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THE LAST DEGLACIATION OF PERU AND BOLIVIA

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ABSTRACT. *The tropical Andes of Peru and Bolivia are important for preserving geomorphic evidence of multiple glaciations, allowing for refinements of chronology to aid in understanding climate dynamics at a key location between hemispheres. This review focuses on the deglaciation from Late-Pleistocene maximum positions near the global Last Glacial Maximum (LGM). We synthesize the results of the most recent published glacial geologic studies from 12 mountain ranges or regions within Peru and Bolivia where glacial moraines and drift are dated with terrestrial cosmogenic nuclides (TCN), as well as maximum and minimum limiting ages based on radiocarbon in proximal sediments. Special consideration is given to document paleoglacier valley localities with topographic information given the strong vertical mass balance sensitivity of tropical glaciers. Specific valley localities show variable and heterogeneous sequences ages and extensions of paleoglaciers, but conform to a generally cogent regional sequence revealed by more continuous lake sedimentary records. There are clear distributions of stratigraphically older and younger moraine ages that we group and discuss chronologically. The timing of the local LGM based on average TCN ages of moraine groups is 25.1 ka, but there are large uncertainties (up to 7 ka) making the relative timing with the global LGM elusive. There are a significant number of post-LGM moraines that date to 18.9 (± 0.5) ka. During the Oldest Dryas (18.0 to 14.6 ka), moraine boulders date to 16.1 (± 1.1) ka, suggesting that glaciers either experienced stillstands or readvances during this interval. The Antarctic Cold Reversal (ACR; 14.6 to 12.6 ka) is another phase of stillstanding or readvancing glaciers with moraine groups dating to 13.7 (± 0.8) ka, followed by retreating ice margins through most of the Younger Dryas (YD; 12.9 to 11.8 ka). During the early Holocene, groups of moraines in multiple valleys date to 11.0 (± 0.4) ka, marking a period when glaciers either readvanced or paused from the overall trend of deglaciation. The pattern of glacial variability during the Late Glacial after ~14.6 ka appears to be more synchronous with periods of cooling in the southern high latitudes, and out-of-phase with the overall deglacial trend in the Northern Hemisphere. While insolation and CO_2 forcing likely drove the* *general pattern of deglaciation in the southern tropical Andes, regional ocean-atmospheric and hypsometric controls must have contributed to the full pattern of glacial variability.*

La Última Deglaciación en Perú y Bolivia

RESUMEN. *Los Andes Tropicales de Perú y Bolivia contienen evidencias geomorfológicas de múltiples glaciaciones y, mediante su datación, permiten comprender las dinámicas climáticas en sitios clave entre ambos hemisferios. La presente revisión se enfoca en la deglaciación a partir de la máxima extensión de los glaciares durante el Pleistoceno Tardío, próximo al Último Máximo Glaciar (LGM) global. Sintetizamos los resultados de los estudios geológicos y glaciológicos publicados en 12 cadenas montañosas entre Perú y Bolivia, donde se dataron las morrenas y sedimentos glaciares por medio de Nucleídos Cosmogénicos Terrestres (TCN), así como las edades máximas y mínimas de sedimentos cercanos por medio de radiocarbono. Dada la fuerte sensibilidad de los glaciares tropicales al balance de masa vertical, documentamos las localidades de los valles paleoglaciares que presentan información topográfica. Dichas localidades muestran secuencias de edad y extensiones de paleoglaciares heterogéneos y variables, pero conforman en general una secuencia regional coherente, como revelan los registros más continuos de sedimentos lacustres. Existen distribuciones claras de edades estratigráficamente anteriores y recientes que agrupamos y discutimos cronológicamente. La datación del LGM local basada en los promedios de edad por TCN de grupos de morrenas es de 25.1 ka, pero existen incertidumbres importantes (de hasta 7 ka) que dificultan la datación relativa con el LGM global. Existe un número significativo de morrenas posteriores al LGM que datan de 18.9 (± 0.5) ka. Durante el Dryas Antiguo (18.0 a 14.6 ka), los bloques morrénicos datan hasta 16.1 (± 1.1) ka, sugiriendo que los glaciares experimentaron tanto estabilidad como también nuevos avances durante este período. La Inversión del Frío Antártico (14.6 a 12.6 ka) es otra fase de estabilidad o avance de glaciares con grupos de morrenas que datan de 13.7 (± 0.8) ka, y que fue seguida por la retracción de los márgenes del hielo durante la mayor parte del Dryas Reciente (12.0 a 11.8 ka). Durante el Holoceno Temprano, grupos de morrenas en múltiples valles datan de 11.0 (± 0.4) ka, marcando un período en que los glaciares detuvieron su retroceso o incluso volvieron a avanzar. Los patrones de variabilidad glaciar durante el Último Glaciar después de ~14.6 ka parecen más sincrónicos con períodos de enfriamiento de otras latitudes más al sur, y a su vez están desfasados con la tendencia general de deglaciación en el hemisferio norte. Mientras que la insolación e influencia de CO_2 pudieron causar el patrón general de deglaciación en los Andes Tropicales del Sur, los factores hipsométricos y océano-atmosféricos regionales pudieron haber contribuido al patrón entero de variabilidad glaciar.*

Key words: Tropical Andes, Last Glacial Maximum, terrestrial cosmogenic nuclides, paleoglaciers, deglaciation.

Palabras Clave: Andes Tropicales, Último Máximo Glaciar, nucleídos cosmogénicos terrestres, paleoglaciares, deglaciación.

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1. Introduction

The Andes of Peru and Bolivia comprise numerous glaciated ranges containing most of Earth's extant tropical glaciers, along with multiple superimposed moraines that have provided glacial geologists appealing time-space markers to infer the extent and timing of late-Pleistocene to Holocene climate changes in the tropics (Clapperton, 1972; Hastenrath, 1985). Initial geomorphologic observations extending from the first decades of the twentieth century documented multiple glacial stages based on the superposition and relative weathering of inset moraines. Because these features appeared similarly in form and position (elevation, distance from headwall) in different regions, this was interpreted as evidence of synchronous advances along the Andes (Clapperton, 1983). A prominent two-stage moraine sequence associated with the Last Glaciation was documented, and appeared well-correlated between different Peruvian ranges (Machare *et al*., 1990). Yet these early reviews featured very few absolute ages. In fact, this region featured only a single maximum limiting age for late-glacial moraines until the 21st century (Mercer and Palacios, 1977). In context, this ample geomorphologic evidence needing further absolute ages inspired field research expeditions into the 1990's. Subsequent glacial geology and lake coring field work gathered radiocarbon dates to test the interhemispheric synchroneity of deglaciation (Seltzer, 1992), as well as the relative magnitude of low latitude climate sensitivity at the LGM (Hastenrath, 2009). Whether the deglaciation from last glacial maximum extents was interrupted by a late-glacial advance in the Andes coeval with the Younger Dryas was identified as a key question for resolving the extent to which the North Atlantic forces global climate (Clapperton, 1993; Rodbell, 2000; Rodbell and Seltzer, 2000), and remains unresolved. At the end of the twentieth century, long sedimentary records extracted from basins beyond the glacial limit provided key hydroclimatic proxies that revised earlier interpretations of a dry LGM, and suggested deglaciation was underway between 22 ka and 19.5 ka BP, thousands of years prior to the Northern Hemisphere (Seltzer *et al*., 2000; Baker *et al*., 2001a, 2001b; Seltzer *et al*., 2002).

In the most recent decades, the chronology of tropical Andean deglaciation has been further refined with more widespread acquisition of terrestrial cosmogenic radio nuclide (TCN) exposure ages on moraines, as well as additional radiocarbon dates. Research has been motivated to better understand the extent, timing and dynamics of low-latitude glaciers in response to both global and local forcing, considering large gradients in precipitation related to prevailing winds and topography. Major questions of global synchroneity of glaciation continue to be actively explored, and as the location with most remaining tropical glaciers, the tropical Andes of Peru and Bolivia are important in efforts to systematically compile databases of glacier activity as a proxy for climate in paleoclimate modeling and intercomparison projects (i.e. Mark *et al*., 2005). TCN-based chronologies of moraines in Peru and Bolivia substantiated the previously hypothesized local maximum extent as occurring early during the last glacial cycle, with a more diminutive extension during the global LGM (Smith *et al*., 2005). However, methodological differences in the application of TCN techniques (sampling, production rate choice, age calculation, and interpretation) have resulted in different interpretations of glaciation timing and paleoclimate forcing (Zech *et al*., 2008; Glasser *et al*., 2009; Smith and Rodbell, 2010). Reviews have assimilated the basic understanding of the age of glacial geomorphic features in various localities, taking care to tabulate all relevant information to enable fair comparisons of TCN methodology (e.g. Rodbell *et al*., 2009; Smith *et al*., 2008), and provided georeferenced maps of moraine features (La Frenierre *et al*., 2011). Other syntheses have used derivatives like equilibrium line altitudes (ELAs) and snowlines to quantify the extent and spatial variability of glacier mass fluctuations in response to climate over time (Rodbell, 1992; Seltzer, 1992; Mark *et al*., 2005; Ramage *et al*., 2005). Given the discontinuous nature of the glacier moraine record (i.e. Seltzer, 1990), other work has used lake sediments (Rodbell *et al*., 2008; Rodbell *et al*., 2009) to document changes in glacier activity within catchments. Recent summaries have refocused particularly on the deglaciation timing as a means to test hypotheses related to understanding global climate forcing, i.e. synchronous glacier responses might indicate changes in atmospheric carbon dioxide as a global forcing (He *et al*., 2013; Shakun *et al*., 2015a).

Our goal in this review is to compile and synthesize the data available from papers published subsequent to the compilations of glacial geology that have tabulated (Smith *et al*., 2008; Rodbell *et al*., 2009) and ArcGIS mapped (La Frenierre *et al*., 2011) glacial geology in Peru and Bolivia from the Late Pleistocene. We will summarize and document localities where combinations of moraine chronology and lake sedimentary records exist. By focusing on deglaciation, we will restrict our review to the late-Pleistocene to Holocene transition. We will not review Holocene to modern changes. We revisit specific localities to identify the extent of evident glacier changes in space and time, documenting relevant topographic dimensions (headwall and terminal elevations, aspect) and providing an overview map to identify the specific locations with key attribute information. This specific contextual information will allow for more effective review by facilitating a 3D visualization of sites that can add insights to local controls, and hopefully guide subsequent research. We will focus primarily on updating reviewed information based on new moraine ages that have been developed since 2009, but will also reference previously published ages derived from other geomorphologic features (lakes sediments, bedrock exposures) that serve as time – position markers for glacial extensions during the last deglaciation.

Since cosmogenic radionuclide exposure age dating is the current state of the art method used to date moraines, it is important to acknowledge the variations in production rate calculations that can impact ages and uncertainties. Our review will follow practices established by others (Shakun *et al*., 2015a) to tabulate individual data on specific samples and enable a standardized procedure of computing shielding and weathering. We will draw a synthesis around known climatic events from other regions to assess how well this tropical region reflects global forcing.

2. Setting

The glaciated Andes of Peru and Bolivia span the latitudes of ~6°S to 23°S, and encompass a range of geology and climates as large-scale circulation features intersect various topographic forms. A general progression from more humid to more arid conditions is encountered along N to S and E to W trajectories across the Andes in this region of Peru and Bolivia. We direct attention to previous reviews for more thorough presentations of regional climate (Clapperton, 1983; Seltzer, 1990; Rodbell *et al*., 2009). Here we summarize some features relating to the orography and climate dynamics that sustain glaciers at these latitudes.

The geology of these tropical Andean ranges is complex, resulting from collisional tectonics of mixed crustal lithology. The physiography of the Andes varies from N–S through Peru and Bolivia, assuming a series of parallel ridges getting successively wider, and ending in Southern Bolivia amidst the Altiplano proper. The uplift history is also complicated in detail but has an overall framework that is recognized, featuring continual movement of orogenic mass into the cryosphere (Smith *et al*., 2008), and with no more than 50% of the elevation attained by 10 Ma (Gregory-Wodzicki, 2000; Insel *et al*., 2012). This uplift history has long imprinted strongly on the resulting precipitation patterns of the region, with a distinctive rain shadow in place by 15 Ma, reinforced by subsequent orographic development (Hartley, 2003). Exposures of glaciofluvial deposits below lavas radiogenically-dated to over 3 Ma near La Paz, Bolivia (Clapperton, 1979) confirm that the Andes were high enough in this region to have been glaciated further back into the Pleistocene, although outcropping of such evidence is rare. This makes the region a likely setting for having the most detailed record of tropical glaciation through time anywhere on Earth (Hall *et al*., 2009).

The climate of the tropical Andes is typical of low latitudes, where the diurnal temperature range is greater than the annual range. Precipitation is derived mostly from Atlantic Ocean moisture that is transported to the Andes via the easterlies (Garreaud *et al*., 2009). Seasonal rainfall variability in the tropical Andes is linked to the position of the Intertropical Convergence Zone (ITCZ) over the Pacific and Atlantic Oceans, and by the strength of the South American Summer Monsoon (SASM) over the Amazon Basin (Zhou and Lau, 1998; Maslin and Burns, 2000; Maslin *et al*., 2011; Vuille *et al*., 2012). Inter-annual and multi-decadal rainfall patterns and temperature fluctuations over South America are affected by variability in mean-state conditions in the Atlantic and Pacific Oceans (Johnson, 1976; Nobre and Srukla, 1996; Henderson *et al*., 1999; Vuille *et al*., 2000; Bradley *et al*., 2003; Vuille and Werner, 2005). For example, the warm phase of the El Niño Southern Oscillation (ENSO) typically produces higher wet season rainfall amounts at low elevations along the Pacific coast of the central Andes, and the opposite during cold phases (Coelho *et al*., 2002). At altitude, glaciers are affected by ENSO through large-scale circulation dynamics and zonal flow anomalies in the upper troposphere that affect snowfall (Vuille *et al*., 2008a). Although the relationship varies geographically and breaks down during certain years, El Niño events generally cause warm and dry conditions, whereas La Niña events are cold and wet in alpine regions of the southern tropical Andes (Vuille *et al*., 2008b). In addition, precipitation amounts are affected by positive sea-level pressure anomalies in the North Atlantic Ocean, as these usually result in a displacement of the ITCZ and a shift in the strength of the SASM (Chiessi *et al*., 2009). Cloud cover data from satellite imagery, and relative humidity values from station data also indicate a seasonal pattern, with generally higher levels during the wet season (Fairman, 2006).

Aspect and the orientation of glaciers are largely controlled by the structural trend of the Andes, and also reflect regional gradients in precipitation and solar radiation (Hastenrath, 2009). The NW-SE trend of the mountain ranges in central Peru generally explains the distribution of glaciers (Kaser and Georges, 1997). While precipitation moisture originates from easterly winds, the local geologic structure of the central Andes and resulting diurnal shading favors the development of more and larger glaciers in SW facing valleys (Kaser and Georges, 1997; Mark and Seltzer, 2005).

The mass balance of glaciers in the tropical Andes responds to both temperature and precipitation changes, but is critically limited by elevation given a steep vertical mass balance gradient. Glaciers in the tropics are distinct from those in higher latitudes because temperatures are fairly consistent throughout the year given constant radiation regime, while distinct seasonality of precipitation allows for accumulation and ablation to occur simultaneously (tropical glacier dynamics are comprehensively discussed by Kaser and Osmaston, 2002). The freezing height of precipitation and relative amount of snowfall are determinative for glacier mass balance. Ablation is more intensely focused below the equilibrium line elevation (ELA) and occurs all year round, while accumulation is restricted seasonally to regions above elevations dividing snow and rain, and this tends to persist at a constant altitude throughout the year (Vuille *et al*., 2008a). Tropical glaciers have high mass accumulation area ratios (Rodbell *et al*., 2009), and are thus fundamentally constrained by landscape hypsometry (area to elevation) and precipitation.

From a glaciological perspective, the central Andes are intermediate between the inner and outer tropics, with precipitation and humidity being seasonal, yet high enough to limit substantial ice loss to sublimation (Kaser and Osmaston, 2002). The dominant mode of ablation in these regions is melting, and the ELA of glaciers mimics the local freezing level height (or 0°C isotherm). Modern temperature values and radiosonde observations indicate that ELA's in the central Andes have risen by at least 70 m since A.D. 1962, as a consequence of warming temperatures (Mark and Seltzer, 2005). At the same time, precipitation has decreased, accelerating the rate of recent glacial retreat (Vuille *et al*., 2008a). Strong gradients in precipitation exist across the Andes in this region, with wetter conditions to the east given predominant precipitation sources of the easterly trade winds. There is also progressively greater aridity encountered toward the south over the Altiplano of Bolivia. These geographic patterns have long been recognized for imprinting spatial variations in glacier-climate sensitivity by influencing the snowline (Seltzer, 1990), so that the reconstructions of previous glacier ELAs also reflects strong topography-moderated gradients (Seltzer, 1993).

3. Material and methods

In this review, we focus on sites that have published data from specific valleys (localities) with radiometrically-dated glacial geomorphologic evidence to provide absolute chronology for deglaciation. We emphasize where dated moraines are coupled to additional sedimentary records to provide more continuous information. We identify 12 sites that are listed in subsections of Section 4 below, and are highlighted by numbered boxes in Fig. 1. Each site contains different specific glacial features with absolute ages, and we have clustered them by mountain range or relative regional proximity.

The basic unit of analysis for glacier reconstruction is the paleoglacier valley locality (i.e. Mark *et al.*, 2005), since the moraines and other glacier features were ultimately emplaced in a valley context featuring a maximum elevation constraining the accumulation zone. Establishing ages for glacial events involves sampling erratics on moraines, detailing information relevant for TCN age calculations (e.g. Licciardi *et al.*, 2009), and seeking sedimentary deposits proximal to moraines to recover maximum or minimum limiting ages with radiocarbon (i.e. Seltzer, 1990).

We strive to tabulate and evaluate the specific geomorphological and topographical contexts for paleoglacier mass changes in each locality (Table 1). The local topographic context plays a role in how much the deglaciation proceeds and how fast. We use a commonly available topographic mapping interface (Google Earth, hereafter GE) to locate published localities with consistent geographic coordinates and variables that constrain the paleoglacier including valley aspect, summit or headwall elevation, and terminal moraine elevation (if discernible). This detail is relevant in efforts to reconstruct paleo ELA's, or conduct modeling to reconstruct paleoglaciers. We distribute the locality information to allow more common evaluations of local factors that modify climatic forcing of deglaciation, and also guide future work by allowing inspection of nearby features that might provide additional detail. We have compiled previously tabulated moraine information (La Frenierre *et al.*, 2011) with additional features (Supplementary GE files are available upon request).

Here we use data for tropical Andean cosmogenic ages from the recent synthesis by Shakun *et al.* (2015a), which applies the most up to date and comprehensive production rate calibration and scaling methods. In the case of Illimani (Smith *et al.*, 2011), ages were not available in the Shakun *et al.* (2015a) composite, and we recalculated with the Quelccaya ^{10}Be production rate calibration (Kelly *et al.*, 2015), and the CRONUS-Earth calculator version 2.3 with the time-invariant 'St' scaling method of Stone (2000) following Lal (1991). Newly published data from the Cordillera Carabaya (Bromley *et al.*, 2016) and Nevado Huagurunch o (Stansell *et al.*, 2015) were calculated by the authors using the Quelccaya production rates. We also use radiocarbon ages in the compilation by Rodbell *et al.* (2009), combined with more recent publications for the Cordillera Huayhuash (Hall *et al.*, 2009), Cordillera Raura (Stansell *et al.*, 2013), and Nevado Huagurun cho (Stansell *et al.*, 2015) (Table 2).

Table 1. Synthesis of regions and localities covered in this review.

Geography		Glacial topography				Deglacial chronology				References
Range/region	Locality (valley)	Aspect	Headwall or Summit (m)	terminal elev (m)	modern glacier?	type	#dates	chronologic context	interpretation	
Cordillera Oriental	Manachaque	E	4300	3560	N	14C	3	minimum ages between ~11.1 and 14.0 ka (9.7 - 12.1 14C kyr BP)	oldest date from Laguna Baja is ~14 ka, meaning deglaciation was underway by then, and proceded rapidly, leaving no ice in catchment except for early-mid Holocene. There is a moraine infront of the 9.7 ka moraine, and this could be YD. However, no buried soil under moraine can uniquivocally prove readvance.	Rodbell, 1993; Birkeland *et al*., 1989
Cordillera Oriental	Laguna de Chochos	SE	4200-4500	3285	N	14C	9	8.79 m core with estimated basal age ~17 ka, max 14C date 14.4ka, and nearby basal date of bog 11.5 ka	Late glacial climate was cool and moist but variable, and this eastern aspect was ice free by 11.5 ka, with warmth at end of YD period. Sediments show some sign of 1500 yr cyclcity from 12-6 ka. Early Holocene continued wet, but interrupted by warm dry period in early Holocene (9.5-7.5 ka)	Bush *et al*., 2005
Cajamarca region	Galeno	N	4075	3800	N	10Be	7	full terminal loops within bounds of LGM, boulder ages 7 of 9 (2 outliers) dated to 19 ka	these loops show laterals max elev of 3900, and summit at 4075 indicating ~150 m snowline change; largely ice free by 20 ka; authors presume recession from more maximal position unmarked, but this is not clear. Image and same elev of laterals with North Camp indicate same advance	Shakun *et al*., 2015b
Cajamarca region	North Camp	SW	4080	3800	N	10Be		lateral moraines dated to 21-24 ka	interpreted as lowest reach of main trunk, but closer inspection suggests they are laterals from side cirques, all terminating ~3800 m.	Shakun *et al*., 2015b
Cajamarca region	San Cirilo	S-SW	4070	3850	N	10Be			same site as Weng *et al*. lake core, but not apparently recognized as such.	Shakun *et al*., 2015b
Cajamarca region	Lake Compuerta	S-SW	4070	3900	N	14C	7	3.7 m core, date with pollen in upper core to 33 ka; estimated basal age >50 ka	increased MS 16,200 BP to peak 13,200 BP interpretted as deglaciation; reduced magnetics 12,500 to 10,000 as YD-event, with cool dry veg. Deglaciation continues 10ka, ice free by 7500 BP. This is the lake in the San Cirilio site	Weng *et al*., 2006

Geography		Glacial topography				Deglacial chronology				References
Range/region	Locality (valley)	Aspect	Headwall or Summit (m)	terminal elev (m)	modern glacier?	type	#dates	chronologic context	interpretation	
Cordillera Blanca	Breque	W	5700	4000	Y	14C	3	2 max, 1 min age from paleolake at 3975 m below moraine pin date to 13.2 - 12.9 ka (10.8-12.8 14-C ka)	Advance is interpreted by cross-cutting moraines, and it seems to have been short lived, so early advance in YD followed by rapid (?) deglaciation during later YD	Rodbell and Seltzer, 2000
Cordillera Blanca	Breque	W	5700	4000	Y	10Be	8	Boulder ages that average to about 12.7 ka on moraine	Well constrained and close to the radiocarbon ages, this is the age assigned to Rodbell's named Manachaque late-glacial moraines	Farber *et al*., 2005; Shakun *et al*., 2015
Cordillera Blanca	Laguna Baja	SW	~6200	~3600	Y	10Be	12	granodiorite boulders with average age of 18.6 ka taken in both Cojup and Llaca valleys	Terminating at similar elevation to L. Baja in Oriental to north, these moraines are inset from Rurec, and Farber sampled them in Llaca and Cojup; Rodbell had min ages of 13.5 ka	Farber *et al*., 2005; Shakun *et al*., 2015
Cordillera Blanca	Rurec	SW	~6200	3450	Y	10Be	13	granodiorite boulders with average age of 24.7 ka taken in both Cojup and Llaca valleys; range of 29-20 ka	Terminating below, these pronounced lateral/terminal loops are considered the maximum extent of LGM stage (MIS2) paleoglaciers. Outside, older, more weathered Cojup forms are pre-LGM.	Farber *et al*., 2005; Shakun *et al*., 2015
Cordillera Blanca	Queshque	SW	5580	4280	Y	10Be		minimum age of moraine abandonment	Two lakes have sediment records, and the upper is bounded by TCN-dated moraine. No late-glacial ages older than 14.4 ka; lower lake is 13.8 ka; upper lake is 12.5 ka	Stansell *et al*., 2013
Cordillera Blanca	Jeullesh	SSW	5600	4150	Y	10Be	26	M3, M4, M5 moraines	Ages from ~16 - 18 ka; interpretted as recessionals. The M5 is further up valley, and could be late glacial, similar to bounding of Queshquecocha upper lake and Tuco	Smith and Rodbell, 2010
Cordillera Blanca	Quenua Ragra	SW	5600	4200	N*	10Be	15	M6 moraine	Ages from 18.8 - 21 ka	Smith and Rodbell, 2010
Cordillera Huayhuash	Jahuacocha	W	6400	4000	Y	10Be, 14C		multiple moraines, minimum lake/bog cores, and bedrock exposures	Oldest age is from striated brx at nick pt (38 ka), and upvalley moraines are late glacial to Holocene	Hall *et al*., 2009
Cordillera Huayhuash	Carhuacocha	E	6400	3750	Y	10Be, 14C		multiple moraines, minimum lake/bog cores, and bedrock exposures	5 stages are dated, corresponding to deglaciation: II are ~9–10 ka; III are ~13–14 ka; IV are ~20–22 ka, and V are >26 ka	Hall *et al*., 2009

Geography		Glacial topography				Deglacial chronology				References
Range/region	**Locality (valley)**	**Aspect**	**Headwall or Summit (m)**	**terminal elev (m)**	**modern glacier?**	**type**	**#dates**	**chronologic context**	**interpretation**	
Cordillera Huayhuash	Mitococha	N-E	5885	3750	Y	10Be, 14C		multiple moraines, minimum lake/bog cores, and bedrock exposures	5 stages are dated, corresponding to deglaciation: II are ~9–10 ka; III are ~13–14 ka; IV are ~20–22 ka, and V are >26 ka	Hall *et al*., 2009
Cordillera Raura	Lutacocha	S	5150	4420	Y	14C	11	Holocene age lake; min age from basal seds of ~9.8 ka	Glacier advance in early Holocene (?)	Stansell *et al*., 2013
Junin	Junin Plain	E	5135	4250	Y	14C	5	minimum ages from lakes on ground moraine of Punrun advance	Wright presents 4 dates from lakes on Junin Plain that suggest the Punrun was late glacial (11.5-16 ka calibrated) after a Rio Blanco stage that predated LGM (>42 ka); currently small glaciers remain on Cerro Chuchpanga to west of Junin.	Wright 1983, 1984
Junin	Alcacocha	SW	4600	4340-4350	N	10Be, 26Al	13(B), 6(C)	boulder ages on moraines of Groups C, B	Group C moraines interpretted as local LGM (32-28 ka); Group B are lateglacial readvance (18-15 ka); both are within 20 m elevation	Smith *et al*., 2005, 2008
Junin	Antacocha	SW	4650	4215-4250	N	10Be, 26Al	7(B), 8(C)	boulder ages on moraines of Groups C, B	Group C moraines interpretted as local LGM (32-28 ka); Group B are lateglacial readvance (18-15 ka); both are within 20 m elevation	Smith *et al*., 2005, 2008
Junin	Calcalcocha	SW	4600	4215-4230	N	10Be, 26Al	14(B), 2(C)	boulder ages on moraines of Groups C, B	Group C moraines interpretted as local LGM (32-28 ka); Group B are lateglacial readvance (18-15 ka); both are within 20 m elevation	Smith *et al*., 2005, 2008
Huaguruncho	Jaico Lake cirque	S	5400	~4000	Y	10Be	48	qtz monzonite erratics sampled on multiple moraines in steep walled cirque with Yanacocha and Jaico lakes	Late glacial 14ka, early Holocene (10-11.6 ka) and LIA (300-400 yr) moraine loops; mapped LGM and pre-LGM moraines with no dates that actually look geomorphically more like late-glacial, making the 14.1 ka a medial in cirque	Stansell *et al*., 2015
Huaguruncho	Yanacocha Lake	E	5000	4350	Y	14C	13	lake elevation is 4350 m, and L-lat terminal loop has CRN age of 14 ka, but lake gives min age of deglaciation	clear sediment transition to more organics gives min age of deglaciation at 13.7 ka; core is analyzed for sediment flux, showing inconsistent matches with moraine ages; 13.7 - 12 ka is declining glacial flux, then abrupt increase at 12 ka, matching moraines at 11-10ka; there are fluctuations suggestive of glacier action 10-4 ka, but no moraines survive; LIA extention with 3 loops are largest of late Holocene	Stansell *et al*., 2015

Geography		Glacial topography				Deglacial chronology				References
Range/region	Locality (valley)	Aspect	Headwall or Summit (m)	terminal elev (m)	modern glacier?	type	#dates	chronologic context	interpretation	
Illimani	Pasto Grande	N	6100	4000	Y	10Be	23	boulders on moraines of series A, B, C	Glacier retreated from lateglacial terminus at 4000 m by 16.6 ka, and other positions are 15.1 ka and 10.1 ka. Evidence for more extensive glacier extend to ~3500 m.	Smith, C. *et al.*, 2011
Carabaya	Quebrada Tirataña	SE	5275	4600	Y	10Be	4	boulders on terminal moraine loops at Minas Tira	Ages from 26-22 ka on inset ridges, consistently older on outside, establish a paleoglacier advance before LGM that stayed or had readvances until 22 ka, when deglaciation underway	Bromley *et al.*, 2016
Carabaya	Q. Jotini	SE	4850	4600	N	10Be		boulders on terminal moraine loops at Minas Tira	14 terminal ridges within 500 m, ranging from 4550-4600 m	Bromley *et al.*, 2016
Carabaya	Aricoma	S	5150	4500	Y	10Be		two granite boulders outside the cross-cutting inner moraine are 19 ka	Maximum extent likely established before LGM, and retreated rapidly by 19 ka	Bromley *et al.*, 2016
Carabaya	Veluyoccocha	S-E	5150	4650	N	10Be		two dates from terminus moraine are ~16 ka	Lateglacial readvance was itself in recession by 16 ka.	Bromley *et al.*, 2016
Cordillera Occidental	Hualca Hualca		6250			36Cl			LGM occurred ~ 17.9 ± 0.1 to 16.8 ± 0.4 kyr, with widespread deglaciation after ~12 ka.	Alcala *et al.*, 2011
Cordillera Ampato	Coropuna	N,S	6400	~4700	Y	3He		various boulders in different aspects	Late Pleistocene maximum ~25-15 ka, followed by recession from the C1 moraines over 7-6 ka before a late glacial advance to C2 moraines dated ~13 ka	Bromley *et al.*, 2009
Cordillera Vilcabamba	Sisaypampa	E	6271	4327		10Be	4	Outer distal moraine	Pre-YD moraine 12.9 ± 0.9 ka	Licciardi *et al.*, 2009
Cordillera Vilcabamba	Sisaypampa	E	6271	4292		10Be	2	Outer proximal moraine;	Early Holocene moraine, 10.5 ± 0.7 ka	Licciardi *et al.*, 2009
Cordillera Vilcabamba	Rio Blanco	S	6271	4046		10Be	5	Outer moraine	Early Holocene moraine, 11.1 ± 0.4 ka	Licciardi *et al.*, 2009
Cordillera Vilcanota	Upismayo	NW	6350	4300	Y	14C	3	10 m peat layer sandwiched between moraine ridges	Pre-LGM advance dated with minimum of 41 ka and terminus ~3600 m, but maximum for late glacial readvance at 16,650 ± 400 cal yr B.P.	Mercer and Palacios, 1977; Goodman *et al.*, 2001; Mark *et al.*, 2002
Cordillera Vilcanota	Casercocha	W	6000	4010	Y	14C	1	basal lacustrine organics on interfluve	Minimum age of deglaciation from local LGM position: 18.3-18.8 ka	Mark *et al.*, 2002

Geography		Glacial topography				Deglacial chronology				References
Range/region	**Locality (valley)**	**Aspect**	**Headwall or Summit (m)**	**terminal elev (m)**	**modern glacier?**	**type**	**#dates**	**chronologic context**	**interpretation**	
Cordillera Vilcanota	Comercocha	N	5500	4600	Y	14C	1	basal organics in moraine-dammed lake	Minimum age of deglaciation from local LGM position: 16.9-17.9 ka	Mark *et al*., 2002
Quelccaya	Huancane	W	5700	4745	Y	14C	1	peat inside H3 moraine loop	Minimum age of deglaciation from lateglacial postion: 14.2 ka	Mercer and Palacios, 1977; Mark *et al*., 2002; Rodbell *et al*., 2009
Quelccaya	Huancane	W	5700	4842	Y	14C	1	basal lacustrine organics inside H3	Minimum age of deglaciation from LGM: 17.2 ka	Kelly *et al*., 2012
Quelccaya	Huancane	W	5700	4825	Y	14C	21	peat in moraine	Age of plants growing upvalley of H2 moraines provide max limiting age of lateglacial H2 advance: 13.6-12.8 ka. Closest limit in 2 valleys is best maximum: 12.5 ka	Kelly *et al*., 2012
Quelccaya	Huancane	W	5700	4850	Y	14C	4	organics in stream cut up valley of H2	Close limiting minimum ages of H2 lateglacial advance: 12.4-12.2 ka	Kelly *et al*., 2012
Cochabamba	Wara Wara	S	4470	3800		10Be	10	4 moraine ridges sampled along with boulders from hummocky glacier free headwall area; 5 clusters of 2 dates each	Oldest dates are 2 from W1 R-lat, ages of 13.6 and 14.2 ka. This interpreted as correlative with H1. An inset R-lat ridge has 2 ages as 11.7 and 11.8, and interpretted as coincident with YD. Younger lower relief terminal loops W3 and W4 are in reverse age, but combined the ages cluster as early Holocene.	Zech *et al*., 2010
Cochabamba	Huara Loma	N	4800	4000	N	various		multiple methods and dating (14C, OSL, 10Be	Two glaciations identified, with four subdivisions for younger dating at ~29-25ka; 20-18 ka; 17-16 ka, then several small readvances until 11-10 ka and complete deglaciation.	Zech *et al*., 2007; May *et al*., 2011
Altiplano	Cerro Azanques	NW	5102	3900	N	14C	1	peat layer below glacial outwash in Q. Lijunimayu	Advance 3 is given a maximum age of lateglacia~16.7 ka l (14,015 ± 95 14C yr BP)	Clayton and Clapperton, 1997; Zech *et al*., 2001
Altiplano	Cerro Tunupa	SE	5300	3770	N	3He		glacio-fluvial moraine with shoreline	M1 moraine in position terminating with lakeshores, and not abandoned until 15 ka	Blard *et al*., 2009
Sajama	Patokho valley	E	6550	4500	Y	36Cl	7	boulders on moraines	Ages vary but oldest is 16.9 ka, and authors interpret it as best age of lateglacial advance	Smith *et al*., 2009

Table 2. Calibrated radiocarbon ages limiting deglaciation, updated from Rodbell et al. (2009).

Country	Region / Locality	Approximate latitude	Approximate longitude	Minimum-limiting age (^{14}C yr BP)	± 1σ	Minimum-limiting age (cal yr BP)	+1σ (cal yr)	-1σ (cal yr)	Maximum-limiting age (^{14}C yr BP)	± 1σ	Maximum-limiting age (cal yr BP)	+1σ (cal yr)	-1σ (cal yr)	Lab number	Notes	Reference
Bolivia	Altiplano	19-20°S	66.5-67.5°W						13330	90	16033	250	278	A-7574	maximum age for Advance 3	Clapperton *et al*., 1997
									14020	100	17030	353	374	A-7572	maximum age for Advance 3	Clapperton *et al*., 1997
									12,900-13,400		15420-16122			not provided	range of 10 dates from peat-maximum age for Advance 3	Clapperton *et al*., 1997
Peru	Quelccaya Ice Cap	14°S	71°W						10910	160	12890	150	100	I-8209	maximum age for Huancane II moraine	Mercer and Palacios, 1977
									11070	130	13010	90	110	DIC-686	maximum age for Huancane II moraine	Mercer and Palacios, 1977
									11190	190	13100	130	160	GX-4325	maximum age for Huancane II moraine	Mercer and Palacios, 1977
									12230	180	14236	759	500	DIC-687	maximum age for Huancane II moraine	Mercer and Palacios, 1977
				9980	260	11563	853	829						DIC-685	minimum-age for Huancane II moraines	Mercer and Palacios, 1977
				10870	70	12757	168	82						AA-27032	minimum-age for Huancane II moraines	Rodbell and Seltzer, 2000
				11460	170	13303	327	310						I-8210	minimum age for Huancane III moraine	Mercer and Palacios, 1977
				12240	170	14248	715	498						I-8443	minimum age for Huancane III moraine	Mercer and Palacios, 1977
Peru	Cordillera Vilcanota	13.75°S	71.25°W						13880	150	16810	467	491	GX-23725	maximum age for late glacial advance	Goodman *et al*., 2001
									13950	400	16893	1047	1088	GX-8081	maximum age for late glacial advance	Mercer, 1984
									14010	190	17001	534	594	I-9623	maximum age for late glacial advance	Mercer, 1984

Country	Region / Locality	Approximate latitude	Approximate longitude	Minimum-limiting age (^{14}C yr BP)	± 1σ	Minimum-limiting age (cal yr BP)	+1σ (cal yr)	-1σ (cal yr)	Maximum-limiting age (^{14}C yr BP)	± 1σ	Maximum-limiting age (cal yr BP)	+1σ (cal yr)	-1σ (cal yr)	Lab number	Notes	Reference
									14500	110	17672	286	290	Beta-1725	maximum age for late glacial advance	Mercer, 1984
									14830	450	18007	995	1183	GX-8189	maximum age for late glacial advance	Mercer, 1984
				10360	70	12223	466	258						AA-27041	minimum age for all late glacial moraines	Goodman *et al*., 2001
Peru	Laguna Junin Plain - Western Cordillera	10.75-11.25°S	75.75-76.5°W	10050	100	11593	383	334						WIS-1068	minimum age for deglaciation from the Punrun Glaciation; late glacial moraines are present downvalley from each of these dated localities	Wright, 1983
				11950	150	13803	341	340						S-1489	minimum age for deglaciation from the Punrun Glaciation; late glacial moraines are present downvalley from each of these dated localities	Wright, 1983
				12800	130	15265	463	340						WIS-1204	minimum age for deglaciation from the Punrun Glaciation; late glacial moraines are present downvalley from each of these dated localities	Wright, 1983
				13540	130	16318	436	389						WIS-1203	minimum age for deglaciation from the Punrun Glaciation; late glacial moraines are present downvalley from each of these dated localities	Wright, 1983
				12100	120	13965	366	370							peat between two tills	Wright, 1983
	Cordillera Huayhuash	10.2-10.4°S	77°W	11525	20	13390	40	40							minimum age for deglaciation	Hall *et al*., 2009

Country	Region / Locality	Approximate latitude	Approximate longitude	Minimum-limiting age (^{14}C yr BP)	± 1σ	Minimum-limiting age (cal yr BP)	+1σ (cal yr)	-1σ (cal yr)	Maximum-limiting age (^{14}C yr BP)	± 1σ	Maximum-limiting age (cal yr BP)	+1σ (cal yr)	-1σ (cal yr)	Lab number	Notes	Reference
				11535	20	13400	20	20							minimum age for deglaciation	Hall *et al*., 2009
				8995	20	10160	30	30							minimum age for deglaciation	Hall *et al*., 2009
				19540	550	23260	700	700							minimum age for deglaciation	Hall *et al*., 2009
				10040	25	11400	140	140							minimum age for deglaciation	Hall *et al*., 2009
				11170	100	13170	30	30							minimum age for deglaciation	Hall *et al*., 2009
				7520	110	8323	220	271							minimum age for deglaciation	Stansell *et al*., 2013
	Nevado Huaguruncho	10.3°S	76°W	10380	25	12253	87	12							minimum age for Late Glacial readvance	Stansell *et al*., 2015
				11880	160	13733	387	324							minimum age for Late Glacial readvance	Stansell *et al*., 2015
Peru	Cordillera Raura	10.5-10.75°S	77°W	12500	340	14699	1082	974							minimum age for deglaciation	Cardich *et al*., 1977
				8330	60	9350	126	214							minimum age for deglaciation	Stansell *et al*., 2013
	Cordillera Blanca	9.25-9.75°S	77.3-77.5°W	10990	60	12856	152	132						GX-19558	minimum age for Breque moraine	Rodbell and Seltzer, 2000
									11280	110	13145	227	262	GX-17674	maximum age for Breque moraine	Rodbell and Seltzer, 2000
									13280	190	15952	536	617	GX-15850	maximum age for Breque moraine	Rodbell and Seltzer, 2000
Peru	Cordillera Oriental	7.5-7.75°S	77.5° W	9700	270	11083	887	788						GX-12853	minimum age for late glacial moraines	Birkeland *et al.,* 1989
				10300	550	11920	1273	1439						GX-15851	minimum age for complete final complete of Range	Rodbell, 1993a, 1993b
				12080	610	14230	1668	1473						GX-16104	minimum age for late glacial moraines	Birkeland *et al*., 1989
				12100	190	14012	749	472						GX-12852	minimum age for late glacial moraines	Birkeland *et al*., 1989

4. Review of sites with chronologic data

4.1. Cordillera Oriental and Cajamarca Region

Three radiocarbon dates from the eastward-draining Manachaque Valley of the Cordillera Central provided the first constraints on the deglacial history of the region (Birkeland *et al*., 1989; Rodbell, 1993b). The valley has headwall elevations reaching ~4300 m, and are no longer glacierized. Numerous well-preserved moraines are present in the 13 km glaciated portion of the valley before the low-gradient U-shape valley form changes to V-shaped. The moraines are prominent forms, but are not distinctively different in age, and have similarly developed soil profiles. The dates were obtained from successively higher positions, and provide minimum-limiting radiocarbon ages between ~14.0 and 11.1 ka (12.1-9.7 ^{14}C kyr BP) for late-glacial moraines in this range.

The furthest down valley date comes from the base of a sediment core extracted from Laguna Baja, providing the oldest minimum-limiting age of 14 kyr BP (12.1 ^{14}C kyr BP). Notably, there was no evidence found for this being a readvanced ice position, despite extensive trench digging at the moraine base looking for buried organic material to date. The next youngest moraine is ~3km upvalley and the basal age of a bog impounded by the moraine is 11 kyr BP (9700 ^{14}C yr BP). This position is ~equivalent to a 50% reduction in glacier ice cover from the maximum. A final date of 6450 yr BP comes from organic material over till behind the highest moraine, marking a position with <10% of the maximum ice extent.

Hansen and Rodbell (1995) provide pollen data from Laguna Baja, and interpret oscillations in late glacial vegetation and climate. The setting was already warm and moist given open mixed montane forest pollen at the base of the core. There is suggestion of a cooler/more arid interval based on expanded paramo vegetation between 11.6 and 10 kyr BP. The progression is apparently rapid warming toward the Holocene, with both temperature and precipitation increasing by about 10 ka, resulting in wet montane forest displacing paramo. Additionally, Laguna de Chochos (3285 m) on the eastern side of the divide below was cored and provides a ~17 kyr record showing wet, cool and variable climate during 17-11.5 ka deglaciation (Bush *et al*., 2005). There is no evidence of glacier readvance at the YD, but a radiocarbon date from a bog above the lake shows the cirque was ice-free by 11.5 ka when conditions warmed at the end of the YD period.

A cluster of recently published TCN dates from moraines located in the Northern Peruvian Andes, near Cajamarca, provide the most northerly situated localities (Shakun *et al*., 2015b). They are currently unglacierized, and the maximum elevations in the catchment at <4100 m constrain the extent of ice cover. The Galeno moraines are NE aspect and show complete inset lateral/terminal loops reaching to 3800 m only 150 m shy of the summit, with maximum lateral moraine elevations of 3900 m and an average age of 19 ka based on seven of nine (2 outliers) TCN sampled boulders. The paleoglacier drains to a larger valley but no lower moraines were identified.

The North Camp moraines comprise two lateral ridges that are described by Shakun *et al*. (2015b) as left and right laterals of a single paleoglacier with SW aspect, sharing a common headwall elevation with Galeno moraines on the opposite side. The average TCN dates of 23.7 ka are slightly earlier than the global LGM. On the basis of this interpretation, the authors presume the Galeno to be recessional positions for a larger extent. Nevertheless, it should be noted that a closer inspection of the topographic context suggests an alternative interpretation that these are not laterals of the main valley, but actually laterals from separate smaller cirque glaciers entering the main trunk. As such, they would share the same terminal elevation as Galeno. Thus there is not convincing evidence that the glaciers extended further than 3850 m during this stage. The glaciated geomorphology of the U-shaped valleys and apparent but undated moraines that appear lower (to 3500-3300 m termini) do suggest there were older, more extensive advances, but no dates yet exist.

The San Cirilo site is located just over 30 km to the WNW of the North Camp moraines, and comprises multiple discontinuous moraine ridges of SW aspect and kettle lakes around summit crags ~4070 m, interpreted to be a site of ice wastage on a broad shallow divide. There are other similar features evident on the landscape to the north. Muted but discernible terminal loops in nearby valleys end at 3850 m. The average age of the 8 boulder and 1 bedrock samples is 21.2 ± 0.8 ka (3 additional were excluded as outliers for being >10 ka older). The elevation profile for this site is very different than the others, but the headwall is similarly ~4000 m.

All told, these data are best interpreted as signifying that an advance of unknown initiation ended at a similar age to the LGM, ~20 ka, leaving ice free conditions for areas with <4100 m headwalls/summits. The downvalley geomorphology suggests there were older, more extensive glaciers, but none younger. This constrains the extent of Holocene climate in the region by snowline/ELA elevations that were within ~1km of modern.

Although hitherto not recognized as being from the same location, another study reports on a 33,000 year lake sediment record recovered from Lake Compuerta, situated amidst the San Cirilo site at 3950 m (Weng *et al*., 2006). The authors use pollen, charcoal, MS and bulk density to make a paleoecological reconstruction of the region, but incorrectly recorded the position of the lake in their paper. Based on the satellite image from the published location figure, this lake is evidently one of the lakes left behind from the collapsed ice cap referenced by Shakun *et al*. (2015b). Significantly, this repositioning also revises the elevation estimate published for surrounding summits to the headwall elevation mentioned previously for San Cirilo of <4100 m.

The Lake Compuerta core shows a sedimentation hiatus from ~30 ka until 16.2 ka. Conceivably, this could be consistent with an episode of glacier advance that initiated before the LGM, but endured throughout, causing ice to override the lake, and end up depositing the hummocky moraines that have erratics dated by TCN at 21-23 ka (Shakun *et al*., 2015b), interpreted as the minimum ages of deglaciation. Weng *et al*. interpret high sedimentation rate and increased magnetic susceptibility as glacial outwash intensity related to glacier recession, not advance. They note a reduction in MS from 12.5 to 10 ka, and see vegetation shifts reflecting cool, dry conditions and interpret this to evidence of a YD chron advance. The subsequent deglaciation resumes at 10 ka and is relatively quick, with complete loss of ice by 7.5 ka.

4.2. Cordillera Blanca

Site of the world’s most glacierized tropical mountains currently, with >25 summits over 6000 m, this range also features multiple stages of prominent moraines that indicate much more extensive glaciers in the past. Equilibrium-line-altitude (ELA) reconstructions indicate that ELAs during the last glacial maximum (LGM: marine isotope stage 2) were c. 4300 m in the Cordillera Blanca, c. 3900 3600 m on the west side of the Cordillera Oriental, and c. 3200 m on the east (Amazon Basin) side of the Cordillera Oriental. Comparison with estimated modern ELAs and glaciation thresholds indicate that ELA depression ranged from c. 700 m in the Cordillera Blanca to c. 1200 m on the east side of the Cordillera Oriental. This augments data from many mountain ranges in middle- and low- latitude regions that indicate that ELAs during the LGM were depressed by c. 1000 m. Published palynological evidence for drier conditions during the LGM in the tropical Andes suggests that ELA depression of this amount involved a temperature reduction (>5-6-degrees-C) that greatly exceeded the tropical sea surface temperature depression estimates of CLIMAP (<2- degrees-C) (Mark *et al*., 2005). The west to east increase in ELA depression during the LGM indicates that the steep modern precipitation gradients may have been even steeper during the LGM.

Initial descriptions of the moraines relied primarily upon superposition and similarity of form between valleys to cluster into four relative age groups (Clapperton, 1981). Rodbell provided more substantive chronological classification based on relative weathering features and minimum radiocarbon dates, identifying two moraine stages, Rurec and Laguna Baja, with ages likely close to (pre and post) LGM (Rodbell, 1993a). Subsequent TCN dates based on samples from the SW aspect Cojup and Llaca Valleys, show a two stages within the last glacial with average ages of 24.7 ka (Rurec) and 18.6 ka (Laguna Baja) (Faber *et al*., 2005). In the Rurec Valley, closely bounded late-glacial Manachaque moraine at the Breque site was confirmed as 12.7 ka, indicating a readvance at this time, followed by relatively rapid recession.

This pattern conforms to a general pattern seen by integrating the TCN moraine ages throughout the region with a stacked, composite record of lake sediments (Rodbell *et al*., 2008) that indicates a decline in clastic sediment flux that began ~20 ka appearing to mark the onset of deglaciation, at least one millennium prior to significant warming in high latitude regions. The interval between 20 and 18 ka was marked by near-Holocene levels of clastic sediment flux, and appears to have been an interval of much reduced ice extent. An abrupt increase in clastic sediment flux 18 ka heralded the onset of an interval of expanded ice cover that lasted until ~14 ka. Clastic sediment flux declined thereafter to reach the lowest levels of the entire length of record during the early–middle Holocene.

The oldest post-LGM moraines from the Cordillera Blanca that have been dated by TCN are located in the Juellesh and Tuco valleys. The M6 moraine presented by Smith and Rodbell (2010) has inner and outer loops that date to ~18.8 ± 2.0 ka and ~18.7 ± 1.6 ka, respectively. Glasser presented similar ages on an outer lateral moraine in the Tuco valley at ~18.3 ± 1.4 ka. The M4 inner lateral moraine dates to ~18.8 ± 2.3 ka, and Glasser *et al*. (2009) similar ages on that moraine from ~17.9 ± 0.9 ka.

The Late Glacial TCN ages from Queshque (Stansell *et al*., 2017) are comparable to the Glasser *et al*. (2009) and Smith and Rodbell (2010) Late Glacial and Holocene TCN ages from the nearby Jeullesh valley. The available The M5 moraine (15.7 ± 1.8 ka) has been interpreted by Smith and Rodbell (2010) as recessional, or possibly a stillstand feature. Similar ages have been presented for the middle Juellesh valley moraine (ca. 14.1 ± 0.1 ka) by Glasser *et al*. (2009). The M3 left-lateral moraine of Smith and Rodbell (2010) date to ca. 14.4 ± 0.5 ka, and could actually be from the M5 ice limit. The M5 ice limit is thus likely associated with the right-lateral moraine below Lower Queshquecocha (ca. 13.8 ± 0.4 ka).

Ice core records from Nevado Huascarán indicate that periods of cooling at the onset of the ACR, and just prior to the start of the YD, punctuated an overall trend of warming conditions during the Late Glacial. The Breque site in the Cordillera Blanca provides a close limiting age for glacier advance between 13.2 and 12.9 ka (11.28 and 10.99 ^{14}C ka BP), with rapid recession afterwards. The age for the Breque moraine is supported by 10Be ages that range from 13.2 ± 0.5 to 10.4 ± 0.4 ka (Farber *et al*., 2005). Notably, there is a lack of TCN ages within the YD for the Jeullesh and Queshque valleys, which is consistent with evidence of retreating ice margins based on the closely dated Manachaque moraine in the nearby Breque valley (Rodbell and Seltzer, 2000).

Evidence for early Holocene readvances or stillstands in the Cordillera Blanca is recorded in TCN ages and supported by the lake sediment data from the Queshque valley (Stansell *et al*., 2017). End moraines enclosing Upper Queshquecocha were constructed ca. 10.8 ka, and then ice retreated sometime after ca. 10.4 ka. These moraine ages generally correspond to the timing of increased clastic sediment flux in Lower Queshquecocha from ca. 10.4 to 9.8 ka. Another early Holocene end moraine ~180 m up-valley from the upper lake formed sometime prior to ca. 9.4 ± 0.3 ka. Similarly, a recessional moraine or stillstand feature upvalley from the M5 position in the Jeullesh valley dates to ca. 11.6 ± 0.4 ka (Glasser *et al*., 2009), which is similar in age to the early Holocene end moraines that are between Upper Queshquecocha and Lower Queshquecocha (10.9 ± 0.1 and 10.5 ± 0.4 ka).

4.3. Cordilleras Huayhuash and Raura

South and east of the Cordillera Blanca, the Cordilleras Huayhuash (10°16’S) and Raura (10°28’S) are currently glacierized, with highest summits over 6500 m (Yerupaja) in the Huayhuash, and just below 5700 m in the Raura. The summits are steep, NW to SE trending ridges, with steeper and more incised valleys on the west. The most comprehensive dataset for the Cordillera Huayhuash, to date, was presented by Hall *et al*. (2009). Here they include both basal radiocarbon ages from lake sediment records and TCN ages on moraine boulders. The revised TCN ages that represent various stages of deglaciation are centered on ~17.8 to 16.5 ka, 14.9 to 14.3 ka, and 11.6 to 9.0 ka. Paleoglacier margins below Lake Jahuacocha on the western side of the Huayhuash were also dated to the late glacial stage. While the moraine that impounds Jahuacocha has revised TCN ages ranging from ~12.2 ± 0.5 to 8.7 ± 0.4 ka, the basal lake sediments radiocarbon date to ~9.0 ka (Stansell *et al*., 2013). These ages combined with basal ages from the Jahuacocha sediment core suggest that the lake formed after the early Holocene glacier retreated up valley, and that the glacier terminus subsequently remained above that elevation.

Very little work regarding the timing of Late Glacial deglaciation has been done in the Cordillera Raura. A radiocarbon age of 14.7 ka (12.5 ± 0.3 ^{14}C kyr BP) from peat inside a Lateglacial moraine on the eastern side of the Cordillera Raura provides a minimum age for deglaciation (Cardich *et al*., 1977). There are no existing records that span the remaining Late Glacial and early Holocene, however, the Lutacocha record from the Cordillera Raura contains a basal radiocarbon age of ~9800 years suggesting that at least one readvance occurred (Stansell *et al*., 2013).

4.4. Junin Region

Wright conducted surveys in the Junin Region that provided additional time constraints on late-glacial to Holocene glaciations (Wright, 1983, 1984). He observed two distinct phases of Pleistocene glacier advances, the Rio Blanco and the Punrun, and concluded that deglaciation from the younger began by at least ~14 ka calibrated (12 ^{14}C k yr BP) based on basal ages from Rio Blanco pond (Wright, 1983; Rodbell *et al*., 2009). The mapping efforts relied on careful distinction of superposition and relative dating of moraines, till and outwash. A section of buried organic lake sediments beneath the Punrun till were dated at >42 ^{14}C kyr BP (SI-1491), and give a minimum for the underlying and slightly more expansive Rio Blanco glaciation. However, constraining the timing of deglaciation from the Punrun is difficult given the potential for dead ice to have remained on the till plain, as well as the hard water effects in carbonate lakes that influenced the radiocarbon dates. Yet given the flat topography and low relief, the deglaciation was likely rapid. A layer of clay within sediments between depths of 12 and 21 m extracted from L. Junin was interpreted to be outwash from Punrun glaciers; bounding dates (uncalibrated): 23,980 ± 320 (Beta-3217) and 12,010 ± 110 yr B.P. (Beta-3216).

In a second publication, Wright (1984) reassessed a readvance for glaciers terminating about 10 ^{14}C kyr BP that he calls the Taptapata. However, the description of moraines is not clear, and reported dates from lakes are contradictory. Wright suggested the lake dates may be too old given carbonate bedrock and hard water effects.

Smith *et al*. (2005) published 146 TCN dates sampled from boulders and bedrock exposures in four of the valleys east of Lake Junin, draining the Cordillera Oriental. These ages cluster into four groupings (A to D), with the oldest (C and D) having ages considerably older (>65 ka to >200 ka) than the last glacial cycle. The second to youngest is what the authors called the LLGM, and recalculated values show ages spanning from ~32 to 27 ka, that predate the LGM and are midway down the valleys. A second late-glacial moraine 1-2 km upvalley from the LLGM moraines typically dams lakes and has dates ranging from ~21-19 ka. A third, smaller group of late glacial moraines dates to ~18 ka.

Notably, the paleoglacier valleys that were sampled are broad low gradient valleys without modern glaciers, with maximum headwall elevations of ~4600 m. Three of the valleys (Alcacocha, Antacocha, and Calcacocha) drain westward to the Junin plain, with a total relief of only ~500 m. Moraines in only one eastern draining valley, Collpa, were sampled, and reveal ages of group C (LLGM). The interpretation is that the LLGM was much earlier than the global LGM, and that deglaciation proceeded rapidly after 15 ka, when the moisture conditions on the Altiplano dried. They make links to the Pacific SST record, and global ice volume, suggesting a decoupling in the timing of Andean mountain glaciers from the global ice sheets.

4.5. Nevado Huaguruncho

Lake sediments and TCN exposure ages provide a detailed integrated record of the timing of Late Glacial and Holocene glacial activity at Nevado Huaguruncho in the Eastern Cordillera of the tropical Peruvian Andes (Stansell *et al.*, 2015). Glaciers expanded ca. 14.1 ± 0.4 ka, during the first half of the ACR. This was followed by an interval of ice retreat from 13.7-12 ka, an interval that spans most of the YD. Glacigenic clastic sediment proxies from Lake Yanacocha indicate an abrupt glacial expansion starting at ca. 12 ka that culminated in moraines constructed from 11.6 ± 0.2 ka to 10.3 ± 0.2 ka. Ice advanced or stabilized under colder and drier atmospheric conditions during the early Holocene.

This mountain setting features a currently glacierized central horn and converging arêtes that attain a maximum summit elevation just under 5700 m, surrounded by lower gradient U-shaped valleys that radiate in different aspects. The features dated by Stansell *et al.* (2015) are contained within a broad cirque with lakes at ~4300 m that captures glaciers with southerly and easterly aspect. The moraine mapped as bounding Yanacocha is parallel with other laterals that exit to the east and south, terminating ~4000 m. These are likely late-glacial in age, but do not extend to the limits of the longer glacial valleys of U-shape form, indicating earlier extensions of ice were larger.

4.6. Cordilleras Vilcabamba, Vilcanota and Quelccaya

Glacier moraines in the Cordillera Vilcabamba (13°60’S), on the NW side of the Cordillera Vilcanota (13°45’S), and the western side of the Quelccaya Ice Cap (13°55’S) have long been recognized for having multiple series of relic moraines. In the Cordillera Vilcabamba, TCN ages indicate an outer distal moraine (Sisaypampa) dates to 12.9 ± 0.9 ka, the Rio Blanco outer moraine has ages of 11.1 ± 0.4 ka, and the Sisaypampa outer proximal moraine dates to 10.5 ± 0.7 ka (Licciardi *et al.*, 2009). Mercer discovered impounded peat in the Upismayo valley draining to the NW from Ausengate (6387 m), the highest summit of the Vilcanota, that gave the first maximum limiting radiocarbon date for a late-glacial advance at 14 ^{14}C k yr BP (Mercer and Palacios, 1977). The site was revisited and a full section of peat exposed that gave a maximum age for the late-glacial moraines of 16.7 ± 0.4 ka. and a minimum age of 41 ka for the older moraines terminating further down valley where a broad till plain ends with moraines as low as 3600 m near Ocongate (Goodman *et al.*, 2001; Mark *et al.*, 2002). On the Quelccaya side, Mercer named the Huancane 1, 2 and 3

(H1-3) moraine stages as successively older and more extensive ice margins around the largest tropical ice cap, Quelccaya (Mercer and Palacios, 1977). The oldest H3 extension was constrained by a minimum of 14.3 ka, and a buried peat under H2 gave a maximum age of 12.8 ka. More comprehensive late-moraine mapping and chronology studies featuring abundant radiocarbon ages further delimited deglaciation from the late-glacial advance with additional minimum ages for H3 positions of 13.6-12.8 ka, as well as a readvance culminating at 12.5-12.4 ka that then receded quickly to Holocene limits by 11.6 ka (Kelly *et al*., 2012). Late Holocene moraines were also dated in high detail (Stroup *et al*., 2014). Ample material for maximum and minimum dates constrain a date of 12.35 ka for H2a moraine, allowing for ^{10}Be production rates to be calculated (Kelly *et al*., 2015).

4.7. Cordillera Ampato - Nevado Coropuna, Hualca Hualca

Bromley *et al*. (2009) conducted thorough geomorphological field mapping on Coropuna, and published a map of glacial deposits, along with ^{3}H ages for LGM and Late Glacial ages. The distribution and stratigraphy of drift deposits and TCN dates suggest a late Pleistocene maximum ~25-15 ka, followed by recession from the C1 moraines over 7-6 ka before a late glacial advance to C2 moraines dated ~13 ka. At least two older pre-C1 advances are inferred from more extensive drift. Recalculating these ages using updated calibration methods yields values that are slightly different than the original published data (Bromley, personal communication). Nevertheless, their data indicate an older advance occurred from ~25.3 to 24.5 ka near the LGM, and another cluster of somewhat younger ages from ~21.1 to 20.7 ka. There are Late Glacial ages that cluster around 19.4 to 14.9, and another group from 13.3 to 10.6 ka.

Alcalá *et al*. (2011) used cosmogenic ^{36}Cl isotopes to date moraine boulders on the Hualca Hualca stratovolcano (15°49'S) in the Cordillera Occidental in southern Peru, near Arequipa. The LLGM here occurred ~17.9 ± 0.1 to 16.8 ± 0.4 kyr. They determined that widespread deglaciation on the Patapampa Altiplano culminated at ~12.6 ± 0.4 kyr, but that moraines were still being constructed until ~12.0 kyr, suggesting that multiple readvances occurred.

4.8. Cordilleras Carabaya and Apolobamba

In the Cordillera Apolobamba (14°35'-15°S), lakes and peatlands bounded by Late Glacial moraines have radiocarbon ages that date between 12.5 and 9.0 ka (10.5 ± 0.1 to 8.1 ± 0.2 ^{14}Cka) (Seltzer, 1990).

The Cordillera Carabaya (14.3˚S) is on the eastern edge of the Altiplano, south of the Quelccaya Ice Cap, comprising relatively low elevation ridges (<5200 m) and broad valleys that drain southward to the Titicaca basin. Field mapping combined with TCN sampling yielded 10Be dates (n=12) from two field sites, Laguna Acrimona and Minas Tira, that range from 26 ka to 15 ka (Bromley *et al*., 2016). These ages were derived by applying the new high elevation tropical production rate calibrated at nearby Quelccaya (Kelly *et al*., 2015) and significantly affirm that the most extensive advance of the last glacial cycle pre-dates the LGM.

At the Minas Tira site, the Quebrada Tirataña is a broad, curving, low-gradient valley draining to the south from draining Nevado Tolqueri (5275 m asl), that defines a ridge with small remaining glaciers at <5200 m. The low relief site is grassy, broad, and lacks many large boulders. There are three distinct lateral-terminal moraines on the western, right-lateral edge, and multiple terminal crests that cross the valley. Four TCN samples were taken from boulders on these terminal moraines, and these have ages from 26-22 ka, showing oldest on the outer limit and consistently younger toward the inner. The close clustering is interpreted to mean that inheritance is limited. A tributary valley, Q. Jotini, has a prominent series of lateral and terminal moraines terminating proximal to, but not merging with, Q. Tirataña. The authors count 14 terminal ridges in the Minas Tira site within 500m (at 4550-4600 m). The paleoglacier that formed these was apparently draining a plateau with hummocky topography, lakes and wetlands (~4850 m) about 4 km west of the summit ridge. Observing independently (using GE), this was likely an outlet glacier from an old ice cap. Also visible on GE is a series of lateral-terminal moraines draining W, with a defined upper edge to the left-lateral at ~4770 m that could have been the ice cap ELA (i.e. Porter, 2001). There is a series of terminal moraines damming a lake ~2.5 km upvalley from the Minas Tira termini that were not described in the paper.

Laguna Aricoma is ~50 km to the ESE and is one of a series of lake filled valleys draining to the south from an E-W trending ridge with headwall summit elevations <5200 m and very small remnant glaciers. The valleys feature a prominent series of inset lateral-terminal loops damming lakes with cross-cutting stratigraphy that clearly indicates that the younger moraines were a readvance that the authors name Veluyoccocha after the lake impounded by the moraine. Two granite boulders from the outer ridge of the older composite right-lateral moraine date to 19 ka. The dates from the terminus (n=2) of the Veluyoccocha readvance come in at around 16 ka. Proximal to the limits, two younger right-lateral moraine ages are 15.5 and 15.2 ka.

The authors interpret these results to suggest that glaciers attained their maximum extent earlier than LGM, with an MIS 2 advance in place by ~28 ka that remained close to its limit throughout the LGM, at least until 19 ka. If the 19 ka is a deglacial age, it represents termination 1. Then, by 16 ka, there had been rapid recession of ~50% of the length before subsequent re-advance at that time. The slightly contrasting moraine sets in the two different valleys also constrains the late-glacial readvance. The 16 ka event that does demarcate a nice ridge and dam lakes to the East at Aricoma where there is a slightly higher headwall, and summits ~5200 m (currently tiny glacierettes).

4.9. Cordillera Real

In the San Francisco valley, Zech *et al.* (2007) dated 2 sets of Late Glacial moraines using ^{10}Be. The older set dated from 18.9 to 13.7 ka. The younger set dated from 15.3 to 14.6 ka. In the Zongo valley of the Cordillera Real (16°17'S) to the southeast, minimum-limiting Late Glacial moraine ages date to ~11.2 ka (9.8 ± 0.1 ^{14}Cka) (Seltzer *et al.*, 1995). In the same Zongo valley, TCN ages on older Late Glacial moraines range from 21.9 to 14.2 ka. A younger group of Late Glacial moraines dates from 18.1 to 14.1 ka

(Smith *et al*., 2005). Basal sediments from moraine-dammed lakes and peatlands in the Palcoco and Milluni valleys have radiocarbon ages that range from 12.8 to 10.9 ka (10.9 ± 0.1 to 9.6 ± 0.1 ^{14}Cka) (Seltzer, 1992). Smith *et al*. (2005) reported TCN ages of late glacial moraines that date from 19.4 to 10.3 ka.

Illimani massif (16°39'S) rises to a summit elevation of ~6400 m at the southern end of the Cordillera Real, separated from the range by the east-draining Khañuma Valley that drains to the SE of La Paz. A geomorphic mapping and chronology study featuring 23 ^{10}Be samples of granodiorite boulders along moraines in the north-facing Pasto Grande valley identified three series of moraines (A - C from oldest to youngest) that are interpreted to represent initiations of deglaciation from late glacial, early and late Holocene positions (Smith *et al*., 2011). Since these moraine ages are not in the Shakun *et al*. (2015a) composite, we recalculated the ages using the Quelccaya production rates and constant production model using the CRONUS on-line calculator. The recalculated ages suggest that glaciers retreated, or experienced stillstands sometime after ~16.6 ka, 15.1 ka, and 10.1 ka. The most extensive glacial advance showed ELA depressions computed to be 400-600 m, consistent with other localities along the Eastern Cordillera.

The oldest dated Group A moraines are subdivided into A1 and A2 because the forms are not continuous between lateral and end moraine. Nor are the moraines detected from GE imagery, but can be located by elevation within the valley. The Pasto Grande valley stream descends as low as 3850 m before converging with a southern aspect glacial valley draining from a 5800 m summit at Tres Rios before draining to the east in the main Khañuma Valley. Well-defined left-lateral moraine ridges are visible at this confluence, indicating paleoglacial extension predating the lateglacial Group A that extended lower (<3500 m), but no dates are available.

4.10. Cordillera Cochabamba

The Wara Wara Valley of the Cordillera Cochabamba (17°17'S) is currently not glacierized, and comprises a broad U-shaped valley rising to a headwall ridge crest at 4300 m. The valley was investigated and a series of inset moraines sampled in 5 clusters (oldest to youngest, W1-W5) for TCN dating (Zech *et al*., 2010). The ages of the two oldest clusters that are sampled on closely inset R-lateral ridges, are interpreted as correlating with H1 (W1) and the YD (W2), with the recession between them thus aligning with the Bolling-Alerod period. The authors suggest that the timing of advances and retreats corresponds to SST changes in the eastern tropical Pacific as recorded by Kienast *et al*. (2006). They also corroborate this with inverse paleoglacier modeling from the region (Kull *et al*., 2008) to suggest wetter conditions prevailed for these advances, consistent with pluvial conditions that raised Altiplano lakes (Placzek *et al*., 2006). The recalculated ages, however, place these moraine groups from oldest to youngest at 19.8 ± 1.5 (W1), 16.9 ± 0.9 (W2), 15.0 ± 0.8 (W3), 14.9 ± 0.6 (W4), and 12.8 ± 0.9 (W5) ka. The W1 moraines thus appear to represent post-LGM ice extent, followed by the W2 moraines that date within the Oldest Dryas.

The authors orginally describe an early Holocene readvance at ~10 ka based on the W3 and W4 moraines, however the recalculated ages place these closer to the ACR.

These are much smaller forms in the valleys, and W4 is upvalley but almost identical in age to W3. The low ridges may therefore also represent recessionals and not distinct re-advances of paleoglaciers in the ACR. Complete deglaciation of the valley was apparently rapid and completed by 13 ka, based on the W5 ages from boulders on hummocky terrain close to the headwall.

4.11. Sajama

Sajama (18°07'S, 68°53'W) is a stratovolcano rising to 6542m on the eastern side of the Western Cordillera with an extant ice cap that was cored to bedrock, yielding a 25 k yr paleoclimate record (Thompson *et al.*, 1998). Comprehensive field mapping and TCN dating of the moraines surrounding Sajama shows a late glacial advance that was cold based, with Cl-36 ages (n=36) coming in at 16-10 ka (Smith *et al.*, 2009). Combined with minimum radiocarbon ages behind inset moraines, the data show glacier recession was initiated from early and mid-Holocene positions at 7-4.4 ka, and 4.7-3.3 ka. The dates are presented as a range, spread between the arithmetic mean and maximum TCN date.

The relative change in conditions from cold-based late glacial extent to warm-based Holocene glaciation suggests that deglaciation featured significant alterations of precipitation and temperature in this part of the now arid western Altiplano.

4.12. Central Altiplano

Aridity increases towards the southern limit of Bolivia, where only the eastern cordillera is glaciated. Multiple archives indicate that glaciers remained advanced in the Salar de Uyuni region well after the global LGM. Clayton and Clapperton (1997) identified till and outwash associated with the local LGM on Cerro Azanques that folded peat with a maximum-limiting age of ~16.7 ka (14.0 ± 0.1 to 13.3 ± 0.1 ^{14}C. Clapperton (1998) presented an additional 10 unpublished ^{14}C ages on the same peat deposits that range from 15.9 to 15.1 ka (13.4 to 12.9 ^{14}C) as support for the timing of the local LGM. These deposits have alternatively been interpreted by Heine (2000) as mass wasting events.

More recently, cosmogenic ^{3}He ages of glacial landforms from Cerro Tunupa support the earlier evidence of Clayton and Clapperton (1997), and indicate that glaciers associated with the last glacial cycle were at their maximum extent until ~15 ka (Blard *et al.*, 2009). The firm chronology suggests that local LGM conditions correspond to cold and wetter conditions during the paleolake Tauca highstand between ~17 and 15 ka (Clapperton *et al.*, 1997; Clayton and Clapperton, 1997; Placzek *et al.*, 2006; Blard *et al.*, 2009). Moraines of similar ages have been identified at Sajama with the outermost features dating from 16.9 to 11.8 ka, and another batch of ages dates somewhat younger from 14.0 to 10.2 ka (Smith *et al.*, 2009). There is also evidence of a glacial readvance sometime between 13.2 and 12.3 ka, which possibly occurred during the Younger Dryas, followed by a complete deglaciation of Tunupa after ~12 ka (Blard *et al.*, 2009).

5. Discussion: Synthesis of dates and climate events

Although considerable uncertainty remains regarding the age distributions for specific moraine chronologies, a general deglacial sequence is apparent when considering post LGM. Sedimentary sequences in Titicaca and Junin, along with compilations of multiple smaller lakes closer to headwalls (i.e. Rodbell *et al*., 2008) provide evidence that the maximum extent of glaciers predates the LGM. Regardless of initiation, many TCN dates on moraines and 14C dates from sediments fall within a range close to the LGM, suggesting that after the global LGM, glaciers either lingered at select locations for several millennia, or ice experienced a readvance. One of the earliest identified close minimum limiting age for glaciation near the global LGM is from Laguna Kollpa Kkota, Bolivia (Seltzer, 1994), where 14C dates from sediments behind moraines delimited the impounding moraine from 23-20 ka. Many moraines do not have dates constraining them, especially max limiting ages. On the other hand, moraine loops at Calcalcocha and Alcacocha in the Junin region yield near-LGM ages (~22 to 20 ka). There are also similar ages on the San Cirilo moraine near Cajamarca, the M6 moraine in the Juellesh Valley of the Cordillera Blanca, and the C1 moraine on Coropuna. In all, the available TCN ages on groups of moraines that date near the timing of the LGM have a mean of 25.1 ka, and standard deviation of 4.0 ka. Notably, there is considerable uncertainty in these apparent LGM ages (up to ± 7.2 ka), especially for boulders with ages greater than ~24 ka, and thus, the timing of the local LGM should be interpreted cautiously. It is also worth noting that the range in possible scaling factors and production rates is another source of uncertainty, however, these variables lead to only ~10% differences in the final calculated ages throughout this study.

There is some evidence of post-LGM moraine abandonment in the southern tropical Andes. The mean age for all observed groups of post-LGM boulders is 18.9 ka with a standard deviation of 0.5. While uncertainties in ages for individual moraine groups range from 0.8 to 4.3 ka, it is clear that a significant number of boulders have ages that are younger than the LGM. In the Antacocha and Calcalcocha valleys near Junin, there is another cluster of moraine ages between ~20 and 18 ka. Moraines near Cajamarca, the Carhuacocha valley of the Cordillera Huayhuash, and the Cordillera Blanca also date within this post-LGM interval. Dated boulders in the outer tropics of Bolivia have also show signs of post-LGM deposition, including the Zongo group C, Huara Loma, Coropuna, and Cochabamba moraines.

Multiple valleys in Peru and Bolivia contain evidence of glacial advances during the Oldest Dryas (~18 to 14.6 ka). The mean of all groups of moraine boulders that date within the Oldest Dryas is 16.1 ka with a standard deviation of 1.1. The Alacacocha valley near Junin, the Juellesh and Tuco valleys of the Cordillera Blanca, and multiple valleys in the Cordillera Huayhuash all have moraine ages that date to within this interval. Further south in Bolivia, the Rio Suturi, Huara Loma, Wara Wara, and San Francisco valleys have moraine boulders that date to within the Older Dryas. Radiocarbon ages from the Cordillera Vilcanota provide evidence that glaciers advanced sometime after ~18.0 to 16.8 BP (Mercer and Palacios, 1977; Mercer, 1984), and radiocarbon ages from the Altiplano indicate an advance occurred there from ~17 to 15.4 ka (Clapperton *et al*., 1997; Clapperton, 1998).

There is evidence for glaciers advancing in multiple regions of Peru of Bolivia during the ACR (14.6 to 12.6 ka). The mean of all groups of moraine boulders that date within the ACR is 13.7 ka with a standard deviation of 0.8. Periods of cooling at the beginning and end of the ACR can be identified in the ice core record from Nevado Huascaran in the Cordillera Blanca, which is consistent with other glacial-geologic evidence. Moraine ages from the Cordillera Huayhuash date to the start of the ACR, whereas the Breque valley in the Cordillera Blanca, and the Cordillera Vilcabamba has moraine ages that date to the end of the ACR. Moraines in the Eastern Cordillera of Peru at Nevado Huaguruncho also date to the start of the ACR. In Bolivia, boulders from the Wara Wara valley date to the start of the ACR, while the Mulluni and Telata glaciers date closer to the middle of the ACR (13.6 and 13.4 ka, respectively).

Referencing the Sajama and Huascaran ice cores spanning to the late-glacial, there is an apparent Deglacial Cold Reversal (DCR) that happens ~1000 yrs prior to the initiation of the YD, and covers the time of glacier readvance. Then, while the NH is experiencing peak cold of YD, the glaciers rapidly recede. The evidence of this recession is constrained by minimum ages behind the moraines. It ties into a site in Bolivia (Abbott *et al*., 1997), where a cirque lake (16S, headwall 5650 m) shows min age of 12.7 ka (10.7 k ^{14}C yr BP). Because the regional conditions were cold, this rapid retreat was initially interpreted to be caused by local aridity, and a non-linear response to changing insolation.

Clapperton (1993) also compiled best dated sites to make a statement that there was compelling evidence for synchronous glacier advances throughout the Andes during the 12.5-10 ka interval ("suggestive if not yet persuasive"), and thus a Late-glacial climate shift that was widespread throughout the range. The Breque site in the Cordillera Blanca has evidence that suggests glaciers advanced just prior to, or at the start of, the YD. Similar evidence from the Vilcabamba in southern Peru suggests ice advanced at the start of the YD, but then ice retreated. The early work of Mercer and Palacios (1977) provides evidence that ice advanced near Quelccaya near the start and end of the YD. Similarly, Kelly *et al*. (2015) provide additional radiocarbon-based evidence that the Quelccaya Ice Cap advanced at the start of the YD, followed by retreat.

The idea of an early and rapid ice margin fluctuation in the tropical Peruvian Andes around the YD was put forward by Seltzer and Rodbell (2000) in consideration of glacial fluctuations at three key Peruvian sites near the YD. In Peruvian tropical Andes, they point at three localities reporting some glacier activity during the YD time:

1. Quelccaya Ice Cap: The radiocarbon evidence suggested initially that there was an ice advance to a position ~6km from modern ice that likely predated the YD (H2 moraine, 14.2 to 12.9 ka, from Mercer and Palacios, 1977). Rodbell and Seltzer (2000) published a minimum age of 12.9 ka from basal peat over glacial sediments in Pacococha, 500 m upvalley and closer to the ice edge, while Kelly *et al*. (2012) argue this was too old, and refer to other sediments dating to 11.6 ka as minimum.

2. Cordillera Oriental, Northern Peru: sediment records in lakes (Rodbell, 1993b) showed some evidence of readvance and reoccupation of higher cirques by glaciers, but no exact moraine has been dated.

3. Cordillera Blanca, Breque site. Detailed stratigraphy, cross-cutting moraines and closer limiting maximum and minimum ages place an ice advance to within 10 km of the modern glacier (with summit elevation 5700 m) between 13.1-12.8 ka. The TCN ages of 8 boulder samples from Farber *et al*. (2005) come in at 12.7 ka.

There is growing evidence of early Holocene advances in the Central Andes. The mean of all groups of moraine boulders that date within the early Holocene is 11.0 ka with a standard deviation of 0.4. For example, multiple valleys in the Cordillera Huayhuash have TCN ages that date between 11.4 to 10.5 ka, suggesting that glaciers either experienced a stillstand or readvance during the early Holocene. Early Holocene features are also well-dated at Huaguruncho (11.6 to 10.5 ka), and a moraine loop in southern Peru at Cordillera Vilcabamba dates to ~10.5 ka. Basal radiocarbon ages from Lutacocha in the Cordillera Raura suggest conditions became ice free, locally, soon after 9.4 ka. In the Vilcanota/QIC, till overlying peat dated to 11.1 and 10.9 ka give maximum limiting ages for the Huancane II moraines (of Mercer and Palacios, 1977), suggesting an early Holocene advance. Other sites recognizing this included Wright's mapped Taptapa moraine at 10.1 ka (Wright, 1984), followed by rapid deglaciation. The Quelccaya Ice Cap was recognized to be at the limit by 10 ka, given peat exposed at the margin (Thompson *et al*., 2006; Buffen *et al*., 2009).

The climatic forcing of deglaciation remains an important object of research, especially the Pleistocene Holocene transition that represents the most recent large-scale climate transition between radically different boundary conditions. The tropical Andes remain an especially important region to study this given its location between hemispheres. There has been much work over the past three decades compiling basic observations from glaciated terrain in these parts of the Andes that document significant variability in climatic conditions that allow glaciers to persist or not. Better age control and broader field coverage has resulted in a steady increase in the understanding of the nature and extent of glacier advances.

Clapperton (1993) was one of the first to compile the available evidence from a variety of paleoenvironmental sources for the entire South American continent to hypothesize the climatic context for the pattern and nature of LGM deglaciation. The few dates available on glacial moraines and lake levels led him to conclude that an early LGM advance (34-27 ka) for the Central Tropical Andes was supported by cold conditions, with enough humidity (i.e. higher lake levels) to support glacier advance. Yet shortly afterwards, as the global LGM was approached, conditions became more arid, forcing deglaciation. With better age control, however, many of these features were alternatively interpreted instead as being associated with late-glacial advances.

In synthesizing the available TCN dates, Zech *et al*. (2008, 2009) discuss that there is a consistent pattern of an early LGM advance, followed by late glacial advance, and rapid deglaciation that is seen in Peru in the Cordillera Blanca and around Junin, and in both the Cordilleras Real and Cochabamba in Bolivia. They pose a hypothesized climatic framework to explain the regional variation whereby the availability of adequate humidity in the tropical Andes makes them more prone to temperature changes, and the glacial advances are in synch with northern high latitudes. While there remain differences in dates resulting from choices of production rate and scaling factors made by different researchers, Zech co-authored a chapter with other regional researchers that listed explicitly different ages, but show how the overall pattern remains consistent (Zech *et al*., 2009).

While overall patterns of glacial-interglacial fluctuations are paced by orbital forcing, the mechanisms that can explain global synchronous changes are unclear. Gradual insolation changes focused on the mid-high latitudes of the NH are insufficient. More specifically, rapid shifts between warmer and colder states seen in records around N. Atlantic imply close coupling between oceanic and atmospheric dynamics not forced by slower, steady shifts in radiation. Nevertheless, these broad-scale oscillations most clearly identified in the North Atlantic region indicate abrupt climate changes that may or may not have had global impacts. A key example is the warm to cold transition recorded in isotopic records from Europe and Greenland ice cores revealing a late glacial climate sequence from a warm Bølling-Allerød (B/A) event followed by the cold YD, before the initially warm Holocene.

The synchroneity or asynchroneity of glacial variability in the tropical Andes relative to the high latitudes of the Northern and Southern Hemispheres is an area of active research. The premise of a global synchroneity of the glacial-interglacial transition implies something leveraging the slow progressive insolation changes to impose control globally. For example, Shakun *et al*. (2015a) suggest globally synchronous glacial variability at the start of deglaciation forced by CO_2 increases. However, regional climatic forcing likewise imposes major controls on glacial variability, and no one single mechanism can explain the timing of ice margin changes at all locations. Indeed, Shakun *et al*. (2015a) note that tropical Andean glaciers show a pronounced early initiation of recession that was likely due to ENSO, or hypsometry. Given the sensitivity of tropical Andean glaciers to SST changes (Bradley *et al*., 2009), it seems logical to focus our attention on coupled ocean-atmospheric processes, with rising CO_2 as a possible critical feedback, to explain the pattern of glacial variability observed across the tropical Andes. One possible mechanism is AMOC changes associated with an orbitally induced retreat of Northern Hemisphere ice sheets (He *et al*., 2013). Temperature changes in the Huascaran ice core record have been interpreted to be the result of SST variability in the North Atlantic (Thompson *et al*., 1995), and North Atlantic conditions strongly modulate the strength of the South American Summer Monsoon and precipitation dynamics in the tropical Andes (Bird *et al*., 2011; Vuille *et al*., 2012). The tropical Pacific Ocean also modulates circulation dynamics, precipitation amounts, and temperature in the Andes, and may have influenced western Andean ranges differentially over time (Smith *et al*., 2009). Other work in New Zealand and mid-latitude Chilean Lakes district (Doughty *et al*., 2015) also show a decoupling of glacier advances from local summer insolation that seems convincingly to pace the large Northern hemisphere ice sheets. In contrast, these southern mid-to-high-latitude sites suggest that glacier extent during the last termination was aligned with Southern Ocean surface temperature and with atmospheric carbon dioxide.

In the tropical Andes, glacier recession was occurring by 20 ka, and sedimentary records suggest that temperature (and perhaps greenhouse gas concentrations) were driving a rapid 1000 m snowline rise. A 24.7 ka lake sediment record from Lake Pacucha near Andahuaylas shows a transition from relatively wet and cool conditions in the LGM, with a marked late-glacial transition to a dry early Holocene (Hillyer *et al*., 2009). At Lake Titicaca, glaciers were in recession by 22-20 ka, even while wetter conditions prevailed from 25-15 ka based on fresh and overflowing conditions (Seltzer *et al*., 2002). This is further consistent with the existence of deep lake conditions on the now dried Salar de Uyuni salt flat from ~26ka to 15 ka. The wet conditions inferred by lake levels prevailed while insolation reached a maximum at 20 ka, and reduced to a minimum at 10 ka. Moreover, the initiation of deglaciation is more closely aligned to methane-tuned Antarctic ice core evidence of warming that initiated thousands of years prior to the NH, leading to the conclusion that tropical warming may have led deglacial warming at higher latitudes by ~5000 years. In relating both Titicaca and Junin sediments (i.e. Seltzer *et al*., 2000) as continuous records beyond the limit of glaciation, Seltzer *et al*. (2002) use peaks in magnetic susceptibility to document glacier advances, and the drop in such sediments as the initiation of deglaciation, since the coarse sediments were accumulating behind terminal moraines uphill. The Junin record shows glacial inputs of high magnetic susceptibility initiated ~30 ka, and persisted until an abrupt end at 22.5 ka. The further analysis of diatoms and carbonate conditions shows that the lake was relatively full of water during the initial deglaciation, suggesting the conditions were wet, and remained so until ~16ka. These wet conditions during initial deglaciation appear to be synchronous with temperature changes in the Northern Hemisphere whereby the strength of the SASM increased during cold periods (Kanner *et al*., 2012). Conditions then became drier during the ACR at a time glaciers were advancing in multiple valleys throughout the southern tropical Andes. During the YD time, Titicaca was fresh and overflowing, followed by a dry spell from 11.5-10 ka while conditions were relatively wet at Lake Junin (Seltzer *et al*., 2000).

Based on the available evidence, the deglaciation of the tropical Andes of Peru and Bolivia appears to be in-phase at times, and other times out-of-phase with cooling and warming trends in the Northern Hemisphere. Even though age control need to be refined, cooling during the Oldest Dryas of the Northern Hemisphere appears to correspond to ice advances in the tropical Andes. However, glaciers advanced during the B-A warming of the Northern Hemisphere, and thus Andean glacial records appear to be more in phase with the ACR during that phase. Likewise, glaciers retreated in the southern tropical Andes during the YD cold phase of the Northern Hemisphere, and then readvanced during early Holocene warming in the Northern Hemisphere.

6. Conclusions and outstanding questions

Studying the deglacial history of the tropical Andes reveals a complicated pattern of ice margin fluctuations, and precisely how the combined influences of both temperature and precipitation changes affected glaciers in the tropical Andes is unresolved. Early work in the Central Andes, based largely on radiocarbon dating methods, sparked considerable discussion regarding the timing and causes of post-

LGM climatic fluctuations in the tropics. More recent work that utilized cosmogenic dating methods has considerably improved our ability to date the timing and position of past ice advances and/or stillstands of glaciers. A major limitation of cosmogenic dating methods, however, is the discontinuous nature of moraine chronologies. More continuous records, like proglacial lake sediments, provide a means to develop more comprehensive paleoclimate records when combined with cosmogenic ages on moraines. In addition, as detailed hydroclimate records using stable isotopes become more available, we are better understanding how precipitation patterns have varied in the past in order to better evaluate the timing and causes of glacial variability on range of time-scales.

The available records suggest that the deglacial sequence is characterized by overall ice retreat punctuated by periods of brief ice advances and/or stillstands. In particular, moraines developed during the Oldest Dryas while it was cold in the Northern Hemisphere. During the remaining Late Glacial, however, glaciers appear to have readvanced and/or paused from retreat during the ACR while it was cold in the southern high latitudes, and dry in the central Andes. Glaciers were advanced just prior to, or at the start of the YD, followed by retreat. It remains unclear, however, how aridity during the YD might have played a role in ice retreat. Recently developed records suggest that an early Holocene ice advance, or stillstand, also occurred in the southern tropical Andes when the Northern Hemisphere was reaching near peak insolation values.

Questions still remain regarding the forcing mechanisms for deglaciation in the tropics. Precession likely drove the pattern of overall retreat, but other ocean and atmospheric mechanisms must have contributed to the glacial variability that interrupted the overall trend. While atmospheric CO_2 no doubt played a role in the deglaciation of the tropical Andes, internal modes of variability like ENSO, and other coupled ocean-atmospheric processes in the tropical Pacific and Atlantic Oceans must have been contributing factors. As records of glacial variability and paleoclimate records from terrestrial and marine locations continue to be developed at higher resolution, we need to improve our limited understanding of the climatic forcing mechanisms that caused ice margins to advance and retreat.

Future geomorphologic work should continue to seek localities to develop both sedimentary and moraine ages. There remain obvious regions lacking records (i.e. Fig. 1, regions between Cusco and the Junin Plain). Focusing on regions below thresholds of modern glaciers that also feature glacial lakes and moraines increases the likelihood of establishing pre-Holocene extents without the possible complications of Holocene readvances. Moreover, new techniques in exposure age dating using paired in situ ^{10}Be and ^{14}C measurements from bedrock exposures (Goehring *et al*., 2011; Goehring *et al*., 2013) that have promising potential to assist in untangling the complex histories and extent of mass changes during repeated glacier advances and retreats would be a high priority for ongoing research.

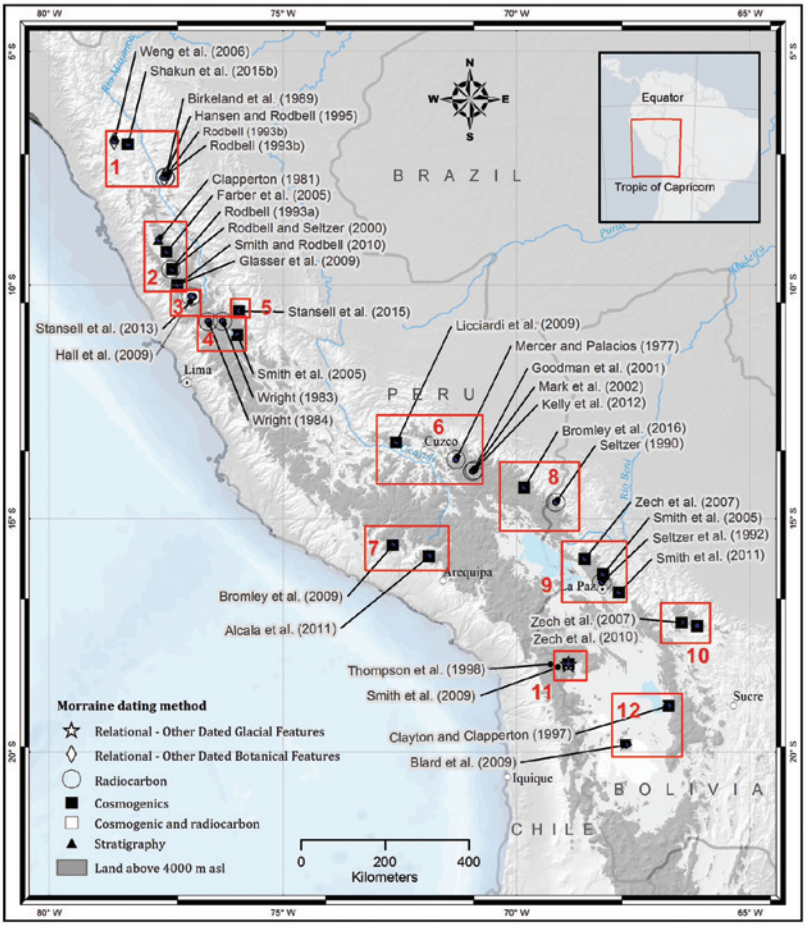

Figure 1: Location map of the major sites referenced in the paper, with key references cited.

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