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Mismatch of glacier extent and summer insolation in Southern Hemisphere mid-latitudes

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ABSTRACT

Here we address a long-standing puzzle of ice-age climate called the "fly in the ointment of the Milankovitch theory." Using geomorphic mapping and ^{10}Be surface-exposure dating, we show that five moraine belts were formed during maxima of the last ice age by the Pukaki glacier in New Zealand's Southern Alps. They afford ages of 41.76 ± 1.09 ka, 35.50 ± 1.26 ka, 27.17 ± 0.68 ka, 20.27 ± 0.60 ka, and 18.29 ± 0.49 ka. These five maxima spanned an entire precessional cycle in summer insolation intensity at the latitude of the Southern Alps. A similar mismatch between summer insolation and glacier extent also characterized the Chilean Lake District in the mid-latitudes of South America. Thus, in apparent contrast to northern ice sheets linked by Milankovitch to summer insolation at 65°N latitude, the behavior of southern mid-latitude glaciers was not tied to local summer insolation intensity. Instead, glacier extent between 41.76 ka and 18.29 ka, as well as during the last termination, was aligned with Southern Ocean surface temperature and with atmospheric carbon dioxide.

INTRODUCTION

A prominent version of the Milankovitch (1941) theory of climate is that changes in summer insolation at high northern latitudes, induced by variations in Earth's orbit, controlled the extent and volume of Pleistocene ice sheets. In support, Roe (2006) showed a zero-lag, anti-phased relation between variations of summer insolation intensity at 65°N latitude and the rate of volume change of these sheets at the precession and obliquity frequencies. However, a long-standing conundrum is that despite summer intensity being anti-phased between the Southern and Northern Hemispheres, during the latter part of the last ice age the Patagonian Ice Field and the southern sector of the Laurentide Ice Sheet varied almost in concert (Mercer, 1984; Denton et al., 1999a, 1999b). The finding of similar climate changes in the two hemispheres was dubbed "a fly in the ointment of the Milankovitch theory" (Broecker, 1978; Mercer, 1984).

Here, we evaluate possible factors controlling glacier extent in the mid-latitude Southern Hemisphere by comparing a ^{10}Be surface-exposure moraine chronology in the Southern Alps of New Zealand that extends well back into the most recent glaciation with the local orbitally induced signature of summer insolation, Southern Ocean sea-surface temperatures (SSTs), and variations of atmospheric carbon dioxide.

SETTING

During ice-age maxima, the Pukaki glacier, located at 44°S latitude, flowed southward from the highest sector of the Southern Alps to deposit moraines, kame terraces, and outwash outboard of the glacier trough now occupied by Lake Pukaki (Barrell et al., 2011). This moraine-outwash complex has been divided into several stratigraphic units (Barrell and Read, 2014), but here we consider only the moraines depicted in red (local Last Glacial Maximum) in Figure 1. In our study area, along the southeastern sector of the left-lateral margin of the Pukaki glacier trough, these moraines compose four successive belts (Figs. 1 and 2). The moraine morphology is well preserved, with little erosion by outwash streams. Glaciers in the Southern Alps are sensitive to the effects of summer temperature (Anderson and Mackintosh, 2012), and thus we use glacier extent derived from mapped moraine belts as a temperature proxy. Glaciological modeling indicates that a snowline ~900 m lower than today, corresponding to atmospheric temperatures 6.25 ± 0.5 °C cooler than present, was sufficient for the Pukaki glacier to expand to these moraine belts (Golledge et al., 2012).

CHRONOLOGY

Quartzofeldspathic sandstone (greywacke) boulders are the predominant lithology in the Pukaki moraines and are well suited for exposure dating. These boulders are sourced from bedrock in the Pukaki catchment and were transported southward by glacier flow. We carried out ^{10}Be exposure dating on samples from large boulders well rooted in moraine tops and hence unlikely to have been rotated since deposition. Samples were collected and then processed at the Lamont-Doherty Earth Observatory Cosmogenic Dating Laboratory (Columbia University, New York, USA) following our standard procedures (Schaefer et al., 2009). ^{10}Be/^{9}Be ratios were determined at Lawrence Livermore National Laboratory (California, USA). A locally established production rate for ^{10}Be was used in the age calculations (Putnam et al., 2010). All processing and measurement details are given in Tables DR1–DR3 in the GSA Data Repository[1].

Morphological relations, including truncation of outer moraine belts by inner moraine belts, combined with dating allow discrimination of four moraine belts in our study area, which is centered on a small distributary outlet of the former glacier, known as the Maryburn lobe. Our chronology (Fig. DR1 in the Data Repository) indicates construction of the oldest moraine belt (*a* in Figs. 1 and 2), comprising three subdued ridges, at 35.50 ± 1.26 ka (n = 3; all ages given are the arithmetic mean age and 1σ uncertainty, and correspond to the "Lm" production-rate scaling scheme given in Table DR2; Balco et al., 2008). The next inboard belt (*b* in Figs. 1 and 2) yields an exposure age of 27.17 ± 0.68 ka (n = 7, one outlier excluded). The outer limit is a prominent moraine ridge; the remainder of the belt shows less-prominent ridges. The third belt (*c* in Figs. 1 and 2)

[1]GSA Data Repository item 2015144, explanation of the CO_2 record, Figure DR1, and Tables DR1–DR3, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

†Deceased

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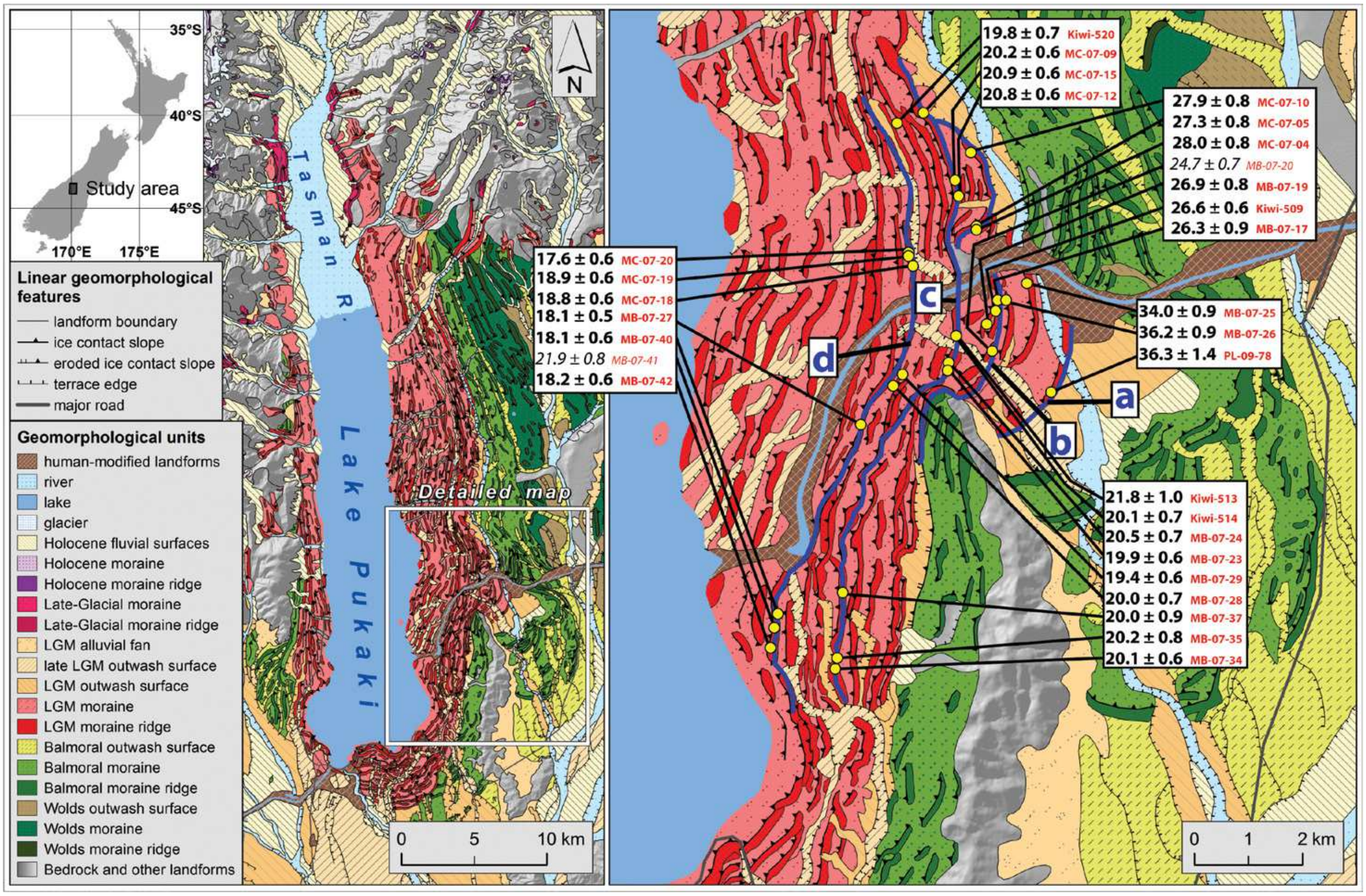

Figure 1. Glacial geomorphology of study area, New Zealand (after Barrell et al., 2011), showing sample sites (yellow) and ^{10}Be ages (ka; see Table DR3 [see footnote 1]). Outliers are in italics. Blue lines mark outer limits of moraine belts *a*–*d*. LGM—Last Glacial Maximum.

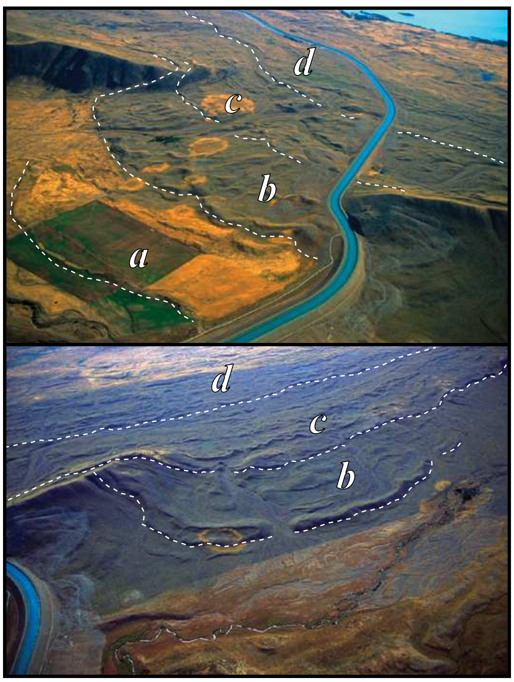

Figure 2. Aerial views of moraines in study area (South Island, New Zealand), looking southwest (top) and south (bottom). White dashed lines depict outer limits of moraine belts *a*–*d*. Canal is 50 m wide.

cross-cuts the adjacent, older belt, and affords an age of 20.27 ± 0.60 ka (n = 13). It consists of a sharp, well-delineated outer ridge backed by several subsidiary ridges. Finally, the outer ridges of the youngest belt (*d* in Figs. 1 and 2) afford an exposure age of 18.29 ± 0.49 ka (n = 7; one outlier excluded). Across the whole data set, just two samples were designated as outliers because they gave ages that are morphostratigraphically out of place.

An additional maximum of the Pukaki glacier is represented by a lateral moraine belt that is preserved between 6 km and 14 km north of the detailed map area in Figure 1 (Kelley et al., 2014). Boulders from this belt yielded an exposure age of 41.76 ± 1.09 ka (n = 13; four outliers excluded). This belt is not present in our study area because it is cut out, and thus either eroded or buried, by the moraine belt dated to 27.17 ± 0.60 ka. The five maxima of the Pukaki glacier are well separated in time and span an interval of as much as 25 k.y., between 18.29 ± 0.49 ka and 41.76 ± 1.09 ka (Fig. DR1). Terminal moraine belts at adjacent Lake Ohau formed at 32.52 ± 0.97 ka and 22.51 ± 0.60 ka (Putnam et al., 2013b), but these moraines were not preserved at Lake Pukaki. Collectively, seven episodes of full-glacial ice maxima have been identified in the Pukaki and Ohau moraine sequences.

DISCUSSION

A plot of surface-exposure ages of the seven moraine belts of the Pukaki and Ohau glaciers alongside orbital-scale variations of summer insolation intensity for 44°S latitude, which is dominated by precession (Fig. 3), shows no obvious relation between glacier maxima and insolation intensity minima. Indeed, glacier maxima were spread through an entire

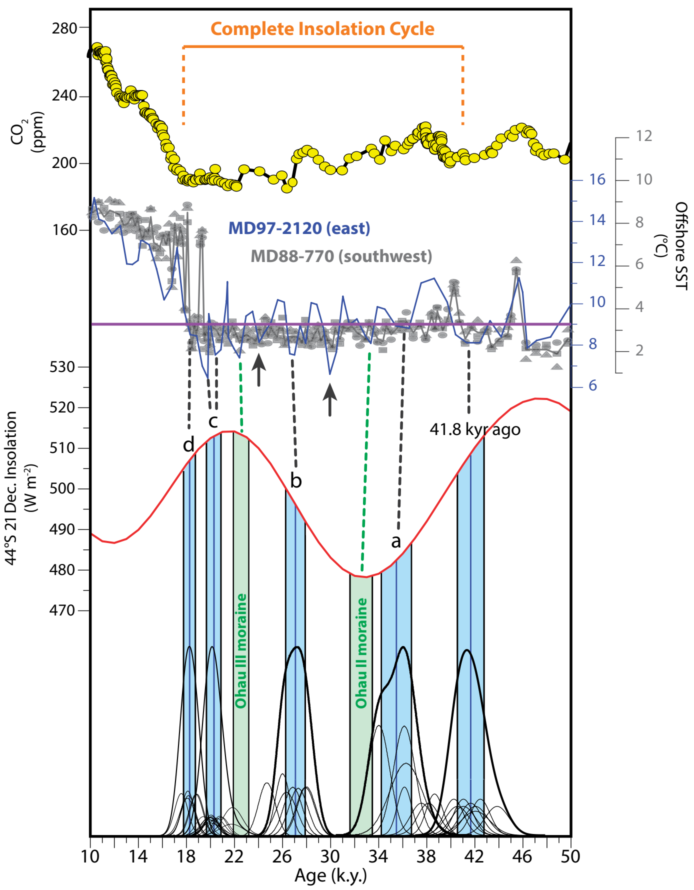

Figure 3. Chronology of moraine belts (*a–d* and 41.8 ka) constructed at maxima of Pukaki glacier, South Island, New Zealand (probability curves [in black] and notation from Fig. DR1 [see footnote 1]), and moraine belts of nearby Ohau glacier (Putnam et al., 2013b) that have not yet been found at Lake Pukaki. These moraine records are compared with 44°S, 21 December insolation (red curve; Laskar et al., 2004), Southern Ocean sea-surface temperature (SST) records from sediment cores MD88-770 (gray, fauna based; Barrows et al., 2007) and MD97-2120 (blue, Mg/Ca; Pahnke et al., 2003), and atmospheric CO_2 concentrations (yellow; see the Data Repository [see footnote 1]). Being fauna based, the MD88-770 record is bi-modal and illustrates persistent glacial, followed by interglacial, ocean conditions. MD97-2120 shows centurial-scale SST fluctuations comparable to nearby moraine records. Horizontal purple line marks 9 °C in the MD97-2120 core, approximating a maximum threshold for fully expanded ice-age glaciers at Pukaki and Ohau. Of the eight troughs of SST < 9 °C between ca. 18 and ca. 43 ka, only two (arrowed) are not represented by preserved moraines in the Pukaki-Ohau study area.

cycle of precession-forced summer insolation variation, and occurred during times of high, low, and intermediate intensity. In addition, extensive glacier retreat during the last termination, documented in the Pukaki drainage (Schaefer et al., 2006), and in the nearby Ohau and Rakaia drainages (Putnam et al., 2013a, 2013b) accompanied declining summer intensity.

Non-correlation between moraine formation and summer insolation is also demonstrated at 40°–43°S in Chile, where outlet lobes of the Patagonian Ice Field advanced repeatedly into the Llanquihue moraine belt between 34 ka and 18 ka, followed by major recession during the last termination (Denton et al., 1999b). The advances occurred during times of low, high, and intermediate summer insolation intensity, and the termination was coeval with decreasing, not increasing, intensity. Thus in neither Chile nor the Southern Alps was glacier behavior related in any obvious manner to changes in local summer insolation intensity at orbital time scales. This lack of correlation extends back in the most recent glaciation to at least 42 ka.

Barrows et al. (2007) proposed a close link between Southern Ocean SSTs and mid-latitude glacier activity. Due to a lack of well-dated, comprehensive moraine records, Barrows et al. (2007) utilized the Deep Sea Drilling Project (DSDP) Site 594 core of bathyal marine sediments 300 km east of New Zealand to investigate glacier-SST linkage. In that core, changes in the ratio of carbonate and terrigenous sediments have been interpreted as a proxy for glacier extent on the adjacent South Island (Nelson et al., 1993). However, Carter and Mitchell (1987) pointed out that eustatic sea level greatly influences the delivery of sediment to offshore deep-water environments. The DSDP Site 594 record may therefore reflect eustatic sea-level variations, and perhaps other hydrodynamic processes, more than glacier activity on the New Zealand landmass. We consider that times of glacier maximum extents afforded by the Pukaki/Ohau moraine chronology are an unambiguous glacial record that can be compared more confidently with SSTs.

Conditions in the outer sector of the Southern Ocean in the vicinity of New Zealand are illustrated by SST records from sediment core MD88-770 (R/V *Marion Dufresne*), located southwest of Australia at 46°S (Barrows et al., 2007), and sediment core MD97-2120, 300 km east of New Zealand's South Island at 45°S (Pahnke et al., 2003). Both sites lie just south of the modern Subtropical Front and highlight a Southern Ocean temperature as much as 4–5 °C cooler than today during the most recent glaciation. The MD97-2120 Mg/Ca SST record (Pahnke et al., 2003) shows a marked signature of temperature variation, with episodes of temperature minima below ~9 °C corresponding well with episodes of full-glacial ice extent, and moraine formation, at Lakes Pukaki and Ohau. Of note is that a temperature of ~9 °C at sea level corresponds, via a commonly applied lapse rate of 6 °C/km, to a 0 °C isotherm at ~1500 m above sea level (asl). This matches the full-glacial average snowline for the Ohau catchment of ~1500 m asl independently calculated by Putnam et al. (2013**b**). Linkage between SSTs and glacier extent is consistent with the dominant ocean temperature signature of modern mid-latitude air masses passing over the Southern Alps (McKinnon et al., 2013). An ocean-glacier linkage also accords with the finding that energy from turbulent heat flux heavily influences present-day glacier mass balance in the Southern Alps (Anderson and Mackintosh, 2012). A SST influence on southern mid-latitude ice fields is further suggested by the similarity between fluctuations of glaciers in Chile (Denton et al., 1999a) and changes in nearby surface ocean temperatures (Kaiser et al., 2005).

There are broad similarities between the CO_2 record and both the glacier and SST record (Fig. 3), but the SST record exhibits sharper variations than the CO_2 record. Between ca. 23 ka and 18 ka, notable signatures in SST fluctuations and glacier maxima are not evident in the CO_2 record. Thus in the New Zealand region, glacier maxima have had a closer association with SST than with atmospheric CO_2.

Overall, we infer that there was a close association between Southern Ocean SSTs and atmospheric temperatures over the Southern Alps and southern Andes, and hence on the respective mountain ice fields, during the last glaciation back at least to 42 ka. Possible controls on ocean surface temperatures and atmospheric temperatures, and therefore glacier fluctuations, in the Southern Hemisphere mid-latitudes include the far-field effect of orbital forcing from high northern (Barrows et al., 2007; Vandergoes et al., 2005) or southern (Huybers and Denton, 2008) latitudes, of a bipolar seesaw in ocean circulation (Broecker, 1998), and of latitudinal shifts of the Subtropical Front (Barker et al., 2009; De Deckker et al., 2012) likely associated with similar shifts of the Southern Hemisphere westerly wind belt (Anderson et al., 2009). The radiative forcing from the associated changes in atmospheric trace gases, including carbon dioxide, undoubtedly affected SSTs and glacier extent at southern mid-latitudes, but its importance is yet to be quantified.

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Notes