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Glacier fluctuations in the southern Peruvian Andes during the late-glacial period, constrained with cosmogenic ^{3}He

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Abstract

The occurrence of pronounced climate reversals during the last glacial termination has long been recognised in palaeoclimate records from both hemispheres and from high to low latitudes. Accurate constraint of both the timing and magnitude of events, such as the Younger Dryas and Antarctic Cold Reversal, is vital in order to test different hypotheses for the causes and propagation of abrupt climate change. However, in contrast to higher-latitude regions, well-dated records from the tropics are rare and the structure of late-glacial tropical climate remains uncertain. As a step toward addressing this problem, we present an *in-situ* cosmogenic ^{3}He surface-exposure chronology from Nevado Coropuna, southern Peru, documenting a significant fluctuation of the ice margin during the late-glacial period. Ten tightly clustered ages from a pair of moraines located halfway between the modern glacier and the last glacial maximum terminus range from 11.9 ka to 13.9 ka and give an arithmetic mean age of 12.8 ± 0.7 ka (1σ). These data constitute direct evidence for a readvance, or prolonged stillstand, of glaciers in the arid Andes of south-western Peru.

Table 1 Sample data and helium concentrations for C-II moraines. Asterisks denote samples published previously by Bromley et al. (2009) and recalculated here according to Balco et al. (2008), as modified by Goehring et al. (2010).

Sample No.	Lat. S	Long. W	Altitude (m)	Type	Thickness (cm)	Density (g/cm^3)	Shielding	Erosion (mm/yr)	$^3He_{cos}$ (atoms/g)	1 Sigma
NC17*	-15.511	-72.5860	5082	Cobble	6.3	2.7	0.967	0	1.862×10^7	4.351×10^5
NC18*	-15.5112	-72.5862	5087	Cobble	7	2.7	0.997	0	1.977×10^7	4.229×10^5
NC19*	-15.5114	-72.5862	5087	Cobble	6	2.7	0.983	0	1.924×10^7	5.464×10^5
NC20*	-15.5116	-72.5861	5089	Cobble	6	2.7	0.997	0	1.493×10^7	3.589×10^5
NC32	-15.5089	-72.5799	5034	Boulder	3	2.7	0.997	0	2.031×10^7	4.92×10^5
NC33	-15.511	-72.5782	5063	Boulder	5	2.7	0.993	0	1.767×10^7	9.619×10^5
NC34	-15.5102	-72.5786	5052	Boulder	1.5	2.7	0.995	0	1.85×10^7	7.368×10^5
NC35	-15.0994	-72.5786	5052	Boulder	1.6	2.7	0.995	0	2.254×10^7	1.293×10^6
NC36	-15.5096	-72.5855	5053	Boulder	3.25	2.7	0.998	0	1.818×10^7	6.873×10^5
NC37	-15.5105	-72.5861	5066	Boulder	3.1	2.7	0.982	0	1.821×10^7	6.886×10^5
NC38	-15.5115	-72.5862	5095	Boulder	5	2.7	0.997	0	1.939×10^7	6.597×10^5
NC39	-15.5139	-72.5869	5130	Boulder	2	2.7	0.998	0	1.832×10^7	8.336×10^5

Table 2 Helium isotope data for all C-II samples. 3He/4He ratios are given as measured and relative to the atmospheric 3He/4He value Ra = 1.384 x 10^{-6}. Asterisks denote samples published previously (Bromley et al., 2009) and recalculated here according to Balco *et al.* (2008), modified by Goehring *et al*. (2010).

Sample No.	$^{3}He/^{4}He$	$^{3}He/^{4}He$ (R/R_a)	1 sigma	^{4}He (atoms/g)	1 sigma	^{3}He (atoms/g)	1 sigma
NC17*	1.571 x 10^{-5}	11	4.729 x 10^{-7}	1.185 x 10^{12}	2.232 x 10^{10}	1.862 x 10^{7}	4.351 x 10^{5}
NC18*	1.738 x 10^{-5}	13	4.782 x 10^{-7}	1.138 x 10^{12}	1.952 x 10^{10}	1.977 x 10^{7}	4.229 x 10^{5}
NC19*	1.845 x 10^{-5}	13	6.204 x 10^{-7}	1.043 x 10^{12}	1.864 x 10^{10}	1.924 x 10^{7}	5.464 x 10^{5}
NC20*	1.343 x 10^{-5}	10	3.978 x 10^{-7}	1.112 x 10^{12}	1.911 x 10^{10}	1.493 x 10^{7}	3.589 x 10^{5}
NC32	1.538 x 10^{-5}	11	3.415 x 10^{-7}	1.433 x 10^{11}	1.387 x 10^{9}	2.031 x 10^{7}	4.92 x 10^{5}
NC33	1.243 x 10^{-5}	9	6.595 x 10^{-7}	1.434 x 10^{11}	1.749 x 10^{9}	1.767 x 10^{7}	9.619 x 10^{5}
NC34	2.234 x 10^{-5}	16	8.372 x 10^{-7}	9.04 x 10^{10}	1.22 x 10^{9}	1.85 x 10^{7}	7.368 x 10^{5}
NC35	2.611 x 10^{-5}	19	1.428 x 10^{-6}	8.855 x 10^{10}	1.542 x 10^{9}	2.254 x 10^{7}	1.293 x 10^{6}
NC36	1.856 x 10^{-5}	13	6.777 x 10^{-7}	1.371 x 10^{11}	1.344 x 10^{9}	1.818 x 10^{7}	6.873 x 10^{5}
NC37	2.004 x 10^{-5}	14	6.905 x 10^{-7}	1.044 x 10^{11}	1.628 x 10^{9}	1.821 x 10^{7}	6.886 x 10^{5}
NC38	1.98 x 10^{-5}	14	6.08 x 10^{-7}	9.765 x 10^{10}	1.428 x 10^{9}	1.939 x 10^{7}	6.597 x 10^{5}
NC39	2.353 x 10^{-5}	17	1.017 x 10^{-6}	8.29 x 10^{10}	1.18 x 10^{9}	1.832 x 10^{7}	8.336 x 10^{5}

Table 3 C-II surface-exposure ages calculated according to the Lm (time dependent) and Li scaling schemes (Balco *et al*., 2008). Asterisks denote samples published previously by Bromley et al. (2009) and recalculated here according to Balco et al. (2008), as modified by Goehring et al. (2010). Italics denote outlier.

Sample No.	Lm (ka)	Li (ka)
Production rate (at/gr/yr)	120 ± 9.4	136 ± 4.1
NC17*	**12.8 ± 0.3**	**10.2 ± 0.2**
NC18*	**13.6 ± 0.3**	**10.9 ± 0.2**
NC19*	**13.2 ± 0.4**	**10.5 ± 0.3**
*NC20**	*10.2 ± 0.2*	*8.0 ± 0.2*
NC32	**13.9 ± 0.3**	**11.1 ± 0.3**
NC33	**11.9 ± 0.7**	**9.5 ± 0.5**
NC34	**12.4 ± 0.5**	**9.9 ± 0.4**
NC35	*15.0 ± 0.9*	*12.2 ± 0.7*
NC36	**12.4 ± 0.5**	**9.9 ± 0.4**
NC37	**12.5 ± 0.5**	**10.0 ± 0.4**
NC38	**13.3 ± 0.5**	**10.6 ± 0.4**
NC39	**11.9 ± 05**	**9.5 ± 0.4**
Age range	11.9 – 13.9	9.5 – 11.1
Mean age	12.8 ± 0.7	10.2 ± 0.5

Keywords: late glacial reversal; last termination; tropics; cosmogenic Helium-3; glaciers

Introduction

The last glacial-interglacial transition ('Termination 1') represents the most significant reorganisation of Earth's climate in the last hundred thousand years. Imposed upon the pattern of rising global temperatures, distinct and sometimes abrupt climate oscillations have been recognised in numerous proxy records from sites worldwide. In the classic view of the late-glacial period, events in the Northern Hemisphere typically are tied to the Younger Dryas (YD: 11.6-12.9 ka), an abrupt return to near full-glacial conditions first identified in Scandinavia (Blytt, 1876; Sernander, 1908; Mangerud *et al*., 1974). In a similar sense, several recent investigations in the Southern Hemisphere (Fogwill and Kubik, 2005; Moreno *et al.*, 2009) have correlated late-glacial events with the slightly earlier Antarctic Cold Reversal (ACR: 12.9-14.5 ka). The importance of understanding abrupt, sub-orbital climate change (Denton *et al.*, 2005) has prompted a substantial body of research directed towards constraining the geographic extent of events such as the YD (e.g., Denton and Hendy, 1994; Gosse *et al*., 1995; Briner *et al*., 2002; Ackert *et al.*, 2008). In the tropics, for example, a YD signature has been recognised in precipitation records (Schulz *et al*., 1998; Hughen *et al*., 2000; Haug *et al*., 2001; Wang *et al*., 2001), suggesting that cold events in the North Atlantic region are intricately linked to changes in the distribution of low-latitude rainfall.

Resolving the exact timing, structure, and geographic extent of late-glacial climate events is fundamental to our understanding of the causes of abrupt climate change and poses a key problem in palaeoclimate research (Denton *et al*., 2005). Nonetheless, the response of glaciers to late-glacial climate variability remains an unresolved and controversial issue. Glaciers are sensitive indicators of climate change (Oerlemans, 1994, 2001; Anderson & Mackintosh, 2006), advancing and retreating in response to small changes in temperature and precipitation, and have the potential to provide valuable, long-term records of climate. Our understanding of past glacier behaviour at tropical latitudes is limited, however, by low spatial resolution of data and insufficient dating resolution (Rodbell *et al.*, 2009).

The occurrence of a late-glacial climate reversal in the tropical Andes of South America has been debated for decades (Mercer and Palacios, 1977; Clapperton and McEwan, 1985; Schubert and Clapperton, 1990; Hansen, 1995; Clapperton *et al*., 1997; Rodbell and Seltzer, 2000) and continues to be contentious. In their comprehensive review of Andean glacier records, Rodbell *et al*. (2009) noted that most tropical moraines of late-glacial age are constrained either by minimum- or maximum-bounding radiocarbon ages, and that few are dated sufficiently to identify discrete patterns in climate behaviour. Adding to the uncertainty, tropical moraine chronologies based on surface-exposure dating – an increasingly common practice in the Andes – are subject to significant systematic uncertainties at these latitudes and altitudes due to ambiguity in nuclide production rates and scaling schemes (Farber *et al*., 2005; Smith *et al*., 2008; Zech *et al.*, 2007, 2008; Bromley *et al*., 2009), requiring a conservative approach to interpreting cosmogenic ages.

In their recent review of published data, Rodbell *et al*. (2009) suggested that a YD-like signal occurs in various records from the tropical Andes, a view supported by at least two recent studies (Mahaney *et al.*, 2007; Glasser *et al*., 2009). Nonetheless, compelling evidence for this event remains elusive (Smith *et al*., 2008) and indications of an advance during the ACR in south-eastern Peru (Goodman *et al*., 2001) and, potentially, in northern Bolivia (Blard *et al*., 2009) emphasise that the pattern of late-glacial climate behaviour in the tropical Andes is far from resolved (Rodbell *et al*., 2009). This uncertainty represents a significant shortcoming of our knowledge both of millennial and sub-millennial climatic variability in the tropics, and of the global extent of abrupt climate-change events.

As an important step toward addressing this problem, we present ten cosmogenic ^{3}He surface-exposure ages from late-glacial moraines on Nevado Coropuna in south-western Peru. The moraines are located midway between the modern glacier terminus and moraines dated to the last glacial maximum (LGM: Bromley *et al*., 2009). We calculated these ages using currently accepted scaling protocols (Balco *et al*., 2008) and a compilation of global ^{3}He production rates (Goerhing *et al*., 2010).

Geologic and climatic overview

Nevado Coropuna (6426 m; 15º 33'S, 72º 93'W), located 150 km north-west of Arequipa (Fig. 1), is both the highest peak in the Cordillera Ampato and the highest volcano in Peru. The mountain comprises four andesite domes separated by broad saddles and rises ~2000 m above the surrounding puna on all but the south side. Here, incision of the underlying ignimbrite by the Rio Llacllaja, a tributary of the Colca Canyon, has resulted in relief of more than 3500 m. Although andesitic eruptions at Coropuna began during the late Miocene, the mountain's present structure is attributed to prolonged Quaternary volcanism (Venturelli *et al*., 1978; Weibel *et al*., 1978). The most recent activity produced three large andesite flows on the west, north, and south flanks (Fig. 2). Although these flows have not been dated directly, they overlie deposits of known late-glacial age (Bromley *et al*., 2009; this study) and, in turn, have been eroded by subsequent glacial activity.

The persistent inversion over the Pacific coast and strong Andean rain shadow effect combine to maintain a semi-arid climate at Coropuna. Most precipitation (~390 mm water equivalent yr^{-1} at 6080 m; Herreros *et al*., 2009) arrives during the brief summer wet season (December-March). Coropuna currently supports an ice cap (~60 km^2: Racoviteanu *et al*., 2007) drained by fifteen outlet glaciers, as well as extensive perennial snow. Due to aridity, glaciers are restricted to elevations significantly higher (5100-5500 m) than the local zero-degree isotherm (~4900 m; Dornbusch, 1998) and ablation occurs both by melting and sublimation. Today, meltwater streams are rare and flow only during clear conditions. The largest drains the ice cap via the north-flowing valley of Quebrada Ullullo (Fig. 2). Glaciofluvial features associated with late Pleistocene moraines indicate the presence of former melting margins.

Glacial-geologic overview

Abundant, well-preserved glacial deposits on the slopes of Coropuna correspond to periods when ice was more extensive than today. Dornbusch (2002) described moraines on the mountain's west flank as corresponding to a single, undated event. This record was expanded by Bromley *et al*. (2009) to include evidence both for older and younger events registered in several locations on Coropuna. In addition, Bromley *et al.* (2009) presented a preliminary cosmogenic ^{3}He surface-exposure moraine chronology and demonstrated the suitability of the ^{3}He method for use in the tropical Andes. The most striking glacial landforms on Coropuna include large lateral moraines, some as much as 100 m in relief and eight kilometres long (Fig. 3), radiating out from the mountain. Bromley *et al*. (2009) attributed these moraines (C-I) to the LGM, between ~21 and 25 ka. Beyond the LGM limit, moraines and drift corresponding to at least two earlier advances are preserved on the plateau north and east of Coropuna (Fig. 3).

On all sides of Coropuna, a prominent set of bouldery moraines (C-II) occurs midway between the LGM termini and the modern ice margin and corresponds to a readvance, or prolonged stillstand, of glaciers during deglaciation (Bromley *et al*., 2009). The best-preserved C-II deposits are located in the north-facing Quebrada Santiago (Figs. 2, 3) and are the focus of this study. Bromley *et al*. (2009) provided four preliminary cosmogenic ^{3}He ages from this complex and suggested it was deposited during the late-glacial period.

Sampling and analysis methods

The geomorphic mapping of C-II moraines in Quebrada Santiago forms the basis of this study and is described in detail by Bromley *et al*. (2009). To obtain a ^{3}He surface-exposure chronology, we sampled the tops of andesite boulders (0.5-3 m high) located on lateral- and end-moraine crests (Fig. 4). We collected the upper few centimetres (≤5 cm) of rock beneath boulder surfaces. Boulder surfaces typically exhibit glacial polish and striae, indicating that post-depositional granular erosion and spallation has been negligible. The size of the samples and the arid conditions at Coropuna minimise shielding effects due to snow or vegetation. We acknowledge the possibility of post-depositional exhumation of boulders, due to erosion or deflation of moraines, but suggest that this process has been minimal on Coropuna due to aridity and the bouldery, sharp-crested nature of the C-II moraines.

We measured helium concentrations in small (125-250 μm diameter) clinopyroxene (augite) minerals. Rock samples first were crushed and sieved to retrieve the 125-250 μm size fraction. Using heavy liquids, magnetic separation, and hand-picking, we then separated the pyroxenes. Gases from the pyroxene separates were released by total extraction at ~1300-1400ºC for fifteen minutes, during which time the furnace was kept exposed to a liquid nitrogen-cooled charcoal trap for gas purification. We purified the gases further by exposing them to a SAES getter at room temperature. Residual gas was collected on a cryogenically cooled trap held at ~13ºK and helium then was separated from neon by heating the trap to 45ºK. Abundance and isotopic analyses were performed with a MAP 215-50 noble gas mass spectrometer calibrated with a known volume of a Yellowstone helium standard (MM) with a $^3He/^4He$ ratio of 16.45R_a, where R_a = $(^3He/^4He)_{air} = 1.384 \times 10^{-6}$. Mass spectrometry measurements were conducted at Lamont-Doherty Earth Observatory following the protocol of Winckler et al. (2005). $^3He/^4He$ ratios of the investigated rocks are extremely high, ranging from 9 to 19 times the atmospheric ratio (Table 2). Therefore, we do not correct our dataset for non-cosmogenic (e.g., magmatic) ^3He as such corrections would be less than 1%.

We present the ^3He ages calculated using globally derived production rates for ^3He (Goehring *et al.*, 2010) and the Lm (Lal, 1991/Stone, 2000/Nishiizumi *et al.*, 1989) and Li (Lifton *et al*., 2005) scaling models (Balco *et al*., 2008, as modified by Goehring *et al*., 2010: see Bromley *et al*., 2009, for a detailed description of our calculation methodology). Our interpretations and discussion are based on the results of the time-dependent Lm scaling, because it is used widely and incorporates geomagnetic variability at low latitudes. Furthermore, ^{10}Be production-rate calibration studies from both Peru (Farber *et al*., 2005) and New Zealand (Putnam *et al*., 2010) have shown that at test sites, the Lm scaling gives the closest match to available radiocarbon constraints (N. Lifton, pers. comm., 2009). We also include here four ages reported by us previously (NC*17-20*: Bromley *et al*., 2009), now recalculated to be consistent with out new data.

Results

C-II deposits preserved in Quebrada Santiago form a closely spaced pair of right-lateral moraines descending to a pair of terminal moraines at ~5000 m. The paired moraines merge to form a single left-lateral moraine (Figs. 3, 5). The length (~1.25 km in *Q*. Santiago, 2.9 km in *Q*. Ullullo), large size, and continuous nature of the lateral moraines suggest that these deposits represent an advance of ice, as opposed to a pause in recession. Moreover, the steep distal slopes of C-II moraines are indicative of deposition along a robust, steep ice margin, a configuration typical of advancing glaciers. By contrast, recessional landforms on Coropuna typically form short, low-relief sections of end moraines with gentle distal slopes and little or no continuity up-valley. Nonetheless, although the morphology of the C-II moraines is strongly indicative of deposition at the margins of advancing glaciers, we acknowledge the possibility that the moraines instead represent a prolonged stillstand during post-LGM deglaciation.

The C-II moraines are prominent, bouldery ridges of 5-10 m relief that exhibit well-defined crests 1-5 m in width. An exception occurs where the left-lateral moraine crosses a bedrock escarpment, becoming instead a thin, bouldery drift unit with a well-defined edge (Figs. 3, 5). This drift edge extends upslope for ~350 m before merging with the continuation of the left-lateral moraine Figs. 3, 5). Moraines with similar morphology, relative position, and weathering occur in neighbouring valleys (Fig. 2) and elsewhere on the mountain (Bromley *et al*., 2009).

Altogether, there are twelve cosmogenic ^{3}He ages from the C-II deposits in Quebrada Santiago. Four samples (NC*17-20*: Bromley *et al.*, 2009) were from the prominent drift edge, described above. We collected an additional six samples from the moraine complex itself: one (NC*33*) from the outer end moraine, four (NC*32, 34-36*) from the inner end moraine, one (NC*37*) from the left-lateral moraine below the drift edge, and two (NC*38, 39*) from the left-lateral moraine upslope of the drift edge (Fig. 5). Sample and helium data are given in Tables 1 and 2 and surface-exposure ages in Table 3. Together, ^{3}He surface-exposure ages from the C-II moraines range from 11.9 ± 0.5 to 13.9 ± 0.3 ka (Fig. 5; Table 3), with an arithmetic mean age of 12.8 ± 0.7 ka (1 σ). Plotted as a probability curve, the C-II ages exhibit a slightly bimodal distribution (Fig. 6), with a principal peak age of 13.4 ka and a secondary peak age of 12.4 ka. We exclude samples NC*20* and *35* as young and old outliers, respectively, both being more than 2σ beyond the mean.

Discussion

The moraine record from Quebrada Santiago indicates that post-LGM retreat was interrupted by a glacier advance or stillstand, during which the C-II moraines were deposited. At this time, the glacier terminus was located approximately mid-distance between the modern ice edge and the LGM limit (Fig. 7), suggesting that a significant portion of deglaciation already had taken place. The dearth of retreat moraines or downwasting deposits up-valley of the C-II limits, both in Quebrada Santiago and in other valleys on Coropuna, indicates that subsequent recession largely was inactive or was too rapid for moraine formation. Thus, the C-II deposits represent a unique event between the LGM and the presumed late-Holocene moraines.

Regardless of scaling scheme, the ten ages from C-II moraines in Quebrada Santiago exhibit a high degree of internal consistency. With Lm scaling, these data constrain the event unequivocally to the late-glacial period. With Li scaling the age range becomes significantly younger at 9.5 ka to 10.9 ka and would suggest an early Holocene age for the advance. We consider this unlikely, however, given both substantial evidence for full interglacial conditions in the tropical Andes by the early Holocene (e.g., Thompson *et al*., 1995, 1998; Seltzer *et al*., 2002; Ramirez *et al*., 2003; Bush *et al*., 2005) and the absence of known events in the early Holocene that might have caused glaciers to advance to half their LGM extent. Therefore, we reiterate that we base our interpretations on the Lm dataset.

The C-II ages range from 11.9 to 13.9 ka and exhibit two peaks of similar size at 12.7 and 13.4 ka (Fig. 6). It is possible that this bimodal distribution represents two distinct age populations and, therefore, that the moraines correspond to two closely spaced yet separate advances of similar extent. However, considering the moraine morphology and sample distribution (Fig. 5), we do not yet have strong physical evidence for this scenario.

Our dataset adds to a growing body of multiproxy evidence for late-glacial climate variability in the tropical Andes. For example, pollen records from Venezuela (Schubert and Clapperton, 1990), Colombia (Kuhry *et al*., 1993; Van de Hammen and Hooghiemstra, 1995), Ecuador (Hansen, 1995), and Peru (Hansen, 1995) all indicate that post-LGM warming in the tropics was interrupted by fluctuations in temperature and/or precipitation. Similarly, compelling evidence for pronounced late-glacial cold reversals is provided by the $\delta^{18}O$ ice-core records from Nevados Huascarán, Peru (Thompson *et al*., 1995), and Sajama, Bolivia (Thompson *et al*., 1998), although the exact nature and timing of these events have yet to be established (Thompson *et al.*, 2000). Preliminary data from the new Coropuna ice core suggest that a similar reversal also is recorded at that site (Buffen, 2008).

In addition to pollen and ice-core records, late-glacial climate variability in the tropics is documented by numerous moraine chronologies (Rodbell *et al*., 2009, and references therein). Clear glacial-geomorphologic evidence for post-LGM advances comes from Ecuador (e.g., Clapperton and McEwan, 1985; Clapperton *et al*., 1997), Venezuela (Mahaney *et al.*, 2007), and Peru (e.g., Mercer and Palacios, 1977; Wright, 1984; Rodbell and Seltzer, 2000; Bromley *et al*., 2009). With the development of surface-exposure dating, our ability to resolve the timing of these events has increased greatly and glacier chronologies documenting late-glacial fluctuations now exist for several tropical Andean sites (Farber *et al*., 2005; Smith *et al*., 2005; Zech *et al*., 2006, 2007; Smith *et al*., 2008; Bromley *et al*., 2009; Blard *et al*., 2009; Glasser *et al*., 2009).

Collectively, these chronologies are in broad agreement. Regardless of method or scaling scheme, each record shows that the last glacial-interglacial transition was not smooth but was interrupted by glacier advances or stillstands. In this general sense, the tropical climate shares a high degree of similarity with higher latitudes, where late-glacial climate reversals are well documented. However, detailed comparison of the tropical moraine dataset reveals substantial variability among sites. For example, whereas some studies have correlated late-glacial advances with the YD (e.g., Clapperton *et al.*, 1997; Mahaney et al., 2007; Glasser et al., 2009), other records document advances that predated the YD (Mercer and Palacios, 1977; Rodbell and Seltzer, 2000; Goodman et al., 2001; Smith *et al.*, 2005; Blard *et al*., 2009). Accepting that some of this discrepancy might be the result of methodological differences, the question remains as to what extent late-glacial climate fluctuations in the tropics were linked to one another and to higher-latitude events.

In addressing this question, it is essential that the nature *as well as* the timing of late-glacial ice fluctuations be established. For example, when compared on the basis of age alone, the late-glacial record from Coropuna bears a striking similarity to that of Quebrada Uquian in the Cordillera Blanca (Fig. 1), site of the 'Breque' moraine (Rodbell and Seltzer, 2000). Specifically, the age range for the C-II moraines (11.9-13.9 ka) is in close agreement with the age of the Breque moraine, constrained by radiocarbon ages to 12.9-13.2 ka (Rodbell and Seltzer, 2000) and with ^{10}Be surface-exposure dating to 10.4-13.2 ka (Farber *et al*., 2005). While it is tempting to infer from this concurrence that the Breque event was regional in extent, there are important differences in moraine stratigraphy and sample distribution between Coropuna and the Cordillera Blanca site.

First, as documented by Rodbell (1991, 1993), the Breque moraine is one of four prominent landforms (termed 'Manachaque' moraines) spread over a distance of ~4.5 km and classed as late-glacial in age. In contrast, the C-II landforms on Coropuna form discrete units of single or closely paired moraines located midway between the LGM and modern ice limits. Such morphologic differences between Coropuna and Quebrada Uquian reflect their different climate histories, and highlight the possibility that glaciers in the tropical Andes responded to local as well as global forcing during the late-glacial period (Rodbell *et al*., 2009). Second, of the four Manachaque moraines, only the Breque moraine (the second youngest Manachaque limit) was dated (Rodbell and Seltzer, 2000; Farber *et al*., 2005), whereas the C-II dataset presented here comprises ^{3}He ages from both the inner and outer moraines. Together, these considerations demonstrate that regional correlations based solely on chronologic parallels, without consideration of morphology, may be inaccurate.

The late-glacial ^{3}He dataset from Coropuna spans much of the YD and ACR. In the face of present systematic uncertainties associated with surface-exposure dating in tropical latitudes, however, we warn that correlation of the C-II advance with either the YD or ACR would be premature. Only minor adjustment of production rate or scaling protocol could shift the C-II chronology to be slightly younger or older than presented here. Considering the overlapping nature of the YD and ACR, this uncertainty highlights the methodological refinement needed before surface-exposure dating can verify millennial- and sub millennial-scale patterns in tropical glacier behaviour. Recent studies (e.g., Kelly *et al.*, 2007) increase optimism that such verification and improvement of cosmogenic-nuclide production rates and international scaling models, at least at high elevations in the tropics, will be achieved soon.

Conclusions

Our C-II moraine chronology from Coropuna affords robust and directly dated evidence for an important climate event in the southern Peruvian Andes ~12-14 ka ago, during which glaciers occupied positions approximately half as extensive as during the LGM. The Coropuna ^{3}He dataset therefore represents an important contribution to a growing body of evidence for climate reversals during the late-glacial period in the tropics. In addition, excellent agreement between mean and peak ages from a tightly clustered age distribution demonstrates that cosmogenic ^{3}He chronologies can be as internally consistent and precise as ^{10}Be datasets.

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Figure captions

Figure 1. Map of Peru showing locations of Nevado Coropuna (NC) and the Cordillera Blanca (CB).

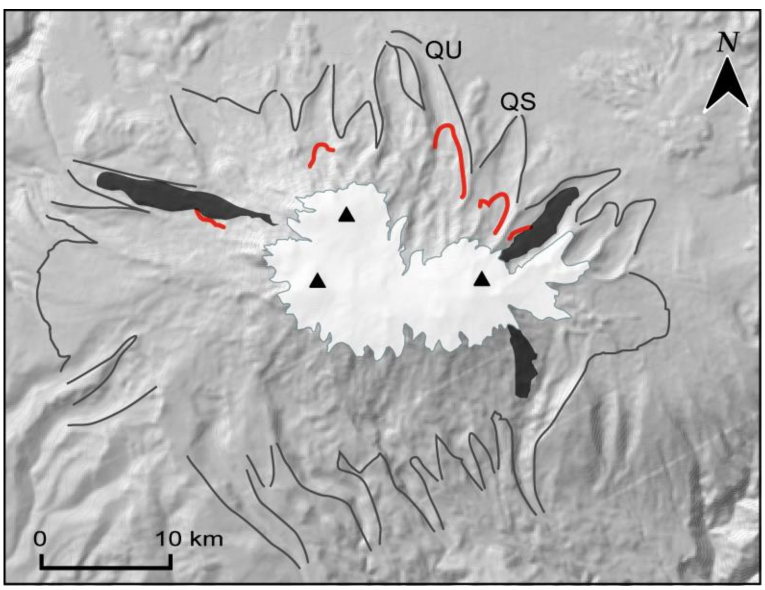

Figure 2. Map of Coropuna showing Quebradas Santiago (QS) and Ullullo (QU), post-glacial lava flows (black), and glacial limits: black lines LGM moraines; red lines late glacial moraines.

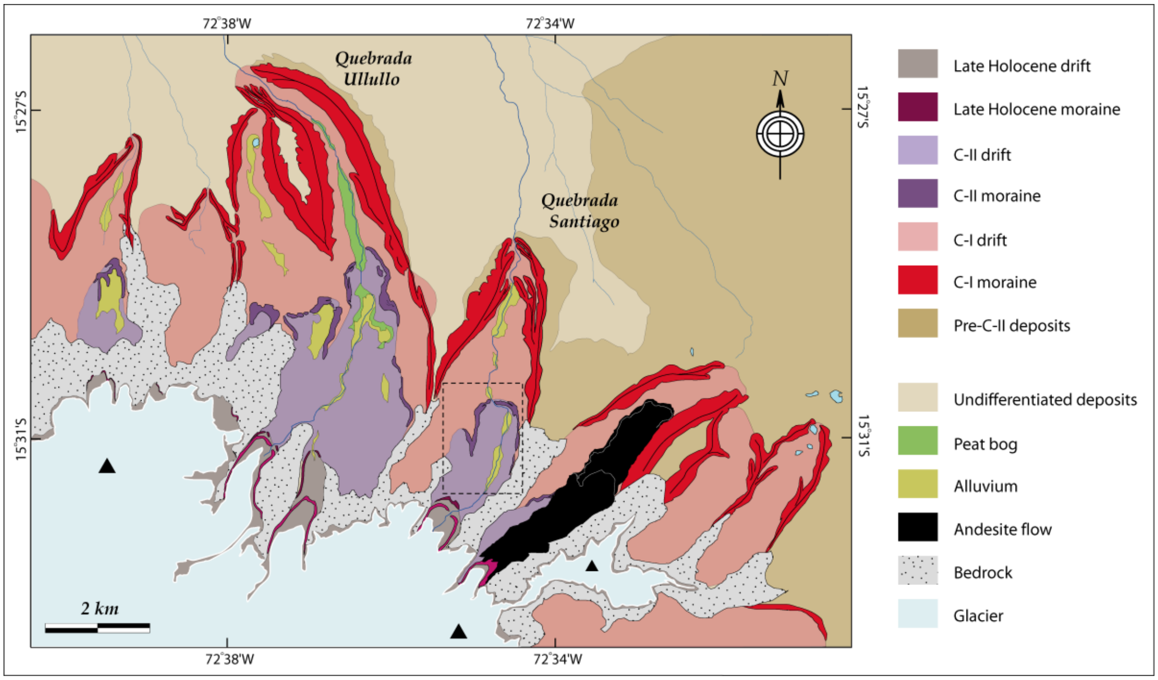

Figure 3. Geomorphic map of Quebrada Santiago area. Dashed line indicates the area shown in Figure 5.

Figure 4. Sampling boulder (NC34) on C-II moraine crest, Quebrada Santiago.

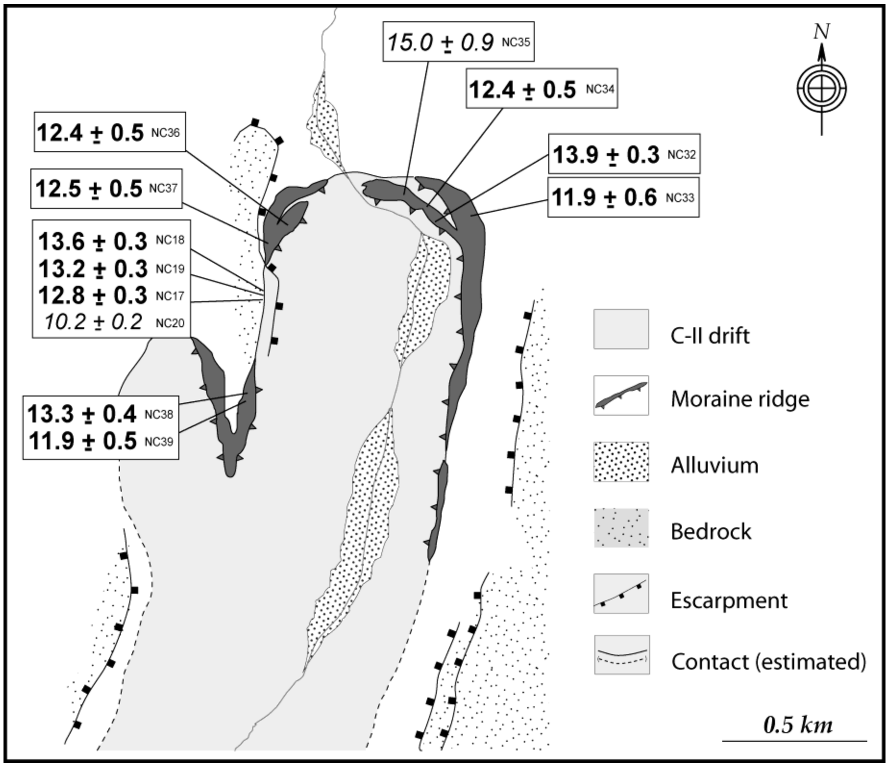

Figure 5. Close-up map of Quebrada Santiago showing distribution of C-II moraines and ^{3}He ages.

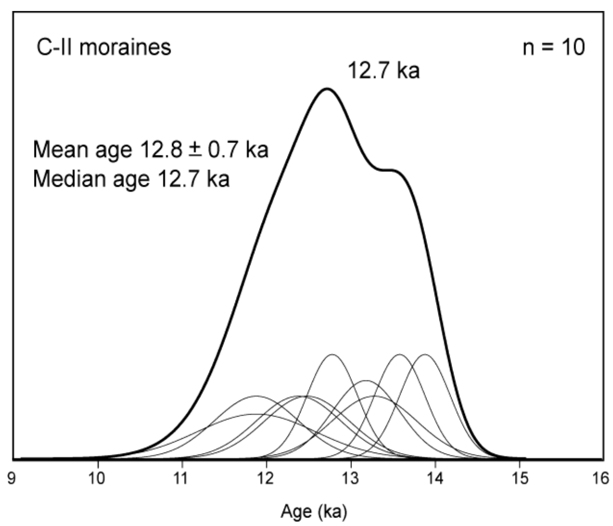

Figure 6. Probability curve of C-II ages. Mean age is given to 1σ uncertainty.

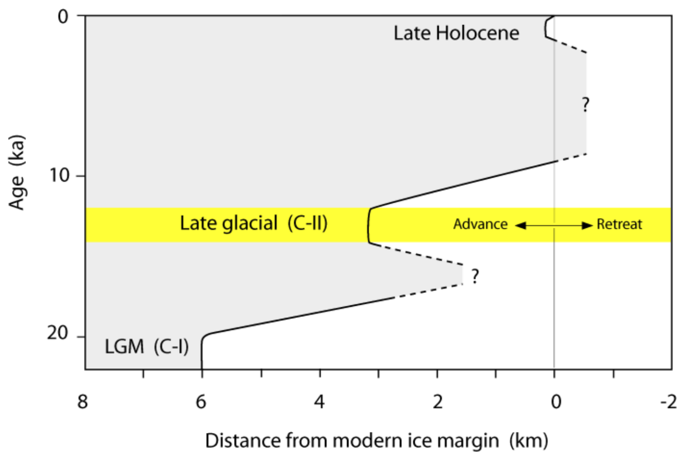

Figure 7. Age-distance diagram depicting former ice-front positions in Quebrada Santiago relative to today. Constraint of the LGM (C-I) event is based on ages from Bromley *et al*., (2009). The late glacial (C-II) advance is constrained by ages given in this study. Although no ages exist for late Holocene moraines, for the purpose of this diagram we assign them a 19th century age, consistent with the last major advance documented elsewhere in the Peruvian Andes (Kaser, 1999; Solomina *et al*., 2007; Licciardi *et al*., 2009). Dashed lines indicate inferred glacier extent.