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A cosmogenic ^{10}Be chronology for the local last glacial maximum and termination in the Cordillera Oriental, southern Peruvian Andes: Implications for the tropical role in global climate

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ABSTRACT

Resolving patterns of tropical climate variability during and since the last glacial maximum (LGM) is fundamental to assessing the role of the tropics in global change, both on ice-age and sub-millennial timescales. Here, we present a ^{10}Be moraine chronology from the Cordillera Carabaya (14.3°S), a sub-range of the Cordillera Oriental in southern Peru, covering the LGM and the first half of the last glacial termination. Additionally, we recalculate existing ^{10}Be ages using a new tropical high-altitude production rate in order to put our record into broader spatial context. Our results indicate that glaciers deposited a series of moraines during marine isotope stage 2, broadly synchronous with global glacier maxima, but that maximum glacier extent may have occurred prior to stage 2. Thereafter, atmospheric warming drove widespread deglaciation of the Cordillera Carabaya. A subsequent glacier resurgence culminated at ~16,100 yrs, followed by a second period of glacier recession. Together, the observed deglaciation corresponds to Heinrich Stadial 1 (HS1: ~18,000–14,600 yrs), during which pluvial lakes on the adjacent Peruvian-Bolivian altiplano rose to their highest levels of the late Pleistocene as a consequence of southward displacement of the inter-tropical convergence zone and intensification of the South American summer monsoon. Deglaciation in the Cordillera Carabaya also coincided with the retreat of higher-latitude mountain glaciers in the Southern Hemisphere. Our findings suggest that HS1 was characterised by atmospheric warming and indicate that deglaciation of the southern Peruvian Andes was driven by rising temperatures, despite increased precipitation. Recalculated ^{10}Be data from other tropical Andean sites support this model. Finally, we suggest that the broadly uniform response during the LGM and termination of the glaciers examined here involved equatorial Pacific sea-surface temperature anomalies and propose a framework for testing the viability of this conceptual model.

1. Introduction

As the energetic powerhouse of the globe, the tropics (23°N–23°S) are the principal source of heat energy and water vapour for the climate system and thus represent a fundamental and dynamic component of global climate (Cane, 1998; Pierrehumbert, 1999; Visser et al., 2003). Today, the tropical influence is exemplified by the El Niño-Southern Oscillation (ENSO), during which equatorial Pacific sea-surface temperature (SST) anomalies are transferred via deep convection to the overlying troposphere and transmitted rapidly to the extratropics. In this way, ocean-atmosphere dynamics in the tropical Pacific dominate present-day climate variability (e.g., Pierrehumbert, 1995). But what role, if any, did the tropics play in abrupt climatic perturbations associated with Late Quaternary glacial cycles? Can phenomena such as glacial terminations and Heinrich stadials be

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attributed to changes in tropical ocean-atmosphere heat transfer? Despite the wealth of palaeoclimate data demonstrating the tropics' capacity for high-magnitude and abrupt transitions (e.g., Stute et al., 1995; Thompson et al., 2000; Blard et al., 2011; Bromley et al., 2011a; Jomelli et al., 2014; Stríkis et al., 2015), plausible mechanisms for such variability remain elusive.

Palaeo-glacier records, particularly those from tropical latitudes, afford a unique opportunity to help address these key problems. Mountain glaciers are sensitive to small changes in temperature (Lowell, 2000; Favier et al., 2004; Oerlemans, 2005; Schaefer et al., 2006; Anderson and Mackintosh, 2012; Rupper and Roe, 2008; Rupper et al., 2012; Malone et al., 2015), as confirmed by their almost global response to modern warming (e.g., Dyurgerov and Meier, 2000), and leave a record of past fluctuations on the landscape in the form of moraines. Recent development of high-resolution glacier chronologies, fuelled by the refinement of cosmogenic surface-exposure dating, has improved our understanding of past climate behaviour and provided much-needed insight into the structure of key events including the last glacial maximum (LGM) and subsequent deglaciation. This time period, encompassing the last glacial-interglacial transition, is especially pertinent as not only does it represent the highest-magnitude climate change of the last ~100 Ka, but many of the climatic transitions also were abrupt in nature (Denton et al., 2010). Studying the extant nature of glacier records from the LGM and termination enables comparison of past climate conditions and potential forcing mechanisms, such as greenhouse gases, Milankovitch cycles, and ocean-atmosphere reorganisations.

In contrast to higher latitudes, the close relationship between tropical glacier mass balance and climate is relatively unimpeded by the complicating effects of mid-latitude ice sheets (e.g., albedo, aerosols: Broecker, 1995; Pierrehumbert, 2002), insolation forcing (Clement et al., 2004; Lee and Poulsen, 2005), and localised SST variations (Pierrehumbert, 1995). Moreover, recent constraint of high-altitude tropical ^{10}Be (Kelly et al., 2015; Martin et al., 2015) and ^{3}He (Blard et al., 2013) production rates has increased the viability of surface-exposure dating in these settings, enabling more accurate constraint of past glacier behaviour. Together, these factors make the tropics the ideal natural laboratory in which to assess the tropical role in Late Quaternary climate change. Building on the wealth of tropical palaeoclimate data pertaining to the LGM and termination, the objective of our study is to help address limitations in the existing data set by providing (1) detailed geomorphic maps of Late Quaternary glacial deposits and (2) a new cosmogenic ^{10}Be moraine chronology from southern Peru and (3) recalculating previous ^{10}Be surface-exposure data with the new production rate of Kelly et al. (2015). We then discuss emergent patterns of past climate behaviour in relation to the equatorial Pacific Ocean, which, at least during the present interglacial, is the dominant influence on tropical climate (Pierrehumbert, 1995; Picaut et al., 1996; Chiang and Sobel, 2002).

2. Geologic setting

The Cordillera Carabaya is a sub-range of the Cordillera Oriental in southern Peru (Fig. 1). Extending from the Bolivian border in the south to the Río Macusani in the north, the range forms part of the Zongo-San Gabán Zone (Farrar et al., 1988) and is underlain by Palaeozoic and early Mesozoic sedimentary, volcanic and intrusive lithologies (Clark et al., 1990; Reitsma et al., 2010). With the exception of Nevado Allinccapac (5800 m asl), a heavily glaciated peak at the northern end of the range, the Cordillera Carabaya is characterised by relatively low-elevation (5000–5200 m asl) alpine topography, in which modern glaciers are largely restricted to steep, shaded aspects (Fig. 2). Annual precipitation values in the

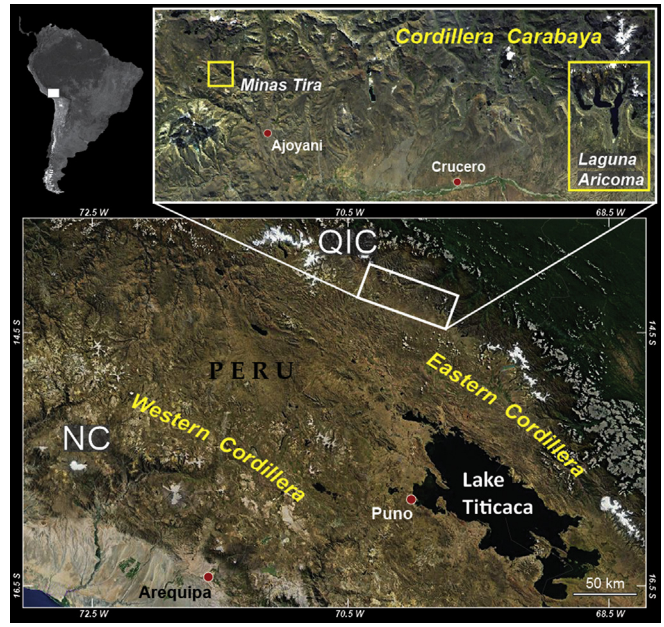

Fig. 1. Location map of the Cordillera Carabaya in southern Peru, with our two field sites – Minas Tira and Laguna Aricoma – indicated. Also shown are the relative positions of the Quelccaya Ice Cap (QIC) and Nevado Coropuna (NC).

cordillera are relatively high, owing to the proximity of the Amazon Basin, and range from ~800 mm/yr on the south-western flank to >1050 mm/yr on north-eastern slopes, with the majority of precipitation occurring during the 4–5 month summer wet season. As elsewhere in the 'outer tropics' (Kaser, 2001), glacier ablation in the Cordillera Carabaya is dominated by melting during the austral wet season and by sublimation during the driest months. However, the dominance of temperature over glacier behaviour is indicated both by recent mass-balance analysis of Andean glaciers (Sagredo and Lowell, 2012) and by the significant retreat of remaining ice masses in recent decades, during which mean-annual air temperature throughout the tropical Andes has risen by ~0.1 °C/decade (Vuille et al., 2008).

Our study centres on two separate valley systems in the central Cordillera Carabaya - Quebrada (henceforth, 'Q.') Tiratańa and Laguna Aricoma (Fig. 1) - both of which are located within the Titicaca catchment. Quebrada Tiratańa is a broad, low-gradient valley draining Nevado Tolqueri (5275 m asl) to the south. At the confluence of Q. Tiratańa and a tributary valley, Q. Jotini, a prominent series of lateral and terminal moraines defines the former termini of Pleistocene glaciers there (Fig. 3) and is a focus of this investigation. At its maximum extent, the Tiratańa glacier extended 9 km from its source at Nevado Tolqueri, while the smaller Jotini glacier drained the ~4850 m-high plateau 4 km to the west. Although both glaciers terminated at the same location – a site known as Minas Tira (4500 m asl; 14.1616°S., 70.2642°W) – the distribution of moraines suggests the two ice tongues were never fully confluent (see Section 4; Fig. 3). Up-valley of Minas Tira, moraines are absent for several kilometres and the valley bottom is characterised by wetland and river-dissected alluvial deposits.

The second site, Laguna Aricoma (4640 m asl; 14.3371°S, 69.8163°W), occupies a broad, glacially excavated basin approximately 20 km north-east of the town of Crucero and 50 km from Minas Tira (Fig. 1). The lake is fed by a series of south-draining valleys and tributary lakes, two of which – Veluyoccocha (4660 m asl) and Cocañacocha (4690 m asl) – are dammed by terminal moraine complexes (Fig. 4). Today, remnant glaciers in the