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Evolution of ice-dammed proglacial lakes in Última Esperanza, Chile: implications from the late-glacial R1 eruption of Reclús volcano, Andean Austral Volcanic Zone

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ABSTRACT. Newly described outcrops, excavations and sediment cores from the region of Última Esperanza, Magallanes, contain tephra derived from the large late-glacial explosive R1 eruption of the Reclús volcano in the Andean Austral Volcanic Zone. New radiocarbon dates associated to these deposits refine previous estimates of the age, to 14.9 cal kyrs BP (12,670±240 ^{14}C yrs BP), and volume, to >5 km^3, of this tephra. The geographic and stratigraphic distribution of R1 also place constraints on the evolution of the ice-dammed proglacial lake that existed east of the cordillera in this area between the termination of the Last Glacial Maximum (LGM) and the Holocene. This proglacial lake generated wave-cut terraces, and also caves, such as the Cueva de Milodón, along the highest prominent terrace. The current elevation of these terraces depends on the total amount of post-glacial isostatic rebound, which is unknown. Due to differential rebound, the highest prominent lake terraces decrease in height from west-to-east, from ~170 m a.s.l. on Península Antonio Varas west of Seno Última Esperanza, to ~150 m a.s.l. around Lago Sofía, and down to ~125 m a.s.l. along their easternmost margin. The presence of thick deposits of R1 tephra in some of the caves around Lago Sofía implies that the proglacial lake had already dropped below its highest level prior to the time of this eruption, and, in fact, even earlier, prior to 16.1 cal kyrs BP (13,560±180 ^{14}C yrs BP), when land mammals first occupied these caves. The depositional environment of R1 in a core from Dumestre bog suggests that the lake level was in fact <80 m a.s.l. at the time of this eruption. The original lake may have drained to this level across the low elevation pass between Fiordo Obstrucción and Seno Skyring, and subsequently into Seno Otway and the Pacific Ocean, when Canal Jerónimo opened up prior to the R1 eruption. Another suite of cores, from the Eberhard site, indicate that the lake persisted at >70 m a.s.l. until 12.8 cal kyrs BP (10,695±40 ^{14}C yrs BP). However, a 14.2 cal kyrs BP (12,125±85 ^{14}C yrs BP) *Mylodon* pelvis from a nearby site, located at only ~7 m a.s.l., suggests that the lake could have emptied, for at least a brief period, to this low level at this time. This latter datum, combined with the lack of any prominent terraces between the highest ones (170-125 m a.s.l.) and much lower ones (at only 30 m a.s.l. on Península Antonio Varas and 20 m a.s.l. along the coast north and south of Puerto Natales), suggests abrupt changes in the lake level after the R1 eruption. The likely mechanism for producing these changes in Última Esperanza was the catastrophic failure and subsequent re-sealing of an ice dam in Paso Kirke, the only below sea-level pathway west to the Pacific north of Fjordo Obstrucción. The final stage of lake drainage, from the lower terrace level (20-30 m a.s.l.) occurred at 10.3 cal kyrs BP.

Keywords: Last Glacial Maximum, Tephra, Ice-dammed proglacial lakes, Lake terraces, Post-glacial isostatic rebound, Mylodon, Chile.

RESUMEN. Evolución de lagos proglaciales embalsados por hielo en Última Esperanza, Chile: Implicancias de la explosión volcánica tardiglacial R1 del volcán Reclús, Zona Volcánica Austral Andina. En este trabajo reportamos hallazgos de tefras derivadas de la gran explosión volcánica tardiglacial R1 del volcán Reclús situado en la Zona Volcánica Austral Andina, a partir de nuevos afloramientos, excavaciones y testigos sedimentarios de lagos y pantanos, obtenidos en la región de Última Esperanza, Magallanes. Nuevas fechas asociadas a estos depósitos permiten refinar su edad a 14,9 ka cal AP (12.670±240 ^{14}C años AP) y su volumen a >5 km^3. Además, la ubicación geográfica y estratigráfica de R1 permite acotar la evolución del lago proglacial represado por hielo que se desarrolló al este de la cordillera al intervalo temporal entre el término del Último Máximo Glacial y el Holoceno. Este lago proglacial generó terrazas y cuevas, producto de la acción del oleaje, como la Cueva de Milodón, a lo largo de la terraza más alta y conspicua. La altitud actual de estas terrazas depende de la cantidad total de rebote isostático posglacial, el cual se desconoce. Debido a las variaciones en el rebote isostático posglacial, las terrazas lacustres más altas y prominentes disminuyen en altitud de oeste a este, desde ~170 m s.n.m. en la Península Antonio Varas, al oeste del Seno Última Esperanza, a 150 m s.n.m. alrededor del lago Sofía y descienden hasta ~125 m s.n.m. a lo largo de su margen más oriental. La presencia de grandes depósitos de la tefra R1 en algunas de las cuevas alrededor del lago Sofía indican que el lago proglacial ya había descendido, con respecto a su nivel más alto, antes de la erupción de R1 y de hecho incluso antes de 16,1 ka cal AP (13.560±180 ^{14}C años AP) que es cuando los mamíferos terrestres ocuparon por primera vez estas cuevas. El ambiente deposicional de R1, en el registro sedimentario del pantano Dumestre, sugiere incluso que el nivel del lago era inferior a 80 m s.n.m. durante el momento de esta erupción. Probablemente el lago proglacial original habría drenado a este nivel a través de sectores de baja altitud ubicados entre fiordo Obstrucción y seno Skyring, siguiendo hacia el seno Otway para desembocar en el Océano Pacífico, una vez que el canal Jerónimo ya estaba libre de hielo antes de la erupción de R1. Otro grupo de testigos, del sitio Eberhard, indican que el lago persistió a >70 m s.n.m. hasta 12,8 ka cal AP (10.695±^{14}C años AP). Sin embargo, a 14,2 ka cal AP (12.125±^{14}C años AP), la pelvis de *Mylodon* de un sitio cercano, ubicado a 7 m s.n.m., sugiere que el lago podría haberse vaciado temporalmente durante este período. Este último dato, combinado con la ausencia de terrazas prominentes entre las más altas (170-125 m s.n.m.) y las más bajas (a solo 30 m s.n.m. en la Península Antonio Varas y 20 m s.n.m. a lo largo de la costa norte y sur de Puerto Natales), sugiere cambios abruptos en el nivel del lago proglacial después de la erupción de R1. Probablemente el mecanismo que ocasionó estos cambios en Última Esperanza fue la ruptura catastrófica y el subsecuente resellamiento del dique de hielo que bloqueaba el Paso Kirke, el único paso al Océano Pacífico bajo el nivel del mar al norte del fiordo Obstrucción. El drenaje final del lago, desde la terraza inferior (20-30 m s.n.m.), ocurrió a los 10,3 ka cal AP.

Palabras clave: Último Máximo Glacial, Tefra, Lagos proglaciales, Terrazas glaciolacustres, Rebote isostático posglaciales, Mylodon, Chile.

1. Introduction

Reclús volcano, one of six volcanoes that comprise the Andean Austral Volcanic Zone (AVZ; Fig. 1; Stern *et al*., 1976, l984, 2007; Harambour, 1988; Stern and Kilian, 1996; Stern, 2004), produced a large (>1 km^3) explosive eruption R1 at ~14.9 cal kyrs BP (12,685±260 ^{14}C yrs BP; Stern, 1990, 1992, 2008), during the transition between the Last Glacial Maximum (LGM) and the Holocene. Distal tephra layers resulting from this eruption are exposed at many sites along the shores of the Estrecho de Magallanes and Bahía Inútil (Fig. 1). They provide an important chronologic marker for the interpretation of the paleo-climatic changes that affected the disappearance of piedmont glaciers that filled the Estrecho de Magallanes during and after the LGM, and they also constrain the evolution of the ice-dammed proglacial lakes that existed in the strait before it was open to

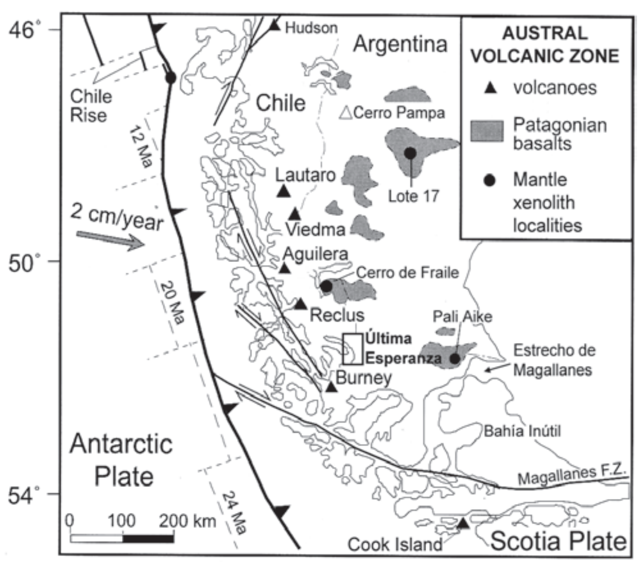

FIG. 1. Location map of the volcanoes of the Andean Austral Volcanic Zone (AVZ), including the Reclús volcano, modified from Stern (2008). Detailed locations of the sites discussed in the area of Última Esperanza, indicated in the box, are shown in figure 2.

the sea (Uribe, 1982; Heusser *et al*., 1989-1990; McCulloch *et al.*, 2005a).

More proximal and significantly thicker tephra deposits from the same R1 eruption are observed in outcrops, excavations and bog and lake sediment cores in Última Esperanza, Chile (Fig. 2; Cárdenas, 2006; Sagredo, 2007; Stern, 2008). These deposits occur both along the shores and inside the area occupied by a large ice-dammed proglacial lake, along with lobes of the generally receding but episodically advancing glaciers, that existed east of the cordillera where Golfo Almirante Montt, Seno Última Esperanza, Fiordo Obstrucción and Lago Sofía are now located. Sagredo *et al*., 2010 refer to this proglacial lake as Lago Consuelo. This paper summarizes the environments within which the tephra derived from the R1 eruption of the Reclús volcano were deposited in the region of Última Esperanza, their ages, and the implications for the evolution of the proglacial lake in this region during the late-glacial transition to the Holocene.

FIG. 2. Location map of the sites of terraces, and sediment cores and outcrops containing R1 tephra (Tables 1 and 2), in Última Esperanza, Magallanes, Chile.

2. Proglacial lake terraces

Evidence for the existence of the ice-dammed proglacial Lago Consuelo in Última Esperanza includes both erosional lake terraces and paleo-shoreline caves (Figs. 3 and 4), and deposition of clay-rich, organic-poor glacial-lake sediment. Elevations of terraces were determined by two independent techniques. One involved the averaging of elevation measurements made with three hand-held GPS instruments, including an E-trek Vista HCX GARMIN, an E-trek Legend and an E-trek Vista Personal Navigator. The instruments were calibrated at sea-level each morning and afternoon. Differences between the instruments were always less than 1% (1.5 m) at 150 m elevation, and repeated measurements on different days at specific sites suggest that the error in the average of these instrumental elevation measurements were actually less than this. A similar or greater uncertainty was introduced due to ambiguities in determining the exact spot to measure where the sub-horizontal terraces contact the sub-vertical bedrock as indicated for different terraces by the arrows in figure 3. This is because the contact between these two units has in general been modified by continued deposition of colluvium derived from the sub-vertical basement slopes.

A second independent estimation of elevation was done using Global Mapper software to analyze 90x90 m resolution Shuttle Radar Topography Mission (SRTM) digital elevation information available from the U.S. Geological Survey through the National Map Seamless Server (http://seamless.usgs.gov/). This provided elevation profiles (Fig. 4) which were essentially the same as those determined by the hand-held GPS instruments, with the greatest uncertainty in determining the terrace level also introduced by determining where the actual nick-mark between the sub-horizontal terrace surfaces and the sub-vertical bedrock walls occur. In any case, the errors in measuring the elevation of the terraces are far below the differences in the heights of the terraces measured, which vary from 2 to 170 m a.s.l.

FIG. 3. Photographs of the highest prominent proglacial lake terraces in the area north of Puerto Natales. **A**. and **B**. The terraces on Peninusla Antonio Varas, which occur at 170 m a.s.l.; **C**. and **D**. The 150 m a.s.l. terraces along the north side of Cerro Benítez where wave-cut caves such as Cueva del Milodón and Aleros Dos Herraduras occur; **E**. and **F**. The 150 m a.s.l. terraces around Lago Sofía. Note the lack of any other terrace in photo F between the highest one and the level of the lake at 40 m a.s.l.; **G**. and **H**. The highest terrace, at 140 m a.s.l., along the base of Sierra Dorotea. Note the lack of any indication of a higher 150 m a.s.l. terrace at this site; **I**. and **J**. Lower 20 and 2 m a.s.l. terraces to the north and south of Puerto Natales.


A
170 m
Península Antonio Varas
Seno Última Esperanza
B
170 m
Península Antonio Varas
C
150 meters
Cerro Benítez
Cueva del Milodón
D
Aleros Dos Herraduras
150 meters
E
150 meters
Lago Sofía
F
150 meters
Lago Sofía
G
Sierra Dorotea
140 meters
H
140 meters
Sierra Dorotea
I
20 meters
2 meters
J
Gruta San Sebastián
20 meters
2 meters

The highest and most prominent lake terrace developed in the area north of Puerto Natales is ~150 m a.s.l. around Lago Sofía (Figs. 3E, F), where this terrace varies from 100 to 200 m wide. A number of wave-cut caves occur within the sub-vertical basement rocks at the elevation of their contact with the sub-horizontal surface of this terrace, including Cueva del Milodón (Fig. 3C) and Cueva Lago Sofía 1 (Prieto, 1991), Aleros Dos Herraduras (Fig. 3D), Cueva de la Ventana and Alero Quemado (Sierpe *et al*., 2009). This highest prominent terrace forms a semi-continuous surface well to the southeast to near the international border with Argentina (Fig. 4). This semi-continuous prominent high terrace decreases in elevation to ~140 m a.s.l. along the base of Sierra Dorotea (Figs. 3G, H) and to ~125 m a.s.l. along its easternmost margin east of Puerto Natales (Fig. 4). Here this highest prominent terrace, which cuts into the Arauco moraine complex that forms Cordón Arauco, is in someplaces over 2 km wide. This represents a decrease of 25 m over a distance of 80 km in a northwest-to-southeast direction, or a distance of ~50 km from west-to-east. Another 15 km to the west, on Península Antonio Varas across Seno Última Esperanza, the highest prominent terrace forms, in some locations, an approximately 300 m wide surface at 170 m a.s.l. (Figs. 3A, B; Fig. 4). Based solely on the observation that it is also the highest and most prominent terrace, we concluded that this terrace on Península Antonio Varas has the same origin and age as the highest wave-cut terraces east of Seno Última Esperanza. This implies a 45 m difference for this same geomorphic feature over a 65 km transect along a west-to-east direction.

Younger and less well developed terraces occur at various lower elevation, with two well developed terraces at 20 m a.s.l. (Figs. 3I, J) and 2-5 m a.s.l. along the coast in the area north and south of Puerto Natales. On Península Antonio Varas, the higher of these two relatively low terraces occurs at 30 m a.s.l. (Sagredo *et al*., 2010). However, a significant observation is that no prominent well developed terraces occur between the highest prominent terrace, at between 170 to 125 m a.s.l., and these lower two terraces (Fig. 3F).

3. Tephra sample sites

Stern (2008) described late-glacial Reclús tephra R1 found in natural outcrops, archaeological excavations and sediment cores in bogs and lakes from 17 different locations in Magallanes and Tierra del Fuego, and tabulates 28 radiocarbon ages from above (12 ages), within (2 ages) and below (14 ages) this tephra from these sites. Here we describe this same R1 tephra from some new locations (Table 1; all locations in UTM Projection HUSO 18°S, DATUM WGS84) that provide further constraints on the thickness (Table 2), size, and age (Table 3) of this eruption. We also present more detailed information for those sites in Última Esperanza that constrain the evolution of the ice-dammed proglacial lake that existed in this area (Cárdenas, 2006, Sagredo, 2007; Moreno *et al*., 2008) during the late-glacial transition from the termination of the LGM to the Holocene (Table 4).

3.1. Outcrops

3.1.1. Última Esperanza

Two thick outcrops of white tephra occur along the road from Puerto Natales northwards to Cerro Castillo (Fig. 2). One, near Estancia Dos Lagu-nas (4,290,421N; 673,251E; 163 m a.s.l.), which occurs in a drainage canal along the roadside, is 40 cm thick and overlies organic material dated as 16.5 cal kyrs BP (13,855±100 ^{14}C yrs BP). The other (Fig. 5A) occurs near Estancia Shotel Aike (4,309,520N; 678,578E; 110 m a.s.l.) in a road cut north of Lago Figueroa. Although not dated, this is clearly the Reclús R1 tephra based on its thickness, which varies along strike from >30 cm to as thick as >50 cm, and chemistry (Table 2). However, unlike distal R1 tephra deposits, both these thick proximal deposits contain a small proportion of brown biotite mica. Nevertheless, their relatively low Rb concentrations (26 and 34 ppm, respectively; Table 2) are within the range of all Reclús-derived tephra (between 15 to 40 ppm; Stern, 2008), and well below the Rb concentrations for Aguilera A1 tephra (Rb >60 ppm), which contains significantly more biotite as well as amphibole. Re-examination of other thick proximal Reclús R1 tephra deposits, at Aleros dos Herraduras for example (see below), reveals that they also contain some minor amounts of biotite. However, distal deposits of R1 tephra from Tierra del Fuego do not (Stern, 2008).

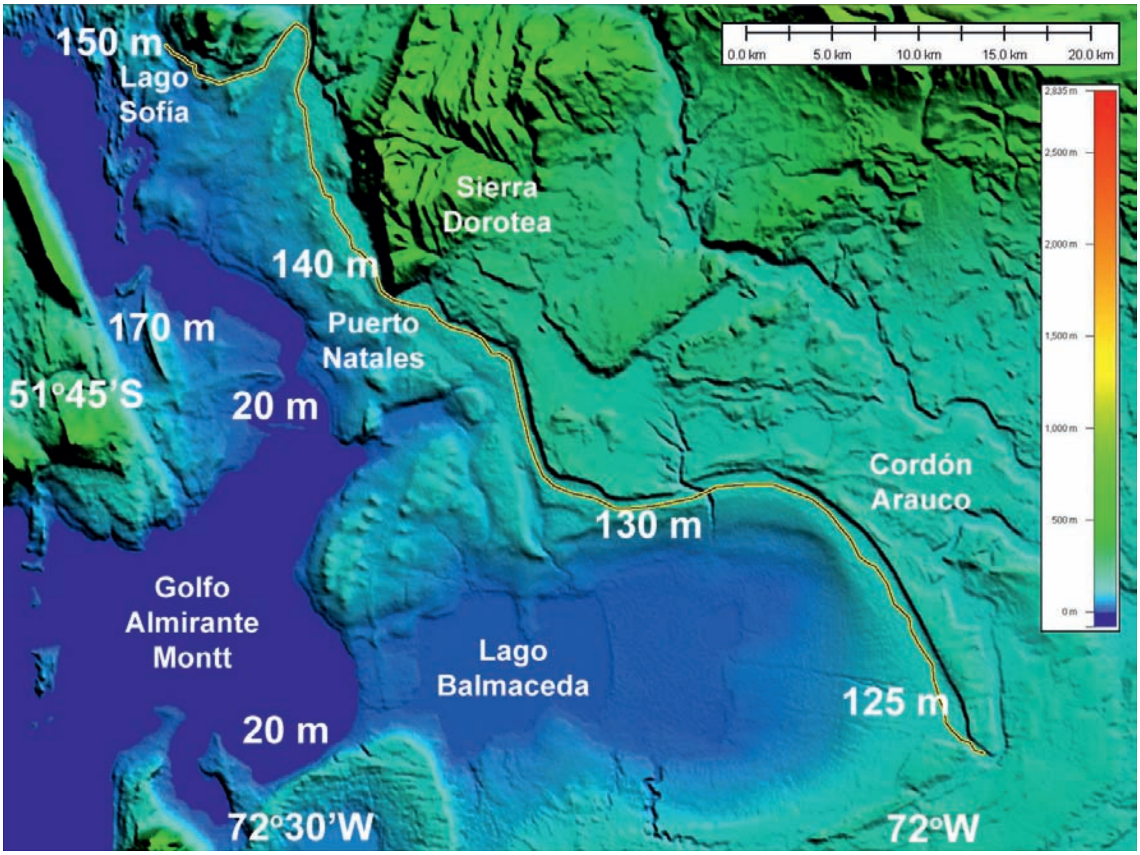

FIG. 4. Digital elevation image of Última Esperanza produced by Global Mapper software from Shuttle Radar Topography Mission (SRTM) 90x90 m resolution digital elevation information available from the U.S. Geological Survey through the National Map Seamless Server (http://seamless.usgs.gov/). The heights of the highest prominent lake terraces (Fig. 3), as determined from both this information and independently by on-the-ground GPS measurements, are indicated in meters a.s.l. Variations in their elevations, which decrease from west-to-east, are due to differences in the extent of post-glacial isostatic rebound.

TABLE 1. LOCATION OF THE SITES WITH R1 TEPHRA DISCUSSED IN THE TEXT.

Site	Type	N	E	m a.s.l.
Juni Aike	excavation	4,237,589	385,588	132
Alero Quemado	excavation	4,286,458	668,034	147
Aleros Dos Herraduras	excavation	4,285,242	664,745	150
Cueva de la Ventana	excavation	4,285,960	664,193	150
Estancia Shotel Aike	outcrop	4,309,520	678,578	110
Dos Lagunas	outcrop	4,290,042	673,251	155
Lago Dorotea	core PS0402	4,285,821	673,804	260
Vega Benítez	core PS0302/0403	4,285,485	667,699	215
Lago Arauco	core PS0602/0505	4,238,306	703,633	180
Pantano Dumestre	core PS0607	4,257,560	667,387	77
Sitio Eberhard	core PS0301/0401	4,283,338	661,707	68
Pozo Consuelo	well	4,280,865	662,596	10

TABLE 2. TRACE-ELEMENT COMPOSITIONS OF R1 TEPHRA FROM DIFFERENT SITES IN MAGALLANES, CHILE.

Location	Sample #	Thickness cm	Rb	Sr	Ba	Y	Nb	La
Juni Aike	B10 136-140 cm	4 cm	28	540	334	11	9	16.8
	2C3	4 cm	26	530	336	10	10	17.4
Estancia Shotel Aike	ESA-1	45 cm	34	495	352	10	9	16.8
Dos Lagunas	Capa #3	40 cm	26	572	361	7	12	16.4
Lago Dorotea	PS0402ET3 1770-1780 cm	37 cm	29	485	366	10	9	19.4
	PS0402ET3 1780-1790 cm	37 cm	30	520	353	10	9	17.3
	PS0402ET3 1790-1795 cm	37 cm	29	508	362	11	10	17.9
	PS0402ET4 1796-1804 cm	37 cm	25	589	360	9	11	16.1
Vega Benítez	PS0302AT7 691-710 cm	24 cm	21	639	304	11	11	17.8
	PS0302AT9 907-912 cm	>40 cm	24	609	467	14	10	21.5
Lago Arauco	PS0602ET1 629-630 cm	10 cm	24	650	292	9	11	16.6
Pantano Dumestre	PS0607BT3 366-369 cm	7 cm	21	597	317	10	13	16.6
Sitio Eberhard	PS0301AT6 550-567 cm	17 cm	21	679	429	11	11	18.0
Alero Ventana	AV	37 cm	24	555	332	10	10	16.8
Lago Grey	Pumice sample R6	-	32	497	398	10	9	20.9

TABLE 3. NEW AGES OF THE R1 TEPHRA FROM MAGALLANES, CHILE.

Site	Age of R1	Ref/comment
Juni Aike	<12,800±60 B.P.	Prieto, 1997
Vega Benítez	<12,580±25	Sagredo, 2007
Lago Arauco	<12,500±60	Sagredo, 2007
Pantano Dumestre	>12,400±60	Sagredo, 2007
	<12,875±45	Sagredo, 2007

3.2. Excavations

3.2.1. Aleros dos Herraduras, Alero Quemado and Cueva de la Ventana (150 m a.s.l.)

Aleros dos Herraduras (Fig. 3D; 4,285,242N; 664,745E) and Cueva de la Ventana (4,285,960N; 664,193E.) are located a few hundred meters north of Cueva del Milodón (Fig. 3C), while Alero Quemado (Sierpe *et al.*, 2009) occurs further to the northeast along the southern shore of Lago Sofía (4,286,458N; 668,034E). These, as well as other caves in this area such as Cueva del Medio (Nami, 1987) and Cuevas 1 and 4 of Lago Sofía (Prieto, 1991; Borrero *et al.*, 1997), are wave-cut rock shelters interpreted to have formed along the shores of the proglacial lake that generated the ~150 m a.s.l. terrace in the area around Lago Sofía (Figs. 3E, F). Excavation of Aleros dos Herraduras exposed >40 cm of Reclús R1 tephra (Table 2; Stern, 2008) containing a *Mylodon* bone dated as 15.2 cal kyrs BP (12,825±110 ^{14}C yrs BP; Favior-Dubois and Borrero, 1997). As noted above, re-examination of this proximal R1 tephra reveals a small amount of biotite mica in this tephra. Cueva de la Ventana and Alero Quemado also each preserve >40 cm layers of petrochemically similar R1 tephra (Table 2). The preservation of

TABLE 4. Stages in the evolution of the proglacial lake in Última Esperanza.

Stage #	Cal kyrs BP	Lake level m	Evidence	Cause
1	17.5	150	Vega Benítez core basal age	Termination T1 of LGM
2	16.4	150	Eberhard site core basal age	Continued ice recession
3	16.1	<120	Land mammal fossil ages in wave-cut caves	Initial complete/partial lake drainage
4	15.2	<80	Dumestre core subaerial peat age	Continued/second lake drainage
	14.9	-	R1 tephra ages	Eruption of Reclús volcano
5	14.2	<7	Age of *Mylodon* pelvis fossil in Eberhard well	Collapse of Paso Kirke ice dam
6a	>12.8	>70	Age of Eberhard site proglacial lake sediments	Resealing of Paso Kirke ice dam
6b	12.8	<70	Eberhard site subaerial peat age	Collapse of Paso Kirke ice dam
	12.6	-	Earliest evidence for human occupation in Última Esperanza	-
7	10.3	<20	Península Antonio Varas subaerial peat age	Final collapse of Paso Kirke ice dam

this R1 tephra in all these rock shelters implies that the level of water in the proglacial lake that cut these shelters must have dropped below ~150 m a.s.l. prior to the R1 eruption. This conclusion is supported by the presence of the Late Pleistocene faunal assemblages in these sites (Favier Dubois and Borrero, 1997), since when this proglacial lake was at 150 m a.s.l., these caves had been isolated from the mainland by water and were inaccessible to these species by land (Sagredo, 2007). In fact, the proglacial lake level must have dropped to <120 m a.s.l. to connect these lake shore caves to the mainland. The earliest evidence for land mammals in these sites is 16.1 cal kyrs BP (13,560±180 ^{14}C yrs BP; Long and Martin, 1974), and several of these caves were later occupied by early human inhabitants in this area at around 12.6 cal kyrs BP (10,610±300 ^{14}C yrs BP; average of 13 best ages tabulated in Sagredo, 2007).

3.2.2. Juni Aike (4,237,589N; 385,588E; 132 m a.s.l.)

Excavation at Juni Aike, an open-air site along the Río Gallegos Chico in the area of the Pali Aike volcanic field (Fig. 1), north of the eastern end of the Estrecho de Magallanes, exposed a 4 cm thick layer of white tephra above an organic rich layer dated as 15.1 cal kyrs BP (12,800±60 ^{14}C yrs BP; Fig. 5B; Table 3; Prieto, 1997). Both its age and chemistry (Table 2) are consistent with this being R1 tephra. This sample is significant because it provides better control on the eastern extent of the 5 cm isopach for the R1 eruption.

3.2.3 Pozo Consuelo (4,280,865N; 662,596E; 10 m a.s.l.)

A *Mylodon* pelvis bone (*Mylodon darwini* Owen, 1839; Fig. 6), dated at 14.2 cal kyrs BP (12,125±85 ^{14}C yrs BP), was uncovered at a depth of 3 meters during the digging of a fresh water well (Pozo Consuelo) at a site 10 m a.s.l. on Estancia Eberhard. This bone is the only evidence of late Pleistocene paleo-fauna in Última Esperanza found below 150 m a.s.l., and could possibly have washed down from a higher lake shore level or have been deposited at this site as a result of the sinking of a dead *Mylodon* floating in the proglacial lake. Alternatively, this large bone could have been found in essentially the location where the animal

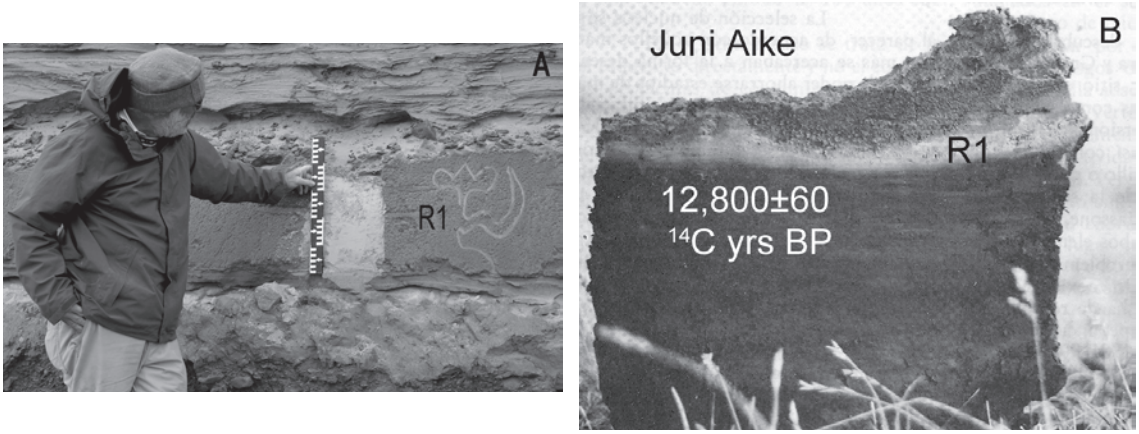

FIG. 5. **A**. Greater than 40 cm thick R1 tephra, near Lago Figueroa (Fig. 2) along the road north of Puerto Natales, which overlies conglomerate sediment consisting of bed-rock clasts, and is overlain by a thick set of dunes formed by the wind-blown re-distribution of this same R1 tephra; **B**. A 4 cm thick R1 tephra layer at Juni Aike in the Pali-Aike volcanic field (Fig. 1).

FIG. 6. *Mylodon* pelvis fossil (*Mylodon darwini* Owen, 1839) discovered at 3 meters depth below the 10 m a.s.l. surface during the digging of the Pozo Consuelo well on Estancia Eberhard.

died, at 7 m a.s.l., indicating a significant decrease in the proglacial lake level at this time.

3.3. Sediment Cores

Sediment cores from lakes and bogs in Última Esperanza that contain tephra produced by explosive eruptions of the Reclús volcano are described in detail in Cárdenas (2006), Sagredo (2007) and Sagredo *et al.*, 2010. The information from these cores concerning the R1 tephra are briefly summarized below in sequence from the highest (>150 m) to lowest (<150 m) elevation of the coring site.

3.3.1. Lago Dorotea (core PS0402; 4,285,821N; 673,804E; 260 m a.s.l.)

Sagredo (2007) reported a series of cores taken from a small lake located well above the elevation of the highest 150 m a.s.l. proglacial lake terrace on a mesa along the western margin of Sierra Dorotea (Fig. 2). Dates of 16.8 and 16.9 cal kyrs BP (14,105±45 and 14,170±45 ^{14}C yrs BP) in basal sediments provide a minimum age for the beginning of glacial retreat from this site at the end of the LGM (Sagredo *et al*., 2010). A 37 cm thick white tephra layer, located 60 cm above these basal dates, occurs between layers of laminated sand and thin lenses of organic silt. This layer has visually distinctive internal layers, grading upward from 20 cm of fine white tephra at the base, to 7 cm of coarse-grained sandy tephra components in the middle, above which occurs another 10 cm finer tephra. This tephra layer is underlain by organic silts dated as 15.4 cal kyrs BP (13,000±60 ^{14}C yrs BP; Table 3), and a date obtained from above the upper layer is 14.5 cal kyrs BP (12,460±90 ^{14}C yrs BP; Sagredo, 2007). The age, petrology and chemistry (Table 2) of all the visually distinctive subdivision of this unit are consistent with their being produced by different phases of the late-glacial R1 eruption of the Reclús volcano.

3.3.2. Vega Benítez (cores PS0302 and PS0403; 4.285,485N; 667,699E; 215 m a.s.l.)

Cárdenas (2006) and Sagredo (2007) discussed the results from a series of cores taken from a bog in a glacial valley located between the two peaks of Cerro Benítez (Fig. 2). A date of 17.5 cal kyrs BP (14,520±140 ^{14}C yrs BP) was determined for the first layer of organic material overlying inorganic components near the base of this core, and this age is interpreted as the closest minimum age for glacial retreat in the Última Esperanza region at the termination of the LGM (Sagredo *et al.*, 2010). A >40 cm thick white layer of tephra, located 50 cm above this basal age, occurs above peat dated at 14.8 cal kyrs BP (12,580±35 ^{14}C yrs BP; Table 3). This is overlain by 1.7 m of laminated sand with organic material, a date from which constrains the age of the underlying tephra layer as >14.6 cal kyrs BP (>12,490±40 ^{14}C yrs BP). Above this sediment occurs another 24 cm thick layer of white tephra layer dated as <14.2 cal kyrs BP (<12,325±40 ^{14}C yrs BP). The age, petrology and chemistry of the lower tephra are consistent with its being produced by the R1 eruption. The upper layer is petrologically and chemically similar, but younger than the R1 eruption and most likely resulted from redeposition of the R1 tephra. A thinner (1 cm) white tephra, which occurs higher in the core and has been dated as <10.2 cal kyrs BP (<9,130±35 ^{14}C yrs BP), also has petrochemical characteristics similar to tephra derived from a younger and smaller eruption of the Reclús volcano (Stern, 2008).

3.3.3. Lago Arauco (cores PS0602 and PS0505; 4,238,306N; 703,633E; 180 m a.s.l.)

These cores were retrieved from a small lake located in a depression between LGM moraines (Fig. 2; Sagredo *et al*., 2010). A 10 cm thick white tephra occurs within organic-rich lacustrine sediments dated at 14.6 cal kyrs BP (12,500±60 ^{14}C yrs BP). Its age and petrochemical characteristics are consistent with its correlation to the Reclús R1 eruption.

3.3.4. Pantano Dumestre (core PS0607; 4,257,560N; 667,387E; 77 m a.s.l.)

This core was taken in a small depression enclosed by bedrock 10 km south of Puerto Natales (Fig. 2; Moreno *et al*., 2008; Sagredo *et al*., 2010). The base of the core consists of >4 m of clay interpreted to have been deposited in the proglacial lake that occupied this area after the LGM. This grades into thin layers of banded shallow lake silts and dense peat, indicating that at this stage, dated as 15.2 cal kyrs BP (12,875±45 ^{14}C yrs BP), the water level in the proglacial lake had decreased to <80 m a.s.l. These layers are overlain by a 7 cm thick white tephra layer. The tephra is overlain by more peat interbedded with lake sediment, dated as 14.4 cal kyrs BP (12,400±60 ^{14}C yrs BP), interpreted to have formed by filling of the Dumestre depression by water due to increased precipitation (Moreno *et al*., 2008; Sagredo *et al.*, 2010). The age, petrology and chemistry of the tephra (Table 2) are consistent with derivation from the R1 eruption of the Reclús volcano.

3.3.5. Eberhard site (cores PS0301 and PS0401; 4,283,338N; 661,707E; 68 m a.s.l.)

Sediment cores were obtained from a small lake (core PS0401) and from an adjacent bog (core PS0301; Cárdenas, 2006; Sagredo, 2007). The base of both these cores consists of glacial clay and silts. Two organic-rich lamina within this unit have been dated as 16.4 and 16.3 cal kyrs BP (13,745±50 and 13,690±45 ^{14}C yrs BP), interpreted as a minimum age for ice retreat and the beginning of proglacial lake sedimentation at this site. A 17 cm thick white tephra layer, petrochemically similar to Reclús tephra R1 (Table 2), occurs near the top of this unit in the cores collected from the bog. The glacial clay and silt unit continues to higher levels in these cores, but just above the tephra it becomes a gravel enriched in lithic clasts. These dropstone gravels may have resulted from an increase in icebergs due to **1**. either ice retreat, producing more icebergs in the lake, or ice advance, resulting in more icebergs in the vicinity of this site; or **2**. collapse and refilling of the proglacial lake producing more icebergs as lake level rose and floated glacial fronts that had descended to lower elevation. Above this gravel occur organic-rich laminated lake sediments, dated as beginning at 12.8 cal kyrs BP (10,695±40 ^{14}C yrs BP), and finally, in the bog core, peat containing a thin tephra layer, dated as 10.7 and 10.8 cal kyrs BP (<9,435±40 and <9,615±35 ^{14}C yrs BP), derived from Reclús volcano (Stern, 2008). The organic-rich lake sediments are interpreted to indicate the retreat of the proglacial lake to <70 m a.s.l. elevation, and the beginning of sedimentation in the local shallow lake that still persists at this site.

4.0 Discussion

4.1. Implication for the R1 eruption

Stern (2008) calculated the age of the R1 eruption of the Reclús volcano as 14.9 cal kyrs BP (12,685±260 ^{14}C yrs BP), based on the average of the 18 best of 28 available radiocarbon ages. The five new age determination in table 3 all fall in the range of the best ages previously identified by Stern (2008). Including these five new ages in the calculated average age of the R1 eruption changes the average ^{14}C age only 15 years, to 12,670±240 ^{14}C yrs BP. This new age remains within the analytical error of other independent estimates, including those of 12,720±50 ^{14}C yrs BP by Heusser *et al.* (2000), 12,640±50 and 12,693±192 ^{14}C yrs BP by McCulloch and Davis (2001) and McCulloch *et al.* (2005a and b), and 12,552±33 ^{14}C yrs BP by Sagredo *et al.*, 2010.

Stern (2008) estimated the size of the R1 explosive eruption as at least >10 km^3. Unfortunately, this estimate was based on an erroneous calculation of the square-root of the area, using the formula $(a \times b)^{1/2}$ instead of $(a/2 \times b/2)^{1/2}$, where a and b are the axis of the elliptical isopachs of a given thickness of tephra (Fig. 7). This error essentially doubled the calculated area of these isopachs and thus also doubled the estimate of the volume. Here we present a new volume estimate (Fig. 8) using new isopachs (Fig. 7), which based on the sections

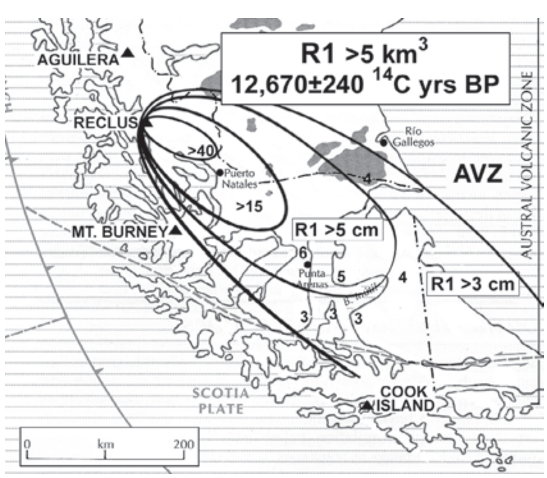

FIG. 7. Isopachs for the R1 eruption based on previously published (Stern, 2008) and new sections (Table 2) containing this tephra. Compared to the previous isopach map, the new isopachs are thicker to the east.

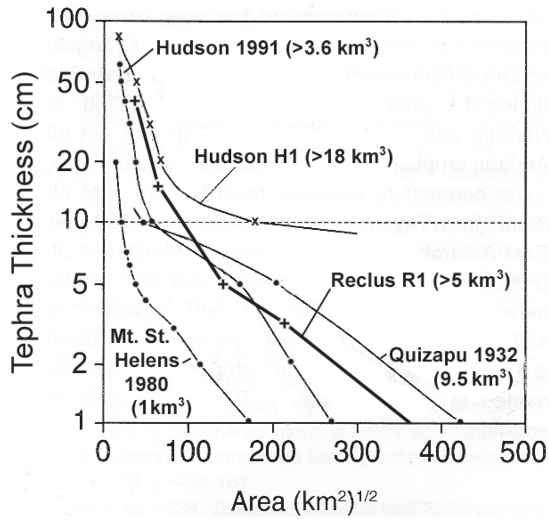

FIG. 8. New volume estimate of the R1 tephra modified from Stern (2008) based on the areas within the isopachs (Fierstein and Nathenson, 1992) illustrated in figure 7. The volume of the R1 eruption, now estimated as >5 km^3, is larger than that of the 1991 eruption of Hudson volcano, but smaller than that of the 1932 eruption of Quizapu.

described above indicate thicker distribution of R1 tephra both in the vicinity of Última Esperanza and also to the east. The new volume estimate for this R1 eruption indicates that the volume is only >5 km^3, half that previously estimated. This eruption was nevertheless larger than that of any other Holocene eruption in the AVZ (Stern, 2008), or the Hudson volcano in 1991 (>3.6 km^3), but not as large as that of the Quizapu volcano in 1932 (9.5 km^3).

4.2. Variations in terrace elevations

Different terraces mark the evolving shoreline of proglacial Lago Consuelo in Última Esperanza, but the current elevations of these terraces are a function of both the level of water in this lake as well as the amount of post-glacial isostatic rebound. We interpret the 45 m west-to-east change in elevation of the highest terrace to be the result of differential post-glacial isostatic rebound, due to both deglaciation and also subsequent drainage of the proglacial lake in the area, with greater rebound to the west where the glaciers were thicker at the time of the LGM and the proglacial lake deeper prior to the Holocene. This amount of differential rebound, approximately 45 m over a 65 km distance from west-to-east, is consistent with that observed from west-to-east in both Seno Skyring (Kilian *et al*., 2007) and from southwest-to-northeast in the Estrecho de Magallanes (McCulloch *et al*., 2005a). Dietrich *et al*. (2010), using Global Positioning System (GPS) measurements, have also documented significant differential west-to-east isostatic rebound east of the Southern Patagonia Icefield as a result of glacial wasting during the last 100 years since the termination of the Little Ice Age (LIA), with rates of uplift decreasing more than 50%, from 39 to 17 mm/yr, over a 240 km transect to the northeast from the crest of the icefield.

The total amount of isostatic rebound in Última Esperanza since the LGM is unknown, but for two reasons it certainly must have been greater than the 35 m estimated by Ivins and James (1999) along the crest of the Andes at this latitude in the first 2,000 years after the LGM (Fig. 3B in the appendix to their paper). First, the observed differential west-to-east uplift of 45 m for the highest terraces in Última Esperanza is greater than this estimate, and this area is 65 km east of the crest of the Andean range along Cordillera Sarmiento. If this differential west-to-east uplift is extrapolated in a linear fashion another 65 km west from Península Antonio Varas, it would suggest 45 m more uplift along the Andean crest, and 90 m more than the easternmost 125 m terrace east of Puerto Natales. Since the total amount of uplift of the 125 m terrace east of Natales is unknown, 90 m must be considered a minimum value for the amount of post-glacial uplift along the crest of the Andes at this latitude.

Second, Ivins and James (2004) estimate that ice loss at the end of the LGM from the region of the Southern and Northern Patagonian Icefields was approximately 60 cm of total Equivalent Sea Level Rise (ESLR) over 2,000 years, while ice loss from the Southern Patagonian Icefield in the last 100 years, since the end of the Little Ice Age (LIA), was only 0.5 cm ESLR. This implies both that the amount of ice loss was 120 times greater at the end of the LGM compared to the loss from the Southern Patagonian Icefield since the end of the LIA, and the rate of ice loss over the 2,000 time period after the LGM would have had to have been 6 times as great as from the Southern Patagonian Icefield during the 100 years since the end of the LIA. Even if isostatic rebound rates were only similar to 39 mm/yr, the rate determined by Dietrich *et al*. (2010) for the current uplift of the crest of the Southern Patagonia Icefield, the amount of uplift above the crest of the Andes in the 2,000 years after the LGM would have been 78 m, more than twice that estimated by Ivins and James (1999).

The vertical rate of uplift of the Southern Patagonian Icefield observed by Dietrich *et al*. (2010) is the largest present-day glacial isostatic signal recorded to date anywhere in the world. They suggest that this is due to the low effective viscosity of the underlying mantle as a result of the regional tectonic setting, which is characterized by active Andean volcanism (Stern and Kilian, 1996). This implies that the regional upper mantle below the austral Andes is warm and rich in volatiles, both being agents which tend to strongly reduce creep strength. Since this same tectonic setting existed at the end of the LGM, it can be expected that isostatic rebound rates would have been at least as large as those after the LIA. Given the large amount of glacial loss at the end of the LGM, isostatic rebound rates may have been even higher, and the total uplift above the crest of the Andes greater than 78 m, as is also indicated by the differential west-to-east uplift discussed above.

Ivins and James (2004) suggest that the locus of glacial growth in the southern Andes during the last glaciations was in the area of the Southern and Northern Patagonian Icefields, and Ivins and James (1999) calculate that the total post-glacial isostatic rebound decreased to both the north and south, as well as to the east and west, of this area. This is consistent with the proglacial lake terraces in Última Esperanza, which is located along the southern edge of the Southern Patagonian Icefield, being higher than further to the south around Seno Skyring and Otway (maximum elevations of only 35 to 50 m; R. Kilian, personal communication, 2010) or the Strait of Magellan (maximum of 60 m; McCulloch *et al*., 2005a). North-to-south differential glacial rebound might have been a significant factor in causing the drainage of the proglacial Lago Consuelo in Última Esperanza southward across the low elevation pass between Fiordo Obstrucción to Seno Skyring and Otway, as discussed in more detail below.

4.3. Evolution of the proglacial ice-dammed Lago Consuelo

The proglacial lake in Última Esperanza may have begun to form after 17.5 cal kyrs BP (Cárdenas, 2006; Sagredo, 2007), the closest minimum date of ice recession in the region as determined from

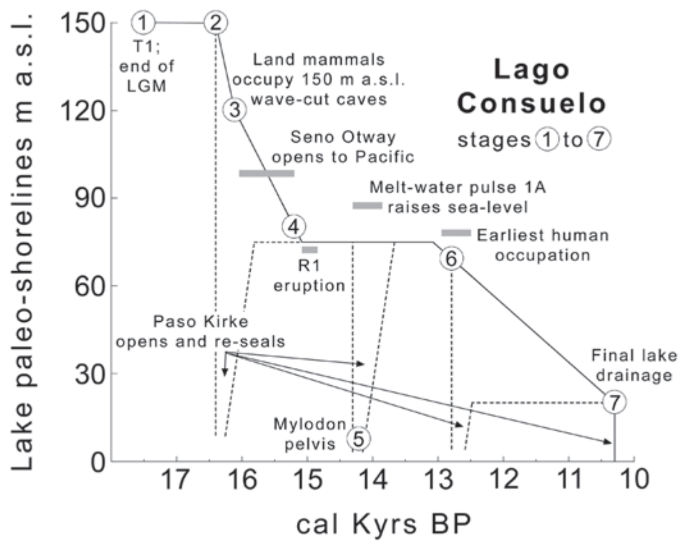

FIG. 9. Model for the seven stages (numbers within circles) of evolution of the shoreline levels of the proglacial Lago Consuelo in the area of Puerto Natales, relative to the prominent 150 m a.s.l. terrace in the area around Lago Sofía. Progressive decrease in the shoreline from 150 m a.s.l. (stages 1 and 2; Table 4), to <120 m a.s.l. (stage 3; Table 4) and <80 m a.s.l. (stage 4; Table 4) was due to glacial retreat during the late-glacial transition (solid line), and/or possibly drainage though either Paso Kirke or Fiordo Obstrucción to Seno Skyring and Otway and the Pacific Ocean when Canal Jerónimo opened prior to the R1 eruption (dashed line). Oscillations in the lake level after the R1 eruption (stages 5 and 6; Table 4) may have been caused again by the failure and re-establishment of the ice dam in Paso Kirke, and the final lake drainage (stage 7; Table 4) was certainly due to the opening of this passage to the Pacific. The current elevation of the 150 m a.s.l. terrace around Lago Sofía reflects an unknown amount of post-glacial isostatic rebound.

the Vega Benítez core (stage 1 in Table 4 and Fig. 9). Lake sediments began to be deposited in the Eberhard site by 16.9 cal kyrs BP (stage 2 in Table 4 and Fig. 9). This early stage of the proglacial lake would have been responsible for the development of the highest and most prominent terraces in the region. The occupation by land mammals, beginning at 16.1 cal kyrs BP (13,560±180 ^{14}C yrs BP; Long and Martin, 1974), of the caves developed along the 150 m a.s.l. terrace around Lago Sofía, suggests that the lake must have dropped from its highest level to at least <120 m a.s.l. prior to this time (stage 3 in Table 4 and Fig. 9). This would imply that the highest and most prominent terraces were generated in less than 1.4 kyrs. The presence of the 14.9 cal kyrs BP R1 tephra in the wave-cut caves along the 150 m a.s.l. terraces around Lago Sofía also implies that the lake had abandoned its highest level prior to this eruption (Table 4; Fig. 9). The core from Dumestre confirms that the proglacial lake level had in fact dropped to below ~80 m a.s.l. prior to the eruption of the R1 tephra (stage 4 in Table 4 and Fig. 9).

The cores from the Eberhard site suggest that the lake level stayed >70 m a.s.l. until approximately 12.8 cal kyrs BP (stage 6 in Table 4 and Fig. 9). However, no prominent terrace formed at this level (Fig. 3F), which is inconsistent with a prolonged lake shore at this elevation for an extended period of time. Furthermore, the 14.2 cal kyrs BP (12,125±25 ^{14}C yrs BP) *Mylodon* pelvis bone found at ~7 m.a.s.l elevation on Estancia Eberhard during the excavation of their well may possibly imply a rapid decrease followed by a rapid increase in the lake level back to its equilibrium level at ~70 m a.s.l. (stage 5 in Table 4 and Fig. 9), although no unconformity is observed in the glacio-lacustrine sediments in the core from the Eberhard site (Sagredo, 2007).

Taken together all these data are not 100% mutually consistent, but may suggest evolving lake levels for the proglacial lake in Última Esperanza between the LGM and the Holocene, with the lake decreasing from its highest level to <120 m a.s.l. prior to the occupation of wave-cut caves around Lago Sofía by land mammals, to <80 m a.s.l. prior to the R1 eruption, and possibly fluctuating rapidly either before, or more certainly after this eruption, until finally emptying to below <70 m a.s.l. at 12.8 cal kyrs BP and <30 m a.s.l. at 10.3 cal kyrs BP (stage 7 in Table 4 and Fig. 9; Sagredo *et al*., 2010). These fluctuations correspond closely in time with the 12.6 cal kyrs BP average age (10,610±300 ^{14}C yrs BP; Sagredo, 2007) for the earliest evidence of human occupation of Última Esperanza (Table 4 and Fig. 9).

4.4. Causes of proglacial lake level variations

A number of processes might explain changes in the level of the proglacial lake in Última Esperanza. However, decreasing proglacial lake level is certainly not simply a direct result of glacial recession, as the melting of glaciers would either not affect the lake level if they were already floating within the water, or they would add more water to the lake increasing its level if they were grounded either on the lake bottom or at higher elevations. Deepening of the eastward drainage of this lake also could lower its level, but the base of the paleo-drainage at the eastern margin of the proglacial lake in Última Esperanza occurs at ~125 m a.s.l., essentially the same height as the high terrace in this area. Another alternative, overflow of water over ice at low elevation, such as in Paso Kirke or the low elevation pass between Fiordo Obstrucción and Seno Skyring, could lower the water level in the lake as erosion of this ice deepened the overflow channel. However, when water levels rise above ice elevation, destabilization and floating of the ice should occur. Furthermore, neither deepening of the eastern paleo-lake drainage channel, nor over-flow of low elevation ice, can explain the possible rapid fluctuations in lake level described above. Neither could these rapid fluctuations result soley from post-glacial isostatic rebound.

We suggest instead that changes in lake level were due to drainage events through one or more ice-dammed low elevation passage to the Pacific Ocean, such as either Paso Kirke (Fig. 9), the current opening to the Pacific west of Última Esperanza, or possibly across the low elevation pass between Fiordo Obstrucción to Seno Skyring, and subsequent resealing of these passages and refilling of the lake. Drainage of Lago Consuelo across the low elevation pass between Fiordo Obstrucción to Seno Skyring as a result of post-glacial rebound could have been the cause of the initial decrease of the level of this proglacial lake from its highest level to either <120 m a.s.l. (stage 3; Fig. 9), which occurred prior to the R1 eruption as indicated by both the preservation of this tephra in the wave-cut caves along the shores of Lago Sofía, or even to <80 m a.s.l. (stage 4; Fig. 9) as indicated by the sediment record preserved in the Dumestre site. This water would have reached the Pacific Ocean by way of Seno Otway, which was already opened to the Pacific Ocean through Canal Jerónimo prior to the R1 eruption (Fig. 9; McCulloch *et al*., 2005a; Kilian *et al.*, 2007), as indicated by the presence of R1 tephra deposits in the eastward paleo-drainage channel of this lake.

At 14.3 cal kyrs BP, melt-water pulse 1A caused a relatively sudden sea-level rise of from -95 to -70 m b.s.l. (Fig. 9; Bard *et al*., 1996; Rohling *et al*., 2004). Thus ice in the narrow Paso Kirke channel, which currently has its base at -65 m b.s.l., but which must have been significantly deeper prior to post-glacial isostatic rebound, could have been floated and destabilized by a combination of rising sea-level on the west, due to the 1A melt-water pulse, and the ice-dammed proglacial lake on the east. We therefore suggest that the rapid decrease and subsequent rise of the lake level around 14.2 cal kyrs BP (Fig. 9), as indicated by the *Mylodon* pelvis bone encountered at 7 m a.s.l. in Pozo Consuelo on Estancia Eberhard, may have been due to the catastrophic collapse of the Paso Kirke ice-dam as sea-level rose and ice-cover thinned, resulting in nearly complete drainage of the lake, followed by the subsequent reformation of this ice-dam. Repeated ice-dam failure and resealing during the LGM to Holocene transition have also been invoked to explain varying lake levels in the Estrecho de Magallanes between 15.6 to 12.3 cal kyrs BP (McCulloch *et al*., 2005a). McCulloch *et al*. (2005a) estimate that lake-free intervals in the Estrecho de Magallanes were of short duration, between 400-700 ^{14}C yrs.

Reformation of the ice-dam in Paso Kirke would not necessarily be dependent on climate change to colder or wetter conditions, although both these occurred in the southern Andes after 14.2 cal kyrs BP as indicated by evidence for younger ice advances (Kilian *et al*., 2007; McCulloch *et al*., 2005a and b; Moreno *et al*., 2009; Sagredo *et al*., 2010). Resealing of Paso Kirke by ice could merely reflect re-establishment of the equilibrium position of the ice front after the dam ruptured due to pressure from the high-water level in the proglacial lake. Once this lake drained to the Pacific Ocean this pressure would disappear and ice could reform relatively rapidly in this narrow passage. This type of process continued to occur until quite recently as a result of the collapse and re-advance of the front of the Perito Moreno glacier between Brazo Sur and Brazo Norte of Lago Argentina. This occurred approximately every 3 years as water level in Brazo Sur of the lake rose 30 m, sufficient to override and float away the front of the Perito Moreno glacier, which after being washed away re-advanced again to its equilibrium position against the peninsula of land that separated the two branches of this lake.

This event was a great tourist attraction until human-induced global warming caused the equilibrium position of the front of the Perito Moreno glacier to no longer advance as far as the peninsula and dam Brazo Sur. Now water merely runs freely from Brazo Sur into Brazo Norte of the lake, just as it has run freely from Seno Último Esperanza into the Pacific Ocean since the beginning of the Holocene. Rupture and collapse of the Paso Kirke ice dam and catastrophic draining of the proglacial lake in Última Esperanza during the LGM to Holocene transition may have been observed by the earliest visitors to this region, who arrived by 12.6 cal kyrs BP (Table 4 and Fig. 9) .

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