Cuadernos de Investigación Geográfica *Geographical Research Letters*	2017	Nº 43 (2)	pp. 649-666	ISSN 0211-6820 eISSN 1697-9540

DOI: http://doi.org/10.18172/cig.3231

LAST LOCAL GLACIAL MAXIMUM AND DEGLACIATION OF THE ANDEAN CENTRAL VOLCANIC ZONE: THE CASE OF HUALCAHUALCA VOLCANO AND PATAPAMPA ALTIPLANO (SOUTHERN PERU)

J. ALCALÁ-REYGOSA[1, 2*]

[1]Facultad de Filosofía y Letras. Universidad Nacional Autónoma de México, Ciudad Universitaria, 04510 Ciudad de México, México.

[2]Research Group of High Mountain Physical Geography, Department of Geography, Complutense University of Madrid, Spain.

ABSTRACT. *The aim of this study is to constrain the timing of the deglaciation process since the Last Local Glacial Maximum in HualcaHualca volcano and Patapampa Altiplano, located in the Andean Central Volcanic Zone. Nine ^{36}Cl cosmogenic surface exposure dating of moraine boulders as well as polished and striated bedrock surfaces are presented. The ^{36}Cl cosmogenic exposure ages indicate that the glaciers reached their maximum extent at ~17-16 ka on the HualcaHualca volcano during the Heinrich 1 event and the Tauca paleolake cycle. Since then glaciers began to retreat until ~12 ka, when they went through a phase of readvance or stillstand. The deglaciation of HualcaHualca was constant since ~11.5 ka, coinciding with the disappearance of the ice cap from the Patapampa Altiplano. These glacial ages do not corroborate a Last Local Glacial Maximum prior to the global Last Glacial Maximum but they indicate a sensitive reaction of the glacier system to precipitation fluctuations. According to the analysis of cosmogenic exposure ages reported from HualcaHualca, Sajama and Tunupa volcanoes, the onset of deglaciation since Last Local Glacial Maximum occurred at the end of the Heinrich 1 event and the Tauca paleolake cycle in the Andean Central Volcanic Zone. However, the glacier retreat was not continuous because at least one significant readvance or stillstand phase has been reported in most of the volcanoes studied in this region although the ages cannot be clearly related to the Younger Dryas and/or the Antarctic Cold Reversal cold events. After this readvance or stillstand, the glaciers of the Central Volcanic Zone retreated, but at least three clear minor readvances evidence a not homogeneous warm and/or dry climate during the Holocene. Even though in situ cosmogenic exposure provides important glacial chronological data, it is difficult to establish a consistent regional glacial reconstruction and clear connections with the main Late Pleistocene cold episodes due to limitations associated with in situ cosmogenic production rates and the use of different scaling schemes. To reduce the uncertainty and compare* *the available cosmogenic ages, it would be necessary to determine a precise in situ cosmogenic production rate for each isotope in the Central Andes, a standard scaling scheme and recalculate the published chronological data.*

El Último Máximo Glaciar local y la deglaciación de la Zona Volcánica Central Andina: El caso del volcán HualcaHualca y del altiplano de Patapampa (Sur de Perú)

RESUMEN. *El objetivo de este trabajo es conocer cuándo comenzó el retroceso de los glaciares desde el Último Máximo Glaciar Local tanto en el volcán HualcaHualca y el Altiplano de Patapampa, ambos localizados al sur de Perú, como en la Zona Volcánica Centroandina. Para ello se presentan 9 edades de exposición a la radiación cósmica procedentes de morrenas y umbrales rocosos pulidos y estriados. Dichas edades indican que los glaciares del HualcaHualca alcanzaron su máxima extensión hace ~17-16 ka en sincronía con el Heinrich 1 y la formación del paleolago Tauca. Desde entonces los glaciares empezaron a retroceder hasta ~12 ka cuando experimentaron un reavance o una fase de estabilización. La deglaciación fue constante desde hace ~11.5 ka en el HualcaHualca, coincidiendo con la desaparición del casquete de Hielo de Patapampa. Esta evolución de los glaciares del área de estudio no corrobora un Último Máximo Glaciar Local más antiguo que el Último Máximo Glaciar global pero sí indica su elevada sensibilidad a los cambios en la precipitación. De acuerdo con el análisis de las edades de exposición a la radiación cósmica de los volcanes HualcaHualca, Sajama y Tunupa, se infiere que el inicio de la deglaciación en la Zona Volcánica Centroandina tuvo lugar al finalizar el evento Heinrich 1 y la fase lacustre Tauca. Sin embargo, el retroceso no fue continuo ya que se registra al menos un reavance o fase de estabilización en la mayoría de los volcanes estudiados aunque la inconsistencia entre sus edades no permite relacionar con claridad dicha fase glaciar con los eventos climáticos fríos Younger Dryas y Antarctic Cold Reversal. Después, las masas de hielo de la Zona Volcánica Centroandina experimentaron un marcado retroceso, interrumpido temporalmente por al menos tres reavances o periodos de estabilización de menor entidad que evidencian que el clima durante el Holoceno no fue continuamente cálido y/o seco. Por último cabe destacar que a pesar de que las edades de exposición a la radiación cósmica proporcionan una información cronológica valiosa, de momento no permiten reconstruir de forma sólida la historia de los glaciares y establecer conexiones claras con los principales eventos fríos debido a las limitaciones que presentan las tasas de producción y el uso de diferentes modelos de escala. Con el objeto de reducir la incertidumbre derivada de estas limitaciones, sería necesario determinar una tasa de producción precisa de cada isótopo cosmogénico en los Andes Centrales, un modelo de escala de referencia y recalcular las edades publicadas.*

Key words: Cosmogenic Surface Exposure dating, Tropical Glaciation, Last Glacial Maximum, Younger Dryas, Antarctic Cold Reversal, Holocene, Andean Central Volcanic Zone, Southern Peru.

Palabras clave: Datación de superficies por exposición a la radiación cósmica, Glaciación en los Trópicos, Último Máximo Glaciar, Younger Dryas, Antarctic Cold Reversal, Holoceno, Zona Volcánica Centroandina, Sur de Perú.

Received: 31 January 2017
Accepted: 6 April 2017

* Corresponding author: Jesús Alcalá-Reygosa, Research Group of High Mountain Physical Geography, Department of Geography, Complutense University of Madrid, Spain. E-mail address: jalcalar@ucm.es

1. Introduction

The current knowledge about the glacial history in the Central Andes is focused on dating the Last Local Glacial Maximum (LLGM) and the subsequent Late Glacial readvances (Rodbell, 1993; Clapperton, 1993; Clayton and Clapperton, 1997; Mark *et al.,* 2002; Seltzer *et al*., 2000, 2002; Farber *et al*., 2005; Smith *et al*., 2005, 2009, 2011; Zech *et al*., 2007a, 2007b; Kull *et al*., 2008; Bromley *et al*., 2009, 2011; Glasser *et al*., 2009; Hall *et al*., 2009; May *et al*., 2011; Úbeda *et al*., 2012; Kelly *et al*., 2012; Blard *et al*., 2013, 2014; Stansell *et al*., 2015). However, our understanding of the LLGM, the readvance or stillstand phases and the beginning of deglaciation is limited in regions such as the Andean Central Volcanic Zone. This scenario does not allow verification of traditional hypotheses of glacier behaviour in the Central Andes as: (i) the LLGM took place several thousand years before the global Last Glacial Maximum (Smith *et al.*, 2005, 2008); (ii) ice masses located in arid regions react to changes in precipitation while glaciers in areas with high levels of precipitation are more sensitive to temperature fluctuations, as proposed by Hastenrath (1971), Klein *et al*. (1999), Amman *et al*. (2001) and Sagredo and Lowell (2012).

The most detailed glacial chronology since the LLGM in the Andean Central Volcanic Zone has been obtained at Coropuna volcano. Based on the application of *in-situ* cosmogenic ^{3}He surface exposure dating and Lm scaling (Lal, 1991; Stone, 2000; Nishiizumi *et al*., 1989) on the outer moraines of Coropuna, Bromley *et al*. (2009) suggest that the LLGM took place between ~15 and 25 ka. This chronology is consistent with the global Last Glacial Maximum (19-26 ka; Clark *et al*., 2009), but the mean age of LLGM moraines show significant changes when the different scaling schemes available are used: 20.95 ± 0.2 ka (Lm), 17.46 ± 0.2 ka (Du; Dunai, 2000); 17.18 ± 0.2 ka (Li; Lifton *et al*., 2005) and 16.85 ± 0.2 ka (De; Desilets *et al*., 2006). Deglaciation since LLGM on Coropuna began at ~19 ka until ~15 ka (Lm scaling) according to the ^{3}He exposure ages from a valley-floor transect in Quebrada Sigue Chico, located on the western flank of the volcano. This post-LLGM recession was followed by a strong readvance dated at ~13 ka, although after that the retreat continued until it reached its modern extent. Similar glacier behaviour occurred on the Quebrada Santiago, located on the northeastern slope of Coropuna (Bromley *et al*., 2011). Nevertheless, deglaciation and readvance chronologies are ~3 ka younger if the other three scaling models (Du, Li and De) are used (Bromley *et al*., 2009).

By contrast, Úbeda *et al*. (2012) used *in-situ* cosmogenic ^{36}Cl isotope to date the outer moraines on the northeastern flank of Coropuna volcano. The ^{36}Cl exposure ages, following the Lal (1991) scaling model, suggest that glaciers reached their maximum extent between ~20 and 16 ka. Then the ice mass began to retreat but it experience a readvance at ~12-11 ka. However, the LLGM on the southern slope was dated at ~14 ka as well as one readvance or stillstand pulse at ~10-9 ka. Other minor readvances at ~9 ka (northern slope) and ~6 ka (southern slope) have been reported. These minor glacier expansions interrupted the deglaciation process that occurred during the Holocene.

In Bolivia, at Nevado Sajama, the outermost moraines were also dated with *in-situ* cosmogenic ^{36}Cl isotope although the Stone (2000) scaling method was used (Smith *et al*., 2009). ^{36}Cl exposure ages indicates that the LLGM occurred between ~16.9-11.8 ka and ~14.0-10.2 ka. The glacier began to retreat after this maximum advance, but glacial deposits have been dated at ~7.0 and ~3.3 ka, suggesting the lack of a homogeneous warm or/and dry climate during the Holocene.

The moraine record of Tunupa volcano (Bolivia) is another site where *in-situ* cosmogenic ^{3}He surface exposure dating was used (Blard *et al*., 2013). Here the exposure ages were calculated though a new and local production rate obtained by Blard *et al*. (2013) from a fluvio-glacial outwash deposit located on the southern flank of the volcano. Moreover, they apply the scaling models of Lal (1991) and Stone (2000). The cosmogenic ^{3}He ages indicates that the LLGM took place between ~17-15.5 Ka, in synchronicity with the Lake Tauca paleocycle (17-15 ka). A recessional moraine has also been dated at ~14.7 ka but this chronology is not consistent with the ages from polished and striated bedrock (~400 years older). Thus, Blard *et al*. (2013) proposed that the onset of glacial recession occurred between ~15.5-14.5 ka, approximately 500 years before the end of Tauca paleolake regression. Both deglaciation and paleolake regression have been related with the Bølling Allerød warm climate event.

Another glacial chronology has also been established on Uturuncu volcano, approximately 270 km to the south of Tunupa volcano, based on ^{3}He surface exposure dating. These ages were constrained using the cosmogenic production rate calibrated in the Tunupa volcano as well as the scaling schemes of Lal (1991) and Stone (2000). Thus, the outer moraine was built between 65 and 37 ka, revealing that the LLGM is significantly older than the global Last Glacial Maximum although glaciers remained close to their maximum position until ~18 ka. At this point the ice mass began to retreat but a readvance or stillstand occurred around 16-14 ka, being in phase with the highest level of paleolake Tauca. After 14 ka the glacier retreated, a process that coincides with the Bølling Allerød interstadial (Blard *et al*., 2014).

To improve the knowledge of the evolution of glaciers since the LLGM in the Central Volcanic Zone, this study present nine ^{36}Cl surface exposure ages of moraine boulders as well as polished and striated bedrock outcrops from HualcaHualca volcano and the Patapampa Altiplano. This glacial chronology also can be useful to infer if the ice masses of the Central Volcanic Zone are sensitive to climatic parameters such as temperature or precipitation or both.

2. Geographical setting

The Andes is the longest continental mountain range extending over 7500 km from the Caribbean coast of Venezuela to Cabo de Hornos in Chile. According to Clapperton (1993) there are three main units: the northern Andes between the Caribbean Sea and the Amotape suture zone; the central Andes, from the Amotape suture zone to the south of Chile; and the Southern Andes, from the south of Chile to the Shackleton-Seotra region. The distinctive characteristic of these regions is the alternation of active and inactive volcanic zones across the whole orogen.

The Central Andean Volcanic Zone (Fig. 1), associated to the subduction of the oceanic Nazca Plate beneath the South American Plate, with a seafloor dip of >25°, presents at least 6 caldera systems and 44 active volcanic centers (Isacks, 1988; Stern, 2004). One of them is the Ampato volcanic complex (15°24´ - 15°51´S / 71°51´- 73°W; 6288 m a.s.l.), located 70 km to the northwest of Arequipa city. HualcaHualca (6025 m a.s.l.) is the northernmost stratovolcano of the Ampato complex and it is considered extinct (Thouret *et al*., 2005). The formation of the HualcaHualca volcano began during the late Miocene or the early Pleistocene and it is compound of andesitic materials. As a consequence of the collapse of the northern flank, the HualcaHualca exhibits a horseshoe-shaped caldera.

HualcaHualca is characterised by a well-preserved moraine record, especially in the four valleys selected for this study: Huayuray (northern slope), Pujro Huayjo (southwestern slope), Mollebaya (eastern slope) and Mucurca (westernern slope). Modern glaciers cover the summit but they are experiencing a marked retreat in recent decades (Alcalá *et al*., 2010, Alcalá, 2015). The other study area, Patapampa

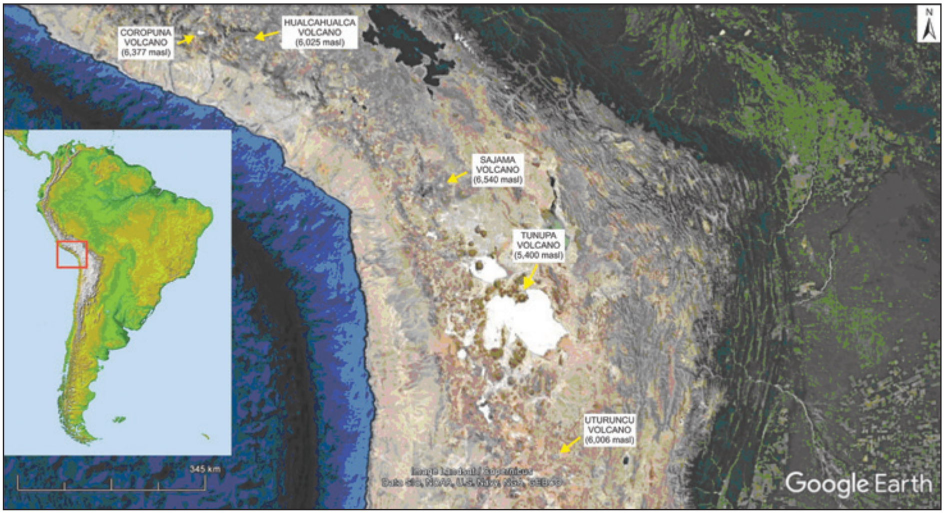

Figure 1. Location of the Andean Central Volcanic Zone and the volcanoes where the glacial record has been dated though in situ cosmogenic Surface isotopes.

(15°43´40´´-15°46´ S / 71°43´30´´-71°36´ W; 4940 m a.s.l.), is an Altiplano situated 17 km southeast of HualcaHualca volcano that presents geomorphological evidences of glacial activity (Fig. 2).

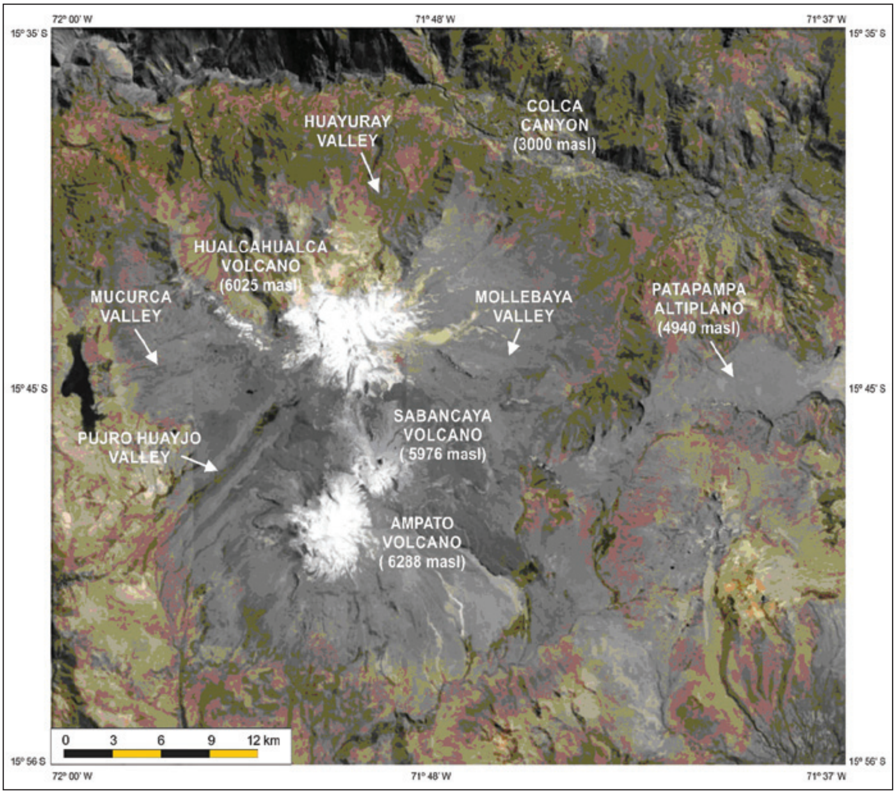

Figure 2. Location of the study area: HualcaHualca volcano and Patapampa Altiplano.

The climate of the study area is mainly determined by seasonal changes in the Intertropical Convergence Zone that generate two marked seasons: the wet season (December to March), when humid air masses arriving the Central Andean Altiplano from the Atlantic ocean produce 70-90 % of the annual precipitation (800-1000 mm) (Dornbusch, 1998; Herreros *et al.,* 2009), and the dry season (April to November) due to the strong influence of high pressure conditions. However, temperatures do not change significantly throughout the year.

3. Methods

To determine the glacier evolution since the LLGM and the pattern of deglaciation on HualcaHualca volcano, the *in situ* cosmogenic nuclide ^{36}Cl was measured. This cosmogenic isotope was selected because it permits dating quartz-free rocks from the glacial deposits and glacially-abraded bedrock of the study area. Moreover, the use of the cosmogenic ^{36}Cl allows comparison with the other glacial areas of the Central Volcanic Zone where *in situ* cosmogenic nuclides have been applied.

3.1. Cosmogenic ^{36}Cl surface exposure dating

3.1.1. Sampling strategy and lab protocol: measure of ^{36}Cl concentration

A detailed geomorphological map at 1:20,000 scale was elaborated to represent glacial landforms of HualcaHualca volcano (Alcalá-Reygosa *et al*., 2016). The map was used to select the sites containing well-preserved lateral and frontal moraines corresponding to the maximum glacier extent, readvance phases and glacially-abraded bedrock for cosmogenic ^{36}Cl surface exposure dating.

To constrain the cosmogenic ^{36}Cl exposure age of the moraines and glacially abraded bedrock, nine samples were collected with hammer and chisel from solid rock surfaces (~5 cm). Seven of them (Hualca 1, 2, 3, 4; Pujro Huayjo 1; Mucurca 1; Patapampa 3) were taken from the surface of andesite boulders >1 m high, situated on the crests of moraines. The other two samples (Pujro Huayjo 2 and Patapampa 4) were collected from the highest surfaces of polished and striated bedrock outcrops. This method succeeded in reducing the potential uncertainty in ^{36}Cl cosmogenic production caused by post geomorphological processes (erosion, weathering, toppling) as well as shielding by snow, tephra layers associated with volcanic activity of the active Sabancaya volcano and soils.

3.1.2. Lab protocol

Lichens, mosses and other organic material were removed from the samples with a brush. Then, the samples were crushed using a roller grinder and sieved to retrieve the sand size fraction (500-850 μm) in the Complutense University of Madrid (Spain). Whole-rock protocol (Zreda *et al*., 1999; Phillips, 2003) was applied for *in situ* ^{36}Cl dating at the PRIME Laboratory (Purdue University). There, the sand fraction size was leached in deionized water and HNO_3 to remove atmospheric Cl and then dissolved in HNO_3 and HF acids. A spike of isotopically enriched ^{35}Cl was added during the dissolution process. The isotope dilution method allowed the ^{36}Cl and total Cl to be measured simultaneously (Desilets *et al*., 2006). The ratios ^{36}Cl/Cl and ^{37}Cl/^{35}Cl were determined by Accelerator Mass Spectrometry (AMS) analysis at PRIME Laboratory.

Aliquots of bulk rock (pre-treated) and target fraction (post-treated) were analysed at Activation Laboratories (Ancaster, Canada) to measure: (i) major elements, by fusion inductively coupled plasma optical emission spectrometry (ICP-OES); (ii) trace elements, by inductively coupled plasma mass spectrometry (ICP-MS); and (iii) boron, by prompt-gamma neutron activation analysis (PGNAA). The field and analytical data are presented in Table 1.

3.1.3. In-situ cosmogenic ^{36}Cl exposure age calculations

In-situ cosmogenic ^{36}Cl exposure ages were calculated using the spreadsheet developed by Schimmelpfennig (2009) and Schimmelpfennig *et al*. (2009). Several production rates of cosmogenic ^{36}Cl from the spallation of Ca were used: 48.8 ± 3.4 atoms

Table 1. Field and analytical data for ^{36}Cl samples from HualcaHualca volcano and Patapampa Altiplano.

Sample ID		Hualca 1	Hualca 2	Hualca 3	Hualca 4	Pujro Huayjo 1	Pujro Huayjo 2	Patapampa 3	Patapampa 4	Mucurca 1
Latitude	(°S)	-15.74	-15.67	-15.68	-15.64	-15.82	-15.82	-15.76	-15.74	-15.75
Longitude	(°W)	-71.76	-71.85	-71.85	-71.85	-71.95	-71.96	-71.63	-71.64	-71.98
Elevation	(masl)	4444	4408	4512	4144	4521	4450	4671	4886	4460
Sample thickness	(cm)	3.0	0.8	1.5	2.0	3.0	3.0	2.0	1.0	3.0
Shielding factor incorporating all efects	(unitless)	0.97	0.99	0.99	0.97	0.99	0.99	0.998	1.0	0.99
Snow shielding factor	(unitless)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Scaling factor for nucleonic production	(unitless)	10.63	10.45	10.93	9.24	11.0	10.66	11.76	12.9	10.7
Scaling factor for muonic production	(unitless)	3.84	3.8	3.92	3.48	3.93	3.85	4.13	4.4	3.86
Effective fast neutron attenuation length	(g cm−2)	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0
Na_2O	(wt.%)	3.76	3.72	3.92	4.37	4.22	3.49	4.01	3.87	4.26
MgO	(wt.%)	2.45	2.46	1.79	1.45	2.11	5.76	1.14	1.15	2.07
Al_2O_3	(wt.%)	15.52	15.33	15.38	16.16	15.67	16.49	18.09	17.03	15.55
SiO_2	(wt.%)	61.50	62.32	62.62	63.90	62.45	53.49	62.94	62.37	62.68
P_2O_5	(wt.%)	0.39	0.56	0.39	0.40	0.10	0.07	0.15	0.24	0.04
K_2O	(wt.%)	3.19	2.84	3.67	3.99	3.24	1.59	3.30	3.49	3.20
CaO	(wt.%)	4.66	4.57	3.85	3.39	4.66	6.37	4.51	4.66	4.66
TiO_2	(wt.%)	0.96	0.99	0.83	0.72	0.96	1.18	0.83	0.96	0.96
MnO	(wt.%)	0.08	0.08	0.06	0.05	0.07	0.11	0.05	0.06	0.07
Fe_2O_3	(wt.%)	5.86	6.31	5.12	4.38	5.86	9.88	4.25	5.86	5.86
Cl	(ppm)	525.1	81.1	228.2	129.7	59.4	101.1	273.34	42.2	27.8
B	(ppm)	11.9	9.8	21.0	19.8	13.0	4.3	28.0	22.1	17.1
Sm	(ppm)	6.2	5.8	5.4	5.2	6.0	4.8	4.7	6.4	6.4
Gd	(ppm)	4.5	3.8	3.9	3.4	3.8	3.6	3.3	4.6	3.9
U	(ppm)	1.5	1.5	2.4	2.9	2.2	0.7	3.3	3.2	2.1
Th	(ppm)	8.8	8.0	13.1	16.5	10.6	3.0	14.2	16.8	10.4
Sample mass	(g)	30.15	30.19	30.18	30.10	30.10	30.57	30.15	30.16	30.23
Mass of ^{35}Cl spike solution	(mg)	1.01	1.01	1.01	0.988	1.04	1.04	1.14	1.003	1.023
Concentration Spike solution	(g g−1)	1.0	1.0	1.0	1.00	1.00	1.00	1.00	1.0	1.00
Analytical stable isotope ratio	($^{35}Cl/(^{35}Cl + ^{37}Cl)$)	3.39 ± 0.01	4.78 ± 0.03	3.729 ± 0.02	4.153 ± 0.02	5.476 ± 0.38	4.49 ± 0.3	3.68 ± 0.04	6.21 ± 0.04	7.88 ± 0.47
Analytical $^{36}Cl/Cl$ ratio	($^{36}Cl/10^{15}$ Cl)	301.2 ± 7.47	726.7 ± 16.11	357.6 ± 6.28	543.6 ± 11.58	504.4 ± 18.57	425.8 ± 18.25	310.53 ± 15.80	906.2 ± 27.72	554.2 ± 24.58
Corrected 36Cl concentration	atoms per gram of rock	2856217.0	1429192.0	1589940.0	1507711.00	806626.00	975356.00	1662912.91	1182168.0	581522.00

^{36}Cl (g Ca) $^{-1}$ a $^{-1}$ (Stone *et al*. 1996), 42.2 ± 4.8 atoms ^{36}Cl (g Ca)$^{-1}$ a^{-1} (Schimmelpfennig *et al*., 2011), 56.27 ^{36}Cl (g Ca)$^{-1}$ a^{-1} (Borchers *et al*., 2016) and 56.0 ± 4.1 (g Ca)$^{-1}$ a^{-1} (Marrero *et al*., 2016).

^{36}Cl production rates from the spallation of K are as follows: 148.1 ± 7.8 atoms ^{36}Cl (g K) $^{-1}$ a $^{-1}$ obtained by Schimmelpfennig *et al*. (2014), 156.09 atoms ^{36}Cl (g K) $^{-1}$ by Borchers *et al*. (2016) and 155 ± 11 atoms ^{36}Cl (g K) $^{-1}$ by Marrero *et al*. (2016) were used. Moreover production rates from spallation of Ti of 13 ± 3 atoms ^{36}Cl (g Ti) $^{-1}$ a $^{-1}$ by Fink *et al*. (2000) and from the spallation of Fe of 1.9 atoms ^{36}Cl (g Fe) $^{-1}$ a $^{-1}$ by Stone *et al*. (2005) were introduced. The production rate of epithermal neutrons from fast neutrons in the atmosphere at the land/atmosphere interface (626 ± 46 neutrons (g air) $^{-1}$ a $^{-1}$; 696 ± 185 neutrons (g air) $^{-1}$ a $^{-1}$; 759 ± 180) proposed by Phillips *et al*. (2001) and Marrero *et al*. (2016) were used. The ages derived from the production rates proposed by Marrero *et al*. (2016) were selected because they were obtained at similar latitude and elevation (Huancané, Peru) than HualcaHualca volcano and Patapampa Altiplano. However, results for the available production rates are presented here to show differences (Table 2). The elevation/latitude scaling factors for nucleonic and muonic production were established using CosmoCalc (Vermeesch, 2007), which is based on the scaling model of Stone (2000). The shielding factor was estimated using the Topographic Shielding Calculator v1.0 provided by the CRONUS-Earth Project (2014).

Table 2. Cosmogenic ^{36}Cl surface exposure ages from HualcaHualca volcano and Patapampa Altiplano. Results for the available ^{36}Cl production rates. (1) Spallation of Ca: 56.27 ^{36}Cl (g Ca)$^{-1}$ a^{-1} (Borchers et al.*, 2016); Spallation of K: 156.09 atoms ^{36}Cl (g K)$^{-1}$; Production rate of epithermal neutrons from fast neutrons in the atmosphere at the land/atmosphere interface: 626 ± 46 neutrons (g air) $^{-1}$ a $^{-1}$ (Phillips* et al.*, 2001). (2) Spallation of Ca: 56.0 ± 4.1 (g Ca)$^{-1}$ a^{-1} (Marrero* et al.*, 2016); 155 ± 11 atoms ^{36}Cl (g K) $^{-1}$ (Marrero* et al.*, 2016); Production rate of epithermal neutrons from fast neutrons in the atmosphere at the land/atmosphere interface: 759 ± 180 neutrons (g air) $^{-1}$ a $^{-1}$ and 696 ± 185 neutrons (g air) $^{-1}$ a $^{-1}$ (Marrero* et al.*, 2016). (3). Spallation of Ca: 42.2 ± 4.8 atoms ^{36}Cl (g Ca)$^{-1}$ a^{-1} (Schimmelpfennig* et al.*, 2011); Spallation of K: 148.1 ± 7.8 atoms ^{36}Cl (g K) $^{-1}$ a $^{-1}$ (Schimmelpfennig* et al.*, 2014); Production rate of epithermal neutrons from fast neutrons in the atmosphere at the land/atmosphere interface: 626 ± 46 neutrons (g air) $^{-1}$ a $^{-1}$ (Phillips* et al.*, 2001). (4) Spallation of Ca: 48.8 ± 3.4 atoms ^{36}Cl (g Ca) $^{-1}$ a $^{-1}$ (Stone* et al.*, 1996); Spallation of K: 148.1 ± 7.8 atoms ^{36}Cl (g K) $^{-1}$ a $^{-1}$ (Schimmelpfennig* et al.*, 2014); Production rate of epithermal neutrons from fast neutrons in the atmosphere at the land/atmosphere interface: 626 ± 46 neutrons (g air) $^{-1}$ a $^{-1}$ (Phillips* et al.*, 2001).*

Sample	Exposure Age (1)	Exposure Age (2)	Exposure Age (3)	Exposure Age (4)
Hualca 1	13.4 ± 2.3	11.7 ± 2.1 / 12.5 ± 2.2	13.9 ± 2.5	13.7 ± 2.4
Hualca 2	17.8 ± 1.6	16.9 ± 1.7 / 17.3 ± 1.7	19.4 ± 1.9	18.8 ± 1.8
Hualca 3	12.0 ± 1.5	11.0 ± 1.5 / 11.5 ± 1.5	12.7 ± 1.6	12.5 ± 1.6
Hualca 4	16.6 ± 1.6	15.5 ± 1.8 / 16.0 ± 1.8	17.6 ± 1.9	17.4 ± 1.8
Pujro Huayjo 1	9.3 ± 1.3	9.0 ± 1.3 / 9.2 ± 1.3	10.2 ± 1.5	9.9 ± 1.4
Pujro Huayjo 2	12.0	11.2 ± 2.3 / 11.5 ± 2.4	13.3 ± 2.7	12.7 ± 2.6
Patapampa 3	10.5 ± 1.3	9.5 ± 1.3 / 10.0 ± 1.3	11.1 ± 1.5	10.9 ± 1.45
Patapampa 4	12.0 ± 0.9	11.8 ± 1.05 / 11.9 ± 1.0	13.3 ± 1.1	12.9 ± 1.1
Mucurca 1	8.0 ± 0.8	7.8 ± 0.8 / 7.9 ± 0.8	8.8 ± 0.9	8.5 ± 0.9

4. Results

The cosmogenic ^{36}Cl exposure ages are shown in Table 2. In Huayuray valley (northern slope; Fig. 3A), the sample (Hualca 4) collected in a moraine that corresponds to the maximum glacier extent yields an age of 16.0 ± 1.8 ka. The other two samples (Hualca 2 and 3) come from intermediate moraines and yield an age of 17.3 ± 1.7 and 11.5 ± 1.5 ka, respectively. In Pujro Huayjo valley (Fig. 3B), the age of the sample (Pujro

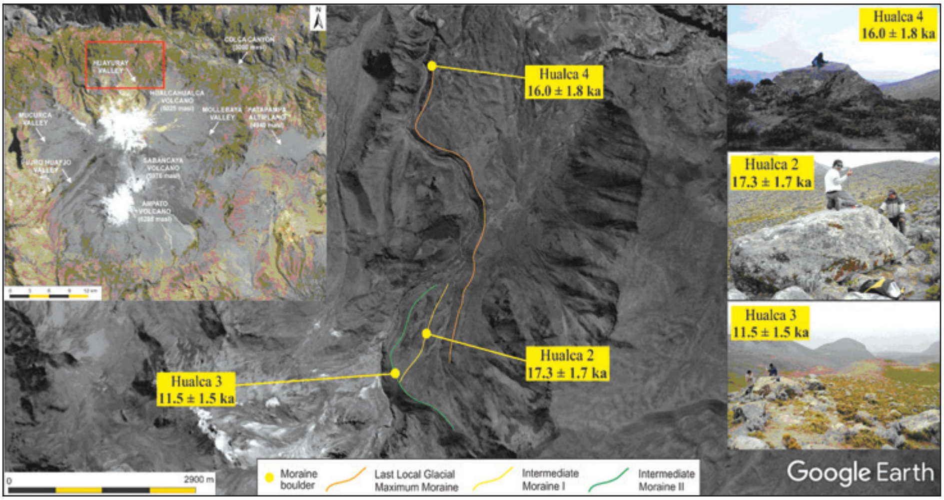

Figure 3 A. Moraine record and location of the samples collected on Huayuray valley (northern flank of HualcaHualca volcano).

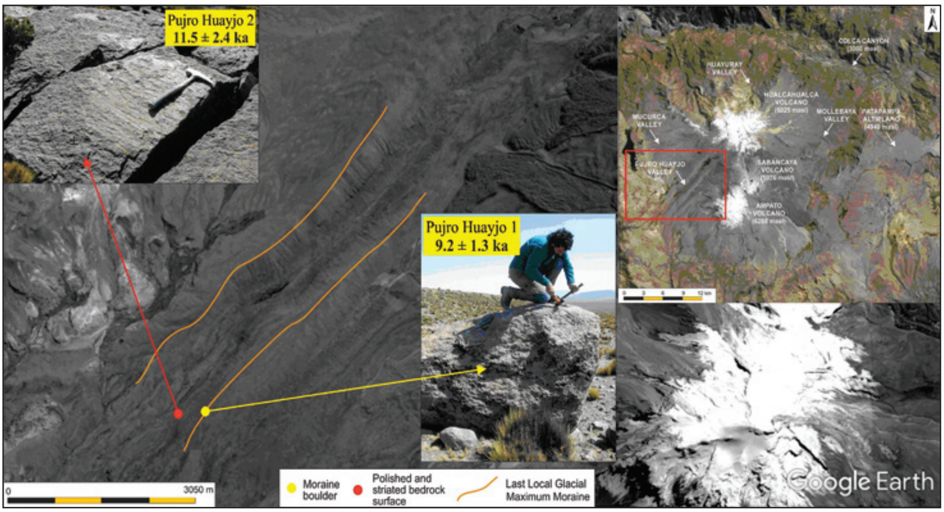

Figure 3 B. Moraine record and location of the samples collected on Pujro Huayjo valley (southwestern flank of HualcaHualca volcano).

Huayjo 1) from the outer and more voluminous moraine is 9.2 ± 1.3 ka, while the sample (Pujro Huayjo 2) collected on a polished and striated bedrock located at the inner base of the moraine reveals an age ~2 ka older (11.5 ± 2.4 ka).

In Mollebaya valley (Fig. 3C), the sample collected from the crest of the outer moraine (Hualca 1) yields an exposure age of 12.5 ± 2.2 ka. Another sample (Mucurca 1) was collected from the outermost moraine, related to the maximum glacier extent in Mucurca valley (Fig. 3D) and yields an exposure age of 7.9 ± 0.8 ka. By contrast,

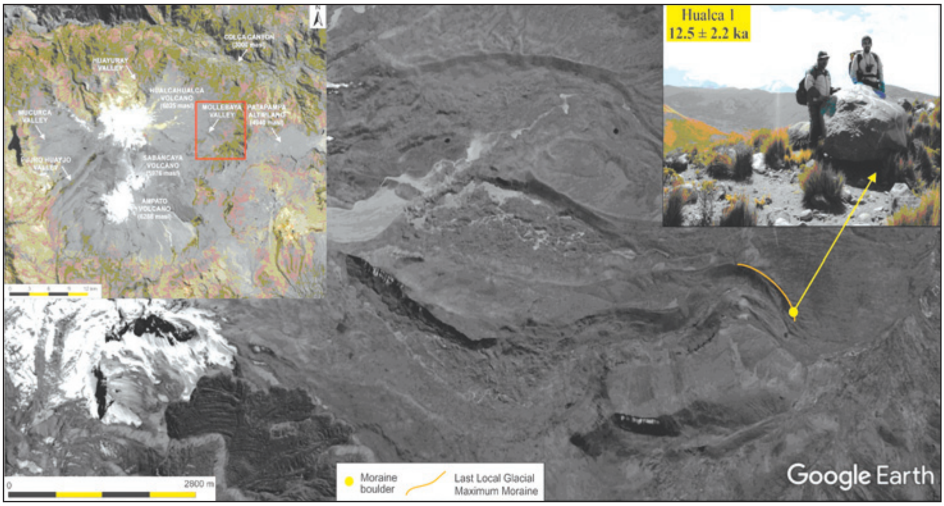

Figure 3 C. Moraine record and location of the samples collected on Mollebaya valley (eastern flank of HualcaHualca volcano).

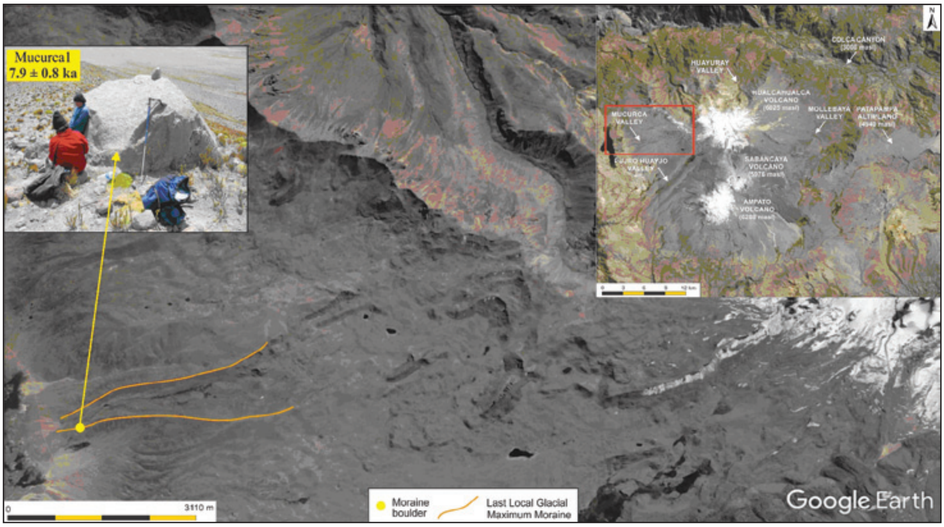

Figure 3 D. Moraine record and location of the samples collected on Mucurca valley (western flank of HualcaHualca volcano).

two samples were taken in Patapampa (Fig. 3E). One sample (Patapampa 4) comes from glacially polished and striated bedrock located on the top of the southern edge of the Altiplano at 4886 m a.s.l., which shows an exposure age of 11.9 ± 1.0 ka. The other sample (Patapampa 3) was collected from a boulder in the outermost moraine located on the southern edge of Patapampa at 4671 m a.s.l., yielding an exposure age of 10.0 ± 1.3 ka.

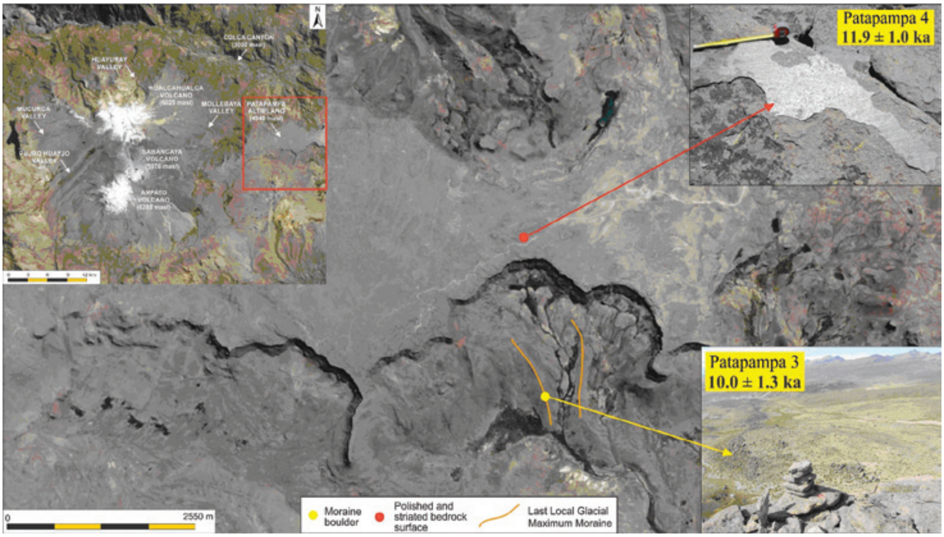

Figure 3 E. Moraine record and location of the samples collected on Patapampa Altiplano.

5. Discussion

The ^{36}Cl exposure ages from the outer moraines on the HualcaHualca volcano, based on the production rate of Marrero *et al.* (2016), indicates that the Last Local Glacial Maximum took place at ~17-16 ka during the Heinrich 1 event and Tauca paleolake cycle. Later, the retreat process began, but a phase of readvance or stillstand formed moraines at ~12 ka. According to the ^{36}Cl exposure ages from glacially polished and striated bedrock, deglaciation would be the main process since ~11.5 ka and the ice cap of the Patapampa Altiplano had already disappeared in phase with the termination of the Younger Dryas, the Coipasa paleolake cycle and the onset of the Holocene. But the scarce number of exposure ages and the presence of outliers in the moraines represent limitations that only allows their use for a preliminary glacial reconstruction. Thus, this glacial chronology suggests that the LLGM in the study area does not coincide with the global Last Glacial Maximum, and a LLGM prior to the global Last Glacial Maximum, as proposed by Smith *et al.* (2005, 2008), is not confirmed. Moreover, the synchronicity between the evolution of glaciers in the study area and the Tauca and Coipasa paleolake cycles corroborates the assumption postulated by Hastenrath (1971), Klein *et al*. (1999), Amman *et al*. (2001) and Sagredo and Lowell (2012) of a sensitive reaction of glaciers located in the Central Andean arid regions to precipitation changes.

However, the ^{36}Cl cosmogenic exposures ages related to the LLGM on HualcaHualca are significantly younger than the chronology established on the nearby Coropuna volcano by Bromley *et al*. (2009) and Úbeda *et al*. (2012) as well as on Uturuncu volcano (Blard *et al*., 2014), where the LLGM is in phase or much older than the global Last Glacial Maximum. Conversely, the LLGM on HualcaHualca is consistent with the chronological data from Sajama and Tunupa volcanoes (Smith *et al*., 2009; Blard *et al.,* 2013), indicating a connection with the Tauca paleolake cycle and the Heinrich 1 cold event. An explanation of this discrepancy is associated with the scaling scheme used in each volcano. For example, Bromley *et al*. (2009) show on Coropuna an LLGM chronology similar to HualcaHualca when the scaling schemes devised by Dunai. (2000), Lifton *et al*. (2005) and Desilets *et al.* (2006) are introduced. On the other hand, the exposure ages from HualcaHualca are ~2 ka older if the production rates for ^{36}Cl proposed by Stone *et al.* (1996) and Schimmelpfennig *et al*. (2011) are applied. These changes confirm the uncertainties linked to imprecise production rates in the high tropics as suggested by Balco *et al.* (2008), which do not allow for a consistent glacial history. Moreover, new production rates for ^{36}Cl have been proposed, such as Marrero *et al.* (2016) and Schimmelpfennig *et al*. (2011), and, therefore, published data associated with this cosmogenic isotope should be recalculated.

A complementary interpretation involves a glacier advance that could be less extensive during the global Last Glacial Maximum than the Late Glacial advances in the Central Volcanic Zone, as proposed by Smith *et al*. (2009). According to several proxy data from the Central Andes, the global Last Glacial Maximum was cold (a temperature decrease of 8-12°) and relatively humid (Minchin or Sajsi paleolake cycles) (Thompson *et al.,* 1995, 1998; Baker *et al.,* 2001; Fornace *et al.,* 2014) whereas the Heinrich 1 and Younger Dryas events were characterised by a substantial increase in precipitation as the Tauca and Coipasa paleolake cycles (Blard *et al*., 2011; Placzek *et al*., 2013) reveal. This scenario would indicate that the glaciers of this region are sensitive to temperature and precipitation fluctuations, and would also explain the chronological differences across the Central Andes.

Due to the discrepancies between the LLGM chronologies, the onset of deglaciation since LLGM presents a heterogeneous age in the Andean Central Volcanic Zone. The cosmogenic exposure ages indicate that glacier retreat began before at Coropuna (Bromley *et al*., 2009; Úbeda *et al*., 2012) and Uturuncu volcanoes (Blard *et al*., 2014) than in HualcaHualca, Sajama and Tunupa volcanoes. However, based on the consistency of ages obtained from these three volcanoes, a preliminary interpretation of the beginning of deglaciation in the Andean Central Volcanic Zone would be related to the end of the Heinrich 1 event and the Tauca paleolake cycle.

Glacier retreat was interrupted by a readvance or stillstand, reported in all the volcanoes except Sajama, although chronologies do not coincide. The exposure ages from HualcaHualca and Coropuna are similar (12-13 ka), but they are older on Tunupa and Uturuncu volcanoes (14-16 ka). These data do not permit to infer clearly if the glaciers in the Andean Central Volcanic Zone reacted in synchronicity with the Younger Dryas and/or the Antarctic Cold Reversal cold events as proposed by Jomelli *et al.* (2014). After this marked phase of readvance or stillstand, the volcanoes of the Central Volcanic Zone experienced a marked retreat during the Holocene. Although on HualcaHualca volcano there are no cosmogenic exposure dates of minor readvances or stillstands phases, the dates reported on Coropuna (~9 and 6 ka; Úbeda *et al*., 2012) and Sajama (~7 and 3.3 ka; Smith *et al*., 2009) indicate a non-homogeneous warm or/and dry climate during the Holocene.

6. Conclusions

The LLGM took place at ~17-16 ka on HualcaHualca volcano during the Heinrich 1 event and Tauca paleolake cycle. Deglaciation began after these cold and wet episodes, although it was interrupted by at least one readvance or stillstand at ~12 ka. Deglaciation was the main process since ~11.5 ka coinciding with the termination of the Younger Dryas, the Coipasa cycle and the onset of the Holocene. These glacial ages do not corroborate an LLGM prior to the global Last Glacial Maximum but they indicate a sensitive reaction of the glacier system to precipitation changes.

Based on the relative consistency of cosmogenic exposure ages from HualcaHualca, Sajama and Tunupa volcanoes, a preliminary interpretation of the beginning of deglaciation since the LLGM in the Andean Central Volcanic Zone would be related to the end of the Heinrich 1 event and Tauca paleolake cycle. At least one significant phase of readvance or stillstand has been reported in most of the volcanoes studied, although the chronologies do not coincide. Thus, establishing a clear connection with the Younger Dryas and/or the Antarctic Cold Reversal cold events is a difficult task. After this positive pulse, the ice masses of the Central Volcanic Zone experienced a marked retreat during the Holocene, only interrupted by three clear but minor readvances that suggest a heterogeneous warm or/and dry climate in this period.

Despite *in situ* cosmogenic exposure provides new relevant chronological information, it is not possible to provide a consistent regional glacier evolution or a paleoclimatic reconstruction since the LLGM, due to limitations associated with *in situ* cosmogenic production rates and the different scaling schemes used. To reduce the uncertainty and compare the available cosmogenic ages, it would be necessary to determine a precise *in situ* cosmogenic production rate of each isotope in the Central Andes as well as a standard scaling scheme.

7. Acknowledgements

This work was carried out with the support of Project CGL2012-35858 funded by the Spanish Ministry of Economy and Competitiveness. I acknowledge two anonymous reviewers, which suggestions helped to improve the manuscript.

References

Alcalá, J., Palacios, D., Zamorano, J.J. 2010. Glacial recession in the Tropical Andes from the Little Ice Age: the case of Ampato Volcanic Complex (Southern Peru). *6th Alexander von Humboldt International Conference*, Mérida, México. AvH6-10, 2010. http://meetingorganizer.copernicus.org/AvH6/AvH6-10.pdf.

Alcalá, J. 2015. *La evolución volcánica, glaciar y periglaciar del Complejo Volcánico Ampato (Sur de Perú)*. Ph.D. Thesis, Complutense University of Madrid, Spain. http://eprints.ucm.es/29492/.

Alcalá-Reygosa, J., Palacios, D., Zamorano Orozco, J.J. 2016. Geomorphology of the Ampato volcanic complex (southern Peru). *Journal of Maps* 12 (5), 1160-1169. http://doi.org/10.1080/17445647.2016.1142479.

Amman, C., Jenny, B., Kammer, K., Messerli, B. 2001. Late Quaternary glacier response to humidity changes in the arid Andes of Chile (18-29º S). *Palaeography, Palaeoclimatology, Palaeoecology* 172 (3-4), 313-326. http://doi.org/10.1016/S0031-0182(01)00306-6.

Baker, P.A., Seltzer, G.O., Fritz, S.C., Dunbar, R. B., Grove, M.J., Tapia, P. M., Cross, S. L., Rowe, H.D., Broda, J. P. 2001. The History of South American Tropical Precipitation for the Past 25,000 years. *Science* 291 (5504), 640-643. https://doi.org/10.1126/science.291.5504.640.

Balco, G., Stone, J.O., Lifton, N.A., Dunai, T.J. 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements. *Quaternary Geochronology* 3 (3), 174-195. http://doi.org/10.1016/j.quageo.2007.12.001.

Blard, P.H., Sylvestre, F., Tripati, A.K., Claude, C., Causse, C., Coudrain, A., Condom, T., Seidel, J.L., Vimeux, F., Moreau, C., Dumoulin, J.P., Lavé, J. 2011. Lake highstands on the Altiplano (Tropical Andes) contemporaneous with Heinrich 1 and the Younger Dryas: new insights from ^{14}C, U-Th dating and $\delta\,^{18}$O of carbonates. *Quaternary Science Research* 30 (27-28), 3973-3989. http://doi.org/10.1016/j.quascirev.2011.11.001.

Blard, P.H., Lave, J., Sylvestre, F., Placzek, C.J., Claude, C., Galy, V., Condom, T., Tibari, B. 2013. Cosmogenic ^{3}He production rate in the high tropical Andes (3800 m, 20ºS): Implications for the local last glacial maximum. *Earth and Planetary Science Letters* 377-378, 260-275. http://doi.org/10.1016/j.epsl.2013.07.006.

Blard, P.H., Lavé, J., Farley, K.A., Ramirez, V., Jimenez, N., Martin, L., Charreau, J., Tibari, B., Fornari, M. 2014. Progressive glacial retreat in the Southern Altiplano (Uturuncu volcano, 22°S) between 65 and 14 ka constrained by cosmogenic ^{3}He dating. *Quaternary Research* 82 (1), 209-221. http://doi.org/10.1016/j.yqres.2014.02.002.

Borchers, B., Marrero, S., Balco, G., Caffee, M., Goehring, B., Lifton, N., Nishiizumi, K., Phillips, F., Schaefer, J., Stone, J. 2016. Geological calibration of spallation production rates in the CRONUS-Earth project. *Quaternary Geochronology* 31, 188-198. http://doi.org/10.1016/j.quageo.2015.01.009.

Bromley G. R.M., Schaefer J.M., Winckler, G., Hall, B.L., Todd, C.E., Rademaker K.M. 2009. Relative timing of last glacial maximum and late-glacial events in the central tropical Andes. *Quaternary Science Reviews* 28 (23-24), 1-13. http://doi.org/10.1016/j.quascirev.2009.05.012.

Bromley, R.M., Hall, B.L., Schaefer, J.M., Winckler, G., Todd, C.E., Rademaker, K.M. 2011. Glacier fluctuations in the southern Peruvian Andes during the late-glacial period, constrained with cosmogenic ^{3}He. *Journal of Quaternary Science* 26 (1), 37-43. http://doi.org/10.1002/jqs.1424.

Clapperton, C.M. 1993. *Quaternary Geology and Geomorphology of South America*. Elsevier, Amsterdam.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., McCabe, A.M. 2009. The Last Glacial Maximum. *Science* 325 (5941), 710-714. https://doi.org/10.1126/science.1172873.

Clayton J.D., Clapperton C.M. 1997. Broad synchrony of Late-glacial glacier advance and the highstand of paleolake Tauca in the Bolivian Altiplano. *Journal of Quaternary Science* 12 (3), 169-182. http://doi.org/10.1002/(SICI)1099-1417(199705/06)12:3<169::AID-JQS304>3.0.CO;2-S.

Desilets, D., Zreda, M., Almasi, P.F., Elmore, D. 2006. Determination of cosmogenic ^{36}Cl in rocks by isotope dilution: innovations, validation and error propagation. *Chemical Geology* 233 (3-4), 185-195. http://doi.org/10.1016/j.chemgeo.2006.03.001.

Dornbusch, U. 1998. Current large-scale climatic conditions in Southern Peru and their influence on snowline altitudes. *Erdkunde* 52 (1), 41-54. http://doi.org/10.3112/erdkunde.1998.01.04.

Dunai, T.J. 2000. Scaling factors for production rates of in situ produced cosmogenic nuclides: a critical reevaluation. *Earth and Planetary Science Letters* 176 (1), 157-169. http://doi.org/10.1016/S0012-821X(99)00310-6.

Farber, D.L., Hancock, G.S., Finkel, R.C., Rodbell, D.T. 2005. The age and extent of tropical alpine glaciation in the Cordillera Blanca, Peru. *Journal of Quaternary Science* 20 (7- 8), 759-776. http://doi.org/10.1002/jqs.994.

Fink, D., Vogt, S., Hotchkis, M. 2000. Cross-sections for ^{36}Cl from Ti at E_p =35-150 MeV: applications to in-situ exposure dating. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 172 (1-4), 861-866. http://doi.org/10.1016/S0168-583X(00)00200-7.

Fornace, K.L., Hughen, K.A., Shanahan, T.M., Fritz, S.C., Baker, P.A., Sylva, S.P. 2014. A 60,000-year record of hydrologic variability in the Central Andes from the hydrogen isotopic composition of leaf waxes in Lake Titicaca sediments. *Earth and Planetary Science Letters* 408, 263-271. http://doi.org/10.1016/j.epsl.2014.10.024.

Glasser, N.F., Clemmens, S., Schnabel, C., Fenton, C.R., McHargue, L. 2009. Tropical glacier fluctuations in the Cordillera Blanca, Peru between 12.5 and 7.6 ka from cosmogenic ^{10}Be dating. *Quaternary Science Reviews* 28 (27-28), 3448-3458. http://doi.org/10.1016/j.quascirev.2009.10.006.

Hall, S. R, Farber, D.L., Ramage, J.M., Rodbell, D.T., Finkel, R.C., Smith, J.A., Mark, B.G., Kassel, C., 2009. Geochronology of Quaternary glaciations from the tropical Cordillera Huayhuash, Peru. *Quaternary Science Reviews* 28 (25-26), 2991-3009. http://doi.org/10.1016/j.quascirev.2009.08.004.

Hastenrath, S.L. 1971. On the Pleistocene snow-line depression in the arid regions of the South American Andes. *Journal of Glaciology* 10 (59), 225-267. http://doi.org/https://doi.org/10.1017/S0022143000013228.

Herreros, J., Moreno, L., Taupin, J. D., Ginot, P., Patris, N., De Angelis, M., Ledru, M.P., Delachaux, F., Schotterer, U. 2009. Environmental records from temperature glacier ice on Nevado Coropuna saddle, southern Peru. *Advances in Geosciences* 22, 27-34. http://doi.org/10.5194/adgeo-22-27-2009.

Isacks, B. 1988. Uplift of the Central Andes Plateau and bending of the Bolivian Orocline. *Journal of Geophysical Research* 93 (B4), 3211-3231. http://doi.org/10.1029/JB093iB04p03211.

Jomelli, V., Favier, V., Vuille, M., Braucher, R., Martin, L., Blard, P.H., Colose, C., Brunstein, D., He, F., Khodri, M., Bourlès, D.L., Leanni, I., Rinterknecht, V., Grancher, D., Francou, B., Ceballos, J.L., Fonseca, H., Liu, Z., Otto-Bliesner, B.L. 2014. A major advance of tropical Andean glaciers during the Antarctic cold reversal. *Nature* 513 (7517), 224-228. http://doi.org/10.1038/nature13546.

Kelly, M.A., Lowell, T.V., Applegate, P.J., Smith, C.A., Phillips, F.M., Hudson, A.M. 2012. Late glacial fluctuations of Quelccaya Ice Cap, southeastern Peru. *Geology* 40 (11), 991-994. http://doi.org/10.1130/G33430.1.

Klein, A.G., Seltzer, G.O., Isacks, B.L. 1999. Modern and Last Local Glacial Maximum snowlines in the Central Andes of Peru, Bolivia, and Northern Chile. *Quaternary Science Reviews* 18 (1), 63-84. https://doi.org/10.1016/S0277-3791(98)00095-X.

Kull, C., Imhof, S., Grosjean, M., Zech, R., Veit, H. 2008. Late Pleistocene Glaciation in the Central Andes: Temperature versus humidity control. -A case study from the eastern Bolivian Andes (17ºS) and regional synthesis. *Global and Planetary Change* 60 (1-2), 148-164. http://doi.org/10.1016/j.gloplacha.2007.03.011.

Lal, D. 1991. Cosmic ray labeling of erosion surfaces: *in situ* nuclide production rates and erosion models. *Earth and Planetary Science Letters* 104 (2-4), 424-439. https://doi.org/10.1016/0012-821X(91)90220-C.

Lifton, N. A., Bieber, J. W., Clem, J. M., Duldig, M. L., Evenson, P., Humble, J. E., Pyle, R. 2005. Addressing solar modulation and long-term uncertainties in scaling secondary cosmic rays for in situ cosmogenic nuclide applications. *Earth and Planetary Science Letters* 239 (1-2), 140-161.http://doi.org/10.1016/j.epsl.2005.07.001.

Mark, B.G., Seltzer, G.O., Rodbell, D.T., Goodman, A.Y. 2002. Rates of deglaciation during the last glaciation and Holocene in the Cordillera Vilcanota - Quelccaya ice cap region, Southeastern Peru. *Quaternary Research* 57 (3), 287-298. https://doi.org/10.1006/qres.2002.2320.

Marrero, M.M., Phillips, F.M., Caffee, M.W., Gosse, J.C. 2016. CRONUS-Earth cosmogenic ^{36}Cl calibration. *Quaternary Geochronology* 31, 199-219. http://doi.org/10.1016/j.quageo.2015.10.002.

May, J.H., Zech, J., Zech, R., Preusser, F., Argollo, J., Kubik, P.W., Veit, H. 2011. Reconstruction of a complex late Quaternary glacial landscape in the Cordillera de Cochabamba (Bolivia) based on a morphostratigraphic and multiple dating approach. *Quaternary Research* 76 (1), 106-118. http://doi.org/10.1016/j.yqres.2011.05.003.

Nishiizumi, K., Winterer, E.L., Kohl, C.P., Klein, J., Middleton, R., Lal, D., Arnold, J.R. 1989. Cosmic ray production rates of ^{10}Be and ^{26}Al in quartz from glacially polished rocks. *Journal of Geophysical Research* 94 (B12), 17907-17915. http://doi.org/10.1029/JB094iB12p17907.

Phillips, F.M., Stone, W.D., Fabryka-Martin, J.T. 2001. An improved approach to calculating low-energy cosmic-ray neutron fluxes near the land/atmosphere interface. *Chemical Geology* 175 (3-4), 689-701. http://doi.org/10.1016/S0009-2541(00)00329-6.

Phillips, F.M. 2003. Cosmogenic 36Cl ages of Quaternary basalt flows in the Mojave Desert, California, USA. *Geomorphology* 53 (3-4), 199-208. http://doi.org/10.1016/S0169-555X(02)00328-8.

Placzek, C.J., Quade, J., Patchett, P.J. 2013. A 130 ka reconstruction of rainfall on the Bolivian Altiplano. *Earth and Planetary Science Letters* 363, 97-108. http://doi.org/10.1016/j.epsl.2012.12.017.

Rodbell, D.T. 1993. The timing of the last deglaciation in Cordillera Oriental, northern Peru based on glacial geology and lake sedimentology. *Geological Society of America Bulletin* 105 (7), 923-934. http://doi.org/10.1130/0016-7606(1993)105<0923:TTOTLD>2.3.CO;2.

Sagredo, E.A., Lowell, T.V. 2012. Climatology of Andean glaciers: A framework to understand glacier response to climate change. *Global and Planetary Change* 86-87, 101- 109. http://doi.org/10.1016/j.gloplacha.2012.02.010.

Schimmelpfennig, I. 2009. *Cosmogenic ^{36}Cl in Ca and K Rich Minerals: Analytical Developments, Production Rate Calibrations and Cross Calibration with ^{3}He and ^{21}Ne.* Ph.D. Thesis, Paul Cezanne Aix-Marseille III University, Aix en Provence, France. https://hal.inria.fr/file/index/docid/468337/filename/PhD_Schimmelpfennig.pdf.

Schimmelpfennig, I., Benedetti, L., Finkel, R., Pik, R., Blard, P.H., Bourlès, D., Burnard, P., Williams, A. 2009. Sources of in-situ ^{36}Cl in basaltic rocks. Implications for calibration of production rates. *Quaternary Geochronology* 4 (6), 441- 461. http://doi.org/10.1016/j.quageo.2009.06.003.

Schimmelpfennig, I., Benedetti, L., Garreta, V., Pik, R., Blard, P.H., Burnard, P., Bourlès, D., Finkel, R., Ammon, K., Dunai, T. 2011. Calibration of cosmogenic ^{36}Cl production rates from Ca and K spallation in lava flows from Mt. Etna (38ºN, Italy) and Payun Matru (36ºS, Argentina). *Geochimica et Cosmochimica Acta* 75 (10), 2611-2632. http://doi.org/10.1016/j.gca.2011.02.013.

Schimmelpfennig, I., Schaefer, J.M., Putnam, A.E., Koffman, T., Benedetti, L., Ivy-Ochs, S., Team, A., Schlüchter, Ch. 2014. ^{36}Cl production rate from K-spallation in the European Alps (Chironico landslide, Switzerland). *Journal of Quaternary Science* 29 (5), 407- 413. http://doi.org/10.1002/jqs.2720.

Seltzer, G., Rodbell, D., Burns, S., 2000. Isotopic evidence for late Quaternary climate change in tropical South America. *Geology* 28 (1), 35-38. https://doi.org/10.1130/0091-7613(2000)28<35:IEFLQC>2.0.CO;2.

Seltzer, G.O., Rodbell, D.T., Baker, P.A., Fritz, S.C., Tapia, P.M., Rowe, H.D., Dunbar, R. B. 2002. Early Warming of Tropical South America at the Last Glacial- Interglacial Transition. *Science* 296 (5573), 1.685-1.686. http://doi.org/10.1126/science.1070136.

Smith, J.A., Seltzer, G.O., Farber, D.L., Rodbell, D.T., Finkel, R.C. 2005. Early local Last Glacial Maximum in the tropical Andes. *Science* 308 (5722), 678-681. https://doi.org/10.1126/science.1107075.

Smith, J.A., Mark, B.G., Rodbell, D.T. 2008. The timing and magnitude of mountain glaciation in the tropical Andes. *Journal of Quaternary Science* 23, 609-634. http://doi.org/10.1002/jqs.1224.

Smith, C.A., Lowell, T.V., Caffee, M.W. 2009. Late glacial and Holocene cosmogenic surface exposure age glacial chronology and geomorphological evidence for the presence of cold-based glaciers at Nevado Sajama, Bolivia. *Journal of Quaternary Science* 24 (4), 360-372. http://doi.org/10.1002/jqs.1239.

Smith, C.A., Lowell, T.V., Owen, L.A., Caffe, M.W. 2011. Late Quaternary glacial chronology on Nevado Illimani, Bolivia, and the implications for paleoclimatic reconstructions across the Andes. *Quaternary Research* 75 (1), 1-10. http://doi.org/10.1016/j.yqres.2010.07.001.

Stansell, N.D., Rodbell, D., Licciardi, J.M., Sedlak, C.M., Schweinsberg, A.D., Huss, E.G., Delgado, G.M., Zimmerman, S.H., Finkel, R.C. 2015. Late Glacial and Holocene glacier fluctuations at Nevado Huaguruncho in the Eastern Cordillera of the Peruvian Andes. *Geology* 43 (8), 747-750. https://doi.org/10.1130/G36735.1.

Stern, C.R. 2004. Active Andean volcanism: its geologic and tectonic setting. *Revista Geológica de Chile* 2, 161-206. http://doi.org/10.4067/S0716-02082004000200001.

Stone, J.O., Allan, G.L., Fifield, L.K., Cresswell, R.G. 1996. Cosmogenic Chlorine-36 from calcium spallation. *Geochimica et Cosmochimica Acta* 60 (4), 679-692. https://doi.org/10.1016/0016-7037(95)00429-7.

Stone, J.O. 2000. Air pressure and cosmogenic isotope production. *Journal of Geophysical Research* 105 (B10), 23753-23759. http://doi.org/10.1029/2000JB900181.

Stone, J.O., Fifield, K., Vasconcelos, P. 2005. Terrestrial chlorine-36 production from spallation of iron. *10th International Conference on Accelerator Mass Spectrom*etry. Berkeley, USA. https://llnl.confex.com/llnl/ams10/techprogram/P1397.HTM.

Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Lin, P.N., Henderson, K.A., Coledai, J., Bolzan, J.F., Liu, K.B. 1995. Late glacial stage and Holocene tropical ice core records from Huascarán, Peru. *Science* 269 (5220), 46-50. https://doi.org/10.1126/science.269.5220.46.

Thompson, L.G., Davis, M.E., Mosley-Thompson, E., Sowers, T.A., Henderson, K.A., Zagorodnov, V.S., Lin, P.N., Mikhalenko, V.N., Campen, R.K., Bolzan, J.F., Cole-Dai, J., Francou, B. 1998. A 25,000-Year Tropical Climate History from Bolivian Ice Cores. *Science* 282 (5395), 1858-1864. https://doi.org/10.1126/science.282.5395.1858.

Thouret, J.C., Rivera, M., Wörner, G., Gerbe, M.C., Finizola, A., Fornari, M., Gonzales, K. 2005. Ubinas: the evolution of the historically most active volcano in southern Peru. *Bulletin of Volcanology* 67 (6), 557-589. http://doi.org/10.1007/s00445-004-0396-0.

Úbeda, J., Palacios, D., Vázquez-Selem, L. 2012. Glacial and volcanic evolution on Nevado Coropuna (Tropical Andes) based on cosmogenic ^{36}Cl surface exposure dating. *Geophysical Research Abstracts* 14, EGU2012-3683-2, 2012. http://meetingorganizer.copernicus.org/EGU2012/EGU2012-3683-2.pdf.

Vermeesch, P. 2007. CosmoCalc: an excel add-in for cosmogenic nuclide calculations. *Geochemistry, Geophysics, Geosystems* 8 (8), 1525-2027. http://doi.org/10.1029/2006GC001530.

Zech, R., Kull, C.H., Kubik, P.W., Veit, H. 2007a. Exposure dating of Late Glacial and pre-LGM moraines in the Cordon de Doña Rosa, Northern/Central Chile (31º S). *Climate of the Past* 3 (1), 1-14. http://doi.org/10.5194/cp-3-1-2007.

Zech, R., Kull, C.H., Kubik, P.W., Veit, H. 2007b. LGM and Late Glacial glacier advances in the Cordillera Real and Cochabamba (Bolivia) deduced from ^{10}Be surface exposure dating. *Climate of the Past* 3 (4), 623-635. http://doi.org/10.5194/cp-3-623-200.

Zreda, M., England, J., Phillips, F.M., Elmore, D., Sharma, P. 1999. Unblocking of the Nares Strait by Greenland and Ellesmere ice-sheet retreat 10,000 years ago. *Nature* 398, 139-142. http://doi.org/10.1038/18197.