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Glacial lacustrine records of Holocene climate variations in the Tropical Peruvian Andes

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By

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ABSTRACT

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Lake sediment cores taken from glacial lakes and wetlands are valuable proxies of glacial activity because they offer a continuous record of sediment input. Tropical alpine glaciers are especially sensitive to changes in precipitation and temperature, and thus the history of glaciation can be used in the reconstruction of past climates. Owing to a steep east-to-west moisture gradient across the Andes, glaciers in the eastern cordillera are more sensitive to changes in temperature whereas those in the drier, western, cordillera are more sensitive to changes in precipitation.

Multiple lacustrine sediment cores were taken from two sites in the central Peruvian Andes in June 2011: one set from the wet, eastern cordillera of the Andes and one set from the dry, western cordillera. These cores were measures for three proxy indicators of glacial erosion: magnetic susceptibility (MS), dry bulk density, and organic carbon content (TOC); cores were dated by radiocarbon. An ~6.7 meter-long core from a bog at the upper end of Laguna Shiurococha, located in the western cordillera (11.905°S, 75.960°W; 4585 m asl), records more than 3550 years of sedimentation. This core reveals a sharp decline in glacigenic sedimentation around 3550 cal yr BP, with very little glacial input thereafter. Laguna Yanacocha, located in the eastern cordillera of the Peruvian Andes (10.558°S, 75.927°W; 4358 m asl) yielded an ~2.6 meter-long sediment core that spans more than 13,700 cal yr. The sediment record reveals a two-step last deglaciation; the initial decline in glacigenic sediment input began about 14,000 cal yr BP and lasted until about 13,000 cal yr BP at which time glacial erosion increases and remained high until about 8,000 cal yr BP. For the past 8,000 cal yr, glacigenic sediment input into Laguna Yanacocha has been at a minimum. Cores from the western cordillera reveal significant ice expansion during the late Holocene that is not seen in the cores from the eastern cordillera. The $\delta^{18}O_{precip}$ record from nearby Laguna Pumococha reveal a period of aridity from the late Glacial through the early Holocene followed by a gradual increase in precipitation throughout the Holocene. Deglaciation of both cordillera appears to have been driven by the onset of drier and/or warmer conditions during the late Glacial. The relatively large readvance of glaciers in the western cordillera during the late Holocene was due to the onset of wetter conditions, which is evident in the depleted isotope values in regional carbonate lake cores. Western glaciers advanced more during this interval because these glaciers are more moisture sensitive than those in the eastern cordillera.

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I would like to thank my advisor and mentor Donald Rodbell for his extensive efforts in this project and without whom it would not have been possible. He was an amazing leader and teacher during the fieldwork in Peru and the extensive lab work at Union College. I would also like to thank the following individuals for field assistance in Peru: Emma Coronado (St. Lawrence University), Professor Alexander Stewart (St. Lawrence University), Christopher Sedlack (Ohio State University), Nathan Stansell (Ohio State University), Jessica Treanton (Colorado College), Erika Rodbell, and Frederico Manrique (Huaraz, Peru). I am also grateful for the funding for thesis project from the National Science Foundation and the Keck Geology Consortium. Finally, I would like to thank Deborah Klein (Geology Department, Union College) for her never ending assistance towards this thesis.

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INTRODUCTION

Climatology

Anthropogenic climate change has become a rising concern in today's society because of its potentially severe consequences to humanity and our modern way of life. This increasingly pressing topic has brought about an onslaught of research in the global scientific community focused on climate modeling and predictions. However, in order to predict the Earth's response to climatic forcing, such as the increased levels of atmospheric carbon dioxide, there must be a comprehensive understanding of the planets complex climate system. To achieve this, research has focused on the reconstruction of past climates that can be seen in the rapidly growing field of paleoclimatology. Paleoclimatology is the study of the planet's climate changes throughout its entire history and uses various proxy methods to determine these changes. This research is absolutely critical to distinguish a difference between natural climate variations, which the Earth has been undergoing for its entire history, and the recent warming we have seen in the past fifty years due to increased greenhouse gas concentrations.

Although early climate research focused on the Northern Hemisphere because of its driving forces in global ocean circulation, recent studies have found the tropics to play a significant role (Fritz et al., 2004; Rodbell et al., 2009). Research suggests that climatic forcing might actually begin in low latitude regions because many records show shifts in climate in the tropics to precede those in higher latitudes. In particular, the tropical hydrologic cycle has been found to affect atmospheric trace gases and global climate change, and the South American tropics are a key player within the tropical climate

system (Seltzer et al., 2000). Changes in sea surface temperature can largely affect the dynamics of atmospheric convection, especially in terms of the Intertropical Convergence Zone (ITCZ). The ITCZ is where the northern and southern trade winds meet near the equator and is where the atmosphere undergoes moist convection lifting air into the upper troposphere. The climate systems in the tropics have been found to be relatively sensitive to changes because this moist convection is so responsive to small changes in the environmental vertical stability. In particular, the location of the Atlantic ITCZ is sensitive to changes in SST, and its location shift can have serious implications for precipitation over South America. The startling power of tropical climate dynamics to affect the rest of the world can be seen in the global changes experienced during El Nino and La Nina years.

Since instrumental records of climate change do not extend beyond the past few centuries, paleoclimatology relies on a variety of proxy measurements to interpret climate variations beyond this. Climate proxies come in a wide variety of forms that all require complex interpretations because they are not direct climate measurements. Instead, a proxy is a preserved physical characteristic that can be understood as a reflection of a particular climate parameter or parameters. A few of the most reliable and commonly used natural archives of past climate reconstruction are ice cores, tree rings, pollen records, corals, speleothems and lake and ocean sediments. Different proxies are used for different focuses of paleoclimatology depending on the time scale, spatial scale, regional limitations and the particular climate aspects the researcher is focused on.

Stable Isotope Records of Paleoclimate

Due to large advances in mass spectrometry technology, stable isotope analysis has become an increasingly popular method of determining past climate variations. In particular, paleoclimatology has focused on the oxygen isotopic signal by using the $\delta^{18}O$ record preserved in ice cores, authigenic calcite in lacustrine sediments, speleothems and corals. The use of $\delta^{18}O$ as a record of paleoclimate is based on the differential fractionation of heavy, ^{18}O, relative to light, ^{16}O, oxygen isotopes that is associated with various natural processes. Different modes of preservation of the oxygen isotopic signal require particular interpretations because they there are many influencing factors that need to be considered. To accurately understand how the $\delta^{18}O$ records reflect paleoclimates, studies have been done on modern records that can be compared to the true instrumental measurements. This understanding is then applied to the paleorecords to increase the reliability of the interpretation.

When using the $\delta^{18}O$ record of calcite preserved in carbonate lake sediments the main driving forces considered are precipitation and temperature. As conditions become drier and/or warmer, it is reflected in the $\delta^{18}O$ record as relatively enriched values, while wetter and/or colder conditions produce depleted values. It is challenging to determine solely from the $\delta^{18}O$ record to differentiate between variation in precipitation and temperature. This is a large impediment in using stable oxygen isotope analysis as a tool for paleoclimate reconstruction because precipitation and temperature do not always vary together.

Glacial Records of Paleoclimate

Glaciers respond to climatic changes that affect their mass balance by either increasing or decreasing ice accumulation. Because of this, past glaciation has commonly been used as a record of regional and global climate patterns (Bradley, 1999). Glaciers are masses of ice that form as snow accumulates over time and is transformed first into firn, and eventually into glacial ice (Ritter et al., 2002). They are flowing bodies of ice constantly adjusting position and distribution in response to climate conditions. The mass balance of glaciers is equal to the amount of accumulation minus the amount of ablation. If the mass balance is positive the glacier must expand to adjust to the increased mass of ice and if it is negative the glacier will recede. There are two main types of glaciers, alpine and continental, and the most notable difference is the magnitude of size. Continental glaciers only exist today in the highest latitude regions of the world and respond slowly to long term, large scale climate changes such as the transitions between glacial and interglacial period of the Earth's history.

Alpine glaciers occur in high elevation mountain ranges where temperatures are low enough to allow for yearly accumulation. They flow down slopes of mountains and can grow large enough to fill valleys and cover mountain ranges. Alpine glaciers are especially sensitive to changes in precipitation and temperature due to their small size and reliance on cool temperatures at high elevations (Hall et al, 2009). For this reason, they can provide excellent records of small and local climate variations within the large scale shifts that affect continental ice sheets.

Glacial processes involve both deposition and erosion leaving various features that can be used for reconstruction. The glacial erosion process of abrasion produce large

amounts of fine-grained sediments called glacial flour as the ice and rocks it has picked up constantly flows over bedrock (Ritter et al., 2002). The most common depositional feature associated with glaciers are moraines, mounds of material (till) the ice has accumulated as it has grown. They are typically exposed after the glacier recedes and terminal moraines can be used to mark the extent of glacial expansion. Cosmogenic radionuclide dating (e.g., Gosse and Phillips, 2001) of surface material on these moraines has recently become a popular method for dating peak ice advances.

The glacial flour produced by through abrasion of alpine glaciers is often washed into glacial lakes and be preserved in these lake sediments. Dating and mapping moraines can give a snapshot of glaciation but cannot provide a continuous record like that preserved in glacial lacustrine sediments (Stansell et al., 2005; Polissar et al., 2006; Rodbell et al., 2008). This means that sediment cores for glacial regions are important proxies for climate reconstruction because they reflect changes in temperature and precipitation. To interpret glacial activity from lake cores, measurements must be made that are indicators of the amount of glacigenic clastic sediment input such as color analysis, magnetics, organic carbon content, and density. It can be difficult to find lakes with fast sedimentation rates that can produce high-resolution cores but the intermontane basins of the Peruvian Andes have potential to provide a long continuous record (Hooghiemstra and Sarmiento, 1991). There is still a relatively small amount of data on alpine glaciation in the Southern Hemisphere and particularly South America, but it is critical to push research in regions within the tropical Andes because of the important role the tropics play in the global climate system (Rodbell et al., 2008).

A major complication in using lacustrine sediment from glacial lakes as a record of climate variability is that alpine glaciers, like the $\delta^{18}O$ record, respond closely to variations in *both* temperature and precipitation (Luckman, 2000). The accurate reconstruction of past climates requires that we be able to differentiate between changes in these two variables affecting glaciation. Owing to steep east-to-west moisture gradients across the Andes, glaciers in the eastern cordillera are more sensitive to changes in precipitation whereas those on the drier, western, cordillera are more sensitive to changes in precipitation (Rodbell et al. 2009). This makes the Andes an excellent place to study alpine glaciation because one can compare records across the moisture gradient and tease out the signal of temperature and precipitation changes.

Because of the relevance of the tropics to global climate systems, the steep moisture gradient, the high sedimentation rates, and sensitivity of alpine glaciers, this study focuses on the tropical Peruvian Andes. It compares records of Holocene glaciation in the Western and Eastern cordilleras by using sediment cores and combines this glacial record with an oxygen isotope record from a carbonate lake to reconstruct climate variations.

OBJECTIVES

The objective of this study is to delineate a continuous record of Holocene glaciation in the tropical Peruvian Andes across a moisture gradient to differentiate between changes in precipitation and temperature (Figure 1). Glaciation is interpreted by measuring three sedimentologic properties: magnetic susceptibility, bulk density, and organic carbon content. The sedimentologic records are compared to a high-resolution and well dated stable oxygen isotope records from the region (Bird et al., 2011) to further interpret relative changes in precipitation and temperature.

Figure 1. Map of Peru indicating the research area within the black box.

METHODS

Multiple lacustrine sediment cores were taken from two sites in the central Peruvian Andes in June 2011 using a Livingstone piston corer: one in the wet, eastern cordillera and one in the dry, western cordillera. All lakes cored were also measured for modern water column properties using a hydrolab: temperature, pH, specific conductivity, dissolved oxygen, and turbidity. All of the cores were split, digitally photographed, and physically described at Union College in Schenectady, NY (Figure 1). They were then measured for magnetic susceptibility (MS) using a Bartington MS2 meter, then sampled, at least every 5 cm, or more depending on stratigraphy, and freeze dried to measure bulk density.

Figure 2. Digital photograph of Union College core lab where all cores were analyzed.

To calculate total organic carbon (TOC), samples were run first through a CM 2500 Autosampler Furnace, measuring total carbon (TC) by combustion at 1000°C to

convert all forms of carbon into carbon dioxide that was then measured with a UIC coulometer. Samples were then run through a CM 5230 to measure total inorganic carbon (TIC) by measuring carbon dioxide released after acidification (TIC). TOC was then calculated by subtracting TIC from TC: TOC = TC – TIC. All MS, bulk density, and TOC data was plotted using DeltaGraph.

To date the records, organic materials were sampled from cores and rinsed in DI water. These samples were then radiocarbon dated at the Keck Carbon Cycle AMS Facility, UC Irvine. The radiocarbon ages were converted to calibrated calendar years using CALIB 4.0, reporting ages in years before present (BP) where present is 1950 AD. An age-depth model was created for Laguna Yanacocha using linear interpolation in Microsoft Excel.

DATA

Modern Lake Properties:

The modern lake water properties of Laguna Yanacocha were measured in June 2011. The temperature plot shows a generally smooth decreasing trend from the water surface downward with two places where there is an increase rate of temperature change (Figure 2). The first occurs in the top meter of the water column, where temperature decreases from 10.09 C° to 9.52 C° and the second between a water depth of 10 to 13 m, in which the temperature decreases from 9.1 C° to 8.6 C°. The pH decreases gradually with increasing water depth, but remains within a range of 6.5-7 (Figure 2). The specific conductivity varies very little throughout the water column but does show a general increase at greater depths (Figure 2). This increase occurs between a water depth of 10 and 12 m. Both dissolved oxygen plots show the same trend of extremely gradual decrease until a water depth of 12 m, below which there is a jump to much lower oxygen levels, however they do not go below 50% (Figure 2). The turbidity of the lake water varies widely throughout the entire column within a range of 0.6-1.5 NTU (Figure 2).

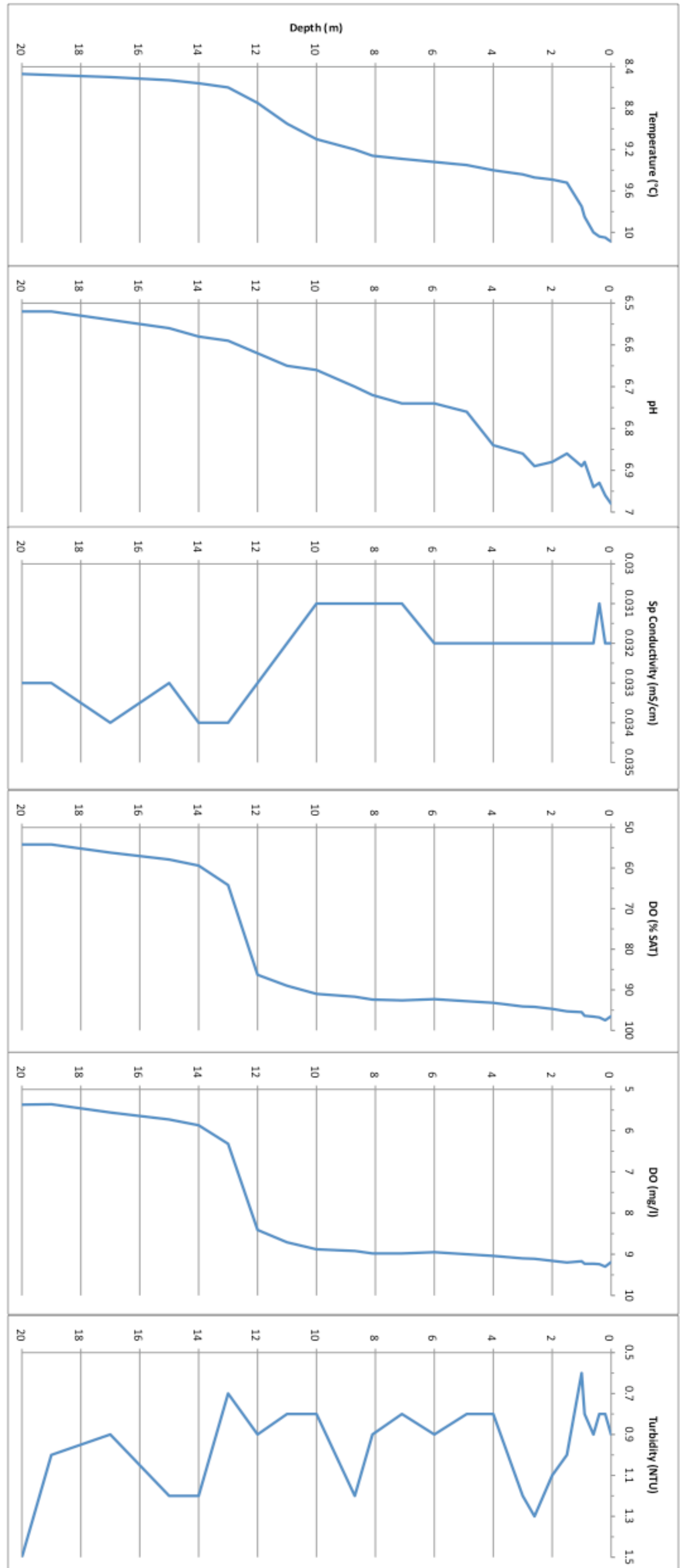

Figure 3. Hydrolab water column profile of Laguna Yanacocha in the Eastern Cordillera

Eastern Cordillera

The first study site is the Jaico Cirque that sits in the eastern cordillera of the Peruvian Andes within the Cerro de Pasco province of Peru. The catchment is located at the southern base of the presently ice-clad Nevado Huaguruncho (5,723 meters above sea level) (Figure 3).

Figure 4. Digital photograph of the peak Nevado Huaguruncho and the Jaico cirque including Laguna Yanacocha (left) and Laguna Jaico (right). Photograph is taken from Yanacocha Bog.

The drainage basin includes two lakes and multiple wetlands. Laguna Yanacocha is 26 m deep, has an area of 0.12 km^2, and sits at an elevation of 4,358 m asl (Figure 4). Laguna Jaico is over 62 m deep, has an area of 0.54 km^2, and is located at an elevation of 4,300 m asl. While in the field the dominant lithology was observed to consist of mostly granodioritic rock. The bedrock of the basin according to geologic

maps of the region is uniformly Paucartambo Formation (Triaasic-Jurassic) granodiorite, monzonite.

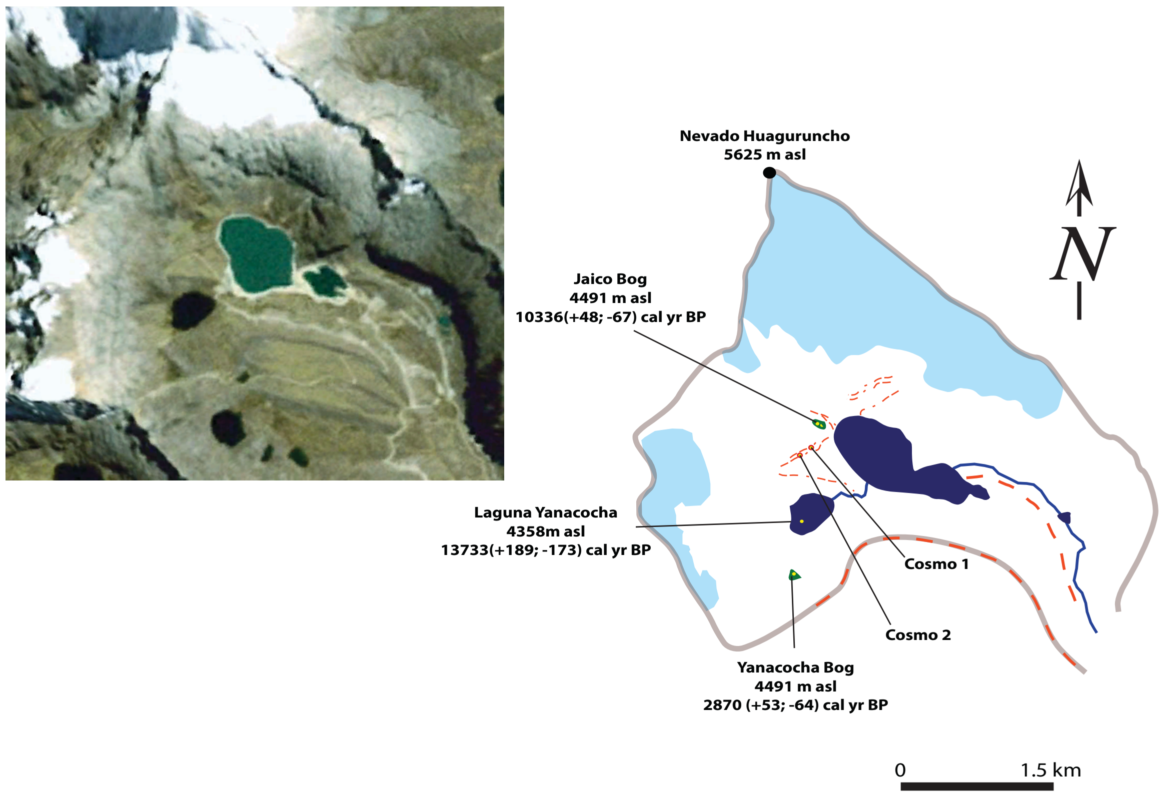

Figure 5. Google Earth image (1970) and geomorphic map of the Jaico Cirque. Light blue represents modern ice cover, red-dashed lines represent moraine crests, dark blue modern lakes and streams, and green indicates wetlands.

One lake core and four bog cores were obtained from the Jaico Cirque. Laguna Yanacocha yielded an ~2.6 meter-long sediment core taken from a shallower part of the lake (10.558°S, 75.927°W) where the depth was 15.86 m (Figure 5). The core was taken from the shallower end of the lake before a steep drop off to the deeper section. When split open, the core shows a well-defined and sharp transition in color from gray to dark brown/black at a depth of 79 cm (Figure 6). There were five radiocarbon ages measured for the Laguna Yanacocha core resulting in a maximum radiocarbon age of 13,733 (+189, -173) calendar years

Before Present (BP). The radiocarbon dates were used to extrapolate an age-depth model that indicates the basal age of the core to be 21,000 cal yr BP, assuming a linear sedimentation rate to the base of the core (Figure 7). However, this is not a validated assumption as sedimentation rates were probably much higher near the base, when ice was closest, so the basal age is most likely younger than 21 ka.

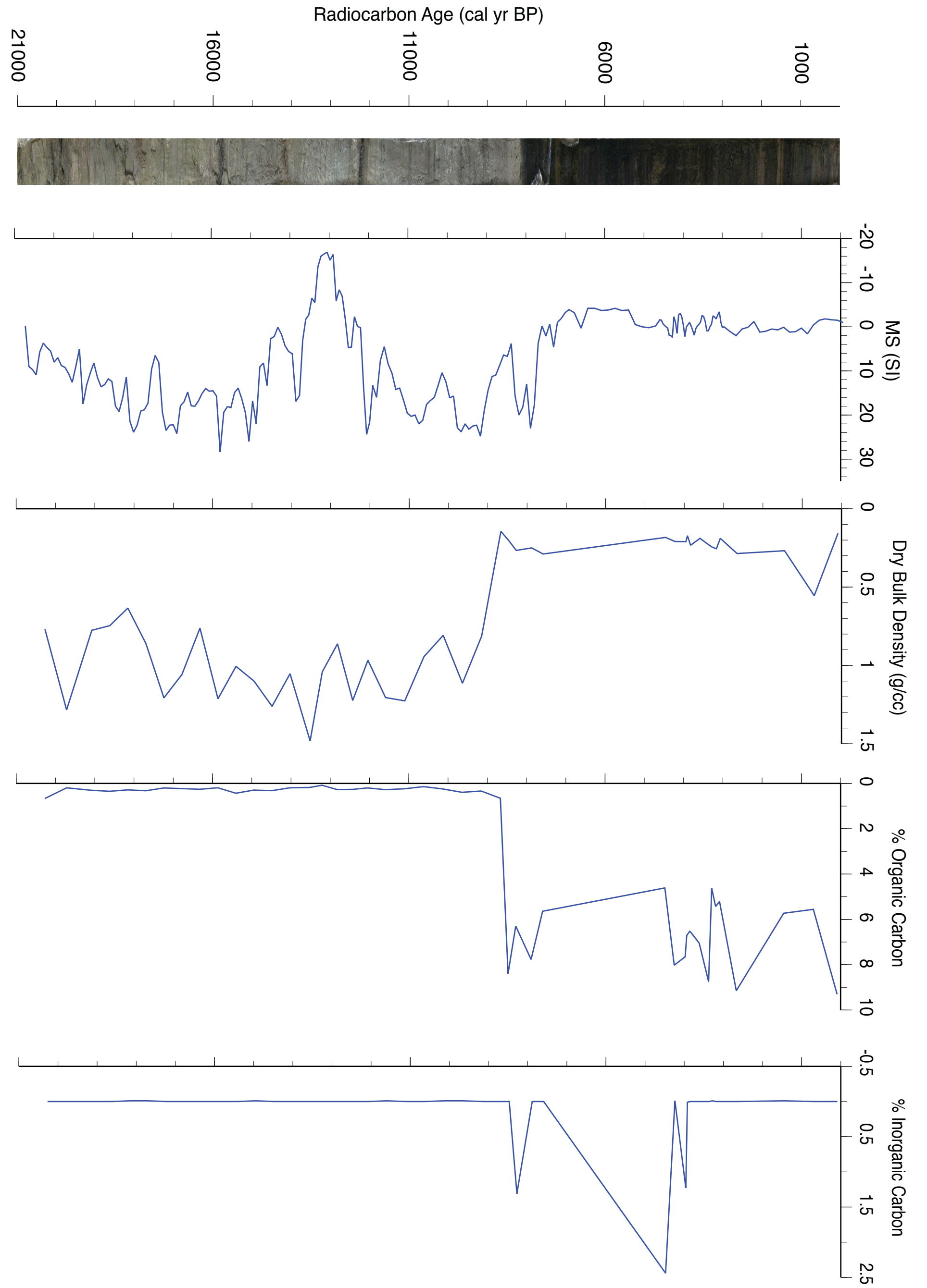

Figure 6. Downcore plot of sedimentologic properties of the Laguna Yanacocha core plotted against ages calculated with the age-depth model.

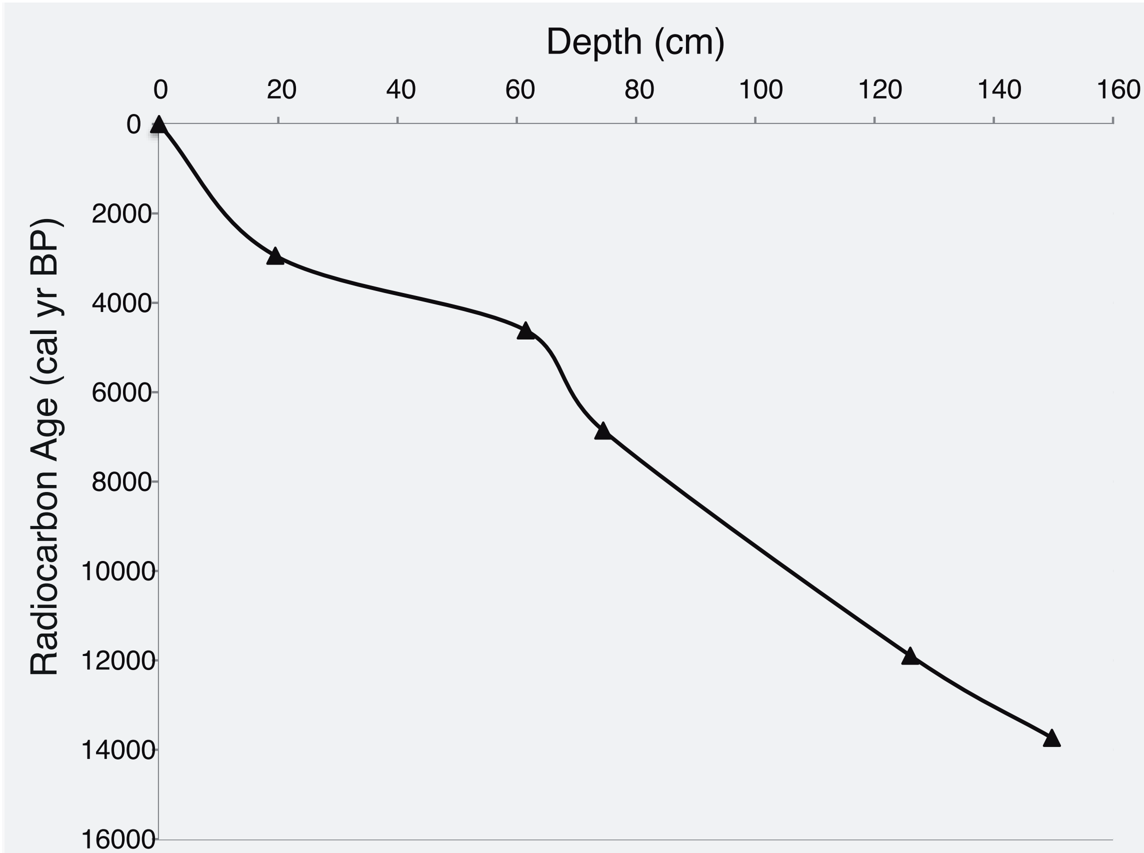

Figure 7. Age-depth model for Laguna Yanacocha.

The MS plots from the Laguna Yanacocha core show two significant declines in the bottom half of the core. The first decrease is from 14,000 -13,000 cal yr BP and the second from 9,000 – 7,500 cal yr BP (Figure 7). After this the values consistently remain around 0 SI throughout the rest of the core. The dry bulk density varies slightly but remains above 1.0 g/cm^3 in the bottom half of the core, then drops significantly between 9,500 – 8,500 cal yr BP from 1.2g/cm^3 to 0.2 g/cm^3 (Figure 7). It then remains around 0.2 g/cm^3 throughout the rest of the core until a small spike at about 600 cal yr BP where it reaches 0.6 g/cm^3. The TOC remains at a value of about 0.5% for the bottom section of the core until ~8,500 cal yr BP where

there is a rapid transition to higher values (Figure 7). From there on going upcore the TOC varies between 4 -10%, but never goes below this range. The TIC is 0% for most of the core except for a section in the middle where there is inorganic carbon present, with values ranging between 1.4 - 2.5%. This section of positive TIC values is between 8,200 - 4,000 cal yr BP (Figure 7).

Two overlapping cores were taken from Jaico Bog (elevation = 4313 m asl): Core A and Core B (Figure 5). Core A is roughly 4.75 m long and was radiocarbon dated at three different depths. The oldest age is 10,336 (+48,-67) cal yr BP and occurs at a depth of 232 cm. The other two ages are 7,595 (+12, -116) cal yr BP at a depth of 381 cm and 10,258 (+15, -22) cal yr BP at a depth of 480 cm. Color changes can be seen throughout the core, but it is dominated by organic rich peaty material (Figure 8). The MS data for Jaico Bog Core A show little significant variation in the core and the values are mostly negative. The dry bulk density plot shows a lot of variation throughout the entire core ranging between 0.1 g/cm^3 and 1.2 g/cm^3 (Figure 8). The two largest peaks occur at a depth of 350 cm and 130 cm. The TOC data also shows a lot of peaks and troughs throughout the core with many peaks reaching values above 40% (Figure 8).

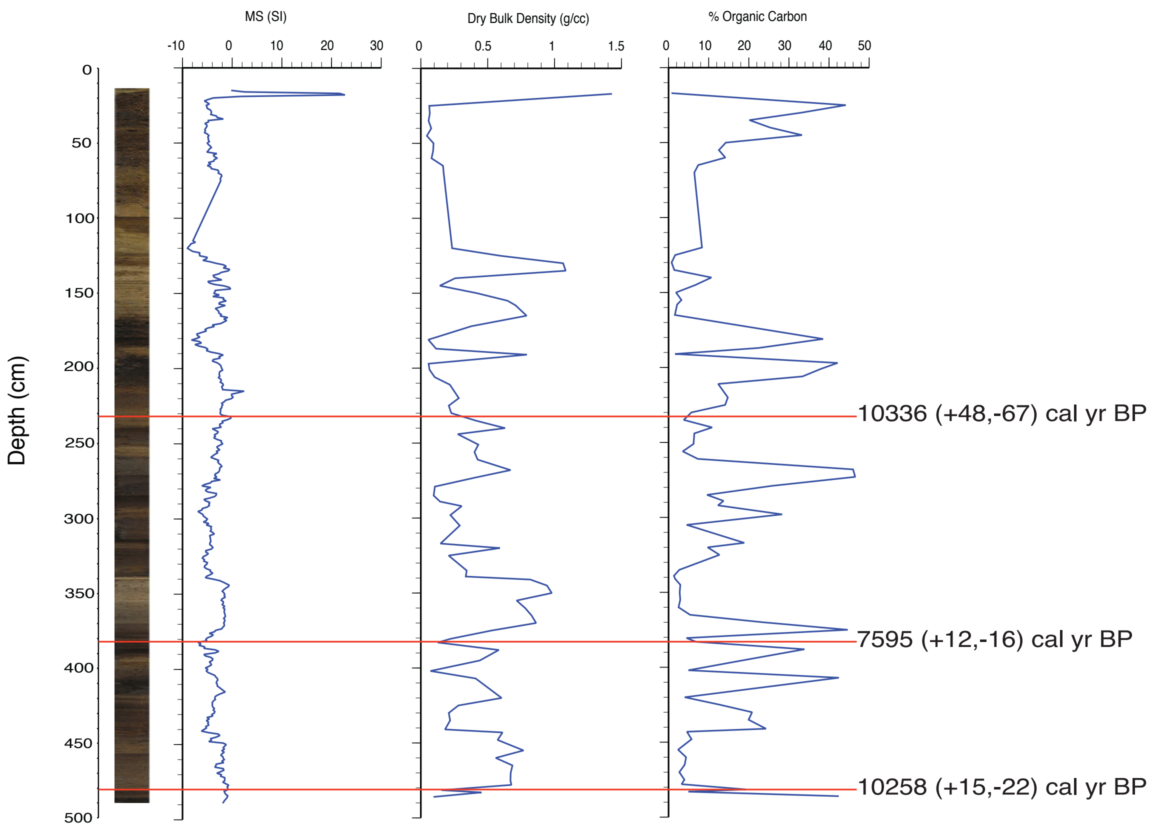

Figure 8. Downcore plot of the sedimentologic properties of Jaico Bog Core A. The depth of the sampled radiocarbon age is indicated by the red lines.

Jaico Bog Core B is about 4.25 m long. It shows a similar MS trend with fairly consistent negative values through most of the core, but it also shows a peak not seen in Core A. This period of increased values occurs between 100 and 120 cm and reaches values as high as 18 SI (Figure 9). The dry bulk density and TOC plots are very similar to Core A, both showing large variations throughout the core (Figure 9).

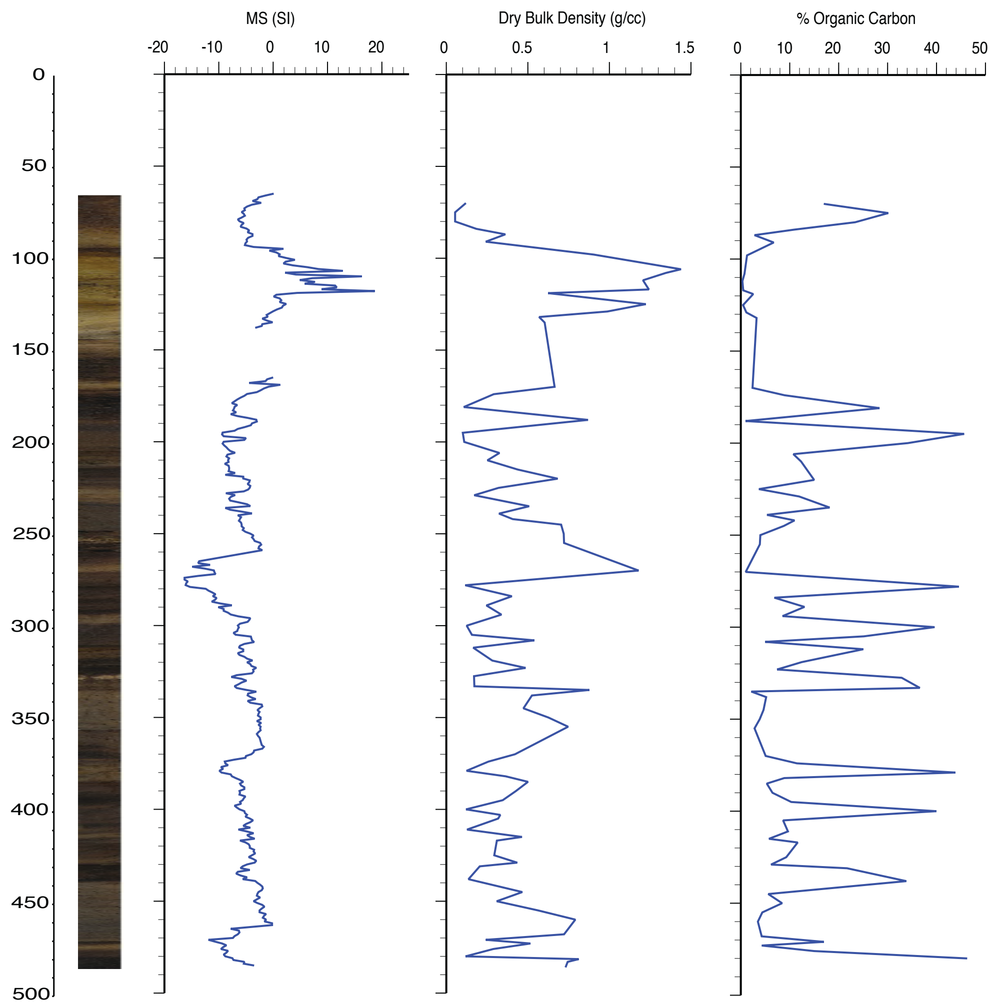

Figure 9. Downcore plot of the sedimentologic properties of Jaico Bog Core B.

Two overlapping cores were extracted from Yanacocha Bog at an elevation of 4,491 m asl (Figure 5). Both cores were sampled once for radiocarbon dating. Yanacocha Bog Core A is 1.10 m long and yielded an age of -3 (+55, -2) cal yr BP at a depth of 116 cm below the surface (Figure 10). The MS data from this core shows that the majority of the core has magnetic values around 0 SI. However, there is a dramatic decrease at a depth of 102 cm where the values dip down to -800 SI, then continuing upcore, gradually increase until they are at 0 SI again. The dry bulk density plot shows a gradual upcore trend of decreasing values, starting at about 1.4

g/cm³ and decreasing 0.1 g/cm³ to at the top of the core (Figure 10). The TOC data shows an opposite trend of values that gradually increase upcore. The bottom of the core has an organic carbon content of nearly 0% and increases upcore to around 30% at the top (Figure 10).

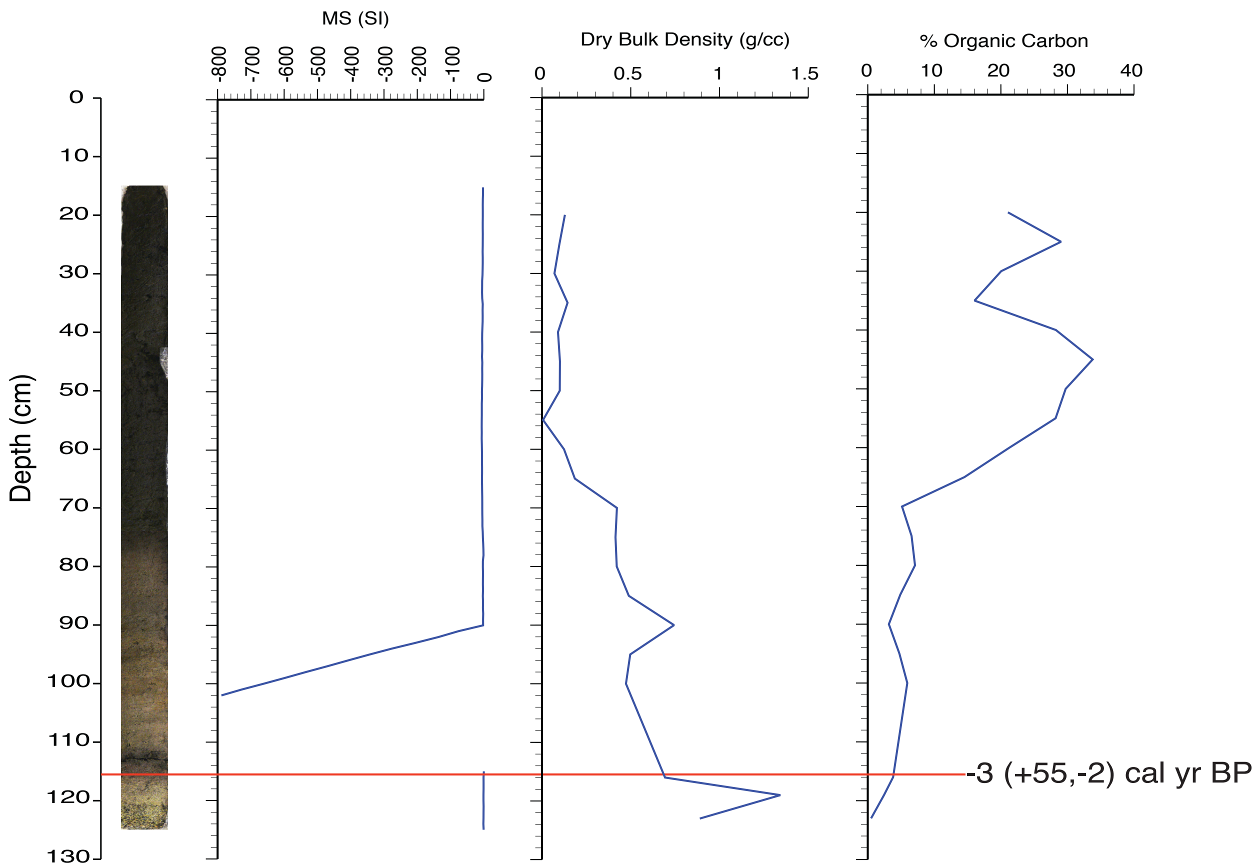

Figure 10. Downcore plot of the sedimentologic properties of Yanacocha Bog Core A. The depth of the sampled radiocarbon age is indicated by the red line.

Yanacocha Bog Core B is 0.58 m long and yielded a radiocarbon age of 2,870 (+53, -64) cal yr BP at a depth of 96 cm below the surface (Figure 11). The core shows a gradual upcore decrease in MS where values begin around 0 SI and gradually become more negative towards the top of the core. The dry bulk density and TOC plots show the same trends as found in Yanacocha Bog Core A (Figure 11).

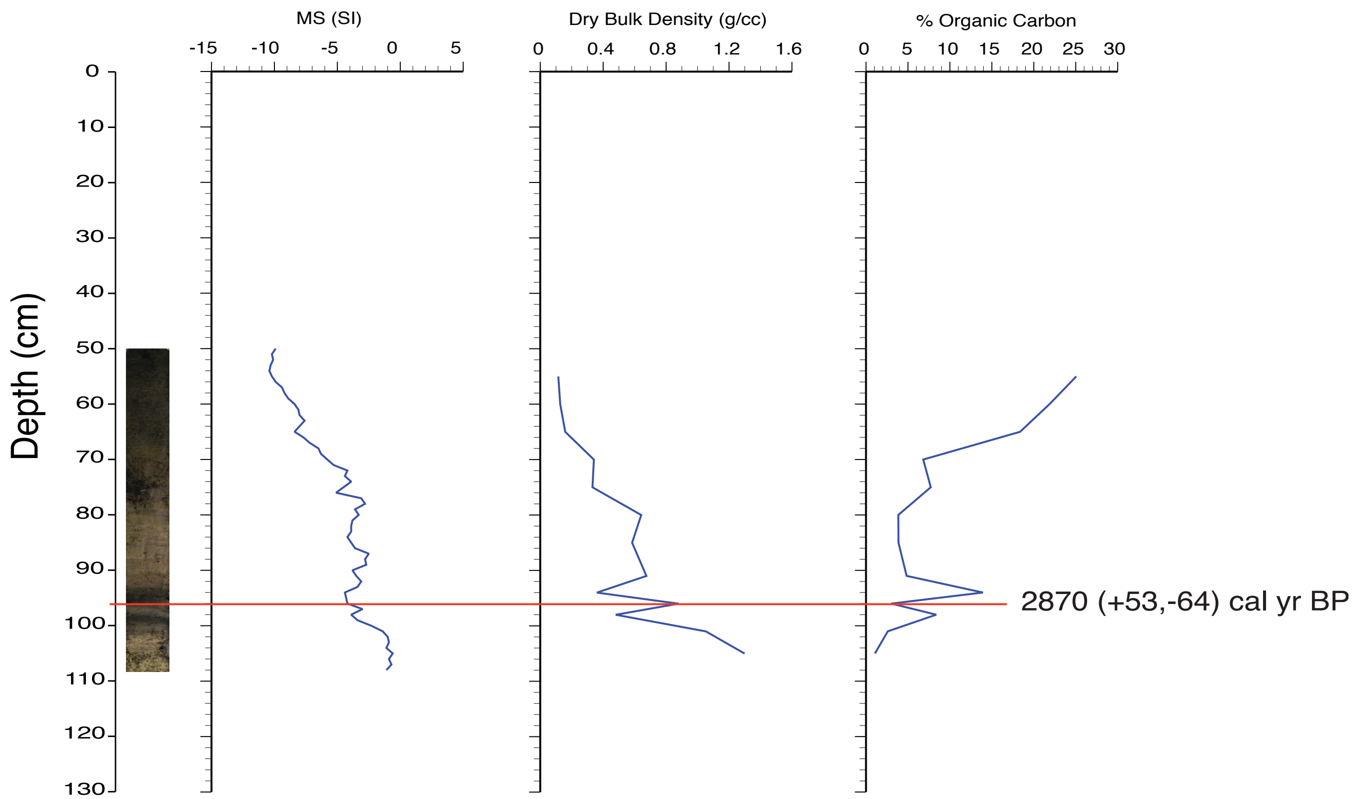

Figure 11. Downcore plot of the sedimentologic properties of Yanacocha Bog Core B. The depth of the sampled radiocarbon age is indicated by the red line.

Western Cordillera:

The second study site is located in the northwestern corner of the Reserva Paisajistican Nor Yauyos-Cochas, a Peruvian national park. The park sits in the Junin province of Peru within the western cordillera of the Peruvian Andes. All cores were taken from within the Tunshu Cirque, which extends eastward from the Nevado Tunshu peak (elevation = 5,677 m asl) (Figure 12).

Figure 12. Digital photograph of the peak Nevado Tunshu and the Tunshu cirque including Laguna Tunshu (center) and Laguna Shiurococha Upper End Bog (right corner).

There are two lakes and multiple wetlands within the catchment. The smaller of the two lakes is Laguna Tunshu with an area of 0.23 km^2 (elevation = 4,600 m asl), which sits upstream from the much larger Laguna Shiurococha that has an area of 0.38 km^2 (elevation = 4585 m asl) (Figure 13). The lithology of the study region is more complicated than that of the eastern site. There are three different types of bedrock within the drainage basin: tonalite-granodiorite, red, quartz-rich mudstone and conglomerates, and sandy red, calcareous mudstones. There are also glacial deposits covering much of the catchment.

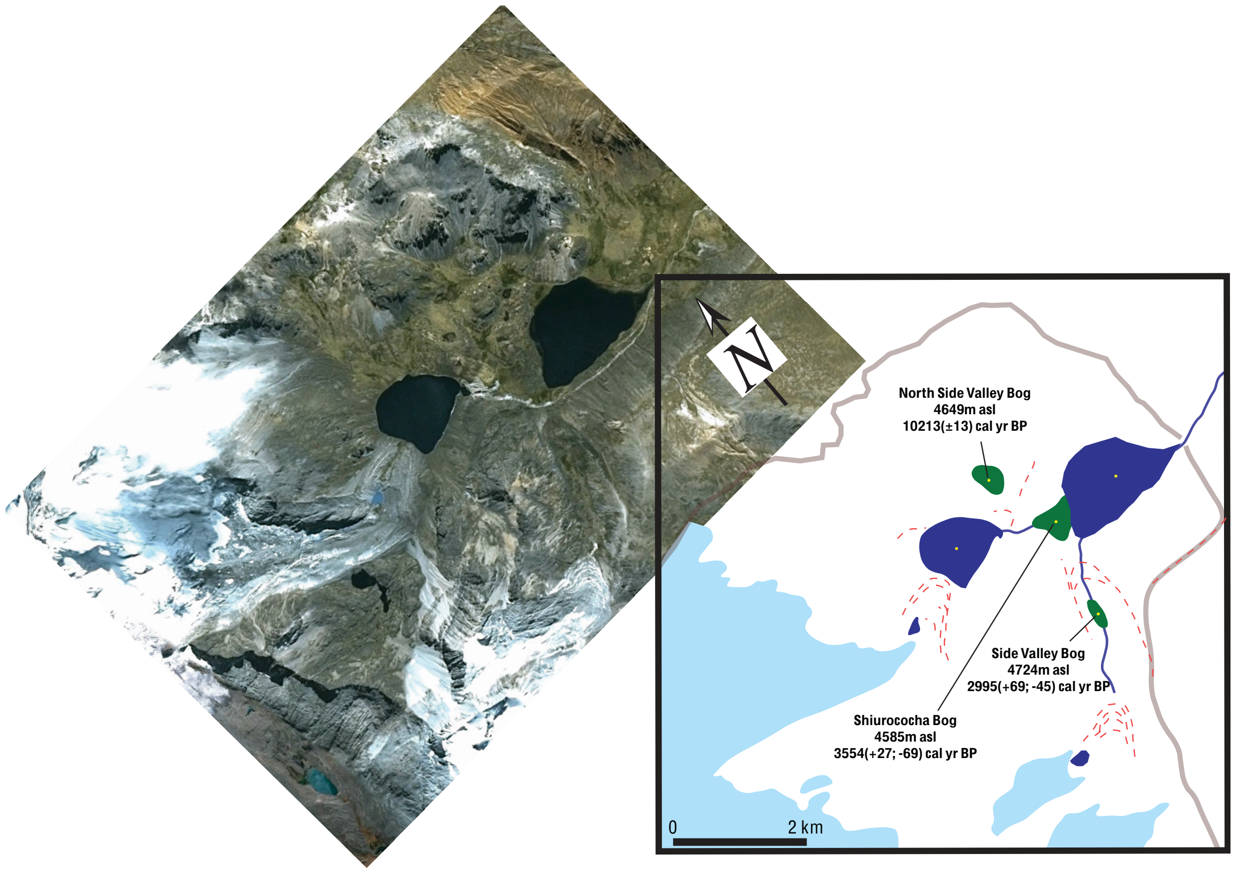

Figure 13. Google Earth image (1970) and geomorphic map of the Jaico Cirque. Light blue represents modern ice cover, red-dashed lines represent moraine crests, dark blue modern lakes and streams, and green indicates wetlands.

An ~6.6 meter-long core was extracted from the upper end bog of Laguna Shiurocochа (11.905°S, 75.960°W). The core shows a strong color and texture transition from gray silt to dark brown-black peak at a depth of 550 cm below the surface (Figure 14). The core yielded two radiocarbon ages. The first was from a sample taken from a depth of 535 cm below the surface and gave an age of 3,554 (+27, -69) cal yr BP. The second sample was taken from a depth of 580 cm below the surface and produced an age of 2,842 (+25, -45) cal yr BP. The magnetic properties of the core show very high magnetic content at the bottom of the core until a depth of roughly 620 cm where it drops to 0 SI (Figure 14). It then remains around 0 SI for

the rest of the core. The dry bulk density of the sediment shows a similar trend with high values around 1.5 g/cm³ at the bottom of the core, depth of 650 cm below the surface (Figure 14). There is a large drop in dry bulk density starting at a depth of 580 cm to about 0.3 g/cm³ and then it remains between 0.1 – 0.3 g/cm³ for the rest of the core, except for a peak at 60 cm. The TOC plot shows that organic carbon content is essentially 0% for the bottom 100 cm section of the core, until a depth of about 550 cm below the surface (Figure 14). Above this level, TOC ranges between 10 - 40 % with many peaks and troughs.

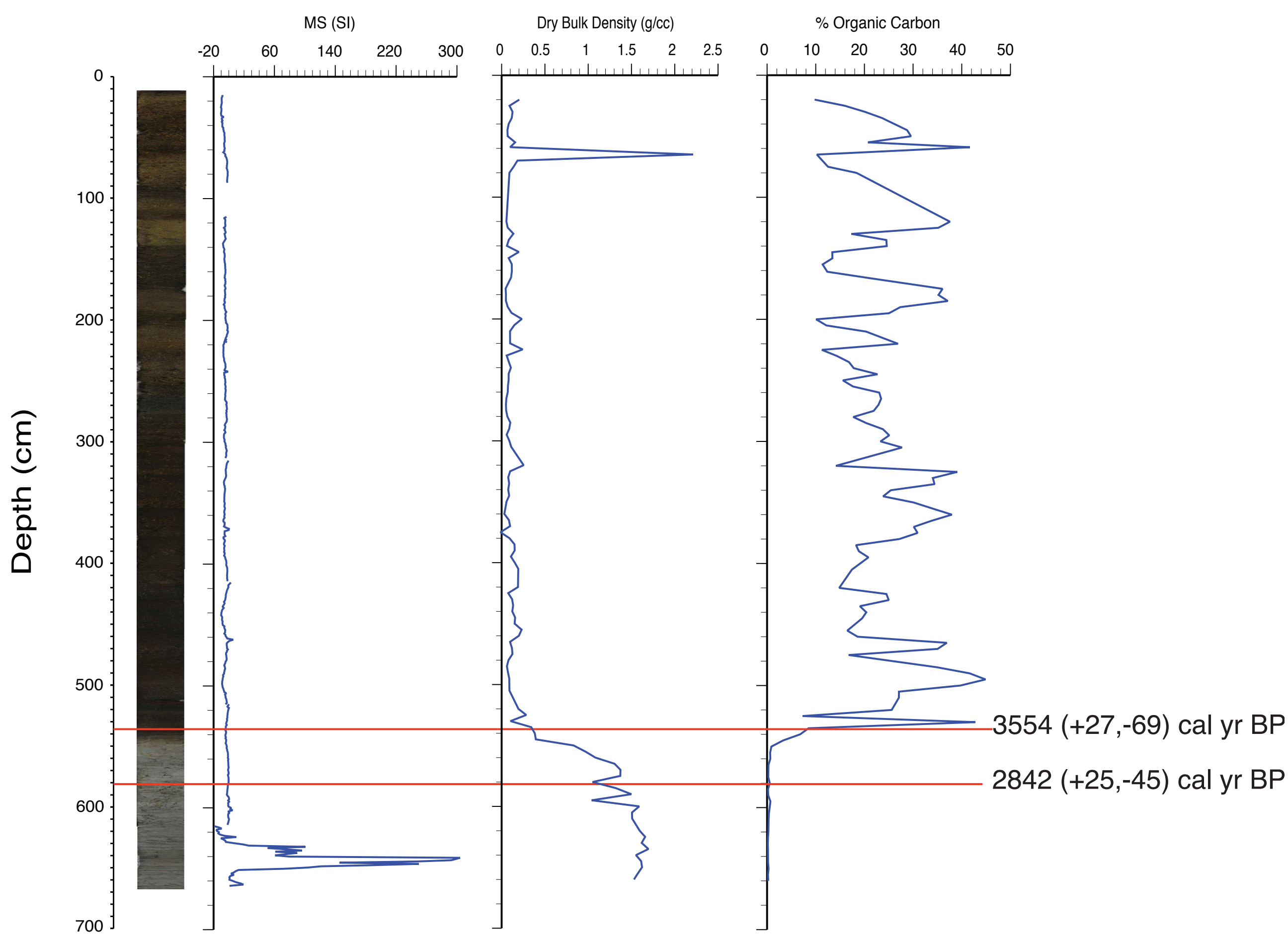

Figure 14. Downcore plot of the sedimentologic properties of the Shiurococha Upper End Bog core. Radiocarbon ages and sample locations are indicated by the red lines.

Three overlapping sediment cores were extracted from the Side Valley Bog located to the south of Laguna Shiurococha at an elevation of 4,724 m asl. The geographic map shows at least two moraines separating the Side Valley Bog from the Shiurococha Upper End Bog (Figure 13). The small catchment is fed by a modern glacier ~2.0 km to the southwest. Side Valley Bog Core A, 66 cm long, yielded a radiocarbon age of 1,974 (+18, -43) cal yr BP at a depth of 77 cm below the surface. The magnetic properties measured in this core show a decreasing upcore trend, it is close to 0 SI for bottom 35 cm of the core, above which values gradually become more negative (Figure 15). The dry bulk density plot also shows decreasing upcore trend, although not as smooth, with a maximum value of about 1.2 g/cm^3 at the bottom of the core. The TOC data shows an opposite pattern as the values increase upcore, beginning at 1% at the bottom and increasing to 17% at the top of the core (Figure 15).

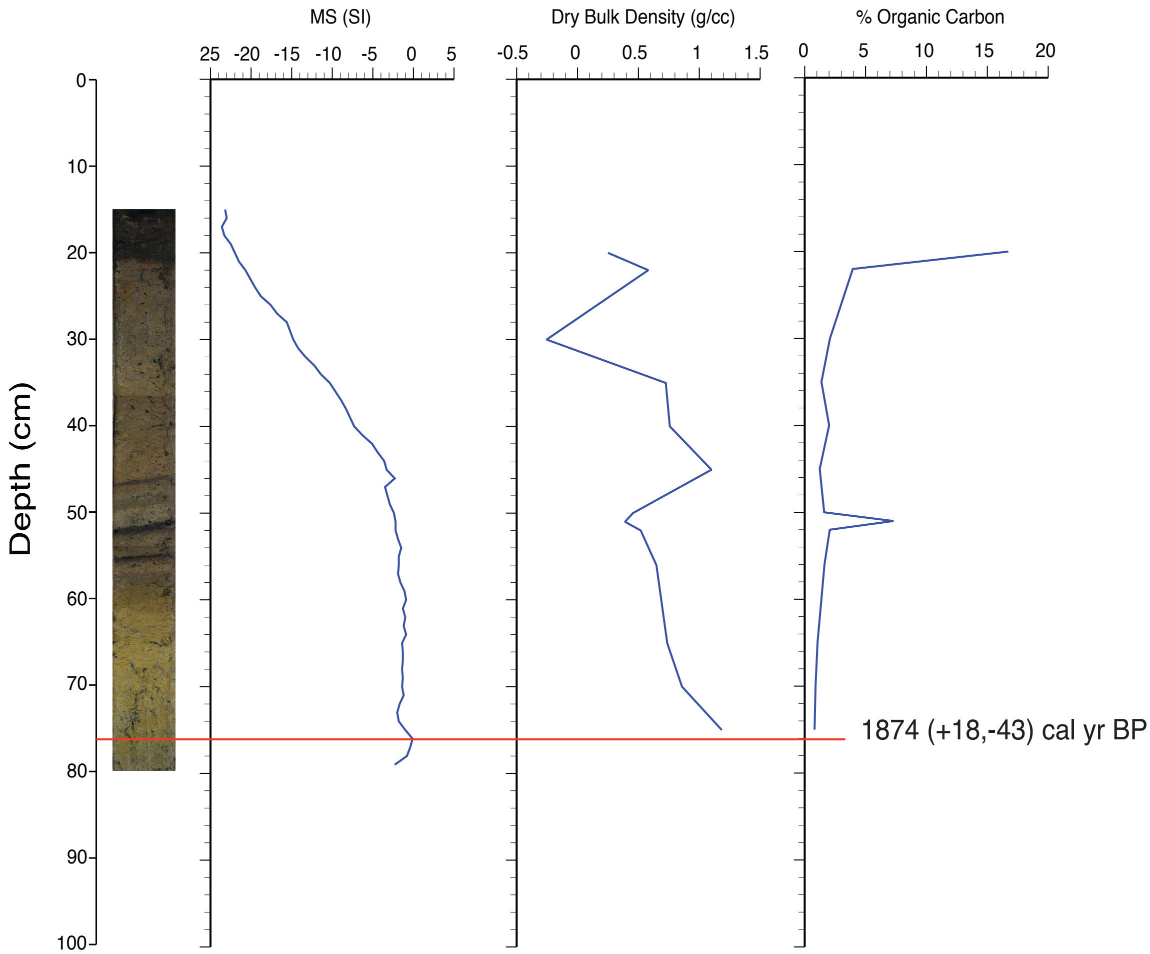

Figure 15. Downcore plot of the sedimentologic properties of the Side Valley Bog Core A. Radiocarbon ages and sample locations are indicated by the red line.

Side Valley Bog Core B is 39 cm long and yielded a radiocarbon age of 2,995 (+69, -45) cal yr BP at a depth of 88 cm below the surface. The magnetic susceptibility data shows more variation than that in Side Valley Bog Core A, but all values are negative (Figure 16). The dry bulk density plot starts with a maximum of 1.4 g/cm^3 at the bottom of the core but remains around 0.6 g/cm^3 above this. The carbon content analysis results showed peaks at the top and bottom of the core but the overall range of variation was minimal, 1.0-1.5% organic (Figure 16).

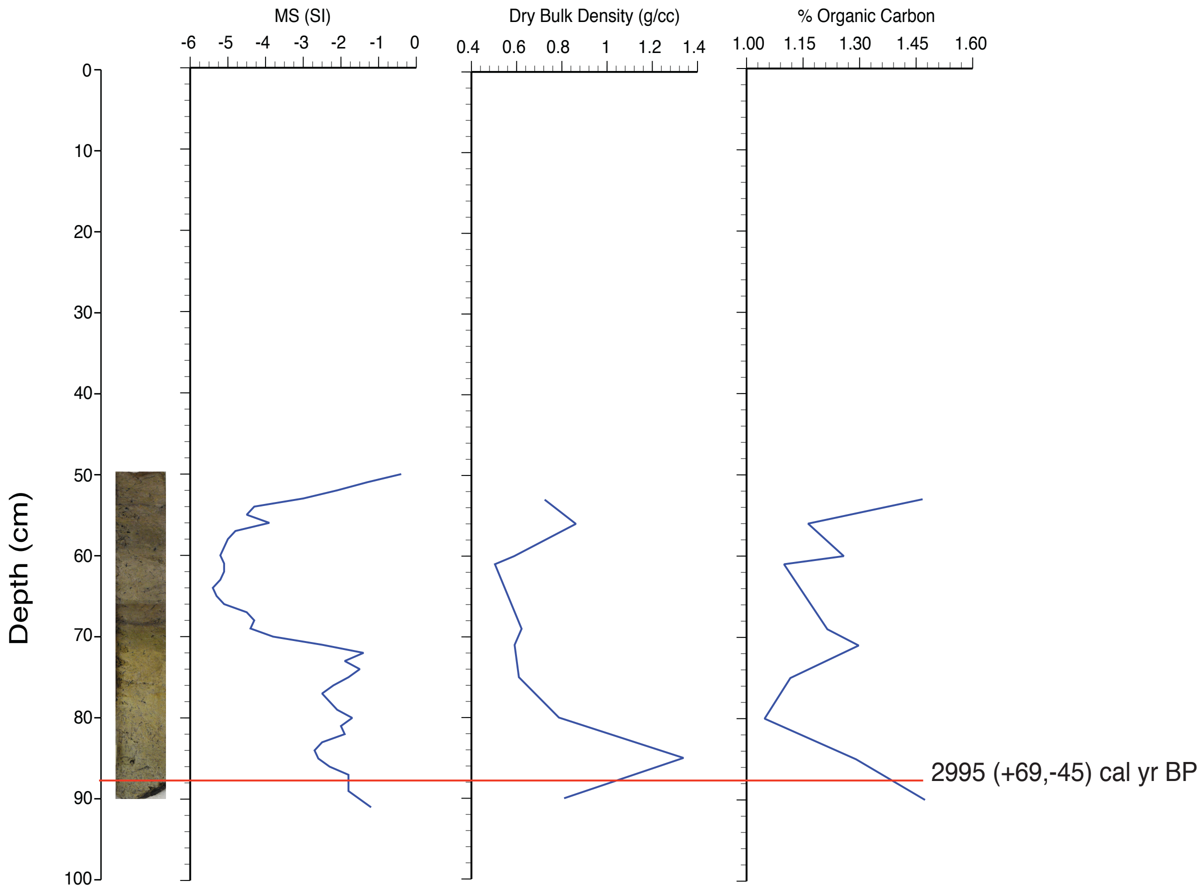

Figure 16. Downcore plot of the sedimentologic properties of the Side Valley Bog Core B. Radiocarbon ages and sample locations are indicated by the red line.

Side Valley Bog Core C is a total of 62 cm long and yielded a radiocarbon age of 2,341 (+4, -6) cal yr BP at a depth of 67 cm below the surface. The MS plot shows a general decreasing upcore trend with some variation and like Cores A and B, all values are negative (Figure 17). The dry bulk density data also show a decreasing trend, beginning around 0.8 and decreasing to about 0.1 g/cm^3. The TOC plot is similar to that of Side Valley Bog Core A, with a decreasing down core trend and a range of 2 -30% organic carbon (Figure 17).

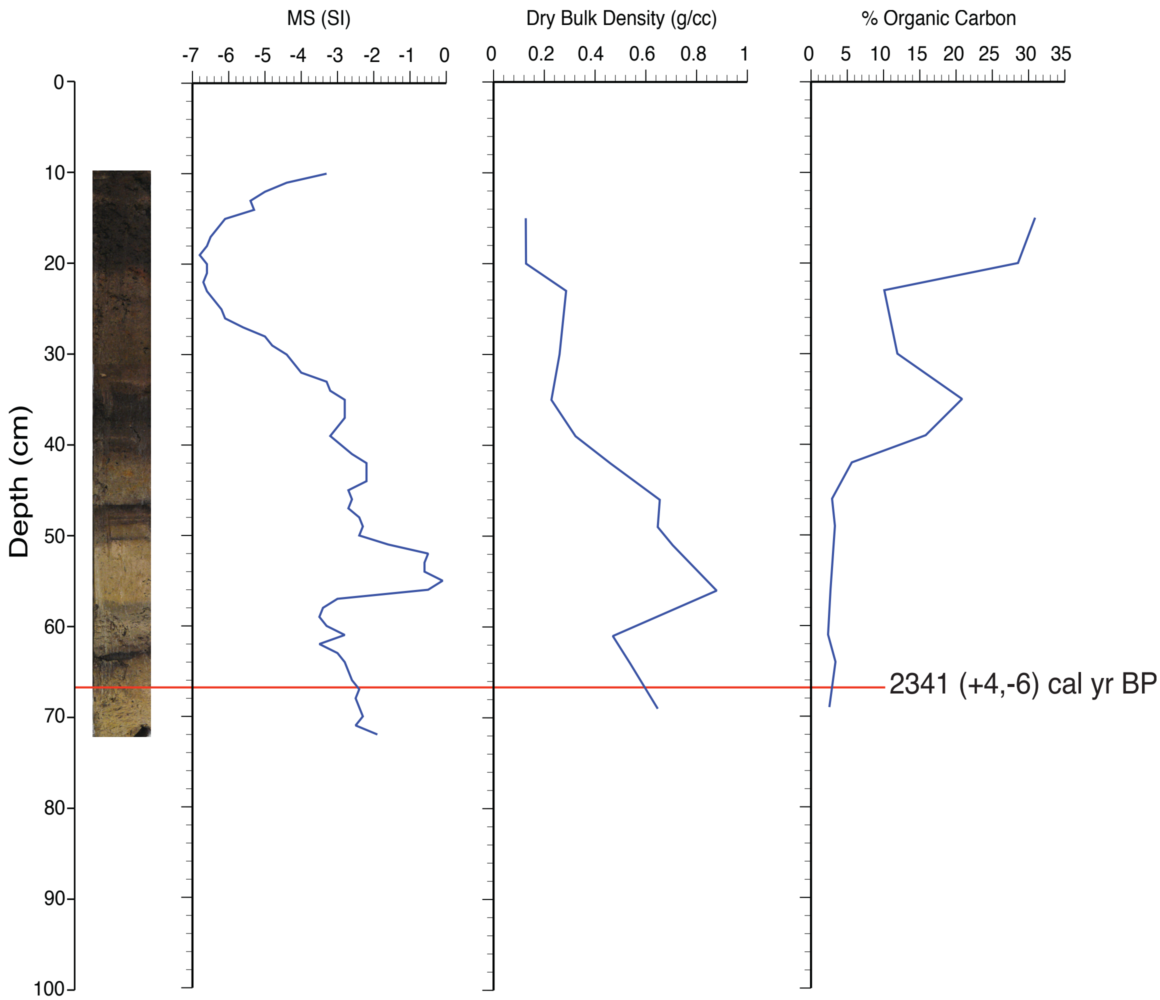

Figure 17. Downcore plot of the sedimentologic properties of the Side Valley Bog Core C. Radiocarbon ages and sample locations are indicated by the red line.

Two overlapping sediment cores were extracted from the North Side Valley Bog (elevation=4,649 m asl), located on the opposite side of Laguna Shiurococha as the Side Valley Bog. An unglaciated ridge to the north and moraines to the south contain this small wetland (Figure 13). Only North Side Valley Bog Core A was radiocarbon dated and it revealed an age of 10,035 (+119, -106) cal yr BP at a depth of 240 cm below the surface and 10,213 (+13, -13) cal yr BP at a depth of 298 cm below the surface. The core is 2.85 m long in total. The MS plots reveals consistently

negative values that range between -25 - -2 SI (Figure 18). The dry bulk density plot shows a peak at the bottom of the core of 0.5 g/cm^3, however remains within a relatively small range throughout the entire core. The TOC data shows a period for most of the core where organic carbon content remains around 50% (Figure 18). It varies at both the top and bottom of the core but restabilizes back to 50% in both instances.

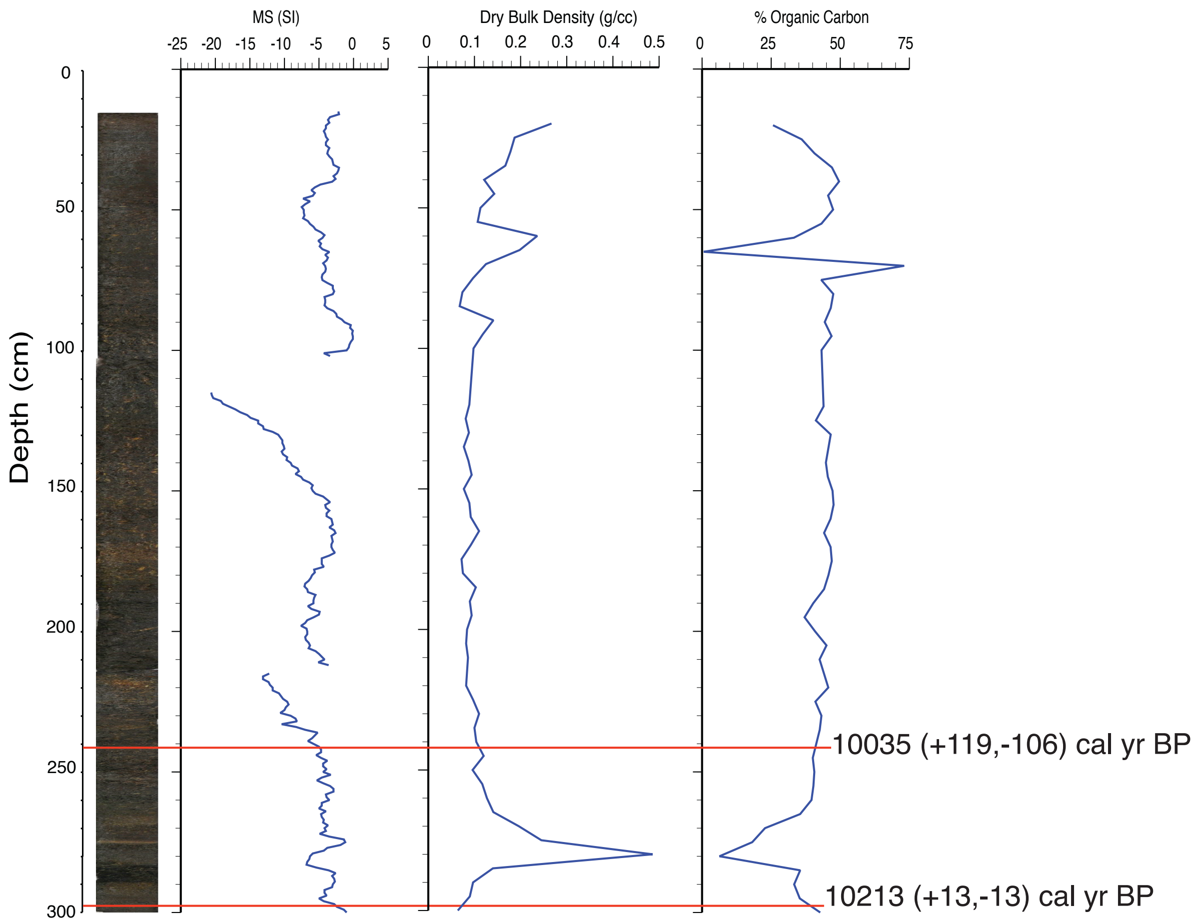

Figure 18. Downcore plot of the sedimentologic properties of the Side Valley Bog Core C. Radiocarbon ages and sample locations are indicated by the red lines.

North Side Valley Bog Core B is 235 cm long and shows the same variations in MS as Core A. It also shows a similar trend in dry bulk density except for a steep

upcore decrease at the base of the core, 290 cm below surface, where bulk density decreases from 1.0 g/cm^3 to 0.1 g/cm^3 (Figure 19). The TOC plot is smoother than that of Core A. At the base TOC is nearly 0%, but it rapidly increases upcore to values between 30-50% and stays within this range for the rest of core.

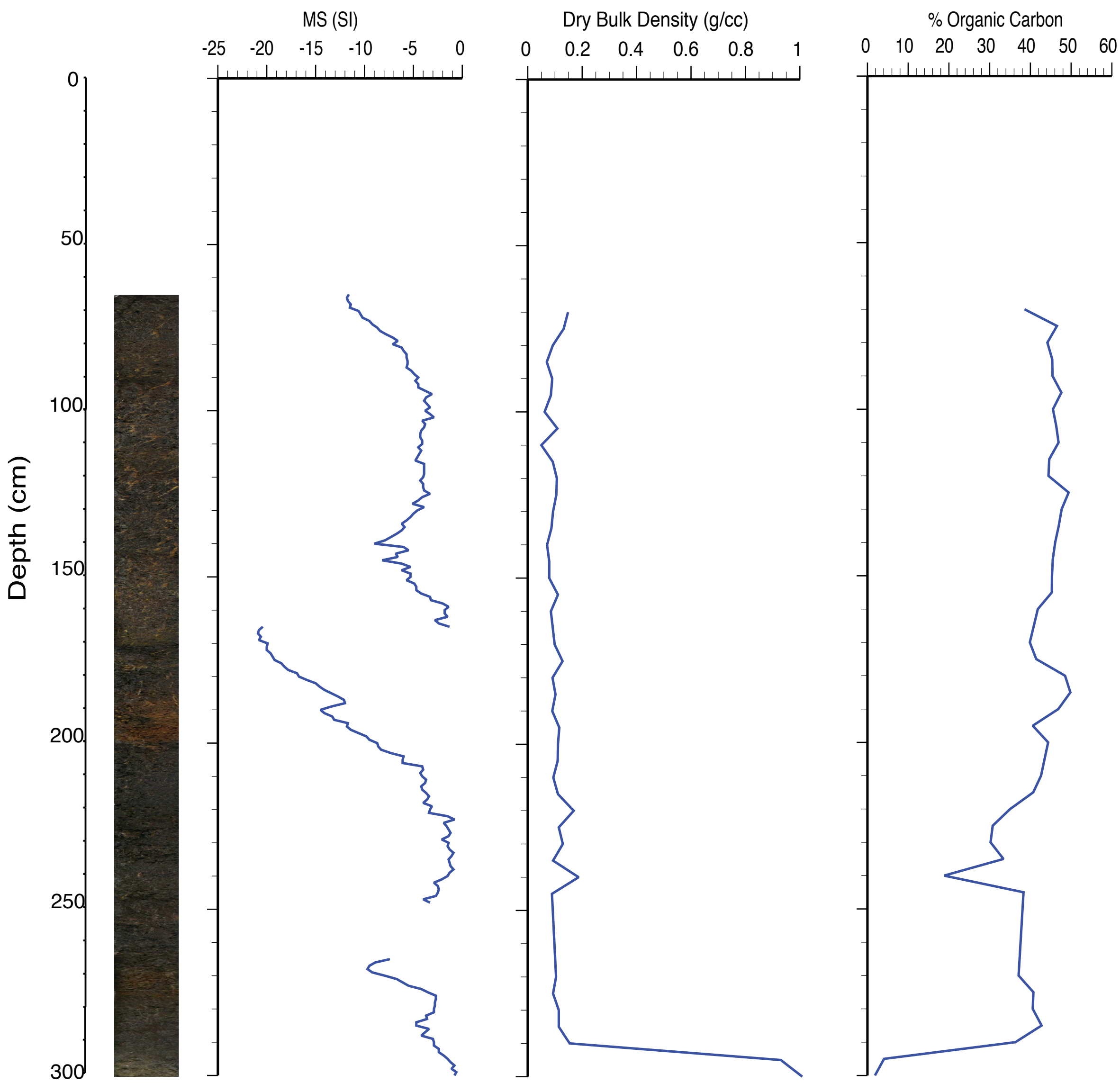

Figure 19. Downcore plot of the sedimentologic properties of the Side Valley Bog Core C.

INTERPRETATIONS

Modern Lake Properties:

Usually the simplest parameter of a lakes limnology to begin analysis with is temperature because it will reveal any thermal stratification and can help identify layers within the water column. The temperature profile of Laguna Yanacocha indicates that although it is ice free there is no epilimnion layer of mixed water. The thermocline occurs in the top 1.5 m of the water column, below which there is little variation in temperature until a water depth of 10 m. At this point there is another steep drop in temperature. Since this is within the hypolimnion, it could indicate an underground spring entering the lake.

The pH of the water is close to neutral throughout the entire water column. The specific conductivity is a measure of salinity, explaining the extremely low values. There is a spike in specific conductivity between the depths of 10 to 13 m. Both measurements of dissolved oxygen indicate a new layer at the bottom of the lake that corresponds to the second drop in temperature. The rapid decrease in DO below a water depth of 12 m suggests that the bottom of the lake is not being mixed with water above it.

The temperature, specific conductivity and dissolved oxygen profiles indicate that a significant change is occurring within the lake at a depth of 12 m. It could be caused by an underground spring or the topography of the lake, but it is difficult to determine anything without more information.

Eastern Cordillera:

The MS plots from the Laguna Yanacocha core reveals two significant declines indicating a two-step deglaciation: the first from 14,000-13,000 cal yr BP and the second from 9,000 – 7,500 cal yr BP. The lack of magnetic signal throughout the rest of the Holocene suggests there has been little ice advance after the second deglaciation and the lake is undergoing eutrophication in the absence of clastic sediment input (Dean, 1999). The large transition in dry bulk density and organic carbon content occurs around the time of the second deglaciation, 9,500 – 8,500 cal yr BP. This further supports the interpretation of the MS drop off as a signal of ice retreat. Glacial flour is much denser than the observed organic material in the upper portion of the core and will have little to no organic material preserved within in it (Stansell et al., 2005). Since there is about a 1000-year difference between the shift seen in bulk density and TOC to the shift seen in MS, there could be a lag time associated with the MS signal. As ice retreated, melt water could still have been draining small amounts of glacial sediment into the lake before it was completely cut off. The large deglaciation around 9,000 cal yr BP suggests major climate shifts because there is little activity throughout the rest of the Holocene. However, it could have been brought on by *either* warmer or drier conditions.

Other climate proxies are used for comparison to increase support for the hypothesis of this major deglaciation. Laguna Yanacocha was the best dated core so its sedimentologic record was compared to the $\delta^{18}O_{precipitation}$ record obtained from authigenic calcite preserved in nearby Laguna Pumacocha (Figure 20) (Bird et al., 2011). The $\delta^{18}O_{precip}$ record shows a period of rapidly increasing aridity or

temperature from 11,000-10,000 BP, followed by a very gradual increase in precipitation or decrease in temperature through the rest of the Holocene (Bird et al, 2011). The period of either drier or warmer conditions peaks roughly 1000 years before the deglaciation shows up in the sedimentologic record shown in Laguna Yanacocha, indicating a lagged ice response typical of glaciers as the mass balance adjusts to new conditions (Hall et al., 2009). The oxygen isotopic record still cannot differentiate between a shift in temperature or precipitation, but it does support the existence of a major climatic shift in this region during the early Holocene.

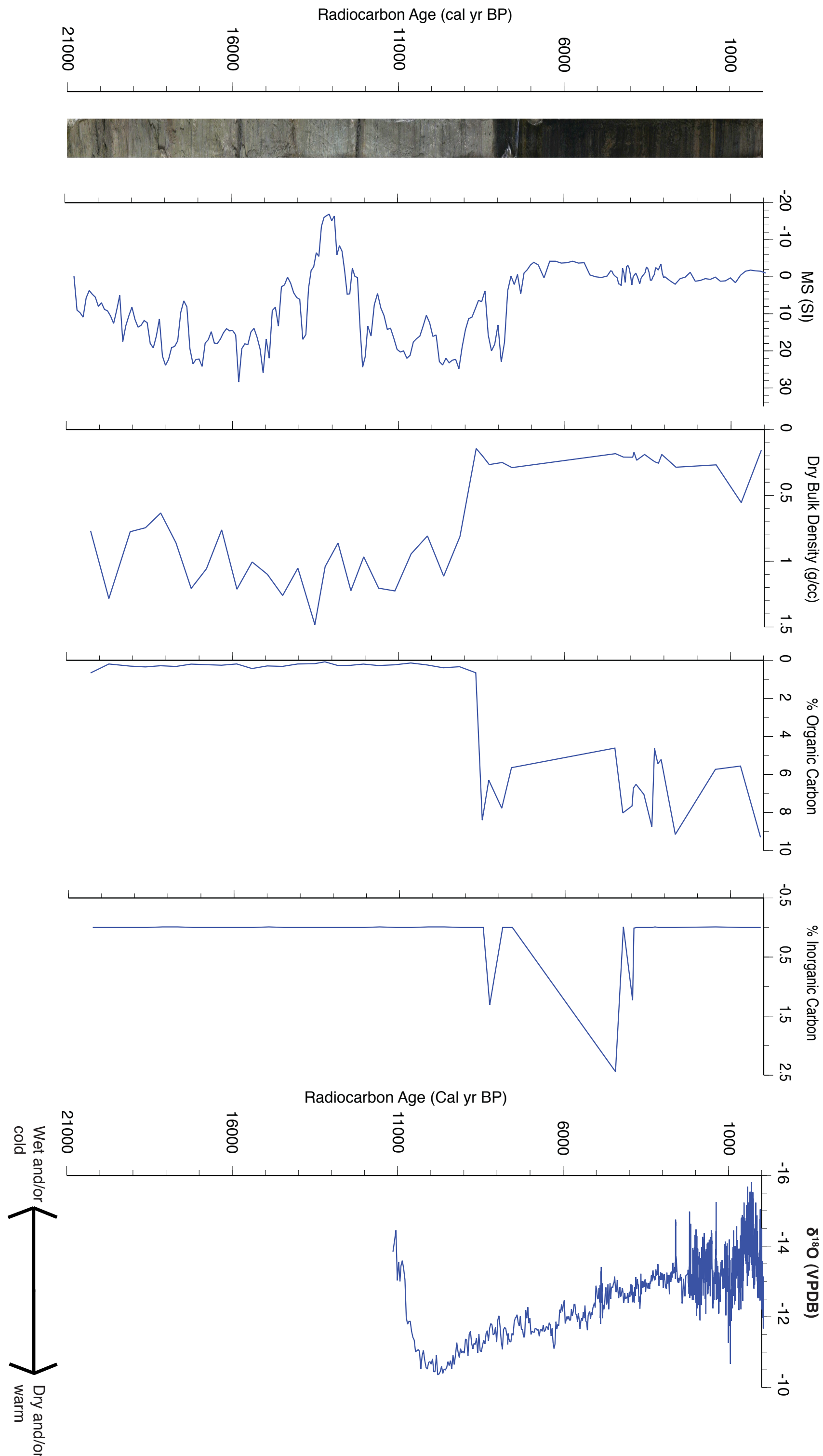

Figure 20. Downcore plot of the sedimentologic properties of Laguna Yanacocha next to the $\delta^{18}O_{precip}$ values from Laguna Pumacocha. Both plots are on the same time scale and arrows represent the conditions the isotopic signal represents.

The presence of inorganic carbon in the sediments of Laguna Yanacocha is extremely unusual because of the strictly granitic bedrock of the basin. This occurs after the deglaciation from 8,200 – 4,000 cal yr BP. It is unusual because there is little possibility of an external source of the calcium and bicarbonate that would be needed for the authigenic precipitation of calcite in lake water (Bird et al, 2011 and Seltzer et al., 2000). Since the Jaico cirque is made up solely of granitic bedrock, drainage from the basin couldn't pick up Ca and HCO_3 in runoff. Eolian input must also be considered as a possible external source, as winds can pick up and carry dust ground from limestone bedrock. Since there is limestone bedrock to the west of the site, well within the range of eolian transportation, this is a strong possibility. Authigenic calcite can only be preserved if organic carbon content is below 12% or it will be dissolved by the acidity of the water and deposited sediment (Dean, 1999). It was preserved in Laguna Yanacocha because, as is shown in the core, TOC has remained below this threshold throughout the Holocene. The precipitation of authigenic $CaCO_3$ indicates extremely dry conditions, drastically lowering lake levels and creating usually high concentrations of dissolved calcium in the water.

The radiocarbon ages in Jaico Bog Core A show a reversal because there is an older age stratigraphically above a younger age. This is not uncommon in bogs because of modern rootlets that can grow through the bog and contaminate the organic material being dated (Blaauw et al., 2004). The oldest age is used as the basal age for the entire core, which was 10,336 cal yr BP. The existence of this bog and the accumulation of peaty organic material for over 10,000 years indicates that the wetland has been ice free throughout the majority of the Holocene. The MS data

from both cores suggests there has been little to no clastic sediment input throughout this entire period because values rarely go above 0 SI. Organic material is known to have negative magnetic susceptibility, which is reflected in the core (Thompson et el., 1975). The variations in dry bulk density and TOC could represent small increases in glacial inputs, but the cores do not have high enough resolution or an age model to interpret them further.

While the Jaico Bog has essentially been present through the entire Holocene, the Yanacocha Bog appears to be much younger. The radiocarbon age of -3 cal yr BP is disregarded as contaminated with modern material, however the other date is still useful. Using the basal age as a measure of the bog's life span, one can conclude Yanacocha Bog is slightly more than 2,870 years old. Yanacocha Bog Core B shows decreasing MS and bulk density towards the modern and increasing TOC. All three parameters suggest an increase in organic activity and a cut off of clastic input. The young age of this bog suggests an additional deglaciation event around 2,870 cal yr BP.

The combined data from the eastern cordillera have suggested at least two Holocene deglaciations. The first occurs in the early Holocene around 9,500 years BP, was shown in the Laguna Yanacocha core, the Laguna Pumacocha isotope data, and the two Jaico Bog cores. The second occurs in the late Holocene around 2800 years BP and is indicated by the basal age of Yanacocha Bog.

Western Cordillera:

The Laguna Shiurococha Upper End Bog core reveals a sharp decline in glacigenic sedimentation around 3,550 cal yr BP. This is seen in the dramatic drop of MS, as well the simultaneous drop in bulk density and increase in TOC. The glacial silt deposited at the bottom of the core disappears as these parameters shift rapidly suggesting a quick cut off of glacigenic sediment. The sedimentologic and observed properties of the core all show no clastic input throughout the rest of the core indicating that after about 3,500 cal yr BP the feeding ice never advanced to that position again. The geomorphic map of the Tunsho cirque shows that the only ice lobe that would be depositing clastic sediment into the Laguna Shiurococha Upper End Bog are the two southwestern lobes feeding the Side Valley Bog (Figure). Laguna Tunsho or other higher elevation lakes would have caught all glacigenic sediment from the main cirque before it reached Shiurococha.

The Side Valley Bog cores revealed a basal age of 2995 cal yr BP indicating a similar age of minimum deglaciation as Laguna Shiurococha Upper End Bog. The sedimentologic properties of the bog indicate a transition from a base of clastic material to organic rich peat. Laguna Shiurococha Upper End Bog deglaciated around 3,500 cal yr BP and as the southwestern ice lobe retreated in steps, it created the moraines that entrap the Side Valley Bog, formed around 3,000 cal yr BP.

The North Side Valley Bog, on the opposite side of Laguna Shiurococha, has a basal age of 10,213 cal yr BP indicating that it has been ice free for most of the Holocene. The extremely high organic carbon and negative MS values in both Core A

and Core B suggest little to no clastic input. This old minimum age of deglaciation is very different from the other two bogs in the western cordillera.

Combined interpretations in the western cordillera have suggested two deglaciations in the Holocene. The first occurring at least 10,200 years BP and the second occurring around 3,500 years BP. The late Holocene ice retreat indicated in the Laguna Shiurococha Upper End Bog cores and the Side Valley Bog cores suggest a neoglaciation prior to retreat. It is still unclear whether this late Holocene ice advance was brought on by wetter conditions or colder temperatures.

Site Comparisons:

The large range in basal ages of these cores, from both the eastern and western cordillera, has been correlated to the head wall elevation of the feeding glacier (Figure 21). The plotting of this relationship shows the minimum age of deglaciation at low-elevation sites to be between 14000-10000 yr BP, while it is only 3500-2500 yr BP for high elevation sites. This not only reveals a late Holocene neoglaciation of higher elevation glaciers in both cordillera, but also suggests an early to middle Holocene interval of dry and/or warm conditions that caused reduced ice cover in both regions (Figure 21). The precipitation of authigenic calcite during this period is a strong indicator that this was an extremely dry period.

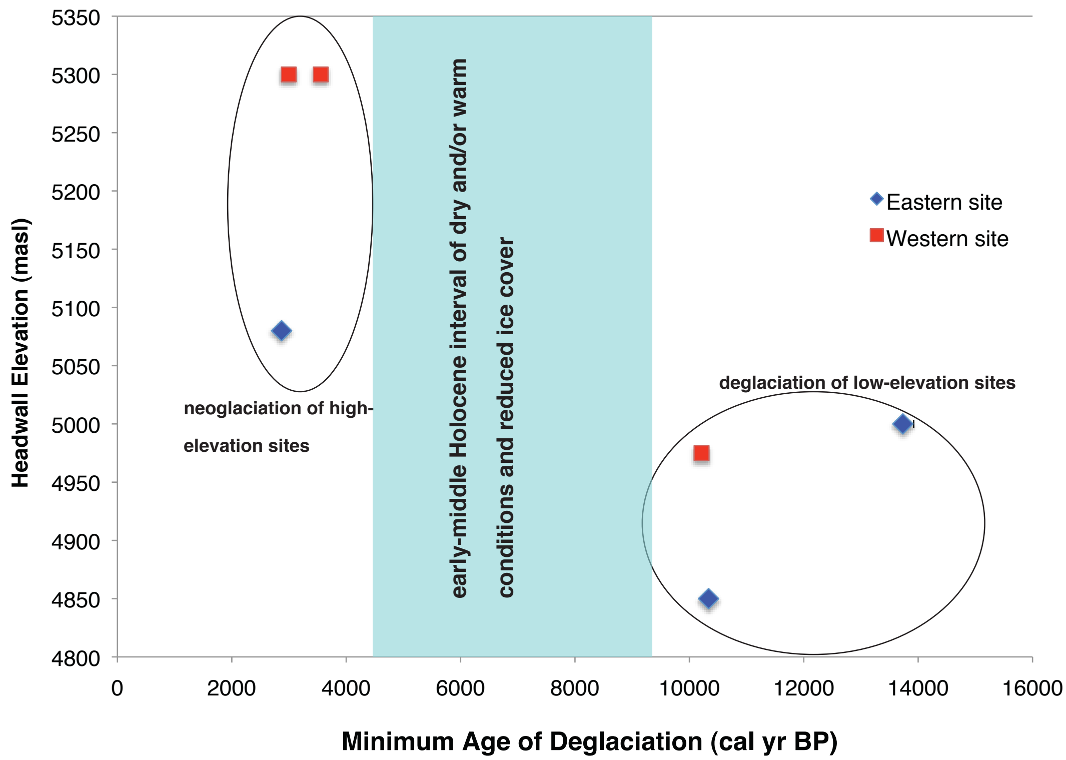

Figure 21. Minimum ages for deglaciation from lakes and wetlands in both study sites; data suggests an interval of reduced ice extent during the early-Middle Holocene.

In order to tease out the signal between precipitation and temperature variations to determine the driving climate factor in this glacial activity you must compare ice extents between the cordillera. This is difficult to do because lacustrine sediments can indicate ice presence but not extent, however it can still be done. Laguna Yanacocha, which showed little to no glacial input throughout the Holocene, is less than 1.0 km horizontally from the modern ice limit. This indicates that any Holocene ice advance in the eastern site must have been minimal because it was limited to this extremely narrow range. Shiurococha Upper End Bog sits more than 2.0 km horizontally from the modern ice limit and was receiving significant glacial input in the late Holocene. Although there is evidence of neoglaciation at both sites, a comparison of its magnitude on the eastern versus the western cordillera shows a

much greater ice advance in the western cordillera. Orographic precipitation of westward moving clouds causes the western cordillera to be much drier than the eastern. Therefore, the main restricting factor for these moisture-starved glaciers in the western cordillera is precipitation and they will be highly sensitive to any changes in this. Since the late Holocene ice advance was much greater in the western cordillera compared to the eastern cordillera, the suggested neoglaciation was brought on by wetter conditions. This hypotheses is also be supported by the depletion of $\delta^{18}O_{precip}$ values from Laguna Pumacocha through the Holocene and by the presence of authigenic calcite in Laguna Yanacocha during the middle Holocene.

CONCLUSIONS

The results of this study have supported previous evidence that the central Peruvian Andes experienced a dry and/or warm period in the early Holocene causing glacial retreat in both the eastern and western cordillera. The lack of glaciation throughout the entire region during the middle Holocene suggests a period of minimum ice cover followed by a neoglaciation. This glacier expansion must have been brought on by an onset of cooler temperatures or increased precipitation, which is also shown in the gradual depletion of $\delta^{18}O_{precip}$ values from Laguna Pumacocha. Since the ice extent was much greater during glacier advance on the western cordillera compared to the eastern cordillera, the climatic forcing was most likely due to an increase in precipitation.

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