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A cosmogenic ^{3}He chronology of late Quaternary glacier fluctuations in North Island, New Zealand (39°S)

Shaun R. Eaves [a, b, *], Andrew N. Mackintosh [a, b], Gisela Winckler [c], Joerg M. Schaefer [c], Brent V. Alloway [b], Dougal B. Townsend [d]

[a] Antarctic Research Centre, Victoria University of Wellington, P.O. Box 600, Wellington 6140, New Zealand
[b] School of Geography Environment and Earth Sciences, Victoria University of Wellington, P.O. Box 600, Wellington 6140, New Zealand
[c] Lamont-Doherty Earth Observatory of Columbia University P.O. Box 1000, Palisades, NY 10964, USA
[d] GNS Science, P.O. Box 30-368, Lower Hutt 5040, New Zealand

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ABSTRACT

Mountain glaciers advance and retreat primarily in response to changes in climate. Establishing the timing and magnitude of mountain glacier fluctuations from geological records can thus help to identify the drivers and mechanisms of past climate change. In this study, we use cosmogenic ^{3}He surface exposure dating and tephrochronology to constrain the timing of past glaciation on Tongariro massif in central North Island, New Zealand (39°S). Exposure ages from moraine boulders show that valley glaciation persisted between c. 30–18 ka, which coincides with the global Last Glacial Maximum. Reinterpretation of moraine tephrostratigraphy, using major element geochemistry analysis, shows that ice retreat and climatic amelioration at the last glacial termination was well underway prior to 14 ka. The equilibrium line altitude in central North Island, during the Last Glacial Maximum, was c. 1400–1550 m above sea level, which is c. 930–1080 m lower than present. Considering the uncertainties in the glacial reconstruction and temperature lapse rates, we estimate that this equilibrium line altitude lowering equates to a temperature depression of 5.6 ± 1.1 °C, relative to present. Our mapping and surface exposure dating also show evidence for an earlier period of glaciation, of similar magnitude to the Last Glacial Maximum, which culminated prior to 57 ka, probably during Marine Isotope Stage 4. Good agreement between the timing and magnitude of glacier fluctuations in central North Island and the Southern Alps indicate a response to a common climatic forcing during the last glacial cycle.

1. Introduction

Explaining the drivers of Quaternary climate cycles in the Southern Hemisphere remains an outstanding goal of palaeoclimate research. New Zealand is one of the few locations in the Southern Hemisphere where terrestrial palaeoclimate can be reconstructed. Furthermore, it is ideally situated to record fluctuations of the southern westerly winds and the oceanic subtropical and subpolar fronts (Fig. 1), which are considered to have played an important role in past climate dynamics (Denton et al., 2010). Regional tectonic uplift and localised effusive volcanism have resulted in high-elevation and high-relief topography in both the North and South Island of New Zealand, which support contemporary glaciers spanning latitudes from 39°S to 46°S. Empirical and model-based analyses show contemporary glacier mass balance in New Zealand is most sensitive to changes in atmospheric temperature (Oerlemans, 1997; Anderson and Mackintosh, 2006; Anderson et al., 2010; Brook et al., 2011). Steep mass balance gradients and relatively high ice velocities mean that mass balance changes are translated to the termini of mountain glaciers over timescales of 10^1–10^2 yrs (Oerlemans, 1997; Purdie et al., 2014). Geological records of past glacier fluctuations in New Zealand therefore represent an important proxy for past climatic change in the southern mid-latitudes (e.g. Anderson and Mackintosh, 2006; Schaefer et al., 2006, 2009; Kaplan et al., 2010, 2013; Putnam et al., 2010a, 2012, 2013a, 2013b; Golledge et al., 2012; Barrows et al., 2013; Doughty et al., 2013; Rother et al., 2014).

Existing reconstructions of late Quaternary glacier fluctuations in New Zealand have predominantly concentrated on large outlet

* Corresponding author. Antarctic Research Centre, Victoria University of Wellington, P.O. Box 600, Wellington 6140, New. Zealand.
E-mail address: shaun.eaves@vuw.ac.nz (S.R. Eaves).

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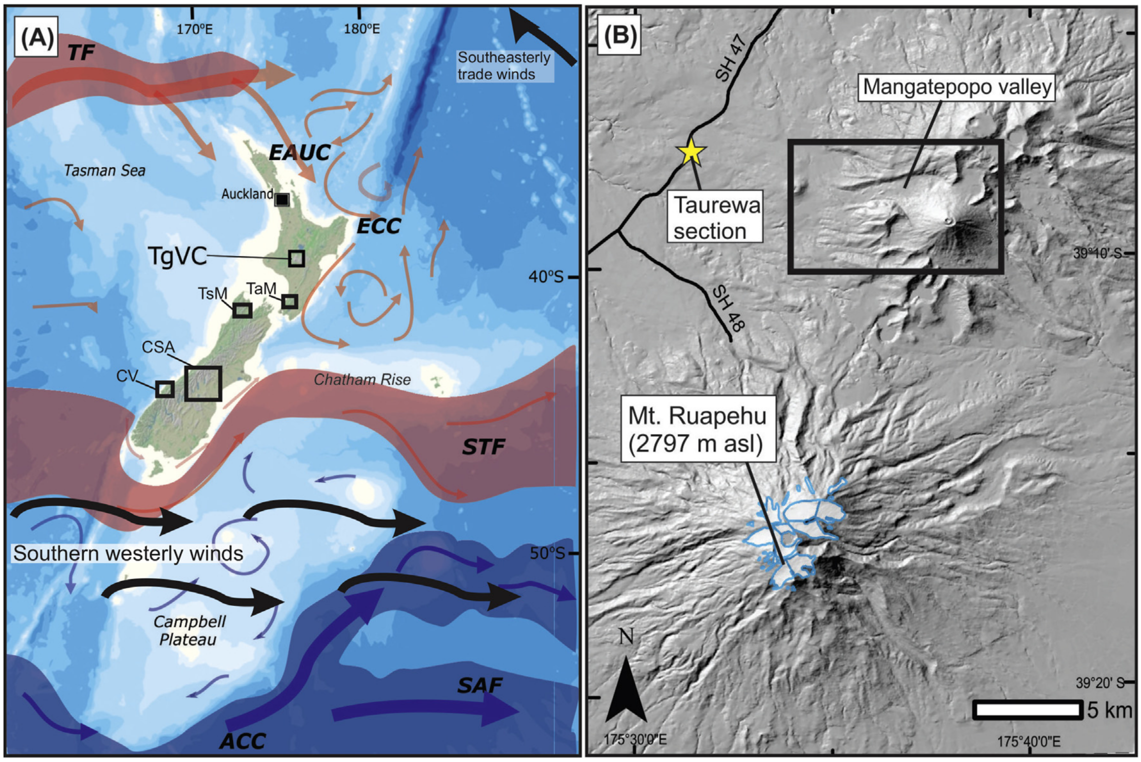

Fig. 1. (A) Contemporary general atmospheric and oceanic circulation in New Zealand and locations of sites referred to in text (background image sourced from National Institute for Water and Atmospheric research (NIWA)). Sites: TgVC = Tongariro Volcanic Centre; TaM = Tararua Mts.; TsM = Tasman Mts.; CSA = Central Southern Alps; CV = Cascade valley. Ocean currents: EAUC = East Australian Current; ECC = East Cape Current; STF = Sub-tropical front; SAF = Sub-Antarctic Front; ACC = Antarctic Circumpolar Current; (B) Hill-shaded digital elevation model (Columbus et al., 2011) of the Tongariro massif and Mt. Ruapehu, with the main study region defined (black outline). The location of proximal tephra reference site at Taurewa and Mt. Ruapehu glacier outlines according to Keys (1988) are also shown.

glaciers that drained the central Southern Alps (e.g. Porter, 1975; Suggate and Almond, 2005; Schaefer et al., 2006; Barrows et al., 2013; Putnam et al., 2013b; Rother et al., 2014). Radiocarbon and luminescence dating of peat and loess units, interbedded with glacial till and glaciofluvial outwash, have provided a broad chronostratigraphic framework for this region (Suggate, 1990; Suggate and Almond, 2005). More recently, cosmogenic surface exposure dating of moraine boulders has provided the means to directly constrain the timing and magnitude of past glacier fluctuations (Schaefer et al., 2006; Barrows et al., 2013; Putnam et al., 2013a, b; Rother et al., 2014). During the last glacial cycle, glacier length in the Southern Alps peaked relatively early (c. 32–26 ka; Suggate and Almond, 2005; Putnam et al., 2013b; Barrows et al., 2013; Rother et al., 2014), in comparison to global ice volume (Clark et al., 2009). At this time, local equilibrium line altitudes were depressed by c. 850 m and temperatures were c. 6–6.5 °C colder, relative to present (Golledge et al., 2012). Subsequently, glaciers fluctuated about these positions until at least c. 18 ka before rising temperatures resulted in widespread deglaciation (Schaefer et al., 2006; Putnam et al., 2013a, b; Rother et al., 2014). Recent work has shown that advances of former outlet glaciers in central Southern Alps, prior to the Last Glacial Maximum (LGM), culminated at 42 ± 1 ka (Kelley et al., 2014), 65 ± 3 ka (Schaefer et al., 2015) and 139 ± 11 ka (Putnam et al., 2013b). Previous research had suggested the occurrence of significant pre-LGM glacial advances in New Zealand (Williams, 1996; Almond et al., 2001; Preusser et al., 2005; Sutherland et al., 2007; McCarthy et al., 2008), but the exact timing of these events was poorly resolved due to low chronological precision or small sample populations.

Resolving the timing and magnitude of late Quaternary glacier fluctuations in locations outside of the central Southern Alps will provide insight to the synchroneity and climatic gradients of past climate change in the southern mid-latitudes. In this study, we use cosmogenic ^{3}He exposure dating, tephrochronology and equilibrium line altitude (ELA) reconstruction techniques, to provide the first direct age constraint on the timing and magnitude of glacier fluctuations on Tongariro massif, central North Island (39°S).

2. Setting

2.1. Regional climatic situation

Situated between 34°S and 47°S in the south west sector of the Pacific Ocean, New Zealand spans subtropical and subpolar climes (Fig. 1). Westerly atmospheric circulation dominates between 30°S and 60°S and is responsible for the eastward migrating troughs and anticyclones that define weather variability in New Zealand year-round (Sturman and Tapper, 1996). Interception of such weather systems by the predominantly NE–SW trending axial ranges results in a distinct zonal precipitation gradient. Meanwhile, interannual to interdecadal air temperature anomalies in New Zealand are strongly influenced by upwind sea surface temperatures (Sutton et al., 2005). The latitudinal range and high topographic relief of the New Zealand landmass result in meridional and zonal gradients in air temperature and precipitation respectively. Contemporary oceanic influences on North Island, New Zealand (34–41°S) are largely sub-tropical, predominantly originating from an eastward flowing branch of the equatorial-sourced East Australian Current, known as the Tasman Front, which descends the northeast coast before continuing eastwards along the northern margin of the Chatham Rise (Fig. 1). In contrast, South Island (40–47°S) intersects the sub-tropical front (STF), where sub-tropical gyres and sub-