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Last Glacial Maximum and deglaciation of Ampato volcanic complex, Southern Peru

El Último Máximo Avance Glaciar y la deglaciación del Complejo Volcánico Ampato, Sur de Perú

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Abstract

The last maximum glacier expansion in the Ampato Volcanic Complex (15º 49’ 09’’S; 71º 52’ 40’’W; max. altitude: 6,288 masl) is dated to 17,9 ± 0.1 – 16,8 ± 0.4 kyr with cosmogenic ^{36}Cl isotope. The ice covered a total area of ~348 km^2. In the Huayuray valley, located on the north side of the HualcaHualca volcano, the most northerly stratovolcano in the complex, the glacier surface area during this period was ~20.7 km^2 and the paleoELA was situated ~4,980 m, i.e. ~820 m below 1955. Dating of a polished surface near the Ampato complex shows widespread deglaciation around 12,6 ± 0.4 kyr. However, there were several later phases of glacier re-advance; the age of one of these phases is estimated at 11,7 ± 0.2 kyr. In historical times, the retreat has been dominant, especially during the last decade.

Keywords: Last Maximum Glacier Expansion, Ampato Volcanic Complex, cosmogenic ^{36}Cl isotope, paleo-ELA, Huayuray valley, deglaciation

Resumen

La edad del último máximo avance de los glaciares en el Complejo Volcánico Ampato (15º 49’ 09’’S; 71º 52’ 40’’W; altitud máxima: 6,288 msnm) oscila entre 17,9 ± 0.1 – 16,8 ± 0.4 ka a partir del análisis del isótopo cosmogénico ^{36}Cl. El área total que ocuparon los glaciares durante este evento es de ~348 km^2. En el valle de Huayuray, localizado en la vertiente norte del HualcaHualca, el volcán mas septentrional del complejo, la superficie glaciar era de ~20.7 km^2 y la paleoELA se situaba a ~4,980 m, i.e. ~820 m por debajo de la ELA de 1955. La datación de una superficie pulida cercana al complejo Ampato, concretamente en el altiplano de Patapampa (15º 44’ 41’’S; 71º 38’ 56’’O; altitud: 4,900 msnm), indica que el inicio de la deglaciación se habría producido en torno a 12,6 ± 0.4 Ka. Sin embargo, existieron varias fases de reavance glaciar; la edad de una de ellas es de 11,7 ± 0.2 Ka. En tiempos históricos, el retroceso de estas masas de hielo ha sido dominante, especialmente durante la última década.

Palabras clave: Último Máximo Avance Glaciar, Complejo Volcánico Ampato, isótopo cosmogénico (^{36}Cl), PaleoELA, valle de Huayuray, deglaciación.

1. Introduction

There is an increasing awareness of the importance of the dynamics of tropical glaciers, especially in the Andes, to improve our understanding of the causes of climate change and to produce more reliable climate models (Mark, 2008). This has become urgent in recent years because of the widespread retreat of these glaciers, the increase in mean annual temperature (+0.1ºC/decade for the Andes area; Vuille et al., 2008) and above all the accelerated growth of the surrounding population, the expansion of irrigation systems and the considerable growth of tourism, increasingly dependent on these water reserves (Mark, 2008; Vuille et al., 2008). Forecasts using current climate models show that the situation is deteriorating; the proposed scenarios for the end of the 21st century suggest that the tropical troposphere will present temperatures 4.5-5º C higher than at present (Vuille et al., 2008).

The study of current glacier dynamics should be carried out within the context of their past evolution, especially since the important advances of the Late Pleistocene, to understand the existing relationship between their mass balance and the thermo-pluviometric climate variations (Zech et al., 2008; Kull et al., 2008).

One of the least known areas within the tropical Andes is the western volcanic range, known as the Central Volcanic Zone (CVZ), an arc extending from southern Peru to northwest Argentina between 14º and 27º S as a result of the subduction of the oceanic Nazca Plate under the South American Plate. The CVZ is characterized by its important volcanic activity, including 44 active stratovolcanoes and at least 6 calderas systems (Stern, 2004).

Hardly any information is given on the CVZ in recent syntheses about glaciation in the Andes (Smith et al., 2005a, 2008; Mark et al., 2005; Zech et al., 2008; Kull et al., 2008; Hastenrath, 2009). It has traditionally been considered that the El Niño phase of ENSO produces considerable increase in temperature and decrease in precipitation (Francou et al., 1995, 2000) in some areas of the Andean range like the Cordillera Oriental in Bolivia and the Cordillera Blanca in Peru, but the real impact of ENSO in the Andean climate is still largely unknown. Climatic conditions in the Cordillera Oriental and the cordillera Blanca are not only different but actually opposed to those of the CVZ. The tropical glaciers in the CVZ depend to a great extent on variations in precipitation, both at present (Wagnon, 1999), and in the past (Kull et al., 2008; Zech et al., 2007a, 2008), which would have important implications for this relatively dry area of the Peruvian and Bolivian Andes.

New data published recently on the age of late Pleistocene advances in the cordillera of the Central Andes (Chile, Bolivia and Peru) show marked differences. Some authors place the maximum advance for the whole tropical Andes around 30 kyr (Smith et al., 2005a, b). This seem to be confirmed for central Chile, within the Arid Diagonal (Zech et al., 2007a). However, recent cosmogenic dating of moraine boulders in the Tropical Andes suggest that the maximum advance coincided with the Last Glacial Maximum (LGM) of the North Atlantic area (Björck et al., 1998; Walker et al., 1999; Johnsen et al., 2001). For example, Zech et al. (2007b) give an age between 25 and 22 kyr for the LGM in the Cordillera Oriental in Bolivia. They hypothesize that glacier fluctuations in the humid Andes depend on thermal variations and therefore they are synchronous with the North Atlantic LGM, while in the arid Andes glaciers are especially sensitive to humidity, implying asynchronous behaviour during the LGM (Zech et al., 2008). However, recent results from Coropuna volcano (Bromley et al., 2009), to the north of the CVZ, well within the Andean arid zone, indicate a maximum advance during the LGM, thus supporting the idea of synchronism between the tropical Pacific and the temperate and Polar Atlantic (Schaefer et al., 2006). This contradicts the hypothesis of a maximum advance prior to the LGM in the Andes, according to which the LGM would have coincided with glacier retreat because of the high temperatures in the region, and despite the prevailing wet condictions (Seltzer et al., 2002). On the other hand, some authors consider that regional variability in glacier advances in the Andes could be related to regional variations in the intensity of the precipitations and other climatic factors (Smith et al., 2005 b, 2008).

The aim of this study is to improve our knowledge of the glacial history in the CVZ (glacier area, ELA and absolute dating) specifically on one of its most important volcanic complexes: the Ampato (15º24´- 15º 51´ S, 71º 51´ - 73º W; 6,288 masl) at the north of the CVZ, where studies of this type have not been conducted yet.

2. Regional Setting

The Ampato Volcanic Complex (AVC) is located in the Cordillera Occidental of the central Andes in the south of Peru (Fig. 1),

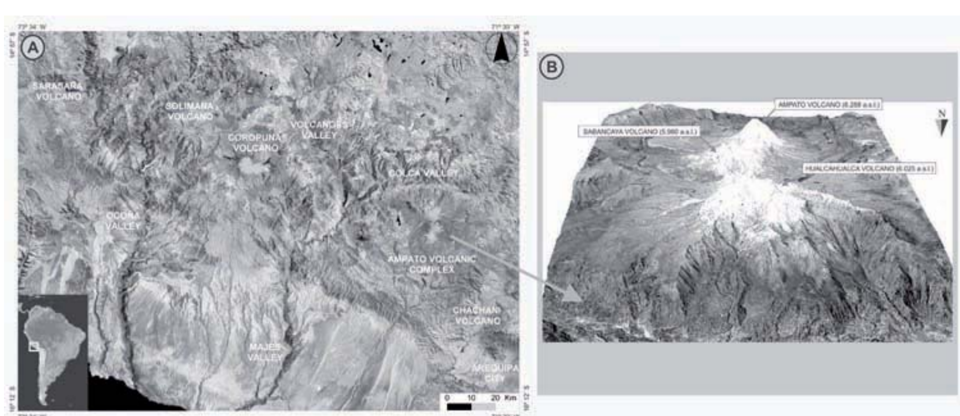

Figure 1. A. Satellite image (Mrsid, 2000, NASA) of the western Andean mountain range showing location of the AVC. B. 3D image of AVC from north to south.

Figura 1. A. Imagen de satelite de la Cordillera Occidental de los Andes centrales donde se muestra la localización del Complejo volcánico Ampato (CVA). B. Imagen tridimensional del AVC de Norte a Sur.

Figure 2. Panoramic view of the eastern side of AVC from Patapampa altiplano. From North to South: H – HualcaHualca volcano; S – Sabancaya volcano; A – Ampato volcano.
Figura 2. Vista panorámica de la vertiente este del CVA desde el altiplano de Patapampa. De Norte a Sur: H-volcán HualcaHualca; S-Volcán Sabancaya; A-volcán Ampato.

80 km NW of the city of Arequipa. It comprises three large andesitic-type stratovolcanoes aligned N-S (Fig. 2). The HualcaHualca volcano (15º 43' 15''S; 71º 51' 14''W; 6,025 masl) at the northern end is the oldest in the complex and is considered to be extinct (Thouret et al., 2005). The evolution of this volcano took place between the Pliocene and the early Pleistocene (Gerbe and Thouret, 2004). It presents a horseshoe shaped caldera open to the N as a result of the collapse of this flank (Bulmer et al., 1999). The Ampato at the southern end (15º 49' 09''S; 71º 52' 40''W; 6,288 masl), is classified as a dormant volcano (Thouret et al., 2005). It presents three superimposed lava domes and, in contrast to the HualcaHualca, a very fresh volcanic morphology only slightly transformed by glaciers. A lava flow located at the base was dated by $^{40}Ar/^{39}Ar$ to 0.80 Ma, confirming that its formation began between the Late Pleistocene and the Holocene (Gerbe and Thouret, 2004).

Between the two stratovolcanoes described above, the Sabancaya volcano (15º 47' 15''S; 71º 51' 16''W; 5,980 masl) has two coalescent pyroclastic cones and is surrounded by lava domes and thick and long blocky lava flows of Holocene age. One of these lava flows, located on the western slope, has been dated to around 5,5 kyr with ^{14}C (Thouret et al., 2002). Layers of tephra linked to the activity of this volcano have also been identified, although

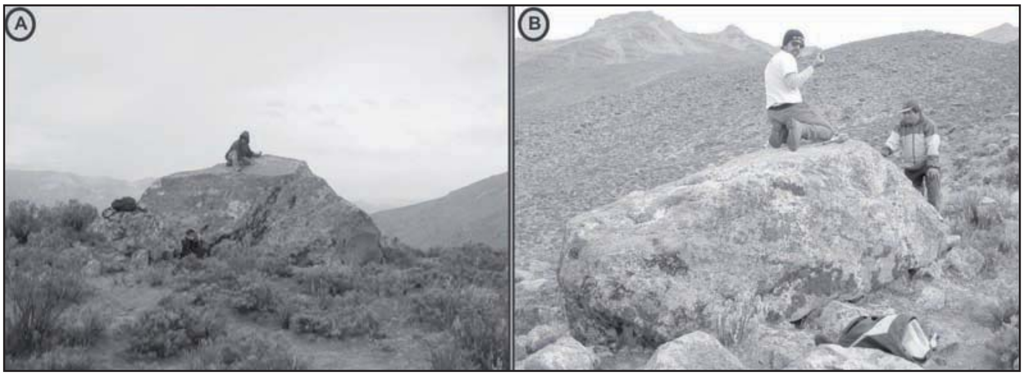

Figure 3. A. Detail of a LGMA moraine boulder in the Huayuray valley, northern HualcaHualca volcano (Sample Hualca 4; 15.7°S; 71.8°W; 4,144 masl). November 2005. **B**. Detail of a GR-I moraine boulder in the Huayuray valley, northern HualcaHualca volcano (Sample Hualca 3; 15.7°S; 71.8°W; 4,512 masl).
*Figura 3. A. Detalle de un bloque morrénico del LGMA en el valle de Huayuray, localizado en la vertiente norte del volcán HualcaHualca (Muestra Hualca 4; 15.7°S; 71.8°W; 4,144 msnm). Noviembre de 2005. **B**. Detalle de un bloque morrénico del GR-I localizado en la vertiente norte del volcán HualcaHualca (Muestra Hualca 3; 15.7°S; 71.8°W; 4,512 msnm).*

they are thin, suggesting limited explosive activity (Gerbe and Thouret, 2004). The Spanish chronicles refer to activity of the Sabancaya during the 18th century, specifically between 1750 and 1784 (Gerbe and Thouret, 2004). After 200 years of calm, the volcano became active again in 1986, with vulcanian and phreatomagmatic type eruptions (Thouret et al., 2002) which lasted until 2003. The events of 1991 covered the glaciers with ash and generated lahars, causing casualties and forcing the evacuation of the population from towns in the nearby.

The nearest meteorological station with data available is Imata (15º 83´ S, 71º 08´ W; 4,519 masl), located on the altiplano 89 km west of the volcanic complex. Mean annual precipitation is 570 mm, concentrated mainly from November to April, and mean annual temperature is 3.5ºC. Above that altitude herbaceous vegetation, predominantly of the genus *Stipa* and *Festuca*, is replaced by cushion-like plant formations, with abundant *Azorella compacta* (yareta); above 5,000 m, vascular plants disappear almost completely and only mosses and lichens survive.

The AVC presents a considerable potential hazard for the local population. To the north it is bounded by the valley of the river Colca, one of the deepest on earth, with a difference in elevation of 3,245 m between the peak of the Hualca-Hualca volcano and the bed of the river Colca, over a distance of only 15 km, with an average gradient of 32%. The valley has a population of over 25,000 people, mainly in Chivay, Achoma, Cabanaconde, Caylloma and Huambo, with rich agricultural land and an incipient tourism industry, that depends on the water from those glaciers.

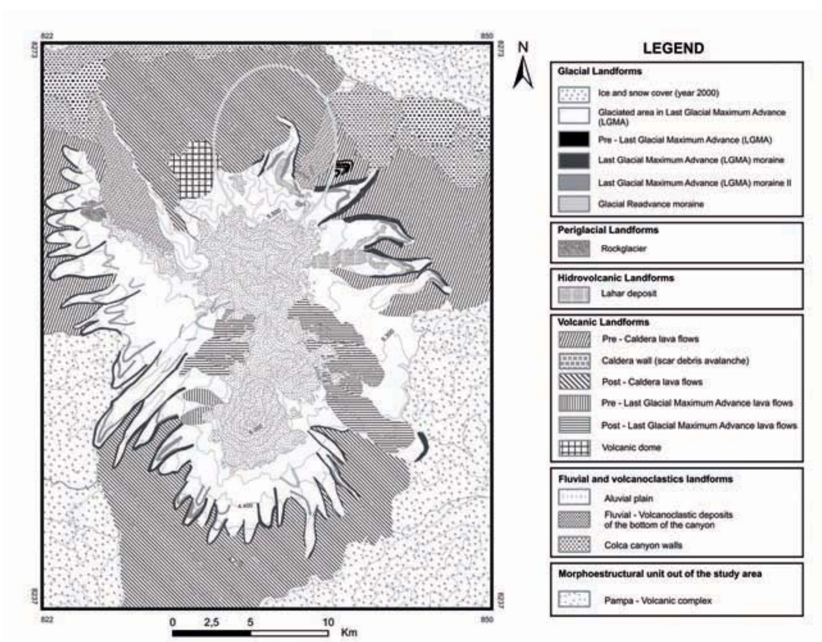

Figure 4. Geomorphic map of AVC. The circle shows the area of Huayuray valley on the northern side of Hualca-Hualca volcano.

Figura 4. Mapa geomorfológico del CVA. El círculo delimita el valle de Huayuray, situado en la vertiente norte del volcán HualcaHualca.

3. Materials and Methods

Glacial landforms, mainly moraines, were identified and mapped. This meant producing a geomorphologic map from vertical aerial photos of 1955 (scale 1:35,000, Instituto Geográfico Nacional de Perú), a high resolution geo-referenced Mrsid satellite image of 2000 (NASA) and a Landsat satellite image of 2008 (Instituto Nacional de Pesquisas Espaciais, Brasil). The map was corrected and improved during field work, then digitized in a GIS, using existing 1:100,000 maps (Instituto Geográfico Nacional de Perú) as a topographic base.

After analysing the geomorphologic map of the whole AVC, the Quebrada Huayuray (15º41´14´´S – 71º51´53´´W) located on the northeast slope of the HualcaHualca volcano was chosen as representative of the mountain. On the basis of the altitudinal position and the preservation of moraines, a relative chronology of glacial landforms was established distinguishing the following phases: Last Glacial Maximum Advance (LGMA), which was preceded by older advances with very poorly preserved remains; Glacial Readvance I (GRA-I) and Glacial Readvance II (GRA-II) which can be linked to the Little Ice Age (LIA). The recent extension of glaciers was also determined by photo-interpretation and remote sensing, specifically for 1955, 2000 and 2008, using the sources cited above.

In each of these phases the topography of the former glacier surface was reconstructed, based on the thickness of the ice indicated by

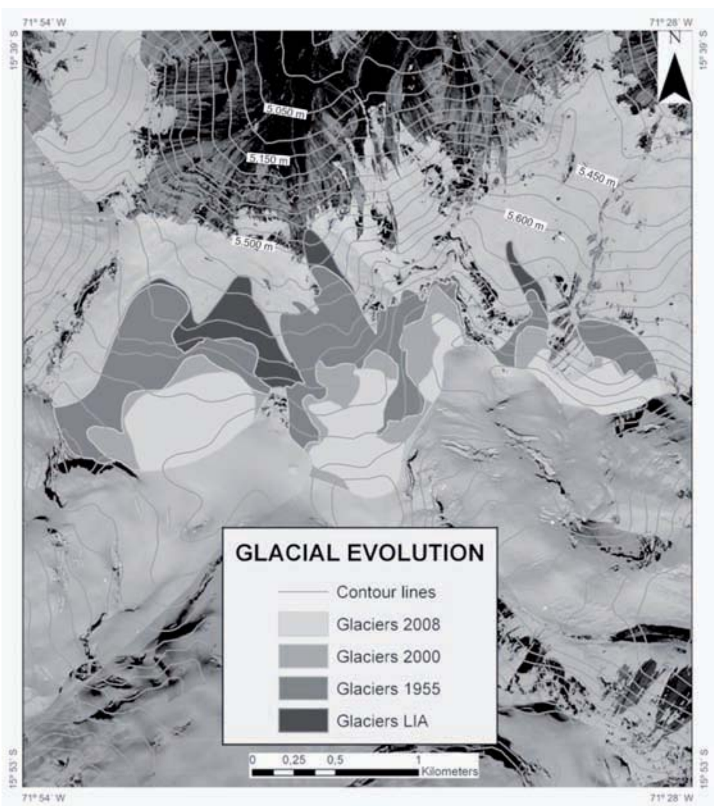

Figure 5. Evolution of glaciers of Huayuray valley from the LIA to 2008.
Figura 5. Evolución de los glaciares del valle de Huayuray desde la LIA hasta el año 2008.

the moraines (Carr and Coleman, 2007), then the surface area of the ice could be calculated in the GIS. The Equilibrium Line Altitude (ELA) of the glacier in each phase was calculated in the GIS using the AA method (Kaser and Osmaston, 2002, Osmaston, 2005).

The ELA is the theorical altitude that limit the accumulation and ablation areas, where annual snow accumulation is equal to ablation (mass balance is 0) (Serrano and González Trueba, 2004).

The AA method yields more reliable ELA estimates than the AAR (Accumulation Area Ratio) or the THAR (Toe-Headwall Area Ratio) methods where the glacier is not of ‘simple standard valley glacier (Osmaston, 2005). The paleo-glacier area was divided into altitude bands and the surface of each one was calculated. The mean altitude and area of each altitudinal band were exported from the GIS to a spreadsheet and the following equation was applied :

$$ELA = \Sigma Z*S / \Sigma S$$

Z = mean altitude of each altitude band
S = surface area of each altitude band

Rock samples were collected for cosmogenic ^{36}Cl surface exposure dating (Gosse and Phillips, 2001). The samples were taken from the least weathered top face of stable boulders >1 m high (Fig. 3), located on the crests of moraines. Samples were also taken of bedrock surfaces with glacial striae and polish, indicative of the timing of deglaciation at a particular site. Samples were processed according to the procedures described by Zreda et al. (1999), Zreda and Phillips (2000) and Phillips (2003). Physical processing was carried out at Complutense University and physical-chemical processing and AMS analyses at PRIME Lab (Purdue University). Ground rock was dissolved in a hot mixture of hydrofluoric and nitric acids, and Cl precipitated as AgCl. A spike of isotopically enriched ^{35}Cl was added

Table 1. Area, minimum altitude and ELA of glaciers at Huayuray valley (north side of HualcaHualca volcano).
Tabla 1. Área, altitud mínima y ELA de los glaciares en el valle de Huayuray (vertiente Norte del volcán HualcaHualca).

Phase	Area (km²)	Area decrease with respect to LGMA (%)	Minimum glacier altitude (masl)	ELA (masl)	ELA difference (with respect to 1955 ELA)
Last Glacial Maximum Advance (LGMA)	20.7	-	3,900	4,980	-820
Glacial Readvance I (GR-I)	17.8	15.0	4,170	5,240	-560
Glacial Readvance II (GRA-II)	2.8	86.5	5,400	5,780	-20
1955	2.45	88.2	5,660	5,800	-
2000	1.45	93	5,700	5,890	+10
2008	0.78	96.3	5,750	5,900	+20

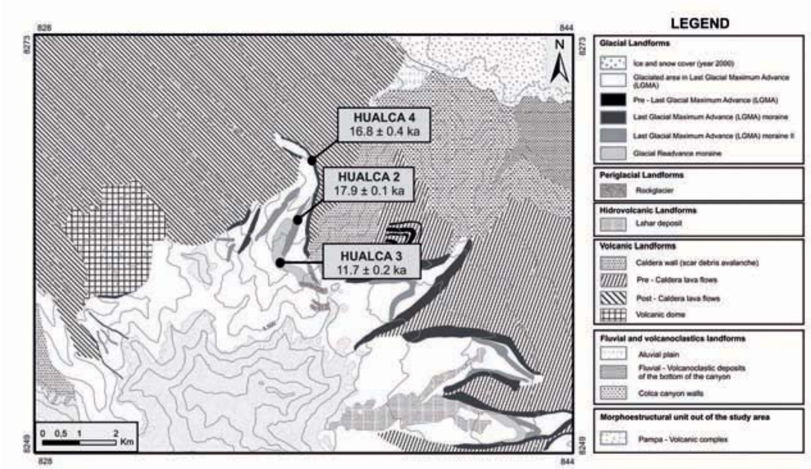

Figure 6. Detail of the geomorphic map of AVC, showing glacial landforms of Huayuray valley, on the north side of HualcaHualca volcano. Details of ^{36}Cl surface exposure ages are reported on Tables 2 and 3.

Figura 6. Detalle del mapa geomorfológico del CVA, donde se muestran las formas glaciares del valle de Huayuray, situado en la vertiente norte del volcán HualcaHualca. Los detalles de las muestras obtenidas para su datación absoluta mediante ^{36}Cl se encuentran en las tablas 2 y 3.

during the dissolution. The $^{36}Cl/Cl$ and $^{37}Cl/^{35}Cl$ ratios were measured on AgCl targets by AMS at PRIME Laboratory (Purdue University). Cl content was determined by means of the isotope dilution mass spectrometry method during AMS. Major elements, U, Th, Sm and Gd were determined by ICP-MS, and B by PGNAA at Activation Laboratories, Canada.

Exposure ages were calculated by means of the CHLOE program (Phillips and Plummer, 1996, version 3 - 2003), using thermal and epithermal neutron distribution equations and ^{36}Cl production parameters by Phillips et al. (2001); production of ^{36}Cl by muons according to Stone et al. (1998); and latitude and elevation scaling of production rates by Lal (1991). Exposure ages were determined for rock surface erosion rates of 0 and 5 mm/ky.

4. Results

Within the AVC there are differences in the extension of glaciers on each stratovolcano. On Ampato the ice tongues reached a mean minimum elevation of 4,270 m during the LGMA, with a minimum on the southern side (4,240 m). During the most important re-advance phase the glacier front was at 4,520 m, as shown by the moraine record. On Sabancaya, the moraine record was largely covered by recent lava flows, except in one of the valleys of the western side, where the moraines show a minimum altitude of 4,430 m for the LGMA.

The glaciers on HualcaHualca volcano reached the minimum altitude of the whole AVC during the LGMA -3,900 m on its northern flank- probably due to the great accumulation basin formed by the caldera opening in this direction, compared to 4,300 m on its other slopes. The most important re-advance glaciers reached 4,645 m on the eastern side, 4,450 m on the western side and 4,170 m on the northern side. Moraine ridges presumably of the LIA can be found in many of the valleys at short distance from the glacier fronts of 1955, with a mean minimum altitude of 5,628 m and an overall minimum of 5,400 m for the AVC as a whole.

During the LGMA glaciers covered ~348 km^2 in the AVC (Fig. 4), and 20.73 km^2 in the Huayuray valley, where the lowest limit was at 3,900 m and the paleoELA at 4,980 m. In 1955 the ELA in the Huayuray valley was located at 5,800 m, which means a difference of ~820 m with respect to the LGMA position. The LGMA was followed by a general deglaciation process, interrupted by small re-advances. An GRA-I phase can be differentiated when the glacierized area of Huayuray valley was ~17.87 km^2, i.e. 2.86 km^2 less than in the LGMA, and the ice front retreated 270 m, reaching 4,170 m. The difference between the GRA-I paleoELA (5,240 m) and the ELA of 1955 (5,800 m) is 560 m. The minimum altitude of the GRA-II moraine ridge in the Huayuray glacier was 5,400 m and the glacier area was 2.81 km^2, i.e. 13,6% of the LGMA glacier area. The GRA-II ELA (5,780 m) lies only 20 m below the ELA of year 1955 and 120 m below the ELA of year 2008 (5,900 m).

In 1955, Huayuray glacier covered 2.45 km^2, 12.8% less than in the GRA-II. In the same year, the glaciers in the Huayuray valley reached a minimum elevation of 5,660 m and the ELA rose 20 m, to 5,800 m. In only 45 years (1955 - 2000) the surface area of the ice was significantly reduced (~1 km^2, i.e. 40.8%). The ELA continued to rise, until it reached 5,890 m in 2000. From 2000 to 2008, the Huayuray glacier was reduced to 0.78 km^2 (i.e. 46%) and the ELA rised ~10 m reaching 5,900 m (Fig. 5; Tab. 1).

Moraine boulders from two successive moraines of Huayuray valley, ascribed *a priori* to the LGMA, show a ^{36}Cl exposure age of 16,8 ± 0.4 kyr and 17,9 ± 0.1 kyr, thus younger on the outer moraine. A boulder from a LGMA moraine on the eastern side of Hual-

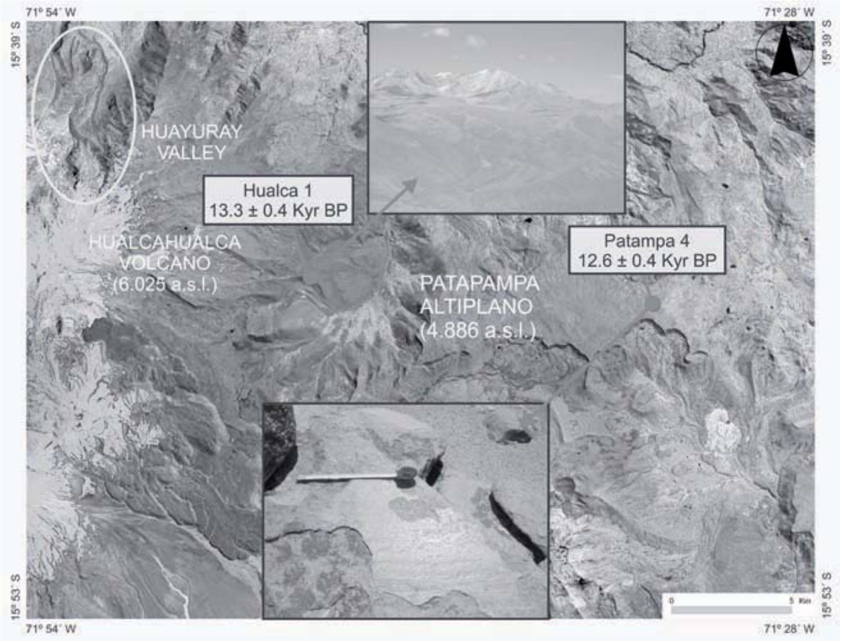

Figure 7. Satellite image (Mrsid, 2000, NASA), showing the location of ^{36}Cl samples Patapampa 4 and Hualca 1 (see Table 2).

Figura 7. Imagen de satelite (Mrsid, 2000, NASA), donde se muestra la localización de las muestras Patapampa 4 y Hualca 1 (ver Tabla 2).

Table 2. Cosmogenic ^{36}Cl surface exposure ages of moraine boulders moraines and polished bedrock of Huayuray valley (north side of HualcaHualca volcano) and Patapampa altiplano. Exposure ages are for zero erosion of sampled surface. Error corresponds to AMS analytical uncertainty.

Tabla 2. Edades obtenidas mediante el análisis del isótopo cosmogénico ^{36}Cl de bloques morrénicos del valle de Huayuray (vertiente norte del volcán HualcaHualca) y superficies estriadas del altiplano de Patapampa. Las edades de exposición son para una erosión superficial de valor 0. El error está relacionado con la incertidumbre del análisis AMS.

Sample	Location	Phase	Sample type	Exposure age (kyr)
Hualca 1	15,75°S; 71,75°W; 4,444 masl	LGMA	Moraine boulder	13,3 ± 0.4
Hualca 2	15,7°S; 71,8°W; 4,408 masl	LGMA	Moraine boulder	17,9 ± 0.1
Hualca 3	15,7°S; 71,8°W; 4,512 masl	GR-I	Moraine boulder	11,7 ± 0.2
Hualca 4	15,7°S; 71,8°W; 4,144 masl	LGMA	Moraine boulder	16,8 ± 0.4
Patapampa 4	15,7°S; 71,75°W; 4,886 masl	Deglaciation of altiplano	Polished bedrock	12,6± 0.4

caHualca yields an ^{36}Cl age of 13,3 ± 0.4 kyr. The moraine boulders from the GRA-I show an age of 11,7 ± 0.2 kyr. A sample of glacially polished bedrock from the altiplano to the east of the AVC, at 4,886 masl, yields an age of 12,6 ± 0.4 kyr, which probably indicates the timing of widespread deglaciation between the LGMA and the GRA-I (Fig. 6; Fig. 7; Tab. 2 y Tab.3).

5. Discussion

Dornbusch (1997, 2000 and 2002) calculated ELAs for the Nevados in the CVZ located to the NW of Ampato, i.e. the Sara Sara (15° 19' 11''S, 73° 27' 1''W; 5.505 masl), Solimana, (15° 24' 36''S 72° 53' 37''W; 6.093 masl) and Coropuna (15°3' 37''S 72°38' 5'' W; 6.377 masl), located at 176, 115, and 82 km from the AVC. This was done using aerial photos from 1955 (the same ones we used in our study), obtaining averages for each glacier based on the data from the glacier inventory by Ames et al. (1988). The modern ELAs (1955) of 5.200 m for the Sara Sara, 5.430 m for the Solimana and 5.640 m for the Coropuna, are lower than those obtained in this study. In fact, the HualcaHualca (6.025 m), which has almost the same altitude as the Solimana (6.093 m), presented an ELA in its longest valley in 1955 of 5.800 m, 370 m higher. The difference may be related to the methods used, although the increasing aridity towards the south, evident in the Central Andes, may also have an influence. In the data provided by Dornbusch, the modern ELA rises towards the south so that our estimate for Hualca-Hualca agrees with this trend.

Using the air photos of 1955 and the Area X Altitude Balance Ratio (AABR) method, Úbeda et al. (2009) estimate an ELA of 5.920 m and 5.810 m for the north and south sides of Coropuna, respectively, The mean ELA is 5.870 m, i.e. 230 m higher than that proposed by Dornbusch for the same volcano. Therefore different methods also influence the differences in results. However, the estimation by Úbeda et al. (2009) agree well with those of the present study. The same applies to the ELA data calculated by these authors for the LIA (mean 5.840 m) and for 2007 (mean 5.915 m), almost identical to our results for HualcaHualca. It is important to point out that the similarity between the AABR method and the AA method used in this study, makes it possible to compare results.

Table 3. Field and analytical data for ^{36}Cl samples from Huayuray valley (N side of Hualcahualca volcano) and Patapampa altiplano, Southern Peru.

Tabla 3. Datos de campo y de laboratorio de las morrenas muestreadas en el valle de Huayuray (vertiente norte del volcán HualcaHualca) y del altiplano de Patapampa, Sur de Perú.

sample ID		Hualca 1	Hualca 2	Hualca 3	Hualca 4	Patapampa 4
map unit		Moraine LGMA	Moraine LGMA	Moraine GR-I	Moraine LGMA	Glacial Polish
$^{36}Cl/Cl$ ratio	($^{36}Cl/10^{15}$ Cl)	321	1026	411	682	1603
$^{36}Cl/Cl$ 1σ uncertainty	($^{36}Cl/10^{15}$ Cl)	8	23	7	15	49
bulk density	(g cm^{-3})	2.5	2.5	2.5	2.5	2.5
sample thickness	(cm)	1.5	0.8	1.5	2.0	1.0
water content	(cm^3/cm^3)	0.005	0.005	0.005	0.005	0.005
elevation	(m)	4,444	4,408	4,512	4,144	4,886
latitude	(decimal degrees)	15,75	15,7	15,7	15,7	15,75
longitude	(decimal degrees)	71,75	71,8	71,8	71,8	71,75
snow shielding	(unitless)	1.0	1.0	1.0	1.0	1.0
total shielding	(unitless)	0.97	0.99	0.99	0.97	1.0
effective fast neutron attenuation length	(g cm^{-2})	148.17	161.36	170.78	151.63	169.37
LOI	(wt %)	1.58	1.27	1.16	0.81	0.71
Na_2O	(wt %)	3.76	3.72	3.92	4.37	3.87
MgO	(wt %)	2.45	2.46	1.79	1.45	1.15
Al_2O_3	(wt %)	15.52	15.33	15.38	16.16	17.03
SiO_2	(wt %)	61.5	62.32	62.62	63.9	62.37
P_2O_5	(wt %)	0.39	0.56	0.39	0.4	0.24
K_2O	(wt %)	3.19	2.84	3.67	3.99	3.49
CaO	(wt %)	4.66	4.57	3.85	3.39	4.42
TiO_2	(wt %)	0.96	0.992	0.826	0.718	0.807
MnO	(wt %)	0.075	0.079	0.06	0.05	0.062
Fe_2O_3	(wt %)	5.86	6.31	5.12	4.38	4.37
Cl	(ppm)	512.64	82.54	227.1	130.5	43.87
B	(ppm)	11.9	9.8	21	19.8	22.1
Gd	(ppm)	4.5	3.8	3.9	3.4	4.6
U	(ppm)	1.5	1.5	2.4	2.9	3.2
Th	(ppm)	8.8	8	13.1	16.5	16.8
sample mass	(g)	30.15	30.19	30.18	30.1	30.16
mass of ^{35}Cl spike solution	(g)	1.014	1.012	1.015	0.99	1.003
concentration spike solution	(g g^{-1})	44.1	12	22.1	14.2	7.1
analytical $^{36}Cl/Cl$ ratio	($^{36}Cl/10^{15}$ Cl)	301.2±7.5	726.7±16.1	357.60±6.3	543.60±11.6	906.2±27.7
analytical stable isotope ratio	($^{35}Cl/(^{35}Cl+^{37}Cl)$)	3.39±0.0113	4.7830±0.0258	3.7290±0.0164	4.1530±0.0231	6.21±0.0391

Since the earliest studies of the distribution of glaciers in the Central Andes (Hastenrath, 1967), it has been evident that the current and recent ELAs in the CVZ cannot be compared with much more humid mountains such as the Andes in the northern and central Peru, (Cordillera Blanca or Plano de Junin), where the current ELAs are as much as 1,000 m lower than our estimate for HualcaHualca (Hastenrath, 1985, 2009; Wright, 1983, 1984; Seltzer, 1990; Rodbell, 1991, 1992; Klein and Isacks, 1998; Smith et al., 2005 a, 2008, Mark et al., 2005; Condom et al., 2007; Vuille et al., 2008). The same is true for the central-Andean Cordillera Oriental, where mountains at a similar latitude receive far more precipitation from the Amazon Basin. This is the case of Cordillera Vilcanota (Mercer and Palacios, 1977, Mark et al., 2002) or Cordillera Real Boliviana (Seltzer, 1990, Seltzer et al., 1995, Wagnon et al., 1999) where ELAs are >700 m lower than in the AVC (Hastenrath, 1967, 1985, 2009; Klein and Isacks, 1998; Smith et al., 2005 a, 2008; Condom et al., 2007; Vuille et al., 2008).

There have been very few studies dealing with paleo-ELAs during the late Pleistocene LGMA in the CVZ. Dornbusch (1997, 2000, 2002) calculated the paleo-ELA for this period, identifying moraines in the northern volcanoes with the help of the photographic collection mentioned above and applying the AAR method. His estimates range between 4.600 and 5.400 m for north facing slopes. On the Nevado Sara Sara he obtained a mean paleo-ELA for the LGMA of ~4.700 m, with a depression of 500 m compared to 1955. The corresponding values are 4.970 m and 500 m for Nevado Solimana; 4.750 m and 670 m for the south side of Coropuna. Our paleo-ELA estimate of 4.980 m for HualcaHualca is very similar to the above values by Dornbusch, but our estimate of ELA depression is larger (~820 m). Úbeda et al. (2009) used the AABR method on both sides of the Coropuna, obtaining results very similar to our results on Hualca-Hualca, with a mean of 5.070 m and a depression of around 850 m.

ELA depressions for the LGMA of ~1,000 m have been reported in models of the general distribution of Pleistocene glaciers in the central Andes (Klein and Isacks, 1998; Hastenrath, 2009) and in specific locations such as the north-central Cordillera Oriental in Peru and the Cordillera Blanca (Rodbell, 1991, 1992).

As mentioned in the introduction, there is controversy over whether or not the LGMA coincides with the Global Last Glacial Maximum (GLGM), defined as the period 24-18 kyr and centered around 21 kyr (Mix et al., 2001). Our chronology for the AVC clearly needs additional dating, but the existing ^{36}Cl ages of 16,8 ± 0.4 and 17,9 ± 0.1 kyr for the LGMA fall just after the GLGM. We interpret the exposure age of 13,4 ± 0.4 kyr from a LGMA moraine boulder on the eastern side of HualcaHualca as a minimum age, but this has to be tested in future work.

In Queñua Ranra gorge of the Coropuna Volcanic Complex, Úbeda and Palacios (2009) dated moraines similar to those of Hualca-Hualca in 17,0 ^{36}Cl kyr. Bromley et al. (2009) have recently published numerous LGMA moraine datings with ^{3}He, also from the Coropuna, with results ranging between 24,5 and 25,3 kyr, and between 16,7 and 21,1 kyr, respectively, depending on the cosmogenic production model used. Interestingly, in many maximum advance moraines there are boulders of both ~21,0 kyr and ~17,0 kyr. In any case, these studies show results for the LGMA and for the GLGM similar to those of our study. In the Cordillera Real and in Cochabamba (Bolivia), LGMA moraines have been dated to between 25-22 kyr with ^{10}Be (Zech et al., 2007 b), with boulders yielding exposure ages between 24 and 18 kyr in the same moraine ridge.

In contrast, the LGMA is older in other areas of the Andes than in AVC: 34,0 – 22,0 kyr in Llanos de Junin, central Peru (Wright, 1983, 1984; Smith et al., 2005a, 2008; Ramage et al., 2005); 30 - 22 kyr in the Cordillera de Vilcanota (Seltzer et al., 1995; Seltzer, 2000, 2002); or ~32,0 kyr much further to the south in northern and central Chile (Zech et al., 2007a).

It is important to point out that moraines older than the LGMA were found on the HualcaHualca, although they are poorly preserved. Their dating is pending.

As suggested by Kull et al. (2008) for the Central Andes, regional differences in the timing of maximum advances is probably related to regional differences in precipitation. While temperature-driven glaciers in the eastern part peak around the LGMA (20 kyr), those in the drier western part are moisture-limited and reach their maximum in reponse to increased precipitation during the Late Glacial (15-10 kyr). The latter may apply to the AVC (and Coropuna), although a more precise chronology is necessary to confirm it.

Sample Hualca 3 (GRA-I) suggests a readvance peaking around 11,7 ^{36}Cl kyr on HualcaHualca, which agrees with data from other nearby massifs such as Coropuna (Úbeda et al., 2009, Bromley et al., 2009) and other sectors of the Central Andes (Zech et al., 2007a & b, 2008; Kull et al., 2008).

Complete deglaciation of Patapampa Altiplano at ~12,6 kyr (sample Patapampa 4, 4886 m) apparently precedes the peak of the GRA-I on HualcaHualca. This is consistent with an ELA of 5,240 during the LGA, i.e. much higher than the elevation of Patapampa Altiplano. There is no moraine record between the GRA-I position and the GRA-II in the Huayuray valley.

Recent observations of glaciers in Peru, Bolivia and Ecuador show a rapid retreat of the glaciers since the LIA, interrupted by various periods of standstill or slight advance (Vuille, et al., 2009; Hastenrath, 2009). The data of this study are very close to those of Úbeda et al. (2009) on Nevado Coropuna, with small retreat between the LIA and 1955, and marked recession in recent years, just as in other mountains of the Central Andes (Ames et al., 1988; Raup et al., 2006; Rabatel et al., 2006; Ramirez et al., 2001; Mark and Seltzer, 2005; Mark et al., 2002; Hastenrath and Ames, 1995; Georges, 2004; Francou et al., 2000, 2005; Solomina et al., 2007, among others).

6. Conclusions

The geomorphologic analysis of Ampato Volcanic Complex and in particular of the Huayuray valley, on HualcaHualca volcano, allowed to identify well preserved moraine ridges of different ages. During the phase of maximum glacier expansion, dated by cosmogenic ^{36}Cl at 17,9 ± 0.1 – 16,8 ± 0.4 kyr, the glaciers covered a surface area of ~348 km^2 on the whole CVA. In Huayuray valley the glacier surface area was ~20.7 km^2 and the paleoELA was located at 4.980 m, i.e.~820 m below the ELA of 1955 and ~920 m below the ELA of 2008.

Our data show that deglaciation on Patapampa Altiplano (4.890 m) culminated around 12,6 kyr but valley glaciers on the mountain probably still built moraines around 12 kyr. During this phase the glaciers covered ~17.9 km^2 and the paleoELA reached 4.300 m in the Huayuray valley.

The differences between the data obtained in this study and other areas of the Andes is probably linked with regional changes in precipitation. At present these glaciers are very sensitive to moisture fluctuations and the same probably occured in the past (Wagnon, 1999; Kull et al., 2008; Zech et al., 2007a, 2008). The chronology of LGMA in the AVC (ages of 16,8 ± 0.4 and 17,9 ± 0.1 kyr) agrees with the chronological interval of the GLGM, but differs substantially from other Andean areas dated with cosmogenic isotopes and coincides with data obtained in nearby areas like Coropuna volcano. Nevertheless the chronology of the glacial readvance largely coincides with the data of others sectors of the Andes. Addditional dating is necessary to further explore these issues. The interpretation of aerial photos and satellite images shows a dramatic retreat of glaciers on AVC since the Little Ice Age, especially after 1955. From 2000 to 2008 glaciers lost ~0.67 km^2 (i.e. 46%) and the ELA rose ~10 m. At present (2008) the glacier area is only 0.78 km^2 and the ELA is located at ~5,900 m.

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