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The Southern Glacial Maximum 65,000 years ago and its Unfinished Termination

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ABSTRACT

Glacial maxima and their terminations provide key insights into inter-hemispheric climate dynamics and the coupling of atmosphere, surface and deep ocean, hydrology, and cryosphere, which is fundamental for evaluating the robustness of earth's climate in view of ongoing climate change. The Last Glacial Maximum (LGM, ~26–19 ka ago) is widely seen as the global cold peak during the last glacial cycle, and its transition to the Holocene interglacial, dubbed 'Termination 1 (T1)', as the most dramatic climate reorganization during this interval. Climate records show that over the last 800 ka, ice ages peaked and terminated on average every 100 ka ('100 ka world'). However, the mechanisms pacing glacial–interglacial transitions remain controversial and in particular the hemispheric manifestations and underlying orbital to regional driving forces of glacial maxima and subsequent terminations remain poorly understood.

Here we show evidence for a full glacial maximum in the Southern Hemisphere 65.1 ± 2.7 ka ago and its 'Unfinished Termination'. Our ^{10}Be chronology combined with a model simulation demonstrates that New Zealand's glaciers reached their maximum position of the last glacial cycle during Marine Isotope Stage-4 (MIS-4). Southern ocean and greenhouse gas records indicate coeval peak glacial conditions, making the case for the Southern Glacial Maximum about halfway through the last glacial cycle and only 15 ka after the last warm period (MIS-5a). We present the hypothesis that subsequently, driven by boreal summer insolation forcing, a termination began but remained unfinished, possibly because the northern ice sheets were only moderately large and could not supply enough meltwater to the North Atlantic through Heinrich Stadial 6 to drive a full termination. Yet the Unfinished Termination left behind substantial ice on the northern continents (about 50% of the full LGM ice volume) and after another 45 ka of cooling and ice sheet growth the earth was at inter-hemispheric Last Glacial Maximum configuration, when similar orbital forcing hit maximum-size northern ice sheets and ushered in T1 and thus the ongoing interglacial. This argument highlights the critical role of full glacial conditions in both

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hemispheres for terminations and implies that the Southern Hemisphere climate could transition from interglacial to full glacial conditions in about 15,000 years, while the Northern Hemisphere and its continental ice-sheets required half a glacial cycle.

1. Introduction

Termination 1 (T1), began about 19 ka ago and transitioned the earth from the global Last Glacial Maximum (LGM; ~26 –19 ka ago) of Marine Isotope Stage-2 (MIS-2; ~26–11.5 ka ago) to the ongoing Holocene interglacial. Important progress in understanding the climate events leading into global glacial maxima and through terminations has been made recently (Barker et al., 2009; Cheng et al., 2009; Clark et al., 2009; Denton et al., 2010). However, theories proposing the Northern Hemisphere and the maximum size of the continental ice-sheets during the LGM to be of critical importance for terminations (Denton and Hughes, 1981; Raymo, 1997; Abe-Ouchi et al., 2013), face opposing scenarios that assign the leading role in glacial–interglacial transitions to Southern Hemisphere drivers (for example WAIS Divide Project Members (2013); Wolff et al. (2006)).

Moreover, other basic questions remain, such as why the durations of mid-to late Pleistocene glacial cycles varied between 80 ka and 120 ka (Huybers and Wunsch, 2005) and why even prominent climate transitions during glacials have failed to end ice ages (Barker et al., 2009). Here we provide new evidence addressing these problems, based on the first comprehensive chronology and modeling of mountain glaciers in New Zealand's Southern Alps during MIS-4.

The MIS-4 cold period (74–59 ka ago) and its transition to the MIS-3 mild period (59–~26 ka ago) are recorded in polar ice cores (EPICA community members, 2004), marine sediments (Chapman and Shackleton, 1998; Kaiser and Lamy, 2010) and speleothems (Wang et al., 2001). However, direct terrestrial evidence and chronologies for glacier and ice-sheet response during these periods remain sparse and controversial (see Supplementary Discussion), in part because MIS-4 is beyond the radiocarbon time-scale. We date and quantify the response of southern middle-latitude summer temperature sensitive mountain glaciers to the MIS-4 cold period and evaluate the response of the cryosphere–atmosphere–ocean system to the transition towards the warmer MIS-3 climate. With the goal to highlight key drivers of terminations, we then compare the MIS-4/3 transition with the inter-hemispheric MIS-2 LGM and the subsequent T1.

2. Geomorphic setting, methods and analysis

2.1. Glaciers and climate

Mountain glaciers in New Zealand's Southern Alps are particularly sensitive recorders of atmospheric change and respond on the centennial and millennial scale primarily to summer temperature variations (Oerlemans, 2005; Anderson and Mackintosh, 2006; Anderson et al., 2010). We interpret our glacial-geological record accordingly.

2.2. Moraines

Outboard of the LGM moraines fringing Lakes Pukaki and Tekapo, are topographically more subdued moraines named 'Balmoral' (green in Fig. 1) as described in detail by Barrell (2014), making New Zealand's Southern Alps one of the few locations where such glacial landforms have not been destroyed by LGM glaciers and related outwash floods (Burrows, 2005; Barrell, 2014). The particularly prominent and well-preserved Balmoral moraine belt fringing Lake Pukaki attests to a full-glacial cold period in New Zealand prior to the MIS-2 LGM (Fig. 1).

2.3. Samples

Numerous large greywacke boulders occur embedded in moraine ridges or ground moraine within the Balmoral moraine belts were the targets of our ^{10}Be surface exposure dating program. We focused on sampling the top 2 cm of flat rock surfaces. The quartzo-feldspathic greywacke lithology is very resistant to erosion, which is mirrored by the surprisingly high internal consistency of the boulder ages (Fig. 1, Supplementary Fig. 2).

We sampled and dated a total of 60 moraine boulders (Fig. 1; Supplementary Table 1): 48 boulders from the Lake Pukaki Balmoral moraines, 2 boulders from the Lake Tekapo Balmoral moraines, and for context, 10 from the Lake Pukaki LGM moraines, extending an earlier chronology (Schaefer et al., 2006) . In order to date the Balmoral glacier culmination, we focused particularly on boulders from the outermost Balmoral moraine ridges at Lake Pukaki. We sampled 6 boulders from outer and 3 from the inner moraine segments of the well-preserved left-lateral Maryburn lobe area (Barrell, 2014). In the less-well-preserved terminal, left and right lateral moraines, we sampled 33 boulders on the outer remnants of the Balmoral moraine ridges (Fig. 1) and 6 boulders forming a transect of the inner Balmoral moraines. From the total of 39 boulders from outermost moraines, we include 36 ages in our final age determination of the Balmoral glacier culmination (3 young outliers excluded; see Fig. 1b). The 9 samples from the inner moraine segments yield generally consistent, and chronologically similar, results (Supplementary Fig. 2). We also present the ages of two samples from Balmoral moraines of the adjacent Lake Tekapo glacial trough (Fig. 1).

2.4. Geochemistry and AMS analysis

All samples were processed at the cosmogenic dating laboratory of the Lamont–Doherty Earth Observatory, the ^{10}Be/^{9}Be analyses were performed at the Center for Accelerator Mass Spectrometry (CAMS) at the Lawrence Livermore National Laboratory. We applied standard techniques (Schaefer et al., 2009) to separate and decontaminate quartz from the whole-rock greywacke samples (http://www.ldeo.columbia.edu/res/pi/tcn/LDEO_Cosmogenic_Nuclide_Lab/Chemistry.html) and standard isotope dilution methods.

^{9}Be currents for our samples ranged from 16 to 26 μA. Individual AMS sample targets were measured during 2–6 runs at 5 min each, providing high counting statistics and an internal control of the stability of the AMS. The data show 1σ analytical error ranging from 1.4% to 5.0%, with an average of 2.5%. Overall background corrections, including boron correction, correction for process blank, and sensitivity variations of the AMS during analysis were below 1% for all samples.