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Rates of Deglaciation during the Last Glaciation and Holocene in the Cordillera Vilcanota-Quelccaya Ice Cap Region, Southeastern Perú

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Moraine chronology is combined with digital topography to model deglacial rates of paleoglacier volumes in both the Huancané Valley on the west side of the Quelccaya Ice Cap and the Upismayo Valley on the northwest side of the Cordillera Vilcanota. The fastest rates of deglaciation (39×10^{-5} to 114×10^{-5} km^3 yr^{-1} and 112×10^{-5} to 247×10^{-5} km^3 yr^{-1} for each valley, respectively) were calculated for the most recent paleoglaciers, corresponding to the last few centuries. These results are consistent with observations in the Venezuelan Andes showing high rates of deglaciation since the Little Ice Age. These rates also fall within the range of 20th century rates of deglaciation measured on the Quelccaya Ice Cap (29×10^{-5} to 220×10^{-5} km^3 yr^{-1}, Brecher and Thompson, 1993; Thompson, 2000). These results imply that rates of deglaciation may fluctuate significantly over time and that high rates of deglaciation may not be exclusive to the late 20th century. Equilibrium line altitude (ELA) depressions for the ice volumes of the last glaciation modeled here were computed as 230 m for the Quelccaya Ice Cap and 170 m for the Cordillera Vilcanota. Maximum ELA depressions are lower than previously published: <500 m for the Cordillera Vilcanota and <400 m for the Quelccaya Ice Cap. These lower values could imply a topographic control over paleoglacier extent.

Key Words: **deglaciation; glacial geomorphology; digital elevation model; ELA depression; tropical glaciers; Andes; last glaciation; Holocene; Little Ice Age.**

INTRODUCTION

The Cordillera Vilcanota–Quelccaya Ice Cap region of the tropical highlands in southeastern Perú is an excellent location to compare different episodes of deglaciation. Glaciers in the region have been observed over three decades and are currently melting at increasing rates. Abundant moraines provide evidence that episodes of deglaciation occurred over much larger spatial scales in the late Pleistocene and Holocene. Various expeditions have provided detailed maps of moraine positions and a chronology of glaciation based on radiometric dates from buried peat and lake cores, pedogenesis, and cosmogenic-isotope dates of erratics (Mercer and Palacios, 1977; Mercer, 1983; Goodman *et al*., 2001). The moraines demarcate paleoglacier extents, which allow volumes to be modeled using digital topography of the glacier valleys. The objective of this article is therefore to combine modeled paleoglacier volumes with moraine chronology to compute rates of deglaciation for discrete episodes of late-glacial and Holocene deglaciation in this region of the central Perúvian Andes. These rates can be compared with the modern observations to test the hypothesis that recent, enhanced rates of deglaciation are anomalously high.

A careful study of Qori Kalis Glacier, which flows from the Quelccaya Ice Cap, clearly demonstrates that glaciers in the region have experienced rapid deglaciation in the late 20th century. Brecher and Thompson (1993) demonstrated the combined use of terrestrial photogrammetry to reconstruct the extent and volume loss of Qori Kalis Glacier from a base position mapped from aerial photographs taken in 1963. The rate of volume loss was calculated over three distinct periods: 29×10^{-5} km^3 yr^{-1} (1963–1978); 131×10^{-5} km^3 yr^{-1} (1978–1983); and 220×10^{-5} km^3 yr^{-1} (1983–1991). Subsequent extension of the observations through 1998 shows a full sevenfold increase in the rate of volume loss from the 1963–1978 period to the 1993–1995 period (Thompson, 2000), with terminal recession rates accelerating to show an exponential curve by 1998 (Thompson *et al*., 2000). Recently updated observations through the year 2000

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reveal current rates of terminal recession up to 33 times that of the 1963–1978 period (L. G. Thompson, 2001; personal communication). These results illustrate a drastic and accelerating retreat of the glacier terminus that is attributed to a global rise in temperature and are complemented by observations in other regions in the tropical Andes throughout the 20th century (e.g., Petersen *et al*., 1969; Kaser and Georges, 1997; Ames, 1998). However, it remains unclear whether these dramatic rates of deglaciation are unprecedented in the history of glaciation for the region.

In the larger context, the timing and magnitude of deglaciation in the central Andes have important implications for understanding the regional hydrology and history of Andean lake levels. Previous work has indicated that glacial meltwater could provide a significant buffer to the runoff during the annual tropical dry season, and even during dry years (Ribstein *et al*., 1995). Accelerated modern rates of deglaciation may therefore be contributing to an enhanced component of stream flow. Similarly, episodes of deglaciation at the end of the Pleistocene could have provided an important buffer to the larger lakes that existed on the Altiplano (e.g., Wirrmann and Mourguiart, 1995; Baker *et al*., 2001). Modeling studies of late Pleistocene lake expansion (Hastenrath and Kutzbach, 1985) have lacked sufficient information on the water budget to account for this deglaciation contribution. Moreover, independent chronological constraints on the sequence of glaciations and volume of meltwater produced during deglaciation are needed to interpret sequences of sedimentation and hence climate history preserved in Altiplano lakes (e.g., Seltzer *et al*., 2000).

SETTING

The Cordillera Vilcanota is located in the eastern range of the Andes of southeastern Perú (Fig. 1). The mountain range

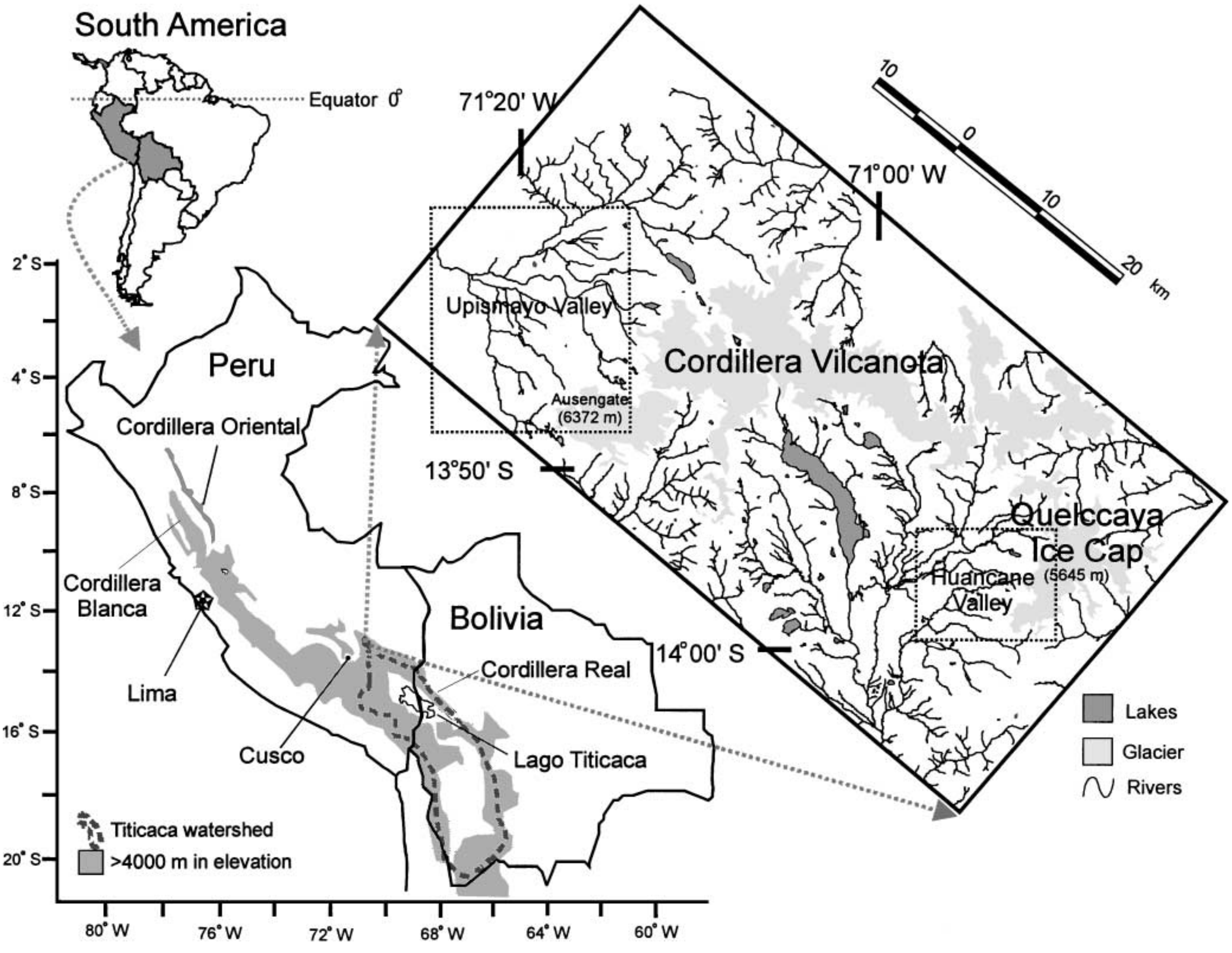

FIG. 1. Map showing location of the Cordillera Vilcanota–Quelccaya Ice Cap region in the central Andes of southeastern Perú. The Lake Titicaca watershed is outlined, and other nearby mountain ranges mentioned in the text are indicated. The two boxes in the enlargement represent the areas of Fig. 2, covering the principal sites where moraine series were used to calculate deglacial rates: (1) the Upismayo Valley on the northwestern side of the Cordillera Vilcanota, and (2) the Huancané Valley on the western side of the Quelccaya Ice Cap.

extends east–west for 50 km near 13°45′S latitude, with the easternmost peaks lying on the western divide of the Amazon Basin. Summits reach over 6000 m altitude, and the highest peak, Nevado Ausangate, attains 6384 m. Most glaciers are short, steep alpine glaciers that terminate above 4600 m. The northwestern side of the range features a broad piedmont of till and outwash extending above 3600 m to the glaciated peaks. Glacially formed valleys within this plain contain accreted sets of lateral and terminal moraines.

Located just south of the eastern end of the Cordillera Vilcanota, the Quelccaya Ice Cap spans 70 km^2 atop an ignimbrite plateau and is the world's largest tropical ice cap (Thompson *et al.*, 1985). The summit of the highest of four domes on the ice cap reaches 5645 m, and short, steep outlet glaciers descend the escarpment of the plateau to elevations as low as 4950 m (Mercer and Palacios, 1977). To the west of Quelccaya is a broad till and outwash plain with an abundance of peat bogs, lakes, and moraines. The southern slopes of the Cordillera Vilcanota and the western and southern sides of the Quelccaya Ice Cap drain to the Lake Titicaca basin.

The climatic regime of the region features distinctly seasonal precipitation. Austral summer (November–March) is the accumulation season. Glacier firn limits reach maximum elevations at the end of the clear and dry winter season (May–September). Based on observations from the 1960s (Dornbusch, 1998), most areas above 4000 m in southeastern Perú have >600 mm yr^{-1} precipitation, with many areas exceeding 800 mm yr^{-1}. The Cordillera Vilcanota–Quelccaya Ice Cap region receives 800–1000 mm yr^{-1}. There is also a distinct gradient in precipitation, increasing to the east and north across the region, reflecting the Amazon Basin as the principal source of moisture.

Similar east–west gradients exist for the regional distribution of temperature and snowline elevation. In the Cusco area to the west, the mean elevation of the 0°C isotherm is 5077 m. Atop the Quelccaya Ice Cap, the mean annual temperature is inferred to be ca. −4.8°C (Thompson, 1979), corresponding to a zero degree isotherm at 5085 m. Thompson estimated the modern snowline to be at 5250 m for the Quelccaya Ice Cap. Mercer and Palacios (1977) estimated that the snowline on the northwestern side of the Cordillera Vilcanota is 5100 m and 5300 m on the Quelccaya Ice Cap. Modern equilibrium line altitude (ELA) distribution was mapped using the glacier inventory (Hidrandina, 1988) and an accumulation area ratio (AAR) of 0.5, showing similar ELA values of 5105 m in the northern Cordillera Vilcanota and 5275 m to the south and over the Quelccaya Ice Cap (Dornbusch, 1998).

Two valleys in particular provide the opportunity to date multiple series of moraines: the Upismayo Valley on the northwestern side of the Cordillera Vilcanota and the Huancané Valley on the western side of the Quelccaya Ice Cap. These valleys were visited by Mercer and colleagues, who provided the first radiometric dates for some of the moraines (Mercer and Palacios, 1977; Mercer, 1983). The Upismayo Valley was noted as containing the only maximum age of the last glaciation in Perú. The Huancané Valley provides evidence of a glacier advance at the onset of the Younger Dryas interval (Rodbell and Seltzer, 2000). The chronology of these and other moraine positions provides the basis for computer terrain modeling and calculations of glacier volumes and deglacial rates.

METHODS

The calculation of volumetric deglacial rates from moraine positions requires that two variables be constrained for each episode of deglaciation: (1) the time interval of deglaciation, defined by the moraine chronology; and (2) the ice volume involved, computed with terrain modeling. Well-preserved terminal moraine positions also allow calculation of ELA depression to evaluate the magnitude of climatic change during each deglacial interval.

Moraine Chronology

During June and July 1997, extensive field reconnaissance was carried out in the Cordillera Vilcanota–Quelccaya Ice Cap region to map and date moraines (Fig. 2). Five lakes and three bogs were cored using a square-rod piston corer (Wright, 1991), samples for cosmogenic isotopic analysis were taken from erratics on moraine crests, and soils were described and sampled (Goodman *et al.*, 2001). Organic material recovered in the field from lake cores, bogs, and buried peat was dated by accelerator mass spectrometry. Dates are presented as calibrated years before present (cal yr B.P.), based on CALIB version 4.0 (Stuvier and Reimer, 1993; Stuvier *et al.*, 1998) (Table 1). Such dates serve as minimum limiting ages for glacial features downvalley and maximum limiting ages for features upvalley.

Ice Volume Reconstruction

Construction of a digital elevation model (DEM) using computer-based geographic information system (GIS) technology facilitated the compilation of mapping and computation of ice volume. The DEM was produced from digitized topographic maps (1:100,000 and 1:25,000 scale) using ArcInfo™ GIS software. Moraine locations were mapped onto the DEM using a combination of Landsat TM satellite imagery, aerial photography, and field-mapped coordinates. Moraines were initially located from the photos and satellite imagery and subsequently mapped in the field with global positioning system technology. Differential correction by postprocessing the data from two handheld Trimble™ GeoExplorer II GPS units yielded an operational accuracy of ±1 m (Trimble, 1995).

The moraine map draped over the DEM served as a base map to reconstruct models of paleoglaciers and calculate volumes of ice. Polygons delimited by the moraines, headwall, and the valley morphology were drawn within the GIS to represent the outlines of paleoglacier surfaces. Contours were drawn across the paleoglacier surfaces following the convention of being convex in a downvalley direction in the ablation area, straight near the ELA, and concave in a downvalley direction in the accumulation

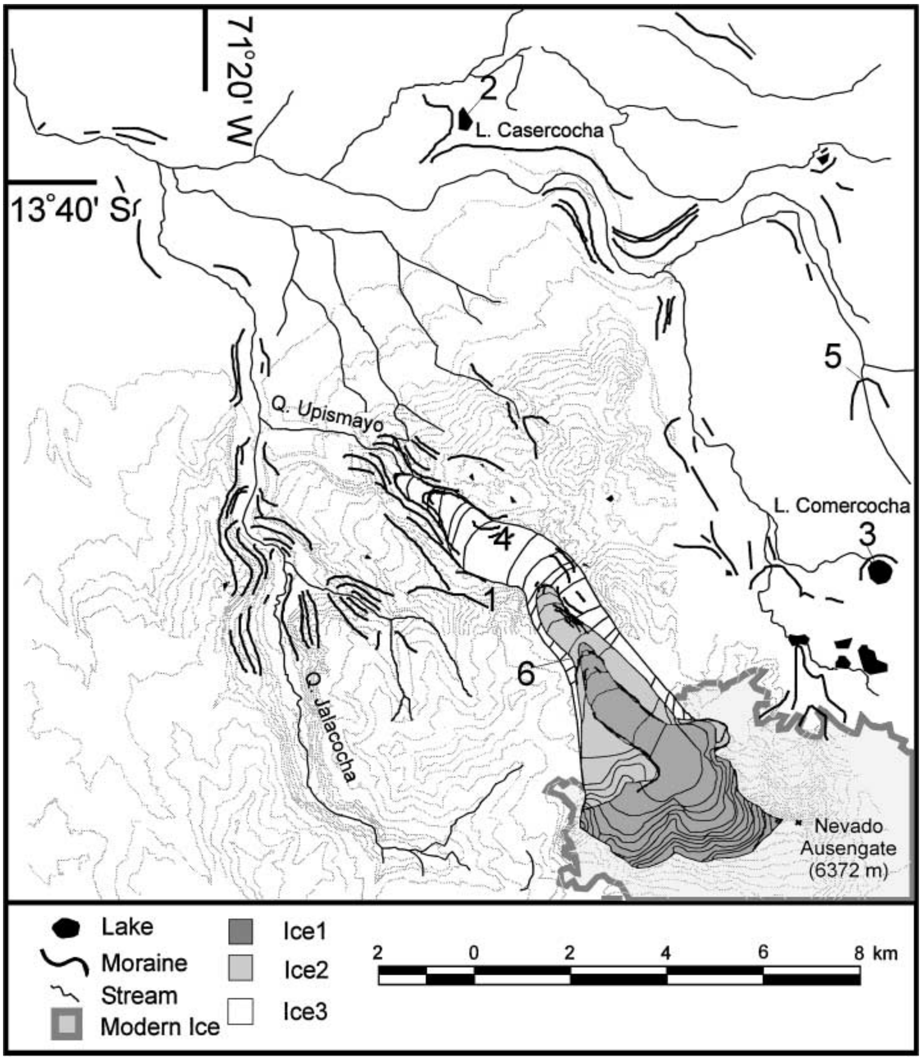

FIG. 2. Map of the study area in two parts: (a) the Upismayo Valley, Cordillera Vilcanota, and (b) the Huancané Valley, Quelccaya Ice Cap. Moraines and the numbered sample sites for radiometric dates (coinciding with Table 1) are shown. Also presented are the modeled paleoglaciers, overlaid on the topography of the digital elevation model (shown by contour lines).

area (e.g., Seltzer, 1992). The contour lines intersecting the edges of the paleoglacier polygons form a number of discrete polygons with constant elevation. A gridded surface was extrapolated from these polygons with the same grid cell resolution as the base map DEM. Volume was then computed by overlaying these grids on the base map DEM of the modern valley topography, multiplying the difference of elevation in each grid cell by the cell area, and summing up all grid cell volumes in the paleoglacier area.

An empirical formula relating surface area to volume of alpine glaciers worldwide, such that $V = 28.5\, S^{1.36}$, where V is volume and S is the glacier surface area, was used to find the volume of the modern glaciers (after Chen and Ohmura, 1990). Modern glacier surface area was defined from the satellite imagery obtained in 1987. For the Huancané Valley glaciers, topography expressed in the DEM was used to discern the outline of the glacier from the main body of the ice cap. Subsequent volume change calculations incorporate this same glacier outline.

ELA Depression

The toe-headwall-altitude ratio (THAR) method was used to estimate the ELA of the different paleoglaciers (Meierding, 1982; Klein *et al.*, 1999). The positive difference between the ELA of the modern glacier and paleoglacier, or the ELA depression, was computed for each moraine position. The THAR assumes that the ELA occurs as a ratio of the difference in elevation between the headwall and terminus (or toe) of the glacier, variables derived for past glaciers by the modern headwall elevation and terminal moraine elevation, respectively. Accurate determination of the glacier height on the headwall can be problematic but is not of concern when dealing with the ELA depression,

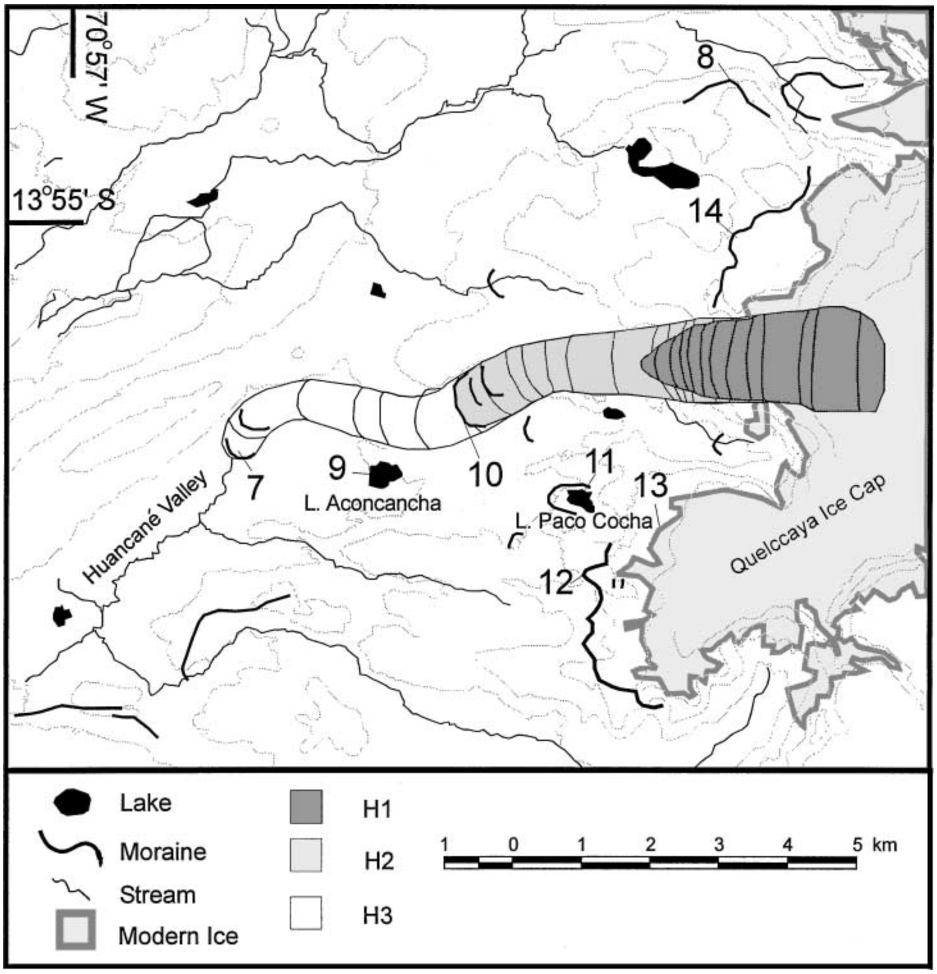

FIG. 2—*Continued*

assuming that glaciers reached similar elevations on the headwall in the past (Seltzer, 1992). Lack of mass balance measurements from the region precluded a calculation of the actual ELA to check the THAR ratio. For this investigation, a THAR of 0.45 was used, which was found by Klein *et al*. (1999) to work best for this region.

RESULTS

Glacial Chronology

In the following section, we evaluate the radiometric dates associated with preserved moraines to define three successively smaller and younger paleoglaciers for each valley. Each moraine represents a position to which the paleoglacier extended in the past and then subsequently melted. We label the paleoglaciers in chronological order from oldest to youngest as follows: Ice3, Ice2, and Ice1 for the Upismayo Valley (Fig. 2a); H3, H2, and H1 for the Huancané Valley (Fig. 2b). The successive ages of the moraines are used to calculate intervals of deglaciation for each paleoglacier position. The intervals of deglaciation range between maximum and minimum values, considering the stratigraphic context of the radiometric dates used for each moraine. These intervals are explained below and summarized in Table 2.

Upismayo Valley. A group of well-defined and closely spaced moraines terminating between 4000 and 4350 m marks the last local glacial maximum in the Upismayo Valley and defines the extent of Ice3. These moraines terminate about 8 km downvalley from the modern ice front, only half the distance to the outer limit of glaciation at about 3600 m. The outermost lateral moraine in this group has covered a peat section at 4500 m, which was subsequently exposed in a stream cut. The lowermost peat in the section is dated to 41,520 ± 4430 ^{14}C yr B.P., providing a minimum age for the maximum glacier extent much further downvalley. The upper section of peat is dated at 16,650 ± 400 cal yr B.P., which is a maximum age for the nested moraines and hence Ice3. As identified by Mercer and Palacios (1977), this date is the maximum age determination for the last local glacial maximum in this area. Soil chronofunctions from the moraines support the hypothesis posed by Mercer (1983) that the maximum glacier advance in the Cordillera Vilcanota, which reached 8 km further downvalley than Ice3, occurred

TABLE 1
Table of All Radiocarbon Ages and Calibrated Calendar Ages for the Region

Paleoglacier	Sample site	Accession no.	Elevation (m)	^{14}C date (^{14}C yr B.P.)	± (^{14}C yr B.P.)	Calibrated age* (cal yr B.P.)	Sample context and origin	Reference
Upismayo Valley								
Maximum	1	GX-23726	4450	41,520	4430		min, bottom of peat inside oldest moraine	This study
Maximum	2	AA-27027	4010	15,640	100	18797 (18540) 18288	min, basal lacustrine organics, L. Casercocha	This study
Pre-Ice3	3	AA-27024	4580	14,500	220	17884 (17370) 16836	min, basal lacustrine organics, L. Comercocha	This study
Ice 3	1	GX-23725	4450	13880	150	17044 (16650) 16225	max, top of buried, distorted peat	This study
Ice 3	4	AA-27041	4380	10362	73	12479 (12250) 11894	min, basal organics from bog	This study
Ice 2	5	NSRL-10485	4400	4450	45	5275 (5045) 4971	max, peat beneath rocky terminal moraine	This study
Ice 2	6	DIC-678	4420	2830	70	3148 (2910) 2771	min, lowest peat under Ice 1 terminal moraine	Mercer and Palacios, 1977
Ice 1	6	AA-27050	4450	328	46	499 (394) 289	max, arched peat under moraine	This study
Huancané Valley								
H3	7	I-8443	4745	12240	170	14855 (14290) 13189	min, bottom of peat behind H3 terminal moraine	Mercer and Palacios, 1977
H3-H2	8	DIC-687	5100	12230	180	14865 (14280) 13787	min, bottom of peat beneath H2 moraine	Mercer and Palacios, 1977
H3	9	AA-27037	4780	11183	109	13350 (13090) 12860	min, basal lacustrine organics, L. Aconcancha	This study
H2	10	I-8209	4820	10910	160	13155 (12830) 12495	max, upper peat beneath H2 terminal moraine	Mercer and Palacios, 1977
H2	11	AA-27032	4940	10870	72	12962 (12800) 12616	min, basal lacustrine organics, L. Paco Cocha	This study
H2	12	DIC-685	5070	9980	255	12426 (11190) 10470	max, undistorted peat under H1 terminal moraine	Mercer, 1984
Ice margin	13	DIC-680	5180	2670	95	2954 (2760) 2489	min, peat plowed under modern ice front	Mercer and Palacios, 1977
H1	14	I-9624	5100	270	80	502 (300) 0	max, upper peat beneath H1 terminal moraine	Mercer and Palacios, 1977

* Calendar age in parentheses bracketed by one-sigma ranges as determined with the CALIB 4.0 program (Stuvier *et al*., 1998). For an explanation of paleoglacier terms used here, see Glacial Chronology in test.

much earlier in the last glacial cycle (Goodman *et al*., 2001). While the moraines are well nested, they display cross-cutting relationships that suggest possible deposition in separate readvances over a longer period of time.

A second series of terminal moraines is located 3.7 km from the modern ice limit and 4.3 km upvalley from the Ice3 terminus. It provides the basis for the reconstruction of paleoglacier Ice2 volume and the deglacial time interval for Ice3. Deglaciation from the Ice3 position was underway by at least 12,250 ± 250 cal yr B.P., as determined from peat accumulating over glacial silts in a bog 0.8 km upvalley from the Ice3 terminus. The extent of deglaciation is not known, but the Ice2 moraines provide the next geomorphically resolvable evidence of glacier standstill after deglaciation from Ice3. Ice2 moraines are distinctly rock covered, and although no maximum age has been obtained in the Upismayo Valley, a similar set of moraines in the nearby Paccanta Valley overlie peat dated 5045 cal yr B.P. This date is used as a maximum limiting age for Ice2 and is considered as evidence for a mid-Holocene readvance in the Cordillera Vilcanota. The deglacial interval for Ice3 therefore ranges between a maximum of 11,605 yr, the difference between 16,650 and 5045, and a minimum of 4400 yr, the difference between 16,650 and 12,250.

The third and final paleoglacier position, Ice1, is delimited by a single grass-covered terminal moraine 1.8 km from the modern ice limit. A stream cut through the moraine reveals 1.5 m of peat that has been arched and distorted under the moraine. The stratification remains intact, and peat from the upper surface yields a maximum age of 394 cal yr B.P. for the advance of Ice1. Peat from deeper within the same section dates to 2910 cal yr B.P., meaning that the Ice2 paleoglacier had deglaciated from the area by at least 2910 cal yr B.P. Thus, the deglacial interval for Ice2 has a maximum value of 4651 yr, the difference between 5045 and 394, and a minimum of 2135 yr, the difference between 5045 and 2910. About 600 m upvalley from this Ice1 position and downvalley from the modern ice front are a number of smaller, sparsely vegetated terminal moraines that are <394 cal yr old but lack further limiting dates and could

TABLE 2
Summary Table of Deglacial Variables Calculated for Each Paleoglacier

Glacier	Volume (km^3)	Deglacial interval (yr)						Deglacial volume (km^3)		Deglacial rate (10^{-5} km^3/yr)					
		(small)			*(large)*			*(small)*	*(large)*	*(small)*			*(large)*		
Upismayo Valley															
Ice3	1.17	4794	4400	3975	11999	11605	11180	0.43	1.31	3.58	3.71	3.85	27.33	29.77	32.96
Ice2	0.74	2365	2135	2061	4881	4651	4577	0.19	0.88	3.89	4.09	4.15	37.21	41.22	42.70
Ice1	0.55	489	384	279				0.55	0.69	112.47	143.23	197.13	141.10	179.69	247.31
Modern	0.14														
Huancané Valley															
H3	0.43	2035	1460	957				0.09	0.57	4.42	6.16	9.40	28.01	39.04	59.56
H2	0.34	1965	1640	1305	10395	10070	9735	0.34	0.48	3.27	3.38	3.49	24.43	29.27	36.78
H1	0.19	492	290					0.19	0.33	38.62	65.52	—	67.07	113.79	—
Modern	0.14														

Note. Preserved moraines define the extent of three different paleoglaciers in each valley, labeled in descending order from oldest to youngest as follows: Ice3, Ice2, and Ice1 for the Upismayo Valley; H3, H2, and H1 for the Huancané Valley. Volume (km^3) of each reconstructed paleoglacier is calculated using gridded-model surfaces and the digital elevation model. Modern glacier volume was estimated from surface area by the formula $V = 28.5\ S^{1.36}$ (after Chen and Ohmura, 1990). Deglacial interval (yr) represents the conceivable time range over which the paleoglacier deglaciated from successively less extensive end moraine positions. The interval is presented as a mean surrounded by the one-sigma range in calibrated radiocarbon ages. Where available radiocarbon dates include more than one constraining age for a moraine, the maximum and minimum possible intervals are provided as large and small intervals, respectively. Deglacial Volume (km^3) represents the volume lost from the paleoglacier in two possible deglacial scenarios: a large volume from complete deglaciation and a small volume considering only the volume lost between successive moraine positions. Deglacial Rate (10^{-5} km^3 yr^{-1}) is calculated by dividing the deglacial volume by the deglacial interval, such that the small rate equals small volume divided by large interval, and large rate equals large volume divided by small interval.

represent still-stands in the recession from Ice1. The deglacial interval from the Ice1 position to the modern ice front is 384 yr, considering that the modern ice was mapped from satellite imagery 10 yr older than the radiocarbon dating.

A lake core record provides further insight into the chronology of deglaciation on the northwestern side of the Cordillera Vilcanota. Lake Casercocha is located at 4010 m, 15 km away from the modern glacial limit, in a tributary valley northeast of the Upismayo Valley. The lake is situated on a raised terrace between two river valleys, but lake formation is not clear as there is not a bounding terminal moraine. A number of large, cross-cutting moraines visible in satellite imagery and aerial photography above Casercocha indicate multiple phases of glaciation on the northwest side of the Cordillera Vilcanota that would have contributed meltwater sediments to the lake. Organic material recovered in the core directly above glacial silts dates to 18,540 cal yr B.P., demonstrating a transition from glacial to nonglacial sedimentation beginning just after 20,000 cal yr B.P.

Huancané Valley. A broad plain covered with till and outwash above 4500 m to the south of the Cordillera Vilcanota and west of the Quelccaya Ice Cap was presumably covered by a large ice mass during the maximum glacial episodes in this region (Mercer and Palacios, 1977). The maximum ice extent is 4500 m altitude, the transition between the broad till plateau and steep, V-shaped valleys. Two cosmogenic ^{26}Al and ^{10}Be ages from quartz-rich erratics on the oldest of moraines at this glacial limit average to about 20,000 cal yr B.P. (Goodman *et al*., 2001). Three terminal moraine belts were first recognized by Mercer as having formed subsequent to the separation of the Quelccaya Ice Cap from the Cordillera Vilcanota. They were named the Huancané III, II, and I moraines, lying about 8, 4, and 1 km, respectively, beyond the modern ice margin in various valleys flowing from the Quelccaya Ice Cap. These moraine positions were revisited in this study, and the ages consolidated to model the paleoglacier positions of H3, H2, and H1, respectively, within the single Huancané Valley (Fig. 2b).

Peat buried in sandy outwash at 4745 m altitude upvalley from the Huancané III terminus provides a minimum age of 14,290 cal yr B.P. for H3. Mercer interpreted the sandy outwash as originating during the later H2 advance. Lake Aconcancha (4780 m) lies in a tributary valley of the Huancané that shares the H3 terminus. Basal organic matter from the lake dates to 13,090 cal yr B.P., also providing a minimum age for deglaciation from this H3 position. Moreover, a peat bog at 5100 m accumulating within 3 km of the modern ice front in a valley to the north is overlain by till from a later advance. The bog has a basal age of 14,280 cal yr B.P. that is contemporaneous with the minimum age of H3 at 4575 m, suggesting that deglaciation from the H3 position was extensive. However, because the H3 moraine is only dated by a minimum age, these dates are not used to compute a deglacial interval for H3.

Disturbed peat found under till associated with a Huancané II moraine provides a maximum limiting age for the H2 glacier advance of 12,830 cal yr B.P. The difference between this date and the minimum age of H3 cited above provides a minimum estimate for the deglacial interval of H3 as 1460 yr. Basal lacustrine organic matter above glacial silt in Lake Paco Cocha, located at 4920 m about 1 km west of the present ice margin and impounded by a moraine upvalley from Lake Aconcancha, dated to 12,800 cal yr B.P. This suggests that the bounding moraine is contemporaneous with the H2 advance and that at no time since ~12,800 cal yr B.P. has the Quelccaya Ice Cap margin been more than 1 km beyond that of today (Rodbell and Seltzer, 2000).

Huancané I moraines are unvegetated and, although present in all valleys surrounding the Quelccaya Ice Cap, are not dated directly in the main Huancané Valley. Peat entrained in a Huancané I moraine from a neighboring Valley provides a maximum limiting age of 300 (+202/−300) cal yr B.P. for the H1 paleoglacier, noted by Mercer to be in the range of the Little Ice Age. Thus, the deglacial interval for H1 is 290 yr, the difference between the maximum H1 date and the satellite imagery demarcating the modern glacier.

Peat buried beneath a Huancané I moraine dates to 11,190 cal yr B.P., a minimum age for the H2 paleoglacier, which indicates that deglaciation of H2 was rapid and extensive. By 11,190 cal yr B.P. the glacier was reduced greatly in size and within its Little Ice Age extent. This results in a 1640 yr deglacial interval for H2. Moreover, the date of 12,800 cal yr B.P. from Paco Cocha provides an older minimum age for Huancané 2 moraines (Rodbell and Seltzer, 2000) and suggests that deglaciation of H2 could have occurred even faster. Other peat exposed at the modern ice margin dates to 2760 cal yr B.P., implying that the Quelccaya Ice Cap at that time was smaller than present and may have disappeared completely during the middle Holocene. Two ice cores drilled 154.8 and 163.6 m to bedrock through the ice cap contain records that are only 1350 and 1500 years old (Thompson *et al.*, 1985).

Volumetric Rates of Deglaciation

The volumetric rates of deglaciation are estimated within a range delimited by both the accuracy of the deglacial interval and the possible glacier volumes involved. To synthesize this range of uncertainty most coherently, we present two rate estimates bounding the widest range for each paleoglacier (Table 2). The "small" estimate is defined as the volume difference between successive moraine positions divided by the maximum difference in ages of the moraines, or maximum deglacial interval. This is a minimum volumetric loss because the moraines are treated as recessional ice positions, and additional mass wastage before potential glacier readvance is not considered. The "large" estimate is computed using a conceptual maximum volume difference between moraine positions divided by the minimum deglacial interval. This maximum volumetric loss is the entire modeled paleoglacier volume for the moraine position added to the modern glacier volume, thus assuming complete deglaciation over the deglacial interval. A range of error is associated with each estimate, based on the one sigma range from the calibrated radiocarbon ages used in the moraine chronology.

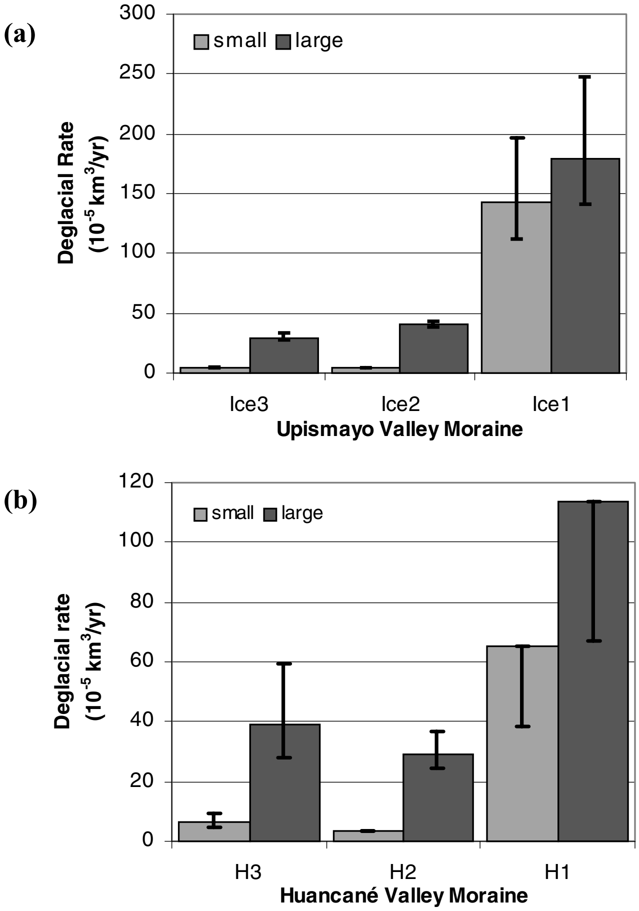

FIG. 3. Comparative rates of deglaciation for moraine positions in (a) Upismayo Valley, Cordillera Vilcanota, with moraines labeled from youngest to oldest as Ice1, Ice2, and Ice3; (b) Huancané Valley, Quelccaya Ice Cap, with moraines labeled from youngest to oldest as H1, H2, and H3. For each moraine position, a "large" and "small" rate are presented to indicate the maximum range of uncertainty. The large rate represents a conceptual maximum volume change over a minimum time interval of deglaciation, or difference in sequential moraine ages. The small rate is conversely the minimum change in volume over the largest time interval. Error bars on each estimate represent the error range associated with a one sigma range in calibrated radiocarbon ages used in the moraine chronology. All rates are presented as 10^{-5} km^3 yr^{-1}.

The greatest volumetric rates of deglaciation are computed for the most recent paleoglaciers Ice1 and H1 (Table 2, Fig. 3). In the Upismayo Valley, the deglaciation from Ice1 ranges from a small rate of 143×10^{-5} km^3 yr^{-1} to a large rate of 180×10^{-5} km^3 yr^{-1}. Given the range of uncertainty in the radiocarbon dates involved, these estimates effectively range from 112 to 247×10^{-5} km^3 yr^{-1}. Deglaciation from H1 in the Huancané Valley ranges from a small rate of 66×10^{-5} km^3 yr^{-1}to a large rate of 114×10^{-5} km^3 yr^{-1}. The one sigma error range in the calibrated date extends the minimum rate estimate to 39×10^{-5} km^3 yr^{-1}. However, the calibrated range in radiocarbon dating has an upper one sigma range date for the H1 moraine of 0 yr B.P., so that the maximum error range approaches infinity and is not reported.

The older paleoglaciers in both the Upismayo and Hancané Valleys clearly had greater volumes, yet the moraines are not well dated. All of the estimates for these older positions fall

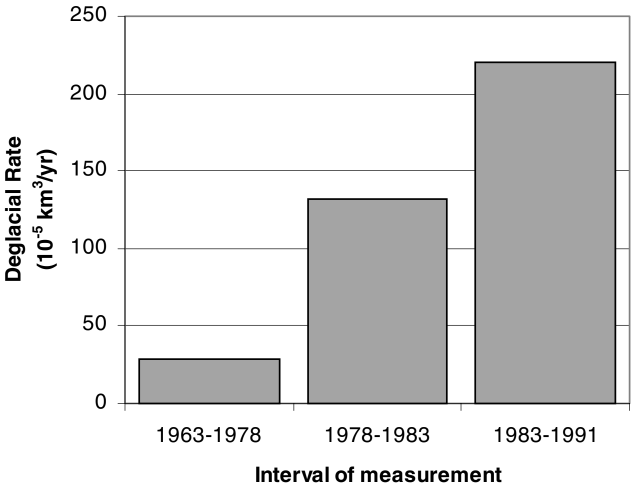

FIG. 4. Rates of deglaciation for Qori Kalis Glacier, largest outlet glacier from the Quelccaya Ice Cap (from Brecher and Thompson, 1993). The calculations were made from terrestrial and aerial photogrammetry for three time intervals: 1963–1978, 1978–1983, and 1983–1993. A clear acceleration in rate over time toward the present is apparent. The rates are presented as 10^{-5} km^3 yr^{-1}, to enable comparison with rates calculated for other moraine positions in the area. The rate for the H1 moraine position falls within the range of values observed for the Qori Kalis over the late 20th century.

below those for the more recent Ice1 and H1 positions, with the exception of the H3 large estimate. This rate of 39×10^{-5} km^3 yr^{-1} lacks a maximum age for the Huancané III moraines and has a relatively large range of uncertainty that extends the rate to as low as 28×10^{-5} km^3 yr^{-1}, well below the small estimate for H1.

Finally, the rates of deglaciation are compared with measured late-20th-century rates of deglaciation from the Qori Kalis outlet glacier of the Quelccaya Ice Cap (Fig. 4). The rates of volume loss observed at different times over the past few decades at the Qori Kalis show an accelerating trend, from a low of 29×10^{-5} km^3 yr^{-1} during the period 1963–1978 to a high of 220×10^{-5} km^3 yr^{-1} from the period 1983–1991 (Brecher and Thompson, 1993). The estimated volumetric rates of deglaciation for H1 cited above fall within this range, showing a small rate that is more than double the lowest, and a large rate about half the highest, of the measured Qori Kalis rates. More recent data from Qori Kalis implies that rates of glacier terminus retreat have accelerated exponentially, with 1998 rates an order of magnitude greater than rates between 1963–1978 (Thompson *et al.*, 2000). Volume loss was reported as accelerating even more rapidly, but lack of published values prevent including these rates in Fig. 4.

ELA Depression

Each moraine group and corresponding modeled paleoglacier position is associated with an ELA depression relative to present. Based only on the dates presented here, the late-glacial ELA depression in the region was 230 m for the Quelccaya Ice Cap (H3 position) and 170 m for the Cordillera Vilcanota (Ice3 position). A maximum ELA depression was also calculated, based on the lower limits of glaciation. For the Cordillera Vilcanota, the lowest and oldest moraine evidence is located at 3600 m, implying an associated ELA depression of 560 m corresponding to moraines ≥41,000 years B.P. old. For the Quelccaya Ice Cap, the maximum extent of ice lies at 4500 m, where the ice was merged from the southern Cordillera Vilcanota and the Quelccaya Ice Cap. This would represent a depression in ELA of 360 m. As previously noted, this maximum position is dated by two cosmogenic-isotope ages with a mean of about 20,000 yr B.P.

Because deglaciation is associated with a rise in the ELA of a glacier, a relative change in volume is associated with ELA variations. When compared with the ELA rises, the changes in ice volumes relative to the present in the Cordillera Vilcanota are shown to be greater than those on the Quelccaya Ice Cap (Table 3). Deglaciation from the H3 position to the modern Quelccaya Ice Cap limit resulted from a 230 m rise in ELA, related to a 75% volume decrease. However, the 170 m rise in ELA for deglaciation from the Ice3 position to the modern on the Cordillera Vilcanota side features an 89% volume reduction. This difference reflects the different hypsometries of the valleys (Fig. 5). The range in elevation is larger in the Cordillera Vilcanota, but the Quelccaya Ice Cap retains a larger area at higher elevation, amounting to a broad dome of ice.

Generally, large changes in area for a given rise in ELA correspond to a much flatter tongue of ice with more area exposed at lower elevation, whereas steeper ice masses lose less accumulation area for the same rise in ELA. Changes in accumulation area

TABLE 3
Loss of Glacier Volume and Rise in ELA for Paleoglaciers Relative to Modern Glaciers

Paleoglacier	Glacier volume (km^3)	ELA rise (m)	Volume change (%)	Accum. area change (%)
Upismayo Valley				
Maximum	—	560	—	—
Ice3	1.17	170	90	18.5
Ice2	0.74	120	85	13.3
Ice1	0.55	100	80	13.1
Huancané Valley				
Maximum	—	360	—	—
H3	0.43	230	75	15.4
H2	0.34	180	70	16.8
H1	0.19	50	60	0.4

Note. ELA, equilibrium-line altitude. Volume (km^3) of each paleoglacier is computed from the digital elevation model. ELA rise (m) shows the positive difference in elevation between the paleoglacier and modern glacier equilibrium line altitudes. Volume Change (%) is computed as the percentage change relative to the modern glacier volume (calculated from the surface area). Accum. Area Change (%) is the percentage change in the accumulation area of the paleoglacier compared with the modern glacier, computed using a toe-head wall-altitude ratio of 0.45. For an explanation of paleoglacier terms used here, see Glacial Chronology in text.

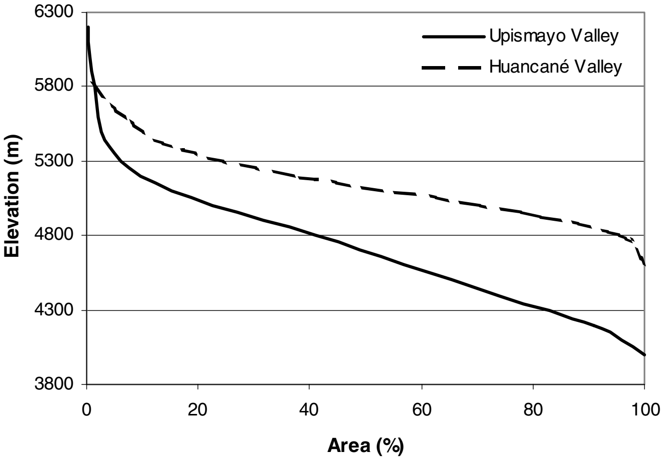

FIG. 5. Regional hypsometries calculated from the digital elevation model of the Upismayo and Huancané valleys.

corresponding to respective ELA changes for each paleoglacier show the effect of hypsometry (Table 3). The older ice positions (H2, H3, Ice2, and Ice3), with large areas exposed as tongues of ice, show greater loss of accumulation area per ELA rise. The percentage of loss is less for the Quelccaya Ice Cap, as more ice is retained at a higher elevation on the broad ice cap. The more recent ice positions (H1 and Ice1) show that the Cordillera Vilcanota glacier is a flatter tongue of ice, retaining a similar percentage loss of accumulation area, whereas the H1 change is much smaller, indicating the steep nature of the outlet glaciers coming from the Quelccaya Ice Cap. It may also be predicted that the loss of volume will increase dramatically for the Quelccaya Ice Cap if the ELA rises above the elevation of the ice dome.

DISCUSSION

Uncertainties inherent in the nature of moraine evidence limit the precision of moraine chronology, therefore limiting the discussion of comparative deglacial rates. Moraines represent accumulations of glacial sediment deposited during stillstands of the terminus when the glacier maintained quasi-equilibrium mass balance. By superposition, successively less-extensive moraines in a single valley delimit successively younger glacier positions. However, because any moraine position could represent an advance that destroyed older and less-extensive moraines, the preserved moraines form an incomplete record of glaciation. Moreover, moraine ages are either maximum or minimum limiting ages. A minimum limiting age usually comes from organic material upvalley from a moraine (often basal lacustrine sediments) that may have begun to form long after the deglacial episode began. There is a lack of understanding of how long the accumulation of organic material lags deglaciation. Cosmogenic-isotope ages are inferred to be close minimum ages. On the other hand, a maximum limiting age is derived from organic matter emplaced before moraine formation, and the sample is often found under moraines or incorporated into till. Such an age would necessarily predate the subsequent deglacial episode. Again, it is not known by exactly how much time the sample predates the moraine. In either case, the uncertainty in the actual age of the moraines translates to an uncertainty of unknown magnitude when using successive moraine ages to calculate an intervening deglacial rate.

Nevertheless, the remnant moraine chronology allows a conservative rate comparison between past episodes of deglaciation. The interval of time between successive moraine ages considered here as the deglacial interval is the maximum time over which deglaciation could have occurred. This time interval brackets the total time between glacier stillstands, without considering possible intervening intervals of deglaciation and readvance, for which no moraines remain; the glacier could have disappeared over a much shorter interval. Furthermore, the calculations of past glacier volumes are also conservative. We calculated paleoglacier volumes by filling glacial valleys of the DEM with modeled ice volume according to the modern valley morphology and moraine locations. This does not account for the depth of glacio–fluvial sediments deposited in the valley during and after deglaciation and thus underestimates the full thickness of the past glaciers (i.e., the true depth scoured by the glacier). A conservative calculation for ice volume, the numerator of the deglacial rate equation, also results in minimal deglacial rates.

Despite the much larger change in volume for late-glacial moraines, the volumetric deglacial rates are highest for the youngest paleoglaciers (Ice1 and H1) of the past few centuries. This is consistent with estimated glacier recession rates in the Venezuelan Andes, showing maximum rates after the LIA (Rull, 1998). Moreover, the calculated rates for the youngest paleoglaciers fall within the range of rates measured at Qori Kalis Glacier (Fig. 4), despite being determined over a longer interval of time. This has two important implications: (1) rates of deglaciation may fluctuate significantly over time, and (2) high rates of deglaciation may not be exclusive to the late 20th century. The large uncertainty inherent in this method of rate calculation prevents a precise comparison with the highly accurate and careful monitoring of Qori Kalis Glacier, and the extremely rapid rates of recession observed at the turn of the 21st century seem far to exceed anything resolvable in the moraine record. Nevertheless, the similarity of modeled rates for Ice1 and H1 with Qori Kalis rates suggests that the older paleoglaciers may have experienced faster rates of deglaciation than the conservative estimates.

To match the rates of deglaciation computed for the most recent intervals, more ice and/or a shorter deglacial time interval in the older deglacial events would be needed. The actual amount of ice required to match the most recent (and best constrained) deglacial rates is unreasonably large (Table 4). However, equal rates can be achieved if the same ice volumes are melted within a few hundred years. The hypsometry of the valleys and of the reconstructed positions supports the possibility of more rapid

TABLE 4

Increments in Volume and Deglacial Interval Required to Equal the Most Recent Deglacial Rate Estimate for the Modeled Paleoglaciers

Paleoglacier	Volume needed (x modeled)	Time needed (yr)
Upismayo Valley		
H3	5–8	210–370
H2	20–40	130–230
Huancané Valley		
Ice3	3–5	500–630
Ice2	20–25	110–150

Note. For an explanation of paleoglacier terms used here, see Glacial Chronology in text.

deglaciation, as the small ELA depressions suggest that relatively small temperature changes could result in large volume changes. In effect, the large paleoglacier tongues would undergo rapid wastage, analogous to the rapidly accelerating present retreat of Qori Kalis Glacier. Moreover, the presence of old peat deposits in close proximity to the modern glacier limit suggests that rapid and complete deglaciation of the Quelccaya Ice Cap has occurred previously, potentially after the H1 and H2 advances, and also before 2760 yr B.P.

ELA depressions for the calculated late-glacial moraine positions are less than estimates for the LGM (global ice-volume maximum during MIS 2). The maximum ELA depression of 560 m for the Cordillera Vilcanota is consistent with the 500–800 m calculated by Klein *et al.* (1999) for paleoglacier positions identified by satellite imagery. The maximum ELA depression is less for the Quelccaya Ice Cap, calculated here at 360 m. However, the late-glacial limit identified by Mercer (1983) as postdating the global maximum has only a 170 m ELA depression, and the maximum limit of glaciation identified by satellite imagery much further downvalley is from an older glacier advance ($\geq$41,000 yr B.P.). Regardless, the ELA depression is far less than the 1200 m depression reported over the eastern flank of the central Andes (Klein *et al.*, 1999). Sites in the north of Perú indicate ELA depressions at the last glacial maximum (LGM) of about 700 m in the Cordillera Blanca, and a gradient from 850 m on the west to 1200 m on the east of the Cordillera Oriental (Rodbell, 1992). To the south in Bolivia, an average 300 m ELA depression is reported for the western side of the Cordillera Real (Seltzer, 1992). The smaller values reported here could reflect some topographic control over glaciation in this area of high elevation on the edge of the Altiplano, causing a nonclimatic threshold to glacier expansion as proposed by Clapperton (1981).

Finally, the regional hypsometry can help resolve the apparent chronological discrepancy of maximum glaciation observed on the northwestern side of the Cordillera Vilcanota and the Quelccaya Ice Cap. The present chronology shows that the maximum extent of glacier expansion of the Quelccaya Ice Cap occured ca. 20,000 yr B.P., whereas the maximum extent in the Cordillera Vilcanota occurred much earlier (>41,000 ^{14}C yr B.P.). However, given the large flat area at higher elevation below the Quelccaya Ice Cap, ice cover is significantly larger for the same ELA depression. The terminal moraine elevation for the full Quelccaya Ice Cap is about 4500 m. Many nested, cross-cut moraines also occur between 4200 and 4400 m on the Cordillera Vilcanota. Whereas the continuous peat section at 4500 m suggested to Mercer that there was no glaciation between 41,000 and 16,650 yr B.P. in the Upismayo Valley that reached as low, the accreted nature of the closely nested moraines does not preclude the possibility that the peat accumulation remained undisturbed by a similar-sized glacier advance ca. 20,000 yr B.P. Furthermore, the slightly lower elevation of the moraines on the Cordillera Vilcanota side can be explained if the modern gradient in ELA is applied. The lake core evidence at Casercocha indicates a termination of glacier activity ca. 20,000 yr B.P., concurrent with maximum ice expansion of the Quelccaya Ice Cap. Likewise, because the elevation below the Quelccaya Ice Cap drops much more rapidly after 4500 m, an ice extent of similar magnitude may have occurred during the earlier maximum of the Cordillera Vilcanota.

CONCLUSIONS

A series of many moraines with a number of radiometric dates indicates that the Cordillera Vilcanota–Quelccaya region has experienced multiple episodes of deglaciation between episodes of moraine deposition. At least three groups of moraines exist on both sides of the Cordillera Vilcanota, yet differences in the dating prevent a clear correlation. The evidence suggests that the local late glacial maximum (LLGM) occurred on both sides ca. 20,000 cal yr B.P., whereas the largest glacier extent on the Cordillera Vilcanota occurred much earlier. The ELA depression associated with these LLGM moraines is considerably less than previously thought, and less than the 1000 m cited by many other studies as characteristic of the LGM. This could indicate a certain topographic threshold for the continued growth of the glaciers, or perhaps less of a temperature depression than the 5° to 9°C cooling that Klein *et al.* (1999) inferred for the LLGM in Perú based on a 500–800 m ELA depression. The strong control of the hypsometry on deglacial rate is also apparent considering that large, flat glaciers lose more accumlation area relative to ELA rise than shorter, steeper glaciers. Furthermore, the hypsometry of the region can be used to support a resolution of the chronological disrepancy of the LLGM raised by previous work (Goodman *et al.*, 2001).

For the discrete glacial episodes demarcated by moraines, the most rapid deglaciation is computed to have occurred over the most recent centuries. The computational technique presented here is fundamentally limited by the incompleteness of the geomorphic record of moraines, so that the rate of the most recent period of deglaciation is also the most accurately computed. Measured deglacial rates at the end of the 20th century far exceed modeled rates for paleoglaciers and provide strong evidence for enhanced global temperatures (Thompson *et al.*, 2000). However, by applying the most rapid rates to the volumes of the past, complete deglaciation would occur in a matter of centuries. This is conceivable, especially considering the hypsometry of the large, flat tongues of the paleoglaciers. Large volume paleoglaciers would have wasted quickly by raising the ELA relatively small amounts, as is currently happening at Qori Kalis Glacier. This accelerated rate of deglaciation may have implications for buffering the modern-day water budget on a seasonal basis and would have impacted Altiplano lake levels during the transition between the last glaciation and Holocene.

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