Radiocarbon dating of well-preserved, in-place vegetation exposed by the retreating Quelccaya Ice Cap of southeastern Peru constrains the last time the ice cap’s extent was smaller than at present. Seventeen plant samples from two sites along the central western margin collectively date to 4700 and 5100 cal yr BP and strongly indicate that current ice cap retreat is unprecedented over the past ~5 millennia. Seventeen vegetation samples interbedded in a nearby clastic sedimentary sequence suggest ice-free conditions at this site from ~5200 to at least ~7000 cal yr BP, and place minimum constraint on early- to mid-Holocene ice cap extent.
Despite its location on the far western edge of the South American continent, the dominant moisture source for the Altiplano is ultimately the tropical and subtropical Atlantic Ocean (Taljaard, 1972). Moisture is transported by northeasterly trade winds over the Amazon Basin, where much of it is recycled during the wet season, and eventually precipitated over the Andes (Salati et al., 1979; Grootes et al., 1989). Movement of moist air from the nearby Pacific onto the Altiplano is inhibited both laterally, by coastal topography, and vertically, by a strong and persistent temperature inversion (∼800 masl) maintained by cool waters offshore and large-scale subsidence over the southeastern Pacific (Rutllant and Ulriksen, 1979).

Mean annual temperature at the QIC’s 5670 masl summit, based on hourly automated weather station (AWS) measurements from July, 2005 through June, 2007, is −4.2°C (Hardy, D.R., personal communication, 2008). Assuming a constant environmental lapse rate of 6.5°C/km, the summit AWS measurements can be adjusted to approximate temperature along the central western margin of the QIC. This produces a mean dry season (June–August) temperature of −3.3°C, with an average daily minimum and maximum of −6.3 and 0.9°C, respectively, and a mean wet season (November–March) temperature of −0.5°C, with an average daily minimum and maximum of −3.1 and 2.9°C, respectively (Hardy, D.R., personal communication, 2008; Hardy, 2008).

The QIC is particularly well suited to study the effects of climate change as its broad dome of ice rests atop a relatively flat ignimbrite plateau (Mercer and Palacios, 1977). Consequently, a small increase in the mean elevation of the 0° isotherm will affect a greater relative area of the QIC surface than for more steeply inclined alpine glaciers. Retreat of the QIC’s largest outlet glacier, Qori Kalis, has been well documented since 1963 using areal and terrestrial photogrammetric techniques (Thompson et al., 2000, 2006). Qori Kalis has experienced a 10-fold increase in its rate of retreat between 1991 and 2005 (∼60 m/yr) relative to the initial measurement period from 1963 to 1978 (∼6 m/yr; Thompson et al., 2006).

Plant deposits recently exposed at the bedrock surface have been discovered at two sites (Base Camp Lake and North Lake; BCL and NL; ∼5200 m), ∼2 km apart, along the central western margin of the QIC. Additionally, an exposed clastic sedimentary deposit, hereafter the Boulder Lake Sequence (BLS; ∼5100 m), is located ∼1 km southwest of BCL at Boulder Lake (Fig. 1). All three sites are characterized by bedrock depressions along the upper margins of the plateau where small lakes have formed subsequent to recent ice retreat. These lakes are presently bounded by the ice cap on their upslope ends and all discovered plants, as well as the BLS, occupy portions of the ice-free downslope margins (Fig. 2).

Collection and dating methods

To obtain the most recent samples possible, only the upper portions of individual vegetation deposits at BCL and NL were collected for dating purposes. Vegetation sampled from the BLS was
retrieved after removing and discarding the weathered, outermost ∼ 10 cm of material. No macroscopic, modern vegetation was observed growing on any of the sampled surfaces.

Samples were dated using AMS radiocarbon techniques at either the Center for Accelerator Mass Spectrometry (CAMS) at the Lawrence Livermore National Laboratory or the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) of the Woods Hole Oceanographic Institution. If sufficient material was available, samples were dated multiple times at one or both facilities. The $^{14}$C ages were calibrated using the Calib 5.0.1 radiocarbon calibration program with the Southern Hemisphere calibration dataset SHCal04 (Stuiver and Reimer, 1993; McCormac et al., 2004). Composite ages were calculated for suites of surface samples from the BCL and NL sites using the ‘C_Combine’ function of the OxCal4 calibration program (Bronk Ramsey, 1995). When a sample was dated multiple times, a combined age was calculated using the OxCal4 ‘R_Combine’ function and weighted as a single sample in the composite site average (Bronk Ramsey, 1995; McCormac et al., 2004).

Results

Base Camp Lake and North Lake surface samples

All sampled specimens represent exposed surface plants observed to be rooted and in original growth orientation, thus strongly suggesting that their positions have not been altered by glacier advance (Fig. 2c). The specimens were identified as Distichia muscoides (Juncaceae), a dioecious, cushion-forming plant that is well adapted to the diurnal freeze–thaw cycles of the Altiplano climate. The deposits were excellently preserved and retained their overall cushion shape as well as finer detail (see Thompson et al., 2006). The modern-day altitudinal limit of D. muscoides at the QIC, based on our field observations, is ∼5100 masl. In contrast, the recently exposed specimens are found above 5200 masl.

Vegetation exposed by recent glacier retreat provides a useful tool for constraining the timing of glacial inception as well-preserved, in-place, surface deposits are indicative of continuous, protective ice-cover since burial (e.g., Anderson et al. 2008). The composite age ranges ($1\sigma$) of 6 discrete BCL and 11 discrete NL samples are 5101–5146 and 4738–4758 cal yr BP, respectively (Table 1). These ages thus identify when these sites were last free of glacial ice cover.

The Boulder Lake Sequence

The BLS is ∼100 m long and ∼6 m high at its thickest section (Figs. 2, 3 and 4). The basal 20 cm consist of a massive diamict characterized by large, subangular and subrounded cobbles supported by a matrix of fines (clay and silt) and coarser grains. These sediments cannot be strictly identified as a till as it was not possible to discern striations on grains. The diamict is conformably overlain by 85 cm of massive nes and sands interspersed with plant fragments that may represent deposition in a lacustrine environment. It is unknown if this vegetation represents in situ plant growth or fluvially transported material, though eolian transport can likely be discounted given the relatively large size (up to 2 cm) of the fragments.

A thin layer of massive, rounded and subrounded gravel in a matrix of fines and sands interrupts these sediments between 55 and 60 cm above the base of the sequence, possibly representing a subaqueous debris flow. Ice rafting is an unlikely explanation for this layer given
the observed rounding and lack of larger grains. The absence of ice rafted debris in the sections of massive fines suggests that this was not a proglacial lacustrine environment. Root structures are observable in the upper 5–10 cm of these fines.

Immediately above is a ∼1.25-m section of planar cross-stratified sands interbedded with horizontal, discontinuous laminae of sands, fines or vegetation. The consolidated nature of the vegetation in this section—vegetation is not dispersed as discrete fragments, but is instead preserved as laminae—would suggest in situ growth. This section is erosively overlain by ∼1.6 m of planar and trough cross-stratified gravels, likely indicative of deposition in a braided stream environment. Again, vegetation is confined to discontinuous horizontal lenses, possibly representing vegetated bars. Continuing upsection are two ∼1 m massive diamict containing subrounded and subangular boulders supported by a matrix of fines and coarser grains.

The uppermost diamict is the most recently deposited by the QIC. Ice advance at this time seems to have been variable as the two diamicts are separated by 15 cm of planar and trough cross-stratified gravels with discontinuous horizontal lenses of vegetation, again interpreted as deposition in a braided stream environment.

The use of recently exposed surface vegetation to reconstruct glacial chronology is limited as ages of these samples reflect only the most recent glacial inception, not the duration of ice-free conditions. However, a minimum temporal constraint for when the QIC site was not glaciated can be deduced from seventeen discrete plant samples retrieved from the exposure that date roughly between 5200 and 7000 cal yr BP, with some variability within the chronology possibly due to fluvial reworking of material (Table 2). The older limiting age of ∼7000 cal yr BP must be viewed as a minimum date for ice-free conditions as a depositional hiatus between the basal fines and diamict cannot be dismissed. The upper bounding age of 5200 cal yr BP, however, is likely a robust estimate for the most recent glacial inception given its similarity to the composite ages of recently exposed surface vegetation at the BCL and NL sites.

**Discussion**

Although the ages of recently exposed vegetation presented here reflect past changes in ice cap extent at only three sites along the present-day western margin of the QIC, we believe that the glacial history of these sites is likely a good approximation for that of the QIC as a whole. This argument rests on two points: (1) the ice that bounds the BCL, NL and NLS sites is not that of steep, lower elevation outlet glaciers but of the QIC itself, and (2) the QIC is a relatively flat ice cap resting on a broad, flat plateau. Consequently, small changes in the mean elevation of the equilibrium line affect relatively large portions of the ice cap, and our sites are well positioned to reflect a response in the QIC's areal extent.

**The mid-Holocene**

Collectively, the ages of recently exposed BCL, NL and BLS vegetation provide evidence for a less extensive QIC from ∼5000 to at least 7000 cal yr BP. In concert with the increase in the paleo-altitudinal extent of *D. muscoides*, these findings suggest warmer and drier climatic conditions in the Central Andes during the early to mid-Holocene. A wide array of multiproxy paleoclimate data support this conclusion (e.g., Thompson et al., 1995, 2000; Seltzer et al., 1998;
The growth of the QIC ∼5000 yr ago reflects the return of cooler and/or wetter conditions. Independent evidence for QIC advance at this time comes from an abrupt increase in the clastic sediment flux—a proxy for advancing ice—to the nearby Laguna Pacococha, which receives direct meltwater input from the QIC (Rodbell et al., 2008). A reduced flux between ∼5000 and ∼12,000 cal yr BP indicates that the QIC was not advancing during this period, and suggests that the ∼2000-yr period of smaller-than-present ice extent inferred from the BLS vegetation may underestimate the actual duration of these conditions. In the adjacent Cordillera Vilcanota, the earliest Holocene age of moraine-cored peat dates to 5045 cal yr BP, providing additional evidence for regional ice advance at this time (Mark et al., 2002).

That the QIC region appears to have undergone a climatic transition ∼5000 yr ago is notable in light of an accumulating body of evidence, from an extensive geographic distribution of paleoclimate records, for abrupt, interhemispheric climate change ∼5000 to 5500 yr ago (e.g., Magny and Haas, 2004; Thompson et al., 2006; Magny et al., 2006 and references therein). For example, cooler and wetter conditions in eastern equatorial Africa, inferred from the Kilimanjaro ice cores and lake levels in the Ziway-Shala basin, ended abruptly ∼5200 yr ago (Street-Perrott and Perrott, 1990; Gasse, 2001; Thompson et al., 2002). In the eastern Mediterranean region, cooling at ∼5200 yr ago is reflected by a large δ¹⁸O enrichment in the Soreq Cave speleothem record (Bar-Matthews et al., 1999). These events are also roughly synchronous with the drying of the Saharan desert at the end of the African Humid Period ∼5500 yr ago (deMenocal et al., 2000a,b).

Such changes were not confined to the Tropics. North Atlantic marine sediment cores document maximum Holocene reduction in meridional overturning circulation and increased drift ice ∼5000 yr ago (Bond et al., 2001; Oppo et al., 2003). Evidence for an abrupt shift to cooler and wetter conditions in central Europe comes from the rapid rise of Lake Constance in the Swiss Alps at 5320 cal yr BP (Magny et al., 2006) and glacier advance in the Tyrolean Alps which quickly buried, and preserved until recently, the “Tyrolean Iceman” 5050–5300 cal yr BP (Baroni and Orombelli, 1996; Rollo et al., 2000).

![Figure 3. Stratigraphic column of the BLS. Calibrated ¹⁴C 1σ age ranges (cal yr BP) of sampled vegetation are noted (Table 2). Lithofacies codes are modified from Eyles et al. (1983) and Miall (1985).](image-url)
Table 2

<table>
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<th>Sample name</th>
<th>Height above bedrock (m)</th>
<th>Lat. (S)</th>
<th>Long. (W)</th>
<th>Elev. (masl)</th>
<th>$^{14}$C age ± 1σ ($^{14}$C yr BP)</th>
<th>Calibrated 1σ age range (cal yr BP)</th>
<th>Laboratory</th>
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<td>-</td>
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<td>5700±35</td>
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<td>NOSAMS</td>
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</tr>
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<td>-</td>
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Samples noted with * were combined at the laboratory noted prior to analysis in order to attain sufficient material for dating. Calibrated ages are given in years before present (cal yr BP), where the origin on the radiocarbon calibration timescale is placed at 1950 AD. The calibrations were carried out using Calib 5.01 (Stuiver and Reimer, 1993; McCormac et al., 2004).