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Glacial geomorphology of the Torres del Paine region (southern Patagonia): Implications for glaciation, deglaciation and paleolake history

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ABSTRACT

The processes affecting paleoclimate variability and Pleistocene glacial landscape development in the southern mid-latitudes remain poorly understood, in part because of the scarcity of comprehensive, well-studied records. Glacial landforms are invaluable for reconstructing past ice-sheet, climate, and associated environmental changes along the southern Andes, but there are significant spatial and temporal gaps in existing data. In this paper, we present new geomorphic and sedimentologic analyses, including surficial maps, for the Torres del Paine region (51°S, 73°W), southern South America. Our findings provide a new framework for understanding changes in the regional glacier history and Pleistocene landscape development. Glacial extent during the local last glacial maximum (LGM) remains unknown but new chronological data supported by geomorphic evidence afford evidence for a larger ice sheet at Torres del Paine than previously assumed. Deglaciation from the local LGM was underway by 17,400 ± 200 (1σ) cal. yr. BP. As opposed to previous suggestions, we have found that most of the moraines fringing the lakes in the Torres del Paine national park were deposited during a late-glacial expansion that occurred between 14,100 and 12,500 cal. yr. BP. Late-glacial advances also have been documented recently for the Última Esperanza and Lago Argentino basins to the south and north of Torres del Paine, respectively, suggesting an overall regional ice response to a climate signal. The Tehuelche paleolake accompanied each of the ice-sheet fluctuations in Torres del Paine. New data document at least three main phases of this paleolake, which drained eastward to the Atlantic Ocean, while the Andes gaps were blocked with ice. During the late phase of glacial lake formation, when water levels reached 125–155 m a.s.l., the lake likely merged with paleolake Consuelo in the Última Esperanza area at the end of the last glaciation. Lake Tehuelche in Torres del Paine had drained into the Pacific Ocean by the late-glacial period, suggesting that ice southwest of Torres del Paine may have retreated back into the mountains by this time.

1. Introduction

Despite the fact that the northern and southern mid-latitudes are influenced by opposing insolation intensity signals, ice-core and marine records from both hemispheres appear to display broadly similar glacial–interglacial climate cycles at orbital timescales (EPICA community members, 2004; Lisiecki and Raymo, 2005; Jouzel et al., 2007). In addition, several investigators have used dated moraine records to argue for (near) synchronous global glacial activity during the global last glacial maximum (LGM) (Denton et al., 1999; Clapperton, 2000; Sugden et al., 2005). Yet southern hemisphere glaciers apparently advanced in the face of unfavorable summer insolation intensity, a problem Mercer (1984) referred to as “the fly in the ointment of the Milankovitch theory”. What then are the drivers of southern hemisphere glaciations? Precisely dated glacial and climate records from both hemispheres afford a means for isolating the causes behind the ice ages, but are relatively scarce in the southern hemisphere. In order to address the problem of the cause of southern hemisphere glaciations, we have begun a program of geomorphic mapping and chronology in the Torres del Paine region (51°S), southern South America, which has well-preserved sets of moraines that are suitable for direct dating with the exposure-age dating method (Fogwill and Kubik, 2005; Moreno et al., 2009a; García et al., 2012). Also, minimum-limiting ^{14}C data for moraine age formation can be obtained, mainly from peat bog cores (Marden and Clapperton, 1995; McCulloch et al., 2000; Hall et al., 2013). Southern Patagonia receives insolation intensity that is opposite to that of the North Atlantic region. Moreover, it is

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located in the core of the southern westerly wind belt, which is a main component of present-day climate (Cerveny, 1998; Markgraf, 1998) and which is thought to play an important role in glacial terminations (Anderson et al., 2009; Denton et al., 2010).

This paper presents the results of our geomorphological mapping and stratigraphic analyses in the Torres del Paine region and provides the critical foundation for: (1) reconstructing the former glacial and proglacial environments and associated landscape changes in the area; (2) understanding the pattern of deglaciation and associated environmental changes as ice receded back into the Andes; and (3) placing recently obtained chronological data (e.g., García et al., 2012) into a geomorphological framework that will allow us to understand the paleoglaciology and timing and significance of past glacial events in the region, including in the neighboring Lago Argentino and Última Esperanza basins. We address the following questions: How extensive was ice during the last glacial cycle in Torres del Paine? When and how did it fluctuate? What environments existed at the termini of the Patagonian outlet glaciers in Torres del Paine? What was the spatial and temporal extent of paleolakes, and how did they relate to the different glacial and deglacial activity in the area? The details of the chronology are mainly presented in separate papers (García, 2011; Strelin et al., 2011; García et al., 2012); here we only summarize salient aspects of the chronology to help place the timing of the geomorphologic and sedimentologic changes into context. In addition, we present new ^{14}C ages that help define the end of the LGM in this region (Table 1).

2. Regional setting

The former Patagonian ice sheet extended all along the southern Andes between 38 and 56°S (Clapperton, 1993; Glasser et al., 2008). During Quaternary glacial fluctuations, this ice sheet built one of the most striking glacial landscapes on Earth, particularly in its southern part (e.g., Patagonian Andes; Steffen, 1919), where ice was thicker and larger than to the north in the Chilean Lake District (Denton et al., 1999; García, 2012).

For the purposes of this work, the Torres del Paine region (50°45′–51°35′S, 73°30″–71°50′W; Fig. 1) is defined as the area between the Andes Cordillera to the west and the outer terminal moraines deposited to the east in Argentina. Lago Argentino and Última Esperanza basins define the northern and southern limits, respectively, of the Torres del Paine region. During Quaternary glaciations, the Patagonian ice sheet was the main source of ice in the region and, together with the Cordillera Paine alpine system (3248 m a.s.l. at its highest point), nourished eastward-flowing outlet glaciers (Glasser et al., 2008) that, in general, have reached less extensive maximums over time (Coronato et al., 2004; Rabassa et al., 2005; Kaplan et al., 2009).

A cold, temperate climate regime, involving significant thermal and precipitation gradients across the Andes, characterizes the study area. Westerly wind cyclones originating in the Antarctic Frontal Zone are associated with elevated precipitation levels (as much as 10 m per year at high elevations; DGA, 1987) and decreased temperatures (Garreaud, 2007) that directly affect local climate. Most of the study area (Fig. 1) falls in the rain shadow of the Andes and displays a semi-arid steppe. Studies on the present ice fields over the 20th/21st centuries, including instrumental data, document that variations in atmospheric temperature and precipitation, with the former playing the principal role, control glacier mass balance along the southern Andes (Warren and Sugden, 1993; Cassasa et al., 2002; Rivera et al., 2002; Rivera and Cassasa, 2004). Cloudiness and precipitation occur year round over the ice fields (Miller, 1976; Carrasco et al., 2002), to the west of the main field area, and their effect on glacier annual mass balance is less clear (e.g., Rivera et al., 2002).

The moraines to the east of the cordillera, rather than the southern Andes, form the hydrologic divide between the Pacific and Atlantic Oceans in the Torres del Paine region. This condition, along with local bedrock topography, has resulted in the Torres del Paine and adjacent Última Esperanza basins being hydrologically connected. A suite of interconnected rivers and lakes in the Torres del Paine region forms a complex hydrological network that ultimately drains to Fiordo Última Esperanza through Río Serrano. Thus, the paleolake histories of the two regions should also be related (Fig. 1).

3. Previous work

Nordenskjöld (1898), Hauthal et al. (1905) and Caldenius (1932) produced the first glaciological observations and physiographic maps that included glacial landforms from the Torres del Paine region. Caldenius (1932) defined four main moraine belts, from outer to inner: 'Initioglacial', 'Daniglacial', 'Gotiglacial' and 'Finiglacial', with the latter enclosing some of the present-day lakes in Torres del Paine National Park (i.e., Laguna Azul, Lago Sarmiento and Lago del Toro; Fig. 1). Because of the freshness and preservation of landforms, Caldenius (1932) suggested that all four moraine belts dated to the last glaciation and assumed that they were analogous to the Scandinavian glacial record. Marden (1993, 1997) and Marden and Clapperton (1995) subsequently separated the 'Finiglacial' moraines of Caldenius (1932) into four distinct belts (A–D), which they thought were deposited during the LGM (B–D moraines) and Marine Isotopic Stage 4 (MIS 4; A moraines). The same authors delineated two additional ice-marginal positions (E and F) from less distinct and discontinuous landforms proximal to the D moraines and linked them to the late-glacial period, or post-'Finiglacial' in Caldenius' (1932) nomenclature. Fogwill and Kubik (2005) and Moreno et al. (2009a) further modified the mapping and dated to the late-glacial the inner D limit of Marden and Clapperton (1995) near Lago Nordenskjöld and along Río Paine. Recent work (García et al., 2012) determined that B, C and D moraines all formed ca. 14,100 ± 520 cal. yr. BP, during the Antarctic cold reversal (ACR, Monnin et al., 2001; Jouzel et al., 2007) chronozone rather than during the LGM as previously thought. To avoid confusion with sites elsewhere in southern South America that use similar labels to refer to different glacial events (i.e., Clapperton, 1993; Sugden et al., 2005), García et al. (2012) renamed the inner Torres del Paine A–D moraines sets accordingly: A = TDP I, B = TDP II, C = TDP III, and D = TDP IV (TDP = Torres del Paine). An outer moraine belt was termed the "Río de Las Viscachas" (RV) by Caldenius (1932) (his 'Gotiglacial' moraines), here differentiated as RV I and RV II.

In addition, a lobe of the Patagonian ice sheet just south of Torres del Paine built another moraine belt, the Arroyo Guillermo (AG) (Fig. 1). The position of this latter moraine belt suggests that it is correlative with the RV I moraines (e.g., Caldenius, 1932). There are no direct ages for the RV moraines but their deposition during MIS 2–4 cannot be ruled out.

4. Materials and methods

One of the primary goals of our research was to produce the first high-resolution, georeferenced geomorphologic maps for the Torres del Paine region (Figs. 2–6). We constructed the maps first from stereoscopic analysis of aerial photographs (Vuelo Geotec 1998, 1:70,000), which cover most of the study area. We then checked our preliminary mapping during five field campaigns between 2007 and 2012. We focused on ice-marginal positions, as defined by glacial and proglacial features (e.g., moraine ridges, glaciofluvial and glaciolacustrine landforms), built during the last glacial period and transition to the Holocene. We delineated the TDP moraines based on morphostratigraphic position and morphology, following Marden (1993). The final map was created in a geographical information system (GIS) software at a scale of 1:50,000. We used hand-held global positioning systems (GPS) to measure the elevation of glaciolacustrine terraces multiple times (±5–10 m). We complemented these measurements with Shuttle Radar Topography Mission (90 m horizontal resolution; vertical uncertainty <15 m) and Google Earth elevation data. We analyzed stratigraphic sections associated with different landforms wherever possible. We divided stratigraphic sections into discrete sediment units based on physical characteristics,

Table 1
Radiocarbon data that concern the geomorphic history of the Torres del Paine region.

Site	Fig. 1 #	Lab code	Core code	Core depth (cm)	Material	^{14}C age (yr. BP)	Age [a] (cal. yr. BP)	Significance	Reference
Vega Chulengo	1	OS-74486	TA	285–87	Wood	14,350 ± 70	17,420 ± 185	Min. age for RV II moraine deposition; ice margin close to TDP II moraine at L. Azul.	This study
Lago Dorotea[b]	2	CAMS-107092	PS0402FT4	1870–71	Bulk organic	14,170 ± 45	17,240 ± 170	Min. age for local ice free conditions	Sagredo et al. (2011)
Vega Benitez[b]	3	CAMS-107093	PS0403AT3	968–70	Bulk organic	14,520 ± 140	17,700 ± 220	Min. age for local ice free conditions	Sagredo et al. (2011)
Lago Guanaco	4	CAMS-107058	PS0404AT4	488–89	Bulk organic	12,605 ± 40	14,940 ± 150	Timing of local ice free conditions? See text for discussion.	Moreno et al. (2009a)
Vega Capón	5	CAMS-118433/4	PS0501BT6/CT6	678-79/682–83	Bulk organic	10,418 ± 49[c]	12,285 ± 105[c]	Deglaciation from ACR – TDP IV moraines	Moreno et al. (2009a)
Vega Baguales	6	OS-74487	LC	272-273	Mollusk	10,550 ± 55	12,460 ± 50	Deglaciation from ACR – TDP IV moraines	García et al. (2012)
Lago Calvario	7	CAMS-118370/431/432	PS0502ET7/ditto/DT6	671–72/ditto/617–18	Bulk organic	10,492 ± 45[c]	12,475 ± 95[c]	Deglaciation from ACR – TDP IV moraines	Moreno et al. (2009a)
Vega Ñandú	8	CAMS-98833	PS0304AT4	398–400	Bulk organic	10,555 ± 40	12,550 ± 40	Deglaciation from ACR – TDP IV moraines	Moreno et al. (2009a)
H	9	QL-1475	n/a	n/a	n/a	10,875 ± 70	12,740 ± 95	Deglaciation from ACR – TDP IV moraines	Heusser (1987)
PH	10	A6364	n/a	n/a	Peat	11,245 ± 85	13,175 ± 95	Deglaciation from ACR – TDP IV moraines	Marden (1993)
Vega Úrsula	11	OS-81259	SAR09T2	355–58	Wood	9700 ± 50	11,150 ± 60	Min. age for local ice free conditions	This study
GP	12	A-6361	n/a	n/a	Peat	9755 ± 95	11,179 ± 95	Min. age for local ice free conditions	Marden and Clapperton (1995), Marden (1993)
PG2	13	n/a	n/a	n/a	n/a	9180 ± 120	10,340 ± 105	Min. age for local ice free conditions	Porter pers. Comm. to Stern (1990); Marden (1993)
LG2(92)	14	A-6812	n/a	n/a	Peat	8750 ± 170	9740 ± 190	Min. age for outermost TDP V moraine deposition	Marden and Clapperton (1995), Marden (1993)
LG2(91)	15	SRR-4582	n/a	n/a	Peat	8150 ± 45	9070 ± 55	Min. age for outermost TDP V moraine deposition	Marden and Clapperton (1995), Marden (1993)
PG1	16	A-6805	n/a	n/a	Peat	6710 ± 120	7575 ± 95	Min. age for outermost TDP V moraine deposition	Marden and Clapperton (1995), Marden (1993)
LG4	17	n/a	n/a	n/a	Peat	4495 ± 130	5140 ± 175	Min. age for outermost TDP V moraine deposition	Marden (1993)
Pantano Margarita	18	CAMS-98828	PS0303AT4	441–43	Gyttja	3545 ± 45	3810 ± 85	Min. age for innermost TDP V moraine deposition	Moreno et al. (2009b)
LG3	19	n/a	n/a	n/a	Peat	3480 ± 135	3745 ± 170	Min. age for innermost TDP V moraine deposition	Marden (1993)
LG1	20	n/a	n/a	n/a	Peat	2835 ± 45	2935 ± 60	Min. age for innermost TDP V moraine deposition	Marden (1993)

[a] Reimer et al. (2009).
[b] Última Esperanza.
[c] Weighted mean.

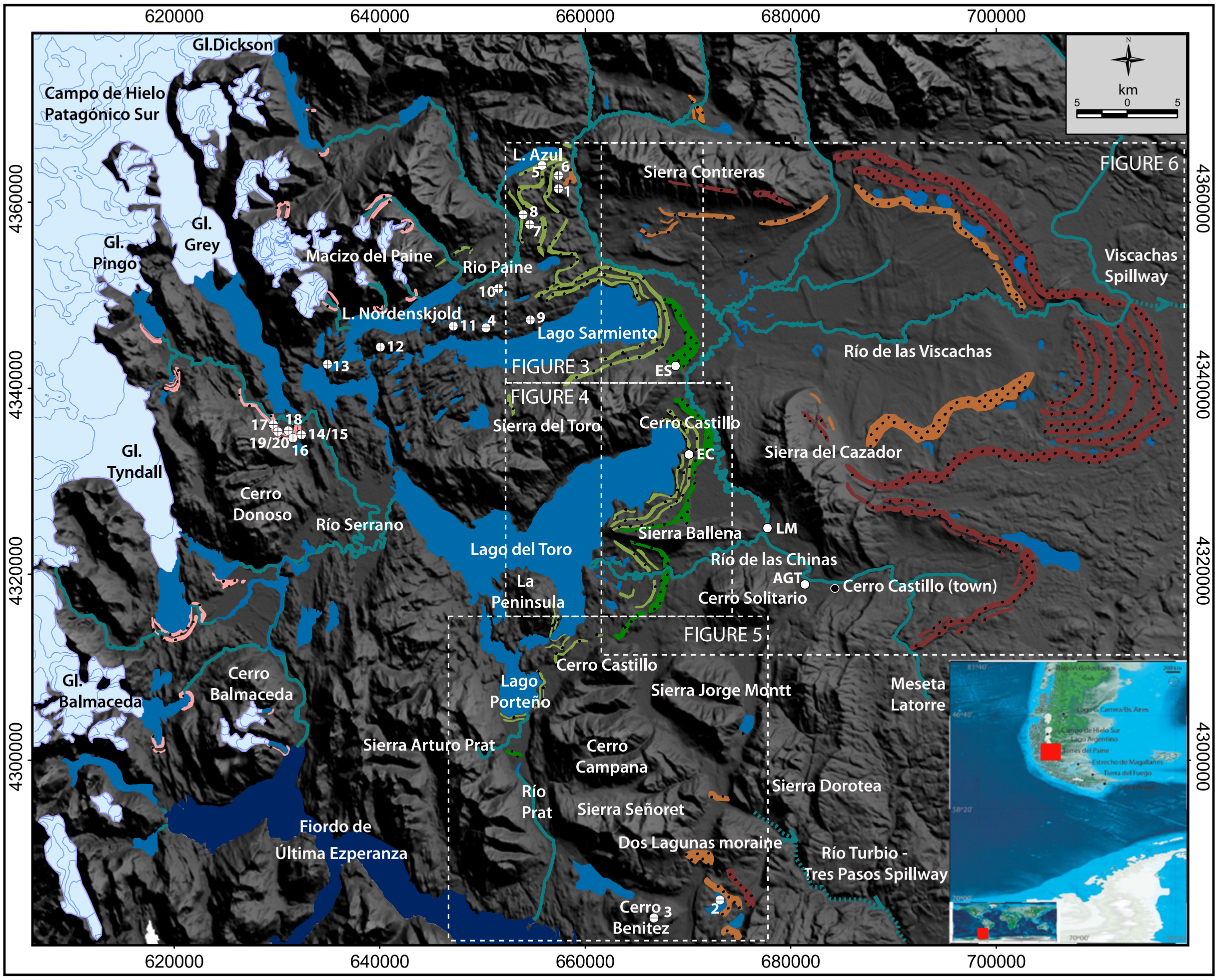

Fig. 1. Physiographic attributes of the Torres del Paine region. Inset shows southern South America, including the location of the Torres del Paine region (solid red box). The map depicts Late Pleistocene and Holocene moraine belts in the study area. ES: Estancia Site; EC: El Canal Site; LM: Las Máscaras Site; AGT: Arroyo Guillermo Tributary Site. For ^{14}C site numbers key see Table 1.

such as sediment texture, color, sorting, fabric and structures, defining different sedimentary facies and the depositional environment evolution (Evans et al., 2012).

We also collected sediments from mires within and proximal to the TDP moraines using a square-rod piston corer in order to obtain minimum-limiting ^{14}C ages for glacier retreat. Here, we report the results from cores in Vega Chulengo and Vega Úrsula. We used CALIB 6.0.1 and the IntCal09 dataset (Reimer et al., 2009) to calibrate all ^{14}C ages presented here, including ^{14}C data published previously.

5. Results

5.1. Moraine belts

Torres del Paine displays multiple prominent moraine belts, whose size, well-preserved morphology and bouldery surfaces (see below) suggest deposition during the last glacial period (Fig. 1) (Clapperton, 1993). These belts are, from outer to inner positions, RV I and II and TDP I, II, III, and IV. They all occur within 50 km of each other and are located 50–100 km from the present ice-field margin. The TDP II, III, and IV moraines are distinctly smaller in size and relief than the TDP I and RV I–II landforms. In addition, whereas the TDP I–IV systems are associated with the present east–west trending lake basins in Torres del Paine National Park (Chile), the RV I and RV II moraines were formed when the Patagonian ice sheet extended farther east into eastern Patagonia outlet valleys. Here, we describe the inner Torres del Paine moraine sets (TDP I–IV) in detail and only give a general overview of the RV moraines, which remain undated.

5.1.1. The outer RV moraines

In the Torres del Paine region, Caldenius (1932) locally named the 'Gotiglacial' landforms the RV and AG moraines. Both are composite terminal moraine belts, made up of several wide, arcuate ridges and located ~100 km from present margin of the Southern Patagonian Ice Field (Fig. 1).

The RV moraines are located between and to the east of Sierra Contreras and Sierra del Cazador (Fig. 1). Two moraine sets are conspicuous: RV I and RV II. These belts are parallel to each other and, in places, are continuous for several kilometers (e.g., Laguna Salada, east of Sierra del Cazador, Fig. 6). Here, outwash plains and apparently older moraine deposits separate the RV I moraine from the AG moraine to the south. Lateral moraines are prominent and exhibit slopes at close to 20°, although they may expose slightly steeper sides when deposited on mountain flanks (e.g., Sierra Contreras). When observing the frontal RV moraine complexes using satellite imagery it is possible to distinguish at least 20 ridges over a distance of about 13 km. Nonetheless, in the field, the RV terminal moraine landscape shows a prominent hummocky topography rather than distinct ridges depicting ice-marginal positions

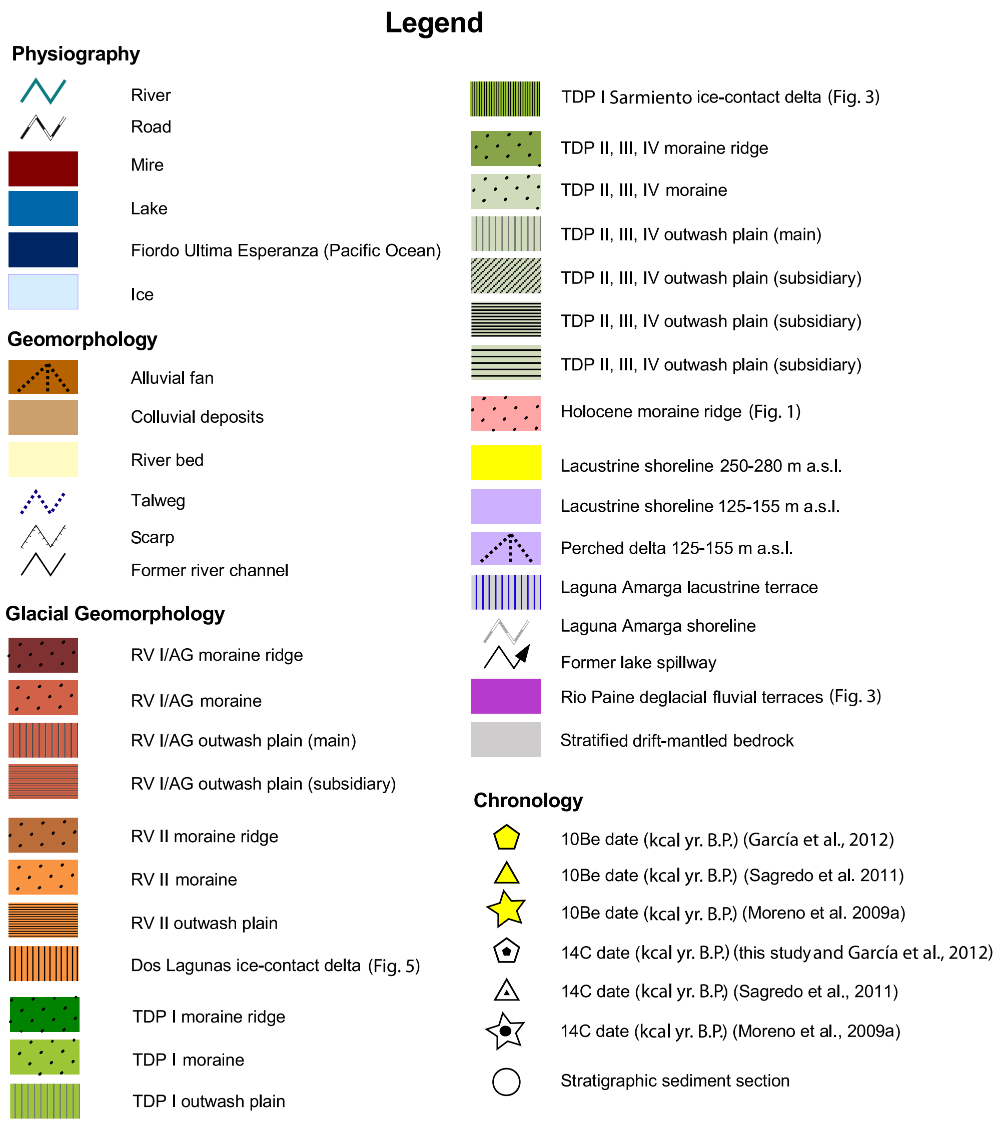

Fig. 2. Legend key for Figs. 1, 3–6.

(those shown on Figs. 1, 6). Moraines are on the order of hundreds of meters wide and are separated by gentle depressions and ice-marginal meltwater channels. Landforms and sediments are well-preserved, although relief is relatively low and the crests are broad, particularly when compared with the TDP I–TDP IV moraines to the west.

As described by Caldenius (1932), the horseshoe-shaped AG terminal moraine belt occurs between Sierra del Cazador and Meseta Latorre, south of the RV I moraine arc and about 85 km east of the present-day ice field (Fig. 1). Several wide, low-relief ridges constitute this moraine belt, which can be traced for more than 30 km. Because both the RV I and the AG lateral moraines appear to merge on the eastern slope of Sierra del Cazador, and exhibit significant morphostratigraphical similarities, we infer they were likely deposited during the same advance (Caldenius, 1932).

5.1.2. The inner Torres del Paine moraines

From outer to inner, the TDP I, II, III and IV moraine systems typically occur within three kilometers of each other, and fringe the eastern shores of Laguna Azul (220 m a.s.l.), Lago Sarmiento (75 m a.s.l.) and Lago del Toro (25 m a.s.l.). The moraines are ~45 km from present-day ice margins and about midway between the outer RV I terminal moraines and the existing Southern Patagonian Ice Field.

5.1.2.1. TDP I moraines. These moraines are distinct from the TDP II, III, and IV landforms, particularly in terms of morphology and relief. For instance, the TDP I moraines are as much as one kilometer wide and have 30–50 m of relief (e.g., at Lago Sarmiento), which is several times the size of the TDP II, III, and IV ridges (Figs. 3, 4). There also is morphological variation within the TDP I moraine belt. At Lagos Sarmiento and del Toro, TDP I occurs as well-defined moraine ridges, whereas at Laguna Azul broad TDP I landforms form a rolling, hilly topography. In this latter area (Fig. 3), broad, low-relief moraines sprinkled with erratic boulders occur in open areas west of Río de Las Chinas and small ridges span narrow basins that punctuate a local north–south topographic barrier (~500 m a.s.l.). The TDP I landforms at Laguna Azul seem to form a wide, low-relief moraine arc that marks the position of ice west of Río de Las Chinas.

At Lago Sarmiento (Fig. 3), the TDP I moraine is a 5 km-long prominent ridge, crosscut by a younger TDP II moraine and breached by a large meltwater channel, which is hundreds of meters across at its widest point. The steep ice-contact slope, both here and as shown by TDP I moraines at Lago del Toro, has as much as 40 m of relief, which has been enhanced, in part, by glaciofluvial and likely wave-cut erosion. The TDP I moraine has a flat, wide crest at about 115–125 m a.s.l., that distally is made up of outwash, as revealed at the Estancia Site (51°03′

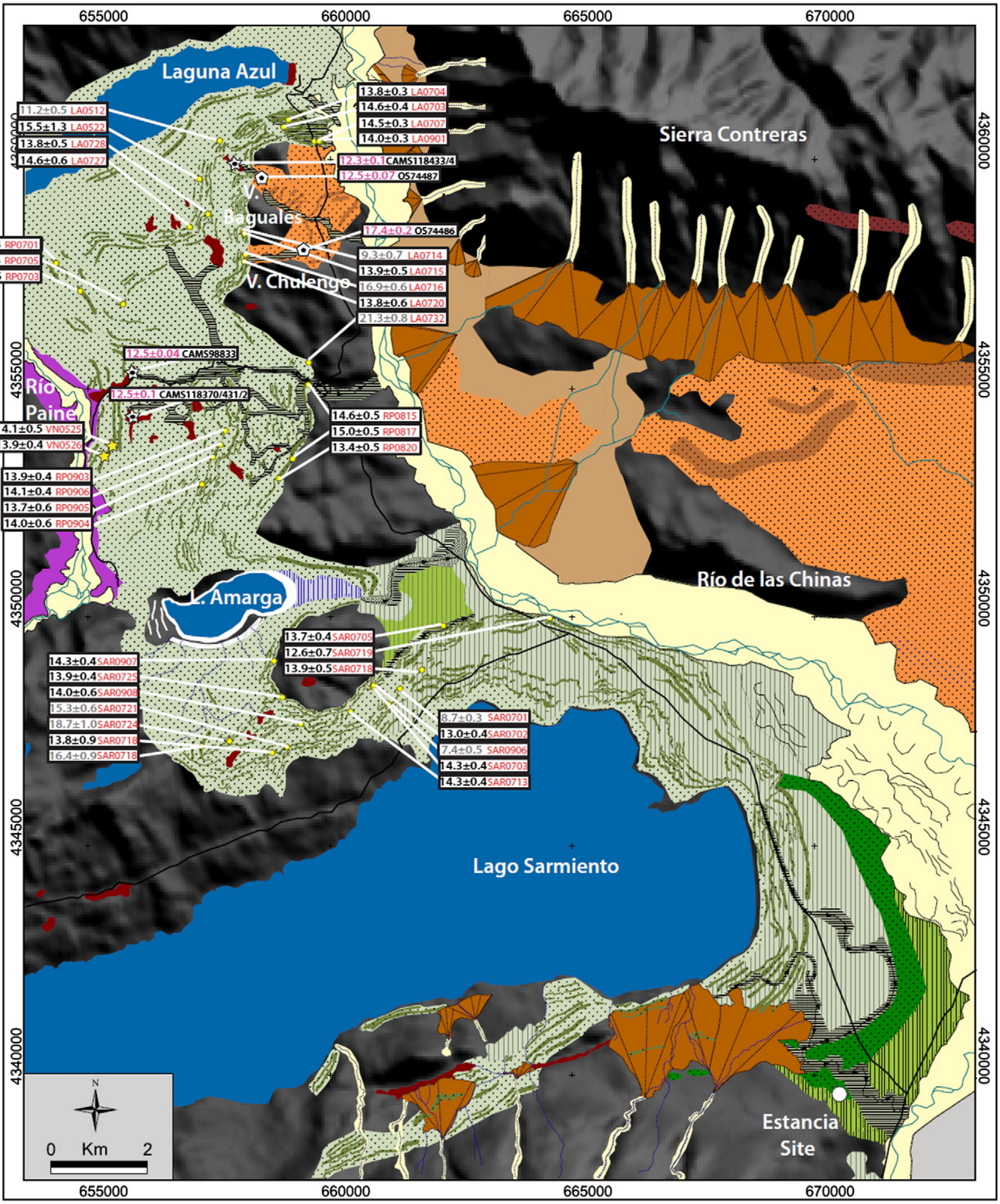

Fig. 3. Glacial geomorphologic map of the Laguna Azul-Lago Sarmiento area. ^{10}Be ages are in black, calculated using production rate of Putnam et al. (2010) and Kaplan et al. (2011). Mean ^{10}Be ages for each TDP II–IV moraine belts are indistinguishable within error (1σ) and were deposited at ca. 14,100 ± 520 cal. yr. BP (n = 29) (García et al., 2012). ^{14}C calibrated ages (Reimer et al., 2009) are in pink, which were obtained from Vega Chulengo and surrounding sites.

51″S and 72°33′51″W, ~125 m a.s.l.; Figs. 3, 7). In this section, well-stratified sandy pebble beds (facies B in Fig. 7) are intercalated with massive to crudely bedded coarse sediment up to cobble size (facies A in Fig. 7). The sandy pebble beds are well sorted and can be traced laterally for tens of meters. They occur as horizontally and planar cross-bedded units and are interpreted as channel deposits. In contrast, the massive to crudely bedded sediment (facies A) contains clasts (≤30 cm in diameter), which are sub-angular to sub-rounded in

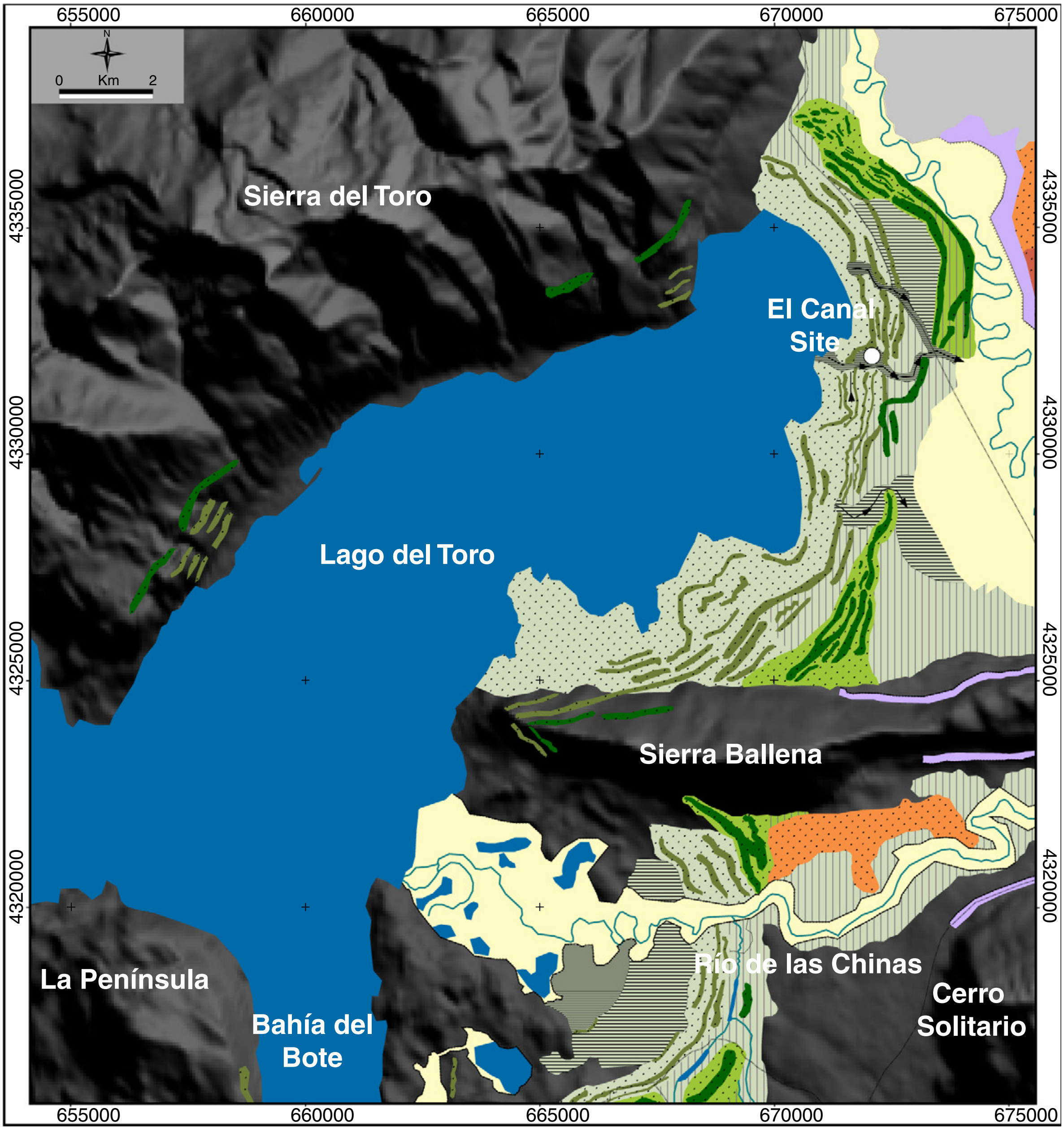

Fig. 4. Glacial geomorphologic map of the Lago del Toro area.

shape. Sorting is poor and the overall aspect is chaotic. We interpret this deposit as debris flows from the ice margin (Fig. 7).

At the eastern margin of Lago del Toro, the TDP I moraine belt consists of a single composite landform made up of three ridges (Fig. 4). From here to Sierra Ballena it has been eroded and partially buried by the main glaciofluvial plain. In the northern foothills of Sierra Ballena, the TDP I moraine belt displays five ridges, which merge to form only a single, sharp ridge along the western slopes of Sierra Ballena. South of Sierra Ballena, the TDP I moraine is represented by a wide discontinuous arc. The moraine may have correlatives as far west as Río Prat valley, south of Lago Porteño (Fig. 5), but these latter landforms remain undated.

5.1.2.2. TDP II and III moraines. These two moraine systems are described together because they closely parallel each other along the eastern margins of the lakes in the Torres del Paine National Park area and are morphologically similar. They commonly occur as two independent moraine systems, separated by subsidiary glaciofluvial plains (e.g., eastern front of Lagos del Toro and Sarmiento) or by hilly topography where moraines are associated with bedrock relief (e.g., between Lagos Sarmiento and Azul; Marden, 1997; García et al., 2012). Nonetheless, in some areas, the two moraine belts merge together into a single landform system (Figs. 3, 4). Each of the TDP II and TDP III moraine belts at Laguna Azul and Lagos Sarmiento and del Toro consists of five-to-ten generally sharp, well-defined ridges, with slopes close to the angle of repose.

The TDP II and TDP III belts are generally continuous for more than 25 km from Laguna Azul to Lago Sarmiento and cross low-relief, bedrock-controlled topography locally dissected by deep channels and lake depressions (Cañadón del Macho, Laguna Amarga, Fig. 3). The outermost TDP II moraine in this area defines a sharp drift limit, which may be marked by a line of boulders (see also Marden, 1993). At Lago del

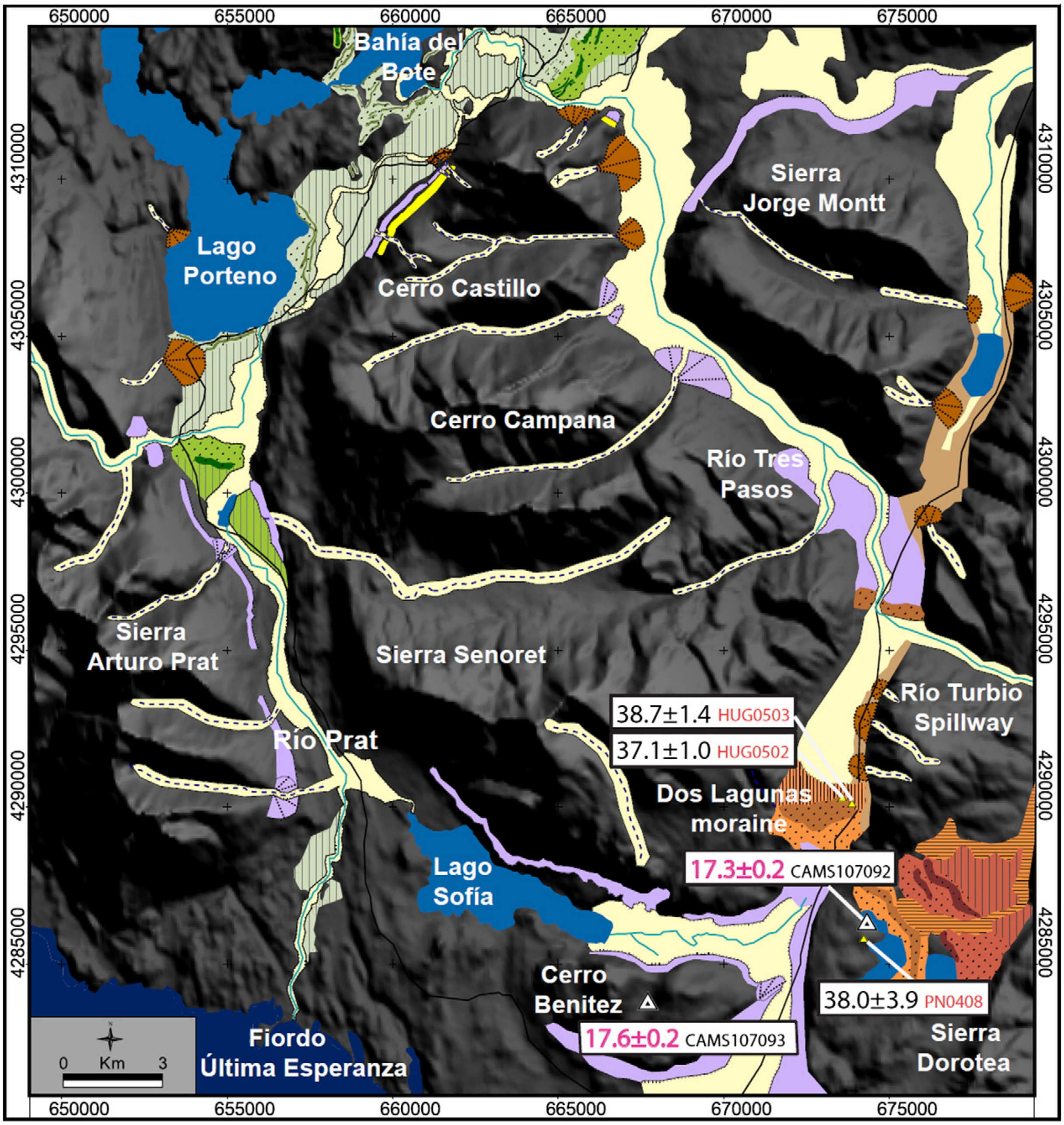

Fig. 5. Glacial geomorphologic map of the Lago Porteño-Cerro Benítez area. ^{10}Be ages (black) and calibrated radiocarbon ages (pink) (Reimer et al., 2009) from Sagredo et al. (2011). Age uncertainties are 1σ.

Toro (Fig. 4), TDP II and III moraines fringe the lake along its eastern and southern margin from Sierra del Toro to La Península promontory, where they are again particularly distinct at Bahía del Bote (Fig. 5). Between Sierra Ballena and Lago Porteño, TDP II and III moraines have been reworked and partially infilled by glaciofluvial sediments.

5.1.2.3. TDP IV moraines. TDP IV deposits commonly form the innermost distinct moraine belt deposited along the present shores of Laguna Azul and Lagos Sarmiento and del Toro. TDP IV moraines are less prominent, less continuous, and smaller than those of the TDP II and III systems. At Laguna Azul, the TDP IV ice margin occurs as a double kame terrace paralleling the east and south coasts of the lake (this study, Marden, 1993). Along the north side of Lago Sarmiento, the TDP IV moraines cross-cut the TDP III ridges, and it is not always possible to differentiate the two sets of landforms. On the east side of Lago Sarmiento, there commonly is no space separating TDP III and TDP IV. At some locations (e.g., Lago del Toro basin), TDP IV moraines may be slightly higher in elevation than TDP II–III ridges. This resulted in locally thick TDP IV sediment drift that partially buried sections of TDP III and II moraines. A prominent ice-contact slope that can be followed as kame terraces along the southern slope of the Macizo del Paine near Lago Nordenskjöld is also included in the TDP IV landforms (Marden, 1993; Fogwill and Kubik, 2005; Moreno et al., 2009a) (Fig. 1).

5.1.2.4. TDP V moraines. The next prominent and well-preserved ice-marginal landforms proximal to TDP IV moraines correspond to the F moraines of Marden and Clapperton (1995). These occur as independent moraine systems closer to the Southern Patagonian Ice Field. For instance, at Lago Margarita (Lago Grey area, Fig. 1) three moraine ridges separated by intermorainic depressions, some enclosing mires and bogs

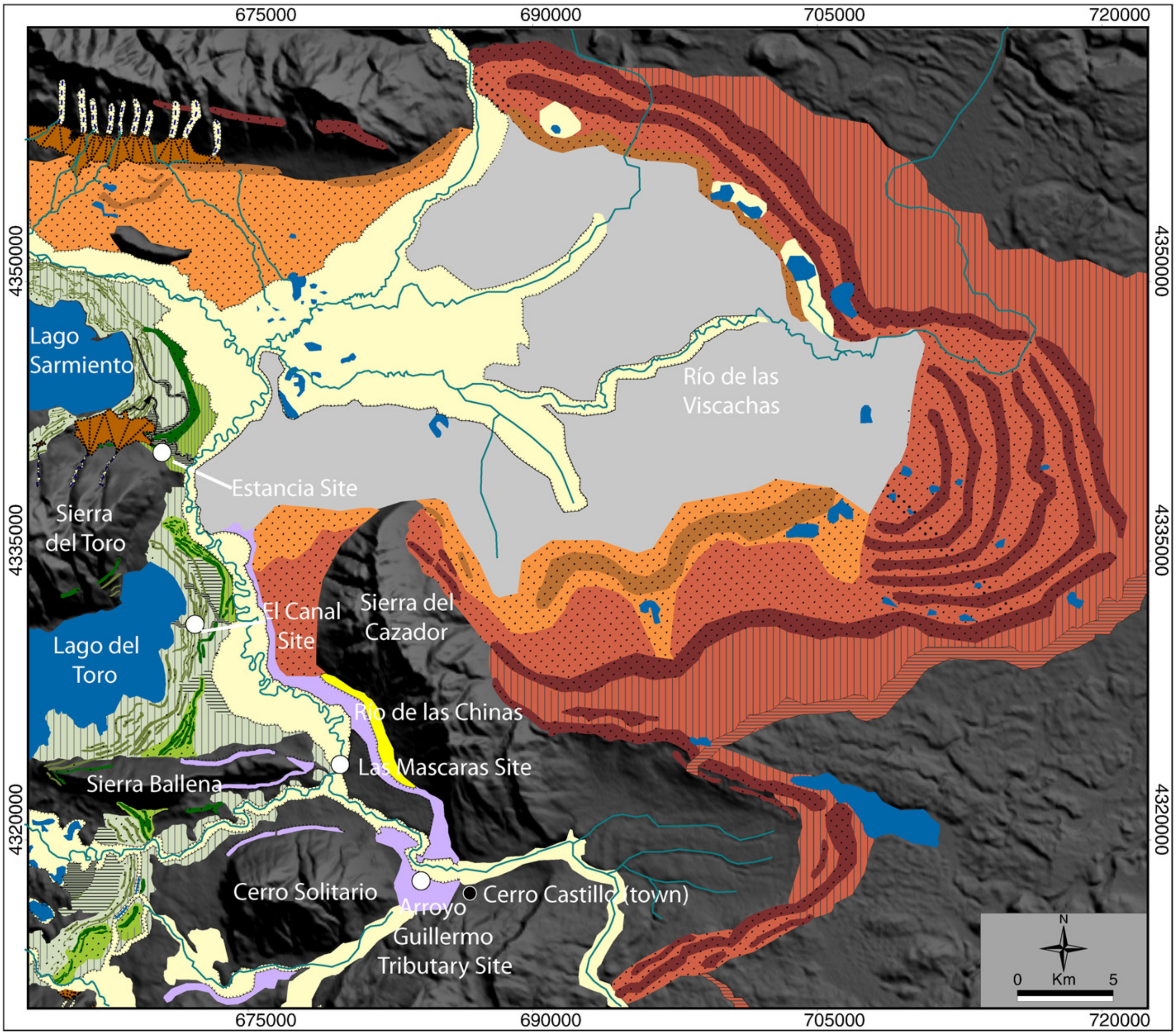

Fig. 6. Glacial geomorphologic map of the Río Viscachas area.

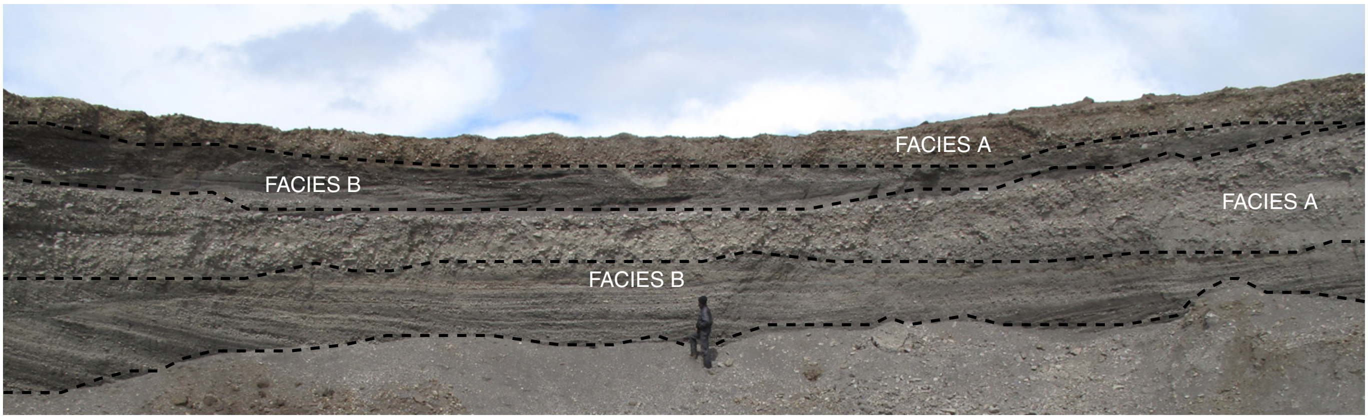

Fig. 7. Estancia Site stratigraphic section at Lago Sarmiento (TDP I moraine). Facies A: Ice-proximal massive gravelly cobbles. Facies B: sandy gravel glaciofluvial sediments. See text for details. See Fig. 3 for site location.

(Marden, 1993; Moreno et al., 2009b) and meltwater channels, define a former ice-marginal position of outlet Glacier Grey, which today terminates 18 km to the north.

Also, a double moraine system that Marden (1993) mapped as F moraines encloses Lago Dickson (Fig. 1). Here, the linear distance to the present ice margin (i.e., Glacier Dickson) is about 11 km. The glaciated Macizo del Paine (Fig. 1) includes on its southern flank a set of moraine arcs that relate to local ice fluctuations after the South Patagonian Ice Field had separated from this alpine system. Here, as in the Lago Grey area, ice flowing out from the Macizo del Paine deposited three distinct moraines ridges, which have not been mapped previously. We refer to all of these landforms, together with those at Lagos Margarita (Lago Grey Area, Fig. 1) and Dickson, as TDP V moraines.

5.2. Outwash plains

The outer RV I moraines grade to a prominent outwash plain, that descends to the Atlantic basin. In contrast, the outwash plains associated with the TDP II–IV moraines east of Laguna Amarga, Lago Sarmiento and Lago del Toro drained ultimately to the Pacific Ocean. At times of the TDP I–IV moraine deposition, mostly narrow corridors were left between the glacier front and the bedrock relief (e.g., Sierra del Cazador, Cerro Castillo), and were used as glaciofluvial conduits. A relatively extensive outwash plain grades from the TDP II moraines at Laguna Amarga (~165 m a.s.l.) to the correlative outwash plain from the Lago Sarmiento lobe at 140 m a.s.l. Along the southern margin of Lago del Toro, glaciofluvial landforms occur in patches separated by bedrock hills. Overall, the elevation of the main outwash plain that grades to both TDP II and III ridges decreases steadily between Laguna Amarga (160 m a.s.l., Fig. 3) and lower Río Prat Valley (~25 m a.s.l.; Fig. 5) and records the route of meltwater drainage into the Pacific Ocean (i.e., Fiordo de Última Esperanza) at times of TDP II, III, and IV moraine deposition.

Meltwater channels and lake spillways developing from the TDP IV moraines are common in the studied glacial basins (e.g., El Canal meltwater channel at Lago del Toro, Fig. 4) and denote deglacial incision after the TDP IV advance. Distally, these channels merge into the main glaciofluvial plain draining into the Pacific Basin. For instance, El Canal meltwater channel dissects the TDP II outwash plain and displays four small-incised outwash terraces similar to those present east of Laguna Amarga (Fig. 3).

5.3. Evidence for paleolakes

Today, drainage to the Pacific Ocean in the field area is through Río Serrano (25 m a.s.l. at the river head in western Lago del Toro) (Fig. 1). When Río Serrano Valley was occupied by ice, Río Prat Valley, a low-elevation (45 m a.s.l.) pass between Lago Porteño and Fiordo de Última Esperanza, was used as a meltwater conduit (Fig. 5). Each time the Patagonian ice sheet advanced eastward in Torres del Paine or northward in Última Esperanza and closed these two outlets to the Pacific Ocean, a recurrent proglacial lake formed in the Torres del Paine region. Glaciolacustrine terraces and sediments are common in the field area and reflect this important aspect of the geomorphic history. In this section, we describe the locations and attributes of the glaciolacustrine terraces and sediments present in the region, with the goal of reconstructing their relationship to ice-sheet fluctuations.

5.3.1. Glaciolacustrine terraces

Mountains east and south of Lago del Toro, such as Sierra del Cazador, Sierra Ballena and Sierra Arturo Prat, exhibit on their flanks discrete single and, rarely, double systems of glaciolacustrine terraces (e.g., Solari et al., 2012; Figs. 4–6, 8–9). Although some of these landforms may resemble kame terraces in places, we interpret them as being lacustrine features, because their elevations do not change over distances of several kilometers. Also, no trace of former fluvial features (e.g., channels) is evident on them. Terraces can be continuous for several kilometers (e.g., 5 km at Sierra del Cazador), but more commonly are discontinuous fragments that range in length from hundreds of

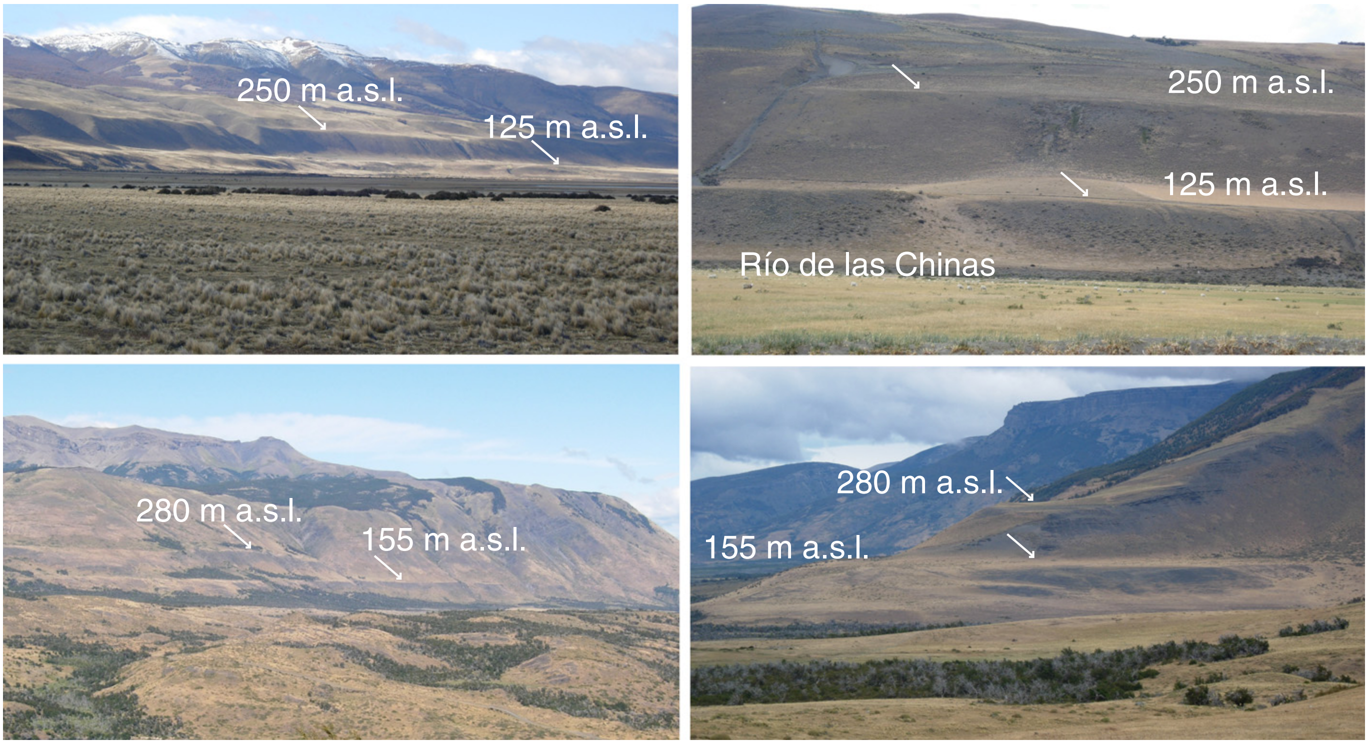

Fig. 8. Double glaciolacustrine terrace systems in Torres del Paine area. Images display shorelines at 280–250 m a.s.l. and 155–125 m a.s.l. on Cerro del Cazador (upper photos) and Cerro Castillo (lower photos). White arrows indicate position of shorelines. See Figs. 1, 3–6 for geographic location.

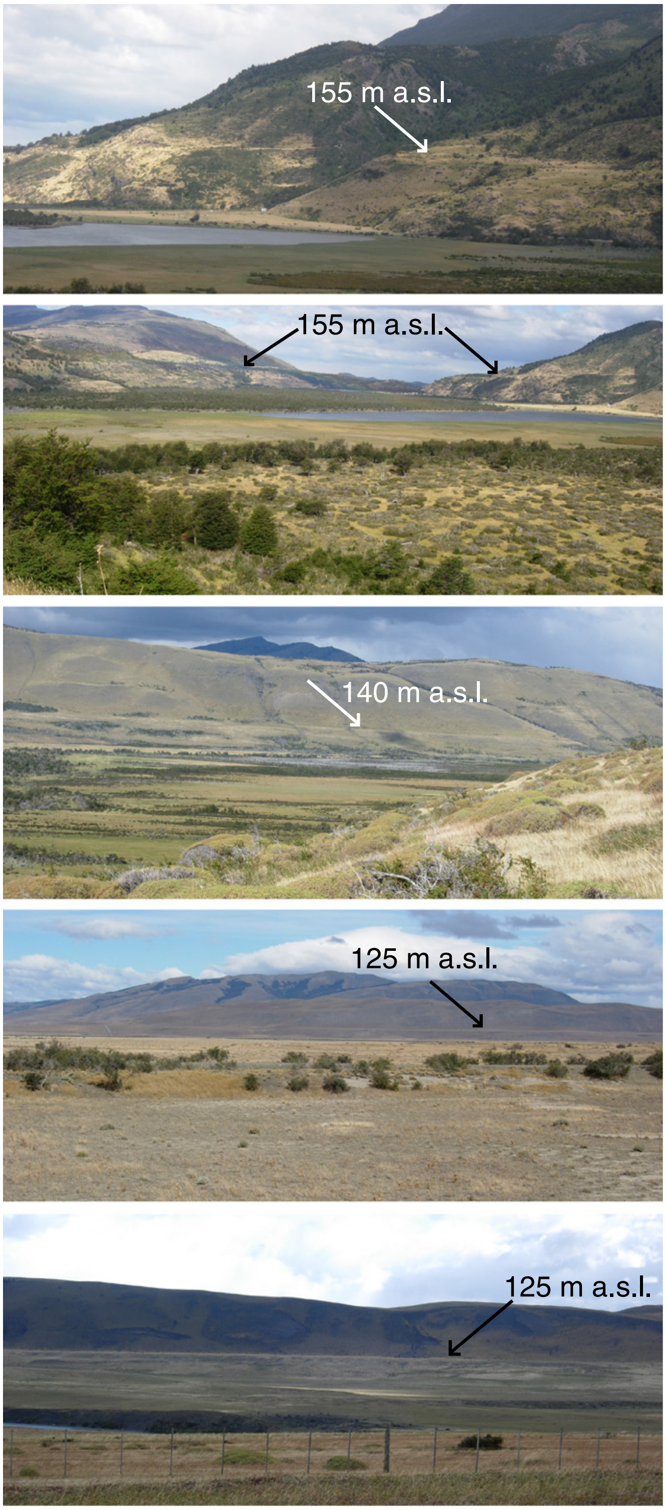

Fig. 9. 155–125 m a.s.l. glaciolacustrine terraces in Torres del Paine area. From upper to lower: Perched delta at Río Prat valley; Río Prat Valley; Sierra Jorge Montt; Cerro Solitario; southern slope at Sierra Ballena. Arrows indicate position of shorelines and deltas. See Figs. 1, 3–6 for geographic location.

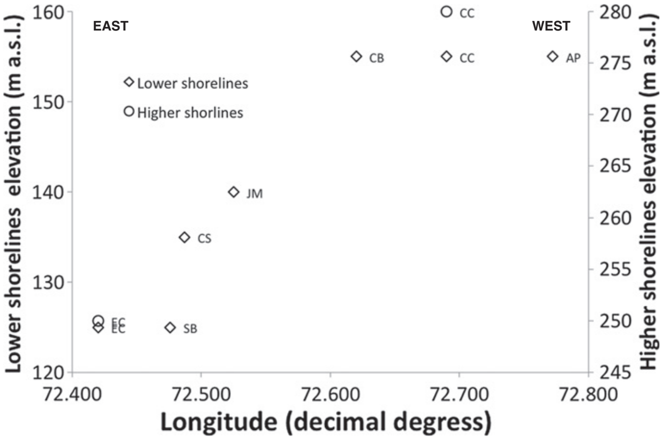

Fig. 10. East–West glaciolacustrine shoreline elevation variation in Torres del Paine area. "Higher shorelines" (rhombus) refer to the 250–280 m a.s.l. terraces, and "lower shorelines" refer to those landforms bracketed between 125 and 155 m a.s.l. AP: Sierra Arturo Prat; CB: Cerro Benítez; CC: Cerro Castillo; CS: Cerro Solitario; EC: Sierra del Cazador; JM: Sierra Jorge Montt; SB: Sierra Ballena.

meters to 1 to 2 km. These discontinuous glaciolacustrine landforms increase very gradually in elevation to the west. For instance, terraces thought to be correlative occur at about 125, 140 and 155 m a.s.l. in the eastern, central and western parts of the field area, respectively, just south of Torres del Paine National Park (Figs. 4–6, 10). Most terraces have been carved into bedrock and lack sediment. Shorelines may be narrow (e.g., tens of meters wide at Cerro Castillo) or wide (e.g., several hundred meters at Sierra del Cazador) and expose a variable shoreward slope (Figs. 4, 5, 8).

Shorelines range from 280 m a.s.l. to 125 m a.s.l., but those at about 125 m a.s.l. are the most common, particularly in the eastern areas adjacent to the Torres del Paine National Park. On the western slope of Sierra del Cazador, a lower terrace (125 m a.s.l.) is very prominent and laterally continuous for about 5 km, whereas a higher level (250 m a.s.l.) is less extensive (Figs. 4, 8). To the west, on the northern slope of Cerro Castillo, two shorelines are also present, at 280 m and 155 m a.s.l. (Figs. 5, 9). Another terrace occurs at ~125 m a.s.l. (Fig. 9) on the eastern side of Sierra Ballena and distal to the TDP I moraines. The same level is also present on the north flanks of Cerro Solitario. Narrow terraces at 140 m a.s.l., on the northwest corner of Sierra Jorge Montt (Figs. 5, 9), are less prominent, but clear in aerial photographs. On the eastern slopes of Cerro Campana, in the Tres Pasos River Valley, relict deltas occur at 155 m a.s.l. and plains at similar elevations also are present. In addition, we detected terraces and deltas with the same elevation (155 m a.s.l.) in Río Prat Valley (Figs. 5, 9). To the south and east of this valley in the Última Esperanza region, a terrace occurs at about 150 m on the slopes of Cerro Benitez and Sierra Dorotea (Sagredo et al., 2011; Stern et al., 2011).

5.3.2. Glaciolacustrine sediments

The Las Mascaras site (51°12′41″S and 72°26′14″W; ~70 m a.s.l.; Lago del Toro basin; Figs. 6, 11A–C) is exposed in the northern bank of Río de Las Chinas before it reaches Las Mascaras bridge. Here, the site reveals several meters of rhythmically bedded glaciolacustrine silt and clay (facies A in Fig. 11A–C) and gravel sediments (facies B in Fig. 11A–B). The gravel beds, which are more abundant in the lower part of the section, are clast-supported, very well sorted, and can be followed laterally for tens of meters. They show cross-bedding and are interpreted as subaqueous fan deposits (Benn and Evans, 2010). Ripples are present in places within fine gravel. Isolated pebbles locally distort the laminations. The silt and clay are very well laminated and form horizontal beds. Rare, isolated cobbles that locally deform underlying laminations occur within the fine sediment and are interpreted as dropstones (Fig. 11C).

The Arroyo Guillermo tributary site (51°15′25″S and 72°22′10″W; ~110 m a.s.l.) is located about 7 km southeast of Río de Las Chinas, where a small tributary of the arroyo cuts into a flat plain and exposes glaciolacustrine sediments (Figs. 6, 11D). The section is only about 3 m thick and consists of finely laminated clay and silt (facies A in Fig. 11D). Clay laminae may contain mud cracks. Rare isolated cobbles, probably dropstones, and rare irregular gravel beds (facies C in Fig. 11D) are present within this fine sediment unit. Sorting within

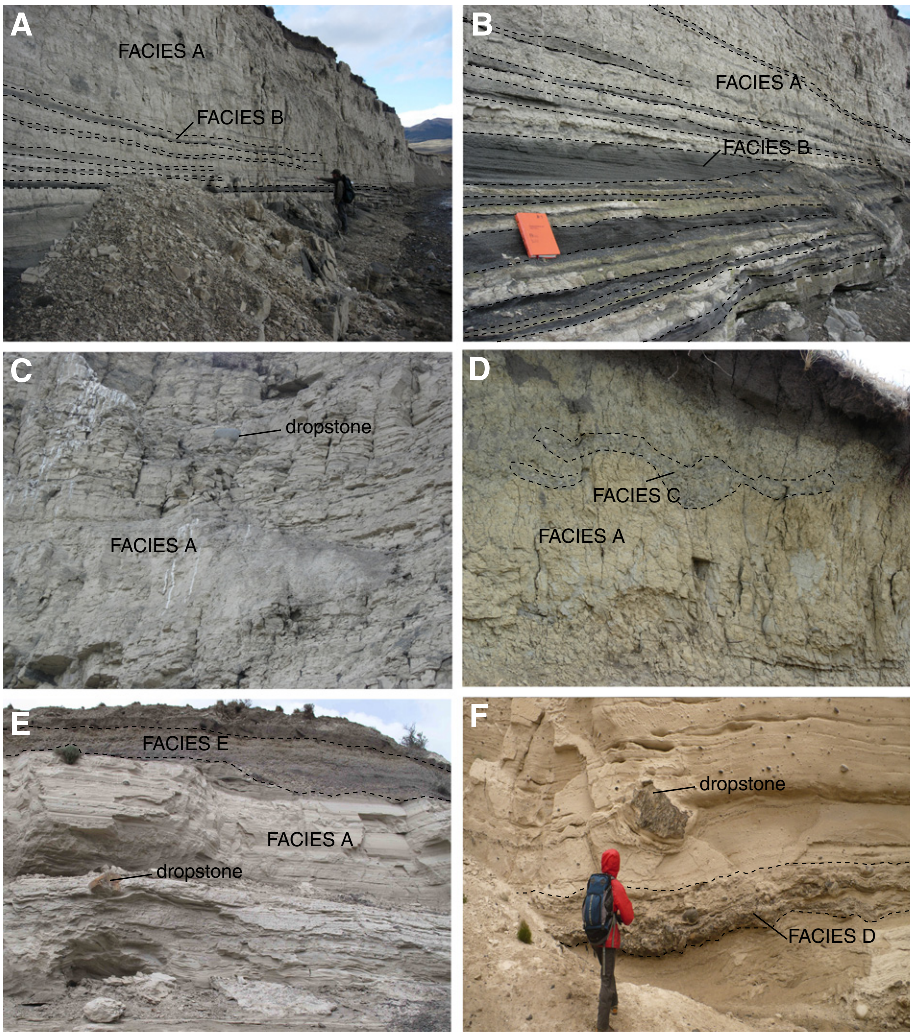

Fig. 11. Glaciolacustrine sediments in Torres del Paine. A–C: Las Mascaras Site; D: Arroyo Guillermo Tributary Site; E & F: El Canal site. Facies A: well-laminated glaciolacustrine sediments, which may contain dropstones, ice-rafted debris (IRD) and gravel layers. Facies B: subaqueous fan sediments displaying well-sorted gravel with cross-bedding and traction structures. Facies C: irregularly shaped gravel lenses embedded within facies A interpreted as IRD (e.g., iceberg dump deposits) at Arroyo Guillermo Tributary sediment section. Facies D: glaciotectonized debris flow sediments. Facies E: coarsely bedded subaerial outwash gravel.

this sediment ranges from moderate to poor and most likely originated as ice-rafted debris in a glacial lake (Gravernor et al., 1984; Benn and Evans, 2010).

An artificial channel, El Canal (51°08′30″S and 72°32′19″W; ~65 m a.s.l.; e.g., Caldenius, 1932; Marden, 1993; Solari et al., 2012; García et al., in prep.), was excavated early in the last century within a natural meltwater channel crossing the TDP moraine belts in front of Lago del Toro (Figs. 4, 11E–F). Along its length of ~2.5 km, there are proximal and distal glaciolacustrine sediments, which include subaqueous fan, debris flows, ice-rafted debris and lake-bottom sediments, as well as sub-aerial glaciofluvial sediments capping the sediment sequence (Fig. 11E–F) (Gustavson, 1975; Gravernor et al., 1984; Benn, 1996; Johnsen and Brennand, 2006; Benn and Evans, 2010; Evans et al., 2012; García et al., in prep.). Sand cross-beds include light-colored tephra grains, which we tentatively correlate with one of the eruptions of the Reclus Volcano widely identified throughout southern Patagonia (Stern, 1990; Marden and Clapperton, 1995; Stern, 2008; Sagredo et al., 2011; Stern et al., 2011).

5.4. Chronological constraints

To afford a minimum age for deglaciation from the TDP I belt, we obtained a sediment core from Vega Chulengo (50°54′33″S; 72°43′52″ W, 370 m a.s.l.; Figs. 3, 12; Table 1), located in the Laguna Azul basin between the TDP II and TDP I moraine belts. The base of the sediment sequence at 2.91 m depth is highly resistant, organic-poor sandy silt, which grades upward into laminated, light-colored, relatively organic-rich clay and then conformably into gravelly sand. The sediment then becomes finer upwards, with a gradual transition to organic-poor silt that, in turn, grades into the organic-rich, fibrous peat forming at present. Wood pieces from the lowermost centimeters of the core (Fig. 12) yielded an age of 17,400 ± 180 (1σ) cal. yr. BP (Table 1), which we infer represents a minimum age for local deglaciation.

A second sediment core was obtained from Vega Úrsula (51°2′8″S; 72°52′38″W, 172 m a.s.l.; Fig. 1; Table 1), located at the northern coast of Lago Sarmiento, inside the TDP IV moraine limit. The bottom sediments of this 3.79 m-long core preserve inorganic gravelly lacustrine clay that grades to organic-poor, pale yellow, plastic sediment, which in turn grades to organic-rich sediment including macrofossils. A piece of wood from near the base of this core was dated to 11,150 ± 60 (1σ) cal. yr. BP (Table 1), which we interpret as locally ice-free conditions at this time.

García et al. (2012) showed that outlet glaciers in the Sarmiento and Laguna Azul basins advanced throughout the ACR chronozone depositing the TDP II–IV moraines. ^{10}Be ages of boulders at the TDP II ridges yield an arithmetic mean age of 14,200 ± 540 cal. yr. BP; those from the TDP III moraines produce a mean age of 14,100 ± 540 cal. yr. BP,

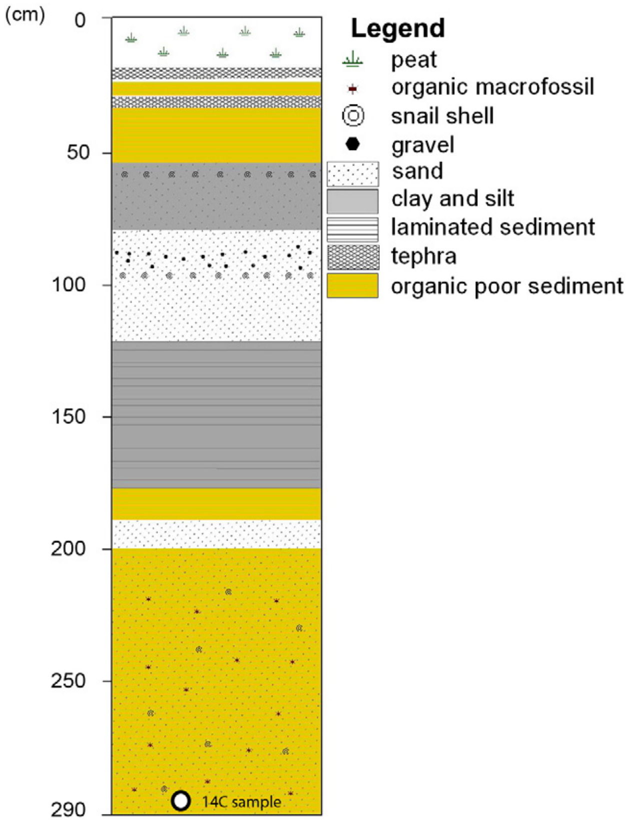

Fig. 12. Stratigraphic column from a core obtained from Vega Chulengo (50°54′32″S; 72°43′53″W; 370 m a.s.l.). A piece of wood was obtained from close to the base (289 cm) of this section and yielded a calibrated ^{14}C age of 17,420 ± 185 (1σ) cal. yr. BP (OS-74486, radiocarbon age 14,350 ± 70 yr. BP, see Table 1). See text for more details.

and those from the TDP IV moraines yield a mean age of 13,900 ± 370 cal. yr. BP (Fig. 3). Subsequently, major glacier recession and deglaciation in the Torres del Paine region occurred by ~12,500 cal. yr. BP, as documented at several sites (Figs. 1, 3; Table 1; Moreno et al., 2009a; García et al., 2012).

From sites both distal and proximal to TDP V landforms at Lago Margarita (sites 14–17, 19–20 in Fig. 1; Table 1), Marden (1993), Marden and Clapperton (1995), and Marden (1997) obtained calibrated ^{14}C ages moraine ranging between 9740 ± 190 and 2935 ± 60 cal. yr. BP. Older ages came from outer sites and younger ages from inner sites across the moraine complex. Within the same moraine system, Moreno et al. (2009b) reported minimum basal ages of 3810 ± 85 cal. yr. BP (site 18 in Fig. 1) for the abandonment of the inner ridges.

In summary, the available chronologic data help place the geomorphic record into an age context. RV moraine belts are older than late-glacial chronozone and older than 17,400 ± 180 (1σ) cal. yr. BP, the basal minimum age obtained at Vega Chulengo. The TDP II–IV moraine belts formed after the end of LGM and over the late-glacial period. Glacier recession from TDP IV occurred by 12,500 yr. BP. At least one prominent glacial readvance occurred between >9740 ± 190 and <3810 ± 85 cal. yr. BP, as defined by the TDP V moraines (Marden and Clapperton, 1995; Moreno et al., 2009b), when the South Patagonian Ice Field front stood about 20 km beyond present ice margins.

6. Discussion

6.1. Glacial advances

6.1.1. RV moraines

These moraine belts have not been mapped in detail before because previous glaciological studies in the region (e.g., Marden and Clapperton, 1995) attributed these landforms to early in the Quaternary, older than the LGM. However, based on the available chronological evidence in Torres del Paine (e.g., García, 2011; García et al., 2012), we cannot exclude the possibility that they date to the last glacial maximum or at least over the last glacial cycle. During RV I deposition, the margin of the Southern Patagonian Ice Field in Torres del Paine was about 100 km beyond its present position. The broad morphology and low relief of the moraines at the eastern front resulted in part from glaciolacustrine sediments infilling inter-moraine depressions. The well-organized suite of smaller, concentric moraine ridges just inboard or proximal to the RV I belt may have been deposited during deglaciation from the maximum RV I ice position. We assume that after the Patagonian ice sheet reached its terminal position it retreated westward. Moreover, we infer that the size and continuity of the RV II moraine belt suggest that this landform also represents a prominent readvance of the Southern Patagonian Ice Field after deposition of RV I and that ice lingered at this position for a significant time in order to build such a prominent landform.

TDP I moraines at Laguna Azul are broad and form a low-relief topography. These physical characteristics differ from the TDP I landforms at Lagos Sarmiento and del Toro, where they occur as well-defined, sharper moraine ridges (lateral moraines at Lago del Toro reach up to ~30° on their proximal slopes). It is possible that these significant inter-basin variations within the TDP I moraines result from differences in the age of the landforms (e.g., older moraines expose more subdued shapes in response to landscape evolution). For example, the broader and less distinct moraines at Laguna Azul could have been deposited during a previous glaciation. Although originally interpreted as TDP I moraines in the Laguna Azul Basin (García, 2011), we now interpret the outer moraines at Laguna Azul as part of the RV II moraine system (see Fig. 3). If true, TDP I moraines at Laguna Azul may correspond to recessional RV II landforms. That is, both TDP I at Laguna Azul and RV II moraines have morphological similarities, including gentle slopes (15–20°) and a general absence of boulders on their surfaces. Based on the deglacial age from Vega Chulengo, which is located inboard from the TDP I moraine belt in the Laguna Azul basin, this correlation would place the RV II moraines at >17,400 ± 200 cal. yr. BP.

At times of RV moraine construction, the Lago Argentino Glacier to the north may have occupied its lake basin and built the correlative El Tranquilo I and II moraines (Strelin and Malagnino, 1996). To the south at Última Esperanza, ice may have expanded to the east and built the Río Turbio and Arauco moraines (Meglioli, 1992; Sagredo et al., 2011). These landforms remain mostly undated except for a few ^{10}Be and ^{14}C minimum-limiting ages that suggest deposition during the MIS 3 and, possibly, 2 for the inner moraines in Última Esperanza (Sagredo et al., 2011).

6.1.2. TDP I–IV moraines

As mentioned above, at Lagos Sarmiento and del Toro TDP I landforms are prominent, well-defined moraine ridges. In addition, the TDP I landforms at Lagos del Toro and Sarmiento are similar to each other in terms of number, size, geographic pattern, morphology and position of ridges. The outer TDP I moraines are nearly continuous between the Sarmiento and del Toro basins, separated by only 3 km of foothills. Based on available chronology in the region and stratigraphic position, TDP I at Lagos Sarmiento and del Toro may date to the last readvance or stillstand of the Patagonian ice sheet during the LGM. Beryllium-10 dating in progress may provide a more accurate age for the TDP I landforms in the future.

As inferred from their geomorphological similarities (Marden and Clapperton, 1995) and mean age of 14,100 ± 520 cal. yr. BP, TDP II, III, and IV moraines represent a distinct stadial (García et al., 2012). Solari et al. (2012) interpreted two radiocarbon ages of 24,220 ± 180 cal. yr. BP and 21,600 ± 195 cal. yr. BP obtained from sediments at El Canal site, as indicating the time of deposition for the inner TDP

(II–IV) moraines at Lago del Toro. Our detailed mapping, together with that of Marden (1993), and our dating program in the adjacent basins to the north do not support that chronological interpretation. Although the moraines at Lago del Toro lack any direct age constraint, based on our interpretation of the local morphological record we suggest that these landforms were deposited at the same time as the TDP II–IV moraines at Laguna Azul and Lago Sarmiento, where they are well dated. At lakes Sarmiento and del Toro, 5–10 ridges form each of these moraine belts and the overall morphological imprint records similar ice-marginal fluctuations at both sites. Therefore, we infer that the dates of Solari et al. (2012), obtained from bulk carbon, instead represent maximum-limiting ages for the landforms. In addition, based on physical attributes and geomorphic context, tephra layers embedded in El Canal glaciolacustrine sediments associated with the TDP II–IV moraines can be linked tentatively to the late-glacial Reclus eruption documented throughout southern Patagonia (R1 tephra: ~14,500 cal. yr. BP) (McCulloch et al., 2005; Stern, 2008; Stern et al., 2011; Sagredo et al., 2011). Although additional data are required to confirm this interpretation, the presence of the tephra may indicate that the moraines at del Toro are indeed correlative with the late-glacial TDP II–IV moraines at Lago Sarmiento and Laguna Azul.

6.2. The last glacial maximum

The timing, structure and extent of the local LGM remain obscure in the Torres del Paine region. Although Caldenius (1932) suggested that the four main moraine belts preserved at this latitude (and throughout Patagonia) were deposited during the last glacial period, Marden and Clapperton (1995) proposed, without absolute chronological data that only the inner TDP II–TDP IV deposits dated to the global LGM. New chronological constraints (e.g., Fogwill and Kubik, 2005; Moreno et al., 2009a; García et al., 2012) demonstrated that the inner TDP II–IV landforms are younger than the LGM and instead were deposited in late-glacial time. The age of 17,400 ± 200 cal. yr. BP from the base of Vega Chulengo, located within the RV II moraines in the Laguna Azul basin (Fig. 3), affords a minimum age for deglaciation from the RV position, leaving open the possibility that the prominent RV moraines could date to the global LGM. The Vega Chulengo basin was fed by meltwater from an ice position close to the TDP II moraine belt (Fig. 3), suggesting that by 17,400 ± 200 cal. yr. BP the glacier was similar in size to that during the late-glacial TDP II advance.

Beryllium-10 exposure ages from a few boulders (i.e., Samples SAR0722, SAR0724, LA0716, LA0732) that are distinctly older than the rest of the dataset ($n = 38$) from the TDP II–IV moraines date (within 2σ) to the global LGM (García et al., 2012) and may represent LGM boulders incorporated into the younger moraines. Alternatively, it is possible that these few ages indicate that the TDP II–III moraines mark the LGM ice position in Torres del Paine (Marden and Clapperton, 1995) and that almost all the late-glacial exposure ages obtained by García et al. (2012) are minimum ages that resulted from boulders being exhumed after moraine surface erosion. We do not prefer this scenario because: 1) these older, statistically defined outliers data represent only about ~10% of the data set and are far less common than the dates from late-glacial time; 2) TDP II–IV moraines are sharp landforms with slopes close to the angle of repose; there are no morphologic signs of significant surface degradation, except perhaps in one area just adjacent to the east side of Lago Sarmiento; and 3) commonly, exposure ages affected by post-depositional landform adjustments show significant scatter as each boulder has an unique history (cf., Hein et al., 2009). This is not the case here, where the ages are strongly coherent even within analytical uncertainties and date to within the ACR chronozone (García et al., 2012). In summary, available data indicate that the LGM ice may have extended to the outer moraines in the Torres del Paine region (e.g., RV moraines). Dating on the TDP I and RV moraines is required to address this important issue.

6.3. Deglaciation

Major deglaciation into the mountains of Torres del Paine occurred after the end of the late-glacial readvance that built the TDP II–IV moraines. Widespread ^{14}C age control shows that the ice front retreated from TDP IV moraines by or just before ~12,500 cal. yr. BP (Heusser, 1987; Marden, 1993; Moreno et al., 2009a; García et al., 2012). In addition, Moreno et al. (2009a) reported a single older age of 14,940 ± 150 cal. yr. BP from Lago Guanaco, about 6 km west of TDP IV north of Lago Sarmiento, and suggested that this particular site may have deglaciated slightly earlier than other sites (Fig. 3). This site should have been covered by ice during the deposition of the TDP II–IV moraines (Fig. 1), which north of Lago Sarmiento reach ≥300 m a.s.l. Further chronological work is required to reproduce this single age, particularly because it is based on bulk lake sediments from an organic silt layer. For comparison, similar evidence for major glacier retreat at the end of the ACR period, by ~12,500 yr. BP, has been found in neighboring basins, such as in Lago Argentino. Here, outlet glaciers deposited the Puerto Bandera moraines shortly after 12,990 ± 80 cal. yr. BP and subsequently retreated back into the Andes at ca. 12,660 ± 70 cal. yr. BP (Strelin et al., 2011).

After ice in Torres del Paine deposited the TDP IV moraines, it retreated westwards. Based on perched deltas at Lago Nordenskjöld and subtle and discontinuous morphologic evidence, Marden and Clapperton (1995) and Marden (1997) proposed a subsequent ice-marginal position they referred to as the E moraines. However, the evidence for such an event is sparse and may represent only local ice fluctuations during retreat from TDP IV position rather than an organized readvance in response to a regional climate change. For that reason we do not give the E moraines a separate designation with the TDP nomenclature. It is possible that the E phase at Torres del Paine may have occurred at the same time as the deposition of the Herminita moraines at Lago Argentino, where inter-lobular moraine deposits are well preserved (12,200 cal. yr. BP; Kaplan et al., 2011; Strelin et al., 2011). Radiocarbon ages constrain significant ice recession to the west of Lagos Sarmiento and Nordenskjöld by at least earliest Holocene time. For example, the near-basal age obtained at Vega Ursula (located north of Lago Sarmiento, 11,150 ± 60 cal. yr. BP) is identical, within uncertainties, to that obtained at Site GP (11,179 ± 95 cal. yr. BP; Marden, 1993), located between Lagos Nordenskjöld and Lago Pehoé, 25 km to the west (Site 12 in Fig. 1 and Table 1).

In contrast to the scanty and incomplete evidence for the E position, the TDP V (formerly “F” of Marden and Clapperton, 1995) landforms are prominent, composite, well-formed moraines (at least three sets) and other ice-proximal landforms that denote Holocene advances (Marden, 1993; Marden and Clapperton, 1995; Marden, 1997). Although Marden (1993) obtained basal ^{14}C ages ranging between only 4500 and 2800 cal. yr. BP from three different sites within the inner TDP V moraine ridges, he concluded that the entire complex represented a single glacial event and that this occurred before 9700 cal. yr. BP. The minimum ages obtained by Marden (1993) for deposition of the inner TDP V moraines were replicated by Moreno et al. (2009b) (3810 ± 85 cal. yr. BP, Table 1), who questioned the interpretation of a single, early Holocene advance. Based on their local chronological and stratigraphical record, they proposed instead that the TDP V moraine complex represented several Holocene advances by the Lago Grey ice lobe. Finally, by latest Holocene time (last 1000 yr), glaciers were near present configurations (Fig. 1) (e.g., Aniya and Sato, 1995). Altogether, available data indicate that in <3000 years the Southern Patagonian Ice field margin at Torres del Paine retreated at least ~35 km from its late-glacial position (e.g., TDP IV moraine), before building the TDP V moraines. This retreat occurred during the Younger Dryas phase (12,800–11,500 cal. yr. BP; Muscheler et al., 2008) and the earliest part of the Holocene; a timing also found at Lago Argentino (Strelin et al., 2011). Although more data are required from Última

Esperanza to define better the local ice-front fluctuations during last termination, previous studies (Sagredo et al., 2011) indicate that ice followed a similar deglacial pattern in this area as well.

6.4. Glacial paleolakes

Caldenius (1932, p.100) stated that an understanding of glacial lakes in the Torres del Paine region "..is one of the most interesting and complicated glaciolacustrine problems in the Andean Cordillera." This is because the hydrological continental divide in this region is mainly defined not by bedrock relief, but by moraine deposits. In addition, the geographic connection between Torres del Paine and Última Esperanza basins results in ice extent to the south having the potential to control lake levels far to the north. During the last glaciation, each time ice extended to Cerro Castillo, blocking the Río Prat pass, or the Última Esperanza ice lobe buttressed against Sierra Dorotea (Fig. 4), a lake formed in the Torres del Paine region. Solari et al. (2012) referred to this as paleolake Tehuelche. Paleolake Tehuelche had different phases linked to distinct elevations, as defined by outlets that conducted water to the Atlantic Ocean. In our interpretation, over the duration of the glacial period represented by the TDP I–IV and RV moraine systems, paleolake Tehuelche attained elevations that ranged from 420 (Caldenius, 1932; García, 2011) to 125–155 m a.s.l. and consisted both of individual lakes in the Río de Las Viscachas and Arroyo Guillermo basins and united lakes covering a significant part of the region.

One important question regarding the littoral terraces present in the vicinity of Torres del Paine National Park is whether all of them (125 m, 140 m, 155 m, 250 m and 280 m a.s.l.) correspond to different lake phases or if at least some of them, despite slight differences in elevation, correspond to the same lake, due to regional glacial-isostatic or tectonic effects. The fact that these terraces are spatially discontinuous makes it difficult to distinguish between these two options for some levels at relatively close elevations.

In one scenario, each of the terrace elevations would represent a distinct phase of paleolake Tehuelche, meaning that the Patagonian ice sheet retreated, allowing a drop in lake level, but that this recession was punctuated by stable ice and hence lake positions (Sagredo et al., 2011). However, an alternative is that differential glacio-isostatic crustal rebound caused small variations among terrace elevations and that some terraces of different elevation actual record the same lake (Hein et al., 2010; Stern et al., 2011). No location displays more than two shorelines. This fact, along with the geographical pattern of landform elevations (Fig. 10), suggests that there may be only two chronologically distinct levels, one at 250–280 m elevation and the other at 125–155 m elevation. Because terraces occur as landform fragments, we cannot trace them continuously from east to west to confirm this hypothesis. Nonetheless, as mentioned above, our multiple measurements indicate an increase in elevation over long east–west distances (30 km) with higher elevations occurring towards the present ice field to the west (Fig. 10), where ice was thicker and lake water deeper during the last glaciation (Stern et al., 2011). Because of this differential loading, the crust may have suffered more extreme vertical movements to the west, resulting in unequal amounts of glacio-isostatic rebound. If this second scenario is correct, it implies a vertical shoreline offset of about 30 m over approximately 30 km of distance, which is slightly greater than, but similar to, values reported previously for southern Patagonia (Ivins and James, 1999; McCulloch et al., 2005; Turner et al., 2005; Stern et al., 2011). For instance, just south of Torres del Paine in Última Esperanza, Stern et al. (2011) estimated 45 m of vertical change in lake terraces along 65 km of east–west distance. In summary, differential postglacial uplift is indeed documented along the southern Andes. Although more study regarding postglacial uplift and crustal rebound in the Torres del Paine region is important, we favor this second scenario to explain the spatial pattern of shorelines related to the Tehuelche paleolake (Fig. 10).

6.4.1. Tehuelche paleolake phases

Here, we provide a possible reconstruction that links littoral terraces, spillways and moraines in the Torres del Paine region. Available exposure-age and ^{14}C data (e.g., this work; Sagredo et al., 2011; García et al., 2012) are used to infer possible temporal scenarios, although we do not intend to tie undated landforms to an absolute age. Our interpretation suggests that the evolution of Tehuelche paleolake can be divided into three phases: Early Phase (lake levels at ≥300 m a.s.l.; Caldenius, 1932), Middle Phase (lake level at 250–280 m a.s.l.) and Late Phase (lake level at 125–155 m a.s.l.) (Fig. 13). Because morphostratigraphic data from the outer RV and AG moraines and associated lacustrine sediments is not completed, here we focus on the lower lake phases (i.e., 250–280 and 125–155 m a.s.l.) that occurred after the deposition of RV II moraines.

Two dependent factors are important for the reconstruction of paleolake Tehuelche: (1) the position of the ice both in Torres del Paine and Última Esperanza, and (2) the elevation of spillways. Normally, in temperate climatic regions, such as Torres del Paine, input from precipitation is higher than output from evaporation, and therefore recurrent formation of wave-cut platforms occurs when lake level is stable at the elevation of a spillway.

The Middle Phase is associated with a lake level at 250–280 m a.s.l. likely tied to the elevation of the Río Turbio-Tres Pasos spillway (Sagredo et al., 2011; Figs. 1, 5). Although there is no shoreline that can be traced to this spillway, based on similarity in elevation, we infer that the spillway and the 250–280 m a.s.l. shorelines at Torres del Paine are linked. During this phase, ice had retreated sufficiently from the Arroyo Guillermo and Río de Las Viscachas basins to clear the Río Turbio-Tres Pasos spillway and to allow a united lake to form. The exact ice position during this phase is unknown, but we infer that it must have formed a continuous front in Lago del Toro basin, west of Sierra Dorotea, allowing waves to carve terraces on both Cerros del Cazador and Castillo (Figs. 4, 5). To the south, the Patagonian ice sheet at Última Esperanza basin may have lingered at the Dos Lagunas moraine between Sierra Señoret and Sierra Dorotea, where an ice-contact delta at 270 m a.s.l. grades from the moraine, built when the ice stood at this site (~38,000 cal. yr. BP; Sagredo et al., 2011; Fig. 5). While ice fluctuated at this position, it blocked drainage and prompted lake formation at 250–280 m a.s.l. in Torres del Paine.

Based on the wide (1–2 km), flat top of the TDP I moraine at Lago Sarmiento, together with its elevation (115–125 m a.s.l.) and association with proximal subaerial glaciofluvial sediments at the Estancia site exposure (~125 m a.s.l.; Figs. 3, 7), we infer that part of this landform is an ice-contact delta grading to a lake at 125 m elevation. The fact that sub-aerial outwash make up the entire sequence at the Estancia site indicates that a deep lake never covered this site after TDP I moraine deposition at Lago Sarmiento. Therefore, we infer that the Middle Phase (e.g., 250–280 m a.s.l.) of the Tehuelche paleolake must have occurred during retreat from RV II moraine, before the TDP I glacial pulse at Lago Sarmiento. It may have occurred at ~38,000 cal. yr. BP (Sagredo et al., 2011), if association with the Dos Lagunas moraines and related ice-contact delta is correct.

The Late (and final) Phase of paleolake Tehuelche at 125–155 m a.s.l. probably occurred during the advance to and retreat from TDP I moraines at Lagos Sarmiento and del Toro (Fig. 13). This scenario is consistent with the ice-contact delta described at the Estancia Site that marks a lake level at 125 m a.s.l. coeval with moraine formation. Similarly, Sagredo et al. (2011) described prominent shorelines at ~125–150 m a.s.l. in Última Esperanza Basin (just south of Torres del Paine), which they interpreted as evidence for a deglacial lake they named Puerto Consuelo (early high phase), which drained through the Frontera outlet to the Atlantic Ocean (Sagredo et al., 2011). Sagredo et al. (2011) obtained two calibrated radiocarbon ages of 17,600 and 17,300 cal. yr. BP (recalibrated here using INTCAL09, Reimer et al., 2009) at Vega Benitez and Lago Dorotea (Fig. 5 and Table 1), respectively, which they interpreted as close minimum-limiting ages for glacial retreat

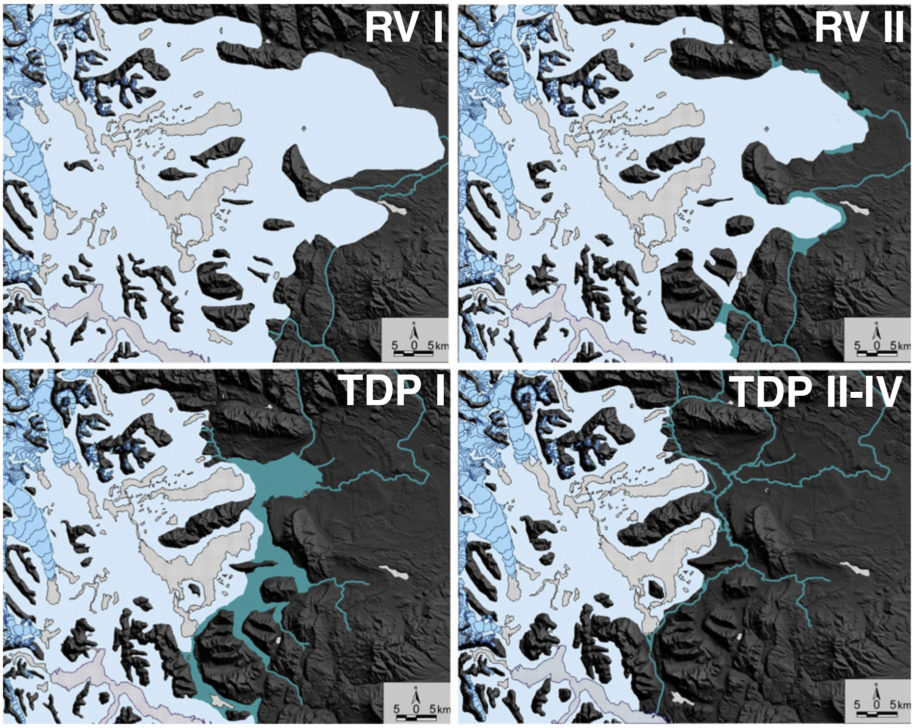

Fig. 13. Evolution of the Patagonian ice sheet and paleolake Tehuelche throughout the last glacial period in the Torres del Paine region. Each of the schematics represents a glacial advance in Torres del Paine region. RV I: glacial maximum; RVII: this readvance and the retreat from this glacial position formed lake levels first at ≥300 m a.s.l. (Early Tehuelche Phase) and then at 250–280 m a.s.l. (Middle Tehuelche Phase), as ice retreated westward and opened the lower Río Turbio Spillway (see Fig. 5). Most likely, the Última Esperanza ice deposited the Dos Lagunas ice-contact delta (280 m a.s.l., Fig. 5) during the Middle Tehuelche Phase (~38,000 cal. yr. BP, Sagredo et al., 2011); TDP I: a lake level at 125–155 m a.s.l. (Late Tehuelche Phase, >17,600–16,800 cal. yr. BP, cf. Sagredo et al., 2011) occurred during the readvance and retreat from TDP I moraine at Lagos del Toro and Sarmiento; TDP II–IV readvance: Antarctic cold reversal phase. Lake Tehuelche had drained by this time.

from LGM positions at or near Dos Lagunas moraine and formation of Consuelo Lake. As inferred from similar elevations of shorelines, hydrological connections between Torres del Paine and Última Esperanza basins (Figs. 1, 5), and available chronological data both the high phase of Puerto Consuelo and the Final phase Tehuelche lakes may have merged together into one lake body during retreat from LGM positions.

Based on the presence of sub-aerial outwash sediments at El Canal stratigraphic site, glaciofluvial plains grading to the late-glacial TDP II–IV moraines at Lagos Sarmiento and del Toro, and a set of about four fluvial terraces that incise the main outwash plain at El Canal meltwater channel, we infer that the Patagonian ice sheet in Torres del Paine terminated under generally subaerial conditions during the ACR period and that the large paleolake Tehuelche had drained by this time (Fig. 13). In this interpretation, the presence of glaciolacustrine sediments at El Canal stratigraphic section denotes the existence of local glacial lakes (Marden, 1993; García et al., in prep.) at ~70 m a.s.l. rather than regional water bodies. This implies that ice had retreated sufficiently in Última Esperanza to open a new lower outlet than the Frontera spillway (~125 m a.s.l.) by late-glacial times (see Sagredo et al., 2011). Therefore, the final phase of Lago Tehuelche at 125–155 m a.s.l. may be bracketed during and after the TDP I event, but before the TDP II advance (Fig. 13).

In order for the lake to drain from 250–280 m a.s.l. (Middle Phase) to 125–155 m a.s.l. (Late Phase), the Patagonian ice sheet must have retreated from a pass between the ice front and Cerro Castillo in Río Prat Valley (Fig. 5). It also must have receded from the undated Arauco moraines (e.g., Sagredo et al., 2011) and Sierra Dorotea in Última Esperanza in order to leave a gap between ice and topography that allowed a passageway to the Frontera spillway (Sagredo et al., 2011; Fig. 13). If ice in Torres del Paine during the TDP I advance had buttressed against Cerro Castillo (Fig. 5), a lake draining through Río Turbio-Tres Pasos spillway (i.e., 250–280 m a.s.l.) would have formed instead. Our evidence from the lower Estancia Site (at ~125 m a.s.l.) does not support this scenario.

Although we know that the Late Phase had begun by the time TDP I moraines at Lago del Toro and Lago Sarmiento were deposited and was over before the deposition of TDP II landforms, the exact timing is not known. If the interpretation of radiocarbon basal ages obtained by Sagredo et al. (2011) is correct then their date of ca. 17,600 cal. yr. B.P. represents a minimum age for clearing of the 125–155 m a.s.l. Frontera spillway, formation of the early highest phase of Lago Puerto Consuelo at 125-150 m a.s.l. (Sagredo et al., 2011; Stern et al., 2011; see below), and likely the culmination of TDP I moraine formation at Lagos Sarmiento and del Toro. Regardless of when ice pulled back from the Dos Lagunas position and Sierra Dorotea, this glacial retreat opened the Frontera spillway, allowed water level to drop to 125–155 m a.s.l. (Late Phase of Tehuelche and early high phase Consuelo), and eventually led to subaerial outwash sediments being deposited at the Estancia Site.

The complete drainage of Lago Tehuelche may have occurred at 16,800 cal. yr. BP (again, recalculated using INTCAL09), the proposed age for the beginning of the drop in lake levels from the Lago Puerto Consuelo high phase recorded in a core from Lago Pintito, (52°1′44″S; 72°28′1″W, ~170 m a.s.l.; Sagredo et al., 2011). This date represents a close-minimum age for ice pulling back from the Lago Pinto moraines at the SW sector of Última Esperanza basin, which likely led to the opening of a lower outlet that allowed lake drainage. The minimum age of 16,800 cal. yr. BP for drainage of the highest Consuelo lake level and Tehuelche lake also corresponds well with calibrated radiocarbon ages of mylodon remains (dung, hair and skin) found at 150 m a.s.l. (Cueva del Milodón, Long and Martin, 1974), which also imply that the highest Lake Consuelo had drained by 16,800 cal. yr. BP. Based on this chronological, hydrological and morphological evidence for glacial lakes at both Torres del Paine and Última Esperanza basins, we suggest that paleolake Tehuelche during the Late Phase (Fig. 13 TDP I) merged with glacial lake Puerto Consuelo through Río Prat Valley to form a lake at 125–155 m a.s.l. and that this phase began some time before

17,600 cal. yr. BP and ended by ca. 16,800 cal. yr. BP. Following the late-glacial readvance at ~14,100 cal. yr. BP (Fig. 13 TDP II–IV), the paleolake Tehuelche had drained.

7. Conclusions

New maps, stratigraphic analyses, and a summary of old and new chronological data allow insight into former glacial, deglacial, and proglacial environments and associated landscape changes in the Torres del Paine region. During the last glacial period, the Patagonian ice sheet in the area experienced significant fluctuations and deposited multiple moraine systems ≥45 km from the present ice front. Available data do not afford adequate evidence for defining the extent and timing of the local LGM, which remains unknown. However, radiocarbon dating of organic macrofossils indicates that local deglaciation in the Torres del Paine region was underway by 17,400 ± 0.2 (1σ) cal. yr. BP, coincident with other sites in Patagonia (McCulloch et al., 2005; Douglass et al., 2006; Hein et al., 2010; Hall et al., 2013) and the Chilean Lake District (41°S; Porter, 1981; Denton et al., 1999), but slightly older than Lago Argentino minimum age (16,000 cal. yr. BP; Strelin et al., 2011). A late-glacial readvance (~14,100–12,500 cal. yr. BP) throughout the ACR occurred in the region, including Lago Argentino and likely Última Esperanza basins (Sagredo et al., 2011; Strelin et al., 2011). Major ice retreat occurred by the Holocene, following associated warmer conditions in south Patagonia (McCulloch et al., 2000; McCulloch and Davies, 2001; Moreno et al., 2009a), which available data suggest was interrupted by a new glacial readvance before 9700 cal. yr. BP in Torres del Paine, likely during the early Holocene.

Our study provides a basis for interpretation of chronology and Patagonian ice-sheet dynamics in the Torres del Paine region through at least the last glacial cycle. Based on our mapping and published chronology, which provides more detail of lake and glacial history than previously appreciated, we propose a major revision of earlier interpretations. Most of the landform assemblage in the Torres del Paine region is now known to be much younger than previously inferred. For instance, since the early 1990s it has been assumed that TDP II–IV were LGM in age, but now we know these landforms are post-LGM in age (García et al., 2012). LGM glacial expansion could have been larger and reached farther east (RV moraines?) than previously mapped, with a potential areal extent of ice sheet in this region (~6700 km^2) twice the size of the late-glacial ice-sheet (~3500 km^2).

Advances and retreats in the area were accompanied by the formation of prominent recurrent paleolakes. In the vicinity of Torres del Paine National Park, there were at least two main lake phases: The Middle Phase is represented by a lake at 250–280 m a.s.l. that used the Río Turbio-Tres Pasos spillway during retreat from the RV II and AG moraines. This phase was most likely coincident with Última Esperanza ice at the Dos Lagunas moraine at about 38,000 cal. yr. BP. The Late Phase was represented by a lake at 125–155 m a.s.l. that, as defined by local topographic conditions, should have merged with paleolake Puerto Consuelo and drained through the Frontera spillway in Última Esperanza basin (cf., Sagredo et al., 2011). Available data indicate that the Late Phase of paleolake Tehuelche coincided with the deposition of TDP I moraine at Lagos del Toro and Sarmiento but was over by the time TDP II was deposited (i.e., ACR period).

Complete drainage of paleolake Tehuelche early in the termination suggests that the Patagonian ice sheet in Última Esperanza had retreated sufficiently to open a new, as yet unknown, outlet in western Patagonia that triggered drainage of paleolake Tehuelche/early highest phase of Puerto Consuelo in Torres del Paine and Última Esperanza.

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References

Anderson, R.F., Ali, S., Bradtmiller, L.I., Nielsen, S.H.H., Fleisher, M.Q., Anderson, B.E., Burckle, L.H., 2009. Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO$_2$. Science 323, 1443–1448.

Aniya, M., Sato, S., 1995. Holocene glacier variations at Tyndall glacier área, Southern Patagonia. Bull. Glacier Res. 3, 97–109.

Benn, D.I., 1996. Subglacial and subaqueous processes near a glacier grounding line: sedimentological evidence from a former ice dammed lake, Achnasheen, Scotland. Boreas 25, 23–36.

Benn, D.I., Evans, D.J.A., 2010. Glaciers and Glaciation. Hodder Arnold Publication, London.

Caldenius, C.C., 1932. Las glaciaciones Cuaternarias en la Patagonia y Tierra del Fuego. Geogr. Ann. A 14, 1–164.

Carrasco, J.F., Cassasa, G., Rivera, A., Aniya, M., Naruse, R., 2002. Meteorological and climatological aspects of the Southern Patagonia Icefield. In: Casassa, G., Sepúlveda, F.V., Sinclair, R.M. (Eds.), The Patagonian Icefields. Kluwer Academic/Plenum Publishers, New York, pp. 29–42.

Cassasa, G., Rivera, A., Aniya, M., Naruse, R., 2002. Current knowledge of the Southern Patagonia Icefield. In: Casassa, G., Sepúlveda, F.V., Sinclair, R.M. (Eds.), The Patagonian Icefields. Kluwer Academic/Plenum Publishers, New York, pp. 67–84.

Cerveny, R.V., 1998. Present climates of South America. In: Hobbs, J.E., Lindesay, J.A., Bridgman, H.A. (Eds.), Climates of the Southern Continents: Present, Past, and Future. Wiley & Sons, Baffins Lane, New York, pp. 107–136.

Clapperton, C.M., 1993. Quaternary Geology and Geomorphology of South America. Elsevier, Amsterdam.

Clapperton, C.M., 2000. Interhemispheric synchroneity of Marine Oxygen Isotope Stage 2 glacier fluctuations along the American cordilleras transect. J. Quat. Sci. 15, 435–468.

Coronato, A.M.J., Martínez, O., Rabassa, J., 2004. Glaciations in Argentine Patagonia, Southern South America. In: Ehlers, J., Gibbard, P. (Eds.), Quaternary Glaciations: Extent and chronology. Part III: South America, Asia, Africa, Australia and Antarctica. Quaternary Book Series. Elsevier, Amsterdam, pp. 49–67.

Denton, G.H., Lowell, T.V., Heusser, C.J., Slüchter, C., Andersen, B.G., Heuseer, L.E., Moreno, P.I., Marchant, D.R., 1999. Geomorphology, stratigraphy and radiocarbon chronology of Llanquihue drift in the area of the southern Lake District, Seno Reloncaví, and Isla de Chiloé, Chile. Geogr. Ann. A 81A, 167–229.

Denton, G.H., Anderson, R.F., Toggweiler, J.R., Edwards, R.L., Schaefer, J.M., Putnam, A.E., 2010. The last glacial termination. Science 328, 1652–1656.

DGA, 1987. Balance Hídrico de Chile. Dirección General de Aguas, Santiago, Chile.

Douglass, D.C., Singer, B.S., Kaplan, M.R., Mickelson, D.M., Caffee, M.W., 2006. Cosmogenic nuclide surface exposure dating of boulders on last-glacial and late-glacial moraines, Lago Buenos Aires, Argentina: interpretive strategies and paleoclimate implications. Quat. Geochronol. 1, 43–58.

EPICA community members, 2004. Eight glacial cycles from an Antarctic ice core. Nature 429, 623–628.

Evans, D.J.A., Hiemstra, J.H., Ó Cofaigh, C., 2012. Stratigraphic architecture and sedimentology of a Late Pleistocene subaqueous moraine complex, southwest Ireland. J. Quat. Sci. 27, 51–63.

Fogwill, C.J., Kubik, P.W., 2005. A glacial stage spanning the ACR in Torres del Paine (51), Chile, based on preliminary cosmogenic exposure ages. Geogr. Ann. A 87A, 403–408.

García, J.L., 2011. Late-Pleistocene glacial and climate fluctuations in the Torres del Paine region (51°S), Southern South America. Unpublished Ph.D. thesis, University of Maine.

García, J.L., 2012. Late Pleistocene ice fluctuations and glacial geomorphology of the Archipiélago de Chiloé, southern Chile. Geogr. Ann. A 94, 459–479.

García, J.L., Kaplan, M.R., Hall, B.H., Schaefer, J.M., Vega, R.V., Schwartz, R., Finkel, R., 2012. Glacial expansion in Southern Patagonia throughout the Antartic Cold Reversal. Geology 40, 859–862.

Garreaud, R.D., 2007. Precipitation and circulation covariability in the extratropics. J. Clim. 20, 4789–4797.

Glasser, N.F., Jansson, K., Harrison, S., Kleman, J., 2008. The glacial geomorphology and Pleistocene history of southern South America between 38 S and 56 S. Quat. Sci. Rev. 27, 365–390.

Gravernor, C.P., Von Brunn, V., Dreimanis, A., 1984. Nature and classification of waterlain glacigenic sediments, exemplified by Pleistocene, Late Palaeozoic and Late Precambrian deposits. Earth Sci. Rev. 20, 105–166.

Gustavson, T.C., 1975. Sedimentation and physical limnology in proglacial Malaspina Lake southeastern Alaska. In: Jopling, A.V., McDonald, B.C. (Eds.), Glaciofluvial and Glaciolacustrine sedimentation. Special publication, No. 23. Society of Economic Paleontologists and Mineralogists, Tulsa, USA, pp. 249–263.

Hall, B.L., Porter, C.T., Denton, G.H., Lowell, T.V., Bromley, G.R., 2013. Extensive recession of Cordillera Darwin glaciers in southernmost South America during Heinrich Stadial 1. Quat. Sci. Rev. 62, 49–55.

Hauthal, Wilckens, Paulcke, 1905. Die obere Kreide Südpatagoniens und ihre Fauna. Ber. d. Naturf. Ges. zu Freiburg i. Br, 15 91.

Hein, A.S., Hulton, N.R.J., Dunai, T.J., Schnabel, C., Kaplan, M.R., Naylor, M., Xu, S., 2009. Middle Pleistocene glaciation in Patagonia dated by cosmogenic-nuclide measurements on outwash gravels. Earth Planet. Sci. Lett. 286, 184–197.

Hein, A.S., Hulton, N.R.J., Dunai, T.J., Kaplan, M.R., Sugden, D., Xu, S., 2010. The chronology of the last glacial maximum and deglacial events in central Argentine Patagonia. Quat. Sci. Rev. 29, 1212–1227.

Heusser, C.J., 1987. Fire history of Fuego-Patagonia. Quatern. S. Am. Antarct. Peninsula 5, 93–110.

Ivins, E.R., James, T.S., 1999. Simple models for late Holocene and present-day Patagonian glacier fluctuations and predictions of a geodetically detectable isostatic response. Geophys. J. Int. 138, 601–624.

Johnsen, T.F., Brennand, T.A., 2006. The environment in and around ice-dammed lakes in the moderately high relief setting of the southern Canadian Cordillera. Boreas 35, 106–125.

Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Minster, B., Nouet, J.M., Barnola, J., Chappellaz, J., Fischer, H., Gallet, J.C., Johnsen, S., Leuenberger, M., Loulergue, L., Luethi, D., Oerter, H., Parrenin, F., Raisbeck, G., Raynaud, D., Schilt, A., Schwander, J., Selmo, E., Souchez, R., Spahni, R., Stauffer, B., Steffensen, J.P., Stenni, B.T., Stocker, F., Tison, J.L., Werner, M., Wolff, E.W., 2007. Orbital and millennial Antarctic variability over the last 800000 years. Science 317, 793–796.

Kaplan, M.R., Hein, A.S., Hubbard, A., Lax, S.M., 2009. Can glacial erosion limit the extent of glaciation? Geomorphology 15 (103), 172–179.

Kaplan, M.R., Strelin, J.A., Schaefer, J.M., Denton, G.H., Finkel, R.C., Schwartz, R., Putnam, A.E., Vandergoes, M.J., Goehring, B.M., Travis, S.G., 2011. In-situ cosmogenic ^{10}Be production rate at Lago Argentino, Patagonia: implications for late-glacial climate chronology. Earth Planet. Sci. Lett. 309 (1–2), 21–32.

Lisiecki, L., Raymo, M.E., 2005. A Pliocene–Pleistocene stack of 57 globally distributed benthic D^{18}O records. Paleoceanography 20, PA1003.

Long, A., Martin, P.S., 1974. Death of American ground sloths. Science 186, 638–640.

Marden, C.J., 1993. Late Quaternary glacial history of the South Patagonia Icefield at Torres del Paine, Chile. Unpublished Ph.D. Thesis, University of Aberdeen.

Marden, C.J., 1997. Late-glacial fluctuations of South Patagonian Icefield, Torres del Paine National Park, southern Chile. Quat. Int. 38 (39), 61–68.

Marden, C.J., Clapperton, C.M., 1995. Fluctuations of the South Patagonian Icefield during the last glaciation and the Holocene. J. Quat. Sci. 10, 197–210.

Markgraf, V., 1998. Past climates of South America. In: Hobbs, J.E., Lindesay, J.A., Bridgman, H.A. (Eds.), Climates of the Southern Continents: Present, Past, and Future. Wiley Eds., Baffins Lane, New York, pp. 249–264.

McCulloch, R.D., Davies, S.J., 2001. Late-glacial and Holocene palaeoenvironmental change in the central Strait of Magellan, southern Patagonia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 173, 143–173.

McCulloch, R.D., Bentley, M.J., Purves, R.S., Sugden, D.E., Clapperton, C.M., 2000. Climatic inferences from glacial and palaeoecological evidence at the last glacial termination, southern South America. J. Quat. Sci. 15, 409–417.

McCulloch, R.D., Bentley, M.J., Tipping, R.M., Clapperton, C.M., 2005. Evidence for late-glacial ice dammed lakes in the central Strait of Magellan and Bahía Inútil, southernmost South America. Geogr. Ann. A 87A, 335–362.

Meglioli A., 1992. Glacial geology and chronology of Southernmost Patagonia and Tierra del Fuego, Argentina and Chile. Unpublished Ph.D. Thesis, Lehigh University.

Mercer, J.H., 1984. Simultaneous climatic change in both hemispheres and similar bipolar interglacial warming: evidence and implications. In: Ewing, M. (Ed.), Climate Processes and Climate Sensitivity. Geophysical Monograph, 29. American Geophysical Union, pp. 307–313.

Miller, A., 1976. The climate of Chile. In: Schwerdtfeger, W. (Ed.), Climates of Central and South America. World Survey of Climatology, vol. 12. Elsevier, Amsterdam, pp. 113–145.

Monnin, E., Indermühle, A., Dällenbach, A., Flückiger, J., Stauffer, B., Stocker, T.F., Raynaud, D., Barnola, J.M., 2001. Atmospheric CO_2 concentrations over the last glacial termination. Science 291, 112–114.

Moreno, P.I., Kaplan, M.R., François, J.P., Villa-Martínez, R., Moy, C.M., Stern, C.R., Kubik, P.W., 2009a. Renewed glacial activity during the Antarctic cold reversal and persistence of cold conditions until 11.5 ka in southwestern Patagonia. Geology 37, 375–378.

Moreno, P.I., François, J.P., Villa-Martínez, R.P., Moy, C.M., 2009b. Millennial-scale variability in Southern Hemisphere westerly wind activity over the last 5000 years in SW Patagonia. Quat. Sci. Rev. 28, 25–38.

Muscheler, R., Kromer, B., Björck, S., Svensson, A., Friedrich, M., Kaiser, K.F., Southon, J., 2008. Tree rings and ice cores reveal ^{14}C calibration uncertainties during the Younger Dryas. Nat. Geosci. 1, 263–267.

Nordenskjöld, O., 1898. Über die Posttertiären Ablagerungen der Magellansländer etc. Svenska expedition till Magellansländerna, Bd 1, No 2. (Stockholm).

Porter, S., 1981. Pleistocene glaciations in the Southern Lake District of Chile. Quat. Res. 8, 2–31.

Putnam, A.E., Schaefer, J., Barrell, D.J.A., Vandergoes, M., Denton, G.H., Kaplan, M., Finkel, R.C., Schwartz, R., Goehring, B.M., Kelley, S., 2010. In situ cosmogenic ^{10}Be production-rate calibration from the Southern Alps, New Zealand. Quat. Geochronol. 5, 392–409.

Rabassa, J., Coronato, A.M., Salemme, M., 2005. Chronology of the Late Cenozoic Patagonian glaciations and their correlation with biostratigraphic units of the Pampean region (Argentina). J. S. Am. Earth Sci. 20, 81–103.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk, Ramsey C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J., Weyhenmeyer, C.E., 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. Radiocarbon 51 (4), 1111–1150.

Rivera, A., Cassasa, G., 2004. Ice elevation, areal, and frontal changes of glaciers from National Park Torres del Paine, Southern Patagonia Icefield. Arct. Antarct. Alp. Res. 36, 379–389.

Rivera, A., Acuña, C., Casassa, G., Bown, F., 2002. Use of remotely sensed and field data to estimate the contribution of Chilean glaciers to eustatic sea-level rise. Ann. Glaciol. 34, 367–372.

Sagredo, E.A., Moreno, P.I., Villa-Martinez, R., Kaplan, M.R., Kubik, P.W., Stern, C.R., 2011. Fluctuations of the Última Esperanza ice lobe (52°S), Chilean Patagonia, during the last glacial maximum and termination 1. Geomorphology 125, 92–108.

Solari, M.A., Calderon, M., Airo, A., Le Roux, J.P., Hervé, F., 2012. Evolution of the Great Tehuelche Paleolake in the Torres del Paine National Park of the Chilean Patagonia during the last glacial maximum and Holocene. Andean Geol. 39, 1–21.

Steffen, H., 1919. Westpatagonien. Die Patagonischen Kordilleren und Ihre Randgebiete. Dietrich Reimer, Ernst Vohsen (Berlin).

Stern, C.R., 1990. The tephrochronology of southern-most Patagonia. Natl. Geogr. Res. 6, 110–126.

Stern, C.R., 2008. Holocene tephrochronology record of large explosive eruptions in the southernmost Patagonian Andes. Bull. Volcanol. 70, 435–454.

Stern, C.R., Moreno, P.I., Villa-Martínez, R.P., Sagredo, E.A., Prieto, A., Labarca, R., 2011. Evolution of ice-dammed proglacial lakes in Última Esperanza, Chile: implications from the late-glacial R1 eruption of Reclús volcano, Andean Austral Volcanic Zone. Andean Geol. 38, 82–97.

Strelin, J.A., Malagnino, E.C., 1996. Glaciaciones Pleistocenas del Lago Argentino y Alto Valle del río Santa Cruz. XIII Congreso Geológico Argentino y III Congreso de Exploración de Hidrocarburos. Actas, IV, pp. 311–325.

Strelin, J.A., Denton, G.H., Vandergoes, M.J., Ninnemann, U.S., Putnam, A.E., 2011. Radiocarbon chronology of the late-glacial Puerto Bandera moraines, Southern Patagonian Icefield, Argentina. Quat. Sci. Rev. 30 (19–20), 2551–2569.

Sugden, D.E., Bentley, M.J., Fogwill, C.J., Hulton, N.R.J., McCulloch, R.D., Purves, R.S., 2005. Late-glacial glacier events in southernmost South America: a blend of ‘northern’ and ‘southern’ hemispheric climatic signals. Geogr. Ann. A 87A, 273–288.

Turner, K., Fogwill, C.J., McCulloch, R.D., Purves, R.S., Kubik, P.W., Sugden, D.E., 2005. Deglaciation of the eastern flank of the North Patagonian Icefield and associated continental scale lake diversions. Geogr. Ann. A 87A, 363–374.

Warren, C.R., Sugden, D.E., 1993. The Patagonian icefields: a glaciological review. Arct. Alp. Res. 25, 316–331.