Quaternary Science Reviews 77 (2013) 70–79

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Latest Pleistocene and Holocene glacier fluctuations in southernmost Tierra del Fuego, Argentina

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ARTICLE INFO

Article history:
Received 19 March 2013
Received in revised form
2 July 2013
Accepted 5 July 2013
Available online

Keywords:
Glacier fluctuations
Holocene
Patagonia
Surface exposure dating
Tephrochronology

ABSTRACT

Some researchers propose that summer insolation controls long-term changes in glacier extent during the Holocene. If this hypothesis is correct, the record of glacier fluctuations at high latitudes in the Southern Hemisphere should differ from that in the Northern Hemisphere. Although the chronology of Holocene glacier fluctuations in the Northern Hemisphere is well established, much uncertainty remains in the ages of Holocene glacier fluctuations in the Southern Hemisphere, especially South America. Here we report on latest Pleistocene and Holocene glacier fluctuations at the southern end of the Andes north and west of Ushuaia, Argentina. Surface exposure ages (^{10}Be) from glaciated bedrock beyond cirque moraines indicate that alpine areas were free of ice by ca 16.9 ka. One, and in some cases two, closely spaced moraines extend up to 2 km beyond Little Ice Age moraines within many of the cirques in the region. The mean age of five ^{10}Be ages from two pre-Little Ice Age moraines is 14.27–12.67 ka, whereas a minimum limiting radiocarbon age for a smaller, recessional moraine in one cirque is 12.38–12.01 ka. Our ages imply that, following glacier retreat beginning about 18.52–17.17 ka, cirque glaciers first advanced during the Antarctic Cold Reversal (14.5–12.9 ka) and may have later advanced or stabilized in the Younger Dryas Chronozone (12.9–11.7 ka). Based on the distribution of thick, geochemically distinct, and well-dated Hudson tephra, no Holocene moraines appear to be older than 7.96–7.34 ka. At some sites, there is evidence for one or more advances of glaciers sometime between 7.96–7.34 ka and 5.29–5.05 ka to limits only tens of meters beyond Little Ice Age maximum positions. Taken together, the data: 1) do not support the summer insolation hypothesis to explain Holocene glacier fluctuations in southernmost Patagonia; 2) confirm paleobotanical evidence for a warm, dry early Holocene; and 3) suggest that some glaciers in the region reached extents comparable to those of the Little Ice Age shortly before 5.29–5.05 ka.

1. Introduction

Most alpine glaciers in the Northern Hemisphere episodically expanded from retracted positions during the early Holocene to maximum Holocene extents 200–300 years ago at the peak of the Little Ice Age (Davis et al., 2009; Menounos et al., 2009). These changes mirror the gradual decline in summer insolation during the Holocene, suggesting that insolation is an important external driver for glacier fluctuations in the Northern Hemisphere.

If summer insolation is an important control of long-term glacier fluctuations during the Holocene, the record of glacier fluctuations at high latitudes in the Southern Hemisphere should be out-of-phase with that in the Northern Hemisphere (Berger, 1978), and Holocene glacier chronologies should differ most at highest latitudes (e.g., Sugden et al., 2005; Barker et al., 2009; Stenni et al., 2011; Murray et al., 2012). A test of this insolation hypothesis, however, has been hampered by uncertainties in the chronologies of many published Holocene glacier records from the

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http://dx.doi.org/10.1016/j.quascirev.2013.07.008

Southern Hemisphere (Porter, 2000), although recent chronological refinements have been made in the Southern Alps of New Zealand (Putnam et al., 2012).

The mountains of the Fuegian Andes are an ideal place to examine latest Pleistocene and Holocene glacier fluctuations and their links to climate change (Rodbell et al., 2009; Kilian and Lamy, 2012). The region is in southernmost South America, and the mountains have dozens of cirques containing small glaciers that should respond rapidly to changes in climate. Climatic inferences from moraines constructed at the margins of large glaciers, especially ice caps, are more difficult to interpret, given their long response times to climate change. And finally, geochemically distinct tephras of known age occur in southernmost Tierra del Fuego, providing chronological markers that aid in dating glacier advances (Stern, 2008; Stern et al., 2011). The two most widespread and useful tephras, which have sources at stratovolcanoes in southern Chile, are a felsic tephra erupted from Mt. Reclus (16.18–14.03 ka; 2σ), and a basaltic tephra from Mt. Hudson (7.96–7.34 ka). These tephras are sufficiently thick on Tierra del Fuego to be used as markers in the field and thus to provide age constraints on moraines (Stern, 2008; Stern et al., 2011).

Our objective in this study was to document the geologic evidence for latest Pleistocene and Holocene glacier fluctuations in cirques and hanging valleys on Tierra del Fuego. We compare our findings to those of other researchers who have worked on the island and at sites at the margin of the Southern Patagonian Icefield (Kuylenstierna et al., 1996; McCulloch and Bentley, 1998; Glasser et al., 2004, 2012; Fogwill and Kubik, 2005; Strelin et al., 2011). We also use the climatic implications of our findings to evaluate the hypothesis that long-term changes in alpine glacier cover at high latitudes of South America are driven by changes in insolation.

2. Study area

We conducted our study in the hanging valleys and cirques of the Valdivieso, Vinciguerra, and Alvear ranges, directly north of Ushuaia, Argentina (Fig. 1). The Fuegian Andes in this area trend west–east and have summits below 1250 m above sea level (asl) and cirque floors between 500 and 600 m asl. Several valleys with NNW–SSE orientations cross the mountain range. Postglacial geomorphological processes include cryogenesis, movement of slope materials, and fluvial activity (Coronato, 1993; Coronato et al., 2009; Coronato and Rabassa, 2012).

This part of the Fuegian Andes is formed mainly of Jurassic and Cretaceous sedimentary and volcanic rocks (Caminos et al., 1981). Rhyolite and dacite lava flows and tuffs are common in Andorra and Carbajal valleys, where we did much of our work (Borrello, 1969). Elsewhere in the study area, the dominant bedrock is the Jurassic–Cretaceous Yahgan Formation, which consists of conglomerates, sandstones, and mudstones (Olivero and Martinioni, 1996, 2001).

The climate of the study area is strongly influenced by Antarctic and Subantarctic air masses moving out from the Southern Pacific Anticyclone and thus is temperate and humid (Tuhkanen, 1992). Mean annual temperature at tree line (600 m asl) is 2.4 °C (Puigdefabregas et al., 1988), and mean annual precipitation at sea level is 546 mm yr^{-1} (Tuhkanen, 1992). There are no rainfall records at high elevations, but precipitation at tree line is estimated to be about three times greater than that at sea level (Iturraspe et al., 1989; Borromei et al., 2010).

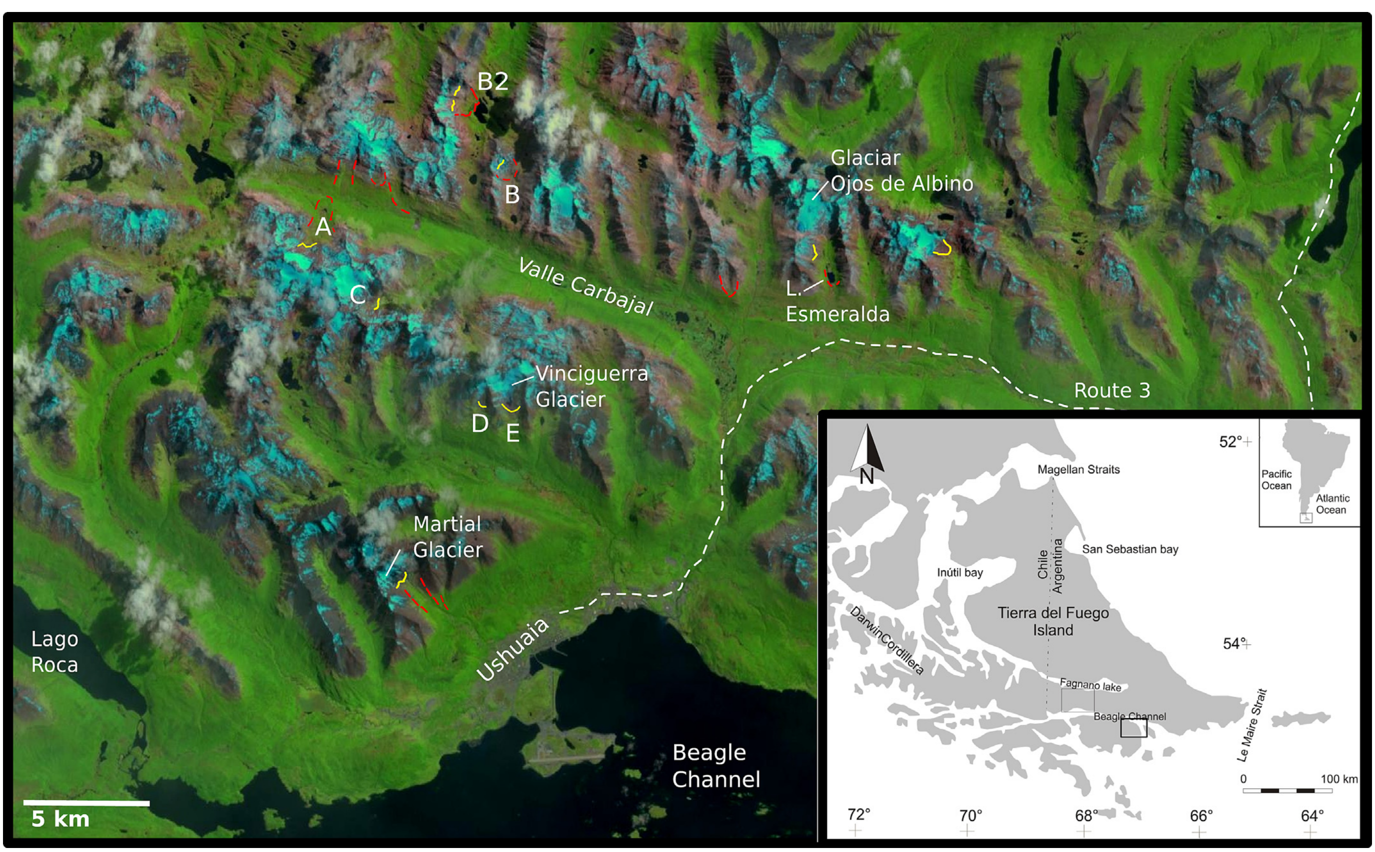

Fig. 1. Landsat TM image (7/4/2 band composite) acquired on 10 January 2010, showing field sites and locations discussed in the text. Latest Pleistocene moraines are delineated with red dashed lines, and late Holocene moraines are shown with yellow solid lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Methods

We used topographic maps, aerial photography (1:40,000 scale), satellite imagery, and digital elevation models to identify cirques and valleys near Ushuaia and Valle Carbajal that contain well preserved lateral and terminal moraines (Fig. 1). We accessed these sites on foot and by helicopter. We searched glacier forefields for rooted stumps and detrital wood to constrain the times of past glacier advances, but found none. We measured lichens on some moraines but do not present the data here because we found evidence of lichen snowkill (Benedict, 1993) and there is no lichenometric growth curve for the Fuegian Andes. We excavated soil pits and used a split-spoon soil auger to search for tephra that would provide maximum- and minimum-limiting ages for moraines and associated landforms.

We obtained accelerator mass spectrometry (AMS) ages on plant macrofossils from four cirques (Table 1). The macrofossils were isolated from peat and roots, and cleaned three times with distilled water. We converted radiocarbon ages to 2σ calendar-age ranges using the calibration program CALIB 6.0 (Stuiver et al., 2010) and the Southern Hemisphere calibration curve for ages less than 10 ka. To facilitate comparison of our results with those of other workers, we report all radiocarbon and ^{10}Be ages as kilo calendar years (ka) BP (before AD 1950).

We collected samples of tephra from dozens of sites within cirques in the study area, preferentially in pits dug in front of, along, and behind moraines. Coloration, degree of weathering, lithic content, and shard vesicularity were used to tentatively identify tephras in the field. We confirmed tephra identifications by determining the geochemistry of individual glass shards and the relative abundance of microphenocrysts at the University of Calgary Laboratory for Electron Microbeam Analysis (UCLEMA). Prior to analysis, we removed organic matter with hydrogen peroxide, washed and wet-sieved the samples through a 230-mesh screen, mounted coarse grains in epoxy, and polished and carbon-coated the mounts. Typically, 20–30 inclusion-free glass shards from each sample were analyzed for K_2O, CaO, FeO, SiO_2, Na_2O, TiO_2, MnO, MgO, and Al_2O_3 with a wavelength-dispersive spectrometer (WDS) JEOL JXA-8200 electron microprobe. The accelerating voltage was 15.0 kV, the beam current was 10 nano-amps, and the beam width was 5 μm. We adjusted data using the ZAF matrix correction scheme to account for differences between the standards and the samples (Armstrong, 1984) and then compared our measurements to microprobe glass geochemistry data reported by Stern (2008).

At two sites we collected samples for ^{10}Be surface exposure dating from the topmost surfaces of large, quartz-bearing boulders using a hammer and chisel. We determined the location of each sample using a hand-held GPS unit and sample elevations from digital elevation data (Danielson and Gesch, 2011). Shielding by the surrounding topography was measured using a hand-held inclinometer or was determined from digital elevation models when weather inhibited measurement in the field.

We processed surface exposure samples at Purdue University PRIME Laboratory following standard beryllium isolation methods. ^{10}Be/^{9}Be ratios were measured relative to the 07KNSTD3110 standard with a ratio of 6.32×10^{-12} (Nishiizumi et al., 2007) and corrected for background ^{10}Be/^{9}Be. All ^{10}Be production rates and ages are reported relative to the renormalization presented in Nishiizumi et al. (2007). We calculated exposure ages using a modified version of the CRONUS-Earth Web Calculator (Balco et al., 2008, 2009). Ages presented below were determined using the scaling model presented in Lal (1991) and recast in terms of air pressure by Stone (2000) with a variable geomagnetic field (Balco et al., 2008, 2009). We calculated air-pressure changes with elevation using the standard atmosphere equation; sea level air pressure and temperature were derived from the NCAR/NCEP reanalysis data product (http://www.cdc.noaa.gov/ncep_reanalysis/). Use of other scaling methods does not significantly affect the calculations because of the relatively high latitudes (>50°S) and low elevations (<700 m asl). We use the regional ^{10}Be production calibration of Putnam et al. (2010a), which yields production rates of 3.84 ± 0.09 and 4.14 ± 0.09 atoms g^{-1} yr^{-1}, respectively, for the scaling models of Stone (2000) and Lifton et al. (2005). Recent work by Kaplan et al. (2011) demonstrates that ^{10}Be production rates in southern Patagonia are similar to those in New Zealand over a similar period and to those reported for northeastern North America by Balco et al. (2009). All uncertainties are reported at the 1σ level and, unless otherwise noted, include analytical uncertainties only.

4. Results

We place moraines and related deposits in the region into three categories. "Outer moraines" extend up to 3 km downstream from cirque headwalls and 1–2 km beyond modern glacier toes (Fig. 1). "Inner" moraines are sharp-crested, uneroded, and unvegetated, and lie up to 1 km from modern glacier toes. Although we have no numerical ages from the inner moraines, we assign the innermost moraines to advances of the Little Ice Age (LIA) (<1.0 ka) based on their fresh, uneroded form, proximity to existing ice, and similarity of their positions to moraines in the vicinity that previously have been assigned to the Little Ice Age (Strelin and Iturraspe, 2007; Strelin et al., 2008; Maurer et al., 2012). In a few cirques, there are moraine fragments or veneers of solifluncted, bouldery diamicton situated 10–100 m downvalley of inner moraines. They, like the inner moraines, do not bear Hudson tephra. The fragments and veneers that we term "intermediate deposits" are interpreted to be till.

The outer moraines are not present in all cirques in the study area; rather they are concentrated in the highest cirques, such as

Table 1
Radiocarbon ages.

Laboratory no.[a]	Site and context	^{14}C age (yr BP)[b]	Calibrated age range (ka)[c]	Latitude (S)	Longitude (W)	Elevation (m asl)[d]
	Cirque A			54.6729°	68.4518°	530
UCIAMS-63117	Terrestrial moss directly above till	10,330 ± 30	12.38–12.03			
UCIAMS-63116	Terrestrial moss directly above till	10,320 ± 25	12.38–12.01			
	Cirque C			54.6991°	68.4164°	650
UCIAMS-90379	Leaves directly above till	4505 ± 20	5.29–5.05			
	Cirque D			54.7338°	68.3154°	730
UCIAMS-93692	Leaves directly above till	10,150 ± 200	12.52–11.23			

[a] UCIAMS is Keck Carbon Cycle AMS Facility.
[b] Laboratory-reported error terms are ±1σ. Ages are normalized to $\delta^{13}C = -25‰$ PDB.
[c] Calendar ages determined using CALIB 6.0 (Stuiver et al., 2010). The range is the 95 percent confidence interval (±2σ) derived from the reported radiocarbon age. Values rounded off to nearest ten years.
[d] Elevation approximate (±10 m).

those at the western margin of Valle Carbajal. In the Martial cirque valley (Fig. 1), lateral and outer moraines lie between 700 and 400 m asl (Planas et al., 2002). In the mountains just north of Ushuaia, the outer moraines are large lateral moraines with indistinct hummocky termini. They may be associated with stagnant ice of the Darwin Cordilleran ice cap in adjacent valley bottoms (Rabassa et al., 2000). Because these moraines are directly sourced from the cirques, they clearly demarcate a major advance of alpine glaciers in the region.

4.1. Outer moraines

4.1.1. Cirque A

Cirque A (Figs. 1 and 2) contains outer moraines that are relatively well preserved. A 3.0 km^2 glacier exists there today, and uneroded, unvegetated moraines extend 300 m beyond the terminus of the glacier. The outer moraines comprise two separate ridges, 2.3 km and 2.0 km beyond the LIA terminus. Peat deposits, 205 cm and 113 cm thick, overlie an olive-gray silty diamicton in pits dug, respectively, on the down- and upvalley sides of the more upvalley of the two moraines. Terrestrial plant macrofossils at the bottoms of the peat layers returned calibrated ^{14}C ages of 12.38–12.03 ka (downvalley pit) and 12.38–12.01 ka (upvalley pit). The age from the upvalley pit is a minimum age for both moraines. An olive-green tephra occurs at depths of 186–200 cm in the downvalley pit and 83–85 cm in the upvalley pit. This tephra is also exposed for tens of meters along incised channels near the pits. The tephra includes abundant coarse basaltic glass, which is typical of Hudson tephra, dated 7.96–7.34 ka (Stern, 2008). Microprobe analysis of the glass confirmed a Hudson origin (Fig. 3). We also found Hudson tephra higher in the cirque, up to an elevation of about 730 m asl. We could not access terrain in the immediate vicinity of the glacier, but the presence of well preserved tephra only 600 m from the glacier terminus indicates that ice did not extend beyond this position after 7.96–7.34 ka.

4.1.2. Cirque B

Cirque B, located about 8–10 km north of cirque A (Fig. 1), contains only small snow and ice patches today. A prominent, multiple-crested outer moraine in cirque B is 850 m beyond and 250 below the snow and ice patches. Fresh inner moraines bordering the snow and ice demarcate glaciers that were one-third to one-quarter the size of the glacier that built the outer moraine at this site.

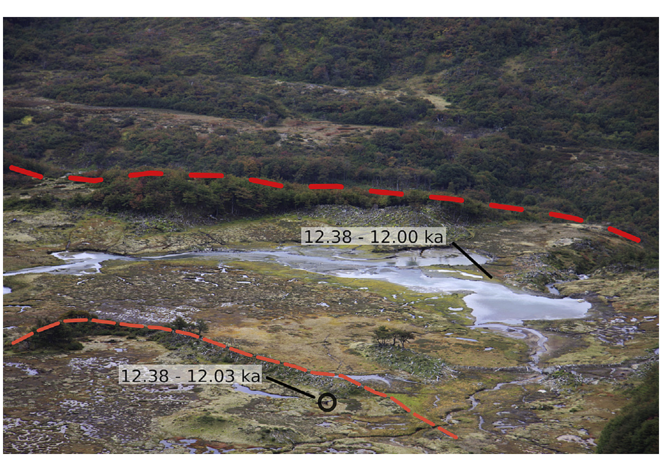

Fig. 2. View looking north (downvalley) from cirque A. Terminal moraine (red dashed line) and recessional moraines (orange dashed line) on the cirque floor are delineated. Fossil leaves directly above diamicton and outwash provide minimum limiting ages for the terminal moraine and bracketing ages for the outermost recessional moraine. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

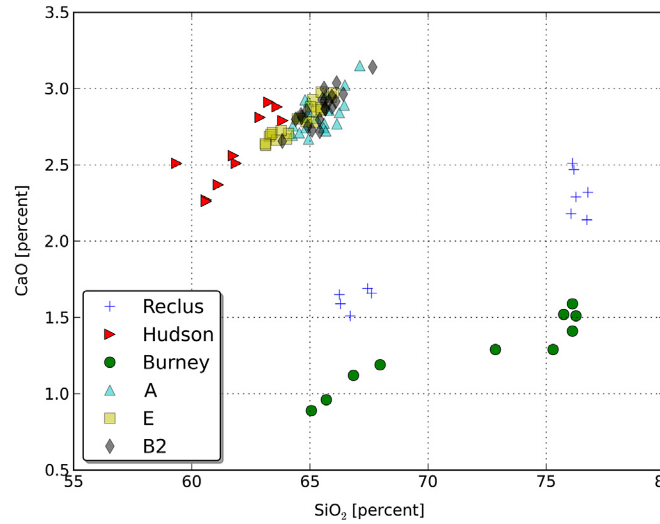

Fig. 3. Scatterplot of SiO_2 and CaO for glass shards from Holocene tephras that occur in Tierra del Fuego (Stern, 2008) and those analyzed in this study.

We collected seven ^{10}Be samples in the vicinity of cirque B (Fig. 4; Table 2). Two of the samples are from bedrock beyond the outer moraine: one from a striated surface 50 m beyond the outer moraine and the other from a glaciated knob at the top of a low mountain pass 1.3 km north–northeast of the moraine. These two samples yielded ^{10}Be ages of, respectively, 16.79 ± 0.79 and 16.95 ± 0.75 ka (Fig. 4). Five samples from boulders lying on the crests of the outer moraine range in age from 12.6 to 14.5 ka, with all individual samples overlapping at 1σ (Fig. 4), and a mean age of 13.47 ± 0.80 ka.

4.1.3. Laguna Esmeralda valley

Glaciar Ojos de Albino is a 0.77 km^2 glacier located 13 km east of cirque B (Fig. 1). It currently terminates at 920 m asl. Steep rock slopes below the glacier and below small ice masses to the east support no end or lateral moraines, but an end moraine dams Laguna Esmeralda 2.5 km beyond the terminus of the glacier (Fig. 5). The moraine is 2–3 m high and partially breached near its distal edge. The moraine is well preserved along the west shore of Laguna Esmeralda. Samples from two boulders on the moraine crest yielded ^{10}Be ages of 14.93 ± 1.59 and 14.57 ± 1.50 ka (Table 2).

4.2. Intermediate deposits

Three cirques (sites C, D, and E), which are, respectively, 4, 10, and 11 km southeast of cirque A (Fig. 1), contain deposits just beyond inner moraines that we interpret to be till of intermediate age. These deposits record one or more pre-LIA glacier advances that reached limits only slightly more extensive than during the LIA. Because the deposits lack Hudson tephra, they are younger than 7.96–7.34 ka.

4.2.1. Cirque C

Cirque C contains a 3.9 km^2 glacier that terminates at 800 m asl. We found no outer moraines like those described above in this cirque. An end moraine 0.9 km beyond the glacier terminus is interpreted to date to the LIA on the basis of its sharp crest, unvegetated surface, sparse lichen cover, and position relative to the modern glacier. About 100 m farther downvalley, fragments of two

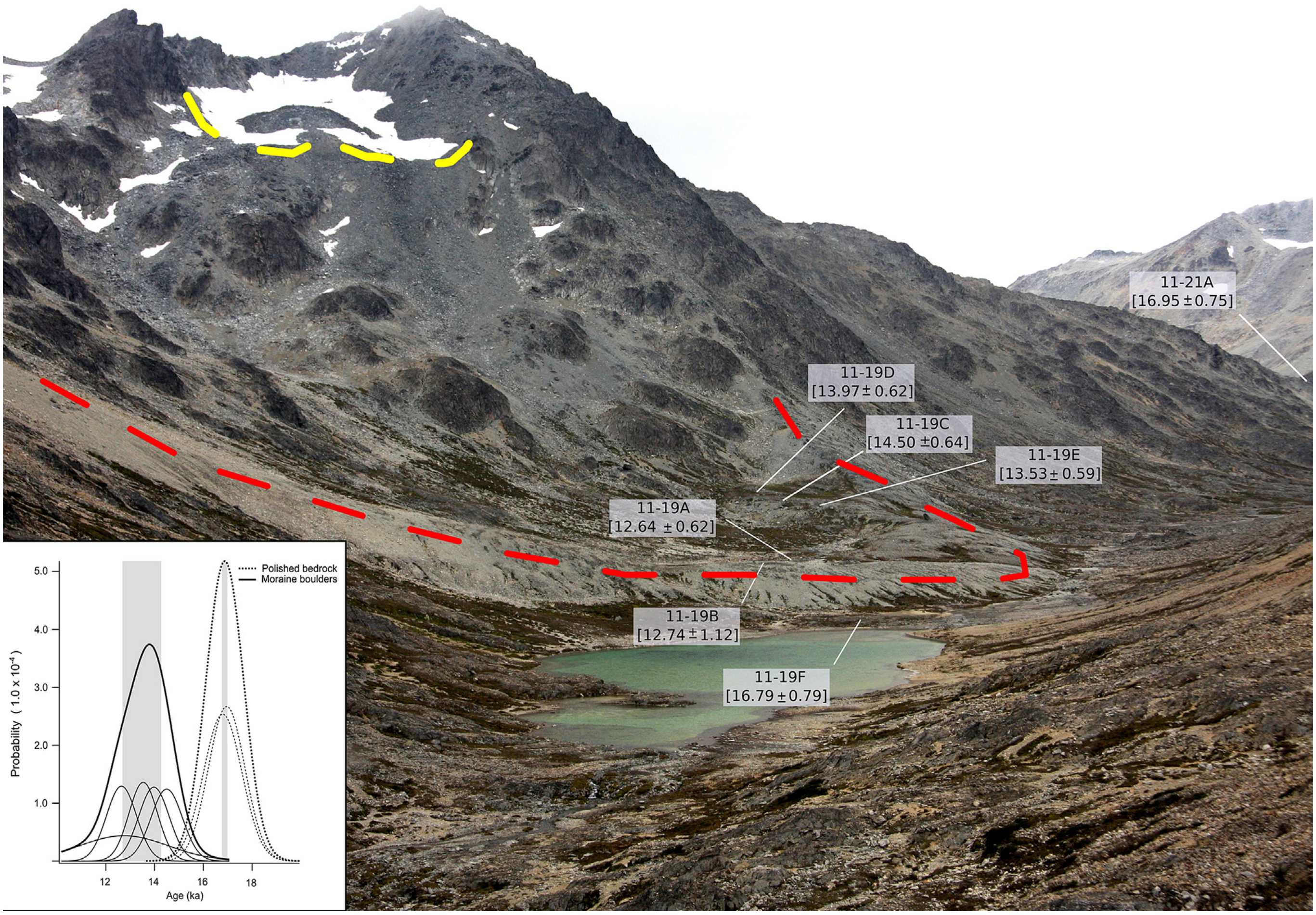

Fig. 4. Outer terminal moraine in cirque B and associated ^{10}Be ages. The moraine extends up to 250 m vertically below the inner moraines that are close to the head of the cirque (yellow dashed line). Two additional ^{10}Be ages [16.79 ± 0.79 and 16.95 ± 0.75 ka] were obtained from glacially polished bedrock beyond the moraine. Probability distribution of the ^{10}Be ages (inset). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

concentric end moraines separated by 30 m sit on bedrock at the outer lip of the cirque (Fig. 6). The terrain drops steeply away from lip of the cirque, and pits dug on the moraines revealed no visible tephra. Hudson tephra was found in pits beyond the moraines, approximately 0.4 km downvalley from the lip of the cirque.

A 74-cm-deep pit dug between the two moraine fragments exposed a brown fibrous peat overlying 3 cm of laminated silt with well preserved leaves and other plant macrofossils. The silt directly rests on a clay-rich diamicton containing subangular pebbles. Several leaves recovered from the silt returned a calibrated radiocarbon age of 5.29–5.05 ka (Table 1). This age and the absence of Hudson tephra allow us to bracket the age of the outer moraine fragment to sometime between 7.96–7.34 and 5.29–5.05 ka.

Table 2
Surface exposure ages.

Sample ID	Site	Latitude (S)	Longitude (W)	Elevation (m asl)	Sample thickness (cm)	Shielding	Mass quartz (g)	Mass carrier (g)[a]	$^{10}Be/^{9}Be$ (10^{-14})	[^{10}Be] (10^4 at g^{-1})	Exposure age (ka)
11-18A	L. Esmeralda	54.6927°	68.1289°	400	3.0	0.98	16.202	0.2155	11.42 ± 0.91	9.37 ± 0.99	14.93 ± 1.59
11-18B	L. Esmeralda	54.6927°	68.1289°	400	3.0	0.98	11.744	0.217	7.60 ± 0.71	9.14 ± 0.94	14.57 ± 1.50
11-19A	Cirque B	54.6620°	68.3321°	647	5.4	0.98	25.633	0.182	19.90 ± 0.93	9.68 ± 0.47	12.64 ± 0.62
11-19B	Cirque B	54.6620°	68.3321°	647	5.9	0.98	9.468	0.1005	16.17 ± 1.36	9.72 ± 1.38	12.74 ± 1.81
11-19C	Cirque B	54.6595°	68.3333°	680	4.6	0.98	28.462	0.1823	25.92 ± 1.12	11.49 ± 0.51	14.50 ± 0.64
11-19D	Cirque B	54.6595°	68.3333°	680	5.7	0.98	31.427	0.1817	27.40 ± 1.20	10.98 ± 0.49	13.97 ± 0.62
11-19E	Cirque B	54.6595°	68.3333°	680	3.6	0.98	27.885	0.1821	24.00 ± 1.00	10.82 ± 0.47	13.53 ± 0.59
11-19F[b]	Cirque B	54.6632°	68.3321°	641	5.2	0.98	29.742	0.1825	30.05 ± 1.40	12.81 ± 0.60	16.79 ± 0.79
11-21A[b]	Cirque B	54.6613°	68.3313°	650	6.6	0.98	30.002	0.1832	32.10 ± 1.40	13.65 ± 0.60	16.95 ± 0.75

Blanks	Carrier (g)	$^{10}Be/^{9}Be$ (10^{-14})	^{10}Be (atoms)
Cblk-2746-2	0.1851	0.80 ± 0.30	10.58 ± 3.70

[a] Be concentration is 1069 ppm; density of all samples is 2.65 g cm^{-3}.
[b] Glacially polished bedrock samples; all other samples from moraine boulders.

Fig. 5. Lateral moraine near the distal end of Laguna Esmeralda.

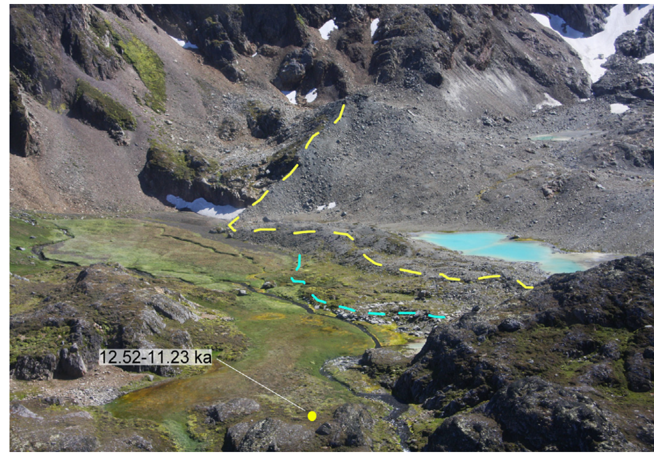

Fig. 7. View upvalley towards cirque D, showing the location of the pit (yellow dot) where plant leaves directly above diamicton and below Hudson tephra were collected and dated. Dashed cyan line delineates the outermost extent of the till surface where Hudson tephra is absent. Dashed yellow line demarcates unvegetated moraines in front of the glacier (100 m upvalley from pit site). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.2.2. Cirque D

Cirque D is located 6 km southeast of cirque C and contains a 1.5 km^2 glacier (Fig. 1). Lateral and end moraines interpreted to be LIA deposits extend 1 km downvalley from the toe of the glacier. The northeast LIA lateral moraine is multi-crested in places. A soliflucted hummocky surface of angular boulders overlies diamicton up to 70 m beyond the end moraine (Fig. 7). We interpret this diamicton to be ground moraine. We dug many pits dug on this surface but found no visible tephras, and sediment samples collected from different depths in the pits contained no glass shards. However, a 4-cm-thick bed of Hudson tephra was found 29–33 cm below the ground surface in a 70-cm pit 50 m beyond the outer limit of the ground moraine. Peat and organic silt in the pit overlie a clay-rich, matrix-supported diamicton. Alpine moss leaves recovered 1 cm above the diamicton returned a calibrated radiocarbon age of 12.52–11.23 ka (Table 1).

4.2.3. Cirque E

Vinciguerra Glacier (4.5 km^2) lies in cirque E, 1.2 km east of cirque D (Figs. 1 and 8). Unvegetated LIA moraines and trimlines extend up to 500 m beyond the glacier toe. No other moraines exist in cirque E but, as in cirque D, a bouldery diamicton extends 10–80 m beyond the unvegetated moraines and trimlines. No tephra was found in pits dug in this material. Hudson tephra, however, was found 90 m beyond the downvalley limit of the bouldery diamicton.

5. Discussion

Previous researchers have identified large end moraines believed to be of late Pleistocene age along Beagle Channel near Ushuaia (Clapperton, 1993; Coronato, 1995; Rabassa et al., 2000; Planas et al., 2002), but these landforms have not been firmly dated. In addition, moraines thought to be Holocene in age have been described in the mountains near Ushuaia (e.g. Rabassa et al., 2000; Planas et al., 2002; Strelin and Iturraspe, 2007), but their ages are also unknown. Our evidence for the ages of moraines in the Ushuaia area, from the oldest to the youngest, is summarized below.

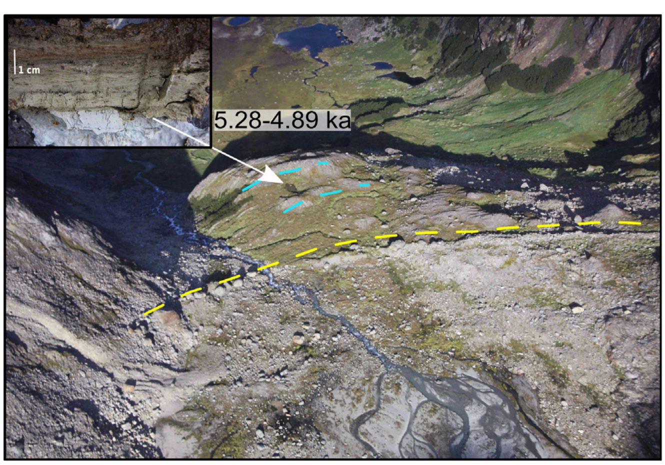

Fig. 6. View downvalley from cirque C. Dashed cyan lines delineate two moraine fragments lacking Hudson tephra. Fossil leaves directly above diamicton (upper left inset photo) provide a minimum limiting age of 5.29–5.05 ka for the surface. The moraine fragments are 100 m beyond inner moraines of the glacier constructed during the LIA (yellow dashed line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

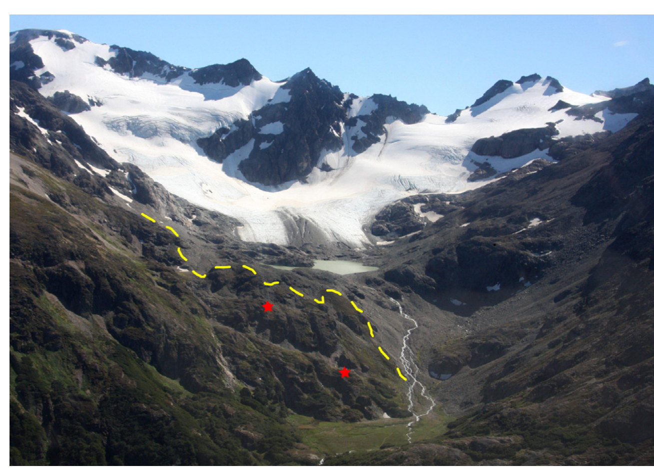

Fig. 8. View upvalley towards cirque E (Vinciguerra Glacier), showing locations where Hudson tephra (red stars) was found in pits beyond the uneroded moraine (dashed yellow line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5.1. Latest Pleistocene advances

Rabassa et al. (2000) argued that the Beagle Channel 50 km east of Ushuaia was ice-free before 18.52–17.17 ka based on bulk radiocarbon ages on peat above outwash. They further showed that Ushuaia itself was ice-free by 13.77–13.43 ka (Pista de Ski site; Fig. 1 of Rabassa et al., 2000). The apparent absence of Reclus tephra (16.18–14.03 ka) around Ushuaia may indicate that the tephra did not reach as far south as proposed by Stern (2008) or that the Ushuaia area was still covered by Cordillera Darwin ice at 16 ka and possibly as late as 14 ka. Hall et al., (2013) conclude that glaciers in the Cordillera Darwin west of Ushuaia were retreating between 18.0 and 14.6 ka and that most glaciers sourced from the Cordillera Darwin ice cap were close to their contemporary margins by 16.8–14.8 ka. They also argue that Beagle Channel 70 km west of Ushuaia was ice free by 14.8 ka.

Our field data indicate that alpine glaciers of the Fuegian Andes advanced at least twice after Valle Carbajal and Beagle Channel were deglaciated. There are two possibilities for the origin of these glaciers. Previous work suggests that the mountains north of Ushuaia harbored alpine glaciers through the Pleistocene and that the area was never covered by an extension of the Cordillera Darwin ice sheet (Coronato, 1995). In a scenario consistent with that interpretation, the small glaciers described in this study were remnants of larger Pleistocene valley glaciers. An alternative scenario, supported by the apparent restriction of the oldest moraines to high-elevation cirques, is that the area was indeed covered by Cordilleran Darwin ice and that downwasting of the ice exposed upland areas before valley floors and allowed cirque glaciers to form during deglaciation. Such a scenario has been documented in north-central British Columbia, Canada, where downwasting of the Cordilleran ice sheet exposed high-elevation areas prior to deglaciation of lower valleys (Lakeman et al., 2008). Further work is required to resolve this question.

A maximum age for the outer moraines in the Fuegian Andes cirques that we studied is provided by the ^{10}Be ages (16.79 ± 0.79 and 16.95 ± 0.75 ka) on striated bedrock beyond these moraines. Radiocarbon ages of 12.38–12.03 ka and 12.38–12.01 ka on plant fossils just upvalley of these moraines are minimum limiting ages for the Lateglacial advances (Table 1). The ^{10}Be ages from the outermost moraines at cirque B and Lago Esmeralda should directly date the advances (Table 2). Collectively, the data argue for a late Pleistocene advance of alpine glaciers in southernmost Patagonia at about 14 ka [12.85–14.83 ka]. The advance is correlative with the Antarctic Cold Reversal (ACR), as described farther north in southern Patagonia by Moreno et al. (2009) and Garcia et al. (2012) and in New Zealand by Putnam et al. (2010b). The exact age of the recessional moraine in cirque A, which has a minimum-limiting ^{14}C age range of 12.38–12.01 ka, remains uncertain. The advance could either date to the end of the ACR or represent a standstill of the glacier during the Younger Dryas (YD).

5.2. Early Holocene and Neoglaciation

The minimum limiting radiocarbon age for deglaciation of cirque D suggests that glaciers had diminished to extents comparable to those of the Little Ice Age (LIA) by 12.52–11.23 ka. Hudson tephra (7.96–7.34 ka) is present in most of cirques in the study area, generally to within 10–100 m of the LIA limit, but we did not find the tephra on any of the Holocene moraines, in spite of extensive searches. Our data thus suggest that any early Holocene glacier advance in southernmost Patagonia was smaller than those of the LIA.

Evidence for pre-LIA, Holocene glacier activity is provided by the post-Hudson moraine fragments and the bouldery surfaces interpreted to be modified ground moraine 10–100 m beyond contemporary ice limits. The glacier in cirque C constructed two Neoglacial moraines, one between 7.96 and 5.05 ka and the other after 5.29 ka.

5.3. Regional comparison

Ackert et al. (2008), Strelin et al. (2011), and Garcia et al. (2012) infer the chronology of late Pleistocene activity of outlet glaciers of the Southern Patagonian Icefield about 500 km north of Ushuaia. Ackert et al. (2008) initially reported that glaciers along the western edge of Lago Argentino built large terminal moraines at 10.5 ± 0.5 ka. Using more recent ^{10}Be production rates, Kaplan et al. (2011) recalculated the ^{10}Be ages reported by Ackert et al. (2008) and suggest that glaciers advanced at about 13 ka. Garcia et al. (2012) report that glaciers at nearby Torres del Paine (51°S) constructed moraines earlier, at about 14.2 ka. Collectively, these data demonstrate that outlet glaciers of the Southern Patagonian Icefield constructed terminal moraines between 14.2 and 12.7 ka during the ACR (14.5–12.9 ka). Kaplan et al. (2011) and Strelin et al. (2011) further suggest that retreat from these moraines was interrupted by a stillstand or minor advance at ca 12.2 ka. Our age for a glacier advance at 14.83–12.85 ka near Ushuaia is in agreement with the age range reported for moraine construction by outlet glaciers of the Southern Patagonian Icefield described above. It thus appears that alpine glaciers in southernmost Tierra del Fuego and outlet glaciers of the Southern Patagonian Icefield synchronously advanced during the ACR.

Whether a Younger Dryas signal is present in paleoecological records from Tierra del Fuego has long been debated and is of considerable interest. Heusser and Rabassa (1987) and Heusser (1989) favored the idea, whereas Ashworth et al. (1991) and Markgraf (1991, 1993a) opposed it. In our study, the minimum limiting radiocarbon age (12.38–12.01 ka) for the recessional moraine in cirque A overlaps the reported age for the minor standstill reported by Strelin et al. (2011) for outlet glaciers of the Southern Patagonian Icefield. It is likely that this moraine dates to the YD. Farther north, near the Northern Patagonian Icefield, Glasser et al. (2012) report fifteen ^{10}Be exposure ages for moraine boulders that generally fall within the YD. They also note that the evidence for advances during the ACR is largely absent. In contrast, Turner et al. (2005) suggest that recession of Northern Patagonian Icefield glaciers from Lateglacial Maximum positions slowed during the period 13.8–12.8 ka and note that final deglaciation commenced at 12.8 ka. The timing and magnitude of late Pleistocene advances for the Northern Patagonian Icefield remain equivocal.

Our data indicate that by 12.52–11.23 ka glaciers in the study area were no larger than those at the maximum of the LIA and never extended significantly past LIA limits through the Holocene (Fig. 9). Non-glacial proxy evidence for early Holocene climate from the study area is somewhat inconsistent. Data from Lago Fagnano (Moy et al., 2011) and from paleosols (Coronato et al., 2011) suggest a warm and wet climate during the Holocene. But a multi-proxy record from Harberton bog, 50 km east of Ushuaia, suggests that peat growth ceased between 10 and 6 ka because of increased fire frequency related to decreased relative humidity (Pendall et al., 2001; Markgraf and Huber, 2010). These interpretations of early Holocene climate in Tierra del Fuego are consistent with palynological studies in the area by Heusser (1989, 1998), Markgraf (1983, 1993b), and Markgraf et al. (2003), which indicate expansion of *Nothofagus* (beech) into the area during the early Holocene. Heusser (1998) also notes that grass species expanded during the early Holocene in response to a reduction in annual precipitation to values about 100 mm less than today. Such climate reconstructions argue against a greater cover of glacier ice on Tierra del Fuego

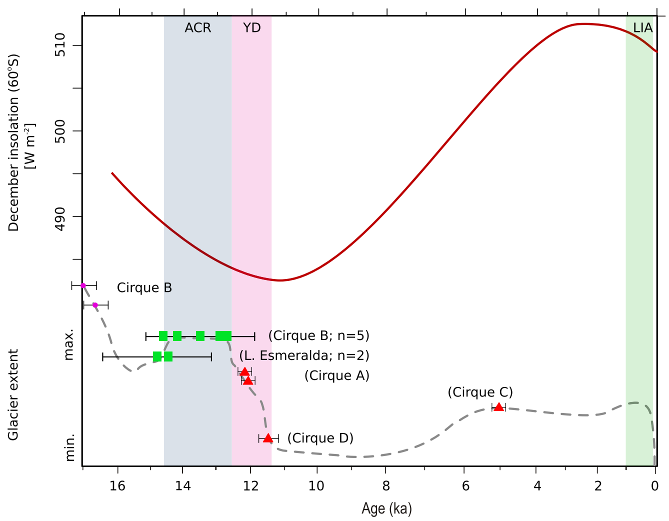

Fig. 9. Comparison of mid-December insolation (solid line) and inferred glacier extent (dashed line) in the study area. ACR, YD, and LIA, respectively, denote Antarctic Cold Reversal (14.5–12.9 ka), Younger Dryas Chronozone (12.2–11.7 ka), and the Little Ice Age (1.0–0.1 ka). Circles and squares are ^{10}Be ages with associated uncertainties ($\pm 1\sigma$). Triangles show radiocarbon ages (Table 1) with uncertainties ($\pm 2\sigma$) from cirques of this study. Insolation data from Berger and Loutre (1991), and inferred extent during the last millennium (Little Ice Age) based on Strelin et al. (2008) and Maurer et al. (2012).

during the early Holocene than today, consistent with the lack of moraines dating to that time.

The outermost, pre-LIA moraine in cirque C is bracketed by ages of 7.96–7.34 ka and 5.29–5.05 ka. The minimum limiting age of 5.29–5.05 ka overlaps the most probable age range (5.4–4.9 ka) that Porter (2000) suggests for the onset of the Neoglaciation in the Southern Hemisphere. This age range is also similar to the age of alpine plants (5.18–5.09 ka) killed during an expansion of the Quelccaya Ice Cap in Peru (Thompson et al., 2006). It is thus likely that the minimum limiting age for the intermediate moraine in cirque C is a close limiting age. Taken together, our data suggest that some glaciers in southernmost Tierra del Fuego advanced at least twice during the middle Holocene, once between 7.96–7.34 and 5.29–5.05 ka and again after 5.29–5.05 ka. The earlier advance coincides with a time when glaciers throughout the Southern Hemisphere expanded (Porter, 2000). On Tierra del Fuego, however, the early Neoglacial advances reached positions only tens of meters beyond those achieved during the late Holocene.

The simplest explanation for why early Neoglacial moraines are not more common in the study area is that more extensive, late Holocene advances overrode and destroyed older deposits. A similar hypothesis explains why, for example, cirque moraines correlative with the YD are found in only about 5% of cirques in the Canadian and American Rocky Mountains (Davis, 1988; Osborn and Luckman, 1988). Another possible explanation is that most LIA moraines in our study area terminate near the outer margins of cirques, beyond which preservation of terminal and lateral moraines on steep bedrock headwalls is unlikely. Whatever the cause, our field data suggest that early or middle Neoglacial advances were comparable in size to those of the LIA.

Previous workers have suggested that Patagonian Neoglacial advances extended well beyond LIA limits, but at least some of that work incorporates assumptions founded only on minimum-limiting ages (Porter, 2000). Clapperton and Sugden (1988), for example, summarize the evidence for a relatively extensive advance in Patagonia at about 5–4 ka, but concede that the evidence for it is equivocal. One possible interpretation reported by these authors is that the San Rafael Glacier in the North Patagonian Icefield did not advance past LIA limits for at least the past 7000 years. Strelin et al. (2008) interpret an undated moraine several kilometers downvalley from LIA moraines at Ema Glacier, 150 km west-northwest of our study area, to be probably 6–5 ka in age. But they acknowledge that it actually could be latest Pleistocene in age. Given the similar extents of middle Holocene and Little Ice Age advances in our study area, it is likely that the moraine at Ema Glacier is correlative with the late Pleistocene cirque moraines that are ACR in age.

Aniya (1995) describes four, successively smaller Neoglacial advances of a glacier in the Southern Patagonian Icefield north of our study area, and Wenzens (1999) reports eight, successively smaller Holocene advances of glaciers about 100 km north of Aniya's site. Porter (2000), however, casts doubt on several of the advances identified by Wenzens (1999), based on an interpretation of radiocarbon ages and the relation of dated deposits to moraines. More recently, Kaplan et al. (2011) and Strelin et al. (2011) have shown that the Hermanitas moraines at Lago Argentino, believed in previous work to be Neoglacial in age, are actually latest Pleistocene in age. Data from our study indicate one, or possibly two mid-Holocene advances, but we emphasize that these advances were only 10–100 m more extensive than the maxima achieved during the LIA. Our data do not support the number or recessive trend of advances suggested by Wenzens (1999) or Aniya (1995). We also did not find evidence for early Holocene advances, either because they did not occur or because the moraines were destroyed by later Neoglacial advances.

Schaefer et al. (2009) and Putnam et al. (2012) describe well dated Holocene moraines in New Zealand that show progressively less extensive advances through the Holocene, supporting summer insolation as a dominant control on long-term glacier activity. In contrast, retracted glaciers in our study area argue against summer insolation as a major control of glacier activity in southernmost Tierra del Fuego (Fig. 9). Other climatic factors such as the strength and position of the Westerlies (Waldmann et al., 2010a, 2010b; Fletcher and Moreno, 2012), changes in solar irradiance, or changes in atmospheric-ocean circulation may be more important controls for glacier fluctuations in Tierra del Fuego.

6. Conclusions

Our work to establish a latest Pleistocene and Holocene chronology for glaciers at the southern end of the Andes has revealed the following:

1) One and locally two closely spaced moraines located up to 2 km downvalley of Little Ice Age moraines demarcate advances of glaciers during the Antarctic Cold Reversal (14.5–12.9 ka) and the Younger Dryas (12.9–11.7 ka). Alpine glaciers had extents no greater than during the Little Ice Age by 12.52–11.23 ka.
2) There is no evidence for early Holocene moraines in southernmost Tierra del Fuego, in agreement with paleobotanical observations suggesting that the early Holocene was warm and dry in the study area.
3) The onset of the Neoglaciation is recorded at some sites, but glaciers achieved extents only 10–100 m downvalley from subsequent Little Ice Age limits during early and middle Neoglacial time. An older, limited Neoglacial advance is bracketed by ages of 7.96–7.34 and 5.29–5.05 ka; indirect evidence suggests that this advance occurred shortly after 6.41–6.30 ka. The younger advance occurred shortly before 5.18–5.09 ka.
4) The hypothesis that summer insolation was important in controlling Holocene glacier fluctuations in southern Patagonia is not supported by our data. Other factors such as changes in solar irradiance, the position and strength of the Westerlies,

changes in atmospheric-ocean circulation, or some combination thereof must play more important roles.

Acknowledgments

Funding for this research was provided by National Sciences and Engineering Research Council of Canada Discovery Grants to Menounos, Clague, and Osborn, and a PRIME Lab seed grant from the National Science Foundation. Davis was supported with a Bentley faculty research grant. Joe Koch and Marilen Feránndez assisted in the field. We thank Mary Samolczyk for preparing tephra samples for microprobe analysis and Darwyn Coxyn for identifying terrestrial plant macrofossils. Our paper benefitted from careful scientific reviews by Mike Kaplan and Charles Stern. This paper is a product of the Scientific Cooperation Agreement between CONICET (Argentina) and University of Northern British Columbia (Canada).

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