Late Glacial-Holocene climate change recorded in proglacial lake sediment cores from the Huaguruncho Massif, Central Peruvian Andes

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ABSTRACT

Alpine glaciers respond rapidly to changes in climate and the growth and decay of alpine glaciers is recorded in sediment cores extracted from lakes immediately downvalley from the margins of former glaciers. These records provide continuous archives of glaciation and climate change that complement the inherently discontinuous records of glaciation preserved by moraines. The aim of this study is to generate a continuous record of glaciation in Jaico cirque from lake sediment cores, which is located on the southeastern side of the quartz-monzonite dominated Huaguruncho Massif (5789 masl) in the eastern Peruvian Andes. The lakes are Laguna Jaico (10.56° S, 75.92° W; 4,271 masl) and Laguna Yanacocha (10.56° S, 75.93° W; 4,357 masl). The records generated will be combined with the record of glaciation preserved in upvalley moraines that are dated by the cosmogenic radionuclide ^{10}Be. The lake cores were obtained using both a Livingstone square-rod piston corer and a modified Nesje Percussion corer from an inflatable raft. Cores were analyzed for total carbon (TC), total inorganic carbon (TIC), bulk density (BD), magnetic susceptibility (MS), stable isotopes of C and O, and major element composition (by scanning XRF). Age control for cores was achieved by radiocarbon dating using accelerator mass spectrometry on detrital charcoal fragments (>250 µm) isolated by sieving. Records of glacigenic sediment input from both lakes reveal similar broad scale patterns; here we describe in detail the record from Laguna Jaico. Glacial flour dominates the core, with little to no organic material (TC<.5%) and high MS (~100-200 SI) from the base of the core (363 cm depth) upcore to

~225 cm (>8264 ± 61/58 cal yr BP); thereafter, the sediment record transitions into a brecciated, high TC (3-9%), low MS (~0 SI) section from ~225 – 90 cm depth (8264 ± 61/58 – 1426 ± 86/48 cal yr BP). Extending upcore to the core top (<1426 ± 86/48 cal yr BP) the record then reveals a section of intermediate TC (.1-3%) and low MS (0-1 SI). These results combined with those from Laguna Yanacocha show that over that last 12,000 years the influx of glacigenic sediment (low TC, high MS and BD) was low from ~13,000 – 11,500 and from ~8,500 – 1,500 cal yr BP. In contrast, from ~11,500 – 7,500 cal yr BP and since 1500 cal yr BP, glacigenic sediment input increased significantly. The intervals of increased glacigenic sediment input correlate well with the age of upvalley moraines, and with a recent summary of glacigenic sediment records from the western cordillera of central Peru (Stansell et al., 2013).

ACKNOWLEDGEMENTS

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INTRODUCTION

Climate and Proxies

Since the Industrial Revolution, anthropogenic fossil-fuel emissions have become an increasingly important topic of discussion due to its precarious connection with global warming, as well as how this climatic change may significantly alter the world (Bradley, 1998). The idea of human-induced "greenhouse" enhancement dates back to 1896, when Swedish scientist Svante Arrhenius postulated that changes in the level of carbon dioxide in the atmosphere could potentially increase surface temperatures globally (Arrehenius, 1896). This avenue of research slightly expanded in the 1970's, when the environmentalism movement became apparent, but research pointedly grew in the late 1980's and early 1990's when the Intergovernmental Panel on Climate Change (IPCC) concluded, albeit somewhat cautiously, that it was "much more likely than not" that our civilization faced severe global warming due to our carbon emissions (Watson, 2001). Today, there is no such ambiguity on the matter: a recent study has found that of the 2258 peer-reviewed climate change articles written by 9136 authors between November 2012 to December 2012, only 1 author rejected man-made global warming (Johnson, 2014). Now that climate change is firmly on the scientific forefront, conversation has quickly transformed into one that focuses on a comprehensive understanding of Earth's climate system. If climatologists correctly assume that the same natural laws and processes that function in the present day have always operated through history (Lyell, 1830), the implications of human disturbance can be fully grasped if comprehension of how the Earth has responded *without* an anthropogenic presence is obtained.

Paleoclimatologists are scientists who study changes in climate taken on a scale of (hypothetically) the entire history of earth, or the pre-instrumental time scale. If the storied maxim of Lyell has any truth, that "the present is the key to the past" (1830), than the notion that the "past is the key to the future" must be equally truthful, and the only way we uncover the climate past is through the work of paleoclimatologists. Projections of global warming, based on a medium-high worldwide emissions scenario, have temperatures rising as much as 7° F by 2100 AD (National Research Council, 2010). The atmosphere, sea level (Nicholls et al., 2007), ice caps and glaciers on the poles and in higher elevations (National Research Council, 2011; Rodbell et al., 2009), the amount of ocean acidification (National Research Council, 2010) and storm magnitude and frequency (Meehl et al., 2007) are all directly affected by changes in temperature. Thus paleoclimatologists may be tasked with understanding how the Earth operated under a warmer temperature regime to better prepare civilization for the changes are to come; for instance many studies have concentrated on the mid-Holocene thermal maximum (6,000 – 7,000 yr BP), in which global temperatures were 1-2° warmer than today (COHMAP, 1988).

Records of past climate are acquired in a multitude of ways, and in a variety of areas around the world (Figure 1). One of the most widely used climate-proxies, due to their especially high spatial range, are tree rings(or dendroclimatology). Tree-rings grow wider when conditions are favorable (generally warmer and wetter) and thinner when environmental stress is increased (generally colder and dryer) (Boninsegna and Villalba, 1996). Trees work especially well because their tree rings can be easily counted, and their growth responds to more than one climatic variable, like temperature, moisture content and cloudiness (this can be a detriment as well, because isolation of one variable can be problematic). However, trees are limited temporally, and some tropical trees do not have annual rings, making analysis difficult, although advances in dating these types of trees have been recently found, including a concentration on vessel density (Verheyden et al., 2005). Another useful climate-proxy is coral which has annual-ring development. $\delta^{18}O$ predictably changes through time in response to salinity content and, more importantly, water temperature: wider ring growth correlates with colder water, while thinner rings indicated warmer water (Fairbanks et al., 1997). Thus, corals can give precise sea-surface temperature readings through time (if salinity stays the same). Fossil corals have been found to have a secondary banding structure beside the annual growth rings, interpreted as changes in Earth's tides (Scrutton, 1964); studies have shown that there were more tidal cycles 440 million years ago than there are today, supporting the view that the Earth spun faster on its axis in the past than it does today (Williams, 2000).

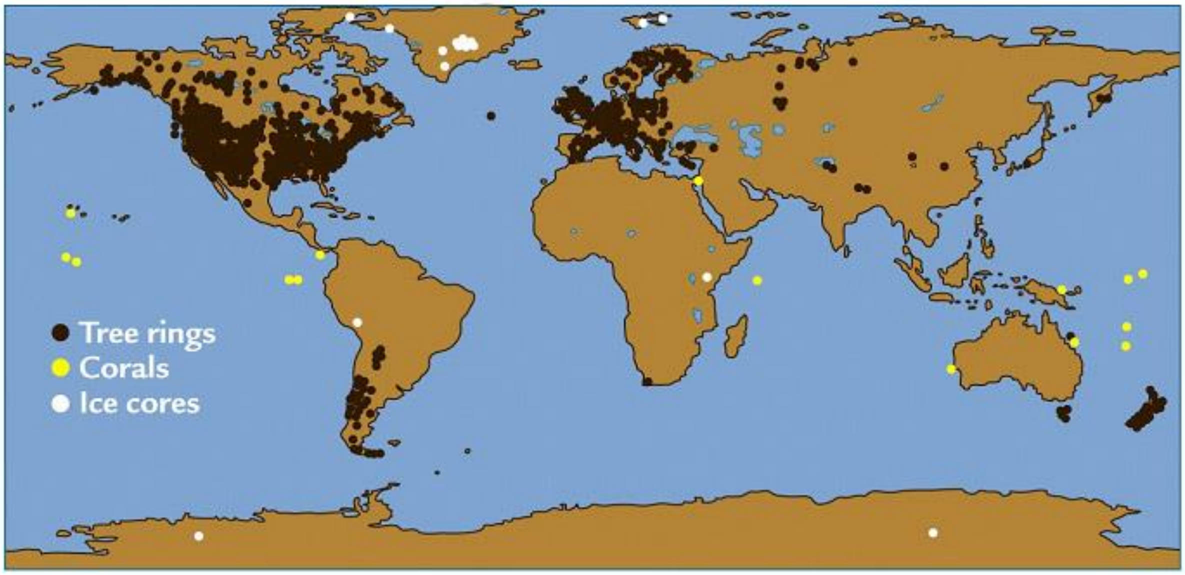

Figure 1 – Areas throughout the world in which common climate proxies have been taken: yellow denotes coral samples, brown signifies tree ring samples, and white indicates ice cores. Tree ring proxies are prominent in the northern Hemisphere, while ice cores are constrained to only the higher latitudes (Photo courtesy of the National Oceanic and Atmospheric Administration).

Ice-cores are perhaps the best known proxy for climate change: they can accurately track changes in atmospheric content, volcanic eruptions, solar variability, ocean volume, precipitation, and temperature on a scale of hundreds of thousands of years (EPICA, 2004). Through Rayleigh distillation of both D (deuterium) and O, the fraction of vapor remaining in clouds decreases as it gets cooler, resulting in only the lightest species of hydrogen and oxygen being held in the cloud (Bradley, 1999). This allows for generally light δD and $\delta^{18}O$, which behave in the same manner (Figure 2), to be precipitated on to glaciers: thus colder times in the past would correlate with strongly negative isotopic values, while warmer times would be recorded by heavier values (EPICA, 2004; Craig, 1961). Temperature reconstructions have been completed with a multitude of ice cores in both Greenland and Antarctica, however due to the lack of constant ice in the tropics of the planet, ice-core reconstructions in these areas are nearly always temporally short, limited to the last 20 ka (Thompson et al., 2000).

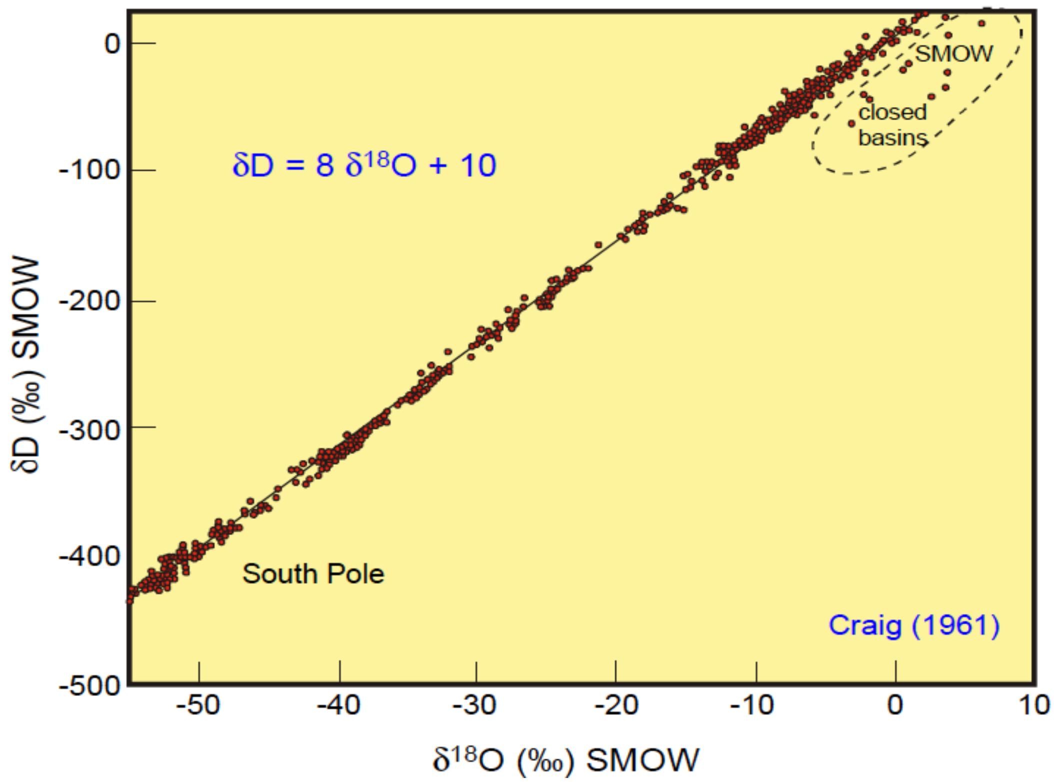

Figure 2 – Linear relationship between δD and δ18O, as first shown by Craig (1961).

The ability to track climate change in the tropics of our planet is of crucial importance if we are to fully recognize the intricate changes of imminent global warming. Through dating and interpreting changes in both the higher and lower latitudes, we can more easily discern the timing of worldwide climatic events (like the Last glacial maximum, Holocene thermal optimum), as well as hemispheric forcing: for instance, the famously termed Little Ice Age (LIA) is generally an exclusively Northern Hemispheric event (Fagan, 2007), and by understanding the changes in the tropics, we can observe just how widespread the event was. Although there is evidence of LIA moraines in a number of Southern Hemisphere localities, such as New Zealand, they are much less prevalent than in the Northern Hemisphere. The tropics are also the heat engine of the planet: the greatest amount of evaporation takes place there, and water vapor is the most abundant greenhouse gas on Earth (McElroy, 2002), thus any change within the tropics can easily be felt worldwide. The number of people that would be directly affected by climate change within the tropics is staggering: nearly 40% of the Earth's population lives between 23° N and 23° S currently, and this percentage is likely to increase to 50% by 2050 (State of the tropics, 2014). The tropics generally lack the ability to hold consistent ice, thus the gathering of continuous climatic records can at first look to be problematic. However, there is one proxy that has the ability to track climatic changes at relatively high resolution through timescales comparable to ice cores: lake sediments.

The first to see the potential for the use of lacustrine sediment as a climatic proxy was Wibjörn Karlén (1981). He studied four different lakes in northwestern Lappland, and through using X-radiography, was able to show glacial flour fluxes throughout the Holocene. Since lakes continually accumulate sediment from their surrounding watersheds, the cores of pro-glacial lakes in the mountains of tropical regions can provide a crucial record of tropical climatic change (Bradley, 1999). Whereas Karlén only utilized the bulk density of his cores, new and improved methods have been modified and perfected to interpret glacial activity: variables that measure glacigenic input must be taken into consideration, such as total organic carbon, clastic flux, magnetic susceptibility (MS), and bulk element concentrations. In addition, varve couplets in the lake sediment as well as moraines surrounding the pro-glacial lakes can help to corroborate different glacial advances and retreats seen within the lake sediment. Often it can be somewhat difficult to find glacial lakes that have high enough sedimentation rates so that high resolution analysis can take place on the lacustrine sediment cores: one such area that has these high sedimentation rates are in the basins of the Peruvian Andes (Hooghiemstra and Sarmiento, 1991). There is currently a relatively small amount of data on alpine glaciation in the tropics; yet as was stated previously, it is crucial to encourage research in these regions, such as the Peruvian Andes, because of the integral role the tropics play in the global climate system (Rodbell et al., 2008).

The Andes: What we know

The Andes span close to 68° of latitude from Columbia in the North to Chile and Argentina in the South (Figure 3). This mountain range includes some of the driest and wettest mountainous expanses on Earth (Rodbell et al., 2009), and thus the glaciers within these ranges can easily be affected by slight changes in either temperature or precipitation, depending on their location. Precipitation in the tropical Andes is derived from the Atlantic Ocean via the easterly winds, and can be transported to the high Andes via convective flow (Rodbell et al., 2009). The wettest areas of the Andes are in the foothills of the eastern cordillera, where the mean annual precipitation can exceed 4000 mm, whereas the western cordillera rarely experiences mean annual precipitation of over 1000 mm (Hoffman, 1975).

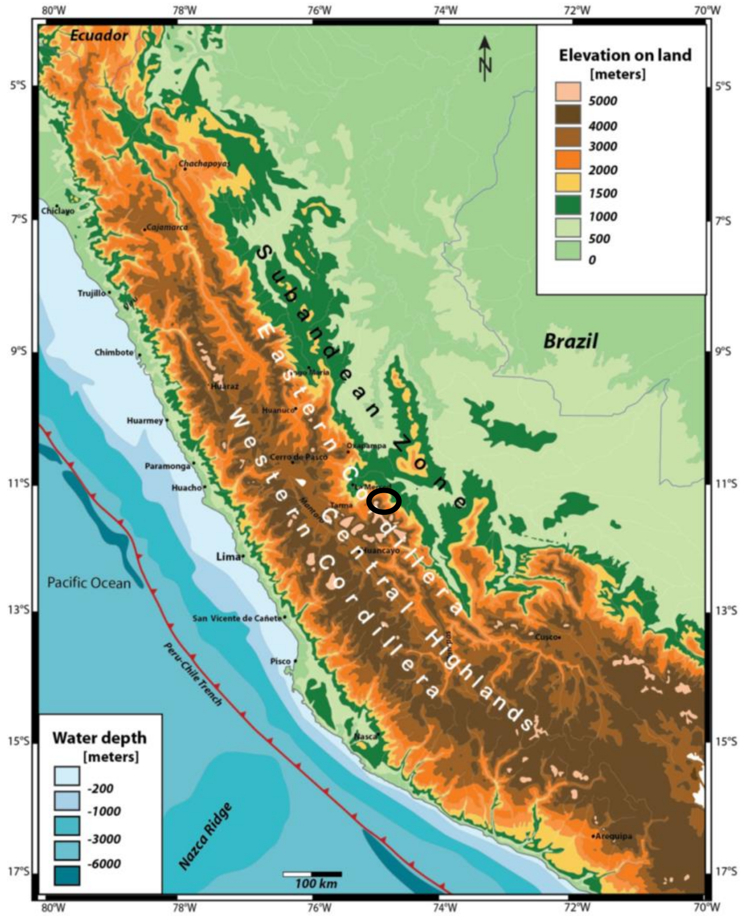

Figure 3 – Elevation map of the Peruvian Andes, illustrating the Eastern and Western Cordilleras. The Peru-Chile Trench is also shown, with approximate water depths along the coast. Our study site is marked with a circle. (from Pfiffner and Gonzalez, 2013).

There is a direct problem with using lacustrine sediments from glacial lakes as a proxy due to the fact that glaciers respond to both temperature and precipitation (Bradley, 1999). Our aptitude to accurately reconstruct climate in the past requires that we differentiate between changes in temperature and precipitation. Luckily, the Andes inherently solves this problem for us: owing to the steep east-to-west moisture gradient across the mountain range, glaciers within the eastern cordillera are more sensitive to changes in temperature while the glaciers within the western cordillera are more sensitive to changes in precipitation (Rodbell et al., 2009). Thus by comparing records from each of the cordilleras, one can create an accurate climatic reconstruction through time.

This overview of glaciation and climatic change in the Andes will concentrate on the Holocene (~11,500 yrs BP to the present). The only unambiguous piece of geologic evidence known to directly record a period of glacial equilibrium is moraines. Thus to understand, in the broadest sense, the climatic fluctuations of the tropical Andes, we can first look to moraines. Licciardi et al. (2009) has studied moraine formations in the Cordillera Vilcabamba in southern Peru that show extensive glacial advances during the early Holocene as well as indicators of the LIA, suggesting an intrinsic linkage between the Northern Hemisphere and climate as far south as 13°S. Additionally Licciardi et al. (Unpublished) has recently studied moraines within the Huaguruncho Massif in northeastern Peru, and has found moraine ages from ~14,000, 11,000, and 700 yrs BP, correlative with the Younger Dryas, just after the Younger Dryas, and the LIA. The moraines for the LIA were much more pronounced in the Huaguruncho Massif than in the Vilcabamba, suggesting a much greater Northern Hemisphere influence in the massif. These moraine ages only give wide-ranging constraints on glacial advances and retreats, and can be doubly problematic because moraines can be easily destroyed by an advancing glacier. Thus we can look to lake sediments to fill in the gaps and give us a higher resolution reconstruction.

Clastic sediment flux to alpine lakes in Peru, Bolivia and Ecuador has been used to show mean ice advances during the late glacial at ~16,000 yrs BP, followed by ice retreat until ~12,000 yrs BP (Rodbell et al., 2008; Rodbell et al., 2009). The early Holocene saw extremely low levels of clastic sediment flux, suggesting significant glacial retreat, and did not pointedly advance again until ~5,000 yrs BP. It is beneficial to know what the ice is doing across a wide area, however by using different proxies such as lake level changes and isotopes within locally obtained ice cores, we can also tell what exactly was driving the ice movement: temperature or precipitation. For instance, in the western cordillera of Peru, lake sediment records show reduced ice extent due to a relatively arid and warm setting during the early Holocene, followed by colder and wetter conditions in the Middle Holocene from ~8,000 to ~4,000 yrs BP (Stansell et al., 2013; Rodbell et al., 2009). The Medieval Climate Anomaly time period shows a relative ice retreat due to drier conditions, while the LIA was marked by ice advance during wetter conditions. Additionally, a recent comparison of the Quelccaya Ice cap in southeastern Peru with other proxies such as the North Greenland Ice Core Project, and the European Project for Ice Coring in Antarctica has shown that southeastern Peru may be affected more greatly by Southern hemispheric forcing rather than Northern hemispheric forcing (Kelly et al., 2012).

At our disposal is a broad understanding of climate during the Holocene and late glacial time periods, but there is still much work to be done. Southern Hemispheric and Northern Hemispheric forcings still need to be fully realized: how far south are Northern Hemisphere events, such as the Younger Dryas and LIA, felt? How far north are Southern Hemisphere events, such as the Antarctic

Cold Reversal, felt? On a more basic level, we still need to take steps towards obtaining a longer, higher resolution climate reconstruction of the tropical area.

Objectives

The objectives for this paper are: (1) to provide a continuous sediment record of upvalley glaciation within the Huagurunchо Massif in the eastern cordillera of the Peruvian Andes, (2) provide minimum limiting ages for downvalley moraines in the local Jaico cirque, and finally (3) test the validity of ^{10}Be dating of moraines both up- and downvalley from the Jaico cirque and compare these findings with other records from the tropics to determine whether or not the tropics "marched in lock step" (Rodbell, 2012) with the higher latitudes.

METHODS

Lake cores were obtained during the summer of 2013 from Laguna Jaico (10.56° S, 75.92° W; 4,271 masl) and Laguna Yanacocha (10.56° S, 75.93° W; 4,357 masl) in the Peruvian Andes using both a Livingstone square-rod piston corer, a Verschuren surface corer (Verschuren, 1993), and a modified Nesje percussion corer (Nesje et al., 1987). Cores were obtained using an inflatable raft. Extracted cores were measured and wrapped in plastic, and then placed in

PVC pipe containers for transportation. Surface cores were placed in larger PVC pipe containers (of the three surface cores, A-C, core A was completely extruded at 2 cm intervals and placed in separate plastic bags). All the cores were split, digitally photographed, and physically described at Union College, Schenectady NY (Figure 4).

Samples, 1 cm^3 in volume, were taken at 2 cm intervals and then freeze-dried to obtain bulk density (BD). MS was completed using a Bartington MS2 meter at 1 cm intervals. Total carbon (TC) was obtained using a CM 2500 Autosampler Furnace (combustion at 1000°C to convert to CO^2), and then measured with a UIC coulometer. Total inorganic carbon (TIC) was measured using a CM 5230 through acidification. Total organic carbon (TOC) was calculated using the TC and TIC results (TOC = TC – TIC). Greyscale was attained using the Image J software. Major element composition was obtained using a portable Bruker XRF sensor at 1 cm intervals (Data reduction was done using the Artax software). Biogenic silica was extracted from the sediment by dissolving the sediment in sodium hydroxide (NaOH), and due to the different dissolution rates of the diatomic and minerogenic sources of silica, these two variables could be quantitatively calculated, as is described in Conley et al. (1993). Radiocarbon dating was done using accelerator mass spectrometry at the UC Irvine Mass Spectrometry Lab on detrital charcoal and plant fragments (>250 µm) isolated by sieving; these dates were then converted to calibrated calendar years using CALIB 4.0, reporting ages in years before present (BP) where present is 1950 AD. Age-depth models were created using linear and polynomial interpolation in Microsoft Excel.

Figure 4 – Digital photograph of the Union College Core Lab in Schenectady, NY. (from Rothenberg, 2011).

STUDY AREA

This study takes place within the Jaico cirque, located on the southeastern side of the quartz-monzonite dominated Huaguruncho Massif (5789 masl) in the eastern cordillera in the Peruvian Andes (Figure 5). The eastern cordillera was chosen to maximize the temperature variable, due to the fact that this area has been incredibly wet through time. Since moisture in the Andes is derived from the Atlantic ocean via the tropical easterlies, the eastern cordillera is on the wet end of a strong moisture gradient (Rodbell et al., 2009); as long as there have been trade winds, this gradient will have existed.

Figure 5 – Digital photograph of the Huaguruncho peak. Yanacocha Lake is on the left while Jaico Lake is on the right in the foreground (from Rothenberg, 2011).

Glacier mass balance changes are directly driven by changes in temperature and precipitation, and on average, sites that are on the wet end of a moisture gradient, like the eastern cordillera, will be more sensitive to changes in temperature than changes in precipitation. The studied lakes are Jaico Lake (10.56° S, 75.92° W; 4,271 masl) and Lake Yanacocha (10.56° S, 75.93° W; 4,357 masl), both located within the cirque. These are two of nearly 70 glacial lakes within the Jaico complex (Pinedo and Borios, 2004). Meteorological data from LaOroya, Peru (city west of Jaico Cirque) show mean monthly precipitation of ~90 mm during the wet months (November-March) and mean monthly temperature of ~11.5 during the same span (Figure 6); Jaico Cirque is probably slightly colder due to the elevation change, as well as slightly wetter. There is a mining operation on the eastern border of the cirque, and there has recently been an artificial lowering of Jaico Lake by nearly two meters for hydraulic engineering purposes, a common practice in the Peruvian highlands to facilitate Peru's electricity: nearly 70% of Peru's electricity comes from hydro-powered sources (Rodbell, 2013).

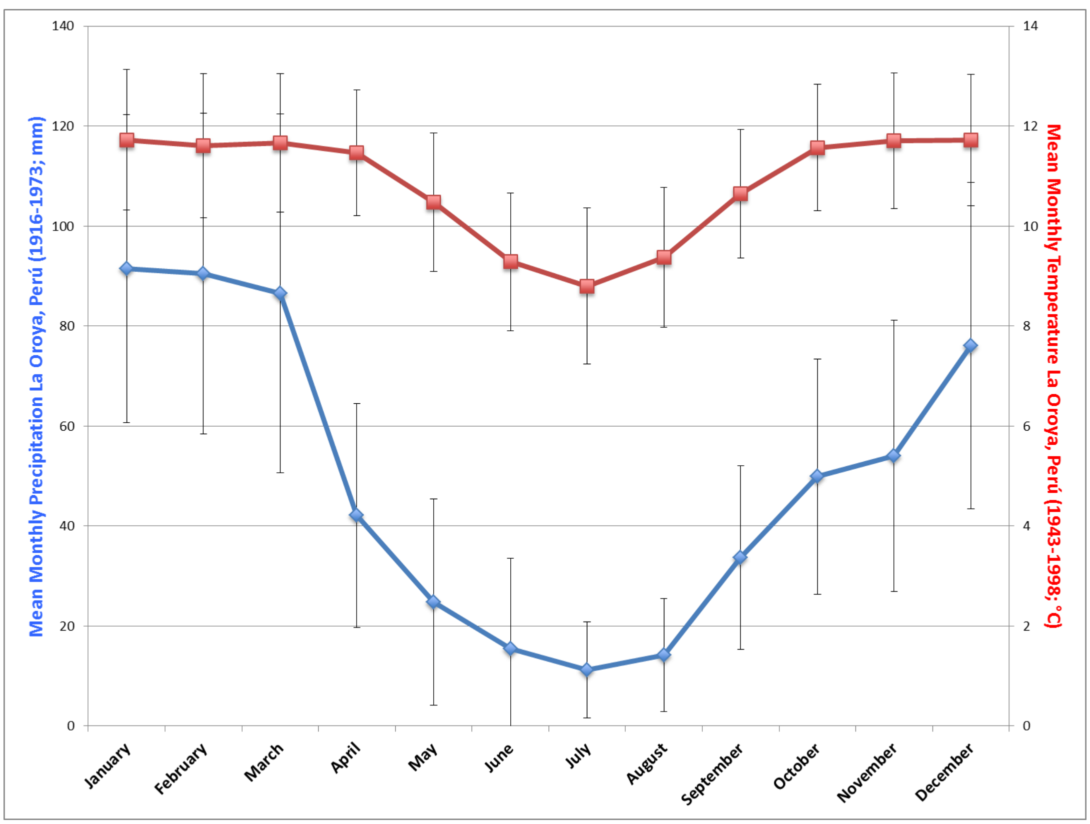

Figure 6 – Mean monthly precipitation and mean monthly temperature at La Oroya, Peru (south of the Huaguruncho Massif).

Moraine ages, obtained using ^{10}Be dating, have been found within the Jaico cirque (Figure 7) (Delgado and Rodbell, 2014). The southern-most moraines are dated to pre-LGM and LGM, and the last glacial advance to directly affect Lake Yanacocha was most likely the Late Glacial. The moraines from the Late Glacial constrain the lake, and the basal age of the lake itself has been radiocarbon dated to be around 13,000 cal yr BP. There are additionally early Holocene, Neoglacial and LIA moraines surrounding Jaico Lake, however no basal age has been obtained from the lake.

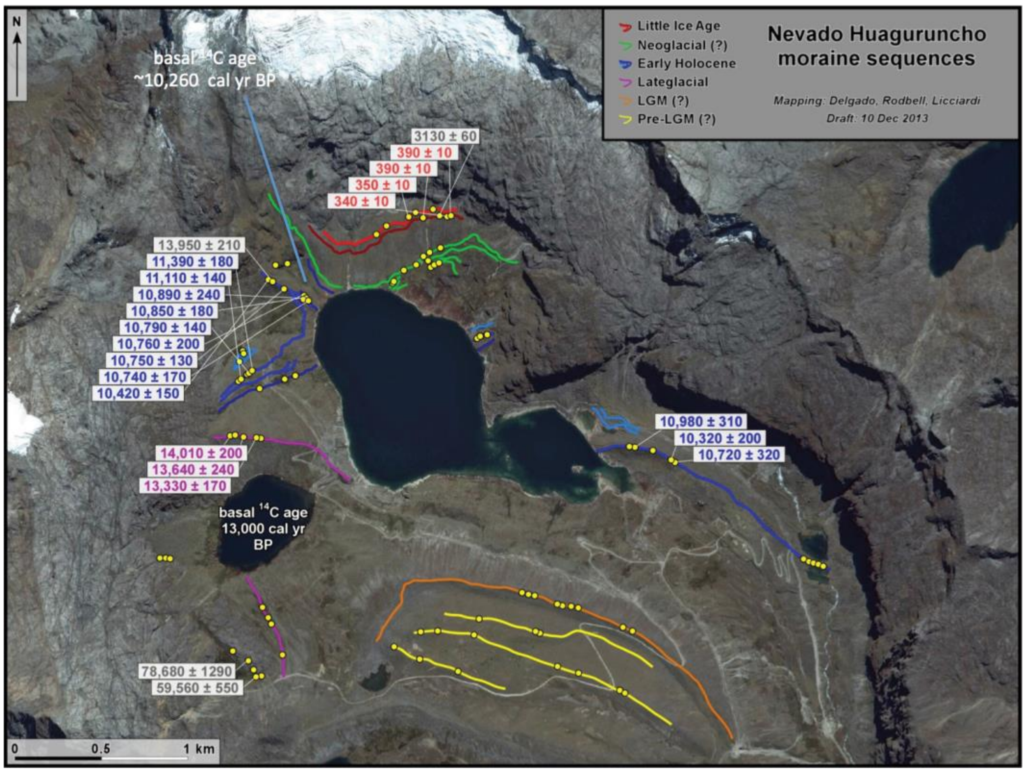

Figure 7 – Bird's-eye view of Lake Yanacocha (bottom-left) and Jaico Lake (center). Ages obtained by 10Be dating (Licciardi et al., 2013). Also denoted are radiocarbon basal ages from the Jaico Bog and Lake Yanacocha.

The Yanacocha Bog and Jaico Bog have both been previously cored (Rothenberg, 2011). The Yanacocha bog core (Figure 8) is about 120 cm long, while the Jaico Bog core (Figure 8) is ~480 cm long. The Yanacocha bog's stratigraphy doesn't change drastically, but does go from light to dark in color from the bottom to the top, coincident with decreasing MS and BD towards the top. The Jaico bog covers a greater span of time, and has a greater amount of distinguishable layers. Lighter layers are observed at ~200, 240, 350 cm and less pronounced layers at ~50, and 425 cm. MS remains relatively stable throughout nearly the entire core. The BD data is erratic, however the large spike near the top overlaps with large spikes in MS and TC, most likely representing the LIA. Additionally, Livingstone and percussion cores were taken in Lake Yanacocha (Figure 9) (Rothenberg, 2011). The Livingstone core is ~250 cm long, and the only significant change occurs at around 75 cm downcore, where MS and BD increase, while TOC decreases. The percussion core is around 325 cm long, and has a number of noteworthy changes, the most striking of which occurs ~305 cm downcore, where MS, Ti concentration, and BD all increase, indicating a period of glacial advance. There are sporadic indications of other glacial increases as well (~151 and 18.5 cm downcore).

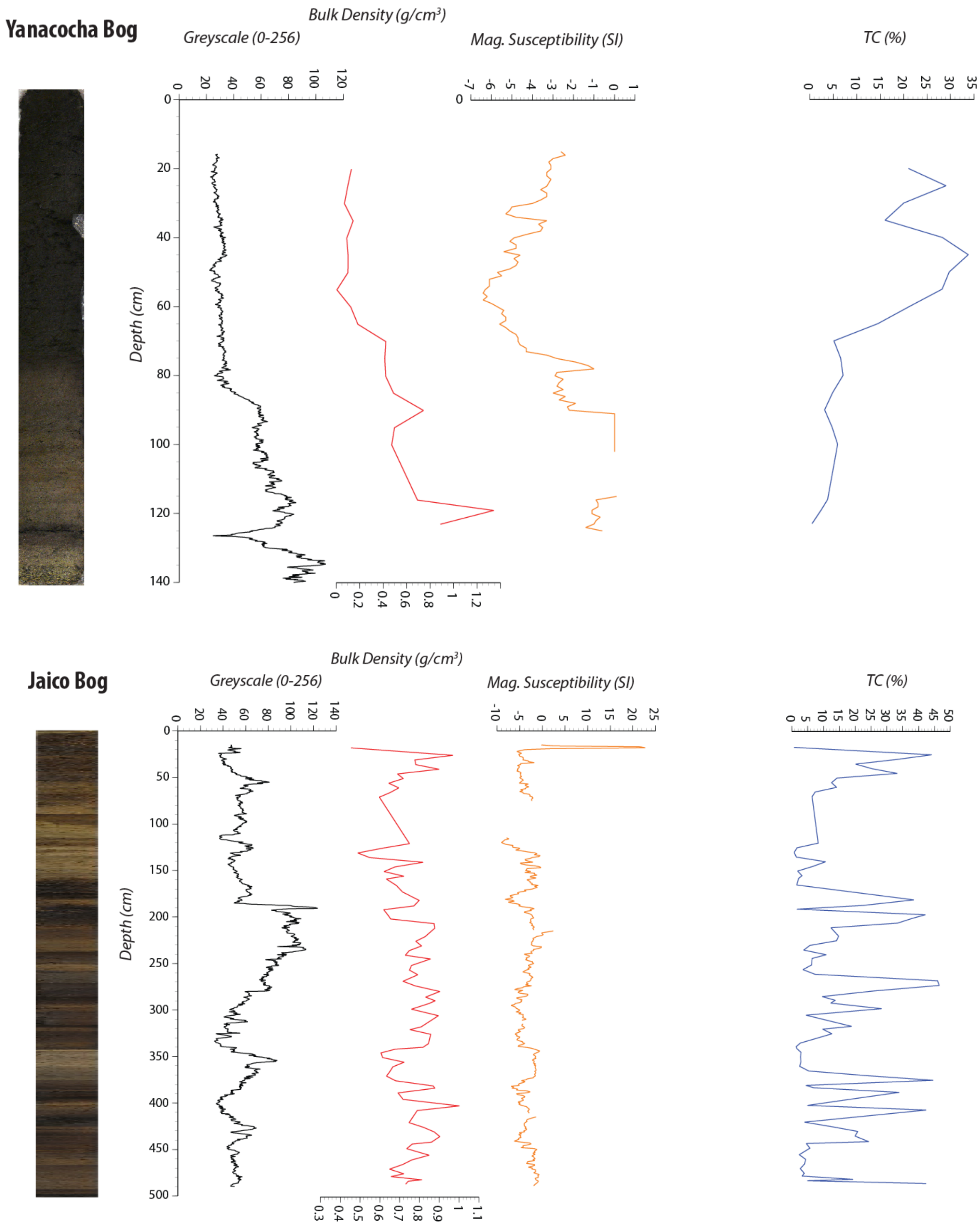

Figure 8 – Compilation of cores taken from the Yanacocha Bog and Jaico Bog. Graphs show variables of greyscale, bulk density, magnetic susceptibility, and total carbon (TC). Downcore plots are compared with depth.

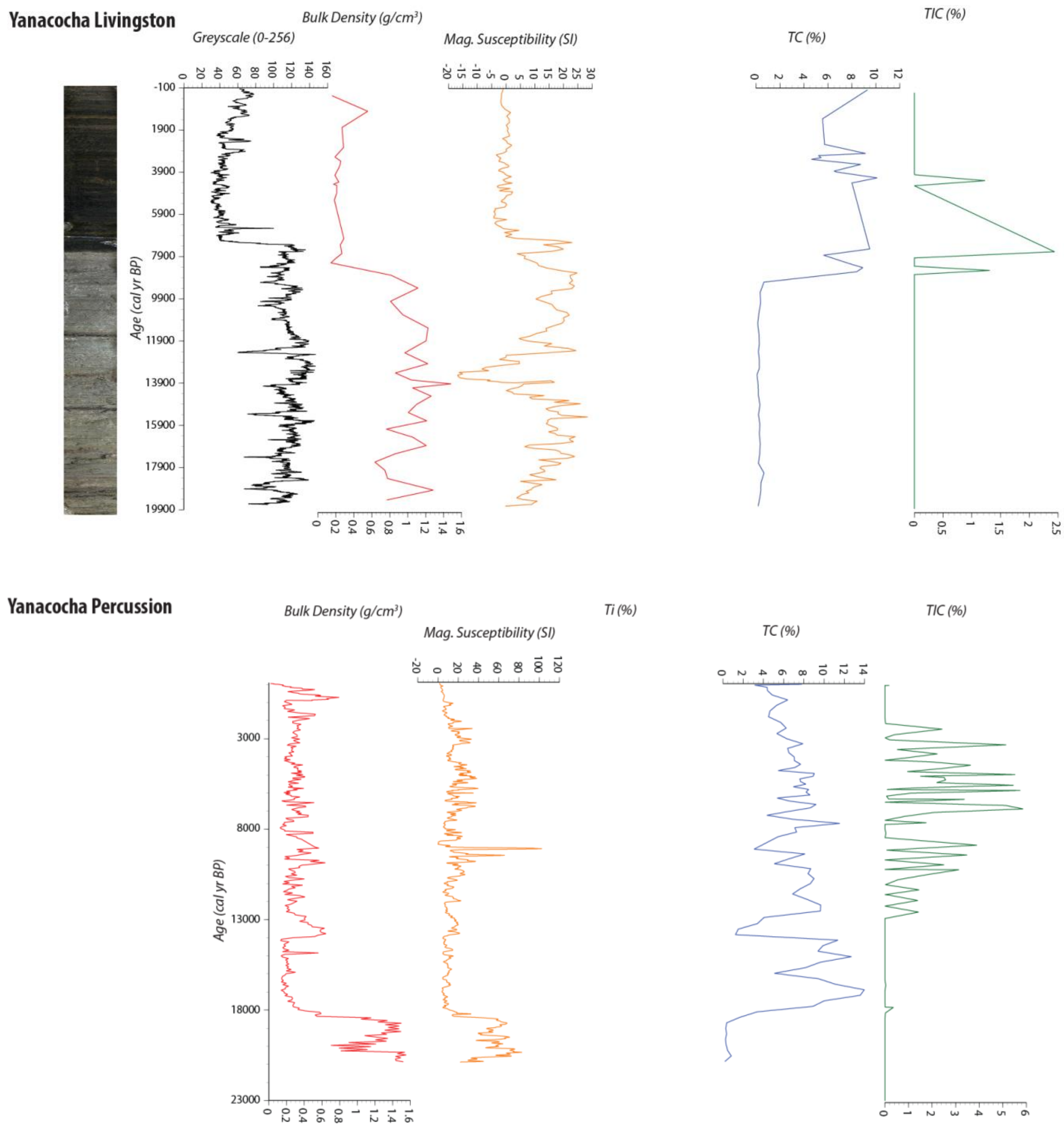

Figure 9 - Compilation of Livingstone and Percussion cores taken from Lake Yanacocha. Graphs show variables of greyscale, bulk density, magnetic susceptibility, total carbon (TC), Ti element concentration, and total inorganic carbon (TIC). Downcore plots are compared with age (Age models discussed in the Data section).

DATA

The Variables

Before analyzing the cores taken from Lake Yanacocha or Jaico Lake, we first must understand fully what the variables that we've obtained tell us. MS, and similarly Ti concentration, is used as a proxy for clastic material (Bradley, 1999). Thus, when glaciers are advancing and move closer to the lake, MS and Ti concentrations will increase. The sediment that is often deposited through glacial processes, especially during periods of glacial advance, is glacial flour, a very dense, often light grey-white material. To account for this material, we can use both BD and greyscale. BD measures the density of a cubic centimeter, so areas that are very dense could represent areas infused with glacial flour. Greyscale measures the light intensity of the core; higher values denote light material, and lower numbers represent darker material. TC measures organic flux, and since glacial advance is characterized by increased clastic material, often times this leads to a decrease in productivity within the proglacial lake. TIC records calcite precipitation; when lake levels are low, supersaturation can occur, and in turn allows the precipitation of inorganic calcite (Hahn, 2013). Additionally, according to Dean (1999), TIC often inversely varies with TOC, thus times with increased productivity will result in a greater dissolution of inorganic calcite. Finally, clastic flux is perhaps the best proxy for glacial movement because it measures the rate of minerogenic material, excluding any biogenic or authigenic material.

Jaico Lake Results

Two separate lake cores were taken from Jaico Lake, however only one was fully worked up due to it having the most complete downcore record. Two cores were obtained: one surface core (CC:D1) and one Livingstone core (CF:D2-4), reaching down to 363 cm below the sediment-water interface (Figure 10). The cores were taken in the shallower, southern end of the lake at around 20 m water depth (the greater bulk of the lake had water depths of greater than 30 m, which would have made the use of the Livingstone corer close to impossible). Drive CC:D1 shows dense, glacial flour for the top 15 cm, transitioning into a darker, sandier sediment. Interspersed throughout the core are pockets of organic material that was preferentially sampled for radiocarbon dating. The darker grey sediment extends until about 90 cm downcore, shifting into a brecciated area, with blocks of foliated clay (Figure 10). CF:D2 continues showing highly foliated areas, nearly turning into varved-couplets 20 cm downcore. These couplets disappear at 50 cm downcore, where an intense and highly unique brecciated area begins, where large blocks of clay are detached within a glacial flour matrix. Lasting just over 30 cm, this area is dominated by large, darker-grey clay blocks (some of which show signs of foliation) ‘floating’ in a light-grey matrix. The reason for this brecciated area occurring is one of debate: one hypothesis is that a large-scale earthquake may have occurred during the time of deposition, resulting in blocks of clay from around the lake to break off and land in this area. This brecciated column also may be responsible for the erratic radiocarbon dates that were obtained from this core. Drive CF:D3 as well as drive CF:D4 transition back to a glacial flour-dominated section. There are certain areas of darker sediment interspersed throughout CF:D3 and CF:D4, however there are no areas of visible organic material. Varve couplets can be faintly seen in both cores; small, darker sediment layers sandwiched between much larger, light grey glacial flour areas.

Figure 10 – Digital pictures of the cores obtained from Jaico Lake; from left to right: CC:D1, CF:D2, CF:D3, and CF:D4. The brecciated area of greatest concern is most concentrated in CF:D2. Also note the gradual transition from light-dark sediment as you travel upcore.

MS for Jaico Lake shows a relatively stable trend, consistently staying near 0 SI until about 200 cm downcore, where MS jumps up to as high as 25-30 SI. The ~200 cm mark is an interesting time for nearly every variable considered: TOC drops close to 0, TIC increases very highly for a short span (~20 cm), BD and greyscale greatly increase, and Ti increases as well (Figure 11) This coincides with the start of the glacial-flour dominated CF:D3 drive, suggesting an increase in glacially derived sediment during this time period. These changes occur at the 200 cm mark, and continue downcore to the base, suggesting that a glacial advance started, at minimum, at the bottom of drive CF:D4. This area is perhaps the strongest and most well-correlated in the entire core, however there are other distinctions in the data. From 100 cm to close to 200 cm, TOC is very high, suggesting either lots of organic allochthonous material or greatly increased lacustrine productivity. One usually sees a sharp decrease in TIC when TOC is high (Dean, 1999), however our data does not show this trend. Towards the very top of the core, there is the glacial flour section that was noted above. This section (the top ~30 cm of drive CC:D1) also has a sharp drop in TOC, a very slight increase in MS, and increase in BD, greyscale and Ti, strongly suggesting another, albeit very recent, glacial advance. This may be an indicator of the LIA or Atlantic Cold Reversal, however a stronger age model will be needed to confidently suggest this.

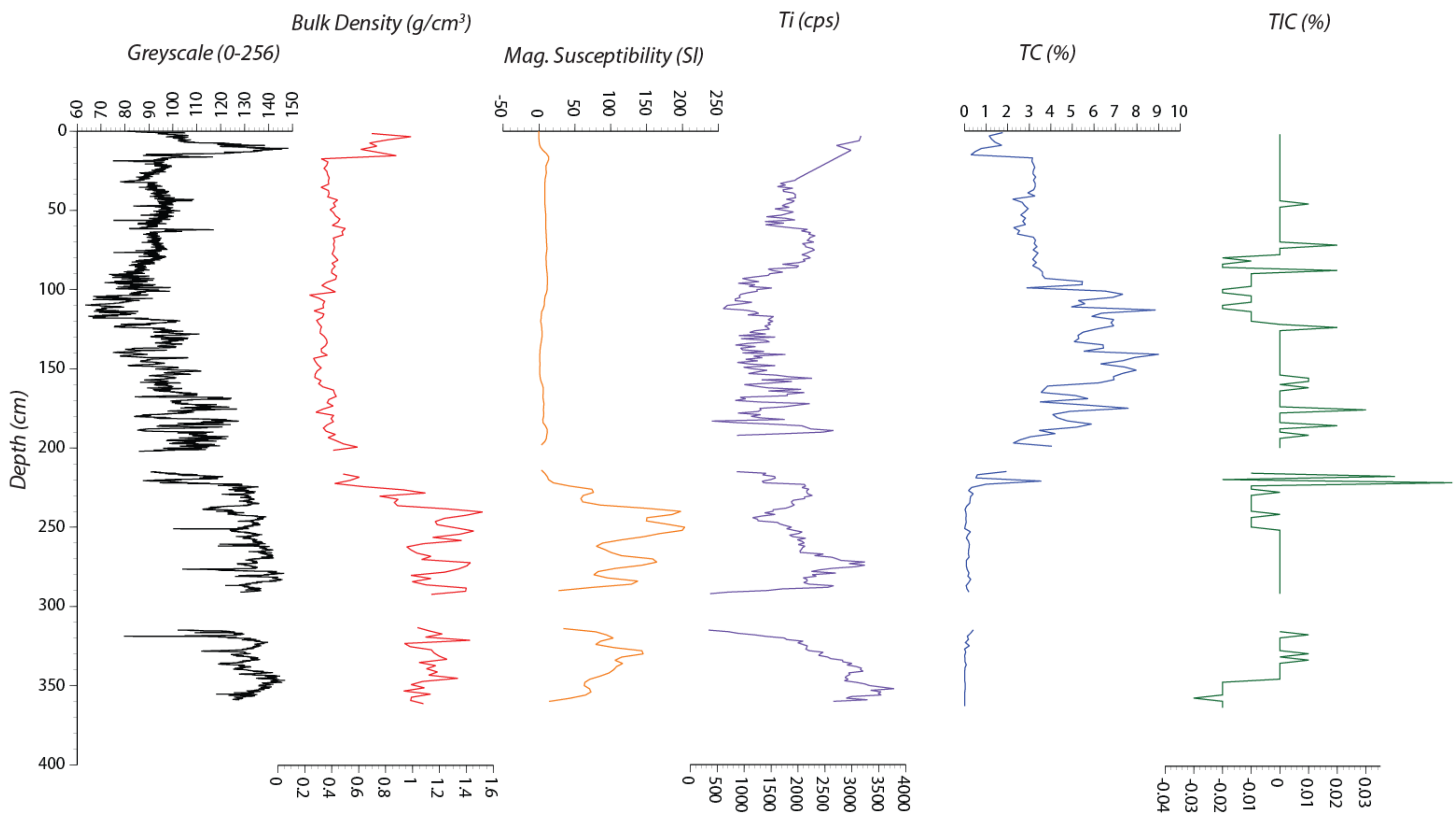

Figure 11 – The major variables recorded in the Jaico Lake Livingstone core, compared with depth.

Additional Work

In addition to the work on Jaico Lake, lab work was also performed on the percussion core from Lake Yanacocha. Firstly, the coulometry data (Figure 9) was completely redone because there was an abnormal amount of inorganic carbon in a lake that has a strictly granitic basin (Rothenberg, 2011). However, the redone samples similarly had the inorganic flux seen during the first run. This led us to attempt to obtain $\delta^{18}O$ isotopic data from the percussion core during the period with the greatest amount of inorganic carbon deposited. The result (Figure 12) shows large decreases in $\delta^{18}O$ at around 7,500 and 5,250 cal yrs BP, which could indicate one of two things: either these periods experienced a cold snap, or the area became very dry.

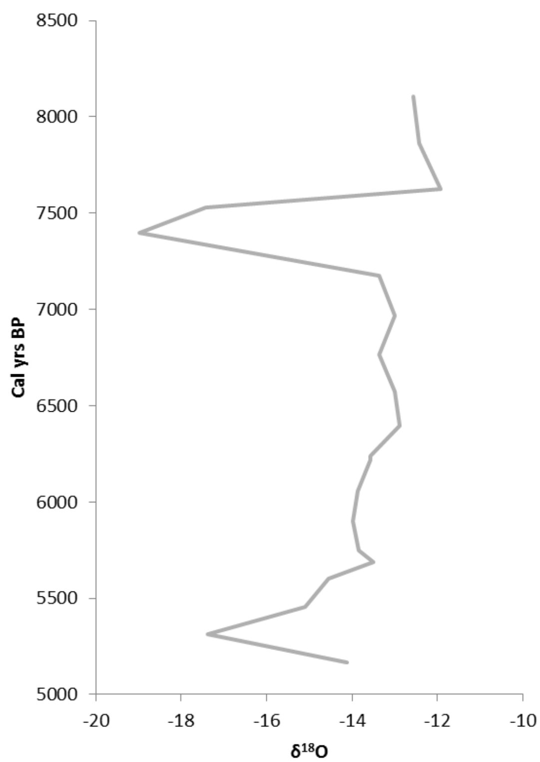

Figure 12 – Oxygen isotope data from ~5,000 to 8,000 cal yrs BP. Significant decreases in isotopic signature occur at around 7,500 and 5,250 cal yrs BP.

Clastic flux was also calculated for the percussion core at Lake Yanacocha (Figure 13). Clastic flux is often considered one of the best variables for sediment core analysis, as it takes into account the important role of sediment rate into the lake. The variable also accounts for TIC, TOC and biogenic silicon, and so truly represents the clastic portion of the material coming into the lake over time.

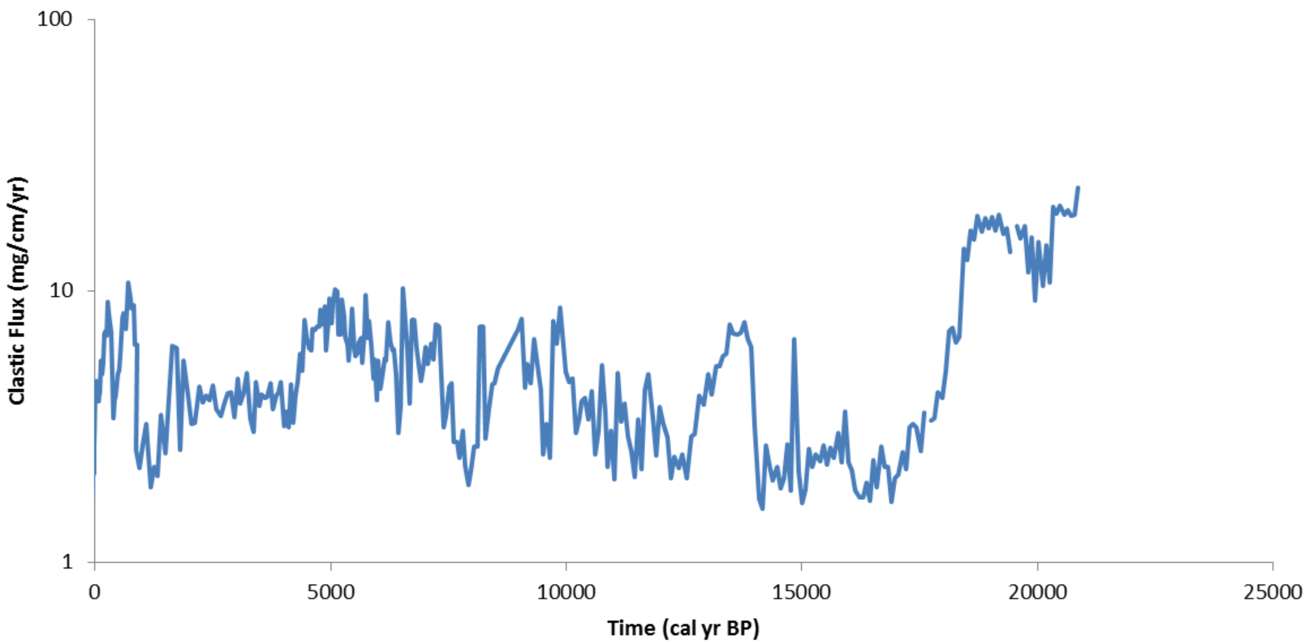

Figure 13 – Clastic flux of the percussion core from Lake Yanacocha compared with time.

Age Models

Radiocarbon dates were obtained for the Yanacocha percussion core, the Yanacocha Livingston core, and the Jaico Livingston core (Figure 14). The radiocarbon dating for both Yanacocha cores was completed by Rothenberg (2011), and due to the consistency of the dates and the high number of dates obtained, both Yanacocha trend line equations were employed for comparisons with the downcore variables of the cores (Figure 7 has the downcore variables compared with ‘Cal yrs BP’ instead of depth). There was irregularity and lack of organic material in the Jaico Livingston core, so only the basal age of 8,264 cal yr BP (221 cm downcore) was considered accurate. Likewise, both bog cores will only be temporally compared using their basal ages: the Yanacocha bog has a basal age of 2,870 cal yr BP at 163 cm downcore, while the Jaico bog has a basal age of 10,258 cal yr BP at 535.5 cm downcore. The moraine ages help to constrain the time domain as well: for Lake Yanacocha the ~14,000 cal yr BP moraine serves as a direct dam for the lake, suggesting that the lake cannot be greater than 14,000 cal yr BP old.

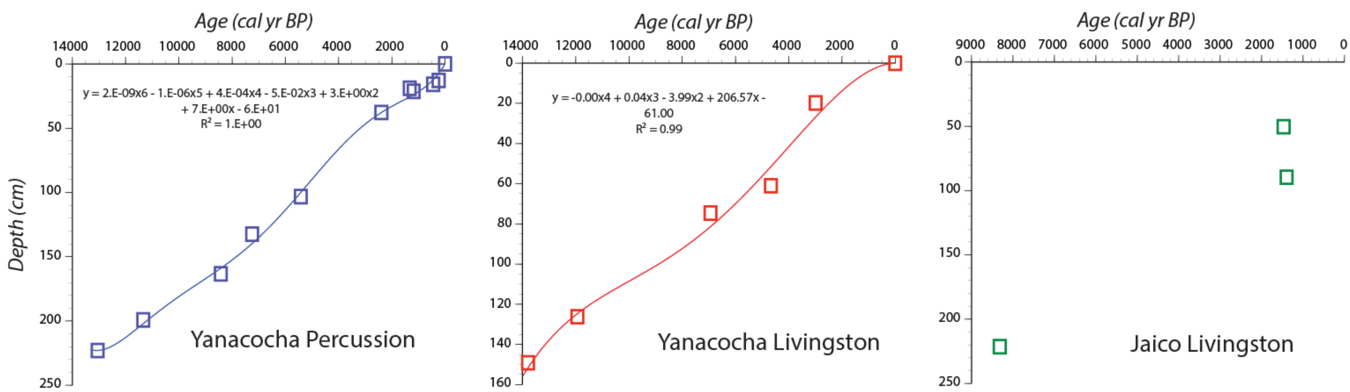

Figure 14 – Age models for the Yanacocha percussion core, the Yanacocha Livingston core, and the Jaico Livingston core. Trend lines were utilized for both Yanacocha cores due to the reliable radiocarbon dates obtained, however no such confidence was found for the Jaico radiocarbon dates.

DISCUSSION

Timeline

The following section will attempt to connect the numerous cores that have been discussed into a succinct timeline listing confident ice advances in the Huaguruncho Massif. The two bogs cores have the least amount of detail and have been deemed the least reliable out of the cores available, so the use of the bog core information will be intermittent at best.

~20,000 cal yr BP Event: Last Glacial Maximum

The only record that is temporally long enough to cover an event occurring nearly 20,000 cal yrs BP is the Yanacocha percussion core (Figure 9). If the age model is correct, than a sharp spike in BD and MS at ~20,000 cal yrs BP, as well as a strong intensification in clastic flux (Figure 13) represents a significant increase in clastic input into Lake Yanacocha, and thus an ice advance. TC also plummets, indicating a decrease in organic productivity.

~14,000 cal yr BP Event: Pre-Younger Dryas

There is a smaller magnitude (compared with the 20,000 cal yr BP event) occurrence at ~14,000 cal yr BP, slightly before the Younger Dryas time period that dominated the Northern Hemisphere (~12,800 – 11,000 cal yr BP). Again, the percussion core is the best record of this event: there is a slight increase in BD, a notable proliferation in clastic flux, a rather large increase in Ti and a significant drop in TC that suggests decreased organic productivity: all signs of an ice advance. Additionally, the Yanacocha Livingston core shows slight increases in MS and BD as well, and perhaps the slightest increase in greyscale (Figure 9).

This event is particularly interesting because it occurs extremely close to the Younger Dryas event. The ~14,000 cal yr BP event recorded here may be a precursor event to the Younger Dryas that was facilitated throughout the Southern Hemisphere. Instead of a cold event, what is more likely is that the Andes experienced a highly wet time period, as is recorded in the Bolivian Altiplano Lakes and the advancing Quellcaya Ice Cap in southeastern Peru (Kelly et al., 2012). This occasion may instead reflect the Antarctic Cold Reversal (ca 14.5 – 12.9), a universally Southern Hemispheric event. Thus, although the Huaguruncho Massif is in the tropics, it was dominated by southern hemispheric events at this time instead of northern hemispheric events, like the Younger Dryas.

~7,500 – 8,000 cal yr BP Event

Across multiple records there is a noteworthy ice advance that occurs around 7,500 to 8,000 cal yr BP (the age discrepancies probably arise from the use of many different age models and radiocarbon ages). The Livingston core from Jaico Lake may record this event the best: at ~8,500 yrs, there is a massive spike in greyscale, MS, BD and a lesser increase in Ti concentration (Figure 11). Additionally, TC plummets, suggesting decreased organic productivity. The incredibly strong signals among nearly all the variables is most likely a result of the ice advance ending directly on the edge of the lake, as is evident in the Neoglacial moraines (Figure 7). These moraines have yet to be dated however, so the correlation cannot yet be made in complete confidence. The Yanacocha Livingston core shows similar increases in greyscale, BD, and MS, however according to its age model, the event occurs closer to 7,000 cal yrs BP. To better constrain the age of the event, the percussion core from Yanacocha records the event (again, using MS, BD and Ti concentration) at a similar age to the Jaico Livingstone core: ~8,500 cal yrs BP. There is also a large decrease in $\delta^{18}O$ recorded in the percussion core at around the same timeframe, again suggesting a colder/wetter setting (Figure 12). The discrepancy with the Yanacocha Livingston core age may be from a lack of samples, or a 'sink-through' event that occurs when dense organic material sinks through the mud to a lower depth, resulting in an anomalous age (Bierman et al., 1997). There also may be a slight signal within the Jaico Bog samples: the basal age of the core is ~10,260 cal yrs BP, and there are increases in greyscale and BD just before the basal age, perhaps correlating with the aforementioned ice advance (Figure 8).

~500 cal yr BP Event: Little Ice Age

The last discernible event from the multitude of cores at hand is one that occurs at around 500 cal yr BP, correlative with the beginning of the LIA in the Northern Hemisphere (IPCC, 2013). The percussion core from Lake Yanacocha, the Jaico Livingston core and the Jaico Bog core all show similar increases in greyscale, BD, MS, and Ti concentration when applicable (Figures 8, 9, 11). Clastic flux from the percussion core also increases dramatically (Figure 13). These notable changes strongly suggest an ice advance event.

Additionally, there are ‘twin-track’ moraines that have been dated to ~300-400 cal yr BP (Figure 7), again suggesting an ice advance.

The Huaguruncho Massif has experienced two northern hemispheric events in the LIA and the Younger Dryas, however unlike the Younger Dryas, the sediment cores and moraine record seem to suggest a strong ice advance during the LIA. This means one of two things: firstly, that the LIA was a more globally-encompassing event than the Younger Dryas. Many have suggested that the LIA was felt globally, but rarely do Southern Hemisphere sediment cores and moraine records occur within the same timeframe as the start of the LIA in the northern hemisphere, which makes the Huaguruncho Massif unique in that it dates well with this same beginning age (~500 cal yr BP). A second interpretation would be that the Peruvian Andes, due to perhaps a combination of different oceanic currents and wind trajectories, has experienced a ‘forcing’ change through time. Where once northern hemispheric events were not felt strongly in the Peruvian Andes (Younger Dryas), they are now more recently being felt in a greater magnitude (LIA). This interpretation suggests a dynamic system in the tropics, where hemispheric forcings can change through time.

Moraine age implications on the lacustrine sediment

There is a conflicting interpretation of the ages of the lakes that can be made if a certain moraine inference involving the Lateglacial moraines (~14,000 cal yrs BP) is thought to be true. If the Lateglacial moraine just north of Lake Yanacocha is considered to be a damming moraine for that lake, than the lake cannot possibly be any older than ~14,000 cal yr BP. This would have severe temporal implications regarding the interpreted timeline of the previous section, especially involving the Last Glacial Maximum, which would in fact not have been chronicled in the lacustrine sediment. Initially it may seem that the rest of the timeline for the percussion and Livingston cores of Lake Yanacocha would be harshly altered, however this is not the case if sediment rate is taken into consideration in that during the retreat of the glacier that formed the Lateglacial moraine, sediment input in the lake would have been monumentally high. Thus, there is a massive spike in sediment rate at the base of the core, and the rest of the timeline is preserved, as can be seen in the two figures of clastic flux/Ti concentration, one with the original age model, and the second with 14,000 cal yr BP as a basal age (Figure 15). The second age model still has spikes during the ~8,000 and ~500 cal yr BP events, although the magnitude might slightly differ.

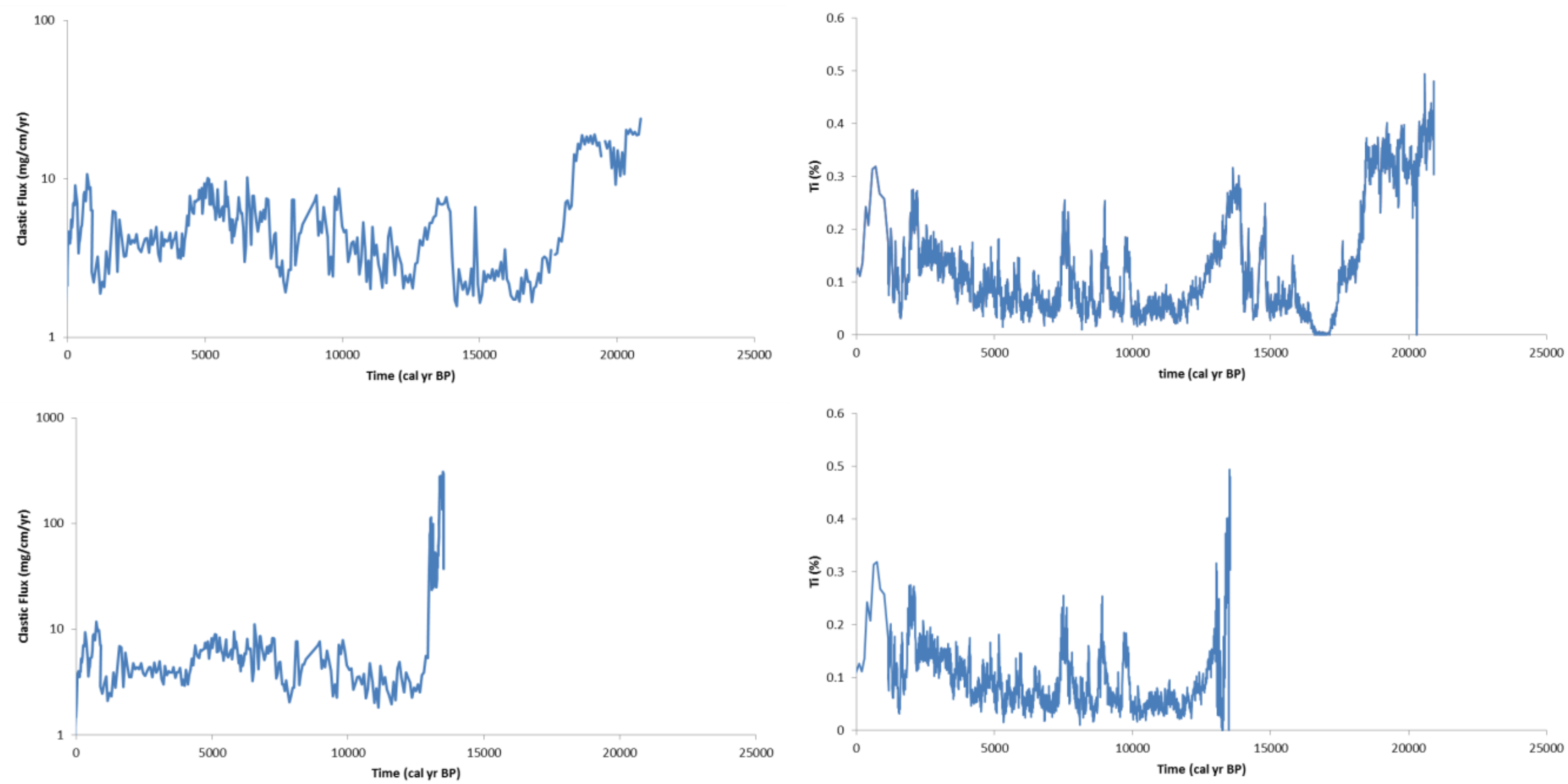

Figure 15 – Graphs of both Ti concentration and clastic flux using two different age models: one using the Lateglacial moraine as a basal age (bottom) and one without (Top).

CONCLUSIONS

In conclusion, the lacustrine cores from both Jaico Lake and Lake Yanacocha have provided a continuous sediment record of upvalley glaciation, and greatly helped in temporally constraining ice advance events through the past in the Huaguruncho Massif. By using multiple variables across the many cores that were obtained, we can confidently conclude ice advances occurred during the LGM (without using the moraine ages), ~14,000, ~7,500-8,000, and ~500 cal yr BP. By utilizing the moraine ages in the cirque as well, an alternative age model can be formed by using the damming Lateglacial moraine as a basal age in Lake Yanacocha, however further geomorphological observations must be made within the Massif to confidently confirm the 'damming' quality of the moraine.

Furthermore, it may be that the tropical Andes have not always marched in lock-step with the northern hemisphere, but instead periods have occurred when the Andes have been more greatly affected by northern hemispheric forcings than during other times. This point is especially driven home by the lack of a definitive Younger Dryas event at ~14,000 cal yrs BP, (instead reflecting the Antarctic Cold Reversal, a primarily southern hemisphere event), and the strong appearance of the LIA, a strong northern hemisphere event. Supplementary effort must be put forth in order to conclusively understand the difference in hemispheric forcings through time, and exactly what drives those differences, albeit wind circulation or ocean currents.

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