Geochronology of Quaternary glaciations from the tropical Cordillera Huayhuash, Peru

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Abstract

The Cordillera Huayhuash in the central Peruvian Andes (10.3°S, 76.9°W) is an ideal mountain range in which to study regional climate through variations in paleoglacier extents. The range trends nearly north-south with modern glaciers confined to peaks >4800 m a.s.l. Geomorphology and geochronology in the nearby Cordillera Blanca and Junin Plain reveal that the Peruvian Andes preserve a detailed record of tropical glaciation. Here, we use ASTER imagery, aerial photographs, and GPS to map and date glacial features in both the western and eastern drainages of the Cordillera Huayhuash. We have used in situ produced cosmogenic 10Be concentrations in quartz bearing erratics on moraine crests and ice-polished bedrock surfaces to develop an exposure age chronology for Pleistocene glaciation within the range. We have also collected sediment cores from moraine-dammed lakes and bogs to provide limiting 14C ages for glacial deposits. In contrast to the ranges to the north and south, most glacial features within the Cordillera Huayhuash are Lateglacial in age, however we have identified features with ages that span 0.2 to 38 ka with moraine sets marking the onset of glacier retreat at ~0.3 ka, ~9–10 ka, ~13–14 ka, ~20–22 ka, and ~26 ka. The range displays a pronounced east-west variation in maximum down-valley distance from the headwall of moraine crests with considerably longer paleoglaciers in the eastern drainages. Importantly, Lateglacial paleoglaciers reached a terminal elevation of ~4000 m a.s.l. on both sides of the Cordillera Huayhuash; suggesting that temperature may have been a dominant factor in controlling the maximum glacier extent. We suggest that valley morphology, specifically valley slope, strongly influences down-valley distance to the maximum glacier extent and potential for moraine preservation. While regionally there is an extensive record of older (>50 ka) advances to the north (Cordillera Blanca) and to the south (Junin region), the apparent lack of old moraines in this locality may be explained by the confined morphology of the Cordillera Huayhuash ranges that has inhibited the preservation of older glacial geomorphic features.

1. Introduction

The Cordillera Huayhuash (10.3°S, 76.9°W) is located between two previously studied sites in the central Peruvian Andes, the Cordillera Blanca to the north (Farber et al., 2005) and the Junin Plain to the south (Smith et al., 2005a, b) and thus completes a north-south glacial geochronologic transect spanning ~1.5 degrees of latitude (Fig. 1). Regional geochronologic studies provide evidence of pre-Last Glacial Maximum (LGM, as defined by Imbrie et al. (1984) as ~21 ka based on the marine oxygen isotope record) through Holocene glacial advances, including pre-LGM moraines that range from 50 to >440 ka (Farber et al., 2005; Smith et al., 2005a, b). The pre-LGM moraines identified in the Peruvian Andes are older and often more extensive than the moraines associated with the LGM or local last glacial maximum (LLGM), a term used in
some regional studies to define moraines that are similar in age and stratigraphic position to LGM moraines, but not exactly LGM in age (Gillespie and Molnar, 1995; Smith et al., 2005a, b; Farber et al., 2005). While on the scale of the Andean orogen this transect is small, the unique geographic location within the tropical Andes provides an opportunity to observe variations in the glacial geochronologic record within different geomorphic and climatic environments. In the north-south trending Cordillera Huayhuash, modern glaciers are confined to elevations above 4800 m a.s.l. Surface uplift in this region during at least the last 10 Myr has produced enhanced river incision on both sides of the range (Gregory-Wodzicki, 2000). However, the proximity to regional base level (the Pacific Ocean) on the western side of the Cordillera Huayhuash has produced much higher stream gradients relative to the eastern valleys, which drain to the Atlantic. Thus, active climatic and tectonic forces have differentially modified the valley morphologies on the eastern and western sides of the range.

In this study, we present: 1) maps of glacial features in selected valleys of the Cordillera Huayhuash, 2) a geochronology of glacial features based on surface exposure dating using cosmogenic $^{10}$Be, 3) $^{14}$C ages from basal organic matter in bog and lake sediment cores, 4) a comparison of local valley chronologies and morphologies in order to evaluate variations in maximum ice extent, and 5) a regional comparison of the Cordillera Huayhuash chronology with those from the Cordillera Blanca and Junin Plain.

2. Regional setting

The tropical Peruvian Andes are a part of the American Cordillera, the longest orogenic belt on Earth, which extends from Alaska to Patagonia. While the high topography of the South American margin is the result of subduction that has been ongoing since the Jurassic (James, 1971; Sebrier et al., 1988; Allmendinger et al., 1997), recent studies suggest that no more than 50% of the current Andean elevation was reached prior to 10 Ma (Gregory-Wodzicki, 2000). Within this orogenic belt, alpine glaciers occupy many of the highest ranges and the Andes of Peru likely contain one of the most detailed records of tropical glaciation on the planet. Furthermore, the north-south orientation of the Andes provides a rare opportunity to study alpine glaciations over a large range of latitudes and between regions with significant differences in tectonic and climatic forcings.

2.1. Regional geology

In southern Peru and Bolivia, the Central Andes (~16–24°S) are greatest in width (~300 km) where the internally drained Altiplano plateau is situated between the Western and Eastern Cordilleras at an average elevation of ~4 km. To the north, in central Peru, the Andes narrow yet still contain intermontane basins such as the Junin Plain (cf. Fig. 1B). In northern Peru, the Western and Eastern Cordilleras merge to form a broad spine dissected mainly by the Rio Marañon.

The timing and extent of Pleistocene glaciations have been established at two locations in central Peru, the Cordillera Blanca (Farber et al., 2005) and the Junin Plain (Smith et al., 2005a, b). The Cordillera Blanca (~8.5–10°S) contains numerous peaks over 6000 m a.s.l. and is bordered on its western side by the active Cordillera Blanca Detachment Fault (CBDF); the northward flowing Rio Marañon borders the Cordillera Blanca to the east (cf. Fig. 1B). Glaciated valleys in the southern part of the Cordillera Blanca empty onto the broad alluvial plains along the Rio Santa (Clapperton, 1972; Rodbell, 1993; Farber et al., 2005). Incised tributary channels, which feed the main channel of the Rio Marañon, characterize the eastern margin of the Cordillera Blanca. In contrast, the Junin Plain (11°S, 76°W) is located in the northernmost portion of the intermontane Andean plateau bounded by the Western Cordillera, with peaks reaching ~5000 m a.s.l., and the Eastern Cordillera, with peaks at ~4600–4800 m a.s.l. Although modern glaciers are confined almost entirely to the high peaks of the Western Cordillera, both ranges contain evidence of past glaciations with preserved moraines extending onto the Junin Plain (Wright, 1983; Smith et al., 2005a, b).

The Cordillera Huayhuash is located between the Cordillera Blanca and the Junin Plain, just south of a tectonic regime dominated by the CBDF, and just north of the region defined by the Junin Plain. Faulted and folded Mesozoic carbonates and quartzites are...
the dominant lithologies with minor Miocene-Pliocene granitic intrusions and silicic volcanic rocks (Coney, 1971). High topography in this region reaches over 6000 m a.s.l. and slopes to the Pacific at \( \sim 2.3^{\circ} \) and to the Amazon Basin at \( \sim 1.5^{\circ} \). The topography of the Andes of Peru is characterized by numerous incised high-elevation, low-relief surfaces that record many phases of uplift, erosion, and incision. The western Cordillera Huayhuash topography reflects the Cañon stage of deep canyon incision, which has persisted since the Pliocene (McLaughlin, 1924; Myers, 1976). The valleys on the western side of the range converge to form the Rio Pativilca that drains 110 km west to the Pacific Ocean. The eastern Cordillera Huayhuash valleys comprise the southernmost propagating headwaters of the Rio Marañón that flows northwestward over 400 km before traveling eastward to the Atlantic Ocean. The Pacific-draining fluvial systems are incised (V-shaped valley profiles) to within \( \sim 11 \) km of cirque headwalls as compared to the Atlantic-draining valleys, which are incised only to within \( \sim 17 \) km of cirque headwalls. The previously glaciated portions of the main western drainages are U-shaped, contain partially incised stored glacially-eroded sediment, and are fed by a few tributary valleys. In contrast, the broad east-west oriented U-shaped valleys of the eastern Cordillera Huayhuash contain many significant tributary streams that follow the regional north-south structural grain of the local fold and thrust belt. The eastern valleys are filled with glacially derived sediment that has been only partially re-incised during the Holocene.

### 2.2. Climatological setting

The South American margin is characterized by strong east-west precipitation and temperature gradients. The primary cause of these east-west gradients is the north-south orographic barrier of the Andes. Combined with Hadley circulation, convective processes associated with the South Atlantic Convergence Zone (SACZ), a regional component of the Intertropical Convergence Zone (ITCZ), promote high precipitation on the eastern flank of the Andes (Johnson, 1976; Houston and Hartley, 2003; Vera et al., 2006). On interannual timescales, precipitation fluctuations are related to variations in sea surface temperatures, the El Niño Southern Oscillation (ENSO) signal, with El Niño events being warmer and drier, and La Niña events cooler and wetter (Vuille et al., 2000). The austral summer is the wet season in the tropical Andes, with \( \sim 75\% \) of the total annual precipitation in the Cordillera Huayhuash (\( \sim 0.5–2 \) m/yr) falling during the months of November-April (Johnson, 1976; Bookhagen and Strecker, 2008). As the position of the SACZ may be influenced by sea surface temperatures (SSTs), procession-driven variations in solar insolation, and atmospheric gradients, it is possible that climate fluctuations due to migration of the SACZ occur on annual-millennial timescales (Placzek et al., 2006).

While there are major differences in moisture across the Andes on a continental scale, precipitation is less variable across the main crest of the Andes as shown in a recent study by Bookhagen and Strecker (2008) based on Tropical Rainfall Measurement Mission (TRMM) rainfall data for the past decade. The seasonal migration of the convergence zone brings moisture down to \( \sim 10^{\circ} \) S. The Cordillera Blanca (\( \sim 8.5–10^{\circ} \) S), Cordillera Huayhuash (10–10.5 \( ^{\circ} \) S), and Junín Plain (11–11.5 \( ^{\circ} \) S) receive moisture due mainly to the seasonal southward migration of the SACZ. While the latitudinal variation between the sites might result in different amounts of seasonal moisture, the TRMM data suggest that the present day mean annual rainfall amounts at each location are similar (\( \sim 0.5–2 \) m/yr; Fig. 2; Bookhagen and Strecker, 2008).

A major conclusion of the Bookhagen and Strecker (2008) study is that the largest gradients in precipitation across the entire Andes are correlated with the largest changes in relief (along the easternmost margin of the range) and thus the largest gradient in precipitation is offset to the east of the main Andean drainage divide. This is evident in the Cordillera Huayhuash where the TRMM data suggest that annual precipitation totals are not strongly correlated with the position or orientation of the...
drainage divide (Fig. 2). We note, that while the TRMM dataset is limited in its temporal coverage, and thus cannot directly address conditions during the pre-LGM, LGM, or Lateglacial it is at present the best representation of rainfall within the Andes. Furthermore, it is likely that since the general precipitation gradients across the range are to a great extent controlled by topography, these general patterns would be relatively stable over the past ~40 ka.

Fig. 3. A) Sampling a typical moraine-crest boulder for ¹⁰Be surface exposure age dating. The sample shown here is from the lowest down-valley left-lateral moraine in the Huancho Valley (MIL-05). B) Collecting a sediment core sample from a moraine-dammed bog (Upper Susucocha Bog) for ¹⁴C analysis on basal organic matter. C) Lateral and terminal lake-damming moraines of the Carhuacocha Valley (orange). Ridge-crest boulders were sampled for ¹⁰Be exposure age dating. Note the right-lateral ridges preserved on the valley wall (yellow). D) Glacially polished and striated bedrock (quartzite) near the maximum glacier extent in the Jahuacocha Valley. The view is to east looking back up-valley. E) Close-up view of striated bedrock in the Jahuacocha Valley. Two ¹⁰Be exposure ages, JAH-01 and JAH05-02, were obtained from this outcrop.
3. Methods

3.1. Field methods

We analyzed aerial photograph and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images to map moraines and bogs, and to select field sites prior to field mapping and sample collection. Within specific valleys, handheld GPS units were used to map the locations of terminal and lateral moraines, cosmogenic samples, and bog and lake sediment core samples. Quartz-rich samples were collected from moraine crest boulders or polished and striated bedrock in order to chemically isolate in situ produced $^{10}$Be and derive cosmogenic surface exposure ages (Phillips et al., 1990). We took care to sample only the outermost $>$5 cm or less of a surface (reported as “sample thickness” on Table 5 in supplemental data 1). Additionally, only large ($\geq 1$ m in diameter) boulders were targeted for sampling, ideally with preserved glacial polish and/or striations, that were free of sediment or debris cover, positioned on moraine crests, and located away from any steep valley walls or slopes (Fig. 3A). The age for a set of moraines is taken as the maximum sample $^{10}$Be age obtained from an end moraine or a correlative lateral moraine. Our model of the genetic and morphologic relationships is that the oldest age measured on a moraine represents the culmination of a period of ice advance, or phrased differently, the onset of a period of retreat. The lowest down-valley position of an end moraine from a particular advance is taken as the “maximum down valley extent” for that given period of glacier advance.

Organic matter was sub-sampled from bog and lake sediment cores for $^{14}$C dating to obtain minimum ages for down-valley moraines (Fig. 3B). Where possible, cosmogenic samples were collected from the moraines damming the cored lakes or bogs. Sediment cores $\sim$2–10 m in length from two lakes and seven bogs were obtained with a square-rod piston corer (Wright, 1991). The cores were taken in 1-meter long, non-overlapping drives. All cores were extruded and described in the field. The lake sediment cores were wrapped in plastic and returned to the Union College Core Laboratory in PVC tubes, whereas the bog cores were sampled in the field for organic matter suitable for radiocarbon dating. The age on basal organic matter from a sediment core records the time following retreat of ice from that position and subsequent deposition of organic matter. Therefore, the basal organic matter age should always be less than the age of the moraine damming the basin.

3.2. Laboratory methods

The quartz purification and the separation of beryllium were performed according to the methodology of Kohl and Nishiizumi (1992). BeO was mixed with Nb metal and loaded into a stainless steel cathode for measurement by accelerator mass spectrometry (AMS). The $^{10}$Be/$^{9}$Be ratio measurements were made at the Center for Accelerator Mass Spectrometry (CAMS) of the Lawrence Livermore National Laboratory in Livermore, CA, USA and normalized using a $^{10}$Be half-life of 1.36 x 10^6 yr to $^{10}$Be standards prepared by K. Nishiizumi (information regarding the specific standards used are provided on Table 5 in supplemental data 1; Nishiizumi et al., 2007). The measured $^{10}$Be/$^{9}$Be isotope ratios were converted to $^{10}$Be concentrations in quartz using the total $^{9}$Be in the samples and the sample masses. Background ratios measured from the process blanks (typically with $^{10}$Be/$^{9}$Be ratios of $\sim$10$^{-14}$–10$^{-16}$) were used to correct the measured sample ratios. Total analytical uncertainties including sample preparation and AMS analysis are typically on the order of $\sim$2–5%.

All age calculations were made using the CRONUS online calculator version 2.2, based on a time-dependent $^{10}$Be production rate of 4.84 $\pm$ 0.41 atoms g$^{-1}$ yr$^{-1}$ (Balco et al., 2008). The ages presented in the table and figures have been scaled for latitude and altitude according Lal (1991) and Stone (2000) and topographic shielding and thickness according to Balco et al. (2008). Along the western margin of Peru, an atmospheric inversion ($\sim$800–2500 m a.s.l.; Houston and Hartley, 2003; Johnson, 1976) caused by global oceanic circulation patterns (present since the mid-late Miocene; Alpers and Brimhall, 1988; Houston and Hartley, 2003) perturbs the air density altitude function and as result, the production rate in this region (Farber et al., 2005). As our sites are located above the inversion layer, it is necessary to include a correction to the standard atmosphere (Farber et al., 2005). We should note that low-latitude high-altitude settings are likely the most uncertain with respect to the scaling of in situ produced cosmogenic radionuclide production. At present, the best control for the production rates in these settings is provided by the Breque calibration site in the Cordillera Blanca, which has some of the tightest $^{14}$C control on the moraine age (Rodbell and Seltzer, 2000) of any calibration site. While the scaling scheme we use here reproduces the Breque $^{14}$C chronology better than more recently proposed scaling schemes (Farber et al., 2005; Zech et al., 2007), the differences between the various scaling schemes are quite small for this time period becoming much more significant for older ($> \sim$20 ka) surfaces. The major differences between the proposed scaling schemes arise from the time dependent magnetic field corrections to the production rates that, at present, are the least constrained and most controversial part of the correction factors. These differences in the proposed scaling schemes are more pronounced for samples that are late Pleistocene in age (cf. Zech et al., 2007). Fortunately, in the present study most of the data and analysis presented is from the Lateglacial and Holocene where the differences in the scaling schemes are small. For additional information, Balco et al. (2008) provide a thorough discussion of derivation of and the differences between the various methods of calculating the time-dependent production rates. We have chosen to present the data in the text and figures using the time-dependent Lal (1991)/Stone (2000) scaling scheme here for two reasons: 1) our goal was to produce ages that are directly comparable to other published global datasets which were calculated based on this scaling scheme (Smith et al., 2005a; Smith et al., 2005b; and Farber et al., 2005) and 2) The Lal (1991)/Stone (2000) production rates have been shown to reproduce the Lateglacial Breque calibration site in the Cordillera Blanca, located less than 100 km to the northwest of the Cordillera Huayhuash (Farber et al., 2005). However, for completeness, we also present ages calculated using the other main scaling schemes (Dunai, 2001; Desilets and Zreda, 2003; Desilets et al., 2006; and Lifton et al., 2005), with version 2.2 of the CRONUS web-based calculator (Table 6 in supplemental data 2).

In addition to the errors associated with analysis and production rate calculation (generally on the order of $\sim$10%; Gose and Phillips, 2001; Balco et al., 2008) that are presented on Tables 1 and 2, geological effects are potentially the largest source of error in the age estimate. These effects include processes such as differential

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1 Table 5 Table of parameters needed to calculate ages using the CRONUS online calculator version 2.2. The data from this table is formatted so that it may be directly copied and pasted into the CRONUS online calculator for age determination. All of the standards listed on this table are those used at the CAMS facility of Lawrence Livermore National Laboratory during the course of this study.

2 Table 6 Ages based on the $^{10}$Be concentrations measured in this study calculated using different scaling methods available on the CRONUS online calculator including: Time-dependent Lal (1991)/Stone (2000), Desilets and Zreda (2003; Desilets et al., 2006), Dunai (2001), and Lifton et al. (2005).
boulder erosion, moraine denudation, inheritance due to a prior exposure history, or differential covering by debris or ice. In general, geologic processes will cause the age spectrum of different samples on the same feature to scatter. While we cannot uniquely identify the post-depositional processes active on these features, errors provide a convenient way to estimate the degree to which a surface may have been affected by any of these processes (Phillips et al., 1990; Briner et al., 2005; Licciardi and Pierce, 2008; Sarikaya et al., 2008). In an attempt to account for the geologic effects, we present the mean age and standard deviation of a feature as well (Tables 1 and 2). In our interpretation, we take the oldest sample age as the depositional age of a moraine, which correlates with the

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Cosmogenic 10Be sample parameters and ages of western drainages.</th>
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<tbody>
<tr>
<td>Sample name</td>
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<tr>
<td>Jahuacocha Valley</td>
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</tr>
<tr>
<td>JAH-10 A</td>
<td>E-W, Western Drainage</td>
</tr>
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<td>JAH-11 A</td>
<td>E-W, Western Drainage</td>
</tr>
<tr>
<td>JAH-12 B</td>
<td>E-W, Western Drainage</td>
</tr>
<tr>
<td>JAH-13 B</td>
<td>E-W, Western Drainage</td>
</tr>
<tr>
<td>JAH-14 B</td>
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<tr>
<td>JAH-15 B</td>
<td>E-W, Western Drainage</td>
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<td>JAH-01 C</td>
<td>E-W, Western Drainage</td>
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<td>Milo Valley</td>
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<td>Huanacpatay Valley</td>
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<tr>
<td>HUA-10 I</td>
<td>E-W, Western Drainage</td>
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</table>

a Ages are zero erosion model ages calculated with the CRONUS web-calculator (Balco et al., 2008) using the Lai (1991)/Stone (2000) scaling factors and time-varied production rates.

b Errors are the “external uncertainty” from the CRONUS calculator which includes the analytical error and the error associated with production rate calculation.

c N.A. – Not Available. Average ages at not available where there is only one sample per feature.
age of the initial ice retreat (Phillips et al., 1990; Putkonen and Swanson, 2003; Zech et al., 2007). Younger ages likely reflect either the erosion of moraine material and exhumation of a partially buried boulder since the moraine was emplaced or minor readvances during glacier retreat. It is possible, however highly improbable, that moraine boulders may contain an inherited nuclide concentration that would result in an apparently old exposure age (Putkonen and Swanson, 2003). For bedrock samples, we base our interpretations on the average age, as it is more likely that geologic processes have uniformly modified the surface. Bedrock sample concentrations may contain some component of inherited nuclides, which would make the ages appear older than they actually are. All of the bedrock samples presented here are from polished and striated sections of valley wall or valley floor bedrock. While Briner and Swanson (1998) suggest that samples of plucked or glacially quarried bedrock yields lower inherited nuclide concentrations than samples of glacially polished and striated bedrock, this study was referring to large continental glaciations and not the more highly erosive mountain valley glaciers of the present study. Moreover, plucked bedrock locations were not accessible within the valleys of the Cordillera Huayhuash. A recent study by Guido et al. (2007) suggests that the inherited concentration is likely a very small portion of the total concentration within polished and striated bedrock samples due to efficient glacial erosion along the valley floor and walls, however we cannot assume there is no inherited concentration in these samples, thus these ages are maximum ages. As the bedrock from these sample locations is glacially striated, it is unlikely that other processes (fluvial erosion or landsliding) have significantly eroded these sampling sites (resulting in apparently young ages) since the time of deglaciation. The individual ages, the average ages, and the oldest ages from each feature are reported in Tables 1 and 2.

The difference between 10Be ages calculated with zero erosion and with 1 m/Ma (the maximum boulder erosion rate calculated at a location in the Cordillera Blanca in the Farber et al., 2005 study) is less than 2%, thus the interpretations based on the ages do not change depending on which erosion rate we use. For simplicity, we present the zero erosion model ages. While all individual, average, and maximum 10Be ages, are presented in Tables 1 and 2, only the maximum ages of each moraine set are presented in the following sections of text and on the figures. The errors presented with the individual 10Be ages reflect the analytical errors and the errors associated with the production rate. Ages of striated and polished bedrock samples are given as the average age of a group of samples with the error reflecting 1σ standard deviation.

Organic matter sub-samples for radiocarbon dating were picked with tweezers in a laminar flow hood; sub-samples were then treated repeatedly with hot (90 °C) 1N HCl to remove carbonate detrital sediment and with 1M NaOH to remove mobile organic compounds. Radiocarbon analyses were conducted at the W. M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory at the University of California in Irvine, California USA. All radiocarbon ages were converted to the calendar year time scale using the CALIB radiocarbon calibration program (v. 5.0.1; Stuiver and Reimer, 1993) and presented in cal kyr BP, which is used here synonymously with “ka”, along with core descriptions on Table 3.

4. Results

The results from the individual valleys are discussed from north to south, first the western drainages, then the eastern drainages (Fig. 4). Mapped and dated geomorphic features are mapped in Fig. 5 and 6 for the western and eastern drainages respectively. All of the ages are presented on Tables 1 and 2, and graphically in Fig. 7. Each cosmogenically dated glacial feature has been assigned a letter to be used to reference the text, figures, and tables. The elevation provided with each age in the text below is the lowest elevation of the sampled feature, however the elevation for each sample is listed on Tables 1 and 2.

In the Jahuacocha Valley we identified three sets of well-preserved moraines with corresponding lakes or bogs, distinctive hummocky topography that likely records dead-ice processes during deglaciation, and an exposure of polished bedrock (Fig. 5A). The oldest 10Be ages on two end moraine sets are 10.1 ± 0.9 ka (feature A; 4095 m a.s.l.) and 12.1 ± 1.1 ka (feature B; 4090 m a.s.l.) and the oldest 10Be ages on two sets of lateral moraines are 13.3 ± 1.2 ka (feature C; 4099 m a.s.l.) and 13.8 ± 1.3 ka (feature D). The hummocky topography located down-valley of these well-preserved moraines, has an oldest 10Be age of 11.8 ± 1.1 ka (feature E; 4058 m a.s.l.). The third main group of moraines is located further up-valley and was not dated. The lake dammed by end moraine A (Laguna Jahuacocha; 4078 m a.s.l.) yields a 14C age on basal organic matter of 7.9 ± 0.4 ka. The oldest ages in this study come from samples of polished and striated bedrock in the Jahuacocha valley floor near the limit of glaciation. These samples, collected at an elevation of 3980 m a.s.l. ~11 km from the cirque headwall yield average 10Be exposure ages of 37.6 ± 2.7 ka (feature F). The valley becomes steeper and narrower at 3800–3900 m a.s.l. just down-valley from the location of these bedrock samples.

In the northward draining Gashapampa Valley, a large tributary to the Jahuacocha Valley, we mapped three sets of moraines and corresponding moraine-dammed lakes or bogs (Fig. 5A). The oldest 10Be age on the lowest down-valley moraine is 12.9 ± 1.2 ka (feature G; 4556 m a.s.l.). A sediment core from the bog dammed by this moraine (Lower Susucocha Bog; 4550 m a.s.l.) yields a 14C age from basal organic matter of 23.3 ± 0.07 ka. Further up-valley, a sediment core from the Upper Susucocha Bog (4644 m a.s.l.) yields a 14C age on basal organic matter of 3.45 ± 0.02 ka. The lake in the upper Gashapampa Valley (Laguna Susucocha; 4690 m a.s.l.) is situated in a remnant cirque suspended above the main valley and yields a 14C age from basal organic matter of 10.2 ± 0.03 ka.

The Huancho Valley is a steep southward draining tributary to the large westward-draining Huayllapa Valley (Fig. 5B). Although three sets of moraines were mapped in the Huancho Valley, low quartz yields precluded most 10Be analysis. One sample from the lowest down-valley left-lateral moraine yielded a 10Be age of 21.7 ± 1.9 ka (feature H; 4297 m a.s.l.). The Huayllapa Valley is a large U-shaped valley with steep valley walls, however no datable glacial remnants are preserved near the inferred ice limit (~3800 m a.s.l.). The sizable Huancapatay Valley is a tributary to the larger Huayllapa Valley and contains three sets of end moraines, two glacially polished bedrock knobs, and three moraine-dammed bogs (Fig. 5B). Where the Huancapatay Valley meets the Huayllapa Valley glacially polished and striated bedrock is abundant at an elevation of ~4100 m. The Huancapatay Valley is the southernmost valley mapped in this study area. The 14C ages from basal organic matter in the bog sediment cores are as follows: the moraine-dammed Lower Huancapatay Bog (4407 m a.s.l.), 13.4 ± 0.02 ka, the moraine-dammed Mid Huancapatay Bog (4419 m a.s.l.), 13.4 ± 0.04 ka, and the Upper Huancapatay Bog (4511 m a.s.l.) located up-valley of a glacially-polished silicic dike, 5.64 ± 0.03 ka.

The glacially polished and striated surface of one of the bedrock knobs, a silicic dike just down-valley from the Upper Huancapatay bog yields an average 10Be surface exposure age of 8.84 ± 0.26 ka (feature I; 4541 m a.s.l.).

On the eastern side of the range, the tributary valleys exploit the structural trend of the fold and thrust belt much more

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<table>
<thead>
<tr>
<th>Sample name</th>
<th>Feature letter (for figures 5, 6, 8, 9)</th>
<th>Valley</th>
<th>Feature</th>
<th>Group</th>
<th>Elevation of sample (m)</th>
<th>Lal/Stone erosion 10Be age(^a) (ky)</th>
<th>Lal/Stone erosion 10Be Age Error(^b) (ky)</th>
<th>Average age on feature(^c) (ky)</th>
<th>Standard deviation(^c) (ky)</th>
<th>Oldest age on feature (ky)</th>
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| CAR-24      | N                                      | E-W, Eastern Drainage | L.L./End Moraine | II   | 4194                   | 7.54                            | 0.68                            | 8.48                        | 1.33                        | 9.42                     |
| CAR-25      | N                                      | E-W, Eastern Drainage | L.L./End Moraine |      | 4189                   | 9.42                            | 0.85                            | 0.53                        | 0.13                        | 0.66                     |
| CAR-28      | O                                      | E-W, Eastern Drainage | L.L./End Moraine | II   | 4183                   | 9.35                            | 0.86                            | 8.90                        | 0.39                        | 9.35                     |
| CAR-29      | O                                      | E-W, Eastern Drainage | L.L./End Moraine |      | 4196                   | 8.69                            | 0.79                            | 0.84                        | 0.25                        | 0.94                     |
| CAR-30      | O                                      | E-W, Eastern Drainage | L.L./End Moraine |      | 4194                   | 8.66                            | 0.79                            | 0.84                        | 0.25                        | 0.94                     |
| CAR-09      | P                                      | E-W, Eastern Drainage | R.L./End Moraine | III  | 4098                   | 13.50                           | 1.23                            | 13.88                       | 0.50                        | 14.50                    |
| CAR-10      | P                                      | E-W, Eastern Drainage | R.L./End Moraine |      | 4090                   | 13.46                           | 1.23                            | 13.88                       | 0.50                        | 14.50                    |
| CAR-12      | P                                      | E-W, Eastern Drainage | R.L./End Moraine |      | 4082                   | 14.50                           | 1.32                            | 14.28                       | 0.50                        | 14.50                    |
| CAR-13      | P                                      | E-W, Eastern Drainage | R.L./End Moraine |      | 4088                   | 14.06                           | 1.26                            | 13.88                       | 0.50                        | 14.50                    |
| CAR-06      | Q                                      | E-W, Eastern Drainage | L.L. Moraine   | III and IV | 4095                   | 12.88                           | 1.19                            | 13.57                       | 0.97                        | 19.53                    |
| CAR-07      | Q                                      | E-W, Eastern Drainage | L.L. Moraine   |      | 4091                   | 14.25                           | 1.28                            | 13.88                       | 0.50                        | 14.50                    |
| CAR-08      | Q                                      | E-W, Eastern Drainage | L.L. Moraine   |      | 4090                   | 19.53                           | 1.75                            | 13.88                       | 0.50                        | 14.50                    |
| CAR-14      | R                                      | E-W, Eastern Drainage | End Moraine    | III  | 4061                   | 14.05                           | 1.32                            | 13.58                       | 0.67                        | 14.05                    |
| CAR-15      | R                                      | E-W, Eastern Drainage | End Moraine    |      | 4075                   | 13.10                           | 1.16                            | 13.88                       | 0.50                        | 14.50                    |
| CAR-36      | S                                      | Tributary - Eastern Drainage | Cirque End Moraine | II  | 4512                   | 9.37                            | 0.84                            | 9.49                        | 1.03                        | 10.58                    |
extensively than the tributaries of the western side of the range, thus our mapping extended into some of these north-south trending tributary valleys as well as the larger east-west trending main valleys. The Mitococha Valley is the northernmost valley mapped in this study area (Fig. 4). The main axis of the Mitococha Valley trends east-west, and north-south tributaries tap an accumulation area >12 km in length along the spine of the range (Fig. 6A). While abundant evidence (e.g., U-shaped valley morphology, glacially polished bedrock, and abandoned cirques in tributary valleys) suggests that paleoglaciers extended down to an elevation of ~3820 m a.s.l., well-preserved moraines and bogs suitable for dating are not plentiful in the main Mitococha Valley. Recent fluvial processes or outburst flooding events may have contributed to the poor preservation of older main valley glacial-depositional features. The Mitococha Valley is the only location in which we have obtained a 10Be age on a Late Holocene moraine (0.26±0.06 ka; feature J; 4384 m a.s.l.). Large slightly denuded moraines with poor quality boulders dam Laguna Mitococha, the large lake in the southwestern part of the catchment. These moraines were not dated, but were mapped in the field (Fig. 6A).

### Table 2 (continued)

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Valley Feature</th>
<th>Feature Group</th>
<th>Elevation of sample (m)</th>
<th>Lal/Stone zero erosion 10Be agea (ky)</th>
<th>Lal/Stone zero erosion 10Be Age Errorb (ky)</th>
<th>Average agec on feature (ky)</th>
<th>Standard deviationc (ky)</th>
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</table>

- Errors are the “external uncertainty” from the CRONUS calculator which includes the analytical error and the error associated with production rate calculation.
- N.A. = Not Available. Average ages are not available where there is only one sample per feature.

### Table 3

<table>
<thead>
<tr>
<th>Valley</th>
<th>Orientation</th>
<th>Lake/Bog name</th>
<th>Elevation (m a.s.l.)</th>
<th>Depth (cm)</th>
<th>Material</th>
<th>14C age</th>
<th>±</th>
<th>Measured 14C age (Cal kyr BP)</th>
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<td>Lower Huanacpatay Bog</td>
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<td>peat</td>
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<td>Laguna Susucocha</td>
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<td>11170</td>
<td>100</td>
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The Mitococha Bog (4250 m a.s.l.), located down valley from Laguna Mitococha and associated moraines, yields a $^{14}$C age on basal organic matter of 13.2 ± 0.03 ka. Just down-valley from this locality a polished granite boulder perched on weathered lime-stone bedrock yields a $^{10}$Be age of 11.6 ± 1.0 ka (feature K; 4247 m a.s.l.). This boulder was one of multiple polished granite boulders deposited and suspended on the bedrock along the right side of the valley near the confluence of a tributary valley and the main valley. Polished bedrock halfway down the main valley yields an average $^{10}$Be age of 11.7 ± 0.4 ka (feature L; 4103 m a.s.l.). Within the town of Queropacca, at the end of the Mitococha Valley, a denuded cluster of moraines is preserved across the main valley. One quartz-rich sample from this moraine yields a $^{10}$Be age of 11.8 ± 1.1 ka (feature M; 3829 m a.s.l.).

Fig. 4. A) Topographic map of the Cordillera Huayhuash (El Instituto Geographico Nacional, 1966a,b). The valleys mapped and discussed in the text are shown here. Moraine sets are colored according to age as discussed in the text (here stage IIa moraines are combined with stage III moraines). Yellow circles indicate the locations of $^{10}$Be samples and red circles indicate the locations of sediment core samples. Chronologic data corresponding to these sample locations in the Jahuacocha, Gashapampa, Huancho, Huanacpatay, Carhuacoche, and Mitococha Valleys are presented in Fig. 5 and 6.
Moraine preservation in the Carhuacocha Valley is much better than in the Mitococha Valley (Fig. 6B). The oldest \(^{10}\text{Be}\) age on the end moraine damming Laguna Carhuacocha is 9.42 ± 0.85 ka (moraine N; 4189 m a.s.l.) and 9.35 ± 0.86 ka (moraine O; 4183 m a.s.l.) on an inset moraine of the same moraine cluster. While this is the youngest moraine dated in this valley, numerous undated younger moraines exist up-valley from this location. Immediately down-valley of this ~9.4 ka set of moraines is the moraine-dammed Carhuacocha Bog (4130 m a.s.l.), which yields \(^{14}\text{C}\) age from basal organic matter of 11.4 ± 0.32 ka. The moraines damming this bog were less well preserved and therefore not dated. The next older set of main valley moraines yield maximum \(^{10}\text{Be}\) ages of 14.5 ± 1.3 ka on a right lateral/end moraine (feature P; 4082 m a.s.l.), and 19.5 ± 1.8 ka and 14.3 ± 1.3 ka on a left-lateral moraine (feature Q; possibly where two ridges have coalesced; 4090 m a.s.l.), and 14.1 ± 1.3 ka on the end moraine (feature R; 4061 m a.s.l.). A tributary entering the main valley from the north introduces a right-lateral moraine just up-valley of the ~14.5 ka set of moraines. This right-lateral moraine yields an oldest \(^{10}\text{Be}\) age of 12.0 ± 1.1 ka (feature T; 4092 m a.s.l.). A moraine within a cirque that fed this tributary valley yields an oldest \(^{10}\text{Be}\) age of 10.6 ± 0.96 ka (feature S; 4510 m a.s.l.). This cirque also contributes to the tributary which enters the main valley from the north slightly down-valley just east of the town of Queropalca. Here, a right-lateral moraine fed by the tributary yields a maximum \(^{10}\text{Be}\) age of 14.3 ± 1.3 ka (feature U; 4058 m a.s.l.). Near the convergence of the Carhuacocha and Mitococha valleys at the

Fig. 5. ASTER image overlain by basin outlines, mapped moraines, and sample positions in the Jahuacocha and Gashapampa Valleys (A) and Huancho and Huanacpatay Valleys (B). Yellow and red circles mark locations of \(^{10}\text{Be}\) and \(^{14}\text{C}\) samples respectively. Model \(^{10}\text{Be}\) surface exposure ages are shown in orange and \(^{14}\text{C}\) ages from basal organic matter are shown in red. For bedrock, the average \(^{10}\text{Be}\) age is given, for moraines, the oldest age from a feature is given. The entire distribution of ages is presented in Tables 1 and 2 and on Fig. 7.
town of Queropalca, polished bedrock (~286 m above the valley floor) yields an average $^{10}$Be exposure age of $26.9 \pm 0.91$ ka (feature V; 4115 m a.s.l.). Just down-valley of Queropalca (at ~3800 m), valley morphology becomes more confined and well-preserved glacial features are absent.

5. Discussion

5.1. Valley chronologies and comparisons

Main interpretations from each valley that are discussed here include maximum glacier extent and stages of glacier retreat (moraine age clusters). The maximum glacier-extent is defined as the lowest down-valley position reached by the glacier at a particular point in time. This is determined by morphologic and stratigraphic observations and based on the geochronology. Generally, the transition from a U-shaped valley profile to a V-shaped profile marks the glacier-extent although recent headward incision could offset the position of the apparent maximum glacier-extent up-valley. Other evidence includes glacially polished or striated bedrock on the valley walls or on the valley floor. Stranded till deposits high on valley walls also mark previous ice positions. Most often these features are not in a state of preservation that would permit accurate surface exposure dating; however they do serve as indicators of the presence of a paleoglacier and thus allow one to make estimates of the local maximum glacier-extent. Dated end moraines assign an age and maximum paleoglacier position to the culmination of an advance. Ideally, the lowest down-valley moraine would give the maximum glacier-extent for the entire valley. However, in this region, subsequent fluvial erosion has largely destroyed these moraine sets. We correlated moraine positions in the valleys to knickpoints in stream profiles in order to fortify our estimate of maximum paleoglacier extent elevations and to make comparisons between valleys (Fig. 8). Thus, we have used all the available stratigraphic and morphologic data to construct the most likely
record of past glacier extents. General valley morphology across
the region suggests that the Lateglacial paleoglacier limit is
~4000 m a.s.l. and pre-Lateglacial advances reached an elevation
of ~3800 m. Maximum paleoglacier extents for different time
periods are discussed in more detail below and are summarized
in Table 4.

Based on the sample yielding the oldest age on a moraine, or
average age of polished bedrock, as discussed above, the features
are grouped by age into stages I–V that represent the onset of
deglaciation (Tables 1 and 2). Stage I features are <5 ka, II are ~9–
10 ka, III are ~13–14 ka, IV are ~20–22 ka, and V are >26 ka. Stage
IIa is a small readvance or stillstand that has ages in the 11.5–12.2 ka
range and are often proximal (down-valley) to the stage II
moraines, thus we have made them a subgroup of the main stage II
moraines. All of the sample ages are shown graphically on Fig. 7
sorted by feature, valley, and age. The oldest sample age on a given
moraine determines the assignment to a specific group (I–V). To
facilitate the comparison with corresponding moraine sets, 14C ages
on organic matter are also shown on Fig. 7. Where we have
obtained both 14C ages from basal organic material in bog/lake
sediment cores and 10Be exposure ages on moraines, we can evaluate
our model of the morphologic and genetic relationships.

As the age on basal organic matter from a sediment core records the
time following retreat of ice from that position and subsequent
deposition of organic matter, the age of the moraine damming
a lake or bog should always be older than the age of the basal
peat in the sediment core. This model holds for some of our data as we
elaborate on below. The discussion of individual valley chronolo-
gies will follow the same order as in the “Results” section, north
to south starting on the west side of the range and continuing to
the east side of the range.

In the northern section of the western margin, the main
Jahuacocha Valley has a well-preserved U-shaped valley
morphology to ~3950 m a.s.l. The average age of the glacially
polished and striated bedrock positioned at 3980 m a.s.l. in the
Jahuacocha Valley (37.6 ± 2.7 ka) is the oldest age determined from
a glacial feature in all of the Cordillera Huayhuash. As these are
bedrock samples, the average age represents the time since that
area has been ice-free. While the potential for inherited nuclide
concentration makes this a maximum age, the onset of deglaciation
(down-valley from this position) may have begun before ~38 ka;
likewise, this is evidence for a more extensive glaciation older than
38 ka. It is plausible that the lower knickpoints on the Jahuacocha
stream profile correspond to maximum paleoglacier positions at
~3800–3850 m a.s.l. during the stage IV and/or V advances
(Fig 7D). The hummocky topography (~12 ka) up-valley from the
polished bedrock may be denuded end moraine material (with a
source in the tributary valley) overlying relic main valley
moraine and terrace deposits, however it is also possible that these
deposits are related to a landslide extending from the tributary
valley. The two well-preserved sets of moraines in the valley are
associated with the stage II and III maximum down-valley paleo-
glacier positions at ~4060 m a.s.l. and 4040 m a.s.l., respectively. The
14C age on basal peat from Laguna Jahuacocha of 7.9 ± 0.04 ka is
2.2 ky younger than the morane damming this lake (10.1 ± 0.9 ka).
Thus, our model suggests that after the stage II ice advance
culminating at ~9–10 ka, the ice retreated up-valley from this
position leaving a sediment trap behind the stage II moraine set.
The transition from the deposition of glacially eroded silt to
organic-rich material in Laguna Jahuacocha signals the onset of
local glacial recession, and establishment of a vegetated environ-
ment and/or an increase in the biological productivity of the lake.
As the basal organic matter age is ~7.9 ka, the transition between
maximum glacial advance and a locally ice-free vegetated environ-
ment in this area occurred over a ~1–2 kyr period. Given the
errors involved with both dating methods, specifically the cosmo-
genic 10Be method which, including both the geologic errors and
errors associated with production rate and scaling factors could be
on the order of ~20%, it is possible that this basal bog age is closer
to the timing of deglaciation than the moraine age. As this moraine
age is in general agreement with moraines at a similar position in
other valleys, perhaps this disagreement between the basal peat
age and moraine age is due to a bias in the scaling factor scheme we
utilize to calculate the model ages (which would affect all of the
ages more or less uniformly). Using the scaling scheme of Lifton
et al. (2005), the maximum boulder age on this moraine would be
9.24 ± 0.96 ka (feature A, Fig. 9 here and Table 6 in Supplemental
Data), which at first inspection one might think improves the
chronology. However, in other locations where we do have comparable data (e.g. in the Gashapampa Valley), there is no systematic offset between the $^{10}$Be and $^{14}$C chronologies that might indicate a bias in the scaling factors and in many cases using the younger ages produced by the scaling scheme of Lifton et al. (2005) violates the $^{14}$C constraints. However, at present, our $^{10}$Be and $^{14}$C chronology is not complete enough to make robust interpretations regarding the lag time between onset of deglaciation and revegetation.

A large northward draining tributary to the Jahuacocha Valley, Gashapampa Valley, contains three sets of moraines, presumably the groups I, II, and III moraines. The group III moraines are given by the $^{10}$Be age of $12.9 \pm 1.2$ ka ($\sim 4560$ m a.s.l.). With respect to the $^{10}$Be age on the group III moraines, the $^{14}$C age of basal peat from the Upper Susucocha Bog ($3.45 \pm 0.02$ ka) makes sense stratigraphically and may be associated with the stage I deglaciation. However, the $23.3 \pm 0.07$ ka age from the Lower Susucocha Bog that is dammed by this stage III moraine (Feature G) is
inconsistent with the moraine age. As the peat age is much older than the moraine age, it is possible that the $^{14}$C age reflects old reworked organic material and thus gives an age that is “too old”. The $^{14}$C age on basal peat from Laguna Susuchocha (10.2 ± 0.03 ka), situated higher in elevation (~4590 m a.s.l.) than the Upper and Lower Susuchocha bogs, but tapping a smaller and more isolated section of the Gashampampa catchment, reflects a stage II age of deglaciation.

The Huancho Valley, a substantial tributary valley with a small catchment area on the east-west spur of the range, has preserved glacial features down to ~4200 m a.s.l. The left-lateral moraine dated at 21.7 ± 1.9 ka, a group IV moraine, marks the existence of a paleoglacier at a specific time in the past, not a maximum down-valley extent. Notably, this is the oldest moraine age obtained from the western side of the Cordillera Huayhuash.

In the main Huaylalpa Valley, the U-shaped valley morphology extends down to at ~3800 m a.s.l. This valley taps a large catchment area that makes up the entire southern region of the western Cordillera Huayhuash (Fig. 8A). Well-preserved glacial features in a tributary valley, Huancapatay, are associated with stages I, II and III paleoglacier positions at 4515 m a.s.l., 4390 m a.s.l., and 4300 m a.s.l., respectively. Two adjacent bogs in the Huancapatay Valley both contain basal organic matter that yields ages of 13.4 ± 0.04 ka. As these two bogs occupy different moraine-dammed positions within the same valley, we interpret this to reflect rapid deglaciation from this position sometime before 13.4 ka. The next up-valley bog is bound down-valley by a glacially polished silicic dike that cross-cuts the valley. A basal organic matter age of 5.6 ± 0.03 ka from a bog up-valley of the dike places a minimum bound on ice retreat from the polished bedrock. The average $^{10}$Be surface exposure age of the polished bedrock, 8.84 ± 0.3 ka (a maximum age) is consistent with the $^{14}$C ages from the basal organic material both up and down valley. Since this exposure age is from bedrock and not from moraine material, the age does not correspond to a specific glacier position within the valley; rather, it suggests that the surface of the dike has been ice-free since ~9 ka.

The age of Late Holocene moraines in the Mitococha Valley is constrained by two $^{10}$Be ages of 0.26 ± 0.06 ka from a well-preserved end moraine damming a lake in the Mitococha Valley. These Late Holocene moraines (group I) reached a down-valley elevation of ~4300 m a.s.l. Based on the stream profiles (Fig. 8E) and the chronology of glacial landforms, maximum down-valley ice positions of the group II and III moraines in the Mitococha Valley reached elevations of ~4240 m a.s.l. and ~4050 m a.s.l., respectively. The $^{14}$C age of 13.2 ± 0.28 ka from basal organic matter in the bog core plausibly corresponds to deglaciation following the group III (~13–14 ka) advance. Up-valley a larger, as yet undated, lake-damming end moraine set may correspond to the group II moraines as suggested by the position of this moraine relative to dated moraines in this and other valleys. The next down-valley dated feature is a polished boulder perched on top of limestone bedrock that yields an apparently anomalous age of 11.6 ± 1.0 ka. It is possible that the boulder was initially encased in fine-grained moraine material that has since been eroded away yielding a younger model age than its true age. Alternatively, the boulder may have been carried on top of the glacier and was abandoned during deglaciation yielding an older model age than its true age. The exact model for how this boulder was transported and abandoned is unclear. Further down-valley, polished valley-wall bedrock with an average $^{10}$Be age of 11.7 ± 0.4 ka marks a period of retreating ice following a minor advance from the multiple tributary valleys. The ~11.7 ka age of the polished boulder and the polished bedrock in this position present an inconsistency with respect to the ~13.2 ka age of organic material in the bog up-valley. Sediment burial and subsequent exhumation of the polished bedrock could explain this discrepancy. Although the presence of intact glacial polish on the bedrock, suggests that extensive fluvial erosion of the surface is unlikely. A more likely explanation might be found in the limestone units that are a major constituent of the local bedrock in this area. It is possible that the $^{14}$C age is influenced by either a hard-water effect making the apparent age up to 2 ky too old or may in fact reflect old reworked organic material and thus yields an age of deglaciation that is too old.

Maximum down-valley ice positions of the group III and II moraines in the Carhuacocha Valley reached elevations of ~4040 m a.s.l. and ~4150 m a.s.l. respectively. Younger Late Holocene moraines (group I) reached a down-valley elevation of ~4200–4400 m a.s.l. The $^{14}$C age from basal organic matter of 11.4 ± 0.1 ka from the Carhuacocha Bog is consistent with the dated main-valley moraine set up-valley (group II) and down-valley (group III) from this position. The undated moraine that dams the Carhuacocha Bog likely corresponds to a minor ice advance at ~11.5–12 ka for which we find minor evidence for in multiple valleys (stage Ila), including a right-lateral moraine (feature T) emanating from a nearby tributary to the main valley. A sample from the left-lateral moraine (feature Q) positioned at ~4090 m a.s.l. yields a $^{10}$Be exposure age of 19.5 ± 1.8 ka. This is the oldest moraine age (group IV) from an eastern valley moraine. Because this moraine is a lateral moraine with additional sub-parallel, less well-preserved lateral moraines inset, and as this moraine also contains samples yielding group III ages, we interpret this feature as a compound lateral moraine containing boulders from multiple advances. In this view, the paleoglacier extent at ~19.5 ka was down-valley of this position. The group III ages fit in well with nearby end moraine ages (features P and R). Alternatively, the sample with the anomalously older age may be the result of contamination by a valley wall rock-fall event.

Near the confluence of the Mitococha and Carhuacocha Valleys (~3800 m a.s.l.), the drainage becomes more deeply incised and V-shaped at the transition from glacial to fluvial erosion, suggesting that this elevation marks the maximum down-valley extent of the ice. The oldest ages obtained from any glacial feature on the eastern side of the range are those from polished and striated valley wall bedrock samples collected near the town of Queropalca where the Mitococha and Carhuacocha drainages converge. The average $^{10}$Be exposure age for these samples (26.9 ± 0.91 ka, a maximum age) represents the time at which the glacier retreated below and/or upstream of this

Table 4
Paleoglacier extent elevations.

<table>
<thead>
<tr>
<th>Orientation Valley</th>
<th>Modern ice extent elevation(m)$^a$</th>
<th>Group I extent elevation(m)$^b$</th>
<th>Group II extent elevation(m)</th>
<th>Group III extent elevation(m)</th>
<th>Group IV extent elevation(m)</th>
<th>Maximum (group V) ice extent elevation(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Jahuacocha</td>
<td>4700</td>
<td>4150</td>
<td>4060</td>
<td>4055</td>
<td>4040</td>
<td>3950</td>
</tr>
<tr>
<td>Huanacapatay</td>
<td>4800</td>
<td>4515</td>
<td>4390</td>
<td>4330</td>
<td>4300</td>
<td>4000</td>
</tr>
<tr>
<td>Eastern Carhuacocha</td>
<td>4500</td>
<td>4200</td>
<td>4150</td>
<td>4100</td>
<td>4040</td>
<td>3830</td>
</tr>
<tr>
<td>Mitococha</td>
<td>4800</td>
<td>4300</td>
<td>4240</td>
<td>4160</td>
<td>4050</td>
<td>3830</td>
</tr>
</tbody>
</table>

$^a$ Elevations determined from a combination of hand-held GPS data, IGN (1986) Topographic Map data, and USGS SRTM (profiles) data.

$^b$ Ages of groups determined by cosmogenic $^{10}$Be surface exposure ages of moraines and $^{14}$C ages on basal organic matter from bog and lake cores.
point and therefore provides evidence for a more extensive glacial advance sometime prior to ~27 ka and in retreat by 27 ka. Our correlation of moraine sets between valleys is based on our mapping of at least three sets of end moraines in each of the main valleys and on the chronology that we have established. Using this approach, we have identified maximum advances (or the onset of deglaciation) during stages I, II (IIa), III, IV and V. The younger Holocene advance is undated on the western side of the range, but based on bog ages and dated correlative moraines on the eastern side of the range, the advance plausibly occurred ~5 ka. The western drainages and eastern drainages contain a similar chronologic record of paleoglacier positions spanning the time frame of late Pleistocene–late Holocene with evidence of maximum advances at ~0.3 ka, ~9–10 ka, ~13–14 ka, ~20–22 ka, and ~26 ka.

5.2. Valley morphologies

On both the eastern and western sides of the Cordillera Huayhuash the maximum glacier extent occurs at similar elevations of ~3800 m a.s.l. Likewise, the maximum down-valley elevations for paleoglaciers associated with the stages I, II, and III moraines and bogs are comparable on both sides of the range (Table 4; Fig. 8).

Valley morphology and down-valley distance to maximum glacier extent are notably different between the western and eastern drainages. The maximum down-valley Lateglacial (stage III) extent occurs ~17 km from the valley headwall on the eastern side of the range (Carhuacocha Valley), and ~11 km from the valley headwall on the western side of the range (Jahuacocha Valley). Eastern drainages have shallower slopes and are part of a larger catchment than the western drainages (Fig. 8a). Based on modern data, there is not in general, a strong precipitation gradient across the range, however, there are pockets of high precipitation located within the accumulation zone of the eastern drainages (cf. Fig. 2; Bookhagen and Strecker, 2008). Together, the larger accumulation area and shallower slopes of the eastern valleys, suggest to us that any increases in precipitation relative to the western drainages would result in a larger ice volume in the eastern valleys during a given cold period. However, while paleo-ice volumes may have been larger in eastern drainages, the lowest elevation paleoglaciers of the past ~14 ka reached was the same on both sides of the range suggesting a temperature controlled down-valley glacier extent. Thus, we argue that the maximum glacier extent was limited to the same specific elevation on both sides of the range due to a potential temperature influence on the glacier mass loss.

One question that arises from these observations is whether the characteristic flat morphology of the eastern valleys with their gentler slopes and less incised drainages is (1) a consequence of long-term glacial erosion with minimal fluvial transport of sediment out of the valleys, or (2) whether this morphology is simply a structural relict, in that the valley orientations mimic the trend of the underlying fold and thrust belt, enabling larger paleoglacier volumes on the eastern margin. The observed morphology is likely a reflection of a feedback between both factors. Without efficient removal of eroded material from the eastern drainages, the eastern valleys remain less incised with an average higher elevation of the valley floor with distance from the headwalls than the western drainages. Glaciers of the eastern valleys can penetrate much farther down-valley than the western margin glaciers simply because the “cut-off elevation” (correlated with a specific temperature) occurs at least 6 km farther down-valley on the eastern side of the range. As a result of inefficient removal of material by the fluvial system, relief has remained comparatively lower on the eastern margin while still maintaining a high average elevation. The extensive glacial erosion and redeposition of glacially derived material that occurred in the eastern valleys has resulted in the preservation or potentially, the creation of, a relatively low-relief surface with an elevation of ~4400–4600 m a.s.l. With at least three ~east-west oriented spurs that contain modern ice, the high relief western side of the range is quite different than the eastern side of the range which does not have any major spurs that support modern ice (Fig. 4). Rather, the ~east-west ridges are low-relief surfaces with denuded morphologies suggestive of scouring by paleoglaciers. The 4400–4600 m a.s.l. low-relief surface in this area is part of the Puna surface as mapped by McLaughlin (1924). We suggest that the preservation and potential rejuvenation of this surface is partly the result of glacial erosion coupled with sediment storage in the glaciated valleys. Further, active tectonism in the region may cause asymmetrical uplift across the range (and asymmetrical erosion). The position relative to the CBDF to the north and the presence of geothermal activity within the eastern valleys suggests recent activity along the north-south
trending thrust system in this range. In contrast to the eastern
valleys, glacial erosion coupled with efficient removal of material
by fluvial systems has resulted in the high relief of the western
drainages in response to regional surface uplift (Coney, 1971;
Garver et al., 2005).

5.3. Regional/global glaciation comparison

While the geochronologic records in the nearby Cordillera
Blanca (Farber et al., 2005) and Junin Plain (Smith et al.,
2005a) suggest extensive pre-LGM glaciations, the Cordillera Huayhuash
does not contain well-preserved datable glacial geomorphic
features that are older than ~38 ka. However, the Lateglacial-
Holocene record preserved in the Cordillera Huayhuash is comparable
to moraine sets dated in both the Junin region and the
Cordillera Blanca. In the Junin region, moraine sets with $^{10}$Be surface
exposure ages 11–14 and 15–20 ka are preserved near the upper
reaches and midpoints of valleys on the western side of the Eastern
Cordillera (Smith et al., 2005a, b; Smith et al., 2008) typically
1–2 km up-valley from LLGM moraine sets that have maximum ages
of ~32 ka. Larger moraines marking the maximum ice position in
the Junin valleys extend onto the Junin Plain and yield ages spanning
60–1400 ka, but predominantly falling in the range 130–430 ka
(zero-erosion ages). As the youngest sets of moraines are located
up-valley of the 60–1400 ka moraine sets, Smith et al. (2005a)
concluded that the LLGM of the last glacial cycle in the Junin region
(~28–32 ka) predated the commonly accepted last global ice
volume maximum (~21 ka, Imbrie et al., 1984). $^{10}$Be surface
exposure ages (zero-erosion ages) of well-preserved moraines in the
Cordillera Blanca range from ~19–29 ka on LLGM moraine sets
and ~16 ka on moraines up-valley for the LLGM sets. Older
moraines down-valley of the LLGM moraines are dated at ~440 ka
which suggests that older more extensive glaciations predated the
LLGM (Farber et al., 2005). In other nearby valleys, Lateglacial – early
Holocene moraines were dated at ~10–13 ka, similar to the group
II-III moraines dated here. Thus, both the Cordillera Blanca to the
north and the Junin Plain to the south of the Cordillera Huayhuash
contain records of a prominent glacial advance at ~28–32 ka, with
retreat initiating by ~21 ka followed by a brief hiatus during retreat
resulting in the deposition of the ~15–20 ka moraine sets. Possibly,
the ~20–22 ka group IV lateral moraines of the Cordillera Huayhuash
dataset correlate with a local ice advance just before or
during the regional ~21 ka retreat. While this glacial advance and
retreat is roughly synchronous with the last global maximum ice
volume (LGM), in both the Cordillera Blanca and the Junin region
older more extensive moraines suggest that the last maximum ice
volume for this locality is in fact much older (~50 ka; Farber et al.,
2005; Smith et al., 2005a, b). A Lateglacial readvance or stillstand
during 11–14 ka followed by deglaciation is observed in both the
Cordillera Blanca and the Junin Plain, similar to the group IIa and III
moraines dated in the Cordillera Huayhuash. Further to the south
in the Central Andes (16–17°S, 66.5–68.5°W), Zech et al. (2007)
present a $^{10}$Be chronology that also reveals the presence of Late-
glacial moraines (~11–13 ka) with a more extensive glaciation
dated at ~22–25 ka (calculated with the Lifton et al. (2005) scaling
scheme and a production rate of 5.87 atoms/g y). Zech et al., (2007)
thoroughly discuss and compare the prominent scaling methods with regard to comparison between datasets and the overall accuracy of the calculated ages. They conclude that the cosmogenic \(^{10}\)Be datasets for the Central/Northern Andes (Smith et al., 2005a, 2005b; Farber et al., 2005; and Zech et al., 2007) are all comparable provided that the same calculation methods are applied. For comparison, we have included Fig. 9, which shows ages based on the \(^{10}\)Be concentrations from this study calculated from multiple scaling schemes. We note that while the choice of scaling scheme will result in different ages (4–11% younger), it does not significantly change the interpretations presented here.

In addition to cosmogenic chronologies, regional proxy datasets are available for comparison (Fig. 10). While ice-core records from Sajama Bolivia (18°S) and Huascaran, Cordillera Blanca, Peru (9°S) extend back only to ~25 ka (Thompson et al., 1995; Thompson et al., 1998), this temporal coverage is well within the range of most of the data collected in this current study. The Vostok, Antarctica ice-core record provides a climate signal back to 50 ka (Fig. 10; Petit et al., 1999). The group II and III deglaciations in the Cordillera Huayhuash pre and post-date the Younger Dryas (YD) stade defined in the North Greenland Ice core Project (NGRIP; Andersen et al., 2004) as 12.9–11.6 ka; however the ~11.5–11 ka moraines recorded in some of the valleys in this study may be related to a YD re-advance. Indeed Thompson et al. (1995) interpret a cold period from the Sajama ice core that precedes the Younger Dryas stade, which they distinctively term the “Antarctic Cold Reversal” (ACR). As the combined colder intervals last from ~11.5–14.3 ka, visible in the Huascaran and Sajama cores, the advances and deglaciations associated with stage II–III (~9–14 ka) in the Cordillera Huayhuash dataset are consistent with the broader South American datasets. Specifically, while \(^{818}\)O values recorded in the Sajama core indicate a cooler and wetter time during the ACR (Thompson et al., 1995), smaller-scale oscillations recorded in the ice-core data during this period may correlate with the multiple moraine sets dated between ~9 and ~14 ka in the Cordillera Huayhuash. These smaller-scale oscillations may reflect an overall instability in the regional climate during a globally cooler period (cf. Fig. 10).

Based on the amount of clastic sediment in cores from lakes in previously glaciated valleys in the Andes (~7°–17°S), Rodbell et al. (2008) infer glacier advances at ~29–21 ka (~20 ka deglaciation), ~16 ka, (~12 ka deglaciation), and a mid–Holocene readvance (~5 ka). One of the lakes from the Rodbell et al. (2008) study, Laguna Huarmicocha, is located on the eastern side of the Cordillera Huayhuash, although not within the area covered in this present study. This lake core reflects Lateglacial deglaciation was underway before ~17.5 ka (the beginning of the core), with two main readvances from ~12.5–9.0 ka and from ~6.0–3.5 ka. Each of these periods of readvance show evidence of glacier fluctuations within the ~3 kyr time period. While the Huarmicocha Lake record is very similar to the chronology presented in this study, Rodbell et al. (2008) note that the Huarmicocha record is slightly different from other regional lake sediment core records in that there is a more pronounced readvance during ~10–12 ka that is absent from the other locations. Our dataset contains as well, a strong signal at ~10–12 ka (group II and IIa moraines; Fig. 10). A recent paleolimnological study of Lake Pacucha, Peru (13.5°S; Hillyer et al., 2009) reveals high lake levels and moist conditions during the LGM with the onset of deglaciation at ~23 ka. Lake levels began to fall at ~16 ka with a low-stand at ~10 ka due to dry conditions associated with insolation minima. After ~9.7 ka, wetter conditions returned, however lake levels were highly volatile, potentially related to a weakened ENSO forcing, until ~5 ka when lakes were again high and ENSO activity was enhanced (Hillyer et al., 2009). Thus, both the Rodbell et al. (2008) and Hillyer et al. (2009) studies present evidence for the minor mid–Holocene readvance that is well documented in the Andes, and for which we see some evidence for in our \(^{14}\)C chronology (~3.5 ka and ~5.6 ka ages). They suggest that when ENSO forcing is weak, insolation changes may have driven the volatile climate and intermittent droughts during ~9–5 ka. By comparing multiple cosmogenic chronologies of glacial features and multiple proxy datasets from regional lake cores and ice cores, we see a consistent regional picture of glacialiation from ~29–20 with deglaciation beginning at ~20, periods Lateglacial readvances during ~16–10 ka, deglaciation and dry conditions ~10 ka with a fluctuating climate until a readvance at ~5 ka and additional minor readvances in the latest Holocene. However, local variations such as the group II moraines (~9–10 ka) of this study, do exist within this rather consistent picture. The group II moraines moraines correlate with a period of a higher clastic sediment flux in a local lake (Rodbell et al., 2008) and the well-documented regional dry period during this time interval. Thus, it is plausible that this readvance may be related to a localized increased precipitation in the Cordillera Huayhuash region possibly due to temporal and spatial changes in the SACZ.

6. Conclusion

The Cordillera Huayhuash of the Central Peruvian Andes preserves a glacial record spanning ~0.3–38 ka. \(^{10}\)Be surface exposure dating of moraines and \(^{14}\)C dating of basal organic matter from bog and lake sediment cores suggest maximum ice advances (or onset of retreat) at ~0.3 ka, ~9–10 ka, ~13–14 ka, ~20–22 ka, and >26 ka. Maximum down-valley glacier extents, on both the eastern and western sides of the range, reach ~3800 m a.s.l., which suggests that temperature variations may have been a dominant control on glacier extent. Valley morphology plays an important role locally, as well as regionally, in glacial landform preservation, down-valley distance to maximum glacier extent, and landscape evolution as result of the extent and efficiency of glacial erosion. Finally, our new moraine chronology, other regional datasets, and climate proxy records from nearby ice cores, all suggest that in the Peruvian Andes, the Lateglacial period was cool and relatively unstable prior to the onset of full Holocene deglaciation.

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Appendix. Supplementary information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.quascirev.2009.08.004.

References
