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HIGH-RESOLUTION $\partial^{18}O$ RECORDS OF HOLOCENE HYDROLOGIC VARIABILITY FROM THE CENTRAL PERUVIAN ANDES

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INTRODUCTION

Oxygen isotope ratios ($\partial^{18}O$) of lacustrine calcite (marl) preserved in carbonate lakes in the central Peruvian Andes can provide records of hydrologic variability with decadal to subdecadal resolution. Here we compare records from Laguna Yuraicocha (12.53°S; 75.50°W; 4460 masl) and Laguna Junin (11.00°S, 76.15°W; 4000 masl) with $\partial^{18}O$ records of precipitation from glacial ice preserved on Nevado Huascarán (9.11°S, 77.61°W; 6048 masl; Thompson et al., 1995) and in the Quelccaya Ice Cap (13.93°S; 70.83°W; 5670 masl; Thompson et al., 1985; Figure 1).

LAGUNA YURAICOCHA

Laguna Yuraicocha in the western cordillera of the central Peruvian Andes is dammed by late glacial moraines and is underlain and surrounded by Jurassic and Cretaceous limestone interbedded with siliciclastic rocks. A 6.9 meter-long sediment core from the distal end of the lake obtained in 2006 is dominated by marl with a mean concentration of 82 weight percent that has accumulated at a rate of ~1 mm yr^{-1} for the past 6200 years. The age model for the core is based on a combination of ^{210}Pb and AMS ^{14}C ages from charcoal; modern lake water has an average conductivity of ~0.247 mS cm^{-1} and is ~1‰ evaporatively enriched from mean regional precipitation. Marl samples were taken with an average sampling interval of 8 years; samples were treated to remove organic matter, sieved to concentrate the <75 µm fraction, and the clay fraction was removed by repeated pipette withdrawal. The <75 µm fraction contains abundant euhedral grains of calcite that are not abraded or corroded, thus reflecting their authigenic origin in Laguna Yuraicocha. The $\partial^{18}O$ and $\partial^{13}C$ stratigraphy reveals decadal, century, and millennial-scale variability, and generally covary with similar amplitudes; $\delta^{13}C$ ranges from -0.5 to 3.5 ‰ (PDB). A pronounced linear trend of $\delta^{18}O$ depletion (from -10.5 to -14.5 ‰) spans the length of record and likely reflects a progressive decrease in hydrologic balance (i.e., the ratio of evaporation/precipitation; hereafter E/P) from the middle Holocene through the late Holocene. This interpretation is consistent with basal core sediment that records pronounced lake low stands, and possible periodic dessication in the early-middle Holocene. The last 1200 yr of record reveals a 2‰ depletion culminating with the most depleted isotopes on record ~ AD 1800 followed by an abrupt 1.5 ‰ enrichment that began ~AD 1900 and continues to the present.

Figure 1. Location of Laguna Junin and Laguna Yuraicocha in relation to Nevado Huascarán and the Quelccaya Ice Cap.

LAGUNA JUNIN

Lake Junin covers approximately 300 km^2 in an intermontane basin between the eastern and western cordillera of the central Peruvian Andes. Bedrock in the eastern cordillera is a mixture of Mesozoic siliclastic and carbonate rocks, and crystalline rocks, while bedrock in the western cordillera is primarily Jurassic carbonates and Tertiary volcanic rocks. Modern Junin water has a mean conductivity of ~0.341 mS cm^{-1} and is evaporatively enriched between 1 and 3‰ relative to modern meteoric precipitation. The lake basin, with a maximum water depth of ~ 15 m, is dammed at its northern and southern ends by coalescing alluvial fans that emanate from glacial valleys in both cordillera. These fans can be traced to moraines that are more than 250,000 years (ka) old, and thus the lake is at least this old. Detailed moraine mapping coupled with nearly 200 cosmogenic radionuclide (CRN; ^{10}Be, ^{26}Al) exposure ages from boulders on the crests of moraines clearly indicate that during the maximum extent of late Cenozoic glaciation (the Río Blanco and Punrun glaciations; Wright, 1983) on the Junin Plain, paleoglaciers reached the lake edge but at no time in perhaps as much as 1 million years, or more, has the Lake been overridden by ice (Smith et al., 2005a, 2005b). **Lake Junin is thus one of the few lakes in the tropical Andes that both predate the maximum extent of glaciation *and* are in a geomorphic position to record the waxing and waning of alpine glaciers in nearby cordillera.**

Based a core taken in 1996 (Seltzer et al., 2000), during intervals of reduced ice cover in the Junin drainage basin, marl accumulated in the Lake at rates of ~1 mm yr^{-1} with a mean $CaCO_3$ concentration of ~80% for the past 11,000 years of record; marl samples were taken with an average sampling interval of ~60 years and processed as noted above. Seltzer et al. (2000) documented an ~6‰ increase in the $\partial^{18}O$ of the bulk marl from the late glacial into the early Holocene that is nearly identical to the isotopic shift reported from the Huascaran ice core ~300 km to the north (Thompson et al., 1995). Moreover, Seltzer et al. (2000) demonstrated that the $\partial^{18}O$ record from Junin tracks precessionally-driven insolation receipts at 10°S, and contains a subcentennial-decadal component that is superimposed on this long-term trend. A pronounced linear trend of $\delta^{18}O$ depletion (from -3.0 ‰ to -11.0 ‰) spans the Holocene and likely reflects a steady decrease in E/P from the late glacial through the late Holocene.

COMPARISON OF SEDIMENT RECORDS AND ICE CORES

The sediment records indicate that the relative state of hydrologic balance (E/P) of the two lakes that is evident in modern water (with $E/P_{Junin} > E/P_{Yuraicocha}$) has remained intact for most of the Holocene; that is, on average, Laguna Junin has had a greater E/P ratio than Laguna Yuraicocha. This is evident in the strong positive covariation in $\partial^{13}C$ and $\partial^{18}O$ seen in the Junin record, and in the weak negative covariation seen in the Yuraicocha data (Fig. 2). Thus, we can conclude that over most of the past 10,000 years, Laguna Junin has been acting more as a "closed basin" lake than has Laguna Yuraicocha. In addition, the Holocene gradient in $\partial^{18}O$ of -0.71‰/1000 yr for Laguna Junin and -0.41‰/1000 yr for Laguna Yuraicocha imply that much of the isotope depletion seen in both lakes was caused by a reduction in E/P through the Holocene (Fig. 3). Finally, the amplitude of centennial-scale oscillations in the $\partial^{18}O$ stratigraphy of Laguna Junin increased through the Holocene, reaching nearly 5‰, ~40%

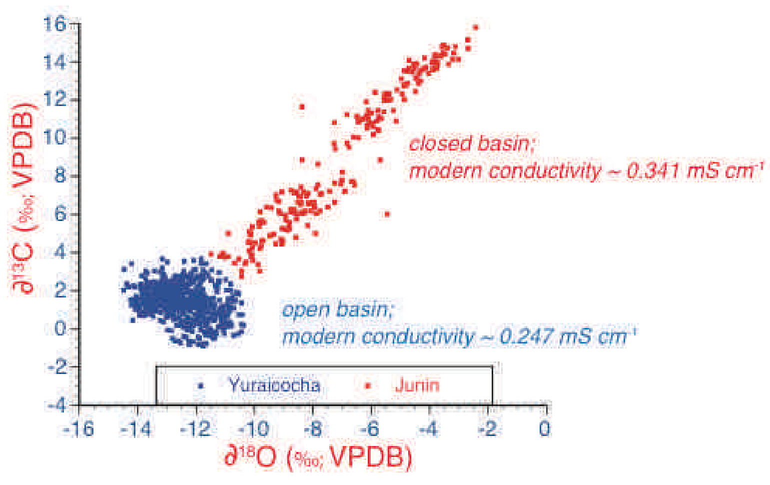

Figure 2. Covariation of ∂13C and ∂18O for Laguna Yuraicocha (open basin) and Laguna Junin (closed basin).

greater than those in Laguna Yuraicocha; this suggests that the severity of oscillations in hydrologic balance have been increasing through the Holocene and have had a significantly stronger effect on closed basin lakes than on open basin lakes.

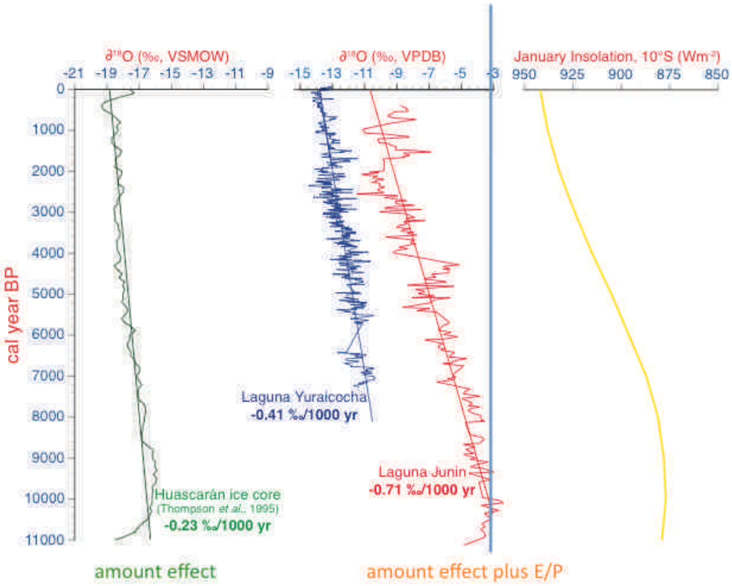

Figure 3. Oxygen isotope records from Laguna Yuraicocha and Laguna Junin compared with the oxygen isotope record from Nevado Huascaran and summer insolation receipts at 10°S.

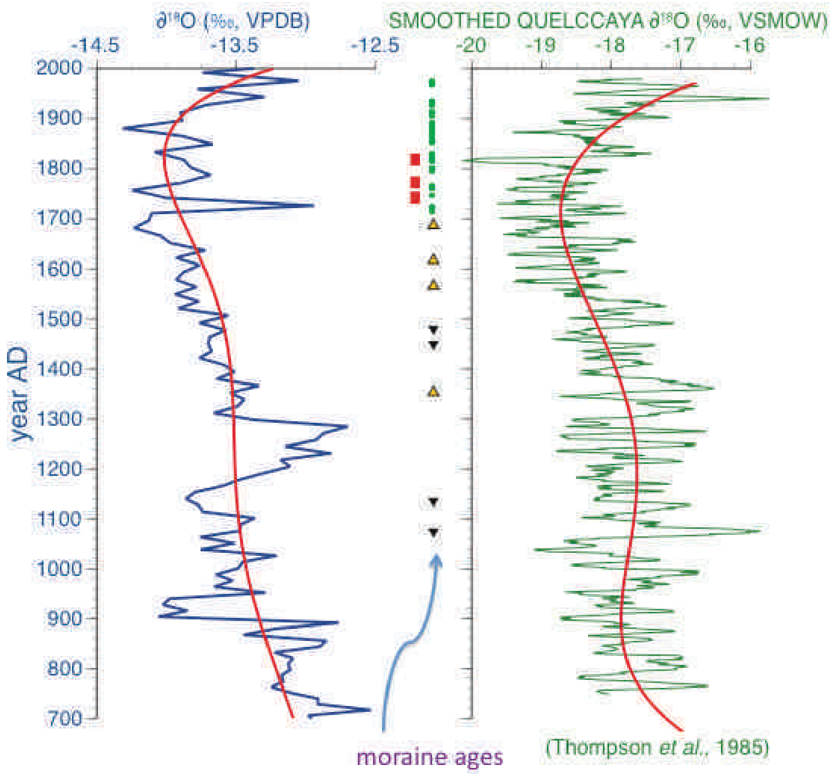

Figure 4. The oxygen isotope record of the last ~1300 years from Laguna Yuraicocha compared with the Quelccaya Ice Cap Record (Thompson et al., 1985) and the ages of late Holocene moraines as summarized by Rodbell et al. (2009).

Deconvolving the apparent influences of temperature, the "amount effect", and hydrologic balance (E/P) on isotope records in the tropical Andes may be possible through a comparison of ∂^{18}O records from ice cores with ∂^{18}O records from carbonate lakes (Fig. 3). Holocene gradients in ∂^{18}O seen in the carbonate lakes exceed the Holocene gradient seen in the Huascarán ice core by factors of nearly 1.8 (Yuraicocha) and 3.1 (Junin). Thus, if the Huascaran ∂^{18}O record is taken as an archive of source water (reflecting some combination of air temperature and the "amount effect"), and the lake records are taken as archives of source water as modified by changes in E/P, then two thirds of the Junin and nearly half of the Yuraicocha ∂^{18}O trends reflect reductions in evaporative enrichment of lake water through the Holocene, and the balance reflects some combination of decreased temperature and/or increased "amount effect".

Long term trends in the ∂^{18}O signal of both the lake records and the Huascarán core correspond with long-term low latitude insolation receipts (Fig. 3), and possibly with the mean state of ENSO as this latter affects moisture advection from the Amazon Basin (Vuille et al., 2000). Detailed trends in ∂^{18}O spanning the last 1300 years in Laguna Yuraicocha correspond closely to trends evident in the ∂^{18}O of the Quelccaya Ice Cap (Fig. 4). Both records reveal an ~1.5‰ depletion from *AD* 700 to *AD* 1800, which may record a region wide cooling and/or increase in precipitation associated with the Little Ice Age.

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