RETREAT OF THE CORDILLERA DARWIN ICEFIELD
DURING TERMINATION I

B.L. HALL\textsuperscript{1*}, G.H. DENTON\textsuperscript{1}, T.V. LOWELL\textsuperscript{2},
G.R.M. BROMLEY\textsuperscript{1}, A.E. PUTNAM\textsuperscript{1}

\textsuperscript{1}School of Earth and Climate Sciences and the Climate Change Institute,
University of Maine, Orono, Maine, USA.
\textsuperscript{2}Department of Geology, University of Cincinnati, Cincinnati, Ohio, USA.

\textbf{ABSTRACT.} During the last glaciation, the Cordillera Darwin icefield expanded northward toward the Straits of Magellan, eastward across Isla Grande de Tierra del Fuego and through Canal Beagle, and south and west across the numerous islands of southernmost Chile. Deglaciation commenced at \textasciitilde18 ka during Termination I. Alpine glaciers in the Fuegian Andes also likely retreated at that time. Radiocarbon ages from the interior regions of Cordillera Darwin suggest ice in at least some locations had retreated close to its present-day limit as early as \textasciitilde16.5 ka. The most likely cause for such rapid ice retreat was rising atmospheric temperatures at the start of Termination I.

\textbf{Key words:} Cordillera Darwin, Termination I, radiocarbon, deglaciation, Tierra del Fuego.

Received: 22 November 2016
Accepted: 3 February 2017
1. Introduction

Cordillera Darwin (~54°S; Fig. 1A) is the southernmost temperate icefield on earth, with glaciers that respond sensitively to changes in temperature (Sagredo et al., 2014). Thus, a history of its fluctuations affords important clues for reconstructing temperature history, as well as the behavior of and mechanisms within the Southern Hemisphere climate system. Moreover, the region lies in a zone of strong climate gradients from the Patagonian icefields to the north (~37-45°S) to the Antarctic Peninsula to the south (67-70°S) and thus is well-situated to aid in understanding the transition in climate between the polar high-southern latitudes and the more temperate mid-latitude regions.

We focus here on the behavior of glaciers in Tierra del Fuego, southernmost South America, during the termination of the last ice age, ~18-14.5 ka. This time period, known as Heinrich Stadial 1 (HS-1) in the North Atlantic basin, coincides with the last termination in the Southern Hemisphere. Understanding the far-field effects of HS-1 and its possible role in Southern Hemisphere climate may be key for unravelling the cause of Termination I. For example, Denton et al. (2010) proposed that cold northern conditions during HS-1 led to southward movement of the Intertropical Convergence Zone and, in turn, of the southern westerly wind belts and oceanic fronts in the vicinity of Tierra del Fuego. This movement of both atmospheric and oceanic boundaries has been documented in southern South America during both glacial and interglacial times (e.g., Lamy et al., 2004, Kaiser et al., 2005; Björck et al., 2012; Moreno et al., 2012; Kohfeld et al., 2013; Vanneste et al., 2015). Anderson et al. (2009) proposed that shifting of the westerly winds over the latitude of the Drake Passage during HS-1 caused increased upwelling, which was instrumental in breaking down Southern Ocean stratification and releasing carbon dioxide to the atmosphere during the last termination.

In this paper, we begin by reviewing evidence for the extent of the Cordillera Darwin ice field at the last glacial maximum (LGM: 19-23 ka, Mix et al., 2001) and then present the current understanding of the timing and causes of deglaciation of this region during Termination I. The goal is to begin to develop an understanding of the process that set in motion the complex changes in ice extent, sea level, and landscape evolution in this region at the end of the last ice age.

Tables 1 and 2 present chronologic information used in this paper. For radiocarbon data, ages quoted in the text are in calendar years obtained from the INTCAL13 dataset and CALIB 7.0 or (in one case) the Marine13 dataset with a delta R of 140 years (Reimer et al., 2013). Original radiocarbon dates are in Table 1. Beryllium-10 surface exposure ages (Table 2) are all calculated using the Lago Argentino production rate (Kaplan et al., 2011) and the Lal (1991)/Stone (2000) scaling scheme.
Table 1. Compilation of radiocarbon ages of basal organic remains in bog cores. Radiocarbon ages were converted to calendar years using CALIB 7 and the INTCAL13 and MARINE13 datasets (Reimer et al., 2013). Dates presented here are calculated as the midpoints of the ranges given by CALIB. Calibrations with a probability <10% are not included. Calibrated ages may differ from those presented in the original papers due to changes in calibration datasets. Superscripts after the calibrated ages are keyed to Figure 3.

<table>
<thead>
<tr>
<th>Location</th>
<th>Core or Depth</th>
<th>Lab #</th>
<th>Material</th>
<th>^14C yr B.P.</th>
<th>1σ</th>
<th>Cal yr B.P.</th>
<th>2σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bahía Inútil/Northern Isla Dawson</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E. Esmerelda II ¹²</td>
<td>300-312 cm</td>
<td>A-6793</td>
<td>Bulk carbon</td>
<td>14 260</td>
<td>350</td>
<td>17 240</td>
<td>930</td>
</tr>
<tr>
<td>E. Cameron II ¹²</td>
<td>420 cm</td>
<td>AA-42413</td>
<td>Plant remains</td>
<td>13 980</td>
<td>120</td>
<td>16 960</td>
<td>410</td>
</tr>
<tr>
<td>E. Esmerelda II ¹²</td>
<td>312 cm</td>
<td>SRR-5143</td>
<td>Bulk carbon</td>
<td>13 890</td>
<td>50</td>
<td>16 810</td>
<td>230</td>
</tr>
<tr>
<td>E. Esmerelda II ¹²</td>
<td>300-312 cm</td>
<td>A-6814</td>
<td>Bulk carbon</td>
<td>13 650</td>
<td>310</td>
<td>16 520</td>
<td>900</td>
</tr>
<tr>
<td>E. California ¹²</td>
<td>341 cm</td>
<td>AA-42414</td>
<td>Plant remains</td>
<td>13 614</td>
<td>86</td>
<td>16 440</td>
<td>300</td>
</tr>
<tr>
<td>E. Esmerelda I ¹²</td>
<td>390-400 cm</td>
<td>A-6807</td>
<td>Bulk carbon</td>
<td>13 425</td>
<td>310</td>
<td>16 160</td>
<td>910</td>
</tr>
<tr>
<td>P. Cameron ¹²</td>
<td>No information</td>
<td>A-6791</td>
<td>Bulk carbon</td>
<td>13 030</td>
<td>260</td>
<td>15 520</td>
<td>860</td>
</tr>
<tr>
<td>Paso Garibaldi ²</td>
<td>284 cm</td>
<td>A-4882</td>
<td>Bulk peat</td>
<td>10 730</td>
<td>180</td>
<td>12 570</td>
<td>450</td>
</tr>
<tr>
<td>Northern Cordillera Darwin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P. Marinelli ²</td>
<td>MARPT-07-02_10.34-10.35m</td>
<td>OS-64095</td>
<td>Peat macro.</td>
<td>13 950</td>
<td>55</td>
<td>16 900</td>
<td>250</td>
</tr>
<tr>
<td>P. Marinelli ²</td>
<td>MARPT-07-02_10.34-10.35m</td>
<td>OS-61545</td>
<td>Gyttja</td>
<td>14 050</td>
<td>70</td>
<td>17 080</td>
<td>290</td>
</tr>
<tr>
<td>P. Marinelli ²</td>
<td>MARPT-07-02_10.35-10.36m</td>
<td>OS-64068</td>
<td>Peat macro.</td>
<td>13 250</td>
<td>85</td>
<td>15 390</td>
<td>260</td>
</tr>
<tr>
<td>P. Marinelli ²</td>
<td>MARPT-07-02_10.36m</td>
<td>OS-61606</td>
<td>Sedge</td>
<td>13 400</td>
<td>85</td>
<td>16 110</td>
<td>270</td>
</tr>
<tr>
<td>P. Marinelli ²</td>
<td>MARPT-07-02_10.36-10.38m</td>
<td>OS-63929</td>
<td>Seeds</td>
<td>13 250</td>
<td>55</td>
<td>15 390</td>
<td>200</td>
</tr>
<tr>
<td>P. Marinelli ²</td>
<td>MARPT-07-02_10.36-10.38m</td>
<td>OS-64070</td>
<td>Peat macro.</td>
<td>13 650</td>
<td>90</td>
<td>16 490</td>
<td>310</td>
</tr>
<tr>
<td>P. Esperanza ²</td>
<td>PE-07-01_8.74-8.77m</td>
<td>OS-61551</td>
<td>Gyttja</td>
<td>13 350</td>
<td>65</td>
<td>16 050</td>
<td>220</td>
</tr>
<tr>
<td>S. Almirantazgo ³</td>
<td>NBP0505 JPC77_0.78m</td>
<td>No data</td>
<td>Marine carbonate*</td>
<td>13 650</td>
<td>70</td>
<td>15 690</td>
<td>320</td>
</tr>
<tr>
<td>Eastern Canal Beagle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harberton ²</td>
<td>Harberton_10.4m</td>
<td>QL-4279</td>
<td>unknown</td>
<td>14 640</td>
<td>260</td>
<td>17 790</td>
<td>650</td>
</tr>
<tr>
<td>Harberton ³</td>
<td>998 cm</td>
<td>A-4817</td>
<td>Drepanocladus</td>
<td>13 360</td>
<td>280</td>
<td>16 080</td>
<td>830</td>
</tr>
<tr>
<td>Harberton ³</td>
<td>HAR12-PB01A/727</td>
<td>GdA-2882</td>
<td>Brown moss</td>
<td>13 335</td>
<td>59</td>
<td>16 040</td>
<td>210</td>
</tr>
<tr>
<td>Caleta Róbalo ²</td>
<td>Caleta Róbalo_9.1m</td>
<td>QL-1685</td>
<td>unknown</td>
<td>12 730</td>
<td>90</td>
<td>15 120</td>
<td>360</td>
</tr>
<tr>
<td>Ushuaia ²</td>
<td>Ushuaia_2.8.2m</td>
<td>Beta 55681</td>
<td>Bulk org.</td>
<td>12 430</td>
<td>80</td>
<td>14 480</td>
<td>510</td>
</tr>
<tr>
<td>Ushuaia ³</td>
<td>Ushuaia_3.5.1m</td>
<td>QL-4162</td>
<td>Bulk org.</td>
<td>12 100</td>
<td>50</td>
<td>13 950</td>
<td>160</td>
</tr>
<tr>
<td>Ushuaia ³</td>
<td>Ushuaia_1.6.7m</td>
<td>QL-4436</td>
<td>Bulk org.</td>
<td>12 060</td>
<td>60</td>
<td>13 920</td>
<td>160</td>
</tr>
<tr>
<td>Lapataia ³</td>
<td>Lapataia_5.1m</td>
<td>RL-2001</td>
<td>Bulk org.</td>
<td>10 080</td>
<td>250</td>
<td>11 820</td>
<td>740</td>
</tr>
<tr>
<td>Southern Cordillera Darwin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V. Holanda ³</td>
<td>H-07-01_3.95m</td>
<td>OS-61638</td>
<td>Peat macro.</td>
<td>12 550</td>
<td>60</td>
<td>14 780</td>
<td>360</td>
</tr>
<tr>
<td>Bahía Pía ³</td>
<td>BL-07-16B_4.56m</td>
<td>OS-64237</td>
<td>Peat macro.</td>
<td>12 350</td>
<td>120</td>
<td>14 500</td>
<td>490</td>
</tr>
<tr>
<td>Caleta Olla ³</td>
<td>CO-07-02_5.3m</td>
<td>OS-61542</td>
<td>Peat macro.</td>
<td>10 300</td>
<td>50</td>
<td>12 090 (80%)</td>
<td>160</td>
</tr>
<tr>
<td>Bahía Pía ³</td>
<td>BL-07-15_1.50m</td>
<td>OS-61603</td>
<td>Grass,sedge</td>
<td>9310</td>
<td>65</td>
<td>10 490</td>
<td>190</td>
</tr>
</tbody>
</table>

¹Heusser (1989a); ²Heusser (1989b); ³Heusser (1998); ⁴Boyd et al. (2008); ⁵Hall et al. (2013); ⁶McCulloch et al. (2005b); ⁷Clapperton et al. (1995); ⁸McCulloch and Bentley (1998); ⁹Vanneste et al., 2015; ¹⁰Markgraf and Huber, 2010
* A delta R of 140 years was applied to this sample, following the original authors.
Table 2. Surface-exposure age data relating to the innermost LGM moraine belt (Belt “D” of McCulloch et al., 2005b) at Bahía Inútil and deglaciation in the Fuegian Andes. Calculations are based on the Lago Argentino production rate and the time-dependent Lal (1991)/Stone (2000) scaling scheme (“Lm”). Ages for the Bahía Inútil region were recalculated from the original papers by Kaplan et al. (2011). Ages are quoted with 1-sigma internal error. Superscripts after the ages are keyed to Figure 3.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elev. (m)</th>
<th>Thickness (cm)</th>
<th>Shielding</th>
<th>^10Be atoms</th>
<th>Error (1σ)</th>
<th>Standard</th>
<th>Age (yr BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BI:C1&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-53.5781</td>
<td>-69.4844</td>
<td>52</td>
<td>4.0</td>
<td>1.0</td>
<td>96 455</td>
<td>6752</td>
<td>S555</td>
<td>18 500 ± 1300&lt;sup&gt;29&lt;/sup&gt;</td>
</tr>
<tr>
<td>BI:C2&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-53.5808</td>
<td>-69.4872</td>
<td>48</td>
<td>4.0</td>
<td>1.0</td>
<td>98 849</td>
<td>14 234</td>
<td>S555</td>
<td>19 000 ± 2800&lt;sup&gt;30&lt;/sup&gt;</td>
</tr>
<tr>
<td>BI:C3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-53.5881</td>
<td>-69.4889</td>
<td>54</td>
<td>4.0</td>
<td>1.0</td>
<td>100 012</td>
<td>9800</td>
<td>S555</td>
<td>19 100 ± 1900&lt;sup&gt;31&lt;/sup&gt;</td>
</tr>
<tr>
<td>SM-02-21&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-53.5783</td>
<td>-69.4852</td>
<td>60</td>
<td>0.6</td>
<td>1.0</td>
<td>107 975</td>
<td>31 430</td>
<td>S555</td>
<td>20 100 ± 5900&lt;sup&gt;32&lt;/sup&gt;</td>
</tr>
<tr>
<td>SM-02-23&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-53.5798</td>
<td>-69.4781</td>
<td>56</td>
<td>2.9</td>
<td>1.0</td>
<td>92 397</td>
<td>8565</td>
<td>S555</td>
<td>17 500 ± 1600&lt;sup&gt;33&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup>McCulloch et al., 2005b
<sup>b</sup>Kaplan et al., 2008a
<sup>c</sup>Menounos et al., 2013

2. Regional Setting and Physiography

Hundreds of islands from the Straits of Magellan to Cape Horn make up Tierra del Fuego (Fig. 1A, B). Cordillera Darwin, an east-west trending crystalline mountain range with peaks that surpass 2000 m elevation, dominates the central portion of region and forms the western peninsula of Isla Grande de Tierra del Fuego (hereafter “Isla Grande”). The mountains stretch nearly from the Pacific to the Atlantic Ocean and are bordered to the northwest by Canals Cockburn, Magdalena, and Gabriel, as well as to the north by Seno Almirantazgo and to the south by the Canals Beagle and Ballenero. The highest peaks lie near the center of the range and decrease in elevation both east and west.

Much of Tierra del Fuego lies under a wet, maritime climate strongly affected by the Southern Westerlies. Average mean annual temperature is ~5°C (Rabassa et al., 2000). Precipitation is several meters per year near the Pacific coast and declines to less than 0.5 m/yr in drier areas of eastern Tierra del Fuego (Lliljequist, 1970; Tuhkanen, 1992; C. Porter, unpublished data, 2007; Fontana and Bennett, 2012). This precipitation gradient has an effect both on modern snowline elevations, which rise from west to east, and on vegetation.

Cordillera Darwin, as well as the islands to the south, display a rugged landscape (Fig. 2) characterized by extensive tracts of areally scoured bedrock and dissected by fjords (~200-400 m water depth). In contrast, eastern Isla Grande has a more rolling topography, and the landscape is dominated by LGM-aged and older moraines and glaciofluvial sediments. Relatively few constructional glacial landforms occur between the LGM moraine belt and Holocene/Late Glacial moraines located in the interior of the mountains near present-day glaciers.
3. Last Glacial Maximum Position

Although well-documented in some locations, the LGM extent of the Cordillera Darwin ice field remains uncertain along most of its perimeter (Fig. 1A). Caldenius (1932) produced the earliest comprehensive map showing proposed LGM ice extent and, in many locations, this map still remains the only resource. During the LGM, ice spread from the high peaks of central Cordillera Darwin and flowed northward to the Straits of Magellan, eastward through Seno Almirantazgo to Lago Fagnano, southeastward through Canal Beagle to the junction with the Atlantic Ocean, and south and westward across the numerous islands of southern and western Tierra del Fuego to end on the continental shelf (Caldenius, 1932; Coronato et al., 1999, 2009; Rabassa et al., 2000, 2011).

Northern ice flow from Cordillera Darwin is characterized best along a flowline through Canal Whiteside to Bahia Inútil, where numerous, low-relief moraines enclose
the eastern end of the bay (Caldenius, 1932; Meglioli, 1992; Clapperton et al., 1995; Bentley et al., 2005; McCulloch et al., 2005a, 2005b; Evenson et al., 2009; Darvill et al., 2014). The moraines can be traced southeastward across Isla Grande, where they are thought to correlate with those enclosing the eastern end of Lago Fagnano (Coronato et al., 2009). One distinguishing feature of the right lateral moraines at Bahía Inútil is the presence of a train of large boulders of Beagle granite (Fig. 2A). Known as Darwin’s
Boulders (Evenson et al., 2009), these erratics mark a former ice flowline from central Cordillera Darwin that, based on lithology, must have originated at the head of Marinelli and/or Brooks fjords (Fig. 1B).

The age of many of the Bahía Inútil moraines is uncertain. The traditional paradigm is that the inner belts of moraines closest to the bay (B, C, and D of Bentley et al., 2005) date to the LGM and that the outer moraines (A and older), particularly those along the Atlantic coast, relate to much older glaciations (Meglioli, 1992; McCulloch et al., 2005; Evenson et al., 2009). In this context, boulders in the older moraine belts that yield what seem to be anomalously “young” ages have been interpreted as having loss of cosmogenic nuclides from significant erosion (e.g., Kaplan et al., 2007; Evenson et al., 2009). However, Darvill et al. (2015), noting that Darwin’s Boulders all appear to be from a single flowline and show similar degrees of weathering, opened the possibility that many of the outer moraines are younger than previously thought and may be from the last glaciation.

The LGM moraine belt trends southeastward from Bahía Inútil to Lago Fagnano, where it extends around the eastern end of the lake. The Lago Fagnano ice lobe was fed by an outlet glacier that streamed southeastward through Seno Almirantazgo, as well as by input from local alpine glaciers (Coronato et al., 2009). Radiocarbon ages of peat layers within deltaic deposits below till suggest that ice advance to the LGM position occurred after ~36 ka (Bujalesky et al., 1997; Coronato et al., 2009), although it is uncertain if the radiocarbon ages are truly finite.

On the south side of the former Darwin ice field, the only flow line known with some confidence is one that extended eastward along Canal Beagle, terminating at Punta Moat, where it formed moraines near the junction with the Atlantic Ocean (Rabassa et al., 1990, 2000). The LGM ice position along the southern and western margins of the icefield remains uncertain, as there are no documented terminal moraines and the ice likely terminated offshore. Caldenius (1932) placed the ice margin near the shelf edge, whereas Coronato et al. (1999) drew it closer to the present-day coast and showed extensive subaerial outwash plains on what is now the continental shelf.

The timing of the youngest LGM moraine –the age of which affords a close maximum limit on the timing of deglaciation– is known only near Bahía Inútil. Here, $^{10}$Be cosmogenic surface-exposure ages of boulders on moraine crests suggest an age of $\sim$18.4 ± 1.7 ka for the innermost moraines along the south shore of the bay (error-weighted mean of five ages published in McCulloch et al. (2005b) and Kaplan et al. (2008a), recalculated in Kaplan et al. (2011); see Fig. 3A and Table 2).

4. Timing of Recession

Information on the timing of ice recession comes primarily from radiocarbon dates of the lowest organic materials found in bogs that lie proximal to the LGM moraine belt. Such dates afford minimum-limiting radiocarbon ages for deglaciation. In humid areas, such as Cordillera Darwin, re-vegetation following deglaciation appears to have occurred quickly. Observation today suggests a lag time there of less than a decade for vegetation growth
following ice retreat in Cordillera Darwin (C. Porter, unpublished data). The delay in revegetation may be more substantial in drier areas of Isla Grande (Coronato et al., 1999).

Radiocarbon dates of basal organic materials in bogs adjacent to Bahía Inútil and on northern Isla Dawson afford minimum ages for initial deglaciation from the D moraines (Table 1). McCulloch et al. (2005b) obtained ages as old as ~17 ka from bogs inboard of the D moraines on the south shore of the bay at Estancias Cameron and California (Figs. 1A, 3A). The northern tip of Isla Dawson may have been deglaciated by about the same time (Clapperton et al., 1995; McCulloch and Bentley, 1998; McCulloch et al., 2005b).

More recently, Hall et al. (2013) cored bogs in the interior of Cordillera Darwin along the same ice flow lines that fed the Bahía Inútil lobe. Ice emanating from Brooks fjord flowed north through Canal Whiteside to feed the Bahía Inútil lobe at the LGM. The flow direction of ice discharging from Marinelli fjord is less clear. Although it is likely that ice from this fjord also augmented the Bahía Inútil lobe, the possibility cannot be discounted that it may have contributed to ice that ultimately fed the Lago Fagnano lobe. In either case, dates of basal organic materials in bogs from these sites afford minimum ages for the retreat of the former Darwin icefield back into the heart of the mountains. At Brooks fjord, a radiocarbon date of organic material within a core at Punta Esperanza yielded a minimum age for deglaciation of ~16.1 ka (Hall et al., 2013; Table 1; Fig. 3B). This date is not thought to afford a close-limiting age, because the core did not penetrate to the glacial clay, and thus it is not known if the lowest organic materials were sampled. To the east at the mouth of Marinelli fjord, six samples of plant remains within four centimeters of the top of the glacial lacustrine clay yielded a weighted mean of 16.3 ± 0.5 ka (Hall et al., 2013; Fig. 2F, Table 1). The location of this bog indicates that ice must have retreated to within seven kilometers of the position it occupied in the 20th century by that time. Additional confirmation for the basal ages in both the Marinelli and Brooks bogs comes from the presence of the Reclus tephra (~15 ka; Stern, 2008) at higher levels in the cores at both sites (Hall et al., 2013). Moreover, a core from the adjacent sound produced an age of ~15.7 ka for the lowest recovered marine carbonate, consistent with deglaciation prior to that time (Boyd et al., 2008). Thus, it seems likely that the Darwin icefield had receded back into the mountains on the north side of the Cordillera by at least ~16.3 ka.

There are also ages for basal organic materials in several bogs on the south side of Cordillera Darwin. Along eastern Canal Beagle ~50 km inboard of the Moat moraines, Heusser (1989a) obtained an age of ~17.8 ka for the lowest organic materials within a bog at Harberton. This age affords evidence that deglaciation from the LGM position was already underway at that time. Other dates from bogs located along eastern Canal Beagle have been interpreted as showing a pattern of gradual ice retreat towards the center of Cordillera Darwin (Fig. 3A, B; Heusser, 1998; Rabassa et al., 2000). Organic material in a bog at Caleta Róbalo on Isla Navarino produced an age of ~15.1 ka. Another bog near Ushuaia gave an age of ~14.5 ka, whereas one farther west at Lapataia yielded a date of ~11.8 ka. However, recent data from the center of Cordillera Darwin conflicts with this pattern of slow retreat. From dates of bogs near Bahía Pía, Hall et al. (2013) concluded that ice had retreated far into the interior of Cordillera Darwin prior to 14.5 ka (Table 1; Fig. 3B). Support for this minimum-limiting age comes from a core near Ventisquero.
Holanda, only 800 m from the late Holocene moraine complex. Plant remains overlying basal gravel there produced an age of 14.8 ka. This date is not thought to be a close-minimum age, because it came from hillside peat rather than from a bog. However, the date shows that ice retreat had progressed to nearly modern positions by at least ~15 ka.

A cosmogenic surface exposure age dataset from the Fuegian Andes along eastern Canal Beagle further constrains the timing of ice retreat in Tierra del Fuego. Although focused primarily on the Holocene record, Menounos et al. (2013) obtained two dates of bedrock just distal to the Late-Glacial (Antarctic Cold Reversal) moraine. Similar to the date from Harberton, these ages indicate that alpine ice in the eastern part of Tierra del Fuego had already begun to retreat by ~17.8 ka and had receded to at least its Late-Glacial position by ~16.7 ka (Table 2; Fig. 3A).

Figure 3. Chronologic constraints on the timing of ice recession in Tierra del Fuego during the last termination. Dates on black background are \(^{10}\)Be surface exposure ages and afford actual ages of moraines and erratics that record former ice position (Table 2). Dates on white background are minimum-limiting radiocarbon ages for deglaciation (Table 1).
Available evidence from Cordillera Darwin suggests only modest ice advance during the subsequent Antarctic Cold Reversal. Although early reports suggested a major ACR advance to the vicinity of Isla Dawson on the north side of Cordillera Darwin (McCulloch et al., 2005a), sediment cores from Puntas Esperanza and Marinelli are at odds with that interpretation, as they lack any evidence for a readvance following initial deglaciation. The Punta Esperanza bog core, in particular, would have been covered by any ice that advanced north from Cordillera Darwin through Canal Whiteside to Isla Dawson. Therefore, we conclude that the deposits attributed to the ACR must date to an earlier time period. The only confirmed ACR-age moraines are from cirque glaciers in the Fuegian Andes, where the ice margins lay only 0.85-2.5 km beyond their present positions (Menounos et al., 2013). Moraines similar in appearance and position relative to the modern glaciers occur in central Cordillera Darwin; work is under way to determine their age (Hall et al., in prep.).

In summary, available data on both sides of Cordillera Darwin, as well as in the Fuegian Andes, suggest rapid ice recession shortly after the start of Termination I (~18 ka), with retreat into the interior fjords no later than ~16.5 ka on the north side and at >14.8 ka on the south flank of the mountain range. The icefield at that time appear to have retreated at least to its Late-Glacial position, if not behind the fronts of present-day glaciers. To put this recession in context, such a retreat resulted in a loss of >85% of the Brooks flowline in <=2000 years. Such a rapid recession is remarkably similar to that in earlier modelling studies by Hulton et al. (2002), who suggested that 80% of the icefield may have disappeared within 2000 years of the start of Termination I, based on application of a rapid 6°C temperature warming in the model.

5. Mechanisms

What caused rapid recession of the Darwin icefield shortly after 18 ka? Although several factors can cause glaciers to retreat (rising air temperatures, decreased precipitation, rapid calving in a marine environment), available information favors a significant air-temperature increase, which caused a rapid rise in regional equilibrium-line altitudes (ELA). Numerous studies have shown the temperature-sensitivity of mountain glaciers (i.e., Oerlemans, 2005; Zemp et al., 2015), but the most pertinent here is an in-depth latitudinal study of Andean glaciers, including those in Cordillera Darwin. Using a surface energy-balance model, Sagredo et al. (2014) found that ELA is relatively insensitive to precipitation changes in humid, cloudy environments, such as Cordillera Darwin, because of the link between surface energy balance and atmospheric emissivity. They further calculated that a precipitation increase of ~75% (in an area already very wet) would be required to offset a 1°C temperature rise in Cordillera Darwin (Sagredo et al., 2014). We thus feel comfortable with concluding that rapid ice recession in Cordillera Darwin during Termination I was due primarily to rising air temperatures and not to precipitation deficits. This interpretation is consistent not only with new Antarctic ice-core temperature records (e.g., WAIS Divide, Buizert et al., 2015; Fig. 4), but also with the marine record offshore of southwestern Chile, which shows a warming ocean at the same time (Lamy et al., 2004; Kaiser et al., 2005;
Retreat of the Cordillera Darwin icefield during Termination I

Caniupán et al., 2011; Saavedra-Pellitero et al., 2011). Although the warm marine water did not directly impact much of the Cordillera Darwin icefield through melting at the grounding line during initial deglaciation [the sea did not flood the Straits of Magellan and Canal Beagle until later (e.g., Bujalesky et al., 1997), and much of the glaciated continental shelf was above sea level], ocean and atmospheric temperatures are commonly linked in this region (e.g., McKinnon et al., 2013). Thus, the rapid recession of the Cordillera Darwin icefield at ~18 ka likely was a symptom of rapidly warming climate during Termination I.

6. Summary

The major pulse of deglaciation of Tierra del Fuego commenced at ~18 ka, with recession of the Cordillera Darwin icefield documented from both Bahía Inútil in the north and Canal Beagle in the south. Alpine glaciers in the Fuegian Andes also likely retreated at that time. Radiocarbon ages from the interior regions of Cordillera Darwin...
suggest ice in at least some locations had retreated close to its present-day limit as early as ~16.5 ka. The most likely cause for such rapid ice retreat was rising atmospheric temperatures at the start of Termination I.

7. Acknowledgements

We are indebted to the late Charlie Porter for his insights into the fjords of Cordillera Darwin, for his knowledge of local weather conditions derived from a network of automated weather stations, and for the use of his boat, Ocean Tramp. We also acknowledge funding for our field work in Tierra del Fuego from the US National Science Foundation and from the Comer Family Foundation. We would like to thank the reviewers and editors for very helpful reviews.

References


Rabassa, J., Heusser, C., Rutter, N. 1990. Late-glacial and Holocene of Argentine Tierra del Fuego. *Quaternary of South America and Subantarctic Islands* 7, 327-351.


