Union College
Union | Digital Works

Honors Theses

Student Work

6-2018

Characterization of glacial sediments from a 700,000-year-old Lake Junín drill core

Tshering Lama Sherpa

Characterization of glacial sediments from a 700,000-year-old Lake Junín drill core

by

Tshering Lama Sherpa

Submitted in partial fulfillment
of the requirements
for Honors in the Department of Geology

UNION COLLEGE
June, 2018

ABSTRACT

Lake Junín (11.0°S, 76.2°W) is an intermontane lake at an elevation of 4085 masl in Junín, Peru. The lake spans ~300 km^2 and has a water depth of ~12m. It is dammed at its northern and southern ends by glacial alluvial fans that have been dated >250 ka, indicating that the lake is at least this old. Lake Junín has never been overridden by ice in the past 1 million years making it one of the few lakes in the tropical Andes that predates the last maximum extent of glaciation and has a continuous record of waxing and waning of nearby Cordilleran glaciers. In July and August of 2015, piston cores were obtained from three sites in Lake Junín. These cores were overlapped to form a continuous record spanning the past ~700 ka. Siliciclastic flux, magnetic susceptibility (MS), mean grain size, and Ti/Ca of sediments from Lake Junín provide proxy records of glacial erosion and glaciation in adjacent valleys. Seven periods of glaciation are determined by relatively high magnetic susceptibility, low $CaCO_3$, high clastic flux and Ti+Si+Al /Ca ratio. Mean grain size during all glacial cycles, irrespective of glacial extent is ~1-2 microns. The dominance of fine glacial sediments and absence of coarse sediments in the lake core indicate that there is no ice rafted debris (IRD) in Lake Junín. This supports the hypothesis that while the glaciers reached the lake edges, it never calved into the lake. The oldest glacial cycle has relatively coarser sediments (>3 microns) but this distinctive change in grain size is hypothesized to indicate a fluvial depositional environment indicating the birth of Lake Junín to be around ~600,000 years. Despite smaller ice extent in the LLGM, siliciclastic flux between MS2-4 is higher than in other glacial periods which indicates that the glacier at the time was warm based with a higher activity ratio. Furthermore, comparison between skewness and mean grain sizes of glacial sediments in Lake Junín show that the two are inversely related. Coarser sediments have negative skewness with a finer tail while finer sediments have a positive

skewness. This variation in mean grain size distributions reflects a mixed signal of different mean grain sizes either from a single dominant valley with different rock types or from different valleys with prominently different rock types. In general, mean grain sizes are very fine (1-2 microns) so the sediments would have followed Stokes Law and travelled into the lake either as an interflow or overflow.

ACKNOWLEDGEMENTS

Firstly, I would like to thank my Aama and Baba for helping me and supporting me throughout this process and my four years here at Union. Thank you for your countless sacrifices, unconditional love, support, and prayers.

I would also like to extend my deepest gratitude towards my advisor, Professor Don Rodbell for whose guidance I am grateful. A special thanks goes to Sarah Katz and the Union College Geology Department for their guidance and support of this thesis.

Lastly, I would like to thank National Science Foundation (EAR- 1402076) and Union College Geology Department for making this thesis possible.

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

Earth's climate has varied naturally for billions of years (Ruddiman., 2001). However, increasing use of fossil fuel by humans since the Industrial Revolution has resulted in an unprecedented change in global climate (Ruddiman., 2001). Instrumental measurements have helped quantify these changes although they are only able to record climate variations for a span of about 150 years (Ruddiman., 2001). However, this is only a tiny fraction of the actual record of Earth's long climatic history. Thus, climate proxies such as ice cores, corals, speleothems, pollen grains, tree rings, marine and lake sediments are used as natural archives of paleoclimate (Bradley., 1999). Proxies chronicle climatic fluctuations and indirectly reconstruct variations in precipitation and temperatures that induced climate change. Proxies can also be used to estimate concentrations of CO_2 in the atmosphere in the past in order to compare and predict future CO_2 levels and infer changes in global climate due to increased concentrations of greenhouse gases Figure 1).

Paleoclimatologists therefore study the natural variability in climate that extends back from instrumental records. Extensive paleoclimate studies can help understand the frequency and amplitude of long term cycles of climate change (Bradley., 1999). A record of natural variability in climate helps to recognize any human induced climatic trends. Long records of climate change are obtained through the study of climate dependent natural phenomena. These phenomena provide proxy records of climate and form the basis for testing climate models about climate change (Bradley., 1999). This is imperative in recent years, where increased human activities have already started to affect global climate. Paleoclimatology can thus help tune models that can be used to predict future patterns of climate change based on past climatic trends.

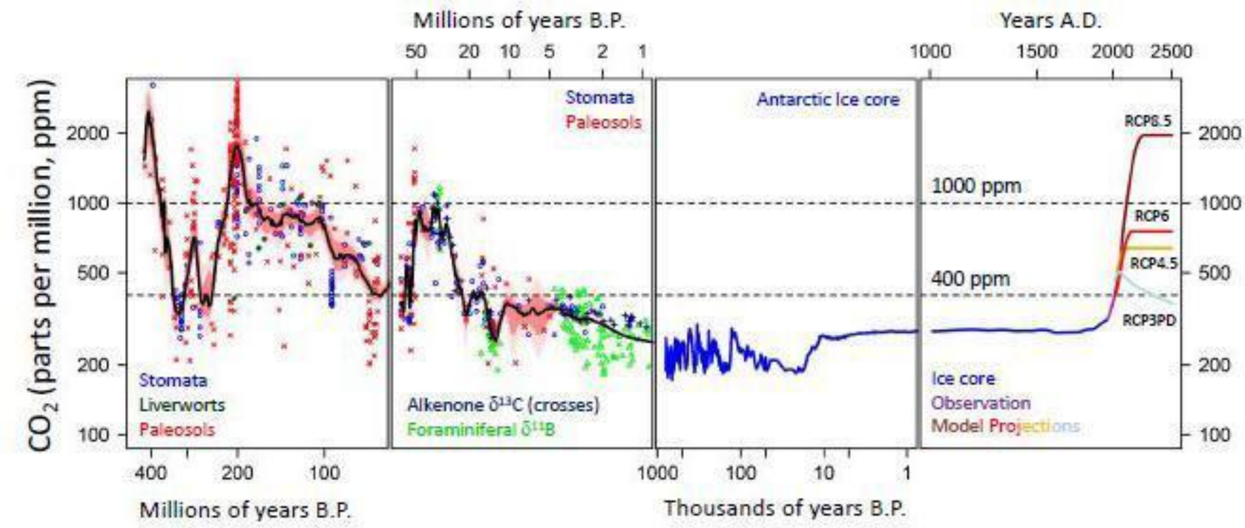

Figure 1. CO_2 measurements are used as a proxy for climate over the past. Different proxies such as forams, stomata, paleosols are used to infer CO_2 levels in the times beyond instrumental measurements (from Inglis et al., 2015).

Climate is a product of the interactions between the atmosphere, oceans, biosphere, land surface and cryosphere. Each proxy records climatic variation, which is a result of the feedbacks between these components. The oceans cover about 70% of the earth's surface and are major reservoirs of CO_2 in solution. A small variation in dissolved oceanic CO_2 could have ramifications in the radiation balance of the atmosphere and consequently the climate (Bradley., 1999). Thus, oxygen isotopic composition of calcium carbonate from the remains of calcareous organisms, variations of species assemblages and morphologies, dissolution rates of deep sea carbonates all indicate paleoclimatic variations in marine sediments (Bradley,1999).

Ice cores can be used to discern changes in past temperatures by melting the ice cores and analyzing stable isotopes of oxygen and hydrogen of melted ice (Figure 2,3). Additionally, ice cores have pockets of atmospheric air stored in them that provide detailed records of carbon dioxide, methane and other gases that help reconstruct atmospheric conditions when the snow was deposited (Bradley., 1999).

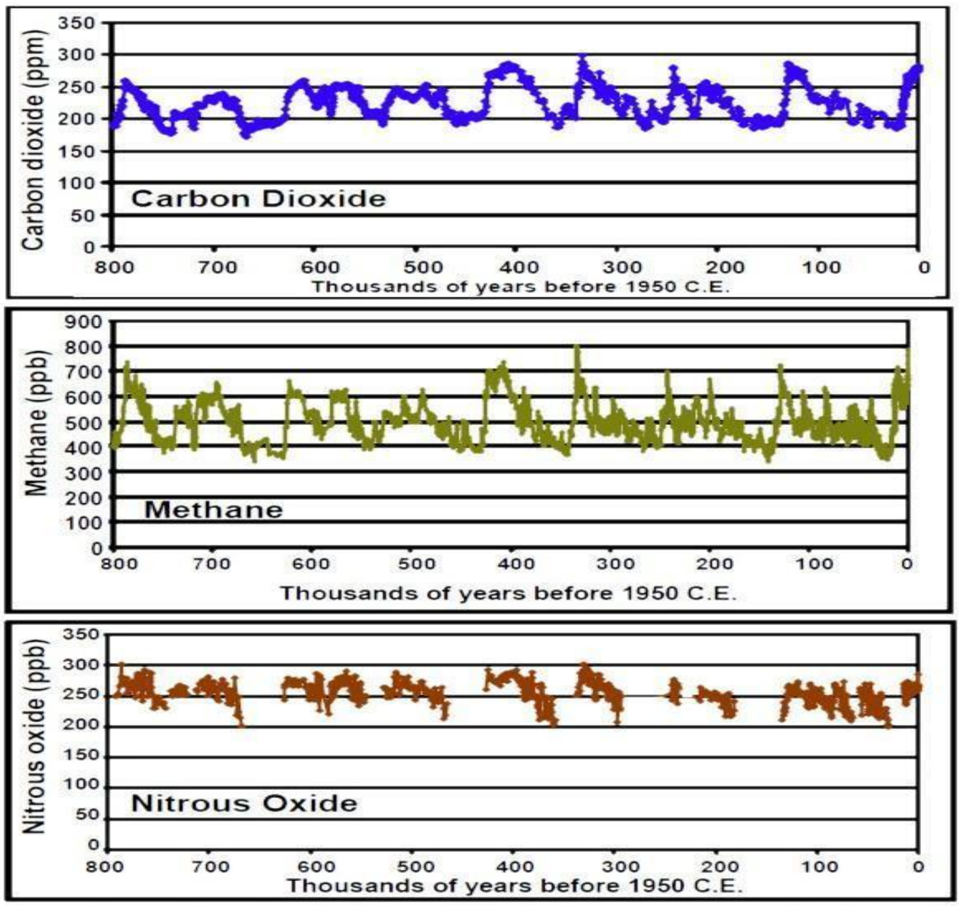

Figure 2. Atmospheric carbon dioxide, methane and nitrous oxide concentrations for the last 800,000 years derived from air bubbles trapped in ice cores from Dome C, Antarctica. Units are in ppm for CO_2 and ppb for CH_4 and N_2O. Year 0 indicates 1950 of the Common Era (C.E) (from Luthi et al., 2008).

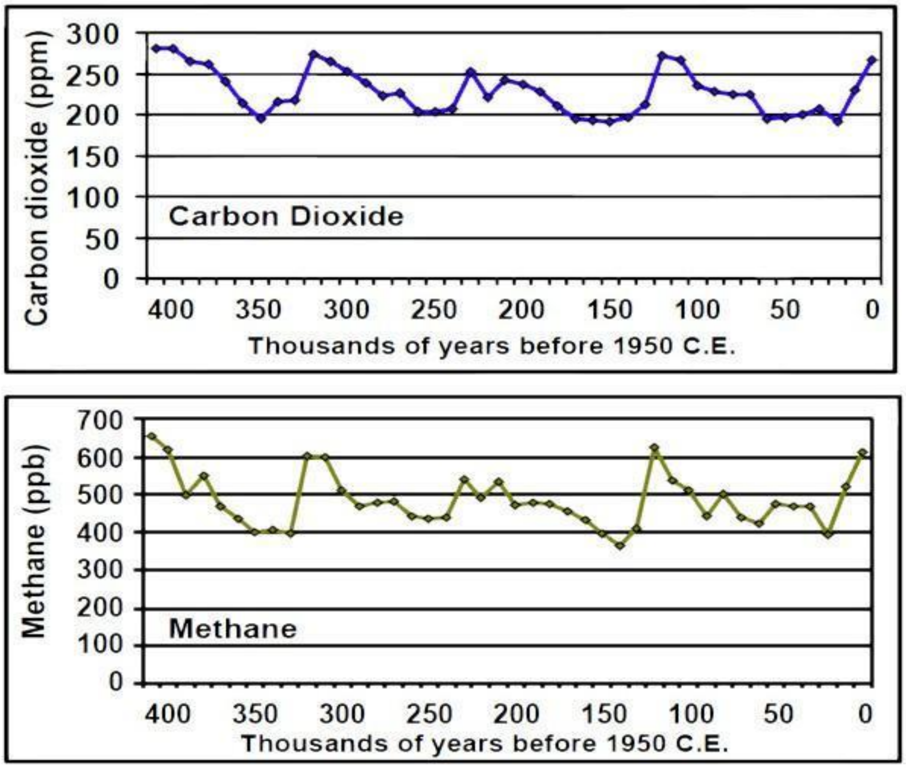

Figure 3. Atmospheric Carbon dioxide and Methane concentrations for the past 400,000 years derived from air bubbles trapped in ice at Vostok Station, Antarctica. Units are ppm for CO_2 and ppb for CH_4. Year 0 indicates 1950 of the Common Era (from Petit et al., 1999).

Terrestrially, tree rings record annual climate in mid and high latitudes unless their growth is disturbed. Climatic conditions influence tree rings producing annual thick light layers alternating with thin dark layers' indicative of climate variations. The light layers are thick due to rapid growth in spring while the dark layers are thin due to cessation of growth in summer or fall-winter (Ruddiman, 2001). Multiple records from different trees can also be combined to form a climate record longer than the timespan of a single tree. Similarly, annual bands in coral skeletons provide information about annual climatic variability. Coral skeletons are made of calcite which incorporates oxygen from the surrounding water. The ratio of oxygen isotopes changes in ocean water changes on the basis of temperature and rainfall and this is reflected in ratio of heavy and light oxygen isotopes in coral growth bands (Ruddiman, 2001). These growth bands can therefore provide information on past climate change and ocean salinity and temperature.

Sedimentary archives of paleoclimate are usually derived from low energy undisturbed marine environments where the degree of disturbance depends upon the amount of turbulent storms and bioturbation (Ruddiman, 2001). Lakes are another excellent high resolution sedimentary archive of paleoclimate (Cohen., 2003). Glacial, tectonic or fluvial processes form most lakes. Glacial and tectonic lakes have the greatest area while tectonic lakes have the greatest volume and are well-preserved (Cohen., 2003). Most lakes lie in mid latitudes where air pressure systems and evapotranspiration rates results in high precipitation. Lakes are also abundant near the equator, which similarly has low pressure, high ratio of precipitation to evaporation.

However, mid latitude lakes are generally glacial in origin while modern equatorial lakes are formed either tectonically or fluvially. In contrast, subtropical lakes receive low precipitation and high evapotranspiration lakes and are usually tectonically formed closed basin lakes with no outlets (Cohen, 2003).

Lakes accumulate sediments, which includes terrigenous sediments, chemical/biogenic sediments, cosmogenic/volcanogenic sediments, exogenic /endogenic fossils, aerosol and waterborne pollutants from the lake catchment, surrounding area and even the atmosphere for thousands of years or even longer (Cohen, 2003). Sediment coring retrieves deposits from deep within the lake providing paleolimnological data. Fossils in lakes demonstrate lake responses to changes in lake ecosystem. Fossil diatoms, biomass and water species from multiple lakes are used to evaluate impacts of human activities on regional and global scale. Additionally, varves, which are the smallest scale events recognized in stratigraphy, provide information about annual sedimentation and paleoclimate of the region. While there has been extensive paleolimnological research in the northern latitudes, research in the tropical lakes of the Southern Hemisphere have only been done since the late twentieth century.

Sabana de Bogota is one of these lakes located in the high plains of Cordillera Oriental in Colombia. At an elevation of 2500 masl, Sabana de Bogota is a remnant lake that has collected sediments over millions of years. A study drilled long cores up to 350 m in length, which documented fifty-five pollen zones corresponding to 27 major climatic cycles spanning 3.5 Mya (van der Hammen, 1985). This record was further correlated with oxygen isotope records from deep sea. Primarily, pollen grains, which are sensitive to temperature changes, infer changes in climate. Three different phases are recorded in the sediments at Sabana de Bogotá based on pollen grain analysis, K-Ar and fission track dating of volcanic layers (van der Hammen, 1985). The first phase before 25 ka was cool and humid causing ice extension. The next phase between 21 ka and 14 ka was cold and dry (Van Der Hammen 1985). This dry period is global but was especially severe in the tropics. This period of aridity is also in the sediments of Laguna De Fuquene in "Valle de Ubate- Chiquinquira', another high plain in Cordillera Oriental, north of Sabana de Bogotá (van Geel and van der Hammen, 1973). Pollen analysis and ^{14}C dating of Laguna De Fuquene's core show an arid period between 21-12 ka (van Geel and van der Hammen, 1973).The last phase after 10 ka is thought to have been relatively warm and humid causing high vegetation and smaller glacial extent (van der Hammen, 1985). Lowering of mean annual temperatures in tropical Andes and climatic fluctuations during the Holocene correspond in magnitude with temperature changes in the northern temperate latitudes.

Lake Titicaca is another intermontane lake located in the northern Altiplano which has had continuous sedimentation >20 ka. A study collected a 136-meter-long drill core of sediments from Lake Titicaca recorded four cycles of glacial and interglacial period over the last 370,000 years based on ^{14}C, U-Th dating and tuning methods (Fritz et al., 2007). Ages were derived by radiocarbon dating of bulk organic carbon samples from the upper 25 m of the core and U-Th dating of aragonite laminae relatively free of detrital sediments in the upper 48 m of the core (Fritz et al., 2007). The chronology of the core >48m was based on interpolation of control points between the lake stratigraphy and the Vostok CO_2 record assuming constant sedimentation rates (Fritz et al., 2007). This study concluded that alternating cold-wet and warm-dry periodic trend in Lake Titicaca was similar to Sabana de Bogotá and was a result of global and local climate forcings such as insolation, precession, global ice volume and Pacific and Atlantic SSTs.

A smaller sediment record at Lake Titicaca provides a very high-resolution data of precipitation in the region for the past 25 ka (Baker et al., 2001). The study concludes that the annual rise of Lake Titicaca is inversely correlated to the North Equatorial Atlantic sea surface temperature (SST) indicating that Amazonia and the Altiplano had wet conditions when Northern Equatorial Atlantic sea surface temperatures was anomalously low. Lake sediments therefore provide a high-resolution record of precipitation and hydrologic balance of the region as well (Baker et al., 2001).

Another example of a lake with high-resolution record of paleoclimate in Southern America is Salar De Uyuni located on the Bolivian Altiplano. A 220 m long drill core from Salar De Uyuni yielded significant information of precipitation in the region for the past 50,000 years. The youngest lake that existed in the Salar has been dated at around 12.5 ka coincident with the Younger Dryas Event in the North Atlantic (Baker et al., 2001). A dry period between 12.5-14.9 ka marks the Bolling-Allerod interstadial in the northern latitudes (Baker et al., 2001). Two periods between 14.9-16.6 ka and 24.3-26.1 ka mark the existence of paleo lake Tauca that coincides with Heinrich events 1 and 2a (Baker et al., 2001). Heinrich events are brief dry and cold periods when massive icebergs floated into the North Atlantic due to changes in the ice sheets. These icebergs eventually melted and deposited ice-rafted detritus, thus changing ocean's circulation (Roberts et al., 2014). Studies also hypothesize that a reduction in the mass of ice sheet along with a change in ocean circulation would have changed atmospheric circulation and climate. This shows that wet events in the tropical South American region were coeval with cold sea surface temperatures in the Northern Hemisphere. Lacustrine muds in the Salar De Uyuni drill core indicate cold and wet periods where precipitation would have been much higher than modern rates. Since variability in precipitation aligns with summer insolation maxima and minima, the authors suggest that the South American Summer Monsoon (SASM) is controlled by variable summer insolation, which induces prolonged wet and dry periods in South America (Baker et al., 2001). As such, a long wet period, coincident with the Last Glacial Maximum is in phase with summer insolation maxima. Shorter wet events were coincident with cold events in the temperate North Atlantic such as Heinrich events 1, 2 and the Younger Dryas events (Baker et al., 2001). Diatom fraction and salt deposits, mostly halite and gypsum, identified wet and dry phases by natural gamma radiation measurements, which is higher for lacustrine deposits than for salt deposits (Baker et al., 2001). Diatom fraction is a measure of the ratio between benthic diatom to freshwater planktonic diatoms in lake sediments.

Lake Potrok Aike, one of the few lakes in the Southern Hemisphere with a high-resolution continental archive of paleoclimate, is a 770,000-year-old maar lake located in Santa Cruz, Patagonia, Argentina. In 2008, The "Potrok Aike Maar Lake Sediment Archive Drilling Project" (PASADO) obtained a 106 m-long drill core extending back up to 51,000 years (Hahn et al., 2013). Multi proxy methods including physical properties, geochemistry, CNS elemental analysis, stable isotopes, pollen and diatom fraction and magnetic susceptibility determined the lake level and environmental and climate change in Lake Potrok Aike over the past 51 ka. From 51-33.1 ka, glacial conditions pervaded and lake levels were high (Hahn et al., 2013). However, calcite precipitation was low during this period and a northerly position of Southern Hemispheric Westerlies (SHW) would have resulted in decreased wind speeds and evaporation (Hahn et al., 2013). Further, Atlantic precipitation due to the SHW blocking easterly winds could have enhanced precipitation in the area. In fact, from 49-44 ka and 34-17 ka,the lake levels were at its highest levels.. At around 40 ka, lake levels dropped indicating higher temperatures which were supported by diatom and biogenic silica concentrations (Zolitschka et al., 2013). Decrease in magnetic susceptibility and increase in clay content until 33.1 ka suggest that the lake had interstadial warm and productive conditions. Until the next glacial extension occurred (Hahn et al., 2013). According to PASADO, local Last Glacial Maximum (LGM) from 33.1 ka-17.2 ka is consistent with other LGM records in Patagonia (Hahn et al., 2013). Deglaciation started 17 cal ka BP and there was an increase in productivity in this warm and humid period as shown by the decrease in MS record and high total organic carbon (TOC), biogenic silica (BSi) and C/N values. After the LGM, the SHW moved southward but only reached their modern position over Lake Potrok Aike in the early Holocene. After 16 ka, productivity was low for about one millennium followed by further low productivity after 14.7 ka (Hahn et al., 2013). While tephra deposits do provide nutrients, the research concluded that increased lake turbidity reducing light penetration and thus photosynthetic activity could have reduced productivity instead (Hahn et al., 2013). On the other hand, low productivity after 14.7 ka is thought to have been due to Antarctic cold reversal, which might have influenced climate as far as Lake Potrok Aike inducing cold conditions (Hahn et al., 2013). However, this is highly controversial and disputed. Pollen based data shows that at 13.5 -11.4 ka temperatures at Potrok Aike were warm. After 9.4 ka, low lake levels occurred due to warm Holocene climate along with strong dry winds (Hahn et al., 2013). The controversy surrounding paleoclimate in Potrok Aike around ~14 ka could be due to dating problems in the cores since the cores at Potrok Aike did have some gaps. Core chronology was based on age depth model created from linear interpolation of median calibrated radiocarbon ages. However, when the age model was compared to Optical stimulated luminescence (OSL), the radiocarbon dates were older than the OSL by a range of 0.85-8.3 ka.

In 2005, a 623-m long drill core recording 1.5 Mya of paleoclimate in the Eastern African Rift valley was retrieved from Lake Malawi, a 40-km wide and 560-km long lake. A complementary drill core encompassing 100 ka was taken from Lake Tanganyika, another eastern rift valley lake (Scholz et al., 2007). Similarly, Lake Bosumtwi, a meteorite impact crater lake in Ghana was drilled in 2004 to retrieve sediments that recorded about 1.1 million years of West African paleoclimate. In 2007, research based on the lake sediment record from Lake Tanganyika in East Africa, Lake Bosumtwi in West Africa, and Lake Malawi concluded that between 135 and 75 ka, a massive drought event occurred in the region that reduced water volume by 95% (Scholz et al., 2007). This period of drought was more severe than the Last Glacial Maximum, which is one of the most arid periods during the Quaternary period (Scholz et al, 2007). Lake Malawi too reflects this period of drought indicating that this was a continent-wide drought event. The drought period eventually transitioned into a progressively wetter climate and it is thought that Milankovitch variations resulted in this period of aridity during the early late Pleistocene (Scholz et al., 2007). This is because the end of the drought coincides with reduced eccentricity and precession driven climate events. Ocean sediment cores support this evidence since they show that tropical African lakes respond effectively to changes in insolation due to Milankovitch cycles (Scholz et al, 2007).

As seen from aforementioned examples, lake deposits provide long, continuous records of glaciation and climate change. While there has been extensive paleolimnological work done in the Northern Hemisphere only a few tropical South American lakes and African rift valley lakes have been studied. Thus, there is a need for a well dated long core from the Andes with a record of regional paleoclimate .

Lake Junín is one of the few lakes that provides an extensive record of paleoclimate in the tropical Andes in the Southern Hemisphere. Glaciers in the Junin basin reached the lake edges during the late Cenozoic glaciation but the lake itself hasn't been covered by ice in the last 1 million years or more, making it one of the few lakes that predate the last maximum extent of glaciation (Rodbell et al., 2008). Furthermore, the position of the lake between the Eastern and Western Cordilleras helps it to capture sediments and record the activity of glaciers in nearby cordilleras. In 2015, three overlapping sediment cores from Junin extending up to 100 m below lake floor (mblf) were extracted.

This research aims to add to prior work done in Lake Junín by characterizing and comparing glacial periods in the Junín core. Siliciclastic flux, magnetic susceptibility, mean grain size and Ti+Si+Al/Ca of sediments from the sediment core are used as proxy records of glacial extent and erosion in adjacent valleys. A secondary objective of the research is to focus on the Last Glacial Maximum and to compare mean grain size parameters such as skewness and kurtosis with other sediment characteristics. Prior research of Lake Junín sediments has only extended through the last 50 ka. Thus, the Lake Junín core, which spans over 700,000 years provides a unique opportunity to compare characteristics of glacigenic sediments from the Late Quaternary.

STUDY AREA

Lake Junín (11.0°S, 76.2°W) is a proglacial lake that sits in an intermontane basin between the Eastern and Western Cordillera of the Central Peruvian Andes (Rodbell, 2008). Roughly 320 km northeast of Lima, the lake is located at an elevation of 4080 m on a grassy altiplano and has a catchment area of about 300 km^2 (Figure 4). More than 40 ka ago, glaciers from the Cordilleras deposited moraines at the northern end while outwash fans from the two cordilleras blocked drainage on the southern side and formed the lake (Hansen 1984).

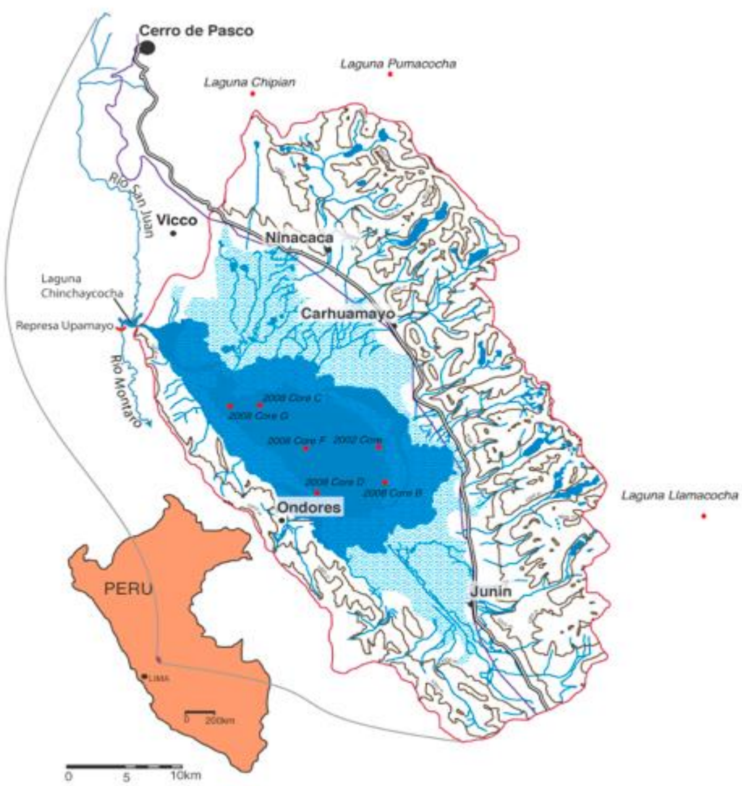

Figure 4. Location map of Lake Junin and its drainage basin in Peru (from Rodbell, 2014)

The lake basin occupies roughly one third of its drainage basin and has a maximum water depth of approximately 15 m (Flusche et al., 2005). Precipitation in this grassy altiplano is a product of the easterlies crossing the Amazon Basin during the austral summer from December-February, along with the development of South American summer monsoon.

In the Eastern Cordillera, Mesozoic siliciclastic, carbonate and crystalline rocks dominate along with some exposed Precambrian crystalline rocks (Figure 5). Bedrock in the Western Cordillera is primarily Jurassic carbonates and Tertiary volcanics. Glacial outwash and marshes in the north and unglaciated bedrock and marsh in the south (Figure 6) primarily surround Lake Junín. Annual precipitation in the lake is ~875 mm/yr, which is mostly derived from the easterlies during the austral summer with about 80% falling during austral summer between November and April (Seltzer et al., 2000) .

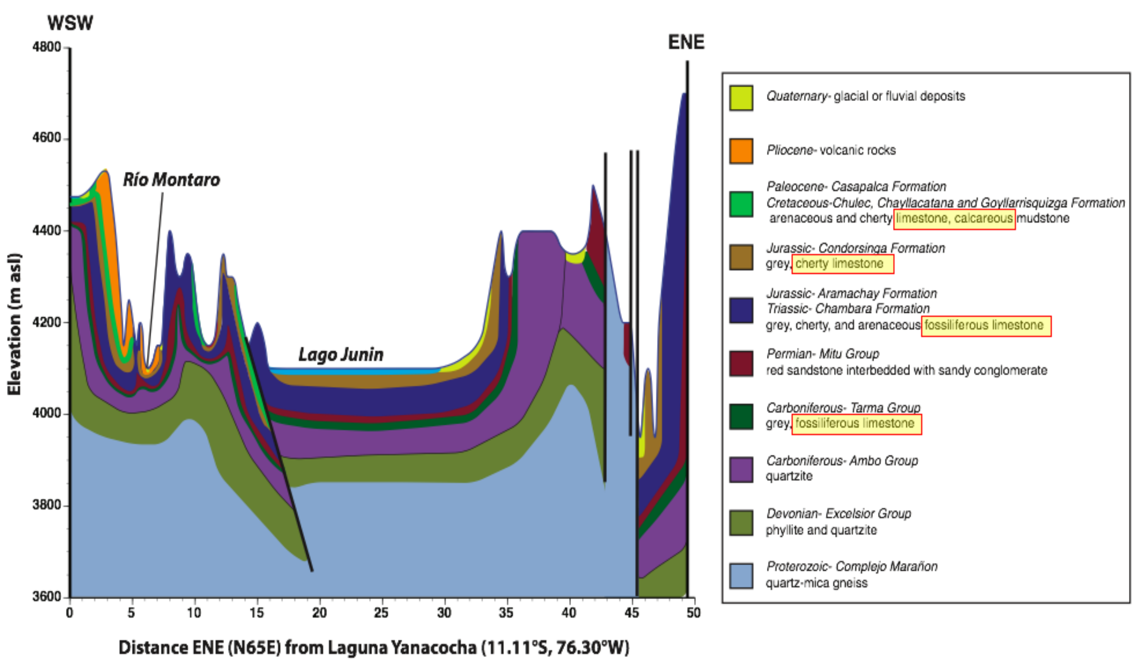

Figure 5. Bedrock cross section of Lake Junin shows bedrock ranging from Devonian to Jurassic (After Rodbell., 2018).

Lake Junin is also one of the few lakes in the Southern Hemisphere that has never been overridden by glaciers and lies beyond the maximum limit of glaciation. As such, it has had continuous sediment accumulation that can help determine glacial advance and retreat in the Tropical Andes (Seltzer et al., 2002). Glacial lakes upstream of Lake Junín also act as sediment traps magnifying the signals of deglaciation in Lake Junín sediments (Seltzer et al., 2002).

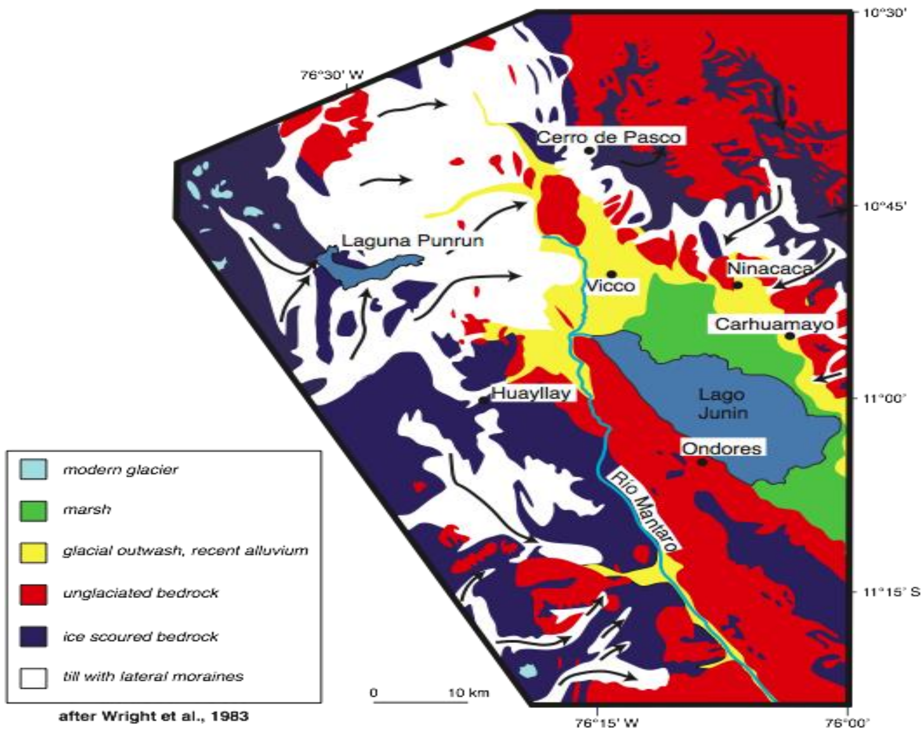

Figure 6. Bedrock Geology of Lake Junín. Lake Junín is surrounded by marsh, glacial outwash and unglaciated bedrock. The lake drains into Rio Mantaro (After Wright et al., 1983).

PAST WORK

In 1983, a 25 m core spanning about 50 ka was extracted from Lake Junin. Wright, Hansen and Bradbury conducted moraine morphology studies on glacial valleys in Junín using this core and delineated two phases of glaciation in the Junín Plain, which they named the Punrun and Rio Blanco glaciations (Hansen et al., 1984). This study provided the first continuous record of glaciation and regional vegetation change spanning the last local glacial maximum and Holocene in the Peruvian Andes. The study was also the first to observe that interglacial periods in Junin were marked by marl in the lake sediments. Radiocarbon dating of lake cores and other samples from the site showed that the Rio Blanco glaciation started before 42 ka while the Punrun glaciation occurred from 24 ka to 12 ka (Smith et al., 2005)

In 1996, another study by Seltzer et al, extracted a 19 m core from Lake Junín to examine lake glacial-interglacial sedimentology. According to their study, magnetic susceptibility sharply dropped at around 21 ka, which they associated with glacial retreat (Seltzer et al., 2008). As glaciers retreated behind their terminal moraines, proglacial lakes would have trapped glacial silt. Magnetic susceptibility records thus show a glacier retreat around 21 ka, a minor glacial advance between 21 ka and 16 ka, and significant deglaciation after 16 ka (Seltzer et al., 2008).

Moraine dating has shown that glacial advancement in Junín occurred >150 ka especially around 175–225 and 340–440 ka (Smith et al, 2008). Surface exposure dating, cosmogenic nuclide dating and geomorphic setting indicates glaciation from around 31-21 ka and 19-15 ka while the most recent period of glaciation is dated at around 12-14 ka (Smith et al, 2008). In 2005, a study by Smith et al. (2005) dated 146 moraines using ^{10}Be exposure dating in the Junín region showed that the glaciers reached their maximum extent as early as ~34 ka preceding the Global Last Glacial Maximum by as much as 10-12 ka. The study suggested that shifting temperature and precipitation changes resulted in increased precipitation and cool temperature in the tropical Andes, which promoted early glaciation compared to continental ice sheet expansion (Smith et al., 2005). Precipitation in the region increased as early as ~60 ka expanding into ~34 ka when a sharp SST cooling occurred (Smith et al., 2005). Glacial retreat started at ~21-16 ka and was followed by steady retreat after 15 ka. The glaciation from 31-21 ka represent an early Last Glacial Maximum in Lake Junín compared to global records. This is consistent with other research based on Lake Junín sediment records, which indicates an early LGM advance. Thus, glaciation in Junín corresponds with increased tropical moisture and sea surface temperature gradients in the North Atlantic (Smith et al., 2008).

Moraine records also show that the glaciers reached the edge of Lake Junin but the lake itself was never overridden by glaciers (Smith et al., 2005). This indicates that the lake has had continuous sedimentation spanning earlier than the LLGM. The best estimate of deglaciation after the Last Glacial Maximum in the Southern Tropics comes from Laguna Kollpa Klota in Bolivia. Radiocarbon analyses of organic matter from basal lake sediments show deglaciation at around 23-20 ka before present (Seltzer et al., 2002). Lake stratigraphy also indicates that deglaciation occurred under relatively wet conditions and that climatic warming in the tropical Andes was at least 5000 years earlier than in the Northern Hemisphere (Seltzer et al., 2002). The authors also state that early onset of warming in the Southern Hemisphere could have stimulated deglaciation in the Northern Hemisphere by atmospheric or ocean circulation processes. A negative and asymmetric relationship is observed between precipitation trends has also been observed in the south compared to northern tropics (Seltzer et al., 2002). According to the $\delta^{18}O$ ostracod records from Lake Miragoane, Haiti (11°N), the northern tropics experienced the most precipitation in the middle of the Holocene. However, there is a time lag in the peak aridity at

Lake Junín, which occurred at least a thousand years earlier than peak precipitation in the Northern Hemisphere, attributed to the impact of precession on insolation. $\delta^{18}O$ records from Junín along with speleothems and other carbonate lake records also show the isotopic shift from Late Glacial to Holocene (Bird et al., 2011). Another study looked at the $\delta^{18}O_{calcite}$ record which showed a 6‰ enrichment during the late glacial followed by a gradual depletion during the Holocene. These isotopic changes were interpreted as a decrease in effective moisture followed by a long-term increase. Furthermore, the $\delta^{18}O_{calcite}$ record followed closely with mean annual temperature and rainy season insolation which indicates that changes in precipitation are linked to orbital variations (Seltzer et al., 2000). The $\delta^{18}O$ values thus provide a record of change in strength of the South American Summer Monsoon on regional Andean hydrological balance (Seltzer et al., 2000). Factors that affect the SASM include the mean position changes of the intertropical convergence zone over the tropical Atlantic Ocean, the El Nino Southern Oscillation (ENSO) and long-term insolation changes (Seltzer et al., 2000).

RESULTS FROM PRIOR RESEARCH AT LAKE JUNIN

In 2008, prior to the Junín drilling project in 2015, preliminary seismic profiling was done on Lake Junín in conjunction with retrieval of surface cores to determine shallow lake stratigraphy (Figure 7). The short cores showed that during the Holocene, Lake Junín precipitated marl at all water depths while the seismic profiles and short cores showed that lake level changes resulted in fluvial channels and reworked sediment during the early-middle Holocene (Drilling Project Proposal).

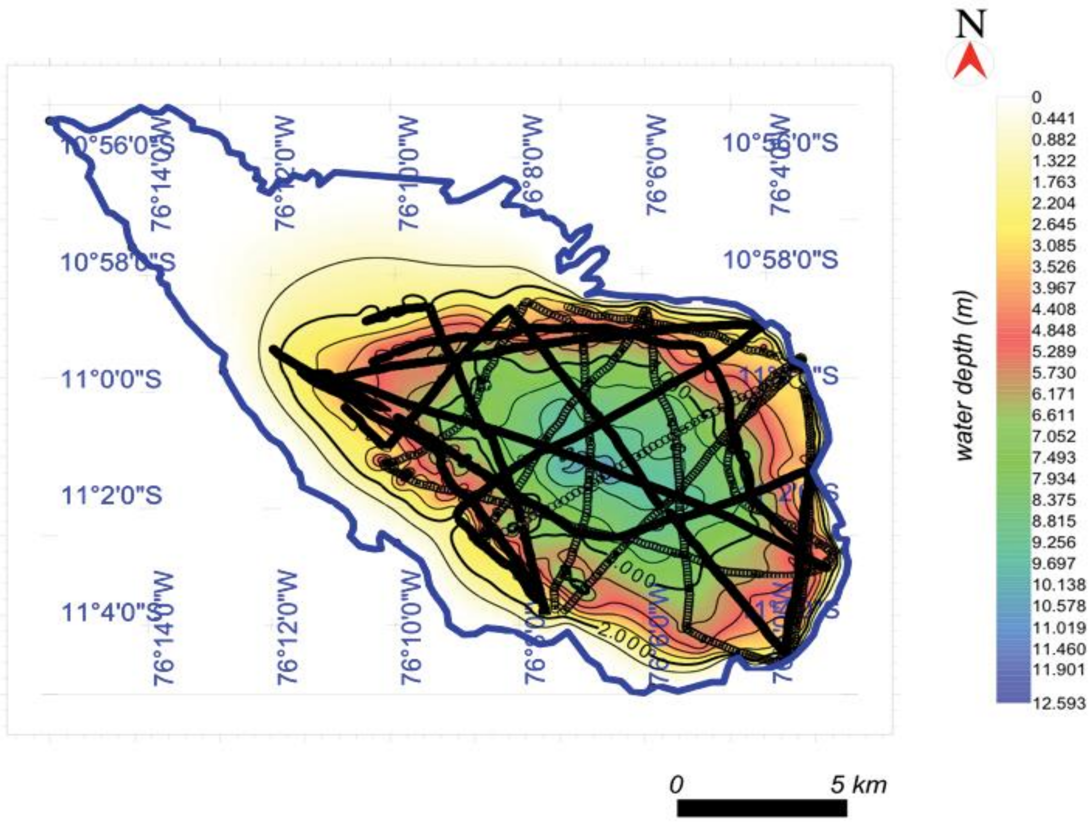

Figure 7. Bathymetric map of Lake Junin with black lines indicating 4-24 kHz sources measured from seismic surveys in 2008-2011. Open circle lines indicate air gun seismic work from May, 2011 (After Rodbell., 2018).

In 2011, another study followed with a seismic survey of Lake Junín to record lake basin stratigraphy. The survey demonstrated that the lake stratigraphy had no large scale deformation, lake level fluctuation, tectonic deformation or widespread gases. Two major reflectors, R1 and RD (Figure 8) marked changes from glacial to post glacial sediments and base of lacustrine deposits. The section below RD are coarse and inferred to be of fluvial origin. Thus, these conclusions were used to consider Lake Junín as an appropriate site for drilling and paleoclimate study.

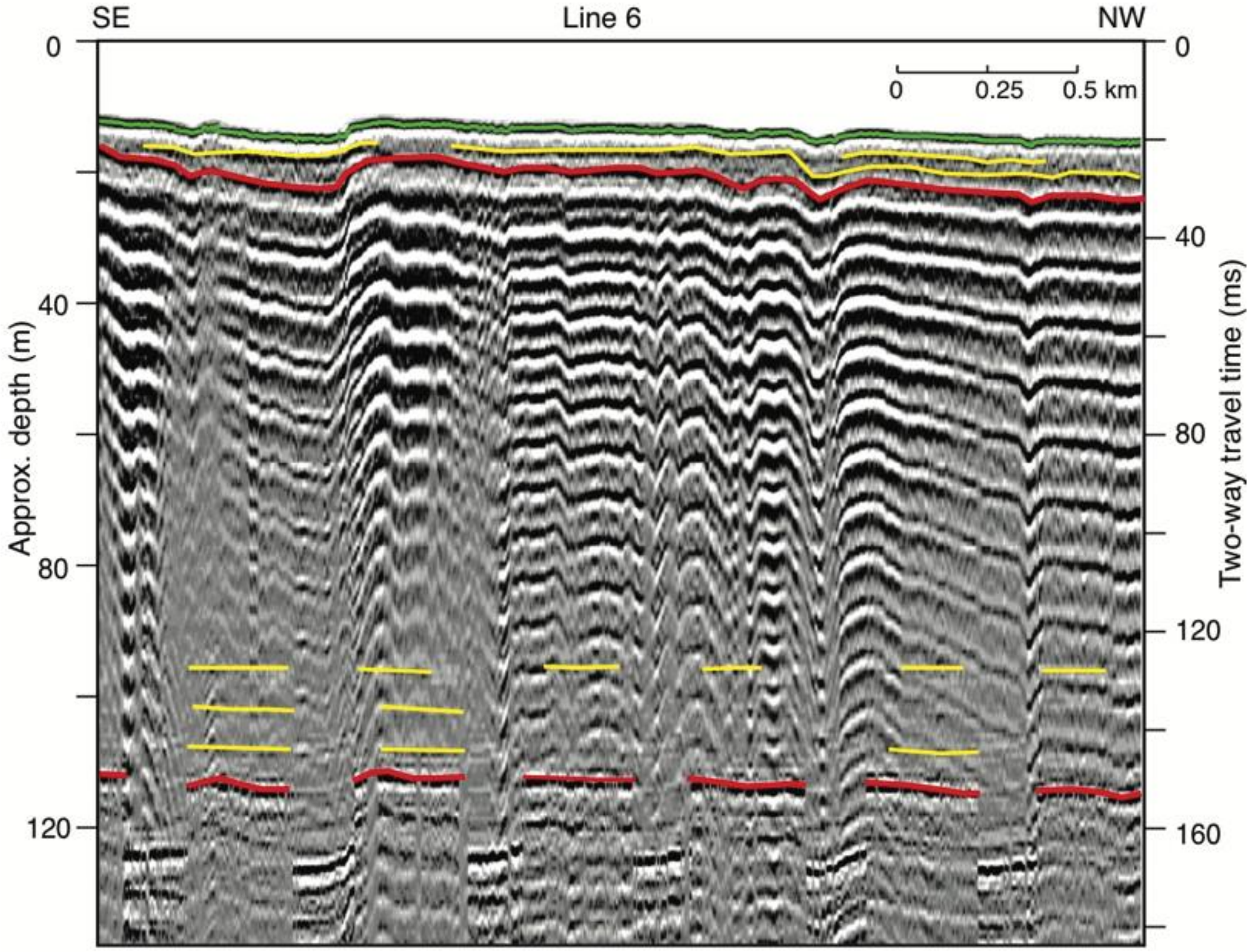

Figure 8. Airgun seismic section through lake middle showing echoes of airgun seismicity. The green line indicates lake floor while the red lines indicate major reflectors. The upper reflector is R1 and the lower reflector is named RD. Yellow lines indicate discontinuous reflections (After Rodbell., 2018).

We also observe that the lake has a moraine coming in through the eastern side of the lake (Figure 9). The moraine is linked to a downstream alluvial fan and provides evidence that Lake Junin was continuously fed sediments from moraines originating in neighboring valley glaciers during glacial periods.

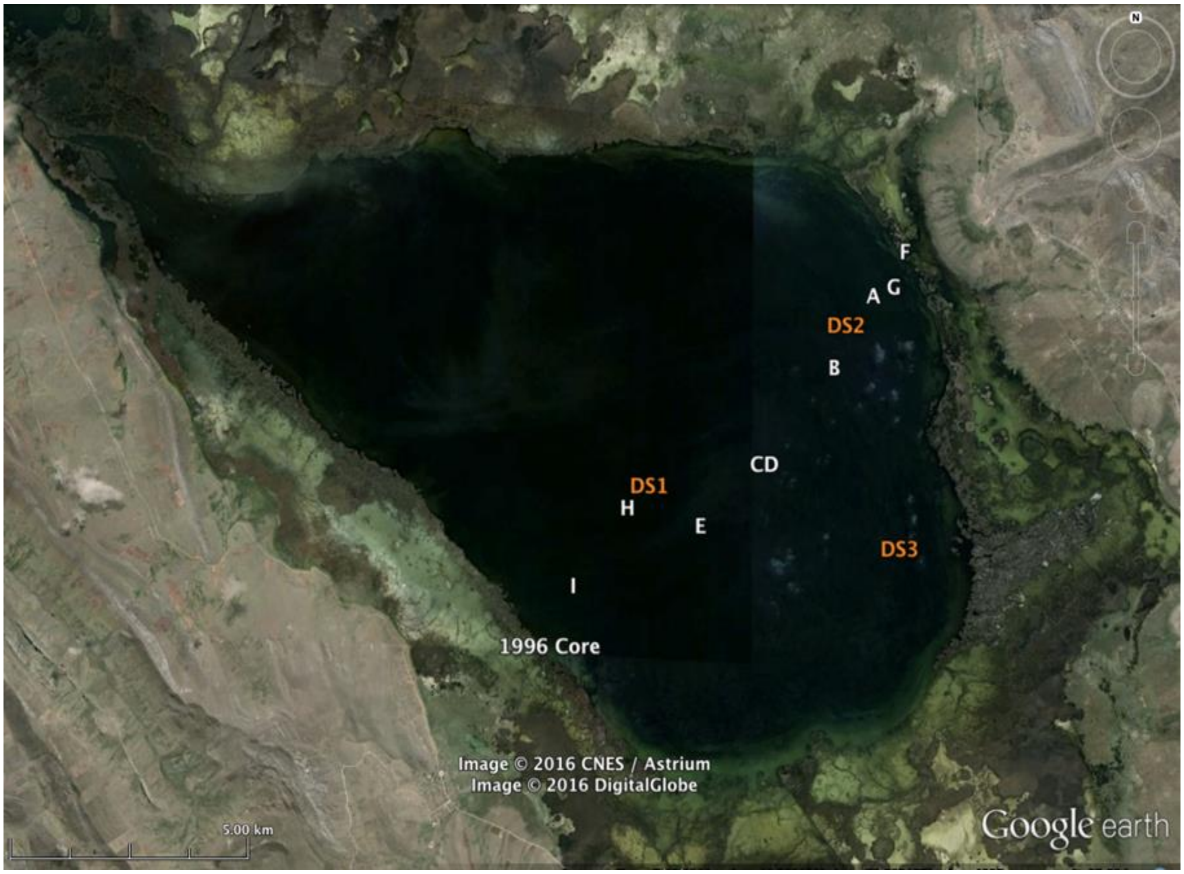

Figure 9. Google Earth Image of Lake Junín with the three coring sites labeled DS1, DS2, DS3. Three cores were extracted from these sites in 2015. The lake is flanked by the Western Cordillera on the left and the Eastern Cordillera on the right (After Rodbell., 2018).

Consequently, the lake was drilled at three sites: DS1, DS2 and DS 3 (Figure 9). DS1 had a maximum water depth ~10m and distal to glacial outwash sources. DS2 had a water of ~5 m and is near glacial outwash sources while DS3 has an intermediate water depth (~8m) at an intermediate position with respect to glacial sources. The drill cores were then brought back for further analysis and dating at University of Minnesota and MIT. Chronology was derived from radiocarbon dates of terrestrial macrofossil, paleomagnetic data and U/Th dates on authigenic calcite (Figure 10). This data was then processed through the Bacon Age Model to create an extensive chronology of Lake Junín sediments.

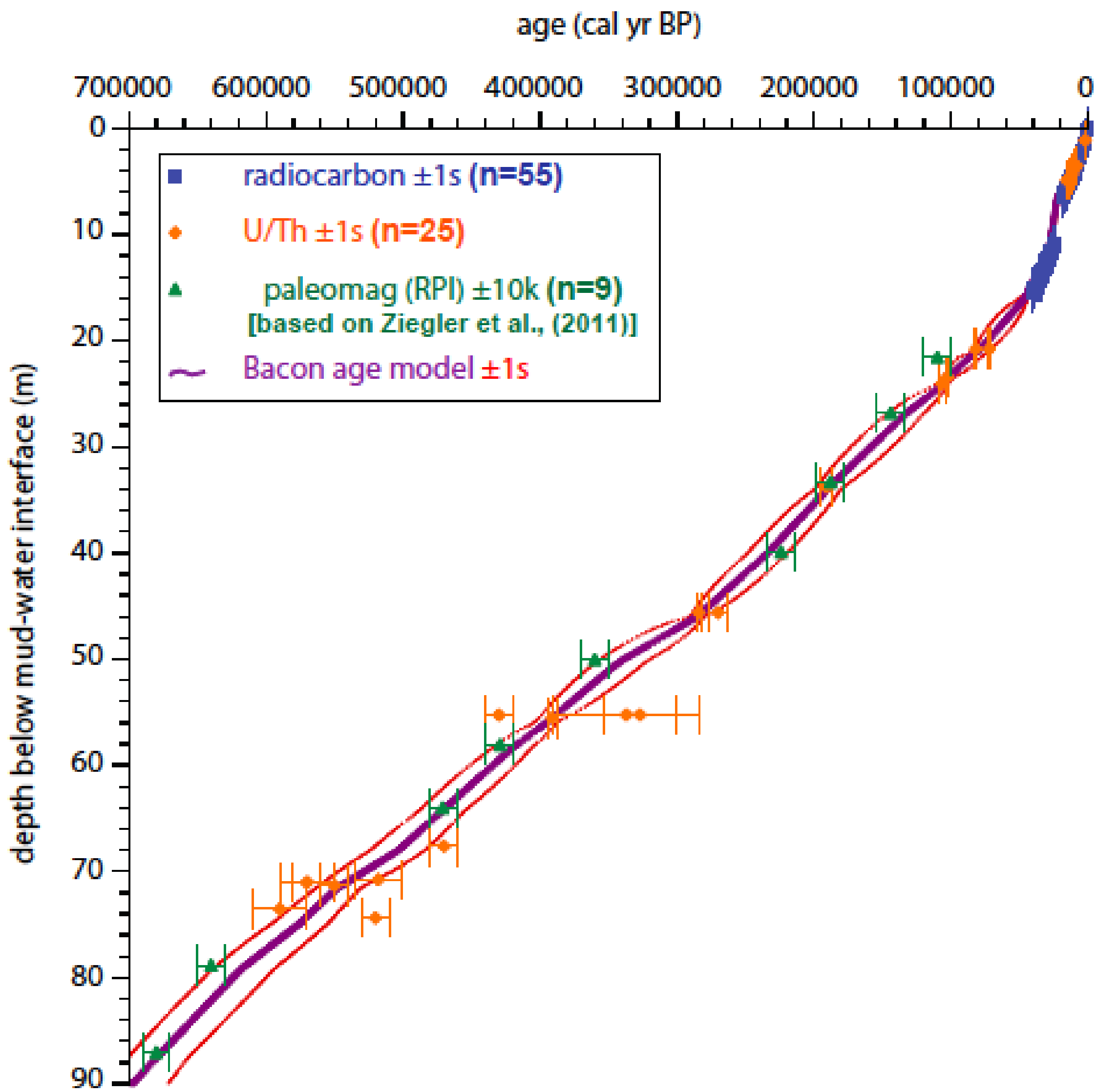

Figure 10. Age depth model for Lake Junín sediments based on multiple methods of chronology such as radiocarbon dating, U/Th dating, paleomagnetism and Bacon Age modelling. (After Rodbell., 2018)

A stratigraphic column from Drill Site 1 was used to preliminarily infer approximate number of glacial cycles preserved in Lake Junín sediments (Figure 11). Various parameters such as magnetic susceptibility (MS), calcite (CaCO3%), organic carbon and dry density were compared with depth in the core to show that there were 7 intervals of glacial and interglacial sediments preserved in ~95 m of fine grained sediments from DS1(Figure 11). Glacial sediments are high in siliclastic material with high magnetic susceptibility (MS) and density with low organic and inorganic carbon. Sediments from interglacial periods have low magnetic susceptibility and density but high organic carbon levels indicating low lake levels.

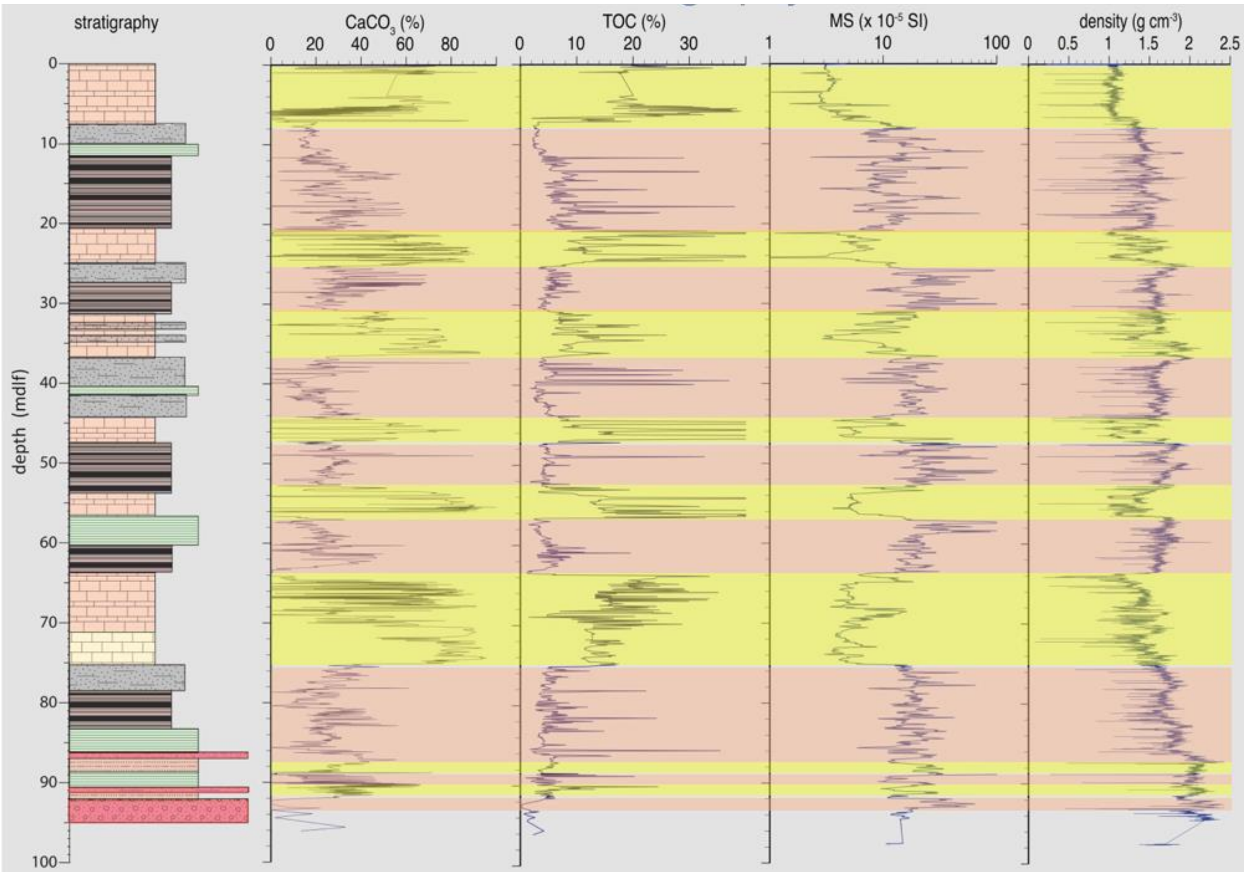

Figure 11. Stratigraphic column at Lake Junin Drill Site 1. Yellow columns are interglacial periods marked by high calcite and TOC, low MS and density. Pink columns are glacial periods marked by low calcite and TOC but high MS and density (After Rodbell., 2018).

In 2005, Lisiecki and Raymo compiled a stack of $\delta^{18}O$ records from globally distributed benthic foraminiferal calcite (Lisiecki and Raymo, 2005). Stacks are averages of $\delta^{18}O$ records from multiple sites and the benthic $\delta^{18}O$ signal is due to combination of relative contributions of ice volume and temperature. Lisiecki and Raymo's $\delta^{18}O$ record spanned beyond 850 ka and recorded Pliocene-Pleistocene marine isotope stages (Lisiecki and Raymo, 2005). The $\delta^{18}O$ stack also acts as a proxy for global ice sheet volume but does not clearly indicate the proportion of sources of ice sheet signals. Thus, there is a need for distinguishing sites contributing to the $\delta^{18}O$ stack and determining whether the tropics contribute to the global signal and if tropical glaciation is synchronous with glaciation throughout the globe.

Initial results from Lake Junín sediments were therefore compared to proxies of global the $\delta^{18}O$ stack to see if the two were in sync and if tropical glaciation followed global trends (Figure 12). MS is used as a proxy for glaciation since it is usually indicative of terrigenous clastic flux and siliciclastic rocks are rich in magnetic minerals such as magnetite and maghemite. During periods of glaciation thick layers of ice rapidly eroded the underlying siliciclastic bedrock producing sediments that are eventually deposited in the lake resulting in high MS peaks. MS is also compared with solar insolation and EPICA (European Project for Ice Coring in Antarctica) Dome CH_4 values which are proxies for temperature and moisture respectively (Spahni et al., 2005). Similarity in glaciation patterns are seen from comparison of MS record from Junín Site 1. MS record of tropical glaciation with proxy records of global ice volume, temperature, methane and tropical solar insolation (Figure 12).

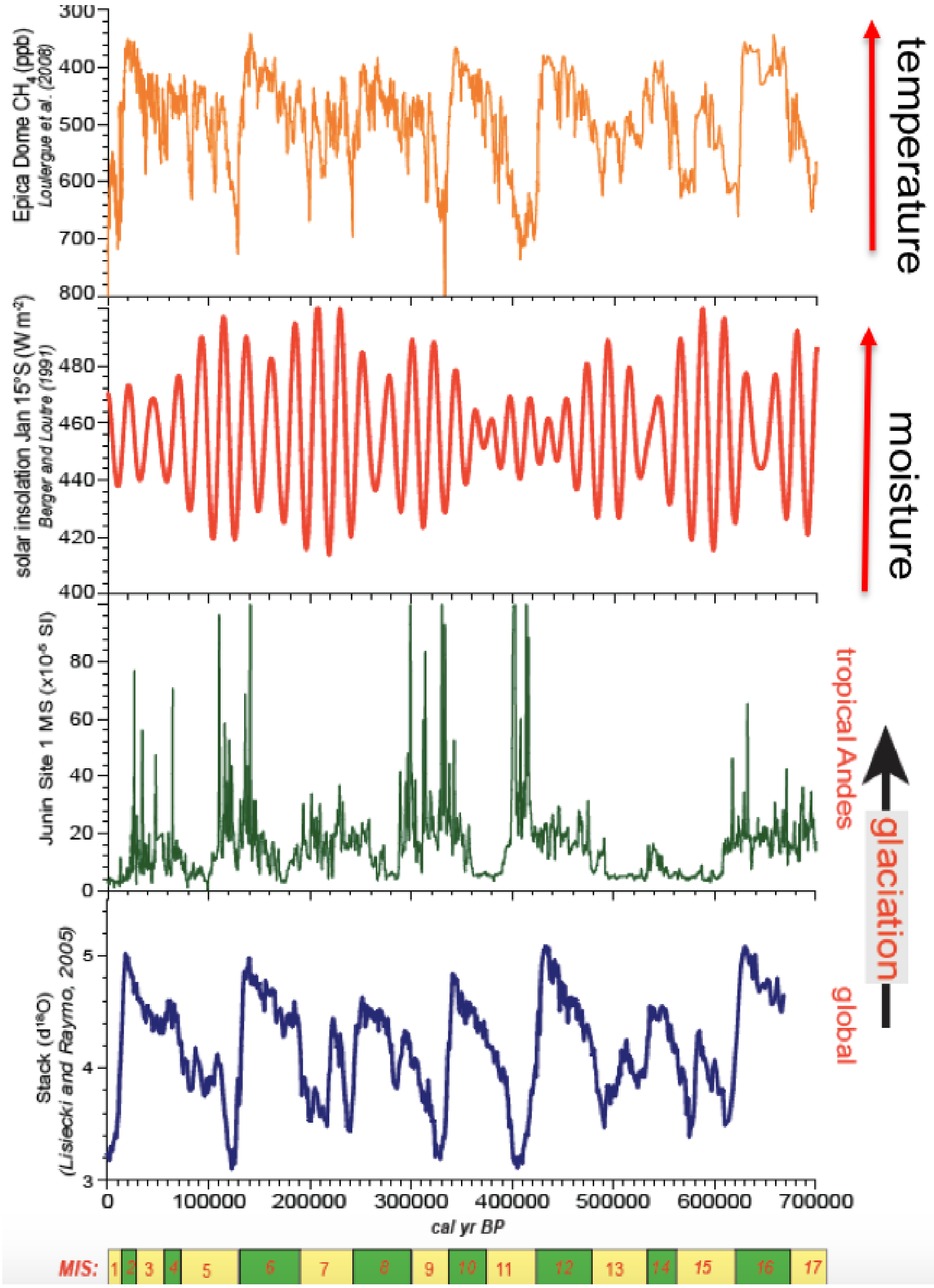

Figure 12. Comparison of glaciation in Lake Junín record with proxies of global ice volume (Stack $\delta^{18}O$), moisture (solar insolation) and temperature (methane). Cyclicity of Lake Junín glacial cycles is synchronous with global ice volume and tropical insolation. (After Rodbell., 2018)

MS peaks follow peaks in tropical insolation suggesting that greater exposure of solar radiation could have resulted in greater convection and precipitation which would have increased glacier mass balance consequently resulting in higher erosion. CH_4 and δD records from the EPICA (European Project for Ice Coring in Antarctica) Dome, which are used as proxies for temperature and global ice volume, seem to be in sync with tropical trends and solar insolation (Spahni et al., 2005). The Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ also show Marine Isotope Stages which are periods of cool or warm climate (Lisiecki and Raymo, 2005). The comparisons also show that the seven glacial cycles recorded in Junín record is similar to global ice volume record.

METHODS

In 2015, The NSF-ICDP Junín drilling project obtained multiple long sediment cores up to 105 m below the lake floor from three sites at Lake Junín, Peru. Site 1 extends to ~100 mblf, while Sites 2 and 3 extend to ~23 and 51 mblf, respectively. The cores were stratigraphically correlated to each other to obtain a sediment record spanning the past ~700 ka. Samples were run through Coulter LS 230 ™ Laser Diffraction Particle Sizer to obtain grain-size distribution. We measured samples at every 5 cm in the Last Glacial Maximum and at every 16-20 cm for every glacial interval in the core. 380 samples were used and their grain sizes were analyzed with the help of Union College Core Lab.

For grain size analysis, it is imperative to remove any non-terrigenous material so three extraction steps removed carbonates, organic matter and biogenic silica respectively (Core Lab Manual, Union College). While some carbonates in the samples might be detrital, it is difficult to separate detrital carbonates from authigenic so we extracted all carbonate material. For carbonate extraction, 20 ml of 15% HCl was added to samples weighed between 0.5 to 0.7 g in centrifuge tubes. We then heated the samples in hot water baths at $50^{o}C$ for 2 hours and placed them in a reciprocating shaker for 30 minutes. Subsequently, we added 5 ml of concentrated (30%) H_2O_2 to the samples and left them overnight to ensure removal of organic matter. Finally, we added 10 ml of 1M NaOH to the centrifuge tubes to completely dissolve and remove any biogenic silica in samples. We placed the centrifuge tubes in a hot water bath at 50°C for 4 hours and immediately placed in a reciprocating shaker for 30 minutes again. After each extraction step, we centrifuged and decanted the sample with distilled water three-times. We then used 10 ml of 0.05 M sodium metaphosphate to disperse the grain size samples and placed them in a reciprocating shaker for a few hours before placing them in an ultrasonic vibrator for 10 minutes. We then processed the samples for grain size analysis by using the Coulter LS 230™ Laser Diffraction Particle Sizer. We also obtained XRF data measured at the University of Minnesota, Duluth.

DATA AND INTERPRETATION

My study followed previously done research on Junín by relating various parameters such as Ti+Si+Al/Ca, siliciclastic flux, mean grain size, calcite, magnetic susceptibility with ages derived from Bacon Age Model (Figure 13). During glaciation, erosion and clastic input is high and we see this reflected in Lake Junín sediment characteristics. Thus, we aim to characterize and compare glacial periods by looking at various geochemical parameters of sediments from the Lake Junín and focus on mean grain size distribution of sediments to determine possible sources of sediment supply.

We used Ti+Si+Al/Ca as a measure of allochthonous clastic input because most siliciclastic rocks have Ti,Si,Al incorporated into their mineral structure. During periods of glaciation and glacial erosion, high siliciclastic flux results in high Ti, Si, Al concentrations while Ca correlates to the amount of calcite precipitated in the lake. Lake Junín is surrounded by carbonate bedrock which dissolves and provides HCO_3 and Ca ions to the lake resulting in authigenic calcite precipitation. The ratio of Ti+Si+Al/Ca accounts for allochthonous clastic input where Ti+Si+Al and Ca tracks siliciclastics flux and detrital sources of $CaCO_3$, respectively. $CaCO_3$ is also used as a proxy for degree of evaporative enrichment of the lake. During glaciation, calcite precipitation is low since it is diluted by a large amount of meltwater and siliciclastic flux into the lake. However, during interglacial periods, absence of meltwater source coupled with high temperatures leads to evaporation and higher concentrations of dissolved solids causing calcite concentrations to be higher.

Clastic flux is a proxy for glacial erosion and thus glaciation in Lake Junín. We calculated the flux of clastic material by using the following formula which subtracts biogenic and authigenic material from the bulk sediment record (Rodbell, 2018).

$$Flux_{clastic} = SR\ (BD - ((BD \times TOM) + (BD \times TCC))$$

Here, SR is the bulk sedimentation rate (cm yr^{-1}), BD is bulk density (g cm^{-3}), TOM is the weight fraction organic matter of bulk sediment and TCC is weight fraction authigenic calcite of bulk sediment (Rodbell, 2018). Magnetic Susceptibility (MS) is also a proxy for terrigenous clastic sediment input since siliciclastic flux is rich in magnetic minerals. On the other hand, mean grain size of sediments can give insight about the transport medium or sources of sediments.

We observe seven periods of glaciation preserved in Lake Junin sediments determined by relatively high magnetic susceptibility, low $CaCO_3$, high clastic flux and Ti+Si+Al /Ca ratio (Figure 13). Glacial periods have higher rates of erosion resulting in high siliciclastic flux, MS and Ti+Si+Al /Ca ratio. Mean grain sizes for the past six glacial cycles are between 1-2.5 µm. However, the oldest glacial cycle recorded in Lake Junín sediments (~ >600,000 years) has very coarse mean grain sizes (>3.5 μm) suggesting these sediments to be fluvial sediments deposited in the valley prior to the formation of the lake. The stratigraphic column also shows a change to coarser gravels and sands (>600,000 years) indicating that these sediments could have been deposited during the first main phase of glaciation that dammed the northern and southern sides of the valley forming Lake Junin.

There are no other proxies which define the birth of Lake Junín so the clear difference in sediment grain size beyond 600,000 years helps us detect a possible time of lake formation on the sediment record.

We also observe that siliciclastic flux is strikingly higher in the Local Last Glacial Maximum which corresponds to MIS 2-4 (Figure 13). All other parameters including MS, $CaCO_3$ and Ti+Si+Al /Ca ratio do not vary greatly from other glacial cycles. This high siliciclastic flux in the LLGM is especially interesting because the LLGM is thought to have been less extensive implying that ice cover was smaller compared to previous glacial cycles (Smith et al., 2005). The smaller ice extent inferred from cosmogenic radionuclide dating of moraines surrounding the lake should result in lower erosion rates and lower siliciclastic flux for LLGM (Smith et al., 2005). However, our conflicting siliciclastic flux data suggests that despite smaller ice cover in the LGM, the glacier was more erosive in the LLGM.

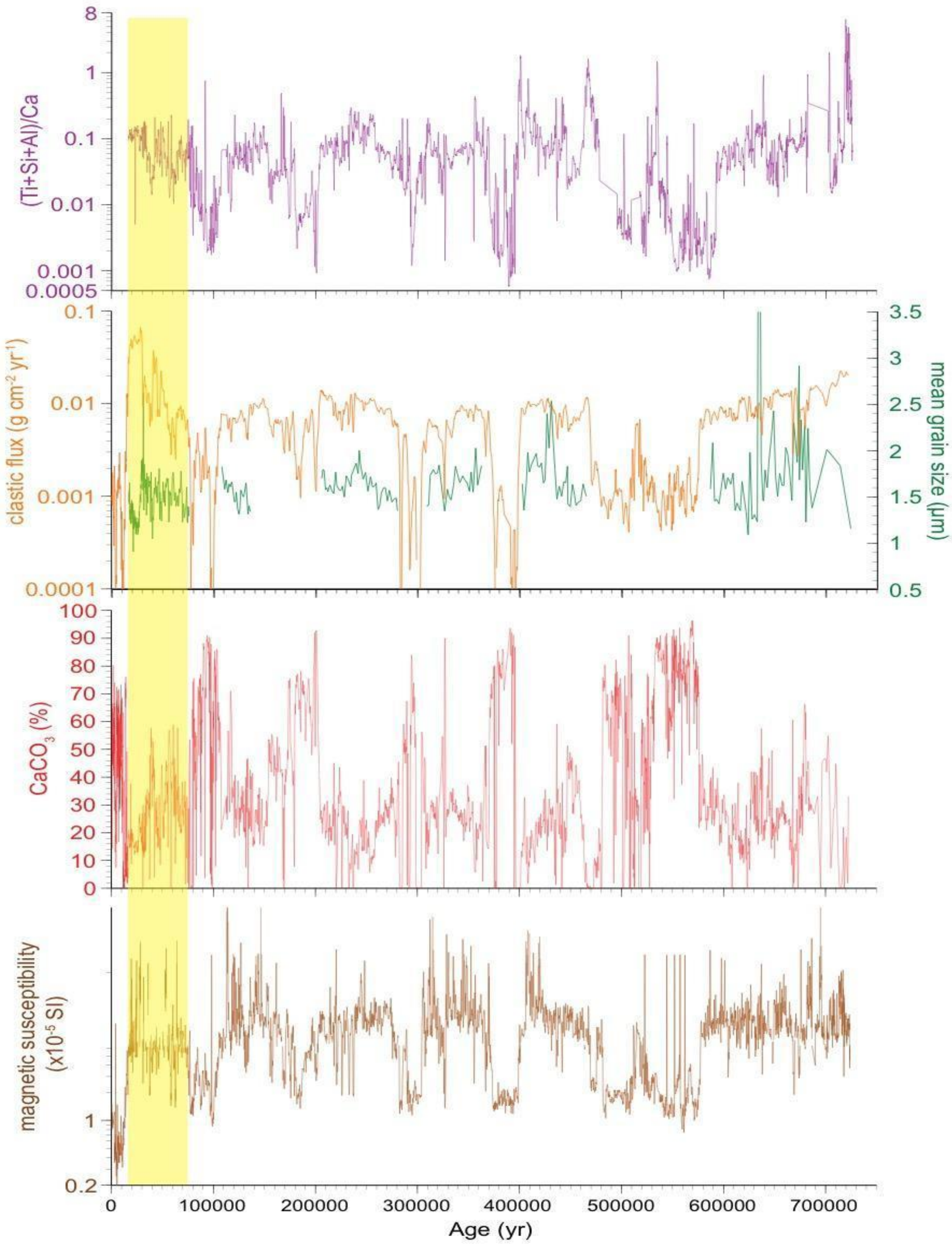

Figure 13. Comparison of MS, $CaCO_3$, Clastic flux and Ti+Si+Al/Ca in Junín record. Seven periods of glaciation are observed. Yellow column corresponds to the Last Glacial Maximum during MIS 2-4.

This indicates that the glacier at LLGM could have had a higher activity ratio compared to other glacial cycles resulting in higher erosion and siliciclastic flux. Activity ratio is a measure of the amount of ice that flows through the ELA in a year and is the inverse of the mass balance gradient at the equilibrium line altitude (ELA). The ELA is a key measure of mass balance in a glacier and is the point in the glacier where accumulation is equal to melting. Mass balance is the difference between snow accumulation and snow/ice loss from glacier.

The Last Glacial maximum in Lake Junín was particularly warm and humid which could have caused the warm based glacier to have a high activity ratio so more ice flowed through the ELA in a year, resulting in more erosion (Seltzer, 2002). On the other hand, older glacial events could have involved either cold based glaciers or warm based glaciers with lower activity ratios resulting in lower erosion and siliciclastic flux. This hypothesis is consistent with paleoclimate records of LGM from other tropical South American Lakes such as Colombia and Bolivia. Lake records from Salar De Uyuni in Bolivia show that the LLGM was long, warm and wet since it coincided with summer insolation maxima. Similarly, lake sediment records from Sabana de Bogota and Lake Titicaca indicate that the Last Glacial Maximum was warm and humid.

We then magnified the resolution of LLGM recorded in Lake Junín sediments to compare and contrast clastic flux, MS, Ti+Si+Al/Ca, skewness and kurtosis of mean grain sizes, mean grain sizes and $\delta^{18}O$ record from Pacupahuain Cave (Figure 14). The $\delta^{18}O$ record from a speleothem record in Pacupahuain Cave, Peru is used as a proxy for local hydroclimate because the cave lies in close proximity to Lake Junín. Mean grain sizes and parameters such as skewness can provide valuable information about the sources of sediment and the travelling medium as well.

Ti+Si+Al/Ca, MS and clastic flux data closely follow each other since both parameters are used as proxies for the flow of glacigenic sediments into the lake. Higher clastic flux is related to depleted $\delta^{18}O$ values from Pacupahuain Cave indicating higher amounts of precipitation. Precipitation and clastic flux are thus coupled. Higher moisture can lead to increase glacial expansion and erosion which could have increased siliclastic flux into the lake. Magnetic susceptibility peaks further support this and can be correlated with peaks in $\delta^{18}O$, clastic flux and Ti+Si+Al/Ca. Interestingly, we observe that between ~28,000 and ~15,000 years, mean grain sizes are relatively lower while clastic flux is high, which could have been due to the transporting medium carrying huge amounts of fine grained sediments.

Prior studies have shown that changes in statistics describing grain size distributions can be used to determine direction of transport (McLaren and Bowles, 1985). A study done in 1985 presented a model where distributions of sediment in transport are related to their source by a sediment transfer function. According to the study, grain size distributions changed in the direction of transport to the shape of the transfer function where negatively skewed distributions result from low flow rates low energy function and positively/near symmetrical distributions result from high flow rates high energy function (MacLaren and Bowles, 1985). They used flume experiments to show that sediment transfer function is seen to define the relative probability that a grain will be eroded and transported. Finer sediments are more likely to go into transport and therefore have more negative skewness than the remaining sediments at source which become coarser and positively skewed on a phi scale (Figure 15). However, this study was done with mean grain sizes in phi scale so converting it to an arithmetic scale inverses the relationship. Our mean grain sizes were collected on an arithmetic scale so it is imperative to inverse the relationship. Thus, on an arithmetic scale, finer sediments will have a positive skewness while coarser sediments are likely to have a negative skewness. We observe this relationship to be true in our data set as well (Figure 16).

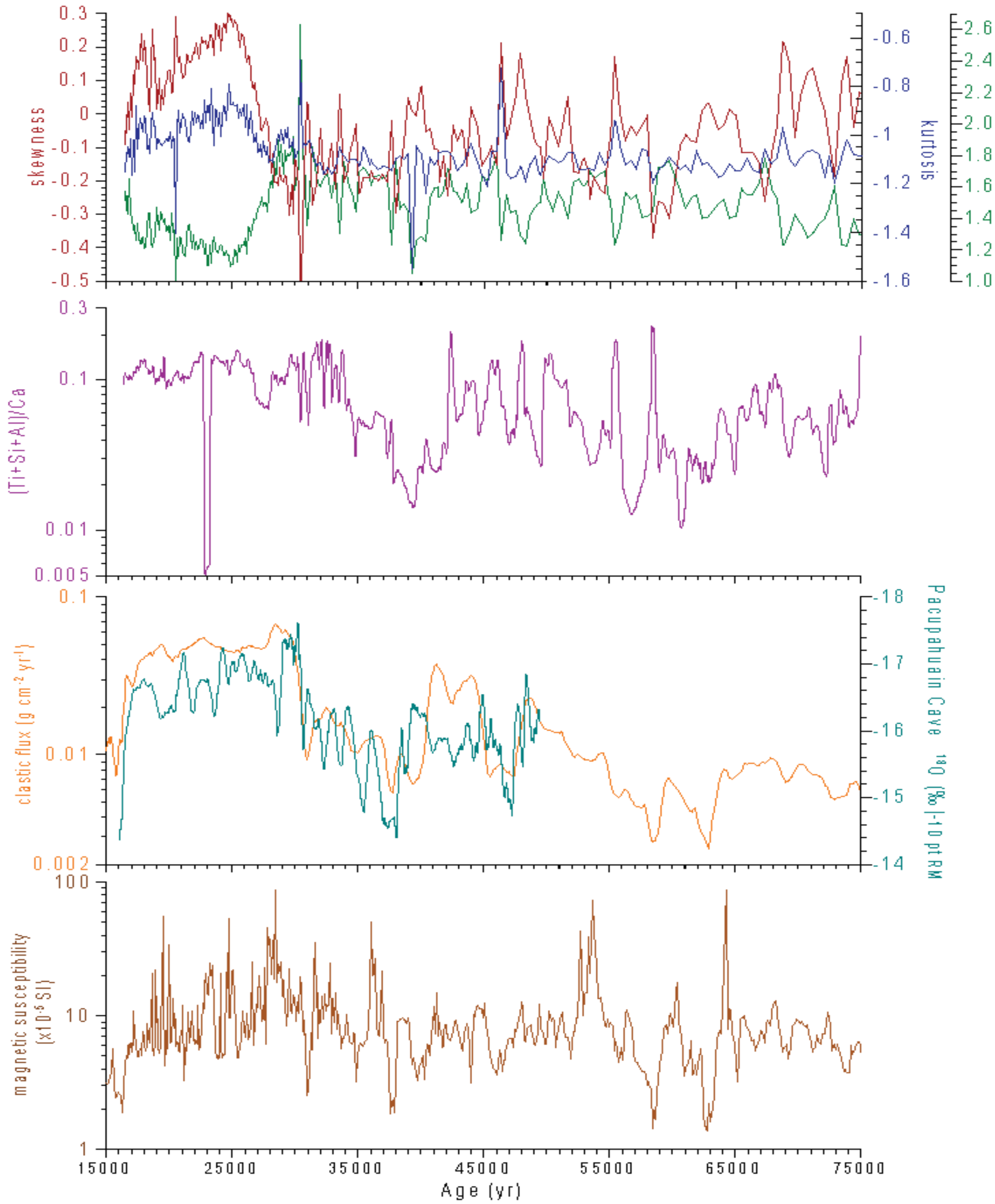

Figure 14. Comparison of LLGM MS, Clastic flux and Ti+Si+Al/Ca,skewness, kurtosis and mean grain sizes in Junín record with an oxygen isotope record from a speleothem in Pacupahuain Cave. High clastic flux is strongly coupled with the oxygen record which is a proxy for local moisture pattern.

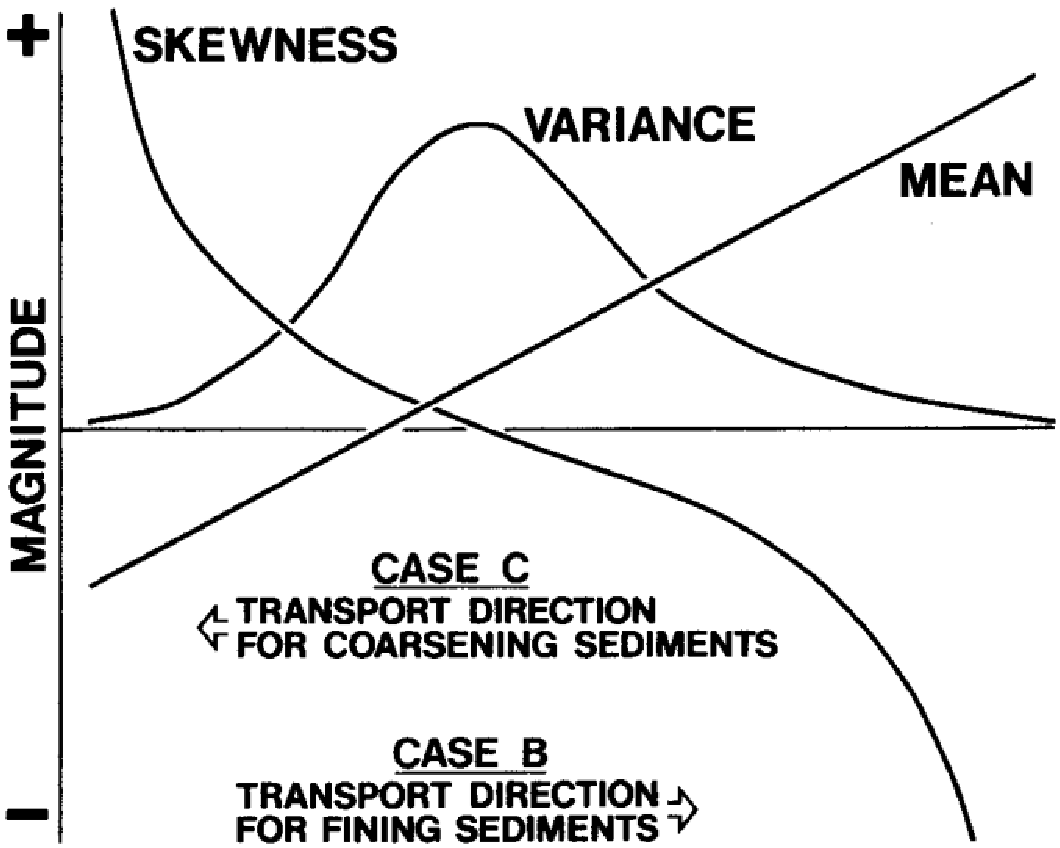

Figure 15. Summary of the changes in grain size measures (in phi scale) that may occur in a given direction of transport (From McLaren and Bowles, 1985)

We then explore the relationship between skewness and mean grain size in order to hypothesise the type of transportation system that could have resulted in high clastic flux but low mean grain sizes. In general, skewness is defined as a measure of symmetry. It helps identify the extent to which a distribution differs from normal distribution. However, skewness of lacustrine grain sizes can also be used as a parameter that responds to transport direction and supply sources. Thus, skewness is compared with mean grain size to understand the distribution of mean grain sizes in our samples. We observe that skewness is a function of grain size and that the two parameters are inversely related to each other (Figure 16). Our data shows that low mean grain sizes correspond with higher skewness and kurtosis values indicating that fine sediments have positive skewness and kurtosis.

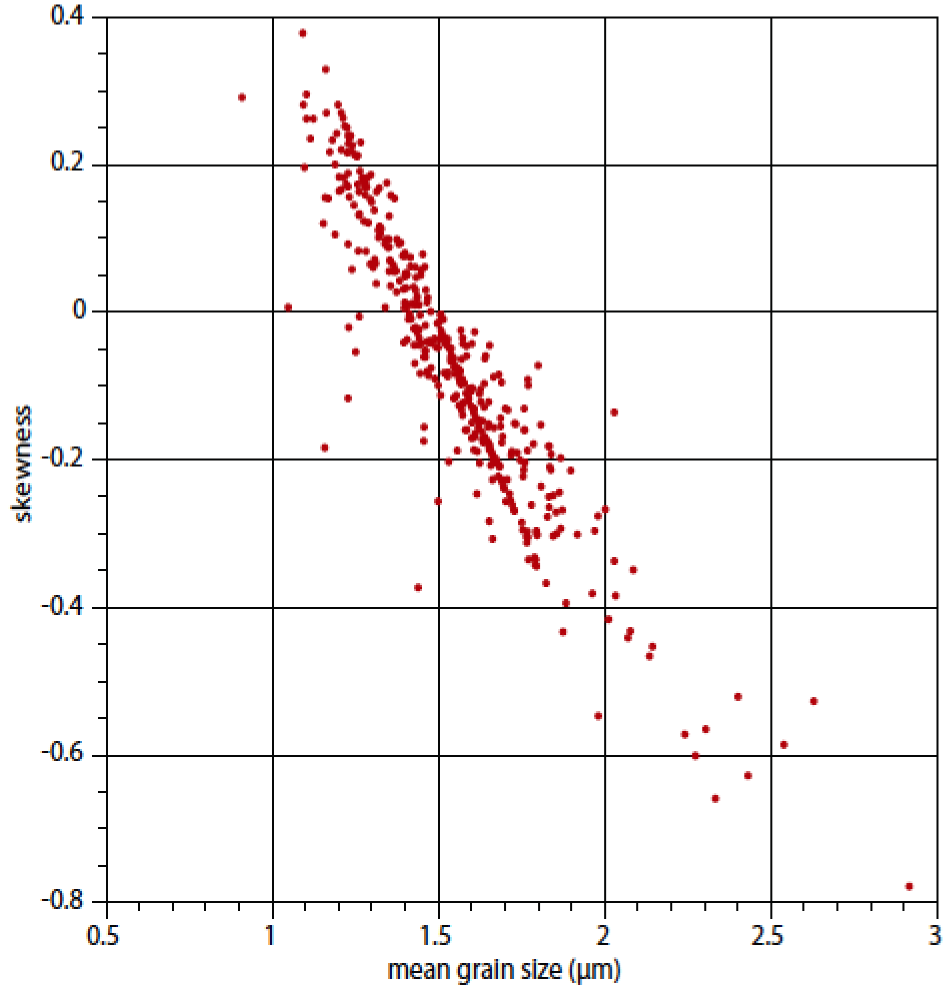

Figure 16. Comparison of mean grain size of glacigenic sediments in Junín record with skewness. An inverse relationship is observed for the two parameters.

Furthermore, we compared five samples to understand the frequency distribution of sediments with low negative and high positive skewness values (Figure 16). The samples with positive skews, 0.252 and 0.378 have greater distribution of fine sediments and have peaks at around 1 um. The sample with negative skews, -0.758, -0.373 and -0.307 all have peaks >1 um. -0.307 and -0.758 have peaks > 4 um indicating greater distribution of coarse sediments (Figure

17). These values complement the previous comparison between mean grain size and skewness where we observed coarser sediments with negative skewness and finer sediments with positive skewness.

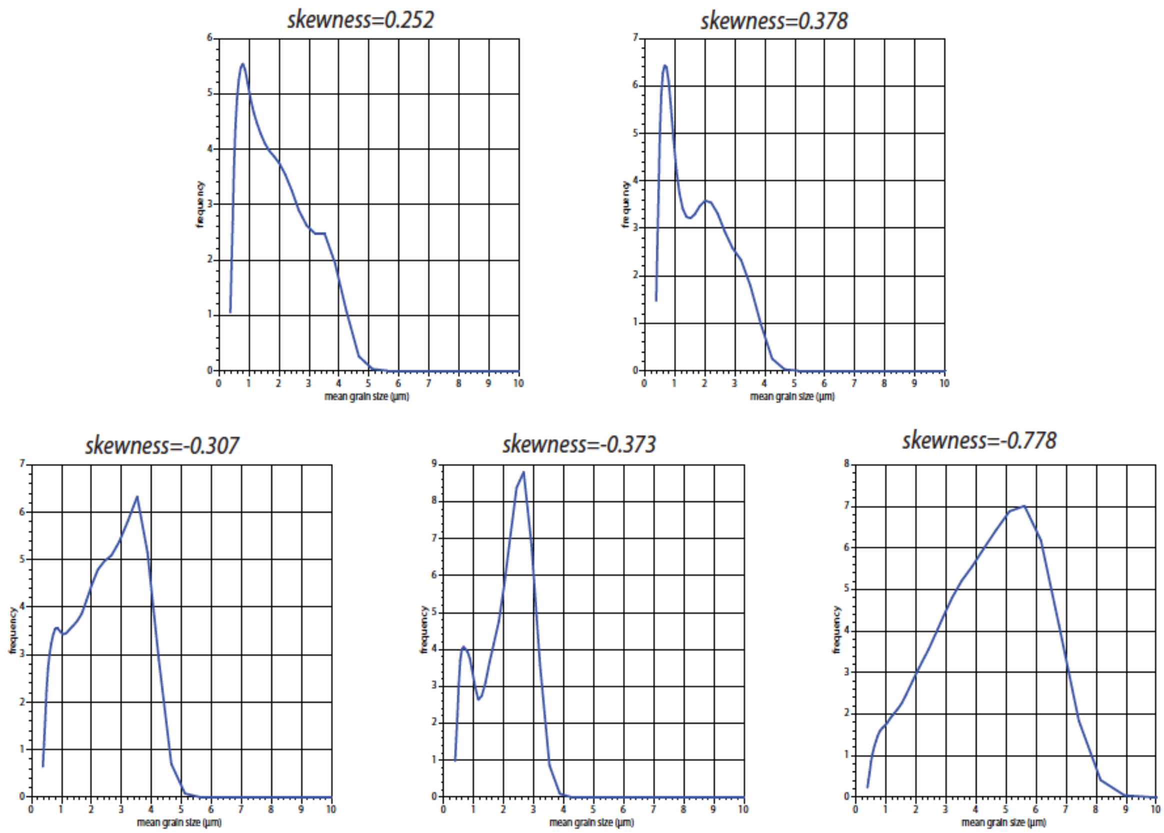

Figure 17. Frequency of mean grain size distribution for two positive skewness and three negative skewness show that coarse sediments have negative skewness and fine sediments have positive skewness.

The comparison between grain size frequency and mean grain size shows that as grain size becomes coarser, skewness becomes negative. Negative skewness has a right modal distribution with a fine tail indicating an excess of fine particles. Additionally, our mean grain size distributions show bimodal distributions or various humps in the statistical distribution indicating that there is a mixed signal of different mean grain sizes. This bimodal distribution can be interpreted to be in various ways. One hypothesis suggests that the mean grain sizes are all derived from one valley. The variation in mean grain sizes from that particular valley could be due to different types of bedrock within a valley. Carbonates result in finer grained sediments while quartzites and gneisses are coarser so it is possible that as the glaciers transported sediments from the valley into the lake, it carried all the coarse silicates and finer clays or calcite along with it.

A second hypothesis is that the the mix of different mean grain sizes comes from different valleys. The bedrock geology of the eastern side of the Junin basin (Figure 5) comprises of mostly carbonates (fossiliferous limestone) to the north of Lake Junin and siliciclastics (gneiss, quartzite, volcanics) to the south. It is likely that our distribution shows a mixing population of the coarser siliciclastics and finer carbonate sediments from different valleys. Here, we make a major assumption about prominent uniform bedrock in different valleys in order to simplify the origin of sediments from these source valleys. Our simplistic interpretation therefore assumes that all carbonates are likely to come from north of lake Junín while siliciclastics might be from the south where there are gneisses, quartzites and other volcanics. However, it is more probable that each valley is comprised of different bedrock geology rather than a uniform bedrock. Similarly, we can also hypothesize that different transport distances from nearby valleys result in wide statistical distribution of mean grain size. In conclusion, it is much more likely that different bedrock types either from a single valley or multiple valleys are causing the variation in mean grain sizes.

Finally, almost all of our mean grain sizes are for each glacial period is in the range of 1-3 um, suggesting interflows as primary methods of sediment transportation into the lake. Overflows occur when the incoming water is less dense than the lake water they flow into.

However, if a sediment plume is slightly less dense than the hypolimnion the flow can spread into the lake at an intermediate depth as an interflow.

Most of the sediments in the core are very fine (1-3 um) and these fine sediments coupled with the absence of coarse sediments indicate that there is no ice rafted detritus/debris (IRD) in Lake Junín sediments. The absence of IRD further supports the hypothesis that sediment transport into the lake was either through interflows or overflows. In fact, the mean grain sizes of sediments prior to the LGM do not vary greatly and are ~1-2 um. Consistent mean grain in each glacial cycle suggests that mean grain size is a function of bedrock type rather than ice cover at Lake Junín. Additionally, the absence of IRD provides evidence that while there were glaciers that reached the edge of the lake, they never calved into Lake Junín.

CONCLUSION

Long lake records from the Southern Tropics hold enormous potential for understanding cyclicity of temperature change and glaciation in the Southern Hemisphere. Our Junín sediment record, which spans over 700,000 years is one of the few lakes in the Tropical Andes that has never been glaciated and has received continuous sediment deposition from alpine glaciers in the nearby Eastern and Western Cordilleras. The comparison and characterization of seven periods of glaciation recorded in the Junín record provides an insight into glaciation and glacial erosion in Junín.

Firstly, we see that the mean grain size during all glacial cycles, irrespective of glacial extent is ~1-2 microns. This indicates that erosion resulting in consistent mean grain sizes are probably a function of the bedrock type rather than glacial extent. The fine glacial sediments and absence of coarse sediments also indicate that there is no ice rafted debris (IRD) in lake sediments. This supports the hypothesis that while glaciers reached the lake edge, ice never calved into the lake or covered it. The oldest glacial cycle differs from other glacial cycles since it has relatively coarser sediments (>3 microns). This distinctive change in grain size and stratigraphy is thus hypothesised to indicate the birth of Lake Junín when the valley was dammed by glacial outwash. It is also worth noting that the high siliciclastic flux between MS2-4 during the Local Last Glacial Maximum in Lake Junín occurred when the ice sheet volume was smaller compared to other glacial periods. Mean grain sizes during the LLGM and other erosion proxies such as Ti+Si+Al/Ca are also low despite high siliciclastic flux. These observation lays down the framework for future research into the factors leading to high siliciclastic flux during the LLGM.

Furthermore, comparison between the the skewness and mean grain sizes of glacial sediments in Lake Junín indicates that the two are inversely related. Coarser sediments have negative skewness with a finer tail while finer sediments have a positive skewness. This variation in mean grain size distributions shows a mixed signal of different mean grain sizes either from a single dominant valley with different rock types or from different valleys with prominently different rock types. Therefore, the difference in mean grain size distribution could be due to abrasion of different rocks in glacial valleys feeding sediments into the lake. Since the mean grain sizes are very fine (1-2 microns), the sediments would have followed Stokes Law and been transported into the lake either as an interflow or overflow. Thus, comparison between the different proxies has helped characterize and compare glaciation and glacial erosion in Junín.

REFERENCES

Baker, P.A., Seltzer, G.O., Fritz, S.C., Dunbar, R.B., Grove, M.J., Tapia, P.M., Cross, S.L., Rowe, H.D. and Broda, J.P., 2001. The history of South American tropical precipitation for the past 25,000 years. Science, 291(5504), pp.640-643.

Baker, P.A., Rigsby, C.A., Seltzer, G.O., Fritz, S.C., Lowenstein, T.K., Bacher, N.P. and Veliz, C., 2001. Tropical climate changes at millennial and orbital timescales on the Bolivian Altiplano. Nature, 409(6821), pp.698-701.

Bradley, R.S., 1999. Paleoclimatology: reconstructing climates of the Quaternary (Vol. 68). Academic Press.

Cohen, S., 2003. Paleolimnology: the history and evolution of lake systems.

Flusche, M.A., Seltzer, G., Rodbell, D., Siegel, D. and Samson, S., 2005. Constraining water sources and hydrologic processes from the isotopic analysis of water and dissolved strontium, Lake Junin, Peru. Journal of Hydrology, 312(1-4), pp.1-13.

Fritz, S.C., Baker, P.A., Seltzer, G.O., Ballantyne, A., Tapia, P., Cheng, H. and Edwards, R.L., 2007. Quaternary glaciation and hydrologic variation in the South American tropics as reconstructed from the Lake Titicaca drilling project. Quaternary Research, 68(3), pp.410-420.

Haberzettl, T., Fey, M., Lücke, A., Maidana, N., Mayr, C., Ohlendorf, C., Schäbitz, F., Schleser, G.H., Wille, M. and Zolitschka, B., 2005. Climatically induced lake level changes during the last two millennia as reflected in sediments of Laguna Potrok Aike, southern Patagonia (Santa Cruz, Argentina). Journal of Paleolimnology, 33(3), pp.283-302.

Hahn, A., Kliem, P., Ohlendorf, C., Zolitschka, B., Rosen, P. and Team, T.P.S., 2013. Climate induced changes as registered in inorganic and organic sediment components from Laguna Potrok Aike (Argentina) during the past 51 ka. Quaternary Science Reviews, 71, pp.154-166.

Hansen, B.C., Wright, H.E. and Bradbury, J.P., 1984. Pollen studies in the Junin area, central Peruvian Andes. Geological Society of America Bulletin, 95(12), pp.1454-1465.

Inglis, G.N., Farnsworth, A., Lunt, D., Foster, G.L., Hollis, C.J., Pagani, M., Jardine, P.E., Pearson, P.N., Markwick, P., Galsworthy, A.M. and Raynham, L., 2015. Descent toward the Icehouse: Eocene sea surface cooling inferred from GDGT distributions. *Paleoceanography*, *30*(7), pp.1000-1020.

Lüthi, D., M. Le Floch, B. Bereiter, T. Blunier, J.-M. Barnola, et al. 2008. High-resolution carbon dioxide concentration record 650,000-800,000 years before present. Nature 453: 379-382.

Petit J.R., Jouzel J., Raynaud D., Barkov N.I., Barnola J.M., et al. 1999, Climate and Atmospheric History of the Past 420,000 years from the Vostok Ice Core, Antarctica, Nature 399: 429-436.

Roberts, W.H., Valdes, P.J. and Payne, A.J., 2014. Topography's crucial role in Heinrich Events. Proceedings of the National Academy of Sciences, 111(47), pp.16688-16693.

Rodbell, D.T., Abbott, M.B. and 2011 ICDP Lake Junin Working Group, 2012. Workshop on Drilling of Lake Junin, Peru: Potential for Development of a Continuous Tropical Climate Record. Scientific Drilling, 13, pp.58-60.

Rodbell, D.T., Seltzer, G.O., Mark, B.G., Smith, J.A. and Abbott, M.B., 2008. Clastic sediment flux to tropical Andean lakes: records of glaciation and soil erosion. Quaternary Science Reviews, 27(15), pp.1612-1626.

Rodbell, D.T., Delman, E.M., Abbott, M.B., Besonen, M.T. and Tapia, P.M., 2014. The heavy metal contamination of Lake Junín National Reserve, Peru: An unintended consequence of the juxtaposition of hydroelectricity and mining. *GSA today*, *24*(8), pp.4-10.

Rosenbaum, J.G. and Reynolds, R.L., 2004. Record of Late Pleistocene glaciation and deglaciation in the southern Cascade Range. II. Flux of glacial flour in a sediment core from Upper Klamath Lake, Oregon. Journal of Paleolimnology, 31(2), pp.235-252.

Ruddiman, W.F., 2001. Earth's Climate: past and future. Macmillan.

Seltzer, G.O., Rodbell, D.T., Baker, P.A., Fritz, S.C., Tapia, P.M., Rowe, H.D. and Dunbar, R.B., 2002. Early warming of tropical South America at the last glacial-interglacial transition. Science, 296(5573), pp.1685-1686.

Seltzer, G., Rodbell, D. and Burns, S., 2000. Isotopic evidence for late Quaternary climatic change in tropical South America. Geology, 28(1), pp.35-38.

Scholz, C.A., Johnson, T.C., Cohen, A.S., King, J.W., Peck, J.A., Overpeck, J.T., Talbot, M.R., Brown, E.T., Kalindekafe, L., Amoako, P.Y. and Lyons, R.P., 2007. East African megadroughts between 135, 75 thousand years ago, and bearing on early-modern human origins. Proceedings of the National Academy of Sciences, 104(42), pp.16416-16421.

Smith, J.A., Mark, B.G. and Rodbell, D.T., 2008. The timing and magnitude of mountain glaciation in the tropical Andes. Journal of Quaternary Science, 23(6-7), pp.609-634.

Smith, J.A., Seltzer, G.O., Farber, D.L., Rodbell, D.T. and Finkel, R.C., 2005. Early local last glacial maximum in the tropical Andes. Science, 308(5722), pp.678-681.

Spahni, R. J. Chappelaz, T.F. Stocker, L. Loulergue, G. Hausammann, K. Kamamura, J. Fluckiger, J Schwander, D. Raynoud, V. Masson-Delmotte and J. Jouzel. 2005. Atmospheric Methane and Nitrous Oxide of the Late Pleistocene from Antarctic Ice Cores. *Science* 310, 1317-1321.

Van der Hammen, T., 1985. The Plio-Pleistocene climatic record of the tropical Andes. Journal of the Geological Society, 142(3), pp.483-489.

Van Geel, B. and Van der Hammen, T., 1973. Upper Quaternary vegetational and climatic sequence of the Fuquene area (Eastern Cordillera, Colombia). Palaeogeography, Palaeoclimatology, Palaeoecology, 14(1), pp.973-5592.

Zolitschka, B., Anselmetti, F., Ariztegui, D., Corbella, H., Francus, P., Lücke, A., Maidana, N.I., Ohlendorf, C., Schäbitz, F. and Wastegård, S., 2013. Environment and climate of the last 51,000 years–new insights from the Potrok Aike maar lake Sediment Archive Drilling prOject (PASADO). Quaternary Science Reviews, 71, pp.1-12.

Wright Jr, H.E., 1983. Late-Pleistocene glaciation and climate around the Junin Plain, central Peruvian highlands. Geografiska Annaler: Series A, Physical Geography, 65(1-2), pp.35-43.