Quaternary Science Reviews 170 (2017) 14–25

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

A beryllium-10 chronology of late-glacial moraines in the upper Rakaia valley, Southern Alps, New Zealand supports Southern-Hemisphere warming during the Younger Dryas

Tobias N.B. Koffman [a], Joerg M. Schaefer [a, b], Aaron E. Putnam [a, c, *], George H. Denton [a, c], David J.A. Barrell [d], Ann V. Rowan [e], Robert C. Finkel [f], Dylan H. Rood [g, h], Roseanne Schwartz [a], Mitchell A. Plummer [i], Simon H. Brocklehurst [j]

[a] Lamont–Doherty Earth Observatory of Columbia University, 61 Rt. 9W, Palisades, NY 10964, USA
[b] Department of Earth and Environmental Sciences, Columbia University, New York, NY 10027, USA
[c] School of Earth and Climate Sciences and Climate Change Institute, University of Maine, Orono, ME 04469, USA
[d] GNS Science, Private Bag 1930, Dunedin 9054, New Zealand
[e] Department of Geography, University of Sheffield, Sheffield, S10 2TN, UK
[f] Department of Earth and Planetary Sciences, University of California, Berkeley, CA 95064, USA
[g] Department of Earth Science & Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK
[h] Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[i] Idaho National Laboratory, Idaho Falls, ID 83415-2107, USA
[j] School of Earth and Environmental Sciences, University of Manchester, Manchester M139PL, UK

ARTICLE INFO

Article history:
Received 6 February 2017
Received in revised form
5 June 2017
Accepted 13 June 2017

Keywords:
Pleistocene
Holocene
Paleoclimatology
Glaciology
Southern Pacific
Cosmogenic isotopes
Glacial geomorphology
Glaciological modeling

ABSTRACT

Interhemispheric differences in the timing of pauses or reversals in the temperature rise at the end of the last ice age can help to clarify the mechanisms that influence glacial terminations. Our beryllium-10 (^{10}Be) surface-exposure chronology for the moraines of the upper Rakaia valley of New Zealand's Southern Alps, combined with glaciological modeling, show that late-glacial temperature change in the atmosphere over the Southern Alps exhibited an Antarctic-like pattern. During the Antarctic Cold Reversal, the upper Rakaia glacier built two well-defined, closely-spaced moraines on Reischek knob at 13,900 ± 120 [1σ; ± 310 yrs when including a 2.1% production-rate (PR) uncertainty] and 13,140 ± 250 (±370) yrs ago, in positions consistent with mean annual temperature approximately 2 °C cooler than modern values. The formation of distinct, widely-spaced moraines at 12,140 ± 200 (±320) and 11,620 ± 160 (±290) yrs ago on Meins Knob, 2 km up-valley from the Reischek knob moraines, indicates that the glacier thinned by ~250 m during Heinrich Stadial 0 (HS 0, coeval with the Younger Dryas 12,900 to 11,600 yrs ago). The glacier-inferred temperature rise in the upper Rakaia valley during HS 0 was about 1 °C. Because a similar pattern is documented by well-dated glacial geomorphologic records from the Andes of South America, the implication is that this late-glacial atmospheric climate signal extended from 79°S north to at least 36°S, and thus was a major feature of Southern Hemisphere paleoclimate during the last glacial termination.

1. Introduction

The last glacial termination is a key interval for understanding the role of millennial-scale climate events in ice-age climate cycles. In seeking to determine the causes and effects of the Antarctic Cold Reversal (ACR) and Heinrich Stadial 1 and 0 (HS 1, HS 0; the latter equating to the Younger Dryas), we must first understand their timings and geographic footprints. Isotope records from Antarctic ice cores indicate cooling during the ACR followed by renewed warming during HS 0 (Brook et al., 2005; Stenni et al., 2011; Pedro et al., 2011; WAIS Divide Project Members, 2013; Buizert et al., 2015; Cuffey et al., 2016). Greenland ice cores show nearly opposite isotopic patterns (e.g., Rasmussen et al., 2006). However, these antiphased changes in the polar latitudes of both hemispheres are of uncertain geographic extent, making it difficult to ascertain their

* Corresponding author. Lamont–Doherty Earth Observatory of Columbia University, 61 Rt. 9W, Palisades, NY 10964, USA.
E-mail address: aaron.putnam@maine.edu (A.E. Putnam).

http://dx.doi.org/10.1016/j.quascirev.2017.06.012
0277-3791/

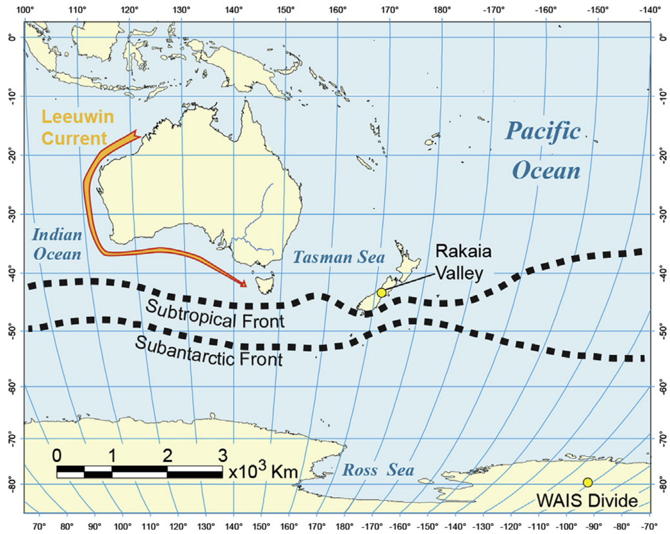

Fig. 1. Map of a portion of the Southern Hemisphere including New Zealand, Australia, and part of Antarctica. Ocean current depictions adapted from Carter et al. (1998) and Orsi et al. (1995).

causes as well as their potential significance in regard to the behavior of Earth's climate system. For example, to what extent did the Antarctic pattern impinge on the Southern Hemisphere's mid-latitudes (Newnham et al., 2012; Pedro et al., 2016)? Glacial landforms in New Zealand's Southern Alps provide archives suitable for ascertaining the timing of climate warming during the last glacial termination, and thereby test hypotheses about the geographic footprints of regional to hemispheric climate events. Here, we present a chronology of late-glacial moraine formation in the upper reaches of the Rakaia valley. Our dataset complements the chronology of ice recession during the last glacial termination obtained by dating of glacial landforms farther down the Rakaia valley (Putnam et al., 2013b). The quantification of glacier recession in a single valley in the Southern Alps reduces possible concerns about valley-specific differences in glacier behavior arising from factors such as topography, aspect and geometry. The Southern Alps are situated near the antipode of the North Atlantic region, and thus are aptly positioned to test the inter-hemispheric phasing of millennial-scale climate changes. Furthermore, the Southern Alps lie athwart the Southern Hemisphere westerly winds at the northern edge of the Southern Ocean, marked by the Subtropical Front (STF, Fig. 1; Bostock et al., 2015). Their location near the STF makes the Southern Alps subject to both tropical and Antarctic influences (De Deckker et al., 2012; Putnam et al., 2012, 2013a). Variations in present-day glacier mass balance in the Southern Alps are largely attributed to changes in air temperature, due both to solar radiation and to turbulent heat flux from air masses passing over the ocean west of New Zealand; precipitation changes play a lesser role (Anderson and Mackintosh, 2006). Consequently, length variations of glaciers in New Zealand's Southern Alps can be linked primarily to changes in air temperature (Oerlemans, 1997, 2005; Anderson and Mackintosh, 2006; Anderson et al., 2010; Purdie et al., 2011; Golledge et al., 2012). This provides a basis for inferring that glacial landforms in the Southern Alps (Fig. 2) document times of greater-than-present ice extent that resulted primarily from atmospheric temperatures that were colder than present.

The Rakaia valley glacial landforms record progressive ice recession during the last glacial termination (Fig. 3) (Burrows and Russell, 1975; Shulmeister et al., 2010; Barrell, 2011; Barrell et al., 2011; Putnam et al., 2013b). A notable feature is that the lower reaches of the Rakaia valley occupy a tectonic depression, rather than being of purely ice-hewn origin (Barrell et al., 2011). Consequently, there is not a well-defined glacial trough. In addition, numerous, glacially-sculpted bedrock hills and spurs project from the valley floor and walls. Glacially-transported boulders on both the ice-sculpted rock surfaces and the morainic deposits afford opportunities for palaeoclimatic investigation (Putnam et al., 2013b). Using mapped glacial landforms as targets (Barrell et al., 2011), we employed ^{10}Be surface-exposure dating and glaciological modeling in the upper reaches of the Rakaia valley to reconstruct a chronology of ice extent and associated climate during the latter part of the last glacial termination. Our work builds upon the chronology of Putnam et al. (2013b), which shows the details of ice retreat during the first part of the last glacial termination in the Rakaia valley from ~18,000 to ~15,000 years ago. On the basis of our mapping, surface-exposure dating, and climate reconstruction, we discuss the climate events of the last glacial termination in the Southern Alps.

2. Geology and geomorphology of the upper Rakaia valley

The Rakaia valley drains a portion of the southeast side of the main hydrographic divide (Main Divide) of the Southern Alps. During the Last Glacial Maximum (LGM) the former Rakaia glacier was a major outlet of the Southern Alps ice field (Barrell et al., 2011). Bedrock in the Rakaia catchment comprises predominantly greywacke sandstone and argillite mudstone of the Rakaia Terrane (Cox and Barrell, 2007). The Rakaia valley is fed by three major tributaries, from north to south, the Wilberforce River, the Mathias River, and the upstream reach of the Rakaia River, hereafter the upper Rakaia River, which flows down the upper Rakaia valley (Fig. 3). The upper Rakaia River has its source at the confluence of the meltwater streams from the Lyell Glacier and the Ramsay Glacier. Although aggradation of the upper Rakaia valley floor, and gully erosion of the valley sides, have obscured or removed much of the glacial imprint in the upper Rakaia valley, important remnants of moraines persist, particularly on the crests and flanks of ice-smoothed bedrock spurs (Barrell et al., 2011). On the eastern flank of Reischek Stream, morainal landforms occupy the northern and western flanks of a bedrock spur. The spur was referred to as “high moraine bluff” by Burrows and Russell (1975) and as “Reischek knob” by Putnam et al. (2013b). The Reischek knob moraines were formed at the margin of a much-expanded Reischek Glacier, at a time when it was confluent with the upper Rakaia glacier, itself the product of the much-expanded and coalesced Lyell and Ramsay glaciers. Burrows and Russell (1975) tentatively correlated the higher and lower portions of a prominent moraine ridge complex on Reischek knob with glacier termini near Lake Stream (higher ridge) and Jagged Stream (lower ridge), respectively ~17 km and ~11 km down-valley of Reischek knob. Standing on the southern side of the confluence of the Lyell and Ramsay valleys is Meins Knob, a broad-crested bedrock ridge, capped with remnant glacial landforms (Meins Knob moraines of Burrows and Russell (1975)). As Meins Knob lies ~2 km up-valley, and as much as 200 m elevation lower than, the prominent moraine ridges on Reischek knob, the Meins Knob moraines were formed after the upper Rakaia glacier had attained a lesser elevation than it had at the time the Reischek knob moraines were formed.

A recent study documented the geomorphology and moraine chronology of the Rakaia valley from Reischek knob downstream (Putnam et al., 2013b). That study examined two landform features on Reischek knob, outboard of the prominent moraine ridges on the knob. Those landform features were given informal names and comprise till-veneered bedrock (Reischek knob I), and meltwater channels incised into, and therefore younger than, the till-veneered