposited by the latest Quaternary glaciers (Fig. 2) (Singer *et al.*, 2004). By contrast to the Meseta del Lago Buenos Aires, its upper surface is not covered with lava flows. The oldest moraine system known north of the Lago General Carrera-Buenos Aires area, the Chipanque moraine system, was recognized on the surface of the Meseta Guenguel, immediately north of Estancia La Golondrina (Malagnino, 1995), at an elevation of 800 m. New observations of this system are described in section 4. From satellite images, the Meseta Guenguel paleosurface extending north of the Chipanque moraines shows a dendritic relict stream network flowing to the east. At the western tip of the meseta, the edges of the stream network are abruptly cut by post-glacial landslides. Tributaries are truncated along the southern sharp edge of the meseta in response to Pleistocene glacial incision and generalized relief inversion of the Cordillera front (Lagabrielle *et al.*, 2004).

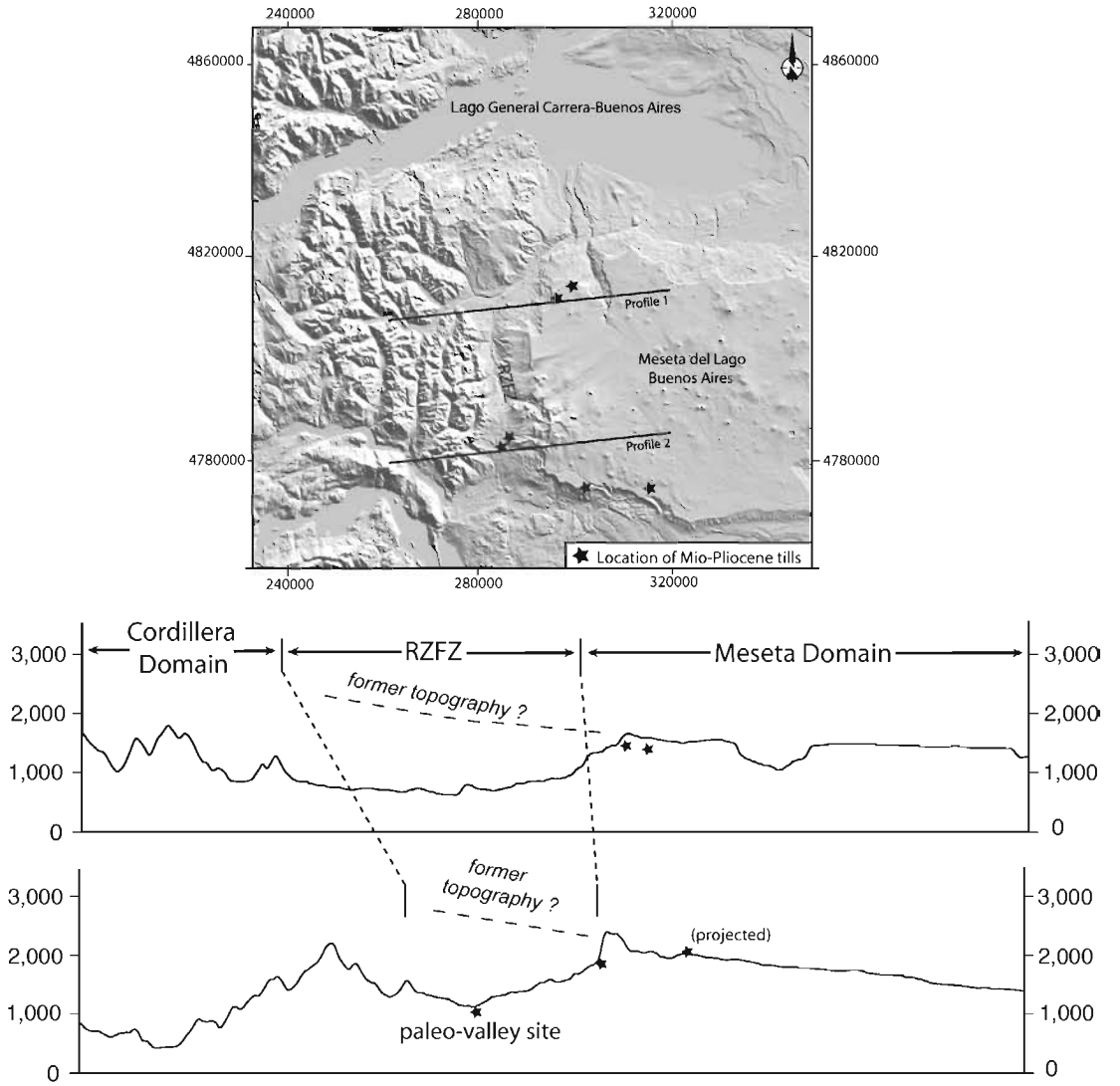

FIG. 3. Location of cited tills and fluvioglacial gravels of Mio-Pliocene age (stars) in Meseta del Lago Buenos Aires. Map view and topographic cross-sections. **RZFZ:** Río Zeballos Fault Zone.

2. A northern meseta having the same triangular shape as Meseta Guenguel, the Meseta del Cerro Galera is lying north of the Balmaceda Plain (Fig. 1). From satellite images, it also shows a paleo-fluvial network. Its western tip corresponds to Cerro Galera which dominates the depression of Coihaique. No lava flows are known from the top surface of this meseta and recent field work reports the presence of a thick pile of glacial and fluvioglacial polymictic conglomerates overlying the Tertiary molase sediments (B. Scalabrino, unpublished information, 2009).

3. The Meseta Chile Chico (46.4°S; 2,160 m a.s.l.) is the westernmost exposure of Eocene and Mio-Pliocene flood basalt volcanism in Patagonia. The Cenozoic volcanic succession, approximately 1,000 m thick, unconformably overlies the Jurassic-Lower Cretaceous volcanic rocks of the Ibáñez Formation and consists of Upper Paleocene-Eocene basalts, Upper Oligocene-Lower Miocene marine sediments and Upper Miocene to Pliocene basalts. These upper basalts, 400 m thick, with alkaline and sub-alkaline affinities gave K-Ar ages ranging between 9.8 Ma±0.1 Ma and 4.4±0.8 Ma (Espinoza, 2003; Espinoza *et al.*, 2005; De La Cruz and Suárez, 2008).

3. Mio-Pliocene glacial deposits of Central Patagonia: a review

3.1. The 7 Ma to 5 Ma tills at the northern edge of Meseta del Lago Buenos Aires

Some of the oldest Cenozoic glacial deposits recognized in South America have been found in the scarps of the Meseta del Lago Buenos Aires between Río Jeinimeni and Río Los Antiguos (Mercer and Sutter, 1982). Till deposits over 30 m in thickness are interbedded with lava flows of the main plateau sequence. Eight lava flows have been dated. The lower basalts yielded whole rock K-Ar ages of 7.34±0.11 to 6.75±0/08 Ma and the upper basalts yielded ages of 5.05±0.07 to 4.43±0.09 Ma (Mercer and Sutter, 1982). In the same locality, Ton-That *et al.* (1999) have obtained $^{40}Ar/^{39}Ar$ isochron ages of 7.38±0.05 Ma and 5.04±0.04 Ma for the underlying and the upper basaltic flows, respectively.

3.2. The 7 Ma to 3 Ma tills at the western edge of Meseta del Lago Buenos Aires

Key exposures allowing observations of relationships between glacial deposits, lava flows, dikes and fault surfaces are located west of Meseta del Lago Buenos Aires, in the Portezuelo area of Alto Río Ghío at 1,170 m elevation, on the western side of the road R.P. 41, north of Paso Roballos (47°04'43.61"S and 71°49'31.55"W) (Fig. 2, No. 17-19, Fig. 4). Here, basaltic lava flows, locally up to 10 m thick, have been emplaced in a paleo-glacial valley trending N35-N40, incised in the fluvial sandstones of the Zeballos Group and filled with glacial sediments (refered to as the paleovalley site hereafter).

a. A sample from the lower flow in the northern part of the outcrop has a whole rock K-Ar age of 4.98±0.15 (Lagabrielle *et al.*, 2007). This flow overlies tills and fluvioglacial conglomerates including

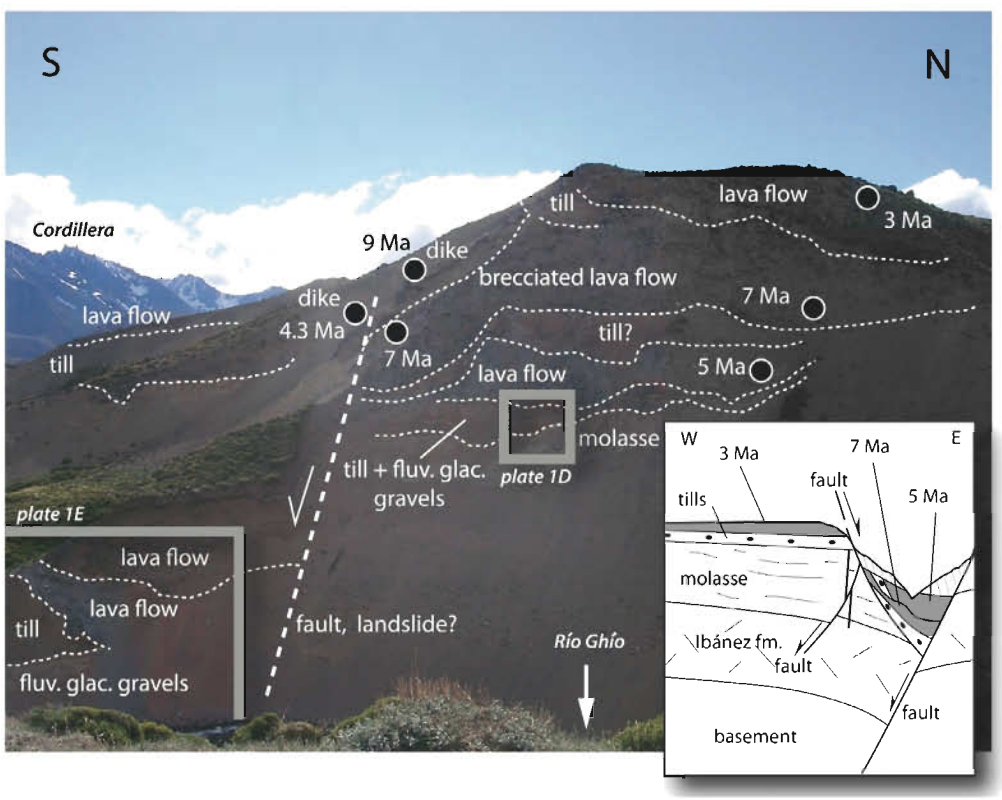

FIG. 4. Photograph of the scarp of the western side of alto Río Ghío along Ruta 41, exposing a paleo-valley infilled with glacial sediments and lava flows. Numbers correspond to the ages of dated samples of lavas and dikes. Insert shows an idealized E-W section across this outcrop.

numerous cobbles deriving from the internal part of the Cordillera (plutonic rocks from the Patagonian Batholith, ignimbrites and lavas from the Mesozoic formations). A new date obtained from a lava flow in direct contact with glacial conglomerates located 200 m south of the previous site gave a Ar^{40}/Ar^{39} age of 6.85±0.15 Ma (Boutonnet *et al.*, 2010). This is the oldest age for a lava flow in contact with tills obtained at this site. The tills immediately underlying this lava flow display a spectacular red-colour along the contact indicating heating and circulation of hot, oxydizing water during lava emplacement (Plate 1B, 1E). This strongly suggests lava eruption in a glacial environment. Close to this site, due to fresh exposures along the current steep valley flank, a spectacular contorted contact between moraine deposits and a lava flow can be observed (Plate 1E), indicating that lava flows deformed soft glacial sedimentary deposits and confirming eruption within a glacial environment. The outcrop belongs to a faulted block, detached along a landslide, making precise correlation with the other dated lavas impossible (Fig. 4).

b. The intermediate flows are brecciated and include basaltic blocks of various types, one of them dated at 6.95±0.24 Ma. The upper flow gave a K-Ar age of 2.96±0.09 Ma (Lagabrielle *et al.*, 2007) (Fig. 4). It extends horizontally farther west over the ancient piedmont surface, developed at the foot of the morphotectonic front of the Cordillera (Fig. 5). This paleo-piedmont, at least 3 Ma old, is now incised by the present-day Río Ghío and is offset to the east by the faults of the Río Zeballos fault zone which control the western scarp of the meseta.

c. The upper flow, 3 Ma old, overlies a second layer of tills that also extends westwards towards the front of the Cordillera (Fig. 5).

The compilation of ages above indicates glacial advance and related deposition of sediments at least during 3 periods at *ca.* 7 Ma, 5 Ma and 3 Ma (Fig. 5). In the same area, a lava flow exposed along the road-cut some hundreds meters to the north, yielded an age of 4.81±0.32 Ma (Lagabrielle *et al.*, 2007). It belongs to a series of flows interbedded with tills,

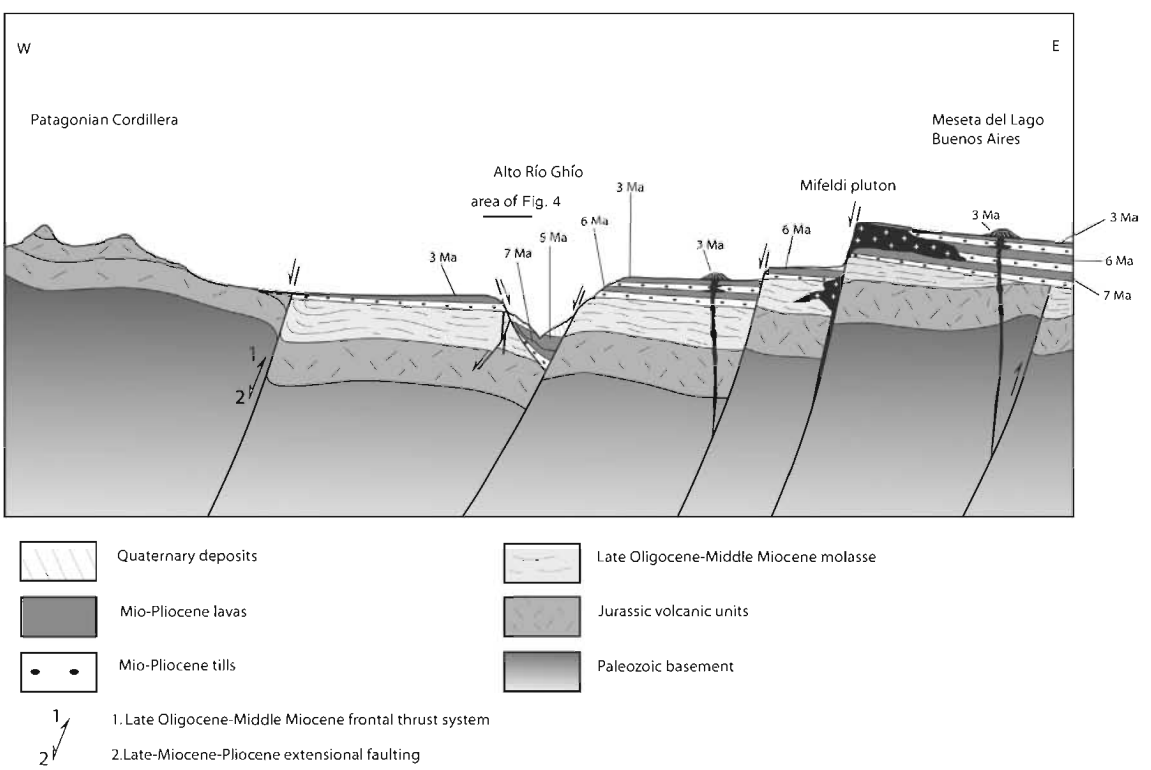

FIG. 5. Idealized cross-section of the western border of Meseta del Lago Buenos Aires showing the location of faults, tills and lava flows. Vertical exaggeration has been partially applied, in order to enhance the occurrence of till layers.

also characterized by the presence of exotic pebbles originating from remote regions of the batholith (Plate 1C). In this region of the Portezuelo area of Alto Río Ghío, few km north of the paleovalley, new dating of lava flows confirm that basalts have been erupted between 6 Ma and 3 Ma (Boutonnet *et al.,* 2010).

In addition to the exposures described above which are located mostly along the western edge of the Meseta del Lago Buenos Aires, perched tills and fluvioglacial deposits have been observed in some localities directly on the top surface of the Meseta del Lago Buenos Aires. First, at the southwestern limit of the plateau, a till, 40 m thick, is sandwiched between two flows dated at 3.64 and 3.32 Ma at 1,454 m elevation (Guivel *et al.,* 2006; Lagabrielle *et al.,* 2007: Fig. 2, Table 1, sites 31-32). The upper part of the till is reddish due to thermal effect during flow emplacement. Second, coarse fluvioglacial gravels and underlying tills have been observed on the western edge of the meseta at 1,350 m elevation (D. Morata, personal communication, 2008; Plate 1A). These deposits have been tilted and are covered by a lava flow dated at 5.84±0.21 Ma (Guivel *et al.,* 2006, Fig. 2, Table 1, site 27). Third, Mercer and Sutter (1982) report the presence of a large moraine in their area of study, in the northwest corner of the Meseta (Fig. 6). Due to its present elevation on the top surface of the meseta and to its location far from the current glacial valley of Lago General Carrera-Buenos Aires, this moraine may be correlated with the tills dated between 3.64 and 3.32 Ma exposed at the opposite side of the Meseta (sites 31-32).

Evidence of faulting during magmatic activity in Alto Río Ghío area is deduced from observations made some tens of meters south of the paleovalley. The Zeballos Group sandstones are intruded by subvertical basaltic dikes which are offset by westward dipping, conjugate normal faults. One dike has given a K-Ar whole rock age of 4.32±0.23 Ma (Lagabrielle *et al.,* 2007) (Fig. 2, Table 1, site 9). Numerous deformation structures are observed in this site (Plate 1D) including an eastward dipping brittle cleavage oriented N35-N40, parallel to the paleo-valley axis, affecting both the Zeballos Group sandstones and the base of glacial deposits. This led Lagabrielle *et al.* (2007) to propose a tectonic control of the paleo-valley. Faulting initiated during the deposition of the first tills and lavas, that is probably as early as 7-6 Ma.

3.3. Fluvioglacial conglomerates and moraines older than 2.3 Ma on top surfaces of various mesetas north of the Lago General Carrera-Buenos Aires basin. The Chipanque glacial event

The Chipanque moraine has been identified by Malagnino (1995) on the surface of the Meseta Guenguel north of Estancia La Golondrina, at an average elevation of 820 m. It consists of a system comprising a 2 km wide frontal push moraine and a series of attached, 10 km wide, internal shear moraines forming a bilobate belt, 12 km in width. These glacial landforms are dismantled to the S, SW, and N by the erosion of three main younger glaciations, the Deseado, Primavera and Guenguel glaciations (preceding the Nacimiento and Fenix glaciations). This allowed Malagnino (1995) to define the Chipanque glaciation as the oldest extra-andean glacial event recognized in Patagonia. As emphasized by Malagnino (1995), the Chipanque event was marked by a series of ample glacial lobes escaping from a smooth piedmont surface covered by an extensive ice mantle. The glacial landscape was thus characterized by the absence of marked relief that allowed the channeling of glaciers. We reach similar conclusions from the observations reported in the following section. From correlations with the oldest glacial accumulations in the region, as reviewed above, the age of this first regional glaciation could range between 7 Ma and more than 2.3 Ma, a conclusion already proposed by Malagnino (1995).

Glacial and fluvioglacial accumulations are known in various localities north of Meseta Guenguel. Despite very few dedicated studies, some rough characteristics of these deposits can be presented here.

First, a sequence of tills and fluvioglacial conglomerates forms the upper part of Cerro Galera, a prominent relief of molasse deposits dominating the Coihaique depression. This perched sequence, more than 100 m thick, shows a spectacular accumulation of pebbles and boulders within a thin sandy matrix. Most of the blocks are of plutonic origin and derive from the batholith. The till is presently disconnected from any former glacial relief around and from any network of old glacial deposits to the west. No dating of these tills has been performed. Since they cover the upper beds of the Galera Formation, they are younger than 16-14 Ma.

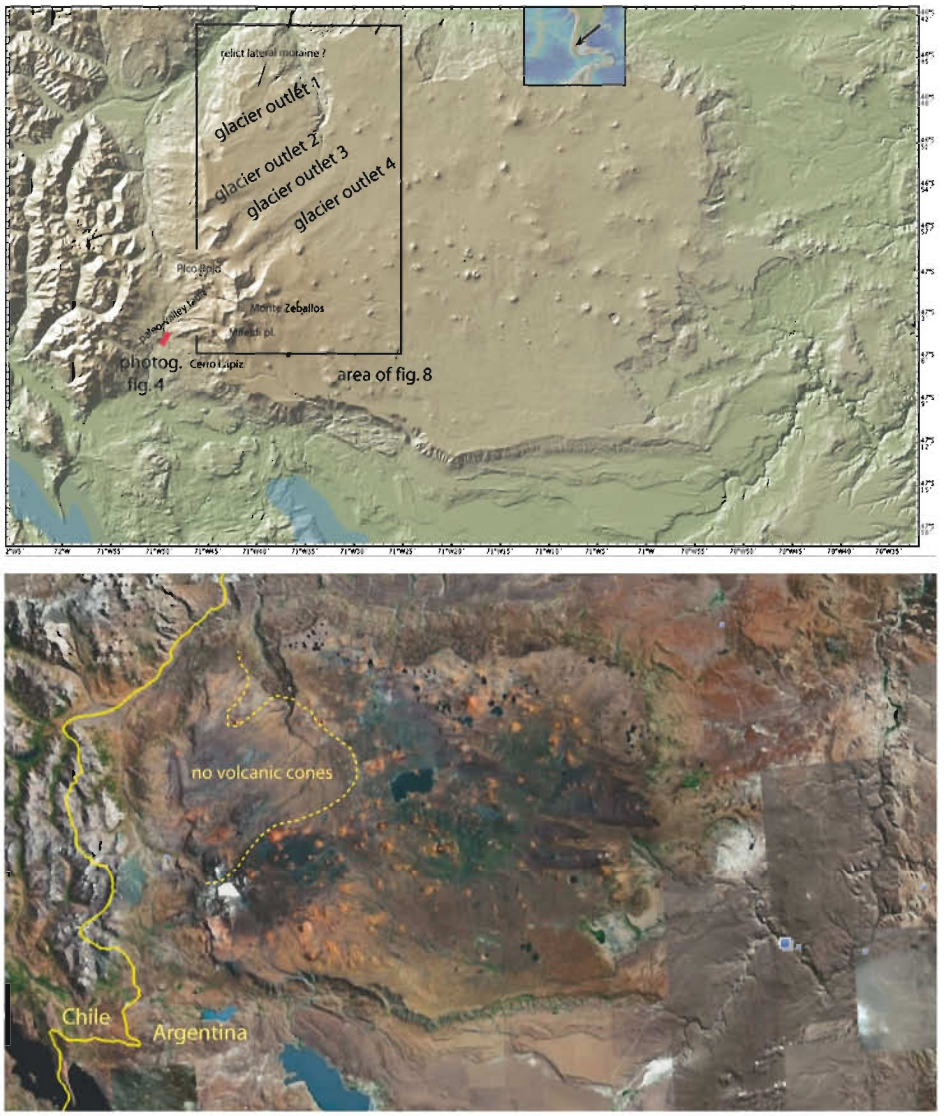

FIG. 6. Topography and satellite image of the Meseta del Lago Buenos Aires showing the main pre-Quaternary glacial features, as observed at a regional scale (lower image from Google).

Second, further north, in the area of Meseta Boscosa and Baño Nuevo, 60 km NE of Coihaique, tuffs dated at 17 Ma (U-Pb SHRIMP, De La Cruz *et al.*, personal communication, 2007), are overlain by fluvial conglomerates assigned to the Upper Miocene Galera Formation and dated nearby at 12 Ma by zircon U-Pb SHRIMP from a sample of an intercalated tuff (R. De La Cruz, M. Suárez and M. Fanning, unpublished information). Varves with dropstones observed in loose blocks are interpreted as formely interbedded in the conglomerates, which allows the inference that the conglomerates are fluvioglacial in origin and that there was a very old glaciation approximately during the Late Miocene (Suárez *et al.*, 2007).

Finally, in these areas north of the Meseta Guenguel, the top of several mountains of the easternmost part of the Cordillera are covered by loose gravels, overlying beds assigned to the Galera Formation and that have been interpreted as representing fluvioglacial deposits of Pliocene or Pleistocene age (Suárez *et al.*, 2007). There are no dates for these

deposits that could represent either the eroded remnants of the Galera Formation or younger beds of Pliocene or Pleistocene age. These deposits are disconnected from other glacial forms or deposits and are elevated in several hundreds of meters with respect to the present day river system, implying important river incision likely in response to tectonic uplift since the Late Miocene-Pliocene. This was followed by the advance of valley glaciers forming a well developed system of frontal moraines at the northern and eastern margins of the Baño Nuevo plains, that dammed a lake during the Pleistocene (Suárez *et al.*, 2007).

3.4. Fluvioglacial and glacial conglomerates exposed inside the Cordillera on top of the relict Avellanos surface (10-4 Ma)

Relicts of polymictic conglomerates representing fluvioglacial deposits have been found in some localities of the inner Cordillera of Central Patagonia (Fig. 1), on both sides of the Lago General Carrera-Buenos Aires. These deposits are exposed on remnants of a flat paleosurface extending west of the tectonic front known as the Avellanos peneplain (Lagabrielle *et al.*, 2004, 2007). The Avellanos surface has an average elevation of 2,000 m and is well-developed in the internal regions of the Cordillera, north of Lago General Carrera-Buenos Aires and west of Puerto Ingeniero Ibáñez (Fig. 1). It has locally a clear erosional origin, erasing folded Jurassic volcanic rocks and Paleozoic basement. The Avellanos peneplain was present during the Pliocene, as indicated by the age of a 10 m thick basaltic lava flow deposited on it, north of the Lago General Carrera-Buenos Aires, dated at 4.57±0.27 Ma (Ar/Ar, Guivel *et al.*, 2006). This basaltic flow correlates with the upper basaltic flows on top of the Meseta Chile Chico, on the opposite side of the lake, exposed at the same elevation (2,150 m a.s.l), which have been dated at 4.4±0.8 Ma (Espinoza, 2003; the Pico Sur basalts of De La Cruz and Suárez, 2008). The latter flow overlies fluvial and fluvioglacial coarse deposits indicating the presence of an old, inverted glacial and proglacial system here, before the foundering of the Lago General Carrera-Buenos Aires Quaternary valley system. The conglomerates overlie, probably with a hiatus, a basaltic lava flow of *ca.* 8.0 Ma, suggesting the existence of an erosional surface developed sometime between 8 and 4.5 Ma (De La Cruz and Suárez, 2008). Therefore, this erosional surface can be correlated with a depositional surface in the Meseta del Lago Buenos Aires, bracketed between 7 and 5 Ma and where glacial deposits accumulated (Mercer and Sutter, 1982; Ton-That *et al.*, 1999). This indicates that the Avellanos surface was formely connected to a piedmont surface of the mesetas.

4. New observations of preserved glacial landforms on the top surfaces of Meseta Guenguel and Meseta del Lago Buenos Aires

Four elongated remnants of glacier outlets, SW-NE oriented, are observed on satellite images and DEM on the NW side of Meseta del Lago Buenos Aires (Figs. 6 and 7). They parallel a ridge which likely corresponds to the lateral moraine described by Mercer and Sutter (1982). These glacial geomorphological features have never been reported so far. Since they are relatively well observed on satellite images, and because they are exposed in an area of high interest regarding the problems of glacial chronology in Patagonia, we attempt a preliminary analysis, as proposed in figure 8. The glacial forms are observed in a region devoid of any volcanic cone contrasting with the remaining surface of the meseta (Fig. 6) and suggesting that glacial advance avoided the growth of volcanic edifices or that the glaciers overode the volcanic cones. To the south, 2 glacial valleys are still in connection with the slopes of the Monte Zeballos, indicating glacial activity during very recent times. By contrast, the two northernmost outlets appear as truncated valleys (Fig. 6) and are disconnected from any current former ice domes in the surroundings. Landforms include glacial ridges and probable eskers, well developed lateral moraines truncating large volcanic cones, lateral moraines and arcuate frontal moraines (Figs. 7 and 8). Detailed field work is now needed in order to describe precisely these features and their chronology. The presence of tills dated around 3 Ma in the western border of the meseta, as reported above, indicates that some of the glaciers that left these features are approximately 3 Ma old. In addition, the frequent interbedding of lavas and glacial deposits as observed along the western border of the Meseta del Lago Buenos Aires confirms a long history of extra-Andean glacier advances starting here around 7 Ma.

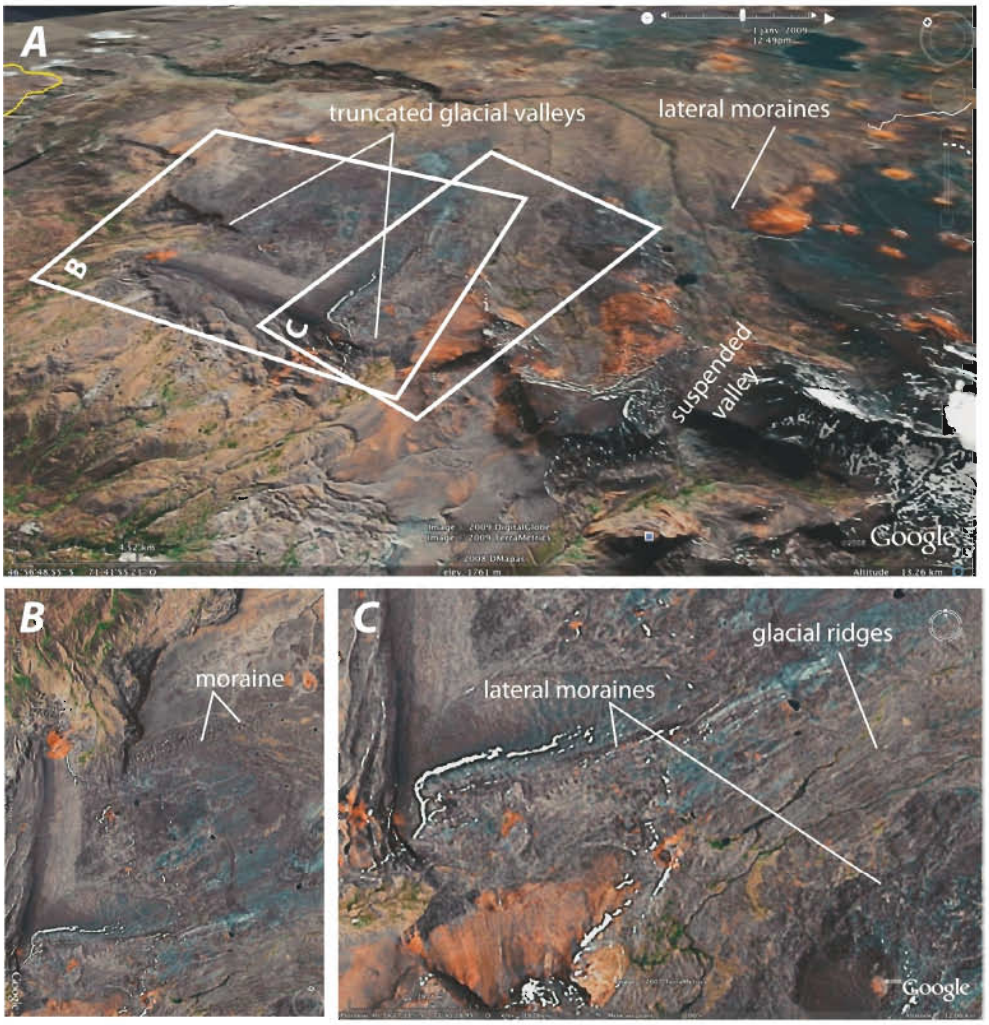

FIG. 7. **A.** Satellite 3D oblique view of the western border of the Meseta del Lago Buenos Aires with some details of glacial features (**B.** and **C.**).

The Meseta del Lago Buenos Aires glacial landforms are not the only remnants recognized on top of the Central Patagonia mesetas. In addition to the field descriptions reported by Malagnino (1995), land observations of the south western edge of Meseta Guenguel by remote sensing provide a relatively clear image of the Chipanque moraine system. Two large arcuate moraines system and associated frontal sandur river and plains marks the presence of an ancient frontal glacier system (Fig. 9). These preserved glacier lobes deposits are labelled the Loma Chipanque moraines (south system) and northern Chipanque moraine (north system), according to the first description by Malagnino at Loma Chipanque (Fig. 9). This system is not very well preserved, but the arcuate shape of the corresponding ridges contrasts with the flat surfaces around, devoid of any glacial fabric.

As first claimed by Malagnino (1995), the presence of this sytem on top of Meseta Guenguel represents an additional strong evidence that important glaciers developed in the extra-Andean domain of Central Patagonia during the Pliocene. Figure 9C is an attempt to map the maximum eastern extension of this system over the frontal Patagonian Cordillera, taking into account the occurrence of glacial remnants on top of most of the mesetas between 45°S and 47°S.

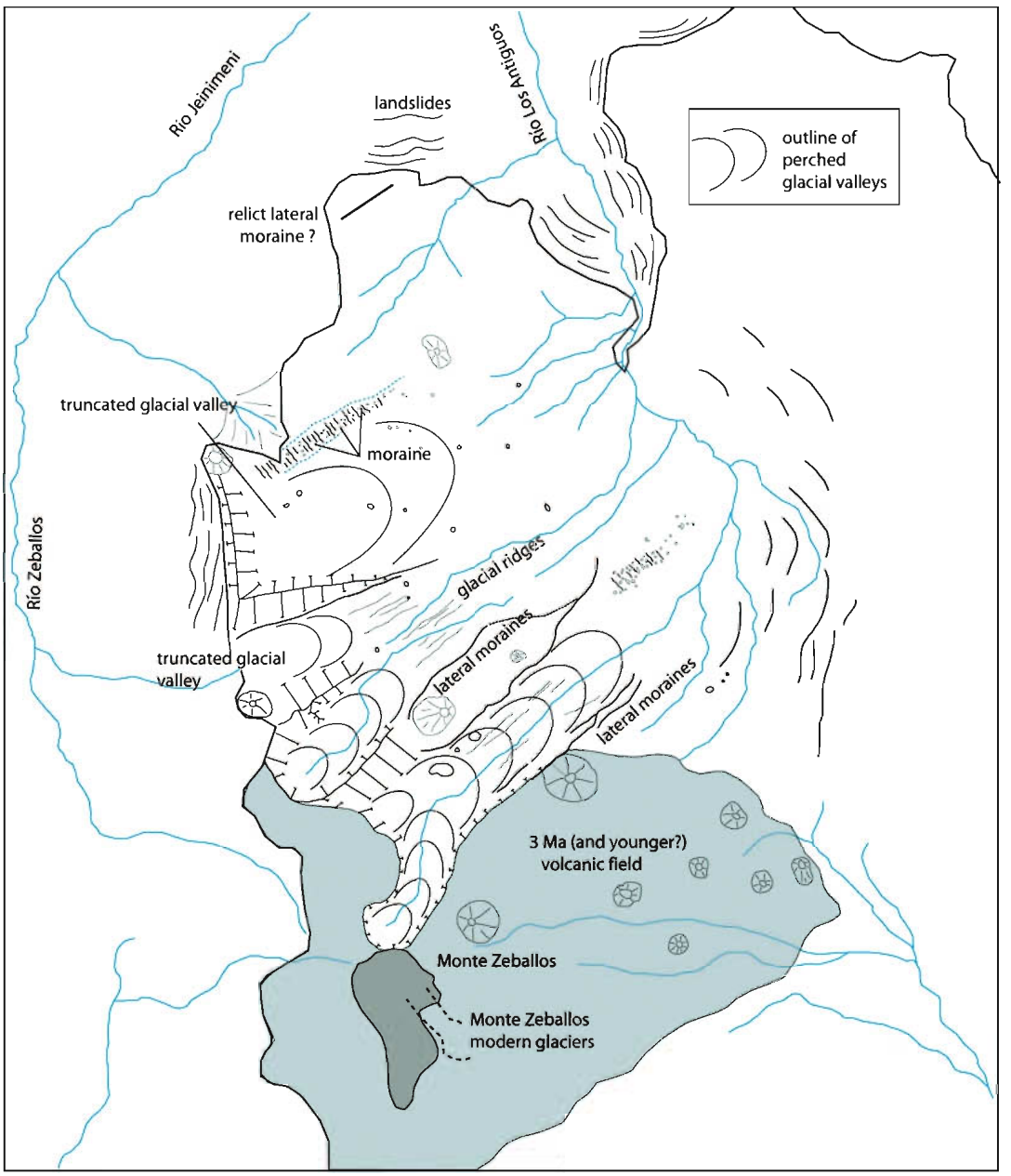

FIG. 8. Geomorphological map interpretation of the western border of the Meseta del Lago Buenos Aires with some details of observed glacial features based on DEM data and satellite images.

5. Discussion: tectonic and paleoclimatic implications

This study highlights 3 major questions concerning the Miocene-Pliocene tectonic-climatic evolution of the Central Patagonian Cordillera. These questions relate to: **a.** the widespread character of the observations reported here, **b.** the timing and origin of the processes reponsible for the disconnection of the glacial landforms from the remaining Cordillera, and finally **c.** the tectonic and paleoclimatic significance of such a major morphological change.

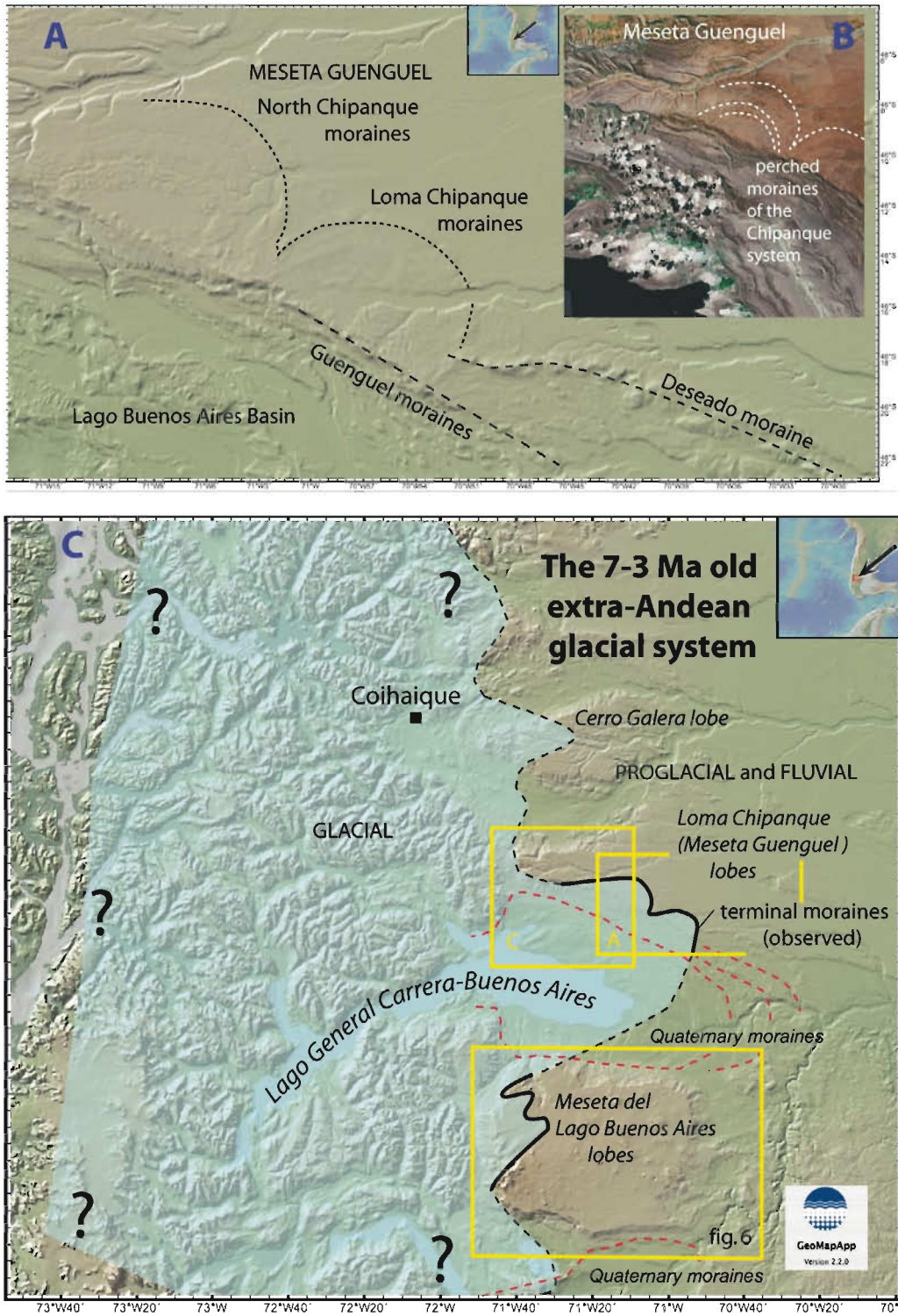

FIG. 9. **A.** and **B.** Maps of the Chipanque moraine system based on DEM data (A) and on Landsat image (B). **C.** A preliminary map of the maximum extension of the glacial system that developed between 7 and 3 Ma over Central Patagonia, based on information from the literature together with the observations reported in this paper.

5.1. Generalization about the presence of old glacial formations in Central Patagonia and the development of the Avellanos surface

The compilation of data presented in this study confirms that the oldest known Patagonian glaciation took place between approximately 7 and 5 Ma (Latest Miocene-Earliest Pliocene). The possibility of a *ca.*12 Ma old glaciation has been also tentatively proposed by Suárez *et al.* (2007) in the area of Baño Nuevo. This has to be compared to recent results from other regions of Patagonia which also indicate local development of early glaciations. Late Miocene glacial deposits have been recognized in northern Patagonia between 39°S and 41°S (Schlieder *et al.,* 1988). Suárez and Emparán (1997) report the observation of erratic boulders and glacial striations at about 2,000 m high in the region of Lonquimay (38°30'S) in Chile, adjacent to the border with Argentina. These erratics occur on hills bordering the present valleys. These feature are probable evidence for an ice cap as far north as latitude 38°30'. The existence of Late Miocene glacial deposits around Lago Cardiel (49°S, 72°15'W in southern South America), as old as 10.5 Ma is reported by Wenzens (2006a). Nine late Miocene glacier advances are identified in this region that until now had been assumed to be unglaciated. Several dating results indicate minimum ages of 6.4 Ma and 6.6 Ma for oldest glaciations of the San Lorenzo and San Martín area. Two further advances have a minimum age of 5.4 Ma.

Our study shows that despite a disruption due to recent tectonics, the succession of lavas and tills exposed in Alto Río Ghío displays similar characteristics to the succession described by Mercer and Sutter (1982) in the northern part of the Meseta del Lago Buenos Aires. In both localities, glacial formations reworking material from remote regions of the Cordillera including the Patagonian Batholith, are comprised between flows dated at 7-6 Ma and 5-3 Ma. In the Alto Río Ghío area, at least two till formations are present and a younger one, dated at 3 Ma is exposed at the same latitude on the top surface of the Meseta del Lago Buenos Aires (Lagabrielle *et al.,* 2007). This indicates finally that during the 7.3 to 3.0 Ma period, Central Patagonia has experienced at least 3 cycles of glaciation, around 7 Ma, 5 Ma and before 3 Ma, contemporaneous with abundant basalt flooding.

The data from the four mesetas reported here indicate that during the Late Miocene-Pliocene, sometime between 7 and 4.5 Ma and after the deposition of the Río Zeballos Group (late Early to early Middle Miocene), glaciers and rivers were flowing to the east or to the north-east, building a regional morphological smooth surface, known as the Avellanos surface. This surface is erosional in the internal Cordillera. In the piedmont domain to the East, abundant lava flows, now capping the Meseta del Lago Buenos Aires were accumulating locally, probably within wide, low-relief, depressed areas of this surface. Interbedding of lava flows and gravels show that just before or during and after 7 Ma, lavas were erupted during the fluvial and glacial processes. Finally, between14 Ma and 3 Ma, the region of the Cordillera corresponding to the study area was smoother and not so deeply incised as the current one. This character was already recognized by Malagnino (1995), based on the analysis of the Chipanque moraine system corresponding to the terminal portion of an extensive ice mantle ending with ample glacial lobes on a smooth piedmont surface. The N160 and N-S oriented valleys paralleling the front of the Cordillera (Río Jeinimeni-Río Zeballos and Río Ghío valleys), as well as the transverse incision of the Lago General Carrera-Buenos Aires did not exist (Lagabrielle *et al.,* 2004). Higher reliefs, the feeders of the paleo-glaciers described in this study were located farther west, suggesting a very different overall morphology of the Cordillera.

5.2. Timing and origin of processes responsible for the disconnection of the glacial remnants from the remaining Cordillera

This study reveals the presence of relict glacial landforms, 3 Ma old and older, preserved on the top surface of the Mesetas del Lago Buenos Aires and Guenguel. These features are now separated from the rest of the Cordillera by N-S oriented valleys. Mercer and Sutter (1982) already noticed that the 7-5 Ma old tills interbedded between lava flows of the northwestern corner of the Meseta del Lago Buenos Aires are disconnected from any initial glacial field in the internal Cordillera due to the presence of the bounding meseta scarp to the west. This already suggested that a tectonic event is responsible for the disconnection of these landforms from the remaining Cordillera as represented in cartoons of figures 10 and 11. The observations of truncated valleys de-

veloped on the top surface of the meseta as reported in section 4, the age of 3 Ma of the youngest tills exposed on the uppermost sections of the meseta, and the exposure of the 3 Ma Mifeldi pluton along the western scarp of the Meseta (Brown *et al.*, 2004; Espinoza *et al.*, 2008), all indicate that this scarp is 3 Ma old or younger. These data, and the fact that there is no visible imprint of glacial flow on the Mifeldi cliff and no relict glacial features preserved such as moraines, striations, meltwater channels and other forms related to glacial processes on and around the Mifeldi pluton, show that relatively large glacier outlets left the domain separating the (future) mesetas from the Cordillera at around 3 Ma.

We have shown that the first events leading to the local disruption of the western side of the Meseta del Lago Buenos Aires occurred in the Alto Río Ghío region, in relation with displacements along faults oriented N30-N40. This led Lagabrielle *et al.* (2007) to propose a tectonic control of the evolution of the paleo-valley area. Faulting initiated during the deposition of the first tills and lavas, that is probably as early as 7-6 Ma. This N30-N40 faulting direction corresponds to a major orientation of morphotectonic features in Central Patagonia such as the normal fault scarp bounding the Lago Lapparent depression to the north and the tectonic-controlled edges of the central part of Lago General Carrera-Buenos Aires and the western part of Lago Cochrane-Pueyrredon. Further north, in the area of Coihaique-Balmaceda, NE faults are a major tectonic element, controlling local lake and river depressions (lagos Pollux and Cástor and ríos Coihaique and Pollux) (De La Cruz *et al.*, 2003b). This direction also corresponds to the elongation of the glacier outlets described from the upper surface of the Meseta del Lago Buenos Aires. We may therefore suspect that N30-N40 oriented faults are important elements of the tectonic evolution of the frontal region of the Cordillera between 7 Ma and 3 Ma. They have been active before the initiation of displacements along the N160 trending faults which led to relative uplift of the western scarp of the meseta after 3 Ma. These tectonic events have been related to a thermal disturbance of the lithospheric mantle above Central Patagonia which coincides in time and space with the subduction of segments of the South Chile Ridge explaining the vertical differential displacements observed between 7 and 3 Ma (Lagabrielle *et al.*, 2007).

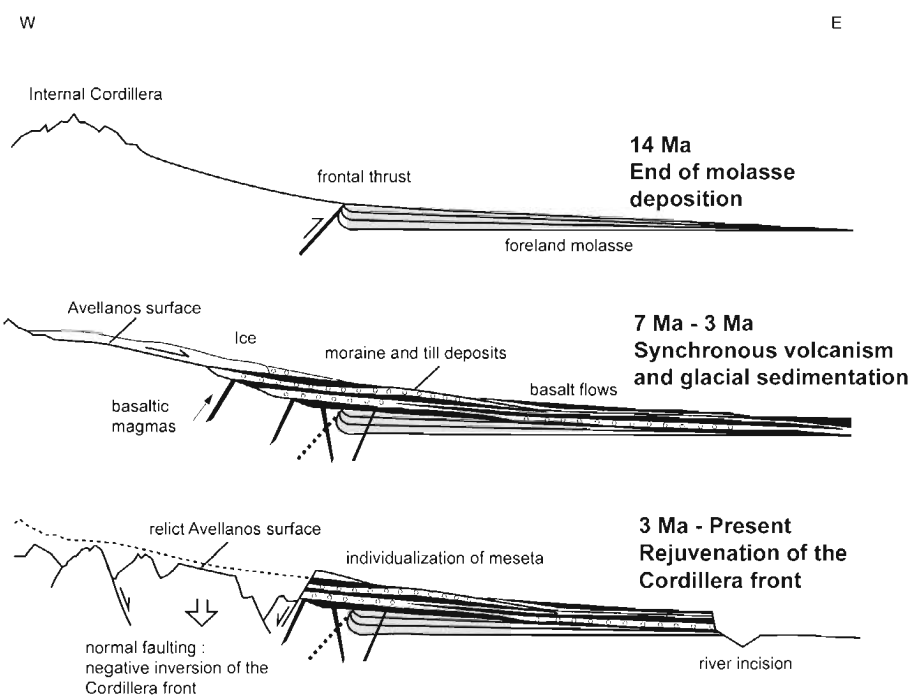

FIG. 10. Cartoons depicting the tectonic evolution of the Cordillera piedmont since 14 Ma.

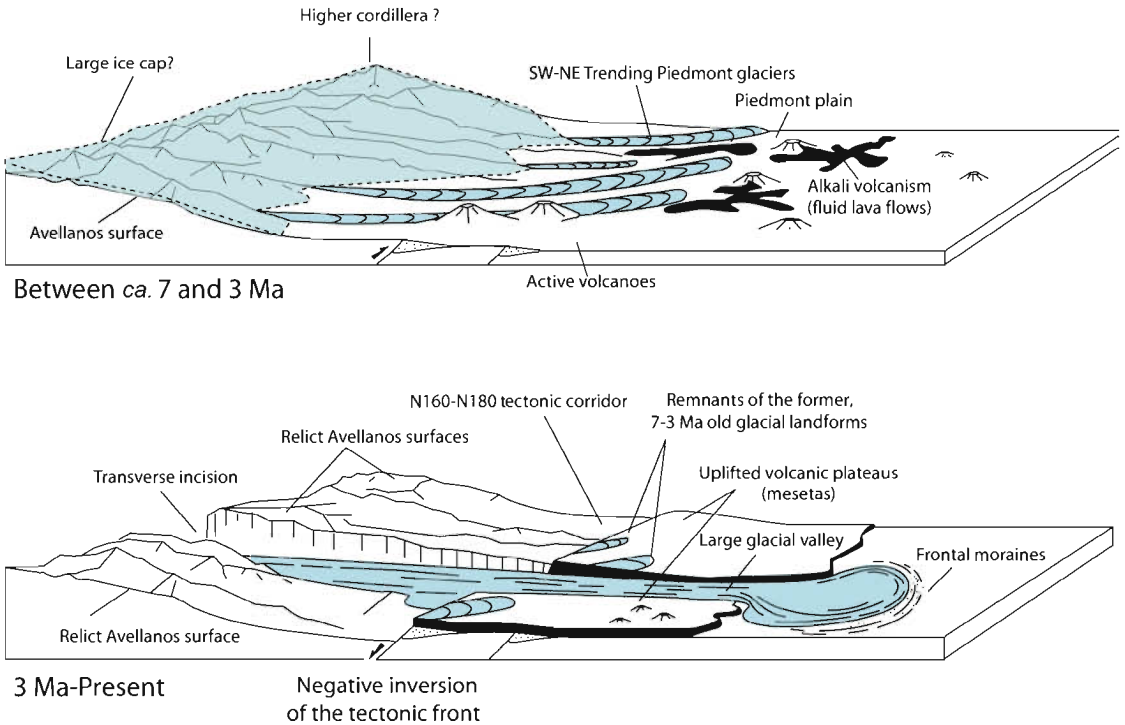

FIG. 11. 3D diagrams showing possible evolution of the distribution of glaciers in Central Patagonia with emphasis on the consequences of the 3 Ma tectonic event.

5.3. Tectonic *versus* climatic significance of a major morphological change at 3 Ma?

The landform record provides evidence of glacier advance in the SW-NE direction at 3 Ma, over a surface which is a paleo-piedmont of a former Cordillera. On a relatively short distance of 20 km, we observe more than 4 outlets, not deeply incised, indicating that the pre-3 Ma glaciers were not constrained within narrow valleys (Figs. 9 and 11). Similar conclusion was reached independantly by Malagnino (1995) from the study of the Meseta Guenguel. Nevertheless, it is possible that despite their present-day elevation, the regions of the mesetas that bear these glacial lobe remnants represent former depressed areas functioning as regional collector for the glacier outlets. In any case, before the 3 Ma tectonic crisis, the overall paleotopography of Central Patagonia was smoother than the current one. Starting at 3 Ma a dramatic change occurred in the entire region of Central Patagonia, corresponding to the relative uplift of the piedmont domain and to its disconnection from the rest of the Cordillera. This event was accompanied by local collapse of internal basins such as the Lago Lapparent depression and by the rapid subsidence of the narrow transverse corridors now occupied by lakes Cochrane-Puyerredon and General Carrera-Buenos Aires. From this date on, glaciers did not expand freely over the piedmont domain but were constrained within narrow valleys. This major change in glacier distribution is mainly due to tectonic causes and triggered in turn major changes in the overall morphology of the Cordillera (Figs. 10 and 11). However we can not exclude that part of this change has been enhanced due to climatic causes such as increases in the frequency of glacial conditions during the Plio-Quaternary.

6. Conclusions

We have evidenced, following Mercer and Sutter (1982) and Malagnino (1995), the presence of relict glacial landforms, 3 Ma old and older, preserved on the top surface of the Meseta del Lago Buenos Aires and Meseta Guenguel. However, at present, the main issue is to decipher the regional significance

of these glaciations. There are 2 main possibilities: these are isolated glaciers of mountainous areas such as those already known through the Miocene in Alaska, Greenland and Iceland. These are not necessarily representative of a major continental glaciation (Ehlers and Gibbard, 2007). The second possibility is that these deposits are the testimonies of a former unsuspected large Patagonian Ice Sheet, permanent or partly ephemeral, developed between 7 and 3 Ma and possibly some m.yrs. before, in a period when large ice sheets also developed over Antarctica. Indeed, the ice sheet in Eastern Antarctica reached a maximum size about 15 million years ago (mid-Miocene) and the West Antarctic ice sheet may have developed for the first time also in this period (*e.g.,* Hambrey and McKelvey, 2000).

a. The first hypothesis implies increased precipitation on relatively high reliefs able to produce abundant ice. In such a case, the mountains had to be much higher at this latitude. However, at the latitude of Lago General Carrera-Buenos Aires, except in some points such as the Mount San Valentin, there is currently no high relief. Rather, the Cordillera displays an average low elevation of +900 m only. If so, reliefs should have either experienced considerable erosion after 3 Ma, or should have partly disappeared due to overall collapse of the entire Cordillera. Evidence for local collapse inside the Cordillera as well as normal faulting along the western edges of the mesetas relies on such scenario (Lagabrielle *et al.,* 2007).

b. The second hypothesis implies the temporary development of a large ice cap over the Cordillera before the Quaternary. The 7-3 Ma tills are known from various places and from various mesetas. This suggests a widespread rather than a localized distribution. If these old glaciers are found to be frequently distributed all along Patagonia with the same concentration as deduced from this study, it will be necessary to estimate the total volume of ice stored over the entire Cordillera during the Neogene. This would have an impact on the global water balance and on our understanding of the global climate evolution during the Late Cenozoic. It is clear that a lot of work needs to be done in this direction, based on increased accurate analysis of field data. In that sense, the issues on global climate raised by Mercer and Sutter (1982) following their major discovery on the NW edge of the Meseta del Lago Buenos Aires still remain to be fully addressed, including possible development of early ice sheets in the Northern Hemisphere.

Acknowledgments

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PLATE 1

Photographs of tills and related glacial deposits representing evidence of glaciations which developed between 7 and 3 Ma in the western region of Meseta del Lago Buenos Aires (all photographs by Y.L., except A by D. Morata).

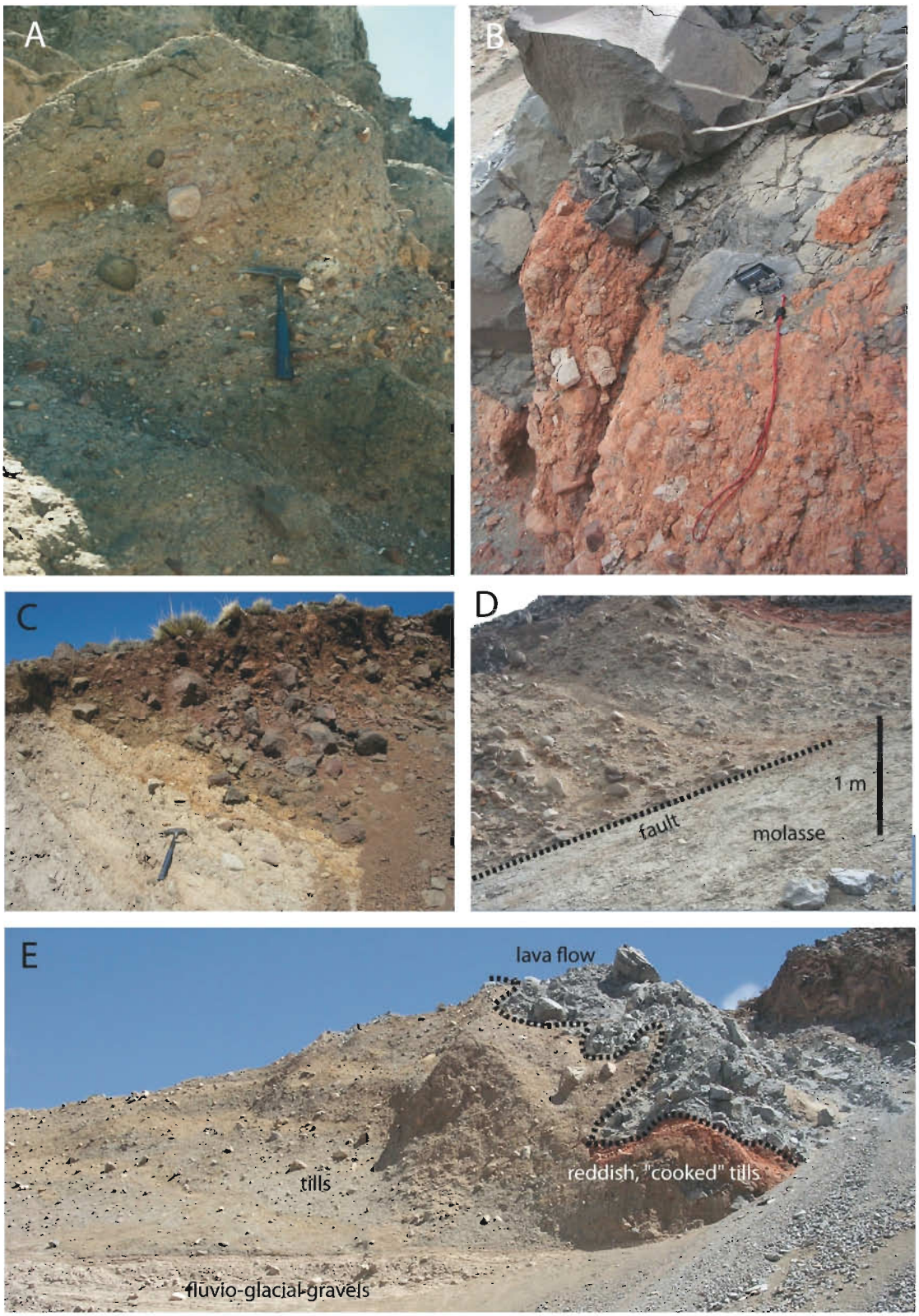
A: Graded-bedded fluvioglacial gravels and tills (upper part of the photograph). NW part of the Meseta del Lago Buenos Aires in area of sites 28-30 (Fig. 2). These deposits underlie lavas dated around 6.5-5 Ma (Table 1). Note the presence of white-colored clasts demonstrating provenance from regions farther west, exposing rocks of the batholith and Ibañez Formation.

B: Reddened till due to emplacement of the overlying lava flow in the northern portion of the scarp shown in figure 4 (paleovalley site of Alto Río Ghío, at 47°04'43.61"S and 71°49'31.55"W). This lava flow correlates with a light-grey flow dated at 5 Ma. Thermal interaction between glacial sediments and lavas is currently observed in the area of study (see upper part of photograph D and lower part of photograph E, as well as Lagabrielle *et al.*, 2007). Note the presence of white-colored clasts within the till demonstrating provenance from inner regions of the Cordillera exposing the North Patagonian Batholith and located farther west.

C: A contact between a brecciated brown-colored lava flow (between 5 and 3 Ma old) and a till including white-colored clasts deriving from the batholith (Alto Río Ghío, along Ruta 41, north of the paleovalley site).

D: Gradded-bedded fluvioglacial gravels and tills in fault contact against molasse deposits (paleovalley site of Alto Río Ghío, location of photograph in figure 4).

E: Lava flow in contact with thick till including white-colored clasts deriving from the batholith. Contorted contact indicates interaction during the progression of lava flow on a former glacial landscape.


A
B
C
D
1 m
fault
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lava flow
tills
reddish, "cooked" tills
fluvio-glacial gravels