Evidence of early Holocene glacial advances in southern South America from cosmogenic surface-exposure dating

D.C. Douglass* }
B.S. Singer } Department of Geology and Geophysics, University of Wisconsin, Madison, Wisconsin 53706, USA
M.R. Kaplan Department of Geology and Geophysics, University of Wisconsin, Madison, Wisconsin 53706, USA, and School of GeoSciences, University of Edinburgh, Edinburgh EH8 9XP, Scotland, UK
R.P. Ackert Department of Earth and Planetary Science, Harvard University, Cambridge, Massachusetts 02138, USA
D.M. Mickelson Department of Geology and Geophysics, University of Wisconsin, Madison, Wisconsin 53706, USA
M.W. Caffee PRIME Lab, Purdue University, West Lafayette, Indiana 47907, USA

ABSTRACT

Cosmogenic nuclide surface-exposure dating reveals that glaciers in southern South America (46°S) advanced ca. 8.5 and 6.2 ka, likely as a result of a northward migration of the Southern Westerlies that caused an increase in precipitation and/or a decrease in temperature at this latitude. The older advance precedes the currently accepted initiation of Holocene glacial activity in southern South America by ~3000 yr. Both of these advances are temporally synchronous with Holocene climate oscillations that occurred in Greenland and the rest of the world. If there are causal links between these events, then rapid climate changes appear to be either externally forced (e.g., solar variability) or are rapidly propagated around the globe (e.g., atmospheric processes).

Keywords: cosmogenic elements, exposure age, paleoclimatology, glacial geology, Chile, Patagonia.

INTRODUCTION

Denton and Karlén (1973) identified three main episodes of Holocene alpine glacial expansion occurring ca. 5300, 2800, and 200–300 calibrated yr B.P. (early, middle, and late Neoglaciation or Little Ice Age, respectively; these and all radiocarbon ages have been calibrated with Calib 4.4 available at http://radiocarbon.pa.qub.ac.uk/calib/). Despite the prediction of glacial advances ca. 8 ka based on the periodicity of the Neoglacial advances, confirming reports are generally not well accepted. In a review of Holocene glaciations (Davis and Osborn, 1988), six of seven papers discuss, but ultimately reject, evidence for glacial advances during the early Holocene. This skepticism stems from poor chronologic constraints for these deposits and the fact that warm conditions during the early Holocene are consistently interpreted from pollen and other paleoclimate records. One notable exception, the Cockburn moraines in northern Canada, marks a readvance before the final collapse of the Laurentide Ice Sheet. However, hesitation to accept early Holocene glacial activity is at odds with the increasing evidence for global, quasi-periodic climate change that has occurred throughout the Holocene (e.g., Alley et al., 1997; Mayewski et al., 2004). Radiocarbon dating of a few small moraines adjacent to the southern Andes (Röthlisberger, 1986; Wenzens, 1999) provides tantalizing evidence in support of these early Holocene advances; however, these results have been characterized as either local anomalous events (Bennett et al., 2000) or as requiring further confirmation (Heusser, 2003).

No clear consensus on the cause of Holocene climate variability has emerged. Some of the proposed mechanisms include (1) cyclic variations in solar output (Denton and Karlén, 1973; Bond et al., 2001); (2) modulation of thermohaline circulation (Teller and Leverington, 2004); (3) the stochastic resonance model, which combines elements of the first two mechanisms (Alley et al., 2001); and (4) changing concentrations of greenhouse gases such as water and methane in the atmosphere (Cane and Clement, 1999; Brook et al., 1999). However, rigorous testing of these hypotheses is hampered by a poor understanding of the synchroneity of climate-change events around the globe, as well as past changes in many of the weather systems of the world, especially the Southern Westerlies (e.g., McCulloch et al., 2000).

The Westerlies dominate the climate of southern South America, delivering an average of 4000 mm of precipitation per year to the west side of the Andes south of 40°S; the core of the Westerlies is focused at ~50°S, which receives almost 8000 mm/yr. Due to steep north-south and east-west precipitation gradients, changes in the position and/or intensity of the Westerlies could cause large changes in precipitation and temperature for a given location. Because glaciers are sensitive to these parameters, determination of the timing and magnitude of glacial advances is a powerful method of reconstructing past configurations of this important climate system and provides first-order data that can be used to test proposed mechanisms of climate change. We present equilibrium-line altitude (ELA) reconstructions and ^{10}Be and ^{36}Cl cosmogenic surface-exposure ages from two moraines in southern Chile that indicate substantial glacier advances ca. 8.5 and 6.2 ka.

GEOLOGIC SETTING

These moraines are located at Fachinal, Chile (Fig. 1A; 46.57°S 72.22°W). In the east, the moraines are two separate ridges, whereas the western part is a single complex of hummocky deposits (Fig. 1B). They are sharp crested, vegetated by sparse grass and shrubs, and dotted with numerous large boulders. The moraines are deposited on a delta surface that is ~100 m above the modern level of Lago General Carrera (this lake spans the Chilean-Argentine border and is called Lago Buenos Aires in Argentina). The delta formed when drainage to the Pacific Ocean via the Rio Baker was blocked by glaciers advancing eastward out of the Northern Patagonian Icecap (Fig. 1A). The moraines contain deformed lake sediment, and outwash channels flow across the delta surface, but do not incise the delta front. From this geomorphic evidence we infer that the moraines at Fachinal are coeval with advances of outlet glaciers of the Northern Patagonian Icecap. This regional synchroneity indicates that these glacier advances were responses to regional climate, rather than isolated glacial surges.

METHODS

The magnitude of climate changes responsible for these advances is estimated from the difference between the modern equilibrium-line altitude and the paleo-ELA at the time of moraine deposition. The drainage currently contains several small (2–3 km) isolated cirque glaciers, from which we estimate a modern ELA of ~1400 m (Appendix DR1[1]). The paleo-ELA is estimated by using an accumulation-

*Corresponding author: douglass@geology.wisc.edu.

[1]GSA Data Repository item 2005041, Appendix DR1 (equilibrium-line altitude reconstructions, cosmogenic surface-exposure methods, and data reduction), Table DR1 (boulder compositions), Table DR2 (^{10}Be data), Table DR3 (^{36}Cl data), and Figure DR1 (valley topography and hypsometry), is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

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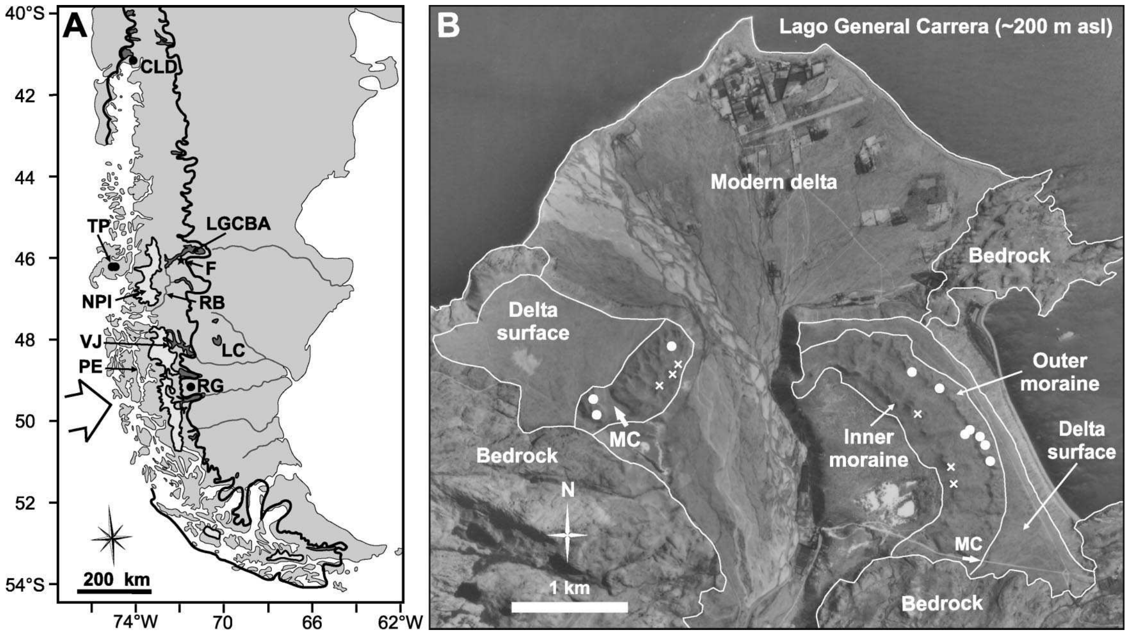

Figure 1. A: Southern South America. Heavy black line indicates ice extent at Last Glacial Maximum. Arrow indicates current focus of Southern Westerlies at 50°S. See text for description of locations. B: Aerial photograph of Fachinal (F) moraines. Circles and crosses indicate sample positions on outer and inner moraines, respectively. Heavy arrows (labeled MC) indicate positions of meltwater breaches of moraine crests onto delta surface. Abbreviations: CLD—Chilean Lake District; NPI—Northern Patagonian Icecap; RB—Rio Baker; TP—Taitao Peninsula; RG—Rio Guanaco; VJ—Ventisquero "Jose"; PE—Puerto Eden; LC—Lago Cardiel; LGCBA—Lago General Carrera–Buenos Aires; m asl—meters above sea level.

area ratio of 0.65 ± 0.05, a value adopted by many other researchers (Brugger and Goldstein, 1999, and references therein). Paleo–glacier extents were digitally traced in a geographic information system over a digital elevation model (DEM) and a satellite image. The DEM was then clipped with the glacier outline and analyzed to determine ELAs for a number of accumulation-area ratios.

Organic material suitable for radiocarbon dating was not found in the moraines; consequently the timing of deposition is determined by measuring the concentrations of in-situ cosmogenic ^{10}Be and ^{36}Cl in 16 erratic boulders. Samples were collected from 0.3–1.5-m-diameter boulders at or near the moraine crests. The preferred boulder is one that has a wide, flat top that can be easily sampled, does not appear to have moved or to be weathering quickly (remnant glacial polish or sculpting is ideal), and has 20%–30% quartz if sampling for ^{10}Be. Lithologies sampled were generally quartz-bearing rhyolite, but also included granites and metamorphic rocks; ^{36}Cl was measured in two basalt samples. Some rocks showed signs of weathering, but many preserved glacial sculpting or polish. Chemical isolation of ^{10}Be from pure quartz was performed at the University of Wisconsin–Madison following the methods of Bierman et al. (2003). Chlorine was separated from whole-rock samples following methods outlined in Stone et al. (1996) at the Cosmogenic Isotope Laboratory at the University of Washington. Accelerator mass spectrometry (AMS) analyses for both ^{10}Be and ^{36}Cl were performed at PRIME Lab, Purdue University.

Cosmogenic surface-exposure ages were calculated using production rates and scaling factors of Stone (2000). Corrections are applied to account for paleomagnetic field intensity, sample thicknesses, topographic shielding, and a slow erosion rate of 2 ± 2 mm/k.y. None of these corrections have significant impacts on the resulting ages. Uncertainties are reported at the 95% confidence level to represent the full uncertainty of the age determinations, and include all analytic errors (weighing of sample, weighing and concentration of spike, and AMS error), as well as erosion rate and attenuation-length uncertainty. Production-rate uncertainties are not explicitly treated; however, a ±10% systematic uncertainty would not fundamentally affect the conclusions of this paper. The full details of the methods and data reduction are presented in Appendix DR1 (see footnote 1).

RESULTS

At the time of moraine deposition, the glacial system was a 25-km-long, 15-km-wide ice field with a paleo-ELA of 1120 ± 65 m, estimated from an accumulation-area ratio of 0.65 ± 0.05 (Brugger and Goldstein, 1999). This ~300 m difference from the current ELA corresponds to conditions 2.4 °C cooler (if no change in precipitation has occurred), or 1000 mm/yr wetter (if no change in temperature has occurred) than present, on the basis of relationships between precipitation and temperature conditions in Patagonia and ELA (Hulton et al., 1994).

Of 6 boulders from the inner moraine, 5 yield a weighted mean age of 6.2 ± 0.8 ka, and 7 of 10 boulders from the outer moraine yield a weighted mean age of 8.5 ± 0.7 ka (Fig. 2; uncertainties at the 95% confidence level). Four outliers between 10.3 and 15.3 ka are identified on the basis of chi-squared statistics and bimodal probability distribution curves; these outliers are excluded from the weighted means. We infer that they contain inherited cosmogenic ^{10}Be from prior exposure. Complete results are available (Appendix DR1; see footnote 1).

DISCUSSION

The high percentage of boulders with inheritance is a departure from prior interpretive guidelines. Putkonen and Swanson (2003) reviewed data from 638 moraine boulders presented in 22 papers. Following the original interpretations of the authors, they found that only 2% of the boulders were thought to have inherited isotopes and that subsequent exhumation was a much more prevalent problem. Nevertheless, we feel justified in excluding the four outliers (Fig. 2). First, the samples that remain in the population have a well-defined mean and show strong central tendency. Second, these glacial advances were much shorter than full glacial conditions (the focus of most of the chronology efforts reviewed in Putkonen and Swanson, 2003). Less material would have been eroded from the landscape, causing the moraine to contain a greater percentage of previously exposed material.

The most widely accepted ages of Neoglacial activity in southern South America are 5200–4500, 2800–1900 cal. yr B.P. as well as the Little Ice Age, 300–200 yr B.P. (Mercer, 1982). However, very few moraines are bracketed by both minimum and maximum ages, thus the first period of Neoglacial activity is poorly constrained, but could have

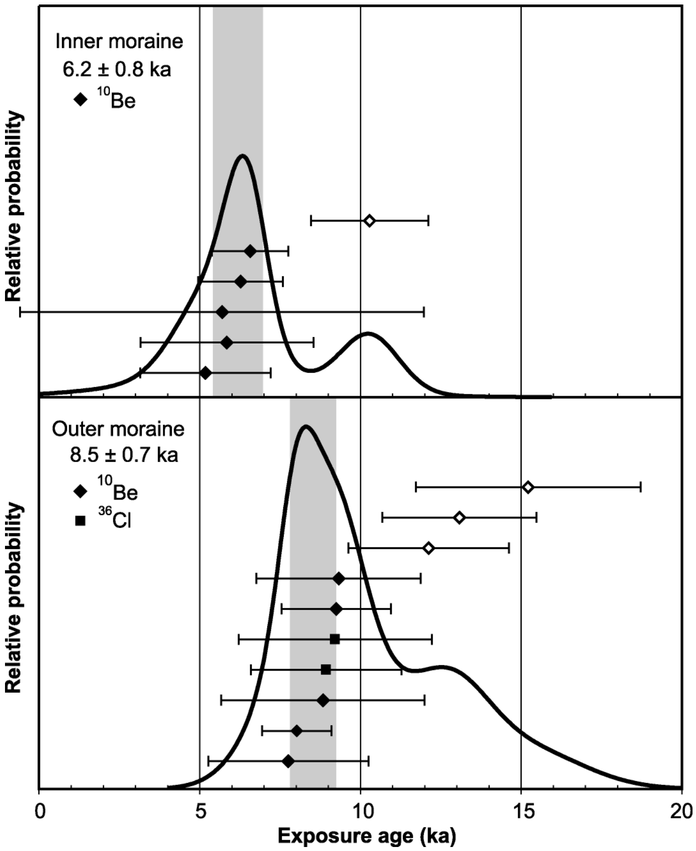

Figure 2. Cosmogenic surface-exposure ages and relative probability distributions for inner and outer Fachinal moraines. Each diamond or square represents ^{10}Be or ^{36}Cl data from one boulder and may represent average of replicate analyses. Open symbols depict outliers. Error bars represent analytical and erosion-rate uncertainties at 95% confidence level. Vertical gray boxes represent weighted means of 5 of 6 and 7 of 10 samples for inner and outer moraines, respectively.

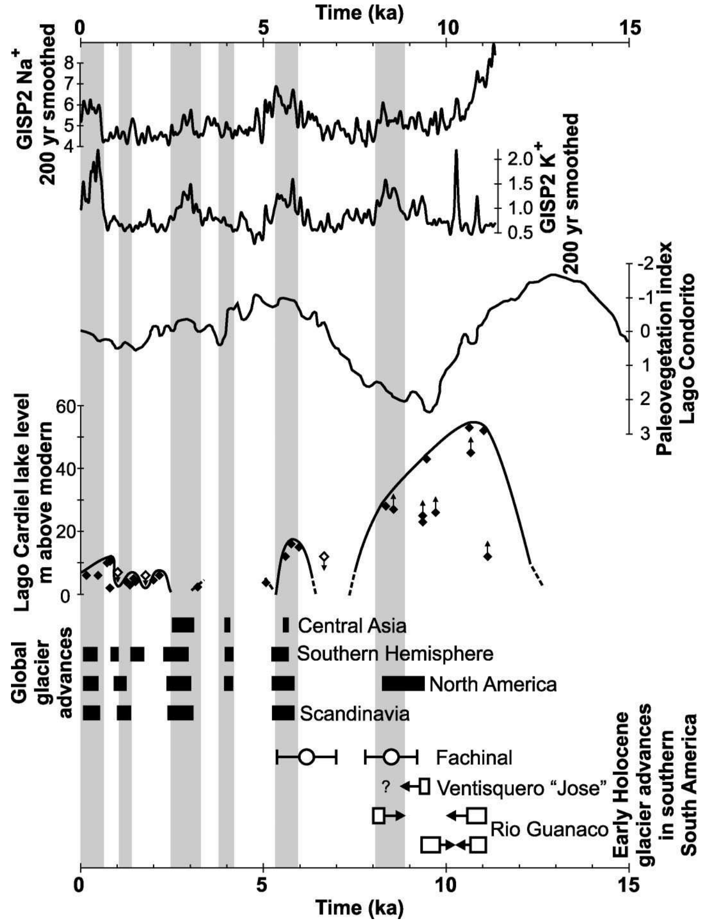

Figure 3. Selected climate records from Northern and Southern Hemispheres. Vertical gray bars represent globally expansive periods of rapid climate change (Mayewski et al., 2004). From top to bottom: Gaussian-smoothed (200 yr) K and Na concentrations from GISP2 ice core (Mayewski et al., 2004), paleovegetation index (positive values are warmer and drier) from Chilean Lake District (Moreno, 2004), lake-level record from Lago Cardiel (Stine and Stine, 1990; Markgraf et al., 2003), global glacial advances (Mayewski et al., 2004, and references therein), early Holocene glacial advances in southern South America at Fachinal, Ventisquero "Jose" (Röthlisberger, 1986), and Rio Guanaco valley (Wenzens, 1999).

occurred between ca. 5400 and 4900 cal. yr B.P. (Porter, 2000). The 8.5 ka surface-exposure age of the outer Fachinal moraine indicates that the most extensive Holocene glacial advance at this location was ~3000 yr earlier than the previously recognized onset of Neoglacial activity. This finding is supported by two other reports of glacier advances in the early Holocene: a maximum ^{14}C age of ca. 9.4 cal. ka for a moraine at Venitsquero "Jose" (Röthlisberger, 1986; Figs. 1A and 3), as well as bracketing ^{14}C ages of ca. 10.9 and 8.2 cal. ka, and 10.9 and 9.5 cal. ka for two moraines in the Rio Guanaco drainage (Wenzens, 1999; Figs. 1A and 3). Outside southern South America, there are few well-documented moraines correlative to the outer Fachinal moraine other than the Cockburn moraines in North America (Fig. 3). This lack of correlatable moraines is probably related to the limited preservation of early Holocene glacial deposits, which may have been eroded or overrun by subsequent advances. The surface-exposure age of the inner Fachinal moraine is potentially older than, but indistinguishable from, Neoglacial activity in South America and on three other continents ca. 5400–4900 cal. yr B.P. (Fig. 3), given the analytical uncertainties and potential systematic shifts in the production rate of the cosmogenic nuclides.

The closest nonglacial, Holocene climate records come from pollen in lakes and bogs on the Taitao Peninsula (Lumley and Switsur, 1993; Bennett et al., 2000; Fig. 1A). They show little evidence for climate change from deglaciation to the middle Holocene. Cores from Lago Condorito, in the Chilean Lake District (Moreno, 2004; Figs. 1A and 3), indicate dry and relatively warm conditions between 10 and 8 ka; precipitation started to increase at 8 ka and reached a maximum ca. 6–5 ka. However, the pollen and beetle record at Puerto Eden (Fig. 1A) indicates wetter conditions in the early Holocene (Ashworth et al., 1991). Reconstructions of the water level in Lago Cardiel (Fig. 1A), an internally drained lake basin that responds to changes in effective precipitation, agrees with a wet early Holocene (Stine and Stine, 1990; Markgraf et al., 2003). Shoreline features and a variety of proxies from sediment cores indicate that lake levels were highest ca. 11 cal. ka, were falling but still high through the early Holocene, and reached approximately modern levels ca. 5 ka (Fig. 3).

Markgraf et al. (2003) hypothesized that this antiphased relationship between Lago Cardiel and the Chilean Lake District is caused by a northward migration of the Southern Westerlies from 50°S to 40°S between ca. 11 and 6 ka. The two glacier advances at Fachinal suggest there may have been two increases in precipitation at 46°S, first ca. 8.5 ka and again ca. 6.2 ka. While there are too few climate records to adequately constrain the position of the Southern Westerlies through the Holocene, there is little doubt that their position is the first-order control on climate in this area. The Fachinal moraines also appear to be synchronous with prominent excursions in sodium and potassium ion concentrations in the Greenland Ice Sheet Project 2 (GISP2) ice core (interpreted to track changes in the Icelandic Low and Siberian High, respectively; Mayewski et al., 2004), as well as myriad other paleoclimate proxies from Greenland and the rest of the world (Alley et al., 1997). This is intriguing because the position of the Southern Westerlies is controlled by the equator-to-pole thermal gradient, the position and strength of the southeast Pacific high-pressure system, and the El Niño–Southern Oscillation (ENSO), and is thereby related to global atmospheric processes in general (Cerveny, 1998). This apparent synchronization of changes in the Southern Westerlies, Icelandic Low, and Siberian High is most easily explained by either external forcing mechanisms such as variable solar output (Denton and Karlén, 1973; Bond et al., 2001) or changes in atmospheric methane or water-vapor contents (Brook et al., 1999; Cane and Clement, 1999). Oceanic heat pumps, such as modulation of the thermohaline circulation (Teller and Leverington, 2004; Alley et al., 2001), are powerful climate-forcing mechanisms, but require a strong coupling between the ocean and the atmosphere to propagate the climate signals rapidly across the globe.

CONCLUSIONS

These substantial changes in glacier size and mass balance were caused by significant changes in regional climate and the Southern Westerlies. The 8.5 ka surface-exposure age of the outer Fachinal moraine is a clear indication that Neoglacial activity started ~3000 yr earlier than previously recognized in southern South America. Collectively, this and other paleoclimate records indicate that millennial-scale climate variability in mid-latitude South America, so prominent during the Last Glacial Maximum (e.g., Denton et al., 1999; Kaplan et al., 2004), continued throughout the Holocene. We hypothesize that the Fachinal moraines are synchronous with changes in the global climate system, and that the outer moraine may be correlative to the 8.2 ka event. However, rigorous documentation of coeval glacier advances across the region and improvements in cosmogenic production rate uncertainties are needed before this hypothesis can be evaluated.

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