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Unique Collections of ^{14}C-Dated Vegetation Reveal Mid-Holocene Fluctuations of the Quelccaya Ice Cap, Peru

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Key Points:

- Mid-Holocene advance of the Quelccaya Ice Cap (QIC) is documented using ^{14}C dating of in situ vegetation exposed during the recent retreat
- Plant ages of ~4.5 to ~7.1 ka BP provide evidence of a mid-Holocene climate transition and the QIC ice-margin expansion
- Analysis of satellite imagery from 1985 to 2020 documents a recent rapid retreat (~20 m/yr) of the QIC margin

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Several studies have analyzed the ice margin behavior of the Quelccaya Ice Cap (QIC), Earth's largest tropical ice cap, through the Holocene. However, continuous integration of new information to produce a more cohesive history of the QIC is necessary. Here, the radiocarbon dates of 33 rooted plant specimens collected in situ along the western ice margin between 2002 and 2018 reveal the timing of its past extent as it advanced during the mid-Holocene. The most recent evaluation of collected specimens indicates that the QIC margin advanced ∼350 m down the Challpacocha Valley between 7.1 and 4.5 ka BP. Past studies of documented ice extent on the western side of the QIC based on a variety of techniques are compiled to create a more comprehensive history of the QIC's behavior throughout the Holocene. Records of documented ice extent, as well as other proxy records, indicate a climate transition ∼5–7 ka BP that created the proper environmental conditions for the expansion of the QIC. Evidence from nearby valleys indicates that the QIC behaved similarly to the documented ice extent in the Challpacocha Valley in response to Holocene climatic fluctuations. The ability to collect the plant specimens and recent analysis of satellite imagery reveals rapid retreat rates of the western outlet glaciers from 1985 to 2020, leaving the western margin of the QIC at its smallest extent since the mid-Holocene.

Plain Language Summary The area around the Quelccaya Ice Cap (QIC) is unique as wetland plant samples have been found preserved in their growth positions, buried by past advancing ice, whereas the ice typically removes vegetation and soil in its advance down a valley. Using the ^{14}C dates of these plants, we map a 350-m advance of the ice margin between 7.1 and 4.5 ka BP. Combined with a variety of previous studies involving different methods and records from ice and lacustrine sediment cores, a larger picture of the QIC's behavior comes into view. A largely accepted global climate shift between ∼7 and 5 ka BP occurred in tandem with the QIC's advance. Although the QIC has fluctuated before, at no time has the western margin receded to the current extent since the mid-Holocene. This is indicated by the exposure of the plants and current margin retreat rates calculated from satellite imagery (1985–2020).

1. Introduction

The high Peruvian Andes contain 70% of Earth's tropical glaciers (Kaser & Osmaston, 2002), which provide a seasonal water resource for consumption, hydroelectric power, and agriculture. Unfortunately, much of the ice in these mountains has been retreating in recent decades (Bradley et al., 2006). Earth's largest tropical ice cap, the Quelccaya Ice Cap (QIC), is located in the southeastern Peruvian Andes (Figure 1). Recent satellite observations indicate a 46% loss in Quelccaya's surface area between 1976 and 2020 (Thompson et al., 2021). The retreating ice has created a need for an improved understanding of the QIC's past behavior to better anticipate its future.

Numerous studies of the QIC detail a variety of methods that have been utilized to investigate the ice cap's past extent. These include radiocarbon dating of organic material found in sediment (Kelly et al., 2012), radiocarbon dating of vegetation remains (Buffen et al., 2009), cosmogenic nuclide surface exposure age dating (^{10}Be) (Kelly et al., 2015; Stroup et al., 2014, 2015), lake sediment records (Rodbell et al., 2008; Stroup et al., 2015), and paleo-glacier reconstruction from moraine mapping (Mark et al., 2002; Mercer & Palacios, 1977). While many studies provide regional paleoclimate records from ice cores, moraines, and lake sediments (Rodbell et al., 2008; Stroup et al., 2015; Thompson, 2000), there are few precisely dated glacial landforms in the tropics (Kelly et al., 2015) which limits the understanding of glacier and ice cap behavior in response to changes in climate.

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The mapping and dating of moraines (Figure 1) has provided valuable but discontinuous records of past glacial fluctuations (Stroup et al., 2015). However, field observations from 1976 to 2020 confirm the 46% decrease in the QIC's surface area over 45 years is largely attributed to increasing air temperature (Thompson et al., 2021; Yarleque et al., 2018). During several expeditions to the QIC from 2002 through 2007, dozens of well-preserved in situ plant specimens were collected along a recently deglaciated ice margin (Buffen et al., 2009) with additional plant specimens subsequently collected through 2018. Radiocarbon dating of these plants, which were exposed by the recent glacier retreat, provides ages of their in situ burial by the advancing ice margin (Anderson et al., 2008; Thompson et al., 2006). While the preservation of in situ plants is extremely rare, their existence provides insight into the likelihood of a time when the QIC was frozen to the bedrock and thus experienced minimal basal sliding and meltwater erosion. In this study, we use the unique radiocarbon-dated plant samples found along the North Lake Lobe on the western margin of the QIC to analyze the ice cap's extent in the mid-Holocene and compare it to other proxy histories from the QIC and the surrounding area. Past studies involving a variety of methods and locations are combined with our data to create a more comprehensive understanding of the QIC's past advances and retreats. Today, the addition of available remotely sensed satellite observations allows us to calculate the rate of its present-day retreat.

2. Study Area

2.1. Geography and Geology

The QIC (13°56′S; 70°50′W) is located in the Cordillera Vilcanota on the northern edge of the Peruvian/Bolivian Altiplano, a large plateau in the central Andes. The average elevation of the Altiplano is ~3,750 m above sea level (m a.s.l.) with an area of ~200,000 km^2. The summit elevation of the highest of the QIC's four domes is 5,670 m a.s.l., and short, steep outlet glaciers descend to elevations as low as 4,950 m a.s.l. on the escarpment of the underlying ignimbrite plateau, an igneous, primarily pumice, pyroclastic flow deposit (Mercer & Palacios, 1977). Landsat-9 satellite imagery from August 2022 indicates that the southern outlet glaciers do not extend below 5,200 m a.s.l. while the terminus of Qori Kalis lies at approximately 5,000 m a.s.l. The low slope of the QIC leaves it vulnerable to changes in the mean elevation of the 0°C isotherm (Thompson et al., 2017). The North Lake, where the plant samples were collected, is at the terminus of the North Lake Lobe of the QIC (Figure 1).

2.2. Regional Climate

The QIC experiences a small range in seasonal temperatures and solar radiation reaching the surface, which varies less than 30% from winter to summer with the maximum insolation occurring a month or two before the rainy season (Garreaud et al., 2003). Seasonal precipitation variations are well defined and mostly occur during the warmer wet season (austral summer) between December and February (Garreaud et al., 2003). This moisture originates in the Atlantic Ocean, and is transported over the Amazon Basin by northeasterly trade winds before it is deposited on the Altiplano (Hurley et al., 2015; Vuille et al., 2000). The Andes experienced an increase in temperature of 0.39°C per decade between 1951 and 1999, which is consistent with global climate trends (Vuille & Bradley, 2000). Recent studies (Bradley et al., 2006; Pepin, 2015; Vuille et al., 2015) document increased warming in the high elevation mountain regions with the high Andes maximum and mean temperatures continuing to increase (Chimborazo, 2022; Toledo et al., 2022).

3. Methods

3.1. Sample Collection

The in situ vegetation samples, which were identified as *Distichia muscoides* (Juncaceae), were collected between 2002 and 2018 from the margin of the North Lake Lobe (Table S1 in Supporting Information S1). *Distichia* is the predominant species among the 10 common wetland plant species in the region. It is a diecious, cushion-forming plant that is adapted to the diurnal freeze-thaw cycles of the Altiplano's climate (Buffen et al., 2009). The plants were collected from their growth positions around the edges of the lakes and within the banks of fine-grained sediment as well as along the ice front (Photo S1 in Supporting Information S1). The plant remains were found only near the lake edge, as *Distichia* is present in bofedale communities, which are peat-forming, high-altitude tropical and subtropic wetlands within the Andes (Gould et al., 2010). The location of the plants indicates that

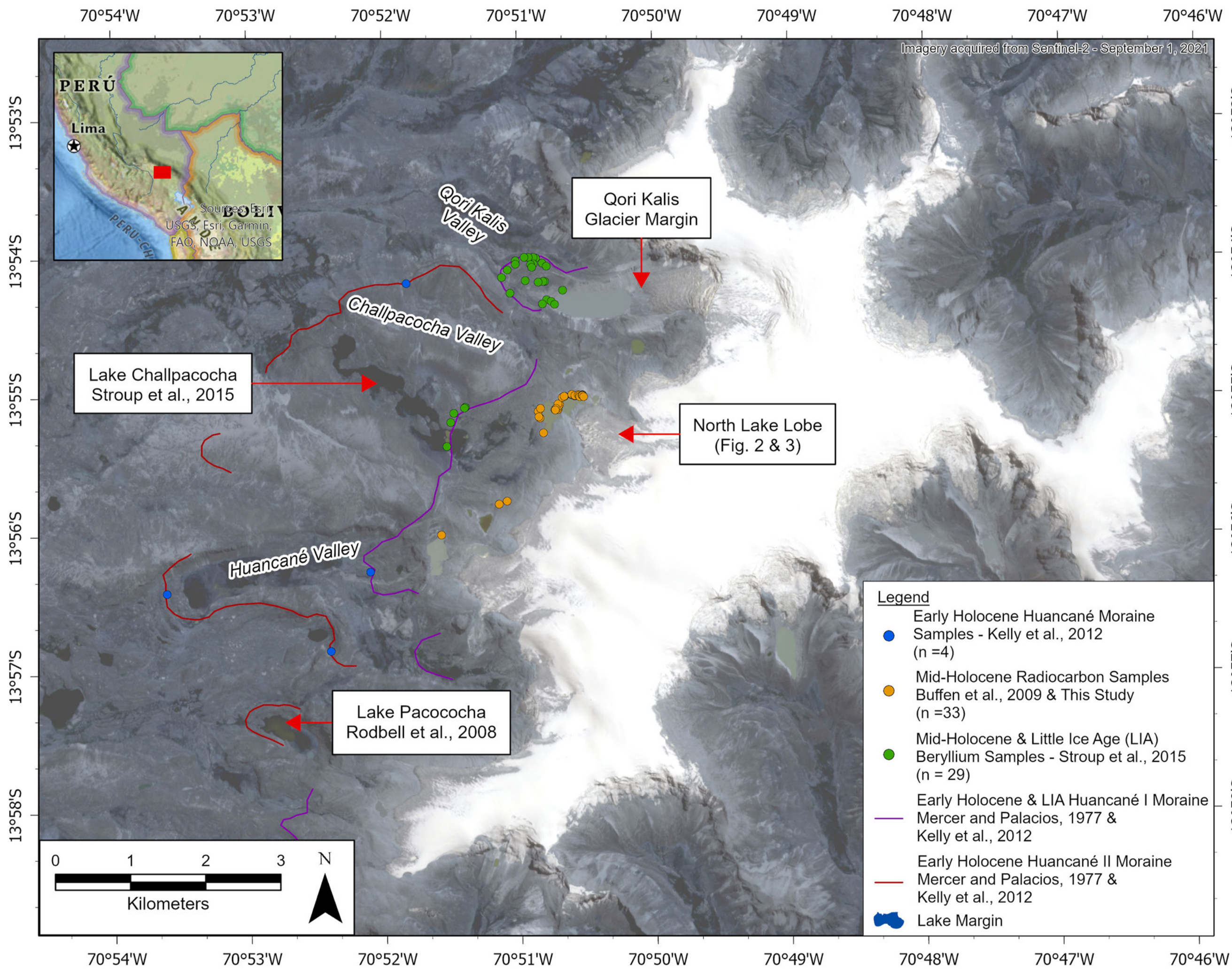

Figure 1. The Quelccaya Ice Cap with all noted sample locations, dated moraines, and analyzed valleys.

a bofedale environment once existed around the lake margin. The collected plant samples were found largely clustered around the northern and northeastern margins of the lake nearest to the retreating ice margin. The ignimbrite bedrock around the North Lake consists of poorly sorted silica-based volcanic ash, which prevents the influx of present-day carbon from soils or peats. No vegetation currently grows in the collection area, and only sparse patches of early colonizing vegetation are present in the immediate vicinity (Gould et al., 2010), confirming the lack of potential influx of present-day carbon. A total of 62 plants were collected over the 16-year period, consisting of 51 surface samples and 11 subsurface samples down to depths of 100 cm. When possible, subsurface samples were collected from layers of sediment deposited in various areas around the lake and their collection depths were measured as the distance below the ground surface. As noted in Buffen et al. (2009), the dominant top layer of sediment is composed of a massive diamict characterized by large subangular and subrounded cobbles supported by a matrix of clay and silt. Location coordinates and elevation for each sample were recorded using Garmin Global Positioning System (GPS) handheld units.

3.2. Radiocarbon Dating

All samples were dated using AMS radiocarbon techniques at the Woods Hole Oceanographic Institution's National Ocean Science Accelerator Mass Spectrometry Facility (NOSAMS) and the Center for Accelerator Mass Spectrometry (CAMS) at the Lawrence Livermore National Laboratory (Buffen et al., 2009). If a sample contained sufficient organic material, it was dated multiple times at one or both facilities. The ^{14}C dates in Buffen

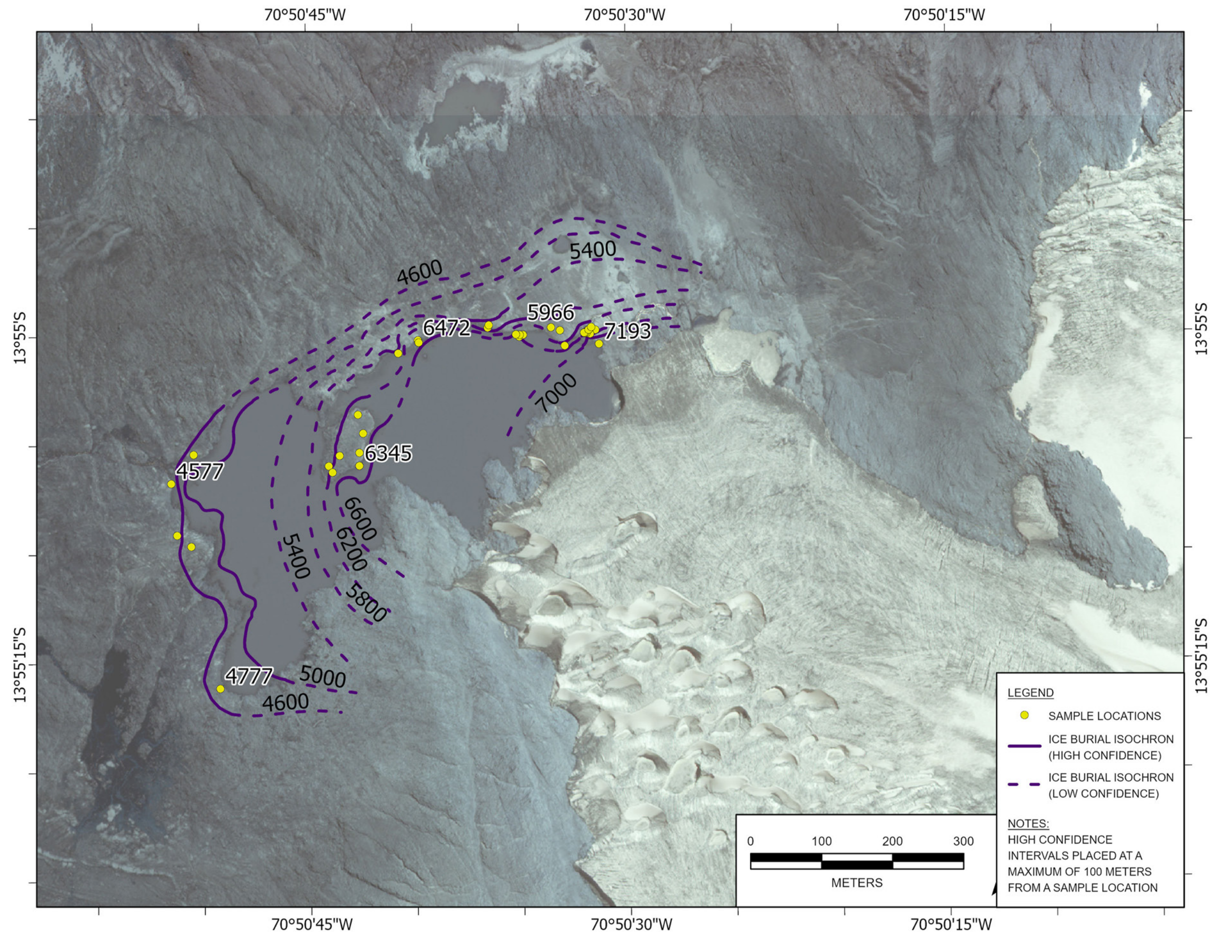

Figure 2. View of the North Lake Lobe, collected plant sample locations, and isochron contours created to approximate ice extent over time as depicted on WorldView-3 (WV03) satellite imagery with 1.24-m multispectral resolution. Isochron contours were extrapolated from the sample points according to Section 3.3.

et al. (2009) were calibrated using the Calib 5.0.1 radiocarbon calibration program with the Southern Hemisphere data set SHCal04 (McCormac et al., 2004; Stuiver & Reimer, 1993) (Table S1 in Supporting Information S1). Composite ages were calculated for samples from the North Lake location using the "C_Combine" function of the OxCal4 "R_Combine" function and were weighted as a single sample for the composite site (Bronk Ramsey, 1995; McCormac et al., 2004). In cases where samples were radiocarbon dated more than once, the mean ages were calculated. Samples collected after 2009 were dated using the same procedures as those collected earlier. For this work, the radiocarbon dates were recalibrated using Calib Rev 8.2.0 with the Southern Hemisphere data set SHCal20 (McCormac et al., 2004).

3.3. Data Analysis

Among the 51 surface samples collected between 2002 and 2018, several groups were collected at the same location, and their mean radiocarbon ages were calculated, yielding 33 sample locations (Figure 2). Spatial interpolations were conducted on the age data points including Natural Neighbor, Kriging, and Spline. These interpolations were not assumed to be accurate due to the low number of data points (33) and the unknown topography of the lakebed around the glacial margin. Instead, they were used as an aid, along with the surrounding topography and notable glacial landforms, to generate ice burial isochrons from the data as a representative of past ice extent. The isochrons were set at intervals of 400 years to encompass all the data points between ~4.5 and ~7.1 ka BP. As the plants were not collected within the lake, interpolations of the ice boundary across the lake surface were necessary. Areas of high and low confidence were noted along each isochron, with high-confidence areas based on the spatial interpolation variances which do not extend more than 100 m from a singular data point

(Figure 2). Although of low confidence, the 7 ka BP isochron is unaligned with the other isochrons due to the flat topography near the current ice-edge. The 11 subsurface samples, the ages of which increase with depth, occurred in a stratigraphic sequence beneath the surface plants. The subsurface samples were buried by other processes at the glacial margin, such as moraine or meltwater movement and thus were not used for interpretation of the ice boundary extent.

Additionally, the North Lake Lobe ice margin was monitored for ice margin retreat rates using the Google Earth Engine Digitization Tool (GEEDiT) (Lea, 2018). The North Lake Lobe was observed via satellite imagery obtained from ASTER, Landsat 5, and Landsat 8 satellites (Table S3 in Supporting Information S1) and the ice margin was delineated every 5 years between 1985 and 2020, a feature of the GEEDiT tool. Due to the irregular shape of the ice margin, retreat rates during the 20th century were determined by drawing 10 transects between the oldest and youngest ice boundary lines to determine the mean value of ice margin movement over time.

4. Results

4.1. North Lake Lobe

Recalibration of the plant ^{14}C ages produced a range of ~4.5 ka BP to ~7.1 ka BP (Table S1 in Supporting Information S1). The recalibration tool provides an integer age for each collected sample (e.g., 5,174 years) although the original data were provided with a margin of error which did not exceed ±40 years. Mean sample ages for groups collected from the same location were calculated as they were within 30 years of each other (Table S2 in Supporting Information S1). All the calculated ages of the remains decrease with distance from the ice margin moving northwest across the lake and down the Challpacocha Valley. Over a period of approximately 2,600 years, the ice advanced ~350 m down the valley to the northwest, and no additional data were found to indicate a larger ice extent (Figure 2). While the plant locations provide evidence for the extent of the ice coverage, the rate of advance is not assumed to be a single continuous process. Instead, the interbedded diamict and stratified sediment stratigraphic sequence described by Buffen et al. (2009) indicates a variably advancing ice margin. During this time the ice margin would have entirely covered the present-day lake. The location of the plants around the lake margin provides an indication of the mid-Holocene behavior of the North Lake Lobe and possibly the QIC as a whole.

Analysis of the North Lake Lobe using the GEEDiT tool shows a retreat rate of ~14 m/yr over a 35-year period between 1985 and 2020 (Figure 3). The 2020 margin was re-traced and edited using WV03 imagery for better resolution. Recent ice margin retreat rates for the Qori Kalis glacier (~28 m/yr) (Figure S1 in Supporting Information S1) and the Huancané Valley glacier (~18 m/yr) (Figure S2 in Supporting Information S1) were calculated using the GEEDiT tool and their retreat rates were similar to that of the North Lake Lobe.

5. Discussion

5.1. Integrating Past Studies

The margins of Quelccaya and its several outlet glaciers have been studied for decades to reconstruct past ice extent, understand the behavior of the ice cap, and determine the dominant drivers of its changing ice extent. To understand the larger picture beyond the North Lake Lobe's behavior and assess surface area changes of the QIC, data from past studies were obtained to augment the North Lake data (all shown in Table S1 of the Supporting Information S1) and improve the overall understanding of the QIC's past ice extent. Figure 4 presents a graphical summary of the movement of the Challpacocha Valley ice margin inferred from the paleo-data points and satellite imagery (Table S1 in Supporting Information S1) relevant to the 1985 position derived from satellite observations.

5.1.1. Challpacocha Valley

The North Lake Lobe descends into the Challpacocha Valley (Figure 1) where the dating of moraines and lacustrine sediment cores were reported in previous studies (Mercer & Palacios, 1977; Stroup et al., 2015). Radiocarbon-dated peat samples from two end moraine belts in the valley (Huancané I and II) have ages ranging from 12.3 to 11.2 ka BP within the Huancané II moraine (located ~4 km from the summit of the QIC) to ~900 yr BP within the Huancané I moraine (located ~1 km from the summit) (Mercer & Palacios, 1977). Recalibration

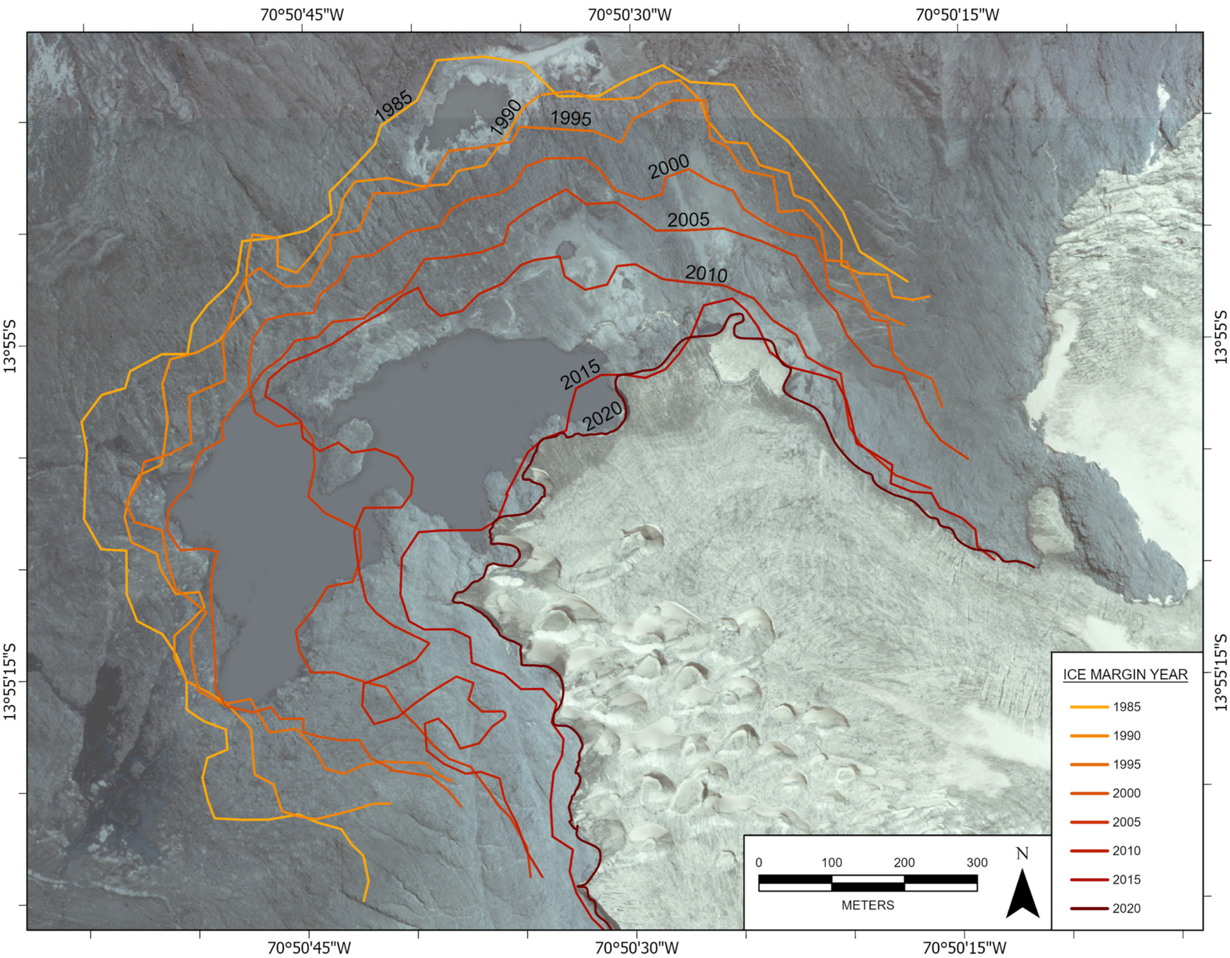

Figure 3. Recent retreat of the North Lake Lobe as outlined using satellite imagery and the GEEDiT Tool (Lea, 2018).

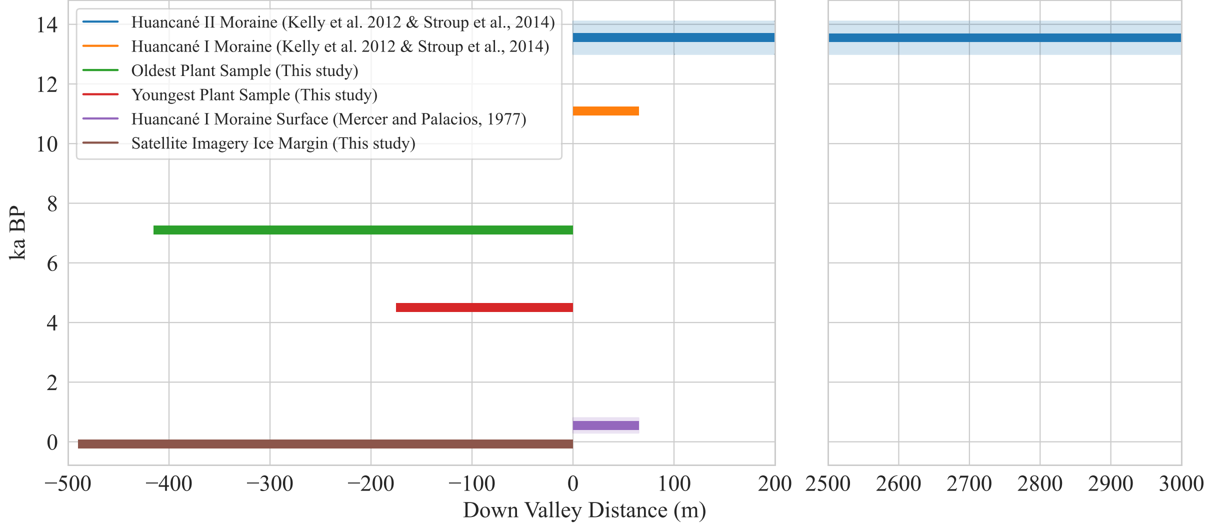

Figure 4. Position of the ice margin in the Challpacocha Valley in relation to the 1985 Satellite Imagery Margin.

of these ^{14}C ages resulted in an age range of 14.1 to 13 ka BP for the Huancané II moraine and 760 yr BP for the Huancané I moraine. The addition of the Mid-Holocene plant sample data provides an indication of a retreat further up the valley than Little Ice Age (LIA) dated Huancané I moraine position. This indicates that a period of retreat must have occurred between the youngest Huancané II moraine (∼13 ka BP) and the oldest plant (∼7 ka BP), leading to the conclusion that the QIC at was least small as it is today. Additional evidence from organic material within moraines in the upper portion of the Challpacocha Valley reveals that the QIC expanded ∼800 yr BP and reached a maximum extent at ∼300 yr BP, which is consistent with ages (270 ± 80 yr BP) from the uppermost portion of Huancané I (Mercer & Palacios, 1977) and with the small increase in clastic sediment flux evident in the Lake Pacococha record (Rodbell et al., 2008). While the dates from the moraines provide limits on the glaciation, they do not provide information about ice margin fluctuations between those limits.

The presence of *D. muscoides* provides evidence that the climate was warmer and drier in this region at ∼6 ka BP and that until recently ice margin retreat had not occurred since the burial of the plants (Figure 4) (Thompson et al., 2006, 2013). The mid-Holocene ^{14}C ages of the plants confirm that this area adjacent to the QIC was not covered by ice at that time and their excellent preservation indicates that the QIC margin expanded beyond the current extent shortly after plant death. The burial of these soft-bodied plants by the ice coincided with the abrupt onset of a wet, cool period that led to the expansion of the QIC. Evidence for the QIC ice advance during the mid-Holocene was deduced by Rodbell et al. (2008) from studies of clastic sediment flux in nearby Lake Pacococha, which receives meltwater directly from the QIC. Clastic sediment flux abruptly increased around 5 ka BP and peaked ∼4 ka BP, after which it declined to present values with a small increase during the Little Ice Age (LIA). The abrupt increase in clastic sediment flux corresponds closely to the burial of the plants by the advancing ice margin ∼5,135 ± 45 cal yr BP.

The unique collection of the *Distichia* plants provides an innovative way to assess glacial margin movement over the course of the mid-Holocene. As radiocarbon dates from moraines typically offer a snapshot of the glacial margin during a point in time, the distance between each moraine cannot be used to draw any conclusions about the intervening nature of the ice movement. Due to both the minimal physical distance and radiocarbon ages between the *Distichia* plants, it becomes possible to track the advance of the glacial margin at the North Lake, filling in the lack of information about the distinct behavior of the glacial margin during the mid-Holocene. The advancing QIC margin that buried plants in their growth positions raises further discussion regarding the basal ice being frozen to the bedrock and thus enabling the preservation of the plants by reducing the flow of meltwater and basal erosion processes. Rodbell et al. (2008) note that tropical glaciers tend to have steep mass balance gradients and are likely to respond to climatic change with little lag time.

Additionally, the recent exposure of the plants coupled with satellite imagery enable the analysis of the present-day retreat at the North Lake as well as multiple locations across the QIC. The North Lake retreat rate from 1985 to 2020 (∼14 m/yr) is compatible with that of the Qori Kalis glacier retreat (∼28 m/yr) and the retreat at the Huancané Valley (∼18 m/yr). A 46% loss of surface area was observed via satellite imagery over the entire QIC between 1976 and 2020 (Thompson et al., 2021). Other studies cite similar evidence for the recent retreat of glaciers across the region such as the Ampay glacier from 1991 to 2017, that experienced an area loss of 48% (Soto Carrión et al., 2022). The total glacial area of the Cordillera Blanca, Peru has declined by more than 30% from 1930 to present-day (Schauwecker et al., 2014) and the Cordillera Huaytapallana, Peru has lost 55% of its glacial surface coverage from 1984 to 2011 (López-Moreno et al., 2014). Similarly in Bolivia, a 30% area loss of glaciers in the Cordillera Real and Tres Cruces is observed from 2000 to 2016 (Seehaus et al., 2020). While discussions of the driving forces for these retreating margins in each respective locations vary, it is clear that the QIC and its outlet glaciers are presently retreating at an accelerated rate, along with many of the glaciers throughout the Andes.

5.1.2. Qori Kalis Glacier

Additional data from studies conducted around the QIC document the extent of other portions of the ice cap beyond the Challpacocha Valley during the mid-Holocene. Beryllium-10 (^{10}Be) ages from moraines around the Qori Kalis Lake (located ∼1 km north of the North Lake) range between 1400 and 1800 CE (150 and 550 yr BP) (Stroup et al., 2014), indicating an ice retreat of 400 m over 400 years. Stroup et al. (2015) compared the clastic sediment flux record using sediment cores and ^{10}Be dating of boulders in the context of QIC behavior in the late Holocene. ^{10}Be ages were not incorporated with the radiocarbon dates because Kelly et al. (2015) indicated that as erosion is assumed to occur on the boulder surface, the ages are influenced by ^{10}Be inherited from prior periods of exposure. It is noted that the Huancané I moraine can be traced almost continuously into the Qori Kalis Valley and is assumed to be apparently old due to prior exposure (Stroup et al., 2015). They are not intended for use as accurate exposure ages, but instead are used to examine the age differences between adjacent and nearby surfaces. However, the CH-2-Unit-2 record contains clastic rich (~95%) sediment, which suggests higher meltwater production and an increase in subglacial erosion, corresponding to the beryllium-indicated QIC retreat from 1490 to 1710 CE (Stroup et al., 2015). The monitoring of Qori Kalis has been discussed in several studies (Brecher & Thompson, 1993; Hanshaw & Bookhagen, 2014; Kelly et al., 2015; Lamantia, 2018; Stroup et al., 2014; Thompson et al., 2006). Qori Kalis has been monitored by aerial photography (Brecher & Thompson, 1993) beginning in 1963, by terrestrial photogrammetry from 1978 to 2004, and by stereo analysis from 2004 to 2017. Between 1963–1978 and 2004–2017, the overall retreat rate increased by an order of magnitude. The increase in the retreat rate between 1978 and 2017 was most likely impacted by the slope of the bedrock or the retreat of the terminus of the glacier from the growing proglacial lake.

The accelerating ice retreat on Qori Kalis is consistent with the retreat of other glaciers in the Cordillera Blanca and is characteristic of most low- and mid-latitude ice fields (Georges, 2004; Schauwecker et al., 2014; Thompson et al., 2006, 2021) and is similar to the shrinkage of the North Lake Lobe and of the QIC as a whole. As of 2020, the ice margin had retreated 200 m east of the lake that is located beyond the terminus of Qori Kalis (Figure S1 in Supporting Information S1). While a slow rate of advance during cooling and rapid retreat rates during warming is expected, as demonstrated by Brook and Buizert (2018), evidence from the North Lake Lobe and surrounding areas indicates accelerated recent retreat rates. While this type of retreat may have occurred during earlier periods of the Holocene, the data are not sufficiently robust to warrant a direct comparison with the recent higher temporal resolution data set.

5.1.3. Huancané Valley

The Huancané Valley, situated approximately 3 km south of the North Lake (Figure 1), has been investigated for indicators of the QIC's past extent. Radiocarbon dating of wetland plants growing up-valley from the Huancané II moraines provides their maximum and minimum limiting ages (Kelly et al., 2012). These results are compatible with ages near the current ice cap margin, which indicate that from ~7 to 5 ka BP the QIC was as small as it is today (Buffen et al., 2009; Thompson et al., 2013). Additionally, the Huancané II moraines outline an almost continuous paleo-ice margin ranging in age from ~12.4 to 11.2 ka BP, providing limiting ages for the extent of the ice margin in the Huancané valley (Kelly et al., 2015). The Huancané II extent was likely short-lived, as indicated by the lower flux of clastic sediment in Lake Pacococha that was dammed by the Huancané II moraines (Rodbell et al., 2008) originally mapped by Mercer and Palacios (1977). The Huancané I moraines indicate the extent of the ice margin further up the Huancané Valley at approximately 300 yr BP (Kelly et al., 2012; Mercer & Palacios, 1977; Stroup et al., 2014). The QIC has been retreating since that time, with marked acceleration within the last 50 years (Kelly et al., 2015). Previous monitoring of the Huancané Valley ice margin between 2000 and 2016 revealed a decrease in surface area that was ~28% greater during 1 year (2015–2016) than the mean annual rate of decrease during the previous 15 years (Thompson et al., 2017). Note that 2015–2016 was one of the strongest El Niño events in the last 100 years. Calculations from satellite imagery of the Huancané Valley from 1985 to 2020 using the GEEDiT Tool (Lea, 2018) indicate a ~18 m/year rate of retreat of the ice margin up the valley similar to its neighboring glaciers.

5.2. QIC Mid-Holocene Ice Advance as Part of a Global Climate Transition

The ages of the *Distichia* plants collected around the North Lake support a large body of evidence for the transition between ~5 and 7 ka BP from a warm Early Holocene to a cooler Late Holocene climate, not only in the central Andes but also on a global scale. Paleoclimate records from the tropics, including the Huascarán, Peru (Thompson et al., 1995) and Kilimanjaro (Thompson et al., 2002) ice core $\delta^{18}O$ time series, changes in Lake Titicaca water levels, water chemistry, and sediments (Baker et al., 2001, 2005), and pollen records from Peruvian and Bolivian lake cores (Abbott et al., 1996; Baker et al., 2009; Rodbell et al., 2022; Urrego et al., 2010; Weng et al., 2006) all suggest a cooling trend that started ~5.5 ka BP. Climate records from other locations in South America such as north central Chile (Tiner et al., 2018) and Columbia (Munoz Uribe, 2012), show that this middle Holocene transition extended beyond the central Andes. Lake sediments from Ecuador also indicate an insolation-linked decrease in the frequency of El Niño Southern Oscillation (ENSO) events (Mark et al., 2022; Moy et al., 2002; Rodbell et al., 1999). Climate records from extratropical locations also show that this cooling event extended beyond the tropical regions. Evidence from peat cores in Patagonia (Huber & Markgraf, 2003), high resolution multi-proxy records from a Korean peninsula (Park et al., 2019), sediment and pollen records from Lake Constance water levels (Magny et al., 2006), North Atlantic marine sediment cores (Bond et al., 2001; Oppo & Cullen, 2003), and speleothems in Israel (Bar-Matthews et al., 1999) suggest cooler and wetter conditions at ~5 ka BP. These collective observations, which include the ages of the QIC plant samples, support the hypothesis of a large and rather abrupt mid-Holocene climatic shift (Figure S3 in Supporting Information S1).

Larger scale climate reconstructions focused on global mean surface temperature (GMST) indicate early Holocene warming (11.3 ka BP) leading to a temperature plateau between 9.5 and 5.5 ka BP and a long-term cooling of 0.7°C from 5.5 to ~0.1 ka BP (Marcott et al., 2013) as well as the peak warm period occurring ~6.5 ka BP followed by a steady cooling of −0.08°C/ky (Kaufman et al., 2020). Both the Marcott and Kaufman reconstructions indicate a period of global cooling, consistent with past paleotemperature/paleoclimate studies, which would create a favorable climate for the down-valley advance of the QIC. Other studies indicate early Holocene warmth between 40°N and 40°S, with models demonstrating steadily rising temperatures due to ice melt and greenhouse gas increases (Bova et al., 2021) followed by a mid-Holocene warming trend with associated cooling in the Northern Hemisphere (30°–90°N) (Liu et al., 2014). Bova et al. (2021) also noted that previous global reconstructions likely indicate that seasonal rather than annual temperature affected the outcome of previous global reconstructions and the discrepancy between proxy records and the model-data could be attributed to either seasonal bias in the sea surface temperature reconstructions or the model bias in regional climate sensitivity (Liu et al., 2014). Most recently, evidence from proxy records and climate model simulations indicates a mild-millennial scale global thermal maximum during the mid-Holocene (~6.5 ka BP) with a decrease in the GMST during the following six millennia prior to industrialization (Kaufman & Broadman, 2023).

6. Conclusions

Since 2002, unique tropical wetland vegetation preserved along the western margin of the QIC has been collected as the ice margin retreated and has been ^{14}C-dated to document the ice cap's fluctuation during the mid-Holocene. Evidence from the North Lake adjacent to the current western ice margin indicates that the entire QIC behaves similarly to the North Lake Lobe in response to climatic fluctuations, with minor variations that depend on the topography of the bedrock and shape of each glacier in its respective valley. However, dating of vegetation in growth positions and other organic materials provides evidence from sites that experienced ice-free conditions along the retreating margins of the ice cap. Advances in the QIC over this time support other paleoclimatic studies which suggest a rapid climate transition during the mid-Holocene on local to global scales. From the extent of North Lake Lobe as well as other QIC outlet glaciers, there are indications that over the last 35 years the western margin of the Quelccaya ice cap has been retreating ~20 m/yr and the extent of the ice cap is now smaller than it has been in over 7,000 years.

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Data Availability Statement

All locations and details of the mapped data are available in Supporting Information S1 along with outlet glaciers GEEiT margin outlines. The GEEiT outlines and ice extent isochrons are available from Lamantia et al. (2023) Zenodo at http://doi.org/10.5281/zenodo.10019398. The software used to monitor the recent retreat was the GEEDiT tool, which can be utilized at (https://code.earthengine.google.com/84ad6c8df0013331b-01ca991257dc73c) (Lea, 2018) and the Holocene ice movement contours and figure creation were completed via the QGIS software, accessed at (https://www.qgis.org/en/site/forusers/download.html). All location data for past integrated studies and this current study are available in Supporting Information S1.

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