Quaternary Science Reviews 149 (2016) 200–214

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

The timing and cause of glacial advances in the southern mid-latitudes during the last glacial cycle based on a synthesis of exposure ages from Patagonia and New Zealand

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ARTICLE INFO

Article history:
Received 29 April 2016
Received in revised form
18 July 2016
Accepted 19 July 2016

Keywords:
Last glacial cycle
Patagonia
New Zealand
Cosmogenic nuclide exposure dating
Glacial advances

ABSTRACT

Glacier advances in the southern mid-latitudes during the last glacial cycle (*ca.* 110–10 ka) were controlled by changes in temperature and precipitation linked to several important ocean-climate systems. As such, the timing of glacial advance and retreat can yield important insights into the mechanisms of Southern Hemisphere climate change. This is particularly important given that several recent studies have demonstrated significant glacial advances prior to the global Last Glacial Maximum (gLGM) in Patagonia and New Zealand, the cause of which are uncertain. The recent increase in chronological studies in these regions offers the opportunity to compare regional trends in glacial activity. Here, we compile the first consistent ^{10}Be exposure-dating chronologies for Patagonia and New Zealand to highlight the broad pattern of mid-latitude glacial activity over the last glacial cycle. Our results show that advances or still stands culminated at 26–27 ka, 18–19 ka and 13–14 ka in both Patagonia and New Zealand and were broadly synchronous, but with an offset between regions of up to 900 years that cannot be explained by age calculation or physically plausible erosion differences. Furthermore, there is evidence in both regions for glacial advances culminating from at least 45 ka, during the latter half of Marine Isotope Stage (MIS) 3. Glacial activity prior to the gLGM differed from the large Northern Hemisphere ice sheets, likely due to favourable Southern Hemisphere conditions during late MIS 3: summer insolation reached a minimum, seasonality was reduced, winter duration was increasing, and sea ice had expanded significantly, inducing stratification of the ocean and triggering northward migration of oceanic fronts and the Southern Westerly Winds. Glacial advances in Patagonia and New Zealand during the gLGM were probably primed by underlying orbital parameters. However, the precise timing is likely to have been intrinsically linked to migration of the coupled ocean-atmosphere system, which may account for the small offset between Patagonia and New Zealand due to differences in oceanic frontal migration. During deglaciation, advances or still stands occurred in both regions during the southern Antarctic Cold Reversal (*ca.* 14.5–12.9 ka) rather than the northern Younger Dryas (*ca.* 12.9–11.7 ka). Our findings suggest that major rearrangements of the Southern Hemisphere climate system occurred at various times during the last glacial cycle, with associated impacts on the position and intensity of the Southern Westerly Winds and oceanic fronts, as well as wind-driven upwelling and degassing of the deep Southern Ocean. Thus, reconstructing the timing of glacial advance/retreat using our compilation is a powerful way to understand the mechanisms of past interhemispheric climate change.

1. Introduction

Patagonia, in southern South America, and South Island, New Zealand, hosted the two largest non-Antarctic ice masses in the Southern Hemisphere during Quaternary glaciations (Coronato and Rabassa, 2011; Barrell, 2011, Fig. 1). The former Patagonian Ice Sheet

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http://dx.doi.org/10.1016/j.quascirev.2016.07.024
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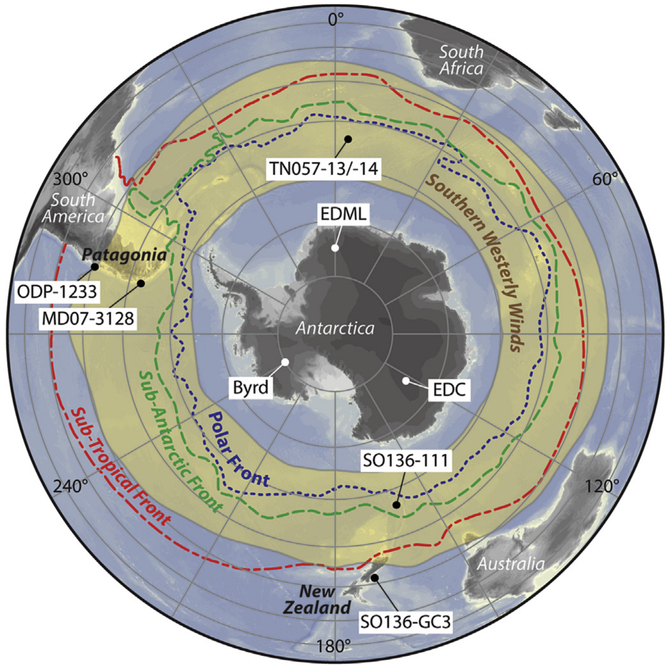

Fig. 1. Map of the Southern Hemisphere showing the modern positions of the Sub-Tropical Front (red), Sub-Antarctic Front (green) and Polar Front (blue) based on Orsi et al. (1995) and Carter et al. (2008), as well as the schematic core region of the Southern Westerly Winds (yellow-brown; Sime et al., 2013) and the locations of ice and marine core records referred to in the text. Note the latitudinal difference of the oceanic frontal systems around Patagonia compared to New Zealand. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

extended from the Andean range to cover significant parts of Chile and Argentina between ~36 and ~56°S (Fig. 2), and the New Zealand icefield occupied much of the Southern Alps between ~40 and ~46°S (Fig. 3). Together, glaciers extending from these two ice masses covered a broad latitudinal range in the southern mid-latitudes and were influenced by important global ocean-climate systems. These include the oceanic Sub Tropical, Sub Antarctic and Polar Fronts, the Antarctic Circumpolar Current and Agulhaus Current leakage, and the position and/or strength of the Southern Westerly Wind system. Moreover, a number of modes of variability such as the Southern Annular Mode and embedded phenomena in the three Walker Circulations (e.g. the Indian Ocean Dipole and El Niño Southern Oscillation) may have influenced glacier behaviour. As a result, glacial records from Patagonia and New Zealand have the potential to improve our understanding of global climate teleconnections and have been widely used to reconstruct past climatic change.

Recent work (Glasser et al., 2011; Putnam et al., 2013b; Kelley et al., 2014; Rother et al., 2014; Doughty et al., 2015; Schaefer et al., 2015; Darvill et al., 2015) has identified that some glaciers in Patagonia and New Zealand advanced to greater extents prior to the global Last Glacial Maximum (gLGM; *ca.* 26.5–19 ka; Clark et al., 2009) and Marine Isotope Stage (MIS) 2. This is not necessarily surprising: Hughes et al. (2013) suggested that many ice sheets around the world did not achieve maximum extent at the same time during the last glacial cycle (*ca.* 110–10 ka). However, it does indicate that our understanding of southern mid-latitude glacial advances might be incomplete, with implications for our understanding of southern climate systems more generally. Specifically, the new glacial chronologies raise two important issues. First, it is unclear whether pre-gLGM glacial advances were representative of the Patagonian and New Zealand ice masses more broadly and, if so, whether they were synchronous across the southern mid-latitudes. Secondly, the forcing factors behind southern mid-latitude glaciation during the last glacial cycle are ambiguous, as is the relationship to climatic drivers in the Northern Hemisphere. For example, insolation does not appear to directly control Southern Hemisphere climate change (Huybers and Denton, 2008; Doughty et al., 2015), whereas the movement of the southern westerly winds and oceanic frontal systems have been invoked as drivers of climate and glacial advances by controlling precipitation and sea surface temperatures (Lamy et al., 2004, 2007; Barrows et al., 2007a; Denton et al., 2010). The roles of sea ice and ocean stratification, whilst likely important, also remain unclear (Allen et al., 2011; Denton et al., 2010; Putnam et al., 2013b). Moreover, the interplay between Southern and Northern Hemisphere climate systems is particularly contentious (Sugden et al., 2005), with some suggesting that global climate is driven by changes in the north (e.g. Denton et al., 2010) and others advocating initial triggers in the south (e.g. Wolff et al., 2009).

Tackling these problems requires a synthesis of the evidence for the timing of glacial activity in Patagonia and New Zealand. Given the high volume of new chronological data that has been published in recent years, this paper compiles glacial chronologies for both regions during the last glacial cycle to examine, for the first time, if similar trends are evident and whether these are replicated over large geographic areas. We then compare the timing of culminations of glacial advances with terrestrial, marine and ice core proxy records and test hypotheses regarding how southern climatic systems operated through time. Whilst other ice caps and glaciers existed in Chile, Australia, Tasmania, North Island (New Zealand) and elsewhere in the sub-Antarctic during the last glacial cycle, we limit our focus to Patagonia and South Island. This is because they hosted the largest ice masses and produced similarly-detailed and well-preserved glacial records that have been studied in the greatest detail. We primarily focus on ^{10}Be cosmogenic nuclide dating because it offers direct age estimates for glacial moraine records and has been used extensively in both regions.

2. Methods

Our compilation consists of ^{10}Be cosmogenic nuclide exposure data from studies across Patagonia and New Zealand (Figs. 2 and 3; Table 1). We collated published ^{10}Be exposure ages for moraine boulders and outwash cobbles, which record the timing of the onset of glacial retreat following an advance (Fig. 4). Only two studies have used outwash cobbles in this manner, and in both cases they are essentially equivalent to exposure ages from boulders (Hein et al., 2009; Darvill et al., 2015). We excluded bedrock and moraine cobble samples due to potential issues with re-setting and because they do not necessarily represent glacial activity in the same way. For consistency, we recalculated all exposure ages, applying the Putnam et al. (2010b) New Zealand ^{10}Be production rate for exposure ages in New Zealand and Patagonia, as well as the Kaplan et al. (2011) Patagonian ^{10}Be production rate for exposure ages in Patagonia. We also calculated ages using five scaling schemes and a range of erosion rates (1 mm ka^{-1} intervals between 0 and 10 mm ka^{-1}) to evaluate the effects of these parameters on age distributions (Fig. 5). All other parameters, including standards, were taken from the original literature or subsequent updates (e.g. Kaplan et al., 2011), and we used a standard density of 2.7 g cm^{-3} where none was given in the original studies. To aid the identification of cumulative peaks in exposure time we employed cumulative Probability Density Functions (PDFs; Barrows et al., 2002) using 100-year bins, and excluded any exposure ages that, within errors, fall outside the last glacial cycle between 110 and 10 ka.