



Four thousand years of environmental change and human activity in the Cochabamba Basin, Bolivia

Joseph J. Williams^{a,*}, William D. Gosling^a, Angela L. Coe^a, Stephen J. Brooks^b, Pauline Gulliver^c

^a Department of Earth and Environmental Sciences, Centre for Earth, Planetary, Space and Astronomical Research (CEPSAR), The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK

^b Department of Entomology, Natural History Museum, Cromwell Road, London, SW7 5BD, UK

^c NERC Radiocarbon Laboratory, Scottish Enterprise Technology Park, East Kilbride, Glasgow, G75 0QF, UK

ARTICLE INFO

Article history:

Received 26 April 2010

Available online 17 April 2011

Keywords:

Charcoal

El Niño/Southern Oscillation

Fire

Fossil pollen

Holocene

Human impact

Inca

Polylepis

Sporormiella

Tiwanaku

ABSTRACT

The Cochabamba Basin (Bolivia) is on the ancient road network connecting Andean and lowland areas. Little is known about the longevity of this trade route or how people responded to past environmental changes. The eastern end of the Cochabamba valley system constricts at the Vacas Lake District, constraining the road network and providing an ideal location in which to examine past human–environmental interactions. Multi-proxy analysis of sediment from Lake Challacaba has allowed a c. 4000 year environmental history to be reconstructed. Fluctuations in drought tolerant pollen taxa and calcium carbonate indicate two periods of reduced moisture availability (c. 4000–3370 and c. 2190–1020 cal yr BP) compared to adjacent wetter episodes (c. 3370–2190 and c. 1020 cal yr BP–present). The moisture fluctuations broadly correlate to El Niño/Southern Oscillation variations reported elsewhere. High charcoal abundance from c. 4000 to 2000 yr ago indicates continuous use of the ancient road network. A decline in charcoal and an increase in dung fungus (*Sporormiella*) c. 1340–1210 cal yr BP, suggests that cultural changes were a major factor in shaping the modern landscape. Despite undisputable impacts of human populations on the *Polylepis* woodlands today, we see no evidence of woodland clearance in the Challacaba record.

© 2011 University of Washington. Published by Elsevier Inc. All rights reserved.

Introduction

The highly diverse ecosystems of the elevated tropical Andes are vulnerable to change from increasing human occupation of the area and predicted future climate change (Cincotta et al., 2000; Myers et al., 2000; Malcolm et al., 2006). To develop an effective policy to conserve and manage this ecosystem, a robust understanding of the region's natural history is required (Godwin, 1956; Willis and Birks, 2006). Today, uncultivated sections of the high Central Andes are principally grasslands within which are pockets of woodlands dominated by the tree genus *Polylepis* (Rosaceae). Kessler (2002) has implied that the relationship between grassland and woodland ecosystems is strongly influenced by human practices and an intensive land use at high elevations has severely limited *Polylepis* woodland distribution today (Ellenberg, 1958; Fjeldså and Kessler, 1996). However, the nature and degree to which human factors ultimately govern the ecology of this region remains unclear and recent research has highlighted the vulnerability of these Andean woodlands solely to climatic lead changes (Gosling et al., 2009).

The main Cochabamba Basin (eastern Andes, Bolivia; Fig. 1) is, today, a major region for food production. The topography favors

agriculture because it is: i) on an easily accessible trade route between upland and lowland areas and, ii) provides a flat area of land upon fertile Quaternary deposits, that largely experience a temperate seasonal climate.

Limited archeological evidence from the region suggests a long human history around Cochabamba with agricultural practices from at least 3000 yr before the present (cal yr BP) (Hensen, 2002). By the time of the Tiwanaku state (c. 1500–900 cal yr BP), the warm fertile main Cochabamba Valley had become a center for farming, and frontier for trade into the subtropical Mizque Valley (Higueras, 1996; Janusek, 2008).

The collapse of the Tiwanaku state, around 1000–900 cal yr BP, has been linked to a prolonged drought on the Altiplano as indicated by the low water levels of Lake Titicaca (Abbott et al., 1997; Binford et al., 1997) and an elevated dust signal from the nearby Quelccaya (Peru) ice core record (Thompson et al., 1985). Elsewhere in the eastern Central Andes (i.e. Marcacocha), the impacts of human occupation on the landscape, identified from lake sediment records, are correlated to changes in agricultural practices, herbivore domestication and cultural adjustments over the last 4000 yr (Chepstow-Lusty et al., 1998, 2007).

Regardless of whether climatic events were coupled with a social transformation (Janusek, 2008), the transition from Tiwanaku fragmentation and collapse (1000–900 cal yr BP), towards rule by the Inca Empire (c. 650–550 cal yr BP, 1400–1533 AD), is certain to

* Corresponding author. Fax: +44 1908 655151.

E-mail address: JJ.Williams@open.ac.uk (J.J. Williams).

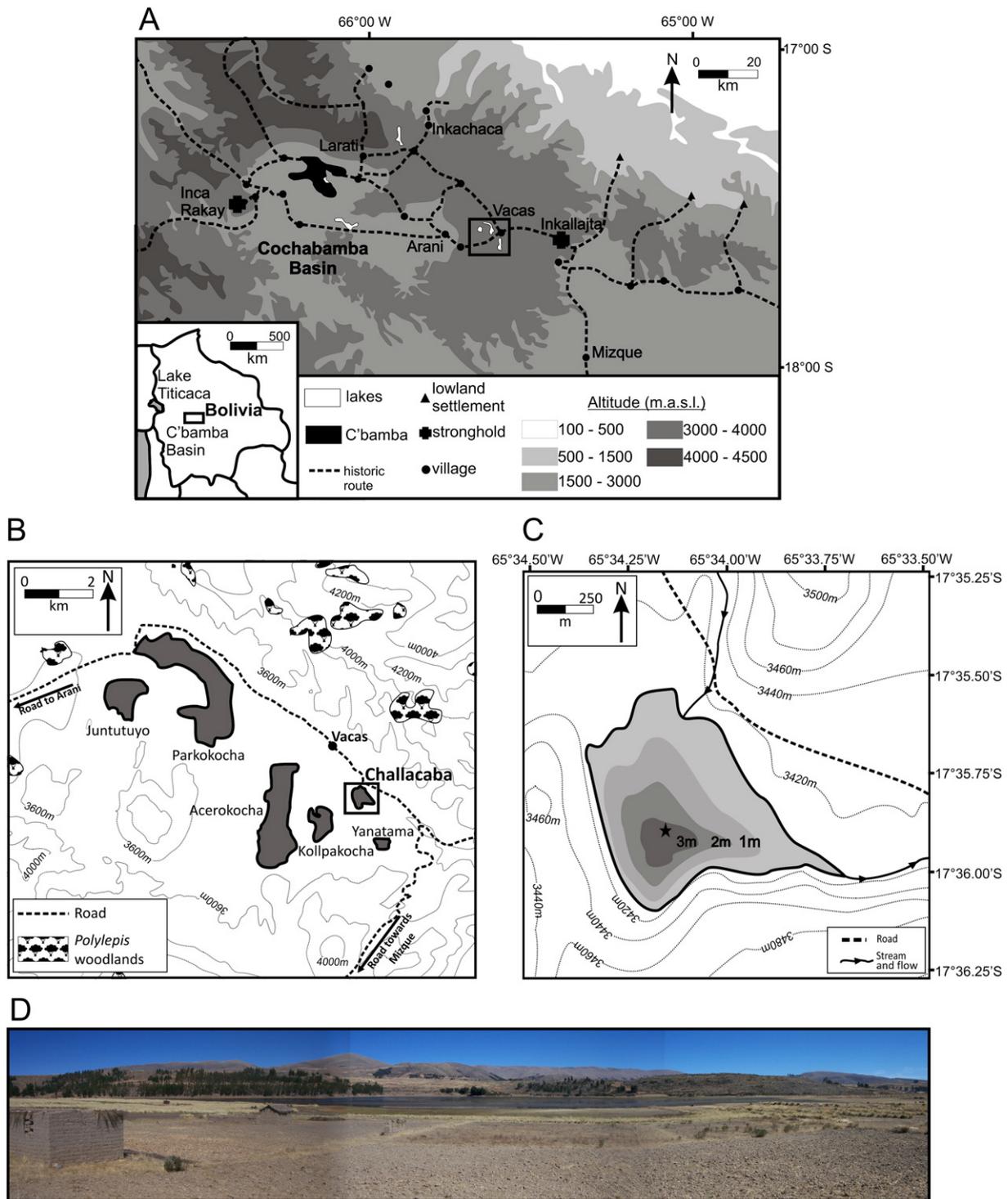


Figure 1. Maps showing study site location within Bolivia. A) Cochabamba Basin with altitudes, current city extent, other settlements and historic routes marked. Modified from Sánchez (2008). Inset map locates Cochabamba Basin within Bolivia. B) Vacas Lake District. The distribution of *Polylepis* woodlands as mapped by Fjeldså and Kessler (1996) is shown. Contour lines at 200 m intervals. C) Lake Challacaba (also known as Pilawitu). Bathymetry shown in meters. Contour lines at 20 m intervals. Coring location marked by star. D) Composite photograph of Lake Challacaba looking south-west. Photographs taken June 2007. W.D.Gosling.

have had major impacts on both societies and the landscapes of the Cochabamba valleys.

In this study, we present a continuous 4000 yr paleolimnological record from the Vacas Lake District in the Cochabamba Basin, using a multi-proxy approach to provide the first submillennial-scale reconstruction of vegetation, fire and cultural change from the Eastern Cordillera of the Bolivian Andes. These data provide new insights into the interaction between climate change, pre-Columbian societies and the environment.

Regional setting

The Vacas Lake District is a system of six lakes located within a cold (7.2–11.3°C), seasonally dry (2.6 mm/month June–August, 114 mm/month January–March), high elevation valley (Ritter, 2000; Hijmans et al., 2005). The district is situated east of the main Cochabamba Basin and north of the Mizque valley (Fig. 1). Located within the inter-Andean/Eastern Cordillera forethrust zone (McQuarrie, 2002), the

local geology is not known in detail, but the surrounding high ground consists of Ordovician quartzite and sandstone, with the Vacas valley, as with the main Cochabamba Basin, sitting on Quaternary sedimentary deposits (Cassard, 1999). Ritter (2000), has speculated that all six lakes within the Vacas municipality were once a single connected system.

Regional climate, predominantly precipitation, is controlled by a variety of systems including the movement of the Intertropical Convergence Zone (ITCZ) (Leduc et al., 2009), and the variability of the South American summer monsoon (SASM; Zhou and Lau, 1998). However, it is the El Niño–Southern Oscillation (ENSO) that is considered to be the largest source of inter-annual variation (Philander, 1990; Chiang, 2009;).

The Vacas Lake District is positioned within the Central Andean Puna ecoregion (Olson et al., 2001), and specifically, within the “northern Puna-semi-humid” and “sub-humid Puna and Punaean woodlands of the Tunari” biogeographic regions (Navarro and Maldonado, 2002; Ibsch et al., 2003). Vegetation types range from grassland, shrubland and woodland (Navarro and Ferreira, 2007). Important genera of these biogeographic regions, include: *Poa*, *Festuca*, *Deyeuxia*, *Muhlenbergia*, *Stipa* (Poaceae), *Gomphrena* (Amaranthaceae), *Baccharis* (Asteraceae), *Polylepis* (Rosaceae), *Peperomia* (Piperaceae), *Astragalus* (Fabaceae) and *Puya* (Bromeliaceae) (Navarro and Maldonado, 2002).

Today, the flatter land surrounding the Vacas lakes is dominated by the cultivation of potatoes and other tubers, and has also been heavily impacted by grazing (Gotkowitz, 2007). Further away from most harshly affected lands, and more typical of the Cordillera of Tiraque-Vacas, the landscape consists of *Polylepis* woodland patches within the Andean grassland. Studies of *Polylepis besseri* woodlands at Sacha Loma (17°44' S, 65°34' W; 3800 m elevation) have provided a detailed inventory of associated species (Fernández, 1997; Fernández et al., 2001). The most local *Polylepis* woodland patches are located c. 5 km away in the mountains to the northeast, and c. 10 km to the southwest (Fig. 1B). Our own observations of a *Polylepis nana* stand by the side of the Arani-Vacas road (17°33.540' S, 65°42.329' W; 3379 m asl), revealed tree heights of 1–1.5 m growing in patches along the edge of a rocky field boundary.

Surveys of the aquatic vegetation at Acerokocha, Juntutuyo, Kollpakocha and Parkokocha lakes (Fig. 1B), highlighted the presence of *Lemna* (Lemnaceae), *Schoenoplectus* (Cyperaceae), *Myriophyllum* (Haloragaceae) and, *Zannichellia* and *Potamogeton* (Potamogetonaceae) (De la Barra, 2003; Molina et al., 2007). The Vacas lakes are regarded as an important source of water and feed (*Myriophyllum quitense*) for cattle which are driven into the lake during the dry season (Ritter, 2000).

Vacas is only c. 15 km away from the well-documented Inca site of Inkallajta. Sánchez (2008) has suggested that the Vacas municipality was significant in regional transport routes (Fig. 1A). Based upon the historical “high road”, the current road passing through the Vacas lakes was once a principle route linking the main Cochabamba Valley and the fuertes (strongholds) of Inca Rakay in the west, to those in the southeast such as Inkallajta and the Tiwanaku archeological site of Mizque (Higuera, 1996) (Fig. 1A). Given the importance of camelid pastoralism and caravans for pre-Columbian peoples (Lynch, 1983) and the movement of Tiwanaku traders between the main valley and the Mizque enclave (Janusek, 2008), it seems likely that many groups of people would have had direct contact with the Vacas lakes.

Following preliminary investigation, Lake Challacaba was selected as the most suitable of the Vacas lakes for coring based upon its apparent permanence, relative freshwater content, suitable depth and accessibility. Our investigation into Parkokocha concluded that only 2 m of sediment would be recoverable from beneath 1.6 to 2 m of water, while Acerokocha proved too deep to core with the equipment available. The only previously published investigation recorded that Juntutuyo dried out for prolonged periods prior to 2300 cal yr BP

(Abbott et al., 2003), despite at present having a maximum depth in excess of 3.5 m (Ritter, 2000).

Study site

Today, Lake Challacaba is a small, c. 1.5 km², freshwater system, 2.5 km from the settlement of Vacas (17°33.257' S, 65°34.024' W; 3400 m elevation; Fig. 1C). Land is worked up to the water's edge with associated small buildings nearer the road (Fig. 1D). Many of the areas of worked land, especially those on the flatter northern shore, are inundated by water during the wetter months. *Myriophyllum* spp. was the dominant component of the aquatic vegetation.

At the time of coring (June 2007) Challacaba had a maximum water depth of 3 m. It is fed at its northernmost point by a stream from the surrounding mountains and drained via an outflow at the southeast end. Water turbidity was defined by measurement of a secchi depth of 0.58 m. A conductivity reading of 332 µS/cm (microSiemens per cm) and a pH reading of 9.45 were recorded using a Hanna 991300 handheld probe. These readings are the average of three taken on 24th June 2007; no longer term data sets are available.

Methods

A sediment core of 2.97 m was extracted from the deepest point in Challacaba during the 2007 dry season using a cam-modified Livingstone piston corer (Fig. 1C). The deepest point was chosen to maximize sediment recovery and reduce the chances of encountering a sediment gap caused by any periods of reduced areal extent of the lake.

Two sediment cores (Challacaba-B and Challacaba-C) were recovered with staggered, overlapping, starting depths below the sediment–water interface (46 cm and 27 cm). The overlap ensured that a continuous record was recovered despite potential loss from some tube ends. Sediment cores were recovered in aluminum tubes (50 mm diameter, 1 m long) and sealed on site. The sediment–water interface and top 60 cm of sediment were recovered using a Perspex surface sampler. The surface sampler was extruded in the field and continuous subsamples of 1 cm thickness bagged. All sediment recovered was transferred to The Open University cold store (4°C). The sediment cores were split and then sediment divided using a fine strand of wire held at tension. Once split, sediments were immediately digitally photographed and described following the Troels-Smith system (Birks and Birks, 1980) and Munsell Soil Color Charts (2000).

A radiocarbon chronological framework was established for Challacaba-B. Three bulk gyttia, two macrofossil plant remains, and one set of picked charcoal/seed case fragments were submitted to the NERC Radiocarbon Facility (Environment) where they were processed to graphite. Samples were digested using an acid–alkali–acid pretreatment (2 M HCl, 80°C, 2 h; 1 M KOH 80°C, 2 h; 1 M HCl 80°C, 2 h) then rinsed free of acid, dried and homogenized. The total carbon in a known weight of the pre-treated sample was recovered as CO₂ by heating with CuO in a sealed quartz tube. The gas was converted to graphite by Fe/Zn reduction. Sample graphites were analyzed using Accelerator Mass Spectrometry (AMS) at the SUERC AMS Facility, East Kilbride. All samples were pre-treated and prepared to CO₂ in the same way but SUERC-32100 contained <500 µgC and required AMS analysis at low current.

All radiocarbon dates were calibrated using CALIB 6.0.1 and the SHCal04 Southern Hemisphere data set (Stuiver and Reimer, 1993; McCormac et al., 2004; Stuiver and Reimer, 2010). Top sediments were assumed to be of modern age (0 yr before present). Radiocarbon samples SUERC-22351, 21929 and 21930 were used to create the age model using the mean value of the largest probability at 2 sigma. Linear interpolations were used between dates and to extrapolate

for the basal sediments. The chronology for Challacaba-C core was established by matching sediment units to Challacaba-B.

For physical and chemical analysis, samples were taken every 5 cm, dried for 7 days at 30°C and ground with an agate mortar and pestle. The magnetic susceptibility of each sample was measured using a Bartington Dual Frequency Sensor (MS2B), corrected for mass differences. Color properties were analyzed using a Canon LiDe flatbed scanner and the software ImageJ (Rasband, 1997–2009). Separate readings for red (R), green (G) and blue (B) color intensities were recorded but after analysis, all three showed similar variance so a mean red, green and blue (RGB) value is used in this work. The abundance of total organic carbon (TOC) and calcium carbonate (CaCO₃) was determined using a LECO CNS-2000 elemental analyzer.

Cores were subsampled (1 cm³) for pollen and fungal spore analysis and, after spiking with microspheres to allow for concentration calculation, chemical preparation followed standard palynological protocol (Faegri and Iversen, 1989). Samples were mounted in glycerol and pollen was identified using a Nikon Eclipse 50i microscope at ×400 and ×1000 magnification. A minimum of 300 fossil terrestrial pollen grains were analyzed in each sample or, where concentration was extremely low, counting was continued until 3000 microspheres had been recorded, i.e. sample concentrations were confirmed to be below 5500 pollen grains/cm³ (barren). Percentage values for aquatic taxa (Lemnaceae cf. *Lemna*, Cyperaceae, *Isoetes*, *Myriophyllum*, *Typha*), the spore group and the green algal genus *Pediastrum* were calculated relative to the pollen sum and their own abundance. Pollen grains and spores were identified using The Open University pollen reference collection, the Neotropical Pollen Database (Bush and Weng, 2006) and other pollen keys (Hooghiemstra, 1984; Roubik and Moreno, 1991). All pollen and spore types recorded were described and digitally photographed for reference purposes.

Charcoal analysis was conducted at the same sampling resolution as pollen. Subsamples of 1 cm³ were deflocculated with 10% KOH for 24 h before being sieved and separated into two size fractions (>180 μm and 100–179 μm). Samples were then suspended in water on a gridded petri dish and counted using a binocular microscope (Olympus SZX12) at ×12.5 to 25 magnifications. A distinction was made between wood and herbaceous fragments based upon appearance.

All data sets were entered as EXCEL spreadsheet files with necessary conversions accomplished using WinTran V1.4 and diagrams plotted using the program C2 (Juggins, 2002, 2003). Pollen zones were determined by optimal sum of squares partitioning (Birks and Gordon, 1985) performed using the software ZONE v. 1.2 (Lotter and Juggins, 1991). Assessment of zonal significance was subsequently completed using the broken-stick model (Bennett, 1996; Birks, 1998) in the software BSTICK v. 1.0 (Line and Birks, 1996). Non-metric multidimensional scaling (NMDS) was performed in PC-ORD v5.0 (McCune and Mefford, 2006).

Results

Chronology

The age–depth model is based on three radiocarbon dates of plant macrofossils or bulk sediment samples (Table 1, Fig. 2). Two bulk sediment and one charcoal/seed case date were not incorporated into the age–depth model based upon the preference for macrofossil dates (leaf/stem) located at the same, or similar, depths. It is likely that a hard-water error and/or mineral carbon error is the cause of the consistently older bulk sediment dates. Mineral carbon error may be further increased due to in-wash of soils from either anthropogenically induced soil erosion or increased precipitation (Oldfield, 1978; Grimm et al., 2009). In addition, the alkalinity of water samples from Challacaba suggests it is rich in bicarbonate ions (Björck and Wohlfarth, 2001). Despite neither macrofossil being formally identified, the leaf remains were almost certainly of a non-submerged

Table 1
Radiocarbon dates and calibrated ages for Challacaba-B core.

Lab. code	Depth (cm)	Description	¹⁴ C yr BP ± 1σ	Cal. range (cal yr BP)
SUERC-22351	91	Bulk sediment	982 ± 37	770–925
SUERC-21929	197	Leaf macrofossil	2333 ± 37	2155–2352
SUERC-22352	197	Bulk sediment	2612 ± 35	2490–2757 ^a
SUERC-32100	265	Micro-charcoal and seed cases	3640 ± 92	3639–4148 ^a
SUERC-21930	284	Stem macrofossil	3611 ± 36	3716–3971
SUERC-22355	284	Bulk sediment	4471 ± 36	4864–5276 ^a

Calibration determined using CALIB 6.01 and SHCal04 data set (McCormac et al., 2004; Stuiver and Reimer, 1993, 2010).

^a Rejected ages.

origin. Stem remains are likely to be from an emergent or submerged aquatic plant. The most modern bulk gyttia date (770–925 cal yr BP), whilst also possibly older than indicated by the bulk data, is accepted here as no other material for dating was available. It is also likely that any difference between a bulk and macrofossil date at this age would be insignificant and probably within the age uncertainty already established. The large age range of the charcoal/seed cases date, due to the small sample size, allows the date to potentially fit a spectrum of age–depth curves. The age range for the calibrated date does not overlap with our age/depth model. We hypothesize that this offset could be caused by the age of the original wood material prior to burning, at Sacha Loma *Polylepis* individuals live in excess of 60 yr (Gareca et al., 2010), and/or the retention of the charcoal in the catchment prior to incorporation into the lake sediments.

Sediments

The 2.97 m core was divided into five sedimentary units (Fig. 3). The lowest, unit 1, comprises greenish-gray sandy clay (297–290 cm, c. 4070–3940 cal yr BP). This is overlain by, unit 2, (290–230 cm, c. 3940–2800 cal yr BP), which comprises darker-colored gytias, with a lower sand content than unit 1 and irregular brownish bands, 1–3 cm thick, with gradational boundaries. The 3rd unit (230–210 cm, c. 2800–2420 cal yr BP) comprises alternating dark and pale colored bands and it has a sharp base and top. Unit 4 comprises mottled sediments progressing from black to gray in color and ending in a moderately sharp boundary at 197 cm (c. 2190 cal yr BP). From 197 cm, up to and including the bagged surface–water interface, the 5th unit comprises sediments which gradually become paler to a medium-gray and contain progressively higher quantities of clays. At 83 to 81 cm (c. 750–770 cal yr BP) there is a horizon comprising mainly microscopic organic fragments.

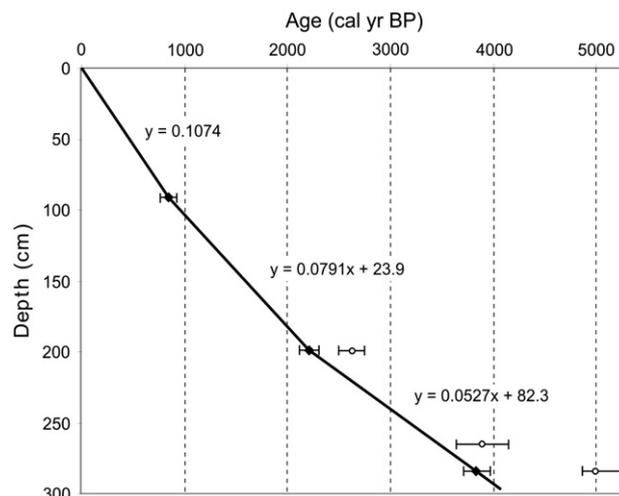


Figure 2. Age–depth curve of sediment cores raised from Challacaba. Rejected ¹⁴C dates shown by open circles. Details of ¹⁴C dates given in Table 1.

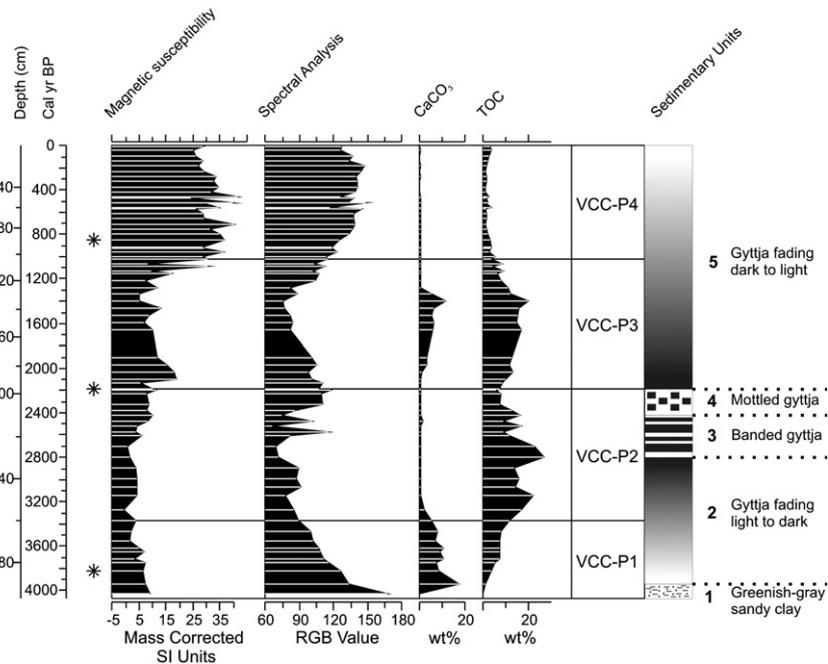


Figure 3. Physical, chemical properties and lithology of Challacaba sediment cores. White lines represent sample points. ^{14}C ages shown (*). (wt% = weight percent. RGB = mean value of red, green and blue color intensities).

Inspection of the sediments indicates no significant breaks in deposition since the inception of the lake, c. 4000 cal yr BP. Assuming there are no hiatuses, sediment accumulation rates gradually increase (Fig. 2) from c. 0.05 cm/yr (c. 4070–2210 cal yr BP), to c. 0.07 cm/yr (c. 2210–850 cal yr BP) to c. 0.11 cm/yr (c. 850 cal yr BP–present). Physical and chemical analyses is sub 100 yr and pollen and charcoal sub 200 yr resolution.

Physical and chemical properties

Magnetic susceptibility (MS) and RGB color values (Fig. 3) show similar overall trends. The RGB values shows an overall decrease from the base of the core to 225 cm (c. 2700 cal yr BP). Superimposed on this are small-scale variations, with one that is particularly well-marked in both the MS and RGB values between 248 and 230 cm (c. 3140–2800 cal yr BP). From 225 to 190 cm (c. 2700–2100 cal yr BP), both data sets show a higher frequency fluctuation and a generally increasing trend. There is a sharp increase in MS values between 193 and 190 cm (c. 2140–2100 cal yr BP). After reaching their highest values in this interval, both MS and RGB show generally decreasing trends up to 135 cm (c. 1400 cal yr BP) where values are similar to those recorded at 225 cm. From 125 cm (c. 1280 cal yr BP) there is an overall increase to the highest MS values (41 SI units) seen in the entire core and the highest RGB values (148) since the base of the core. Both MS and RGB values show high-frequency and high-amplitude variations in parts of this interval. There is a slight decline occurring from 22 cm (c. 200 cal yr BP) into the modern-day sediment readings.

Two intervals of high CaCO_3 values are evident (Fig. 3). These span 290–248 cm (c. 3940–3140 cal yr BP) and 185–125 cm (c. 2040–1280 cal yr BP), and have maximum values of 17.2 and 11.6 wt% respectively. The remaining sediments have fairly constant low values (0.1–0.5 wt%) with the exception of a single reading of 1.4 wt% at 213 cm (c. 2480 cal yr BP). TOC values increase from the base of the core to 278 cm (c. 3710 cal yr BP) where relatively high values (>5 wt%) persist until 103 cm (c. 1000 cal yr BP). This interval of high TOC values is marked with three maxima at 248, 230 and 135 cm (22, 27 and 21 wt% respectively). From 103 cm to the core top, lower values of <5 wt%, are recorded (Fig. 3).

Pollen, spore and charcoal zone description

Pollen assemblage zonation was completed using the pollen taxa included in the pollen sum, i.e. all terrestrial pollen and excluding aquatics, spores and charcoal values. The genus *Ludwigia* (Onagraceae) was included in the pollen sum and other statistical analysis because it: i) comprises both terrestrial as well as aquatic species (Wagner, 2007), ii) is associated with lake margin habitats (Marchant et al., 2002), and iii) can be a weed in cultivated fields (Wagner, 2007). Broken stick modeling assessment concluded that four Vacas Challacaba pollen (VCC-P) zones were significant; VCC-P1, VCC-P2, VCC-P3 and VCC-P4 (Fig. 4). Percentages are calculated from the pollen sum, except for aquatics and spores which are of the pollen sum plus their respective group. Charcoal is shown as particulates per cm^3 (counts/ cm^3) (Fig. 4B). In total, 88 different pollen types were identified from 38 families. 37 unknown spore/pollen types were also recorded.

VCC-P1. 297–260 cm (c. 4070–3370 cal yr BP). 4 samples

Except for the basal sample (295 cm), which contained only a few spores and damaged grains, fossil pollen concentration is high (c. 370,000–480,000 pollen grains/ cm^3) (Fig. 4A). The major constituents of the pollen assemblage throughout this zone are Poaceae (20–30%), Caryophyllaceae (5–10%) and, except one sample, Chenopodiaceae/Amaranthaceae (20–30%). Asteraceae, Moraceae/Urticaceae, Bromeliaceae and *Acalypha* increase towards the upper part of this zone. *Polylepis/Acaena* pollen is recorded in this zone and throughout the sedimentary sequence at low levels (<7%). *Myriophyllum* (30–60%) and Cyperaceae (<2%) are the only recorded aquatics. There is also one occurrence of the green algal genus *Pediastrum* (Fig. 4B). Large (>180 μm) herbaceous charcoal is absent while the other fractions all show increasing trends (Fig. 4B).

VCC-P2. 260–197.5 cm (c. 3370–2190 cal yr BP). 8 samples

This interval is characterized by substantially reduced fossil pollen concentrations (c. 8000–180,000) and higher percentage values of Poaceae (40–50%), Moraceae/Urticaceae and *Acalypha* (both 5–15%), although their concentration values remain constant or decrease.

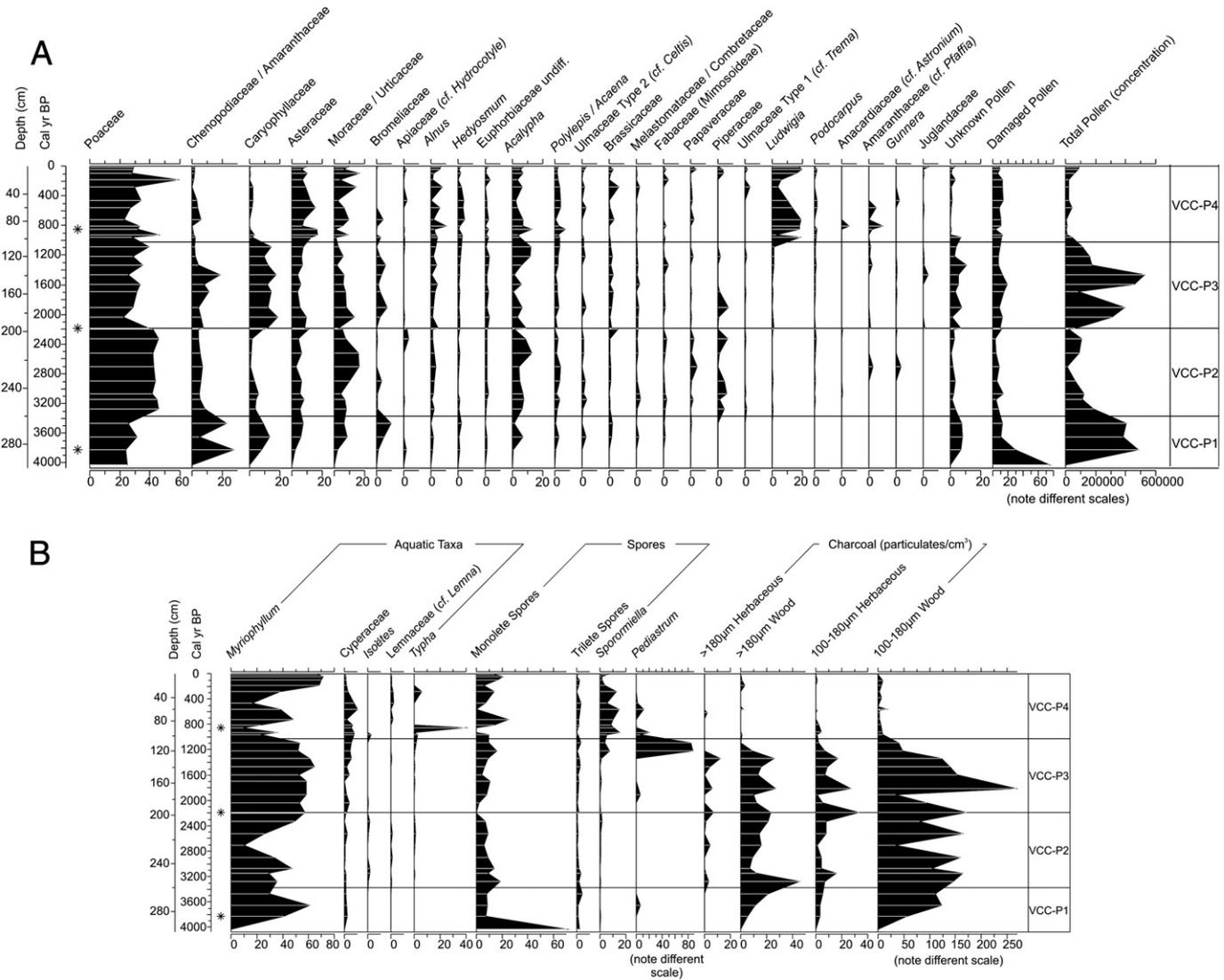


Figure 4. Pollen, spore, algal and charcoal diagrams for Challacaba. White lines represent sample points. ¹⁴C ages shown (*). A) Percentage diagram of pollen sum taxa and total pollen concentration. B) Percentage diagram of aquatic taxa, spores and algae. Carbon particulates shown in counts per cm³.

There are first occurrences of Piperaceae and Papaveraceae, and values of Cheno/Ams and Caryophyllaceae decrease to <9%. The aquatics *Isoetes*, Lemnaceae and *Typha* are recorded for the first time, and both the percentage composition and concentration of *Myriophyllum* decrease. Large (>180 µm) herbaceous charcoal is recorded, and whilst rapid fluctuations are shown in the smaller wood fraction (100–180 µm), counts per cm³ remain relatively high (>40) (Fig. 4B).

VCC-P3. 197.5–105 cm (c. 2190–1020 cal yr BP). 9 samples

This zone has high total fossil pollen concentrations (c. 62,000–530,000 pollen grains/cm³) and the percentages of the majority of taxa are similar to zone VCC-P1. The most striking exception to this is the continued presence of Piperaceae, Papaveraceae and cf. *Pfaffia*. In addition *Polylepsis/Acaena* is present and Juglandaceae pollen is first recorded. From c. 1470 cal yr BP a slight decline in Caryophyllaceae and an increase in *Acalypha* are shown. *Myriophyllum* and Cyperaceae again dominate the aquatic assemblage and from c. 1210 cal yr BP a maxima (80%) in *Pediastrum* occurs. This is accompanied by the first significant amount of spores of the dung fungus *Sporormiella* (Fig. 4B). Charcoal particle levels are similar to the two previous zones but all

size fractions show a well defined and large magnitude decrease trend by c. 1340 cal yr BP.

VCC-P4. 105–0 cm (c. 1020–0 cal yr BP). 12 samples

Characterized by the appearance and significant percentage of the wetland associated genus *Ludwigia*, this zone represents the period of lowest fossil pollen concentration (c. 4000–90,000 pollen grains/cm³). Caryophyllaceae percentages are substantially reduced (<3%), and *Alnus*, *Hedyosmum*, cf. *Pfaffia*, Brassicaceae and Asteraceae reach previously unattained high levels. Whilst Cheno/Ams percentages are reduced a slight increase (3–6%) is recorded between 77 and 50 cm. *Polylepsis/Acaena* reaches its highest percentage in this zone, up to 3–6%, but show large fluctuation. As in zone VCC-P3, *Myriophyllum* percentage is generally low until 20 cm (c. 190 cal yr BP). Lemnaceae (0–2%) and *Typha* (0–40%) abundances fluctuate throughout VCC-P4, while Cyperaceae maintains the high levels from the previous zone (VCC-P3) before showing a decreasing trend from c. 560 cal yr BP till the modern day. *Sporormiella* is present throughout this zone but does show a decreasing trend from c. 190 cal yr BP. *Pediastrum* is present at mid to low values in 5 sample depths. A large-scale reduction of all charcoal fractions is evidenced throughout this zone (Fig. 4B).

Ordination

NMDS ordination was run to explore trends within the variability of the pollen sum data. NMDS was preferred as it makes no assumption as to the distribution of the variables (McCune and Mefford, 2006). The ordination was run using the pollen sum taxa with rare types (<3% abundance) removed. A three-dimensional solution was then chosen with distance relationships established using Sorensen's index (Bray–Curtis). Final stress levels stabilized at 9.06% after 109 iterations. After examination of the output data, axis 1 and 2 scores are plotted against time (Fig. 5B). The biggest changes occur during the transitions from VCC-P2 to P1 and VCC-P4 to P3. The ordination plot (Fig. 5A) demonstrates how samples from different zones plot in distinctly different spaces. The most unique sample relates to the very base of the core (295 cm) which has high values in both axis one and two. The rate of change (Fig. 5B) is calculated as the Euclidean distance between two adjacent samples, divided by the time between them (see Urrego et al., 2009). While this ordination can provide us with a rudimentary rate of change (RoC), a more robust chronology would be required to refine this sufficiently and make it comparable to other studies.

Environmental reconstruction and discussion

Late Holocene climatic changes: moisture balance fluctuations

The Challacaba Lake formed at c. 4070 cal yr BP as shown by the deposition of lake sediments on top of what is interpreted to have been windblown deposits. The very basal sample (295 cm) attests to this period of lake formation as pollen grain concentration is low and preservation poor. Spores, which are more robust to the affects of oxidation, dominate (Fig. 4B). The basal sample at 295 cm, plots in a unique space on the NMDS ordination (Fig. 5A), indicating its general dissimilarity to all other samples.

The relatively higher quantity of sand present in the sediment from 297 to 290 cm (c. 4070–3940 cal yr BP) (Fig. 3), supports the pollen and spore data and suggests a shallow, ephemeral lake. The transition from sandy silt to gyttia deposits, sometime before 3820 cal yr BP, indicates the point at which the basin center became more-or-less continually inundated. The presence of a permanent water body resulted in improved microfossil preservation and deposition of a local- to regional-scale pollen assemblage. The multi-proxy analysis of the sediment cores, indicates two periods of

reduced moisture availability (pollen zones VCC-P1 and VCC-P3) and two adjacent wetter episodes (VCC-P2 and VCC-P4).

After the (c. 250 yr) period of lake stabilization, high abundances of drought tolerant pollen taxa (Caryophyllaceae, Chenopodiaceae and Bromeliaceae) (VCC-P1; Fig. 4A), are evident. CaCO₃ has been shown in other Andean records to be an indicator of dry events and lowered lake levels (Baker et al., 2001; Hillyer et al., 2009). High CaCO₃ values (up to 17.2 wt%) (Fig. 3) at Challacaba during VCC-P1 are therefore interpreted here to indicate that the lake was not overflowing and that water level was lower than today. Although zone VCC-P1 is considered a period of reduced moisture availability compared to other periods of the Challacaba record, the zone does represent a reduction in drought events which dominated the mid-Holocene dry phase between c. 8000 and 5000 yr ago.

The VCC-P1 period reconstructed from Challacaba supports the water-level history reported from Lake Titicaca (c. 370 km north-east). Abbott et al. (1997), indicate a regional climate influence and suggest lake levels were at their lowest prior to 3500 cal yr BP, and that the mid-Holocene dry phase ended abruptly between 3500 and 3350 cal yr BP. Challacaba seems to have undergone a more gradual transition out of the mid-Holocene dry phase, but it is considered likely that Challacaba Lake formation is linked to this wide, regionally recognized, moisture signal. In the Eastern Andes, other sediment records also attest to the presence of the mid-Holocene dry phase, either by lowered lake levels (e.g. Lake Consuelo; Urrego et al., 2010) or post event lake formation (e.g. Marcacocha; Chepstow-Lusty et al., 1998).

The increase in regional moisture, which led to the inundation of the Challacaba Lake basin could have been caused by a resumption of more “normal” (less declined) ENSO activity following the “weak” El Niño regime that it has been suggested dominated during the mid-Holocene period, 8–5.6 ka (Rein et al., 2005). The timing of formation of Challacaba does not concur with that of nearby Juntutuyo (Abbott et al., 2003), which shows lake development some c. 1500 yr later. This may be a result of Challacaba being fed, in part, from the surrounding hills to the east and/or that the Juntutuyo core record of CaCO₃ was not taken from the deepest part of the lake (Abbott, M., personal communication, 2010). There is no evidence to suggest that a local tectonic change created a depression in which Challacaba formed.

The initial phase at Challacaba (VCC-P1) persisted until a change sometime between 3460 and 3270 cal yr BP where arid and salt tolerant taxa, particularly Chenopodiaceae, begin to decline, CaCO₃ wt%

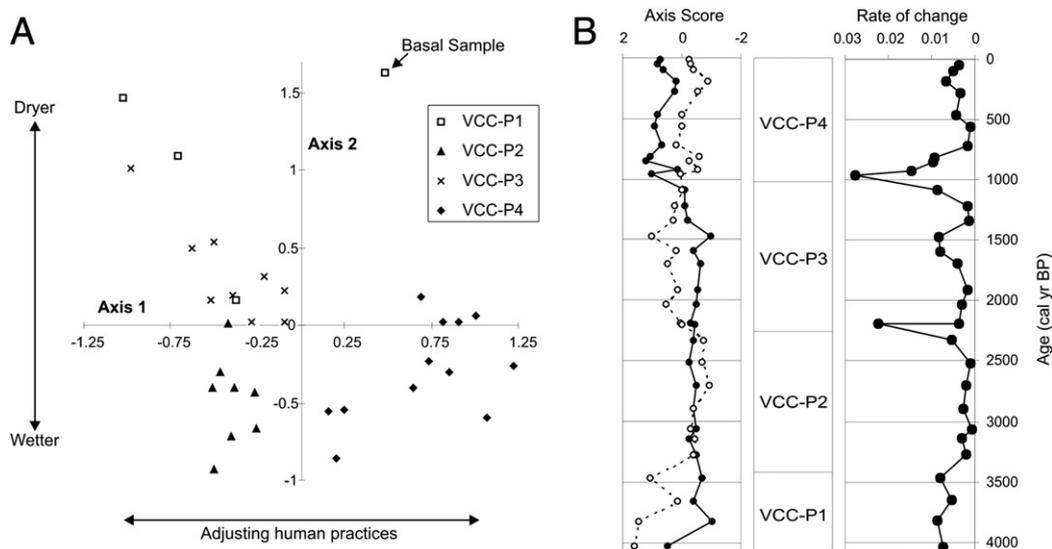


Figure 5. Results of NMDS of pollen sum taxa for Lake Challacaba. A) Ordination plot of sample scores for Axis 1 and 2. Point symbols refer to relevant attributed zone. B) Axis 1 (solid line) and Axis 2 (dashed line) scores (left graph), and rate of change (right graph) both plotted against time.

decreases and TOC begins to increase. The ordination of samples from the first wetter phase, VCC-P2, shows a distinct clustering with negative scores in both axis 1 and 2 (Fig. 5). A marked decrease in fossil pollen concentration throughout VCC-P2 is here interpreted to show an increased areal extent and deepening of the lake and thus a dilution of the pollen input. This conclusion is supported by the decreased percentage of *Myriophyllum*, a genus which has been observed to predominate in shallow waters, 0.4–4 m (Ybert, 1992), as it becomes further removed from the core location at the lake depth maxima. The shift towards a wetter interval again correlates well to an increase in ENSO variability recorded at Laguna Pallcacocha in southern Ecuador sometime from 3500 to 3400 cal yr BP (Moy et al., 2002).

From c. 2190 to 1020 cal yr BP (VCC-P3) a shift in the NMDS ordination (Fig. 5A) highlights a change in the pollen data which, in our interpretation, suggests a return to conditions of reduced moisture; this is particularly well-demonstrated by an increase in Caryophyllaceae (10–19%), which favors dry conditions. In addition Cheno/Ams and Bromeliaceae percentages increase as does the total pollen concentration (Fig. 4A). While the vegetation does share many similarities with that immediately after lake formation (VCC-P1), important differences exist, the most noticeable being the continued presence of Piperaceae and the gradual continued increase of Cyperaceae. This second interval of drier conditions, is supported further by significantly higher CaCO₃ concentrations between c. 1970 and 1340 cal yr BP, suggesting a lowered lake level.

From c. 1020 cal yr BP (VCC-P4) a reduction in the abundance of arid and salt tolerant taxa, together with the much lower concentrations of CaCO₃, we interpret to indicate a return to conditions that, on average, were locally wetter than the previous period (VCC-P3). As in the previously recorded wet period, VCC-P2, *Myriophyllum* percentage is generally reduced. The very low total pollen concentration values are, at least in part, a result of the dilution effect of a larger lake, but it is also possible that this reflects a less productive landscape. We recognize however that short phases of increased aridity, particularly regional scale ones, may have occurred within this period that are not represented in the limnological record either due to their duration or a buffering effect of the locality. Nonetheless, the apparent shift to on average wetter conditions at Challacaba could be related to a more widespread Andean trend of ENSO events as evidenced in the Laguna Pallcacocha record. At Pallcacocha a frequency maximum has been identified at c. 1200 cal yr BP and a general increased number of ENSO events between c. 900 and 300 cal yr BP, albeit punctuated with shorter term reductions and a steadily declining frequency trend (Moy et al., 2002).

Intriguingly, the pollen spectra recovered from VCC-P4 is markedly different to that of the previous wet interval (VCC-P2). The NMDS ordination (Fig. 5A), whilst supporting the general conclusion that samples aging from c. 1020 to 0 cal yr BP display a wetter environment signal (more negative values on axis 2), also highlights that from 1030 cal yr BP, the pollen assemblage is distinctive from that of VCC-P2 (less negative values on axis 1). In addition, the maxima in the RoC score that centered around the VCC-P2 to VCC-P1 boundary (c. 1020 cal yr BP) (Fig. 5B) indicates a major vegetation change in the Challacaba record that we associate here with an adjustment in human activity.

While the Challacaba record supports the conclusion of a period of increased moisture availability during the zone VCC-P4, adjusting human impact on the local landscape undoubtedly complicates the signal of moisture fluctuation. With this mind, we interpret the period after c. 1020 cal yr BP, to primarily represent a time of changing, possibly increasing, human impact levels. The site of Marcacocha also points to increasing human activity around this time as indicated by both archeological and sedimentary records (Chepstow-Lusty et al., 2009). However, the Marcacocha record has been interpreted to indicate a temperature increase from around c. 900 cal yr BP which

led to warm and relatively stable conditions, but crucially, without any associated increase in precipitation (Chepstow-Lusty et al., 2009). While we are unable to speculate if warmer conditions might also have begun at Challacaba around this time, due to the lack of an independent temperature proxy, we interpret the combined data sets here to indicate a general increase in the moisture availability, which could be linked to either changes in temperature, precipitation or both.

Changing human activity

The high level of charcoal from the start of the Challacaba record (>50 particulates/cm³) probably indicates that people have utilized this area continually from at least c. 4000 cal yr BP (Fig. 4B). The high abundance of large woody charcoal fragments and low levels of woodland pollen taxa between c. 4030 and 1090 cal yr BP suggest that people were possibly transporting fuel wood collected elsewhere to burn close to the lake. The earliest indicator of trading and pastoralism is recorded by a marked rise in fungal dung spores, and tentatively algal remains c. 1280 cal yr BP (Fig. 4B). As neither of these biological groups were included within the pollen sum, they have no influence upon the statistical zonation or the NDMS ordination.

The first significant occurrence (>2%) of *Sporormiella* fungal spores in the core occurs at c. 1340–1210 cal yr BP (Fig. 4B). *Sporormiella* is a coprophilous ascomycete fungi common on the dung of herbivores (Ahmed and Cain, 1972). Recent work on modern lakes acknowledged *Sporormiella* as a useful proxy to indicate herbivore presence, but highlighted a strong positive relationship between proximity to shoreline and *Sporormiella* abundance (Raper and Bush, 2009). However, in the case of Challacaba, the *Sporormiella* increase coincides with a transition from drier to wetter conditions as attested to by both the terrestrial palynological and the geochemical data indicating that the lake shoreline became further away from the coring site. We can therefore be confident in the assessment that herbivore presence around Challacaba substantially increased between c. 1340 and 1210 cal yr BP. The increase in *Sporormiella* is concurrent with the oribatid mite record from Marcacocha, which shows a progressive increase in livestock number, from c. 1200 cal yr BP (Chepstow-Lusty et al., 2007).

Challacaba is the freshest lake in the Vacas Lake District and is located close to a narrowing of the valley which constrains the historic road running east to Inkallajta (Fig. 1a). It therefore seems likely that any pre-Columbian increase in dung deposition surrounding the lake would have been due to an increase in domesticated camelids (alpaca and llama herds) being watered at the lake whilst being driven along the road. The tendency of camelids to defecate in restricted communal piles, often close to a water source (Sillar, 2000) adds weight to this interpretation. While the primary rise in camelid numbers, inferred from the increased abundance of *Sporormiella*, coincides with archeological evidence indicating Tiwanaku cultivation expansion between 1200 and 1000 yr ago, it is possible that a second increase in *Sporormiella* seen in the Challacaba record (c. 920 cal yr BP) is related to Tiwanaku fragmentation. The abandonment of urban centers around Lake Titicaca is evidenced by a silence in monument construction between c. 800 and 500 yr ago, which may represent a dispersal of people into new, more rural, lands (Albarracin-Jordan, 1992; Kolata, 1993; Binford et al., 1997).

Two multi-centennial dry events (c. 1410–1190 and 850–550 yr ago) that have been associated with the collapse of Tiwanaku (Binford et al., 1997) do not appear to have had as much a dramatic impact on the terrestrial vegetation or the human impact levels around Challacaba (Fig. 4A). Given the current chronology available it is difficult to tie the Challacaba record to these rapid fluctuations; however the Challacaba record does hint at responses that are roughly concurrent with this dry-wet-dry oscillation noted around Lake Titicaca: i) the decrease in CaCO₃ in Challacaba at c. 1270 cal yr BP

coincides with the end of the first of these dry episodes (Fig. 3), ii) the peak in *Pediastrum* (c. 1210–920 cal yr BP) straddles the intervening wet period (Fig. 4B), iii) the peak in *Typha* (c. 850 cal yr BP) coincides with the onset of the second dry period (Fig. 4B), and iv) drought tolerant *Cheno/Ams* values are slightly elevated (c. 720–470 cal yr BP) through the second dry episode (Fig. 4A). The absence of elevated CaCO_3 during the second dry phase may be due to camelid dung acidifying the lake. The persistence of high *Sporormiella* values through these postulated short-term lake level fluctuations supports the interpretation that the rise in *Sporormiella* is due to higher numbers of camelids visiting the lake.

Simultaneous with the initial herding increase (c. 1270 cal yr BP) a maxima in the algal genus *Pediastrum* is also detected. This algal peak is interpreted to reflect an adjustment in lake nutrient status. Whilst other studies have interpreted lake eutrophication to be a result of increased nutrient in-wash after deforestation (Paduano et al., 2003; Woodward and Shulmeister, 2005), we here suggest that a direct input of nutrients from a local increase of animal activity is responsible. The *Pediastrum* maxima of 88% are simultaneous with the arrival of substantial quantities of camelids for the first time, as indicated by the abundance of *Sporormiella* spores. Two later increases in *Sporormiella* (c. 920 and 560 cal yr BP) also correlate to *Pediastrum* blooms, albeit ones of lower magnitude.

The large increase in *Ludwigia* marks the transition from zone VCC-P3 to VCC-P4. *Ludwigia*, as discussed previously, is a genus generally associated with wetland habitats (Marchant et al., 2002). The increased abundance of *Ludwigia* is contemporaneous with the reduction in arid and salt tolerant taxa and we interpret the pollen record from c. 1020 cal yr BP to represent vegetation composition typical of an increased marshy habitat, created as the lake level rises and water inundates the flat expanse of the north and east shores.

The sudden increase of *Ludwigia* at this time and lack of a similar abundance during the early wetter phase (VCC-P2) may be linked to human influence. The arrival of increased camelid numbers and thus nutrient input, together with increased grazing on existing moist vegetation (aquatics), may have led to the creation of a niche space suitable for *Ludwigia* to exploit. *Ludwigia* is an invasive species and it is plausible that its arrival in the Challacaba region is related to the transport of *Ludwigia* seeds by camelids from wetlands they have previously visited. The sporadic increase in *Typha*, that is seen through zone VCC-P4, also indicates a response to changing nutrient status through this time (Marchant et al., 2002).

Fire history

There appears to be no connection between the fire history and the wider vegetation signal at Challacaba and we attribute the majority of carbon particulates throughout the last 4000 cal yr BP to be from local anthropogenic sources (fuel wood for cooking, heating and possibly some clearance burning). The main shift occurs from c. 1340 cal yr BP when all size fractions show a dramatic decreasing trend and by c. 1020 cal yr BP, the start of VCC-P4, particulate counts are consistently under 20 per cm^3 (Fig. 4B). A similar scale decrease was found in the Titicaca record (Lago Grande), as particulates declined and ultimately disappear after 2 ka (Paduano et al., 2003). Paduano et al. associated the decline in charcoal at Titicaca with a reduced availability of fuelwood, as supported by a concomitant woodland pollen decrease. At Challacaba there is no palynological evidence for decreased woodland cover instead the decline in charcoal abundance is coincident with the rise in camelid dung fungus.

In many rural Andean regions today dried cattle dung acts as a main energy source and in Bolivia it accounts for 19% of total biofuel (Winterhalder et al., 1974; World Bank, 1994; Yevich and Logan, 2003). Since wood has been a scarce resource in these environments for a considerable time, including Tiwanaku times, camelid dung has long provided an alternative fuel for fires (Janusek, 2008). While

traditionally the importance of dung burning may have its origins in pottery firing, its long term historical use suggests that during times of increase camelid numbers, dung supply would have been greatly increased and so would its utilization in a much wider context (Sillar, 2000). It therefore seems plausible that between c. 1340 and 1020 cal yr BP the people traveling through the Vacas region switched from collecting fuelwood, or possibly traveling with or trading, to the utilization of dried dung.

The *Polylepis* woodland/grassland matrix

Through the duration of Challacaba record, except for two samples (basal and 2190 cal yr BP), *Polylepis/Acaena* pollen has low abundances (0.2–6.6%). It is assumed that the pollen recorded here is predominantly from the tree genus *Polylepis* rather than *Acaena*; the latter is a herb genus associated closely to moist valleys, typically within cloud forests (Chepstow-Lusty et al., 2005; Weng et al., 2006).

Modern ecological data suggest that today the high Andean *Polylepis* woodland only covers around 10% of its potential distribution (Fjeldsø and Kessler, 1996). However, the fossil pollen record from Challacaba shows no evidence for a reduction in *Polylepis* woodland cover around Vacas during the last 4000 yr. The continually low abundance at Challacaba is contrary to the decline in *Polylepis* pollen at c. 3100 cal yr BP evident from Lake Titicaca (Paduano et al., 2003) but parallels the c. 4000 yr record from Marcacocha (Peru) (Chepstow-Lusty et al., 1998).

The regionally variable pattern of the past *Polylepis* woodland extent emphasizes uncertainty in the assumption that the natural state of the Andes is a continuous belt of a permanent *Polylepis* woodland (*sensu* Ellenberg, 1958), and supports the case for persistent regional variability defined by microclimate conditions (Gosling et al., 2009). Given the long history of human occupation of the Andes it is possible that woodland clearance was completed prior to the formation of the Challacaba record (pre c. 4000 cal yr BP), or that the *Polylepis* forests never recovered after the mid-Holocene dry period, as around this time major human impact (agriculture) in the Andes began. However, the vegetation reconstruction presented here shows only minor fluctuation in the grass to *Polylepis* woodland matrix through the period of major regional pre-Columbian cultural expansion and contraction.

The conclusion of late Holocene *Polylepis* woodland stability is supported by Lake Pacucha pollen record in the central Peruvian Andes, which represents a site for continuous human occupation for at least the last 4000 yr (Valencia et al., 2010). At Pacucha there is no evidence for *Polylepis* woodland reduction in response to human activity. The *Polylepis* woodland was most abundant during deglaciation (c. 16,000–14,000 cal yr BP), which parallels new findings from the pollen record of Laguna Khomer Kocha Upper (17°16' S, 65°43' W; 4153 m elevation), situated 40 km north-west of Challacaba (Williams, unpublished data).

Conclusions

The complete paleolimnological history of Lake Challacaba reveals that vegetation change in the Cochabamba Basin, Bolivia, has been driven by both human and climatic factors during the last 4000 yr. Two distinct drier than modern stages; before c. 3370 and 2190–1020 cal yr BP are recorded. The older dry event can be linked to the latter stages of lower regional moisture availability caused by the “weak” El Niño system that dominated during the mid-Holocene (Rein et al., 2005). The second drier interval, whilst likely to be again related to a regional ENSO signal, is less clearly correlated with other records. Between the Challacaba dry phases there was an interval of increased moisture availability (c. 3370–2190 cal yr BP).

Although the pollen data from Challacaba may suggest a shift to generally wetter conditions from c. 1020 cal yr BP, it is likely that shorter term reductions in the moisture balance occurred throughout.

Ultimately however, there is strong evidence to show that a change in human activity at some point between c. 1340 and 1210 cal yr BP was a major factor in shaping the modern regional landscape. The pollen assemblage from the last 1000 yr is very different to that from any other time during the preceding 3000 yr. The charcoal record indicates that the local ecosystem has been under anthropogenic influence for the duration of the time spanned by the Challacaba core (c. 4 ka). As such we are unable to obtain a baseline record for what is the natural state of the ecosystem without human influence, but, it is evident that overall the *Polylepis* woodland maintained a relatively stable presence and abundance even during the height of human pressure.

This research supports the interpretation that the Vacas Lake District was an important point on the ancient roadway network during pre-Columbian times. Further work is required to clarify the extent to which the observed changes in human activity are a product of unconnected wider social changes or smaller scale local impacts. In particular, refining the chronology of the sequence will help to better constrain the timings of significant environmental changes observed within the record and this will be critical if they are to be linked to any known cultural events.

Acknowledgments

This research was funded by a NERC Open CASE studentship with the Natural History Museum, London (NE/F008082/1), NERC radio-carbon facility support (1287.0408 and 1463.0410) and a National Geographic Committee for Research and Exploration grant (8105–06). In addition we thank Eric Martinez Costas and Lydia Meneses Lizarazu for assistance in the field, and John Watson for LECO analysis support. Finally, we are grateful for the comments of Alex Chepstow-Lusty and Henry Hooghiemstra whose vigorous evaluations helped to improve the strength of this manuscript substantially.

References

- Abbott, M.B., Binford, M.W., Brenner, M., Kelts, K.R., 1997. A 3500 ¹⁴C yr high-resolution record of water-level changes in Lake Titicaca, Bolivia/Peru. *Quaternary Research* 47, 169–180.
- Abbott, M.B., Wolfe, B.B., Wolfe, A.P., Seltzer, G.O., Aravena, R., Mark, B.G., Polissar, P.J., Rodbell, D.T., Rowe, H.D., Vuille, M., 2003. Holocene paleohydrology and glacial history of the central Andes using multiproxy lake sediment studies. *Palaeogeography, Palaeoclimatology, Palaeoecology* 194, 123–138.
- Ahmed, S.I., Cain, R.F., 1972. Revision of the genera *Sporormia* and *Sporormiella*. *Canadian Journal of Botany* 50, 419–477.
- Albarracín-Jordan, J. (1992). Prehispanic and early colonial settlement patterns in the Lower Tiwanaku Valley, Bolivia. Unpublished Ph.D. thesis. South Methodist University.
- Baker, P.A., Seltzer, G.O., Fritz, S.C., Dunbar, R.B., Grove, M.J., Tapia, P.M., Cross, S.L., Rowe, H.D., Broda, J.P., 2001. The history of South American tropical precipitation for the past 25,000 years. *Science* 291, 640–643.
- Bennett, K.D., 1996. Determination of the number of zones in a biostratigraphical sequence. *The New Phytologist* 132, 155–170.
- Binford, M.W., Kolata, A.L., Brenner, M., Janusek, J.W., Seddon, M.T., Abbott, M., Curtis, J.H., 1997. Climate variation and the rise and fall of an Andean civilization. *Quaternary Research* 47, 235–248.
- Birks, H.J.B., 1998. Numerical tools in palaeolimnology – progress, potentialities, and problems. *Journal of Paleolimnology* 20, 307–332.
- Birks, H.J.B., Birks, H.H., 1980. *Quaternary Palaeoecology*. Edward Arnold, London.
- Birks, H.J.B., Gordon, A.D., 1985. *Numerical Methods in Quaternary Pollen Analysis*. Academic Press, London.
- Björck, S., Wohlfarth, B., 2001. ¹⁴C Chronostratigraphic techniques in paleolimnology. Tracking Environmental Change Using Lake Sediments. In: Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), *Basin Analysis, Coring and Chronological Techniques*, Volume 1. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 205–245.
- Bush, M.B., Weng, C., 2006. Introducing a new (freeware) tool for palynology. *Journal of Biogeography* 34, 377–380.
- Cassard, D., 1999. GIS Andes: a metallogenic GIS of the Andes Cordillera. 4th International Symposium on Andean Geodynamics. Institut de Recherche pour le Développement Publisher, Paris Göttingen, Germany, pp. 147–150. Extended Abstracts.
- Chepstow-Lusty, A.J., Bennett, K.D., Fjeldsá, J., Kendall, A., Galiano, W., Herrera, A.T., 1998. Tracing 4,000 years of environmental history in the Cuzco area, Peru, from the pollen record. *Mountain Research and Development* 18, 159–172.
- Chepstow-Lusty, A.J., Bush, M.B., Frogley, M.R., Baker, P.A., Fritz, S.C., Aronson, J., 2005. Vegetation and climate change on the Bolivian Altiplano between 108,000 and 18,000 yr ago. *Quaternary Research* 63, 90–98.
- Chepstow-Lusty, A.J., Frogley, M.R., Bauer, B.S., Leng, M.J., Cundy, A.B., Boessenkool, K.P., Gioda, A., 2007. Evaluating socio-economic change in the Andes using oribatid mite abundances as indicators of domestic animal densities. *Journal of Archaeological Science* 34, 1178–1186.
- Chepstow-Lusty, A.J., Frogley, M.R., Bauer, B.S., Leng, M.J., Boessenkool, K.P., Carcaillet, C., Ali, A.A., Gioda, A., 2009. Putting the rise of the Inca Empire within a climatic and land management context. *Climate of the Past* 5, 375–388.
- Chiang, J.C.H., 2009. The tropics in paleoclimate. *Annual Review of Earth and Planetary Sciences* 37, 263–297.
- Cincotta, R.P., Wisniewski, J., Engelman, R., 2000. Human population in the biodiversity hotspots. *Nature* 404, 990–992.
- De la Barra, N., 2003. Ecological classification of aquatic vegetation of lacustrine systems in Bolivia. *Revista Boliviana De Ecología y Conservación Ambiental* 13, 65–93.
- Ellenberg, H., 1958. *Wald oder Steppe? Die natürliche Pflanzendecke der Anden Perus*. Umschau 1958 645–681.
- Fægri, K., Iversen, J., 1989. *Textbook of Pollen Analysis*. Blackburn Press, New Jersey.
- Fernández, E., 1997. Estudio fitosociológico de los bosques de keuña (*Polylepis* spp., Rosaceae) en la Cordillera de Cochabamba. *Revista Boliviana De Ecología y Conservación Ambiental* 2, 49–65.
- Fernández, M., Mercado, M., Arrázola, S., Martínez, E., 2001. Estructura y composición florística de un fragmento boscoso de *Polylepis besseri*. *Revista Boliviana De Ecología y Conservación Ambiental* 9, 15–27.
- Fjeldsá, J., Kessler, M., 1996. Conserving the Biological Diversity of *Polylepis* Woodlands of the Highland of Peru and Bolivia: A Contribution to Sustainable Natural Resource Management in the Andes. NORDECO, Copenhagen, Denmark.
- García, E., Fernández, M., Stanton, S., 2010. Dendrochronological investigation of the high Andean tree species *Polylepis besseri* and implications for management and conservation. *Biodiversity and Conservation* 19, 1839–1851.
- Godwin, H., 1956. *History of British Flora*. Cambridge University Press, Cambridge.
- Gosling, W.D., Hanselman, J.A., Knox, C., Valencia, B.G., Bush, M.B., 2009. Long-term drivers of change in *Polylepis* woodland distribution in the central Andes. *Journal of Vegetation Science* 20, 1041–1052.
- Gotkowitz, L., 2007. *A Revolution for Our Rights: Indigenous Struggles for Land and Justice in Bolivia, 1880–1922*. Duke University Press, Durham.
- Grimm, E.C., Maher Jr., L.J., Nelson, D.M., 2009. The magnitude of error in conventional bulk-sediment radiocarbon dates from central North America. *Quaternary Research* 72, 301–308.
- Hensen, I., 2002. Impacts of anthropogenic activity on the vegetation of *Polylepis* woodlands in the region of Cochabamba, Bolivia. *Ecotropica* 8, 183–203.
- Higueras, A. (1996). Prehispanic settlement and land use in Cochabamba, Bolivia (Unpublished Ph.D. dissertation). University of Pittsburgh.
- Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* 25, 1965–1978.
- Hillyer, R., Valencia, B.G., Bush, M.B., Silman, M.R., Steinitz-Kannan, M., 2009. A 24,700-yr paleolimnological history from the Peruvian Andes. *Quaternary Research* 71, 71–82.
- Hooghiemstra, H., 1984. *Vegetational and Climatic History of the High Plain of Bogota Colombia: A Continuous Record of the Last 3.5 Million Years*. Gantner Verlag, Vaduz.
- Ibisch, P.L., Beck, S.G., Gerkmann, B., Carretero, A., 2003. Ecoregiones y ecosistemas. In: Ibisch, P.L., Mérida, G. (Eds.), *Biodiversidad: la riqueza de Bolivia. Estado de conocimiento y conservación*. FAN, Santa Cruz de la Sierra, Bolivia, pp. 47–88.
- Janusek, J.W., 2008. *Ancient Tiwanaku (Case Studies in Early Societies)*. Cambridge University Press, New York.
- Juggins, S., 2002. *WinTran Version 1.4*. University of Newcastle, Newcastle upon Tyne, UK.
- Juggins, S., 2003. *C2 Data Analysis (Version 1.4 Beta)*. University of Newcastle, Newcastle upon Tyne, UK.
- Kessler, M., 2002. The “*Polylepis* Problem”: where do we stand? *Ecotropica* 8, 97–110.
- Kolata, A.L., 1993. *Tiwanaku: Portrait of an Andean Civilization*. Blackwell, Cambridge, MA.
- Leduc, G., Vidal, L., Tachikawa, K., Bard, E., 2009. ITCZ rather than ENSO signature for abrupt climate changes across the tropical Pacific? *Quaternary Research* 72, 123–131.
- Line, J. M., and Birks, H. J. B. (1996). *BSTICK Version 1.0*. Unpublished computer program. Botanical Institute, University of Bergen.
- Lotter, A.F., Juggins, S., 1991. POLPROF, TRAN and ZONE: programs for plotting, editing and zoning pollen and diatom data. INQUA–Subcommission for the Study of the Holocene: Working Group on Data-handling Methods, 6, pp. 4–6.
- Lynch, T.F., 1983. Camelid pastoralism and the emergence of Tiwanaku civilization in the south-central Andes. *World Archaeology* 15, 1–14.
- Malcolm, J.R., Liu, C., Neilson, R.P., Hansen, L., Hannah, L., 2006. Global warming and extinctions of endemic species from biodiversity hotspots. *Conservation Biology* 20, 538–548.
- Marchant, R., Almeida, L., Behling, H., Berrio, J.C., Bush, M., Cleef, A., Duivenvoorden, J., Kappelle, M., De Oliveira, P., Teixeira de Oliveira-Filho, A., Lozano-García, S., Hooghiemstra, H., Ledru, M.-P., Ludlow-Wiechers, B., Markgraf, V., Mancini, V., Paez, M., Prieto, A., Rangel, O., Salgado-Labouriau, M.L., 2002. Distribution and ecology of parent taxa of pollen lodged within the Latin American Pollen Database. *Review of Palaeobotany and Palynology* 121, 1–75.
- McCormac, F.G., Hogg, A.G., Blackwell, P.G., Buck, C.E., Higham, T.F.G., Reimer, P.J., 2004. SHCal04 Southern Hemisphere calibration 0–11.0 cal kyr BP. *Radiocarbon* 46, 1087–1092.
- McCune, B., Mefford, M.J., 2006. *PC-ORD. Multivariate Analysis of Ecological Data (Version 5)*. MjM Software, Gleneden Beach, Oregon, U.S.A.
- McQuarrie, N., 2002. The kinematic history of the central Andean fold-thrust belt, Bolivia: implications for building a high plateau. *Geological Society of America Bulletin* 114, 950–963.

- Molina, J.A., Navarro, G., de la Barra, N., Lumbreras, A., 2007. Andean aquatic vegetation in central Bolivia. *Phytocoenologia* 37, 753–768.
- Moy, C.M., Seltzer, G.O., Rodbell, D.T., Anderson, D.M., 2002. Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature* 420, 162–165.
- Munsell Soil Color Charts, 2000. Munsell Soil Color Charts, Revised Washable Edition. New Windsor, New York.
- Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B., Kent, J., 2000. Biodiversity hotspots for conservation priorities. *Nature* 403, 853–858.
- Navarro, G., Ferreira, W., 2007. Mapa de vegetación de Bolivia. CD-ROM interactivo. The Nature Conservancy & Rumbol.
- Navarro, G., Maldonado, M., 2002. Geografía Ecológica de Bolivia: Vegetación y Ambientes Acuáticos. Centro de Ecología Simón I, Patino, Santa Cruz, Bolivia.
- Oldfield, F., 1978. Lakes and their drainage basins as units of sediment-based ecological study. *Progress in Physical Geography* 1, 406–504.
- Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'Amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., Loucks, C.J., Allnutt, T.F., Ricketts, T.H., Kura, Y., Lamoreux, J.F., Wettengel, W.W., Hedao, P., Kassem, K.R., 2001. Terrestrial ecoregions of the world: a new map of life on Earth. *Bioscience* 51, 933–938.
- Paduano, G.M., Bush, M.B., Baker, P.A., Fritz, S.C., Seltzer, G.O., 2003. A vegetation and fire history of Lake Titicaca since the Last Glacial Maximum. *Palaeogeography, Palaeoclimatology, Palaeoecology* 194, 259–279.
- Philander, S.G.H., 1990. *El Niño, La Niña, and the Southern Oscillation*. Elsevier, New York.
- Raper, D., Bush, M., 2009. A test of *Sporormiella* representation as a predictor of megaherbivore presence and abundance. *Quaternary Research* 71, 490–496.
- Rasband, W.S., 1997–2009. ImageJ. U. S. National Institutes of Health, Bethesda Maryland, USA. <http://rsb.info.nih.gov/ij/>.
- Rein, B., Lückge, A., Reinhardt, L., Sirocko, F., Wolf, A., Dullo, W.-C., 2005. El Niño variability off Peru during the last 20,000 years. *Paleoceanography* 20.
- Ritter, N. P. (2000). Biodiversity and Phytogeography of Bolivia's Wetland Flora. Unpublished Ph.D. dissertation thesis, University of New Hampshire.
- Roubik, D.W., Moreno, E., 1991. Pollen and Spores of Barro Colorado Island. Missouri Botanical Garden.
- Sánchez, W.C., 2008. Inkas, "Flecheros" y Mitmaquna. Cambio social y paisajes culturales en los Valles y en los Yungas de Inkachaca/Paracti y Tablas Monte. (Cochabamba-Bolivia, siglos XV–XVI). Uppsala University-Universidad Mayor de San Simón, Suecia.
- Sillar, B., 2000. Dung by preference: the choice of fuel as an example of how Andean pottery production is embedded within wider technical, social and economic practices. *Archaeometry* 42, 43–60.
- Stuiver, M., Reimer, P.J., 1993. Extended ¹⁴C database and revised CALIB radiocarbon calibration program. *Radiocarbon* 35, 215–230.
- Stuiver, M., Reimer, P.J. (2010). CALIB Radiocarbon Calibration Program 6.0.1 WWW program and documentation.
- Thompson, L.G., Mosley-Thompson, E., Bolzan, J.F., Koci, B.R., 1985. A 1500-year record of tropical precipitation in ice cores from the Quelccaya Ice Cap, Peru. *Science* 229, 971–973.
- Urrego, D.H., Bush, M.B., Silman, M.R., 2010. A long history of cloud and forest migration from Lake Consuelo, Peru. *Quaternary Research* 73, 364–373.
- Urrego, D.H., Bush, M.B., Silman, M.R., Correa-Metrio, A.Y., Ledru, M.-P., Mayle, F.E., Paduano, G., Valencia, B.G., 2009. Millennial-scale ecological changes in tropical South America since the last glacial maximum. In: Vimeux, F., Sylvestre, F., Khodri, M. (Eds.), *Past Climate Variability in South America and Surrounding Regions*, pp. 283–300.
- Valencia, B.G., Urrego, D.H., Silman, M.R., Bush, M.B., 2010. From ice age to modern: a record of landscape change in an Andean cloud forest. *Journal of Biogeography* 37, 1637–1647.
- Wagner, W.L., 2007. Revised Classification of the Onagraceae. American Society of Plant Taxonomists, Ann Arbor, Michigan.
- Weng, C., Bush, M.B., Curtis, J.H., Kolata, A.L., Dillehay, T.D., Binford, M.W., 2006. Deglaciation and Holocene climate change in the western Peruvian Andes. *Quaternary Research* 66, 87–96.
- Willis, K.J., Birks, H.J.B., 2006. What is natural? The need for a long-term perspective in biodiversity conservation. *Science* 314, 1261–1265.
- Winterhalder, B., Larsen, R., Thomas, R., 1974. Dung as an essential resource in a highland Peruvian community. *Human Ecology* 2, 89–104.
- Woodward, C.A., Shulmeister, J., 2005. A Holocene record of human induced and natural environmental change from Lake Forsyth (Te Wairewa), New Zealand. *Journal of Paleolimnology* 34, 481–501.
- World Bank, 1994. *Bolivia: Household Rural Energy Strategy*, 62/94, Washington, D. C.
- Ybert, J.-P., 1992. Ancient lake environments as deduced from pollen analysis. In: Dejoux, C., Iltis, A. (Eds.), *Lake Titicaca. A Synthesis of Limnological Knowledge*. Kluwer Academic Publishing, Dordrecht, pp. 49–60.
- Yevich, R., Logan, J.A., 2003. An assessment of biofuel use and burning of agricultural waste in the developing world. *Global Biogeochem Cycles* 17, 1095–1135.
- Zhou, J., Lau, K.M., 1998. Does a monsoon climate exist over South America? *Journal of Climate* 11, 1020–1040.