TECTORNIC EVOLUTION OF THE CHUGACH-PRINCE WILLIAM TERRANE, SOUTH-CENTRAL ALASKA
Faculty: JOHN GARVER, Union College, Cameron Davidson, Carleton College
Students: EMILY JOHNSON, Whitman College, BENJAMIN CARLSON, Union College, LUCY MINER,
Macalester College, STEVEN ESPINOSA, University of Texas-El Paso, HANNAH HILBERT-WOLF, Carleton
College, SARAH OLIVAS, University of Texas-El Paso.

ORIGINS OF SINUOUS AND BRAIDED CHANNELS ON ASCRAEUS MONS, MARS
Faculty: ANDREW DE WET, Franklin & Marshall College, JAKE BLEACHER, NASA-GSFC, BRENT GARRY,
Smithsonian
Students: JULIA SIGNORELLA, Franklin & Marshall College, ANDREW COLLINS, The College of Wooster,
ZACHARY SCHIERL, Whitman College.

TROPICAL HOLOCENE CLIMATIC INSIGHTS FROM RECORDS OF VARIABILITY IN ANDEAN PALEOGLACIERS
Faculty: DONALD RODBELL, Union College, NATHAN STANSELL, Byrd Polar Research Center
Students: CHRISTOPHER SEDLAK, Ohio State University, SASHA ROTHENBERG, Union College, EMMA CORONADO, St. Lawrence University, JESSICA TREANTON, Colorado College.

EOCENE TECTONIC EVOLUTION OF THE TETON-ABSAROKA RANGES, WYOMING
Faculty: JOHN CRADDOCK, Macalester College, DAVE MALONE, Illinois State University
Students: ANDREW KELLY, Amherst College, KATHRYN SCHROEDER, Illinois State University, MAREN MATHISEN, Augustana College, ALISON MACNAMEE, Colgate University, STUART KENDERES, Western Kentucky University, BEN KRASUSHAAR

INTERDISCIPLINARY STUDIES IN THE CRITICAL ZONE, BOULDER CREEK CATCHMENT, FRONT RANGE, COLORADO
Faculty: DAVID DETHIER, Williams College
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Faculty: BRENNAN JORDAN, University of South Dakota, MEAGEN POLLOCK, The College of Wooster
Students: KATHRYN KUMAMOTO, Williams College, EMILY CARBONE, Smith College, ERICA WNELAND-THOMSON, Colorado College, THAD STODDARD, University of South Dakota, NINA WHITNEY, Carleton College, KATHARINE, SCHLEICH, The College of Wooster.

SEDIMENT DYNAMICS OF THE LOWER CONNECTICUT RIVER
Faculty: SUZANNE O’CONNELL and PETER PATTON, Wesleyan University
Students: MICHAEL CUTTLER, Boston College, ELIZABETH GEORGE, Washington & Lee University, JONATHON SCHNEYER, University of Massachusetts-Amherst, TIRZAH ABBOTT, Beloit College, DANIELLE MARTIN, Wesleyan University, HANNAH BLATCHFORD, Beloit College.

ANATOMY OF A MID-CRUSTAL SUTURE: PETROLOGY OF THE CENTRAL METASEDIMENTARY BELT BOUNDARY THRUST ZONE, GRENVILLE PROVINCE, ONTARIO
Faculty: WILLIAM PECK, Colgate University, STEVE DUNN, Mount Holyoke College, MICHELLE MARKLEY, Mount Holyoke College
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TROPICAL HOLOCENE CLIMATIC INSIGHTS FROM RECORDS OF VARIABILITY IN ANDEAN PALEOGlaciers
Project Faculty: DONALD T. RODBELL, Union College & NATHAN STANSELL, Byrd Polar Research Center, Ohio State University

XRD ANALYSIS OF SEDIMENT-CORE MATERIAL AS AN INDICATOR OF THE TRANSITION FROM VALLEY GLACIERS TO CIRQUE DWELLING GLACIERS IN THE PERUVIAN CENTRAL CORDILLERA
EMMA A. CORONADO, St. Lawrence University
Research Advisor: Alexander K. Stewart

GLACIAL LACUSTRINE RECORDS OF CLIMATE VARIATION IN THE TROPICAL PERUVIAN ANDES
SASHA ROTHENBERG, Union College
Research Advisor: Donald Rodbell

HOLOCENE GLACIAL VARIABILITY RECORDED IN LAKE SEDIMENTS FROM NEVADO HUAGURUNCHO, PERU
CHRISTOPHER SEDLAK, Ohio State University
Research Advisor: Nathan Stansell

HOLOCENE CLIMATE CHANGE AND GLACIAL EVOLUTION OF THE CENTRAL PERUVIAN ANDES: LACUSTRINE RECORD FROM THE PROGLACIAL LAKE JAICO
JESSICA TRÉANTON, Colorado College
Research Advisor: Donald T. Rodbell
INTRODUCTION

Glaciers and lakes are recorders of high altitude climate changes, and these archives are important in our understanding of past global changes (Abbott et al., 2003; Rodbell et al., 2009). Records of these changes are needed in the paleoclimate archives because they provide evidence of tropical ocean-atmospheric dynamics that are critical components of the global climate system. Thus, more records from the tropical Andes, in particular, need to be obtained to better document past shifts in temperature and the regional hydrologic cycle. Additionally, the climate of Peru is sensitive to tropical Pacific, tropical Atlantic, as well as North Atlantic influences. Therefore, better records of glacial changes from the Central Andes provide insight into high altitude temperature and precipitation during the Holocene were linked to both high and low climatic variability (Baker et al., 2001).

The ice margins of the tropical Andes fluctuated in response to climatic changes during the Holocene (Rodbell et al., 2009; Stansell et al., 2010). This resulted in sediments within the glacier being expelled and deposited into the lakes below. Sediment cores taken from these lakes provide records of glacial advances and retreats (Nesje et al., 2001). These glaciers also deposit sediment and leave glacial landforms on the landscape surrounding the lake itself. The resulting landforms provide another tool for determining the glaciers’ extent and its timing when paired with sediment core data (Rodbell et al., 2009; Stansell et al., 2010). Sediment cores from other Central Andean pro-glacial lakes highlight the potential of these systems to contain records of continuous up-valley glacial fluctuations that can be dated. Andean lakes have also recorded precipitation variability in the tropics over the Holocene (Seltzer et al., 2000; Polissar et al., 2006; Rodbell et al., 2008; Stansell et al., 2010). When combined with glacial records, these existing paleoclimate records contain valuable information about the timing and pattern of climatic fluctuations throughout the Holocene.

This study aims to provide further insight into how temperature and precipitation varied in the past and combined to drive glacial variability. Specifically, new sediment core data from pro-glacial Yanacocha Lake on the eastern front of the Peruvian Andes are presented to reconstruct the regional Holocene climate history. The addition of this sediment core from the tropical Andes will help refine the chronology of the glacial events in the region. This archive will also

Figure 1. Location map of sites mentioned in the text. Lake Yanacocha is on a west-facing slope of Nevado Huaguruncho in the Peruvian Andes.
be compared to other nearby paleoclimate records in order to better determine the timing and causes of Holocene climate variability in the tropical Andes.

**STUDY SITE**

Lake Yanacocha (10°33.590 S, 75°55.815 W, 4,360 m a.s.l.; Fig. 1) is located on the relatively wet eastern slope of the Central Peruvian Andes in the valley watershed adjacent to Nevado Huaguruncho. The lake was cored from its depocenter which measured 21.65m. It sits below one of the peaks of Nevado Huaguruncho which measures 5,010m a.s.l and is dominated by quartz monzonite igneous bedrock.

<table>
<thead>
<tr>
<th>Lab #</th>
<th>Depth (cm)</th>
<th>(^14)C Age</th>
<th>Measured error (±)</th>
<th>1σ calibrated age</th>
</tr>
</thead>
<tbody>
<tr>
<td>UCI-101317</td>
<td>13</td>
<td>165</td>
<td>15</td>
<td>168±(190)-220</td>
</tr>
<tr>
<td>UCI-101392</td>
<td>38</td>
<td>2345</td>
<td>15</td>
<td>2340±(2350)-2456</td>
</tr>
<tr>
<td>UCI-101393</td>
<td>97</td>
<td>4685</td>
<td>20</td>
<td>5322±(5390)-5419</td>
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<tr>
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<td>6235</td>
<td>20</td>
<td>7155±(7190)-7250</td>
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<tr>
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<td>7580</td>
<td>20</td>
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<td>UCI-101320</td>
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<td>9865</td>
<td>20</td>
<td>11220±(11250)-11278</td>
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<tr>
<td>UCI-101395</td>
<td>218</td>
<td>11100</td>
<td>25</td>
<td>12806±(13000)-13119</td>
</tr>
</tbody>
</table>

Table 1. Radiocarbon ages measured on aquatic macrofossils used in study. The median ages represent the maximum likelihood median ages exported from CALIB version 6.0 and the IntCal 09 dataset. The error bars represent the 1-sigma error range.

**METHODS**

**Geochronology**

The sediment chronology of Lake Yanacocha was determined by measuring radiocarbon on 7 aquatic macrofossil samples from the sediment core. Samples were picked using jeweler’s tweezers under a binocular dissecting microscope. These samples were pretreated at the University of Pittsburgh using standard acid-base-acid protocols (Abbott and Stafford, 1996), and then measured at University of California, Irvine using accelerated mass spectrometry. The CALIB version 6.0 was used to convert the radiocarbon ages to calendar ages (present defined as 1950 A.D.). The median ages represent the maximum likelihood values exported from the Intcal09 dataset (Reimer et al., 2009). Depths were converted to ages using a 2nd order polynomial fit between the median ages (R²=0.99) (Table 1 and Fig. 2).

**Fieldwork, Sedimentology and Geochemistry**

The Late Holocene glacial record was obtained by taking sediment cores from Lake Yanacocha. Overlapping sediment was taken from the depocenter of the lake that was sounded using a Garmin® fish finder GPS. The sediment was extracted using a percussion core system and stored in polycarbonate tubing. Another percussion core was taken in order to capture the sediment-water interface and be paired with the other percussion cores. The top 25 cm of the surface core was extruded into plastic sample bags in the field at 0.25cm intervals. The percussion cores were shipped to The Ohio State University where they were further processed.

Sedimentology of the cores was analyzed at the Mercer Sedimentology Laboratory at the Byrd Polar Research Center at The Ohio State University. In the lab, sediment cores were split vertically into working and archive halves. Cores were then described for Munsell color and major sedimentological features. Cores were also digitally photographed using a DMT CoreScan II at 40pixel/mm resolution. Bulk density was sampled over 1 cm intervals, every 2 cm down-core.
Lake Yanacocha’s sediment core geochemistry was measured using multiple methods. The core was analyzed using an X-Ray Fluorescence (XRF) instrument, ITRAX, (Croudace et al., 2006) at the Large Lakes Observatory at the University of Minnesota, Duluth. The core was measured for XRF at 1mm resolution using a 10 second exposure time for each interval. The surface samples were also analyzed at 0.5cm intervals every 2cm of the core which was extruded into plastic sample bags. Surface sediments were measured using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and sent to ALS Minerals commercial facility in Reno, Nevada where they were analyzed. The samples were pulverized to a size <75μm and then measured using 48 element four acid ICP-MS. Finally, scanning XRF data (CPS values) were converted to concentration (%) using linear regression (Stansell, 2009).

Coulometry of the core was measured to record the content of organic carbon, calcium carbonate, and residual flux in the lake (Englemann et al., 1985; Dean, 1999) every 5-10cm. Combustion of samples at 1000°C in a UIC 5200 furnace was used to determine total carbon (TC). Total inorganic carbon (TIC) was measured using a UIC 5240 acidification module by acidifying samples in 1.0N HClO4. In both cases, carbon dioxide is released and recorded using a UIC Coulometrics carbon dioxide coulometer in the Core Analysis Laboratory at Union College. Total organic carbon was calculated as a weight percentage by subtracting TIC from TC (TOC=TC-TIC). Total organic matter (TOM) was then calculated as 1.724*TOC, and the residual values were determined by subtracting TOM and calcium carbonate from 100. Finally, residual flux was determined as the percent residual values multiplied by BD and the accumulation rate of each respective interval in the sediment core (cm/yr) (Fig. 3).

RESULTS

Changes in clastic sediment concentrations in the Yanacocha core are represented by shifting values of Ti, K, bulk density, organic carbon, and residual flux. Concentration data for the elements Ti and K

![Figure 3. The Yanacocha sediment core data plotted versus age.](image)
The transition from the Late Glacial Stage to the Early Holocene is well captured in the Yanacocha sediment record. Following a period of low clastic sediment values at the end of the Late Glacial Stage, the Yanacocha sediment record contains tentative evidence of an Early Holocene advance between 10,300 and 9,300 cal yr BP (Fig. 3). Similarly, Rodbell (1992) and Röthlisberger (1987) reported data showing early Holocene glacial advance in the Cordillera Blanca using lichenometric and radiocarbon dated moraines (Rodbell et al., 2009). More recently, Licciardi et al. (2009) documented evidence of an early Holocene advance in the Cordillera Vilcabamba using CRM dating methods. Thus, combined with our Yanacocha record, there is provisional evidence of early Holocene glaciations in multiple valleys in the Peruvian Andes. Following the purported advance from 10,300 to 9,300 cal yr BP there was a decrease in clastic sediments in Yanacocha from 9,300 to 7,000 cal yr BP indicating the beginning of a period low glacial activity.

The Middle Holocene 8,000 to 3,700 cal yr BP

The middle Holocene period was generally an interval lacking in glacial activity. There is no clear evidence in Yanacocha of any mid-Holocene glacial advance from 7,000 to 5,000 cal yr BP. Clastic sediments then increase in the period from 5,000 to 4,200 cal yr BP. This corresponds to the rapid ice growth on the Quelccaya Ice Cap that began ~5,000 cal yr BP, followed by wetter and/or cooler conditions for the remaining Holocene (Buffen et al., 2009). This shift from relatively dry to wet conditions is also apparent in the Yanacocha record, with high calcium carbonate values peaking at ~7,500 cal yr BP, followed by decreasing values for the remaining middle and late Holocene. This can also be seen in the Oxygen isotope work done by Seltzer et al. (2000) in the Lake Junin (Fig. 4) record suggesting a trend towards wetter conditions in the region. In addition, in Rowe et al. (2002) organic carbon shows an increase in the lake level at Lake Titicaca, also insinuating wetter conditions. Also, it was mentioned by Rodbell et al. (2009) there may be evidence of a mid-Holocene glacial advance as seen in the lichenometric and radiocarbon ages recovered. From 4,200 to 3,700 cal yr BP clastic sediments were relatively low in the Yanacocha core. 

DISCUSSION

The Early Holocene 10,300 to 8,000 cal yr BP

The sediment core is characterized by multiple transitions of clastic sediment concentrations throughout it. For example, the period between 13,000 cal yr BP and 12,050 cal yr BP contain decreasing values of clastic sediments, and this interval of values is at or near the lowest levels shown on the entire core. This decrease in clastic sediments is followed by sustained low values until 10,300 cal yr BP. After this lull, an increase in clastic sediments occurred from 10,300 until 9,300 cal yr BP. The time span from 9,300 to 5,000 cal yr BP has a trend of low clastic sediment values overall, however, decadal to centennial scale fluctuations in clastic sediment values. Nevertheless, the stretch of time 5,000 to 1,750 cal yr BP is characterized by a general increase in concentration of clastic sediment values with a step-wise transition to lower values from ~4,500 to 3,500 cal yr BP, but the overall trend is toward higher values. However, the interval from 1,750 to 650 cal yr BP is characterized by a distinct shift toward lower values of clastic sediments, while the period from 650 to 100 cal yr BP rebounds back to higher values (Fig. 3).
Therefore, conditions in the region were wetter overall (Rowe et al., 2002) however clastic sedimentation rates did not spike implying precipitation does not solely affect glacial activity.

The Late Holocene 3,700 BP to present day

Clastic sedimentation rates in the late Holocene did not remain in a lull as they had been in the mid-Holocene. There was a trend toward higher clastic sediment values between 3,700 and 1,750 cal yr BP, which was also an interval of wet conditions in the Lake Titicaca region (Rowe et al., 2002). Then, from 1,750 to 700 cal yr BP a decrease in the clastic sediments was seen in Yanacocha. This decrease in clastic sediments began approximately 750 years before the start of the Medieval Climate Anomaly (MCA) which corresponds to the decrease in Sr isotopes in the Lake Gueshgue record (Fig. 4). Bird et al. (2011) found O18 values in the late Holocene to be some of the highest of the entire Holocene, indicating an arid interval. From 600 to 200 cal yr BP it is seen in Yanacocha to be a period of increased glacial activity, which corresponds with the Little Ice Age (LIA). Additionally, the Quelccaya Ice Cap recorded a cold and wet interval from 450 to 230 cal yr BP and a cold and dry phase from 230 to 70 cal yr BP (Thompson et al., 1986; Liu et al., 2005). A wet phase during the LIA is seen in the oxygen isotope records that were taken from the Huascaran ice cap and Lake Pumaco.

Figure 4. Yanacocha sediment core data (A-B) plotted versus regional paleoclimate records. High values of clastic sediments in the Yanacocha record correspond to periods of increased glaciation in the Cordillera Blanca (C-D). Glaciers generally advanced in Peru during the Holocene at times of colder and wetter conditions (E-F). The dashed line indicates the timing that multiple regional records from the region identify a shift from relatively warm and dry conditions during the early Holocene, to cold and wet conditions in the late Holocene.
cha, Peru (Fig. 4). Lake levels as recorded by Rowe et al. (2002) also indicate increased lake levels from ~500 cal yr BP to present day. The increased appearance of clastic sediments in Yanacocha during this period follows suit with other proxies to signify a correspondence between the Lake Yanacocha sediments and wetter conditions and cooling temperatures in the region.

CONCLUSION

The Lake Yanacocha sediment core records fluctuating ice margins during periods of shifting climate during the Holocene. In general for Peru, glacial advances during the Holocene occur at times of cold and wet conditions, whereas dry and warm periods are characteristic of ice retreat. Specifically, there is evidence for a glacial advance in the Yanacocha watershed during the early Holocene. More records are needed, however, in order to determine the scale and magnitude of Early Holocene climate variability. Furthermore, the mid-Holocene is characterized primarily by decrease in glacial activity at Lake Yanacocha prior to ~5,000 cal yr BP, during a period of pronounced aridity. Thus, evidence for a lake level low-stand at Yanacocha coincides well with the arid mid-Holocene that has been documented in other nearby paleoclimate regional sediment records during the same interval. Consequently, the early part of the mid-Holocene was a period of overall restricted ice cover and more arid conditions in the Yanacocha watershed followed by renewed glaciation later on and leading into the late Holocene. Additionally, a period of pronounced ice retreat just prior to the local LIA is apparent in Yanacocha and multiple regional records. These records also identify a consistent pattern of colder and wetter conditions during the LIA. Although many of the paleoclimate records available from Peru show similar changes during the Holocene, differences in the individual archives are apparent and can be attributed to small regional variations in both climate forcing and response of local geomorphic systems. The Yanacocha sediment record provides new evidence of Holocene glacial variability, and more archives of its type are needed to further understand paleoclimate systems.

REFERENCES


