JOURNAL OF QUATERNARY SCIENCE (2005) **20**(7–8) 703–714

Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/jqs.983

A 17 000-year history of Andean climate and vegetation change from Laguna de Chochos, Peru

MARK B. BUSH,[1]* BARBARA C. S. HANSEN,[2] DONALD T. RODBELL,[3] GEOFFREY O. SELTZER,[4†] KENNETH R. YOUNG,[5] BLANCA LEÓN,[5,6] MARK B. ABBOTT,[7] MILES R. SILMAN[8] and WILLIAM D. GOSLING[1,‡]

[1] Department of Biological Sciences, Florida Institute of Technology, Melbourne, FL, USA
[2] Limnological Research Center, University of Minnesota, Minneapolis, MN, USA
[3] Department of Geology, Union College, Schenectady, New York, NY, USA
[4] Department of Earth Sciences, Syracuse University, Syracuse, New York, NY, USA
[5] Department of Geography and the Environment, University of Texas at Austin, Austin, TX, USA
[6] Museo de Historia Natural, U.N.M.S.M., Lima, Peru
[7] Department of Geology and Planetary Science, University of Pittsburgh, Pittsburgh, PA, USA
[8] Wake Forest University, Winston-Salem, NC, USA

Bush, M. B., Hansen, B. C. S., Rodbell, D. T., Seltzer, G. O., Young, K. R., León, B., Abbott, M. B., Silman, M. R. and Gosling, W. D. 2005. A 17 000-year history of Andean climate and vegetation change from Laguna de Chochos, Peru. *J. Quaternary Sci.*, **Vol. 20** pp. 703–714. ISSN 0267-8179.

Received 8 June 2005; Revised 8 September 2005; Accepted 23 September 2005

ABSTRACT: The manifestation of major climatic events such as the timing of deglaciation and whether, or not, the Younger Dryas affected Andean systems has garnered considerable recent attention. Even the Holocene is rapidly emerging as a time of considerable interest in Neotropical palaeoclimatology and palaeoecology. The Holocene of the Neotropics is now revealed as a time of some temperature change with precipitation:evaporation ratios fluctuating markedly. Major changes in lake level, ice-accumulation, and vegetation are indicative of changes both in precipitation and temperature regimes. Although global-scale forcing mechanisms may underlie some of these changes, e.g. the precessional rhythm, other variability appears to be localised. In a record from near the upper forest limit of the eastern Peruvian Andes, pollen, charcoal, and sedimentary data suggest that the deglaciational period from ca. 17 000 to ca. 11 500 cal. yr BP was a period of rapid climatic oscillations, set against an overall trend of warming. A warm-dry event is evident between ca. 9500 and ca. 7300 cal. yr BP, and comparisons with other regional archives suggest that it was regional in scale. A ca. 1500-yr periodicity in the magnetic susceptibility data is evident between 12 000 and 6000 cal. yr BP, reaching a peak intensity during the dry event. A weaker oscillation with a 500–600-yr periodicity is present throughout much of the Holocene. The uppermost sample of the pollen analysis reveals deforestation as modern human land use simplified the landscape. Copyright © 2005 John Wiley & Sons, Ltd.

Journal of Quaternary Science

KEYWORDS: Andes; climate cycle; cloud forest; fossil pollen; Holocene; magnetic susceptibility; Pleistocene; precipitation; temperature.

Introduction

The Neotropical Andes are well-suited to provide high-resolution archives of palaeoecological change. Steep ecological gradients and a suite of species with well-defined altitudinal ranges combine to provide a system that is sensitive to environmental changes. The elevational gradient from the lowlands to the mountains, with just 50 km separating lowland forest from snowline, results in a strong, linear, temperature gradient in which temperatures declines ca. 5.2 °C with each 1000 m vertical increment. Other gradients such as precipitation, UVB, atmospheric pressure, and the partial pressure of CO_2 can also significantly influence biological, geomorphological, and hydrological processes.

Prior studies have demonstrated how these factors have influenced vegetation within the Quaternary and that these montane systems have the potential to provide high-resolution proxy archives of palaeoeclimatic change (Chepstow-Lusty *et al.*, 2002; Colinvaux *et al.*, 1997; Hansen *et al.*, 1984, 2003; Hooghiemstra, 1984; Hooghiemstra *et al.*, 1993; Paduano *et al.*, 2003; van der Hammen and González, 1959; Van't Veer and Hooghiemstra, 2000).

Fossil pollen records from Colombia to Bolivia reveal that at the Last Glacial Maximum (LGM) temperatures were about 7–8 °C cooler than modern in high Andean settings (e.g. Hansen and Rodbell, 1995; e.g. Paduano *et al.*, 2003; van der Hammen and Hooghiemstra, 2000). At this time, in wetter regions of the Andes, glaciers moved downslope, reaching as

* Correspondence to: Mark B. Bush, Professor & Chair, Ecology Program, Department of Biological Sciences, Florida Institute of Technology, Melbourne, Florida, FL 32905, USA. E-mail: mbush@fit.edu
† Deceased.
‡ Current address: Department of Earth Science, The Open University, Milton Keynes, UK

low as 2800 m in the eastern cordillera of Colombia, 3100 m in Ecuador, and 3000 m in northern Peru (Clapperton, 1993; Rodbell, 1992, 1993b).

Evidence for an Andean climatic oscillation concurrent with the Younger Dryas (ca. 12 600–11 500 cal. yr BP) is equivocal (Hansen, 1995; Hansen and Rodbell, 1995; van der Hammen and Hooghiemstra, 1995; van't Veer *et al.*, 2000). At Lake Titicaca the Younger Dryas event was reported by Ybert (1992), but in the pollen analysis of a well-dated deepwater core, there is no clear evidence of a Younger Dryas oscillation (Paduano *et al.*, 2003). However, a climatic oscillation attributed to the Younger Dryas has been registered only 500 km to the north in Lake Junin (Seltzer *et al.*, 2000a). Although the transition from glacial to near-modern temperatures was complete at most tropical Andean sites by 11 000 cal. yr BP, the Holocene was not a period of climatic stasis in this region (e.g. Abbott *et al.*, 2003; Moy *et al.*, 2002; Paduano *et al.*, 2003; Rodbell *et al.*, 1999).

Most Andean sites between 0° and 24°S reveal a marked dry period in the early- to mid-Holocene, but as more records become available it is evident that this was not a single, synchronous event. At Titicaca, lake level dropped by ca. 90 m between 8000 and 4400 cal. yr BP (Baker *et al.*, 2001a), whereas at Junin the driest time was inferred to be ca. 10 000 cal. yr BP (Seltzer *et al.*, 2000). The nearest palaeoecological record to Chochos, from Laguna Baja, suggests some drying between c. 9000 and 6000 cal. yr BP (Hansen and Rodbell, 1995).

Lowered lake levels at Titicaca at ca. 2300 cal. yr BP are suggested to be linked to the decline of the Chiripo and the rise of the Tiwanaku cultures (Abbott *et al.*, 1997a) (for a contrary view, see Erickson (2000)). A detailed palaeoclimatic record from Marcacocha (Chepstow-Lusty *et al.*, 2002, 2003) revealed several climatic oscillations over the past 4000 years with notable dry events at ca. 1100 cal. yr BP and possibly at ca. 600 cal. yr BP. These events are suggested to have played a role in cultural overturn associated with the decline of the Chanka and the rise of the Inca civilisations (Chepstow-Lusty *et al.*, 2003).

In this paper we discuss the palaeoclimatic and human-environment record from the Peruvian Andes by examining a palaeoecological reconstruction from Laguna de Chochos (northern Peru) that spans the late glacial and Holocene period. Results are then compared to the previously published record from Laguna Baja (260 m upslope) to provide a more comprehensive regional picture (Hansen and Rodbell, 1995).

Site description

The eastern cordillera of the northern Peruvian Andes divides the catchments of the Huallaga River to the east and the Marañon River to the west (Fig. 1). Laguna de Chochos, located on the eastern Andean flank at 3285 m (7°38.175′ S, 77°28.473′ W), overlooks steep, forested slopes that encompass the full 3000 m gradient from montane to lowland rain forests over ca. 70 km horizontal distance (Fig. 2).

Local bedrock is dominated by granite, granodiorite, quartzite, and volcanic rocks (Rodbell, 1993a). The lake is at the base of a vertical cliff created by a large valley glacier originating on the higher elevations of the divide, the ridge of which reaches 4200 to 4500 m. The lake is dammed to its south by a recessional end-moraine and to its west by a large medial moraine. Both moraines correlate with the Manachaqui moraines of Rodbell (1993a, 1993b), from which ages of ca. 11 500 and 15 000 cal. yr BP have been obtained (Rodbell,

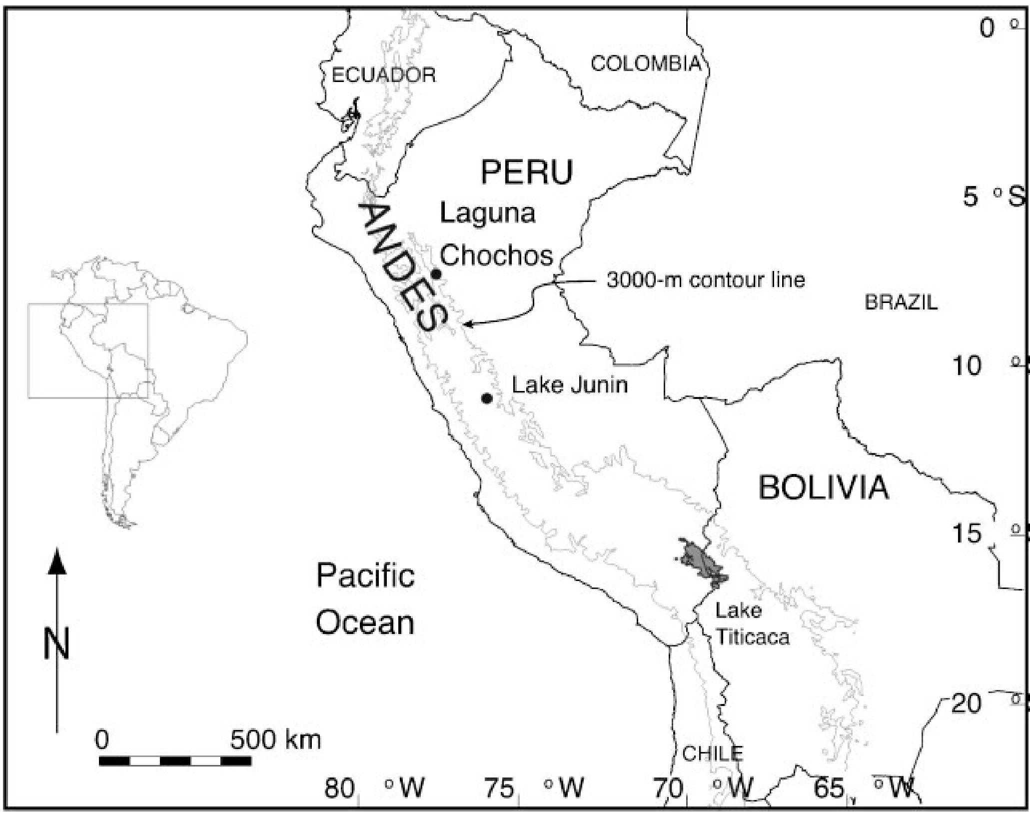

Figure 1 Sketch map showing the location of Laguna de Chochos, Peru

Figure 2 Photograph showing Laguna de Chochos, its modern forest and the glacier-cut cliff

1993b). A basal radiocarbon date from a bog in a cirque at 3850 m in the headwaters of the main drainage basin that feeds Laguna de Chochos indicates that the drainage became ice-free ca. 11 500 cal. yr BP; there is no evidence for any significant ice in the region after this date (Rodbell, 1993a).

While partially encircled today by timberline forest, the lake is situated in an ecotone, with tropical alpine vegetation (known locally as '*páramo*' or '*puna*'). Within these grasslands are tussock-forming *Calamagrostis, Cortaderia*, and *Festuca*, with poorly drained areas dominated by sedges (*Carex, Isolepis, Oreobolus, Scirpus, Uncinia*). The lake has abundant submerged *Isoetes lechleri*.

Prevailing winds are from the east and the forests from 2800 to 3500 m are immersed in fog several hours every day. These cloud forest trees are 8 to 25 m tall, dominated by Lauraceae, *Brunellia, Cinchona, Clethra, Hedyosmum, Ilex, Miconia, Myrsine, Prunus, Ruagea, Symplocos*, and *Weinmannia*, with occasional large specimens of Podocarpaceae (*Podocarpus, Prumnopitys*) and *Polylepis pauta*, and a dense understorey of *Chusquea* bamboos. Yearly precipitation is presumably 2500 mm or more, with mean temperatures at the lake's elevation about 7 °C. Frosts are frequent during the brief dry season, often in July, when skies clear at night and local winds come from the west.

Vegetation studies have shown that the dominant woody plants change in the timberline area over short environmental gradients (Young, 1991, 1993b, 1993c, 1998; Young and León, 1991, 1993). Current land use is concentrated on the western side of the divide and consists of agriculture, mining, and livestock grazing (Young, 1993a).

The lands on the eastern side are within Rio Abiseo National Park, and land use is limited to livestock grazing in the upper elevation grasslands. Within the forest are numerous archaeological sites representing a cultural group that abandoned their settlements after Inca conquest but before Spanish contact (Church, 1996; Church and Morales Gamarra, 2004; Young *et al.*, 1994).

Methods

A piston-core 8.79 m long was raised from the deepest portion of the lake (10 m) from an inflatable rubber raft in July 1996. Cores were extruded and wrapped in the field. Upon returning to the laboratory, cores were passed through a Bartington MS2C 7.5 cm diameter magnetic field, and the low-field 0.46 kHz reversible magnetic susceptibility (MS) was measured every 2 cm. Subsequently, cores were split, described, and subsampled for pollen, bulk density, carbon concentration, and radiocarbon dating.

Pollen subsamples (0.5 cm^3) were treated using standard extraction protocols including spiking the sample with microspheres to permit the calculation of concentration (grains per cm^3) and influx (grains per cm^2 per year). Pollen and charcoal were counted at the University of Minnesota by Hansen. Counts were made to a total of 300 pollen grains at 400 × and 1000 × magnification. Identifications were based on the reference collection of Hansen and published works (e.g. Heusser, 1971; Hooghiemstra, 1984; Markgraf, 1978; Roubik and Moreno, 1991). Owing to probable over-representation of Urticaceae/Moraceae/Ulmaceae, this pollen taxon was excluded from the pollen sum in the calculation of all other species, and was also excluded from the ordination.

Pollen data were plotted using C2 (S. Juggins, University of Newcastle upon Tyne) and the same pollen types (i.e. the most abundant 20 genera) were ordinated in PC-ORD4 (McCune and Mefford, 1999) using non-metric multidimensional scaling (NMS) and detrended correspondence analysis (DCA). NMS was run with 100 iterations of real data, with three dimensions selected and variance explained was based on Sørenson's index.

Charcoal concentrations were estimated from separate counts on the pollen slides and sizes are based on the longest axis. The number and size of charcoal fragments were tallied

Table 1 Radiocarbon ^{14}C AMS dates and calibrated ages based on Calib 5.1 (Stuiver and Reimer, 1993) for sediments from Laguna de Chochos, Peru

Laboratory code	Core depth (cm)	δ^{13}C	^{14}C yr BP	+/−	Weighted mean probability (cal. yr BP)	Upper Age -1σ (cal. yr BP)	Lower Age $+1\sigma$ (cal. yr BP)
NSRL-11261	8.0	−28.1	590	30	540	530	550
NSRL-10758	177.0	−28.5	3090	65	3260	3160	3350
NSRL-10759	270.5	−38.9	6830	75	7200	7090	7230
NSRL-10760	417.0	−26.9	7400	50	8130	8010	8160
AA-28270	615.5	−25.0	8250	65	9120	9000	9250
AA-24009	673.5	−28.0	9320	65	10 250	10 140	10 350
AA-24010	707.0	−26.4	9985	175	11 060	10 980	11 779
AA-28271	757.5	−42.0	11 770	140	13 670	13 500	13 870
AA-28272	782.5	−26.7	12 340	110	14 370	14 180	14 580

per ca. 50 exotic microspheres, from which total concentration was calculated.

Total carbon (TC) was measured by coulometry. Samples were combusted at 1000 °C using a UIC 5200 automated furnace, and the resultant CO_2 measured using a UIC 5014 coulometer. Similarly, total inorganic carbon (TIC) was measured by acidifying samples using a UIC 5240 acidification module and measuring the resultant CO_2 by coulometry. Total organic carbon (TOC) was calculated as TOC = TC − TIC.

Samples for radiocarbon dating were obtained from core sections that possessed abundant macrovegetal material. Samples were each sieved to obtain the >250 μm fraction, and then rinsed in DI water and placed in precombusted glass vials. Samples were then sent to either the University of Arizona or the University of Colorado (Institute of Arctic and Alpine Research, INSTAAR, Table 1) for preparation of AMS targets.

Time series for magnetic susceptibility, bulk density and organic carbon were analysed by Murrelet wavelet decomposition using the continuous one-dimensional wavelet transform in MATLAB 7.0 (Torrence and Compo, 1998). Data were transformed to provide a 20 yr resolution. Oscillations observed in the record were tested against the null hypothesis of correlated (red) noise. Cross-wavelet transforms were performed to look at commonalities and phase relationships between the three proxies (Jevrejeva *et al.*, 2003).

Results

Chronology and stratigraphy

A chronology was based on 9 AMS ^{14}C samples and all ages were calibrated using Calib 5.0. There were no reversals within this data set and all ages are accepted to provide the chronology (Table 1). Sedimentation rates varied by an order of magnitude. From 14 400 to 9100 cal. yr BP sediment accumulated at an average rate of 0.3 mm yr^{-1}. The rate of sedimentation increased markedly from 9100 to 7200 cal. yr BP when 1.9 mm yr^{-1} of sediment accumulated in the lake. After 7200 cal. yr BP, sedimentation rates dropped abruptly back to 0.4 mm yr^{-1}, and they have maintained this rate ever since (Fig. 3). The core was comprised of dark gray gyttja, unevenly banded with pale clastic material.

Palaeoecological zonation

The zonation of the palaeoecological records is based on major changes in sediment type as indicated by carbon content and MS (Fig. 3). Four zones were derived on this basis. A further sub-zone was defined on the basis of ordination of the fossil pollen data.

The NMS ordination of the pollen data had a stress test value of 11, suggesting a relatively robust analysis. NMS axes 1 and 2 were almost identical to Axes 1 and 2 of the DCA. Axes 1 and 2 of the NMS accounted for 57% of the variance in the dataset. While either ordination could be reported, we will use the NMS data for the remainder of this analysis. An additional sub-zone was identified on the basis of the pollen NMS analysis in which the samples from the upper versus the lower portion of zone 3 were clearly discrete on Axis 2.

The NMS analysis revealed a robust separation of most of the pollen samples according to the zonation imposed on sedimentological grounds (Fig. 4). Species scores for Axis 1 placed *Alnus*, *Hedyosmum*, and *Myrica* toward the negative extreme of Axis 1 and *Escallonia*, Melastomataceae, Solanaceae, and *Weinmannia* at the positive extreme. The negative extreme of Axis 2 was characterised by *Alnus*, *Hedyosmum*, Apiaceae, and *Weinmannia*, and the positive extreme by *Alternanthera*, *Celtis*, and *Polylepis*. Samples within zone Ch-1 had negative scores on both Axis 1 and 2, and only one sample from Ch-2 overlapped with them. The overlapping sample from Ch-2 was not from near the bottom of the zone. The Ch-2 group of samples was centrally located on Axis 1 and had a broad range of negative scores on Axis 2. Ch-3a samples had mostly positive scores on Axis 1 while being weakly negative on Axis 2. The placement of the uppermost samples of Ch-2 (marked on Fig. 4) was the only 'mismatch' of zone boundary placement that occurred due to using the sedimentological data rather than the fossil pollen NMS scores to establish zones. According to the NMS these two samples were more similar to the samples of Ch-3 than Ch-2.

Zone Ch-3b was characterised by samples that had positive scores on Axis 2 with a general trend to progress from positive toward negative values on Axis 1 with decreasing age of sample.

Ch-4 samples are mostly clustered close to the midpoint of both axes, but the uppermost sample of this zone is strongly negative on Axis 1.

Zone description

Ch-1 (8.82–8.20 m; ca. 17 150–15 500 cal. yr BP)

This zone is characterised by sediments with exceptionally high values of MS (>100 × 10^{-3} SI units) and very low values of carbon (<1%). The rate of sediment accumulation is ca. 0.4 mm yr^{-1}. Pollen concentration and influx values are very low in this zone: concentrations <12 000 grains per cm^3 and influx <5000 grains per cm^2 per year (Fig. 5). The pollen spectrum is dominated by *Hedyosmum, Alnus, Podocarpus*, and Poaceae, with abundant spores of Cyatheaceae. Taken together these elements are entirely consistent with a cloud

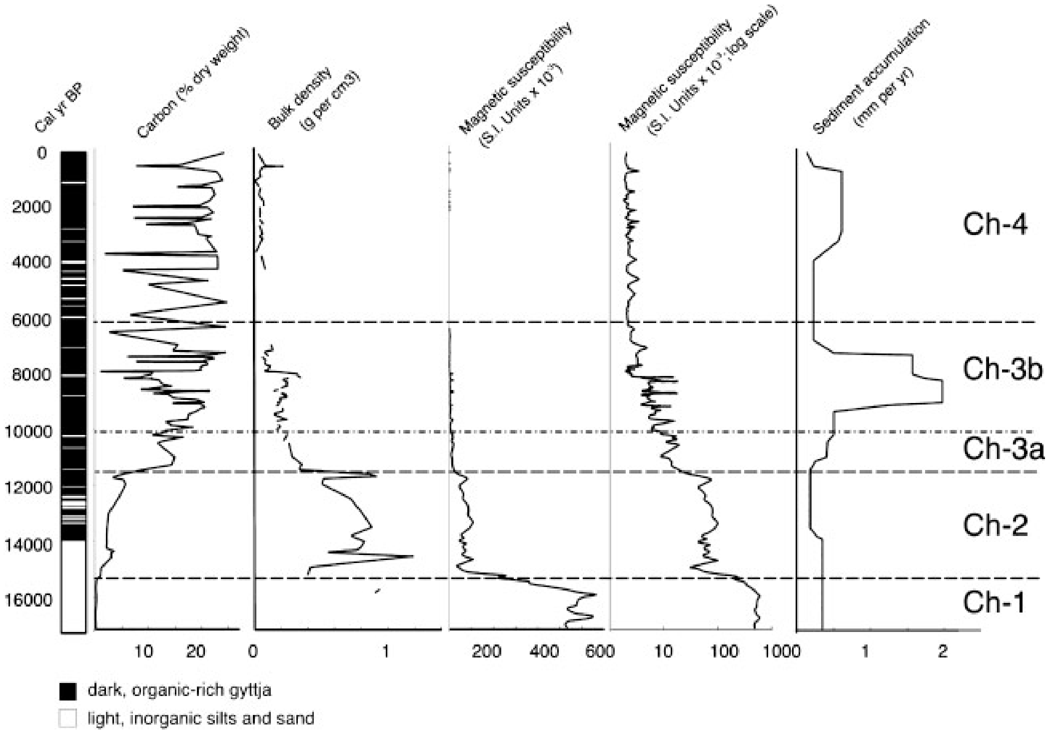

Figure 3 Physical characteristics of the core recovered from Lagune de Chochos, Peru, showing stratigraphy, percentage carbon, bulk density, magnetic susceptibility (ordinal and log-scaled), rates of sedimentation, and the zonation

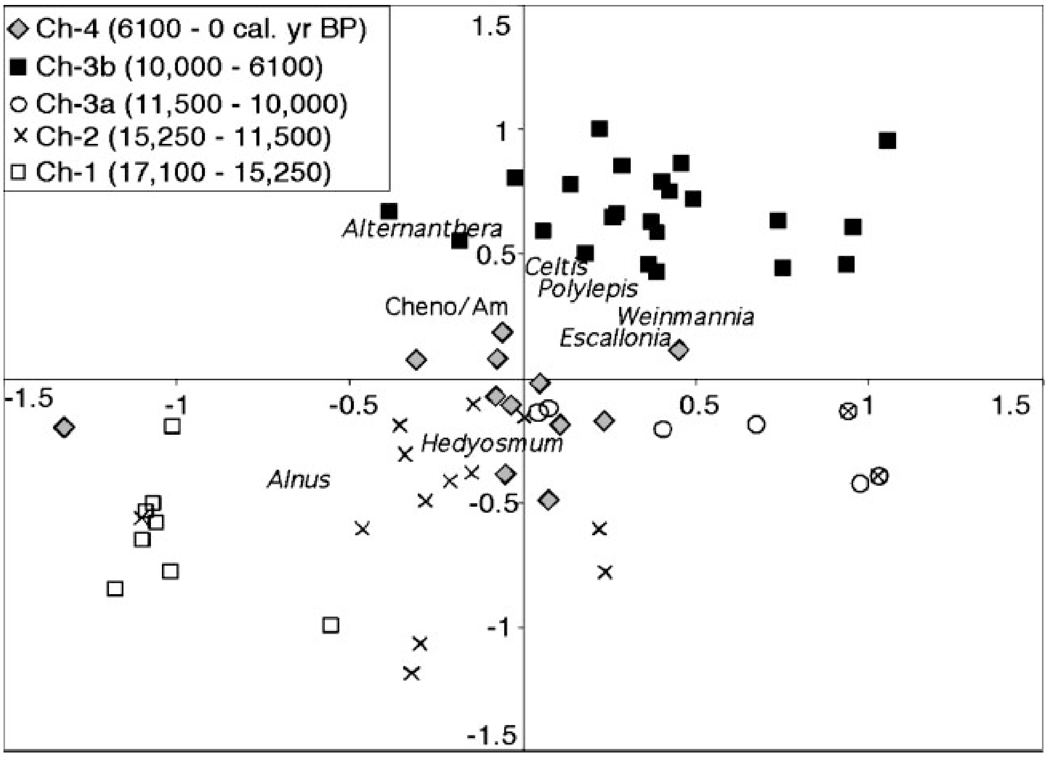

Figure 4 Results of a non-metric multivariate scaling (NMS) analysis, Axes 1 versus 2, for the samples ordination of selected fossil pollen taxa (pollen types shown in Fig. 5) from Laguna de Chochos, Peru. Samples are divided into their respective zones based on sedimentary characteristics. Samples with a cross superimposed on a circle with an asterisk are 'misplaced samples' placed at the upper limit of one zone, but whose NMS placement suggests affinity with the immediately overlying zone. Species that characterised these axes are shown by their relative placement

forest, but in the light of very low pollen influx these probably represent updraughted pollen grains into a largely barren environment. The greater abundance of small (<100 μm), rather than large (>100 μm), charcoal fragments suggests that this signal could also represent long range transport.

Ch-2 (8.20–7.17 m; ca. 15 250–11 500 cal. yr BP)

This zone is characterised by an order of magnitude reduction in the MS susceptibility and an estimated rate of sediment accrual of ca. 0.4 mm yr^{-1}. Fossil pollen influx and

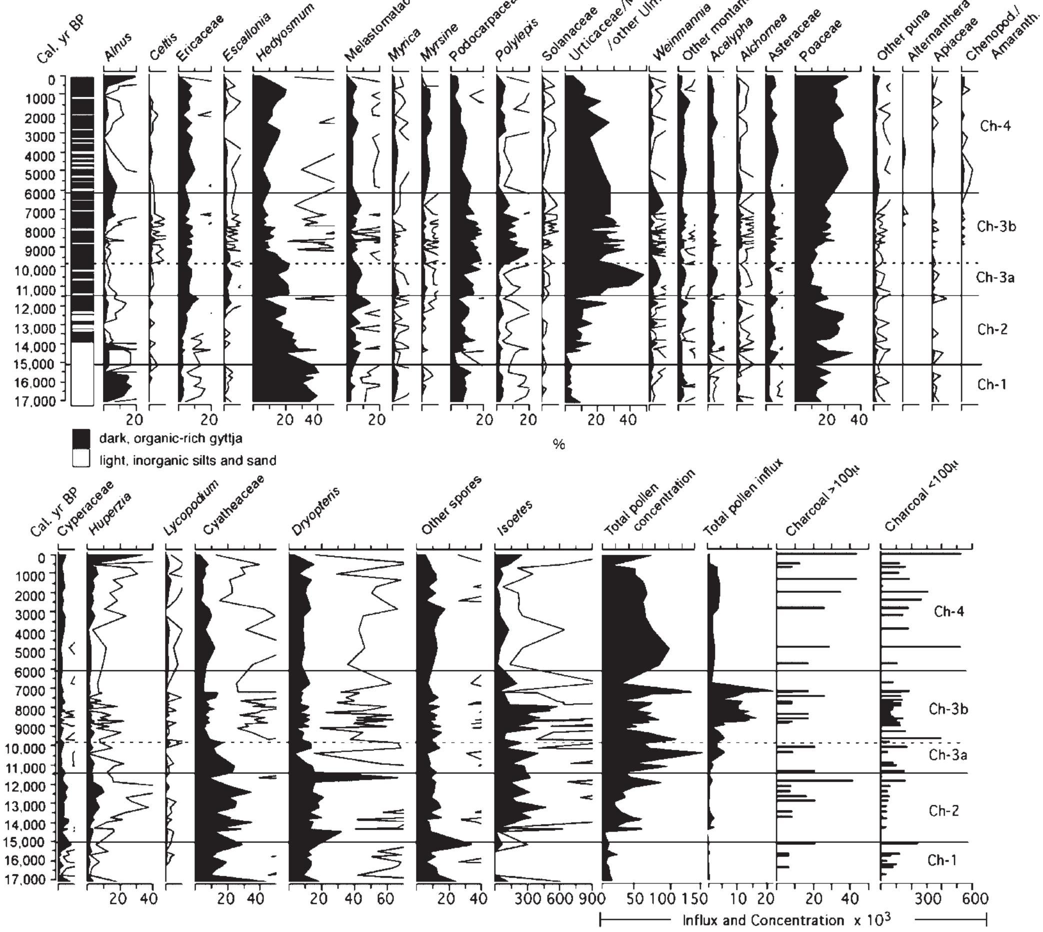

Figure 5 Selected fossil pollen and spores taxa and charcoal data from Laguna de Chochos. Note the *x*-axis scale for *Isoetes* has a more compressed scale than other taxa. Urticaceae/Moraceae/Ulmaceae are expressed as a percentage of the total terrestrial pollen sum, all other taxa are expressed as a percentage excluding Urticaceae/Moraceae/Ulmaceae

concentration are initially similar to that of the preceding zone, but both increase at ca. 14 400 cal. yr BP. Within this zone the pollen of montane forest species decline in abundance as Poaceae increase in abundance. *Isoetes* spores increase in abundance at ca. 14 400 cal. yr BP and account for >300% of total pollen. Large fragment charcoal abundance is somewhat higher and more consistently present in the upper portion of this zone than in Ch-1. A spike of

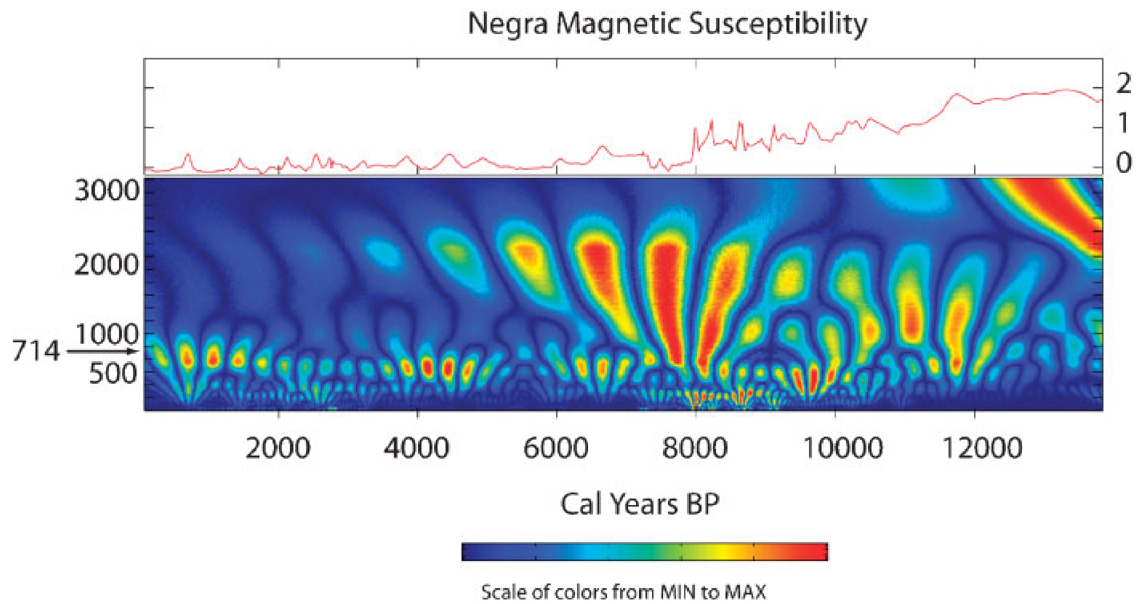

Figure 6 Wavelet analysis of magnetic susceptibility data from Laguna de Chochos based on a 20-yr sampling regime. During the early Holocene dry event a ca. 1600-yr periodicity is a strong feature of this record. A 500–700-yr cycle is apparent for much of the Holocene, and a statistically significant 216-yr period is evident in the early and late Holocene

Dryopteris type spores occurs in the uppermost sample of this zone preceded by a peak in large and small charcoal fractions.

Ch-3a (7.17–6.65 m; ca. 11 500–10 000 cal. yr BP)

A further strong reduction in MS characterises the onset of this zone and carbon content increases to ca. 15%. An overall decline in MS within this zone is interrupted, apparently rhythmically, by pulses of elevated MS. Influx values exhibit a two-step increase, with the first rise occurring at ca. 10 200 cal. yr BP and the second, a more marked increase, at ca. 8700 cal. yr BP. This event coincides with highest rates of sediment accumulation, and as sedimentation slows at 7300 cal. yr BP, influx rates fall abruptly. The onset of zone Ch-3a is marked by a rise in the abundance of the pollen of montane forest species, e.g. *Podocarpus* and *Hedyosmum*. The onset is also marked by a rise in Cyatheaceae, but this spore then declines in abundance through this zone. *Isoetes* spores exhibit an erratic record but increase in abundance to >600% of the pollen sum, and their proportional input is correlated with high sedimentation rates that contribute to the apparently high rates of pollen influx.

Ch-3b (6.65–2.50 m; ca. 10 000–6100 cal. yr BP)

This zone is composed of organic-rich sediment (>20% C), but strong bands of elevated MS coincide with very inorganic sediments (<10% C). Sediment accumulation accelerates from ca. 0.5 mm yr^{-1} to ca. 2 mm yr^{-1} after 9400 cal. yr BP, before falling back to about 0.5 mm yr^{-1} at 7300 cal. yr BP. Pollen concentration and influx have markedly different patterns within this zone. Concentrations are variable during this zone ranging from ca. 40 000 to 120 000 grains per cm^3. Floristically, this zone is characterised by an increase in *Polylepis* and *Poaceae* pollen abundance as *Hedyosmum* declines.

Ch-4 (2.50–0 m; 6100–0 cal. yr BP)

This zone is characterised by the stabilisation of MS susceptibility at low levels; however, a marked oscillation is evident even within these low values. Again percentage of carbon and MS are inversely correlated. Charcoal abundance increases within this zone and small fragments are consistently present at relatively high concentrations while the large fragment record oscillates (Fig. 5). Poaceae increase in abundance and attain modern percentages between 5000 and 4500 cal. yr BP. Around 2000 cal. yr BP a slight resurgence of cloud forest taxa is evident, including *Hedyosmum*, Melastomataceae, *Podocarpus*, *Polylepis*, *Weinmannia*, and the spore *Huperzia*. In the uppermost sample of the core peaks of *Alnus*, Poaceae, and *Huperzia* and charcoal, represent the highest Holocene values of each.

Wavelet analysis

All three proxies analysed (MS, organic carbon and bulk density) showed periodicities that varied in intensity through time. Magnetic susceptibility showed significant oscillations with 500–700-yr periodicity, and a more variable oscillation with a ca. 216-yr periodicity that was strong from modern to ca. 2900 cal. yr BP, weak or absent from 3200 to 6400 cal. yr BP, and strong again from 8000 to 10 000 cal. yr BP (Fig. 6). The major features common to the bulk carbon and organic carbon proxies were a 1480- to 1700-yr oscillation that gradually changed periodicity ca. 1200 yr after 8000 cal. yr BP.

Discussion

The Laguna de Chochos core documents the deglaciation and subsequent re-vegetation of a lake catchment lying near the modern upper limit of Andean cloud forest. The deglaciational phase is evidenced in the onset of lake formation, which is probably coincident with retreat of an ice-tongue at ca. 17 000 cal. yr BP. Cloud forest replaced a glacial foreland habitat about 15 100 cal. yr BP and deglaciation was locally complete at ca. 11 500 cal. yr BP.

The earliest sediment deposited into the lake is rich in rock-flour and has very high MS values (Fig. 7). The overall landscape at this time was a glacial foreland with correspondingly low pollen input to the lake. Such conditions of low local productivity coupled with input from long distance dispersal serves to elevate a few anemophilous pollen types in the percentage data, yielding proportions that do not reflect local vegetation (e.g. Bush, 2000; Hansen *et al.*, 1984). From the low pollen influx and charcoal values we infer that the initial deglacial conditions were markedly cooler than today with low to moderate precipitation, and that there was not enough vegetation biomass to sustain fire.

A progressive increase in pollen concentrations and charcoal suggests a corresponding increase in vegetative cover and biomass between ca. 15 000 cal. yr BP and 11 000 cal. yr BP. A similar pattern has been recorded in other high Andean records, e.g. Titicaca (Paduano *et al.*, 2003), Junin (Hansen *et al.*, 1984, 1994), and Surucucho (Colinvaux *et al.*, 1997). The Chochos record also closely parallels that of nearby Laguna Baja, lying about 200 m upslope of Chochos in an adjacent westward-draining valley.

Laguna Baja started to accumulate sediment about 15 300 cal. yr BP and shows a similar initial pattern of pollen deposition to Chochos, with the same unusual mix of Poaceae, Cyatheaceae, and *Hedyosmum* in a glacial foreland, or sparse *puna*, landscape. As conditions warmed, vegetation density increased at Baja, and by ca. 13 000 cal. yr BP biomass was sufficient to carry fire in a *puna* landscape. At Laguna de Chochos, a little further downslope, the first increase in pollen concentration signifying elevated productivity occurred a little earlier, at ca. 14 000 cal. yr BP, than at Laguna Baja. However, conditions were still markedly cooler than present as the habitat of *puna* with tree ferns and *Hedyosmum* was maintained until ca. 11 500 cal. yr BP. In both records this period prior to 11 500 cal. yr BP was wet.

The period of the Younger Dryas event (12 600–11 500 cal. yr BP) is not marked by an obvious glacial readvance according to the Chochos data, nor is there evidence of cold-air drainage influencing the vegetation. Indeed, based on the fossil pollen data, this period appears to have been a rather warm dry episode, with relatively high pollen concentrations and a peak in the fern *Dryopteris*. The NMS analysis of the fossil pollen data produced two axes that are broadly interpreted to indicate increasing temperature (Axis 1) and decreasing moisture availability (Axis 2) (Fig. 7). However, the presence of the Younger Dryas, though not fully constrained by ^{14}C dates at Laguna Baja, is suggested to have caused a cooling (Hansen and Rodbell, 1995). In both data sets a significant

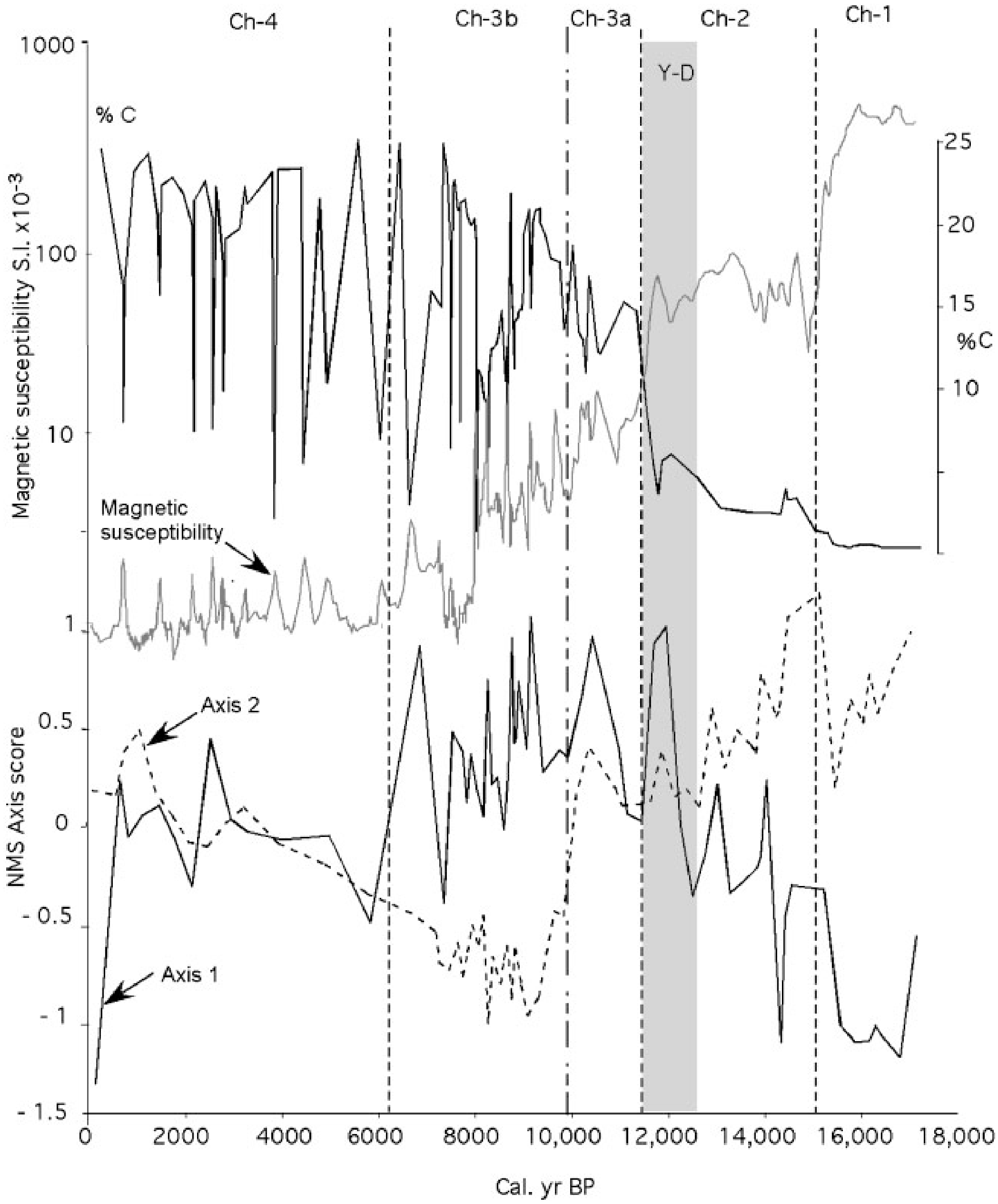

Figure 7 Synthesis of data from Laguna de Chochos showing the temporal variability of magnetic susceptibility, percentage carbon content, and NMS Axes 1 and 2 sample scores plotted against time. Vertical lines depict the zonation of the record and the shaded area represents the Younger Dryas period (12 600–11 500 cal. yr BP)

climatic change took place at 11 500 cal. yr BP, coincident with the end of the Younger Dryas.

In Lagunas de Chochos and Baja a warming is signalled by the arrival of cloud forest to both sites at 11 500 cal. yr BP. This event correlates closely with the deglaciation of up-valley cirques, ca. 7 km west of and 550 m higher than Laguna de Chochos, which was largely complete by this time (Rodbell, 1993a). This period is marked by a peak of *Podocarpus* pollen (>35%) in Laguna Baja and a broader array of forest taxa, with Urticaceae/Moraceae/Ulmaceae (almost certainly Urticaceae, or *Lozanella* in the Ulmaceae, at this elevation), *Hedyosmum* and Cyatheaceae, as prominent pollen types. Local charcoal (>100 μm) abundance drops in both records indicating a warm, wet climatic phase in which forest line had risen above 3500 m elevation and fire was rare.

As temperatures continued to rise in the early Holocene, precipitation either remained constant or fell, resulting in another transition in both the Baja and Chochos records. While the message is the same, a warm, dry event, its manifestation is a little different. In Laguna de Chochos, this interval is characterised by a dramatic increase in the abundance of *Isoetes* spores. *Isoetes* is a fern ally genus that exists in the shallows and marsh fringes of many Andean lakes. This taxon does not grow at a water depth of more than 4 m and is sensitive to hard freezes (Ybert, 1988). Consequently, *Isoetes* is a good proxy for the existence of a shallow lake, or extensive shallow margins. Today the predominant aquatic plant in the lake is *Isoetes lechleri*. Three additional *Isoetes* species grow in the study area today (*I. andicola, I. andina, and I. novo-granadensis*), but these are relatively uncommon terrestrial herbs growing in saturated soils. Consequently, we use the abundant *Isoetes* as a proxy for the existence of a shallow lake, or extensive shallow margins. Based on the *Isoetes* abundance data, which are independent of the NMS results as *Isoetes* was excluded from the analysis, the Laguna de Chochos lowstand lasted from ca. 9500 to 7300 cal. yr BP, with a peak at ca. 8700 cal. yr BP.

A further indicator of the timing of the dry event is *Polylepis*. This pollen type peaked during the Holocene dry period at Titicaca ca. 4500 cal. yr BP (Paduano *et al.*, 2003; Hanselman *et al.*, 2005). At Laguna de Chochos, *Polylepis* has its maximal abundance between 10 000 cal. yr BP and 7300 cal. yr BP (Fig. 5), with an absolute maximum occurrence at ca. 9200 cal. yr BP. The inferred drier and warmer climate of this interval is consistent with the presence of forests with *Polylepis* and Podocarpaceae. The *Polylepis* currently around the lake, *P. pauta*, is an occasional element of the upper montane cloud forest. However, *P. racemosa* is in the area today on the western side of the divide, although relatively uncommon. The rather open *Polylepis* woodlands amid a tropical alpine grassland, while without exact modern analogue, resemble some modern forests formed by *P. racemosa.*

The *Isoetes* and *Polylepis* data provide a robust overall image of a warm dry event that resulted in the greatest net moisture deficit ca. 9000 cal. yr BP. It is important to note that peaks in MS indicate a number of discrete wet events within this dry cycle. Particularly intense storms or other erosive events may have elevated clastic sedimentation. Consequently, these pulses of iron-rich material may not represent prolonged changes in precipitation. These wet episodes provide the 1600-yr rhythm evident in the wavelet analysis. A similar pattern of overall dry interrupted by wet events was also suggested for the mid-Holocene dry event at Titicaca (Paduano *et al.*, 2003).

Species of humid montane forest characterise the negative extreme of Axis 2 of the NMS analysis, while the positive extreme is characterised by marsh, and drought-hardy species. This axis appears to reflect a gradient of decreasing moisture availability and reflects this early Holocene event as the strongest drought in this record (Axis 2 is inverted in Fig. 7 to make reading it more intuitive).

The transition out of the lake lowstand phase is marked by the decline of *Isoetes* at 7300 cal. yr BP. A further transition, possibly to even wetter conditions, is evident at ca. 6100 cal. yr BP as *Isoetes* and *Polylepis* continue to decline in abundance, and Poaceae increase in importance.

In comparison with this history, the effect of the dry event is evident, but possibly more muted at Laguna Baja. *Podocarpus* starts to decline in abundance ca. 9500 cal. yr BP as local fires increase in occurrence. By ca. 9000 cal. yr BP *Alnus* and other upper montane elements have become important floral components, consistent with a drier and more fire-disturbed setting. *Isoetes*, declines slightly in abundance and these are taken by Hansen and Rodbell (1995) to indicate drier conditions. Around 6000 cal. yr BP the period of *Alnus*-rich forest ends with an increase in Poaceae, Chenopodiaceae/Amaranthaceae (hereafter Cheno/Ams) and a little later an increase in *Miconia*-type pollen (Melastomataceae).

Treeline and human activity

Treeline in the Andes is often fire-sensitive, and is probably artificially lowered by human activity. Fires, as recorded with large and small charcoal fragments are found throughout the 17 000-yr record, showing that fire is an important ecological process acting upon Andean landscapes, even those under perhumid conditions. The charcoal in the sediment of the 8000–9000-yr event could conceivably represent evidence of the first human presence in shaping the landscape. However, an alternative that fits the data is that these were natural fires that burned because the study area was drier or at least more seasonal.

The ample evidence of charcoal throughout the last five thousand years, corresponds to times when archaeologists can date the presence of first hunters and gatherers, then farmers and herders, in the area. Today, local people burn even very humid grassland areas in the study area by choosing the several weeks a year to set a fire that are dry enough to carry the flames (Young, 1993a). The charcoal in modern sediments of Chochos lake is associated with cattle-raising, a land use that has a least a century-long history in the area.

Two possible interpretations, that are not mutually incompatible, can be raised to explain observed changes in the abundance of tree taxa in the pollen record post-7300 cal. yr BP at Laguna de Chochos. First, as the thermal optimum of the early Holocene gives way to cooler temperatures the upper forest limit would be expected to migrate downslope. Declines in the pollen abundance of *Alnus*, Melastomataceae, *Weinmannia*, and *Podocarpus* are all consistent with forest retreat. *Hedyosmum*, which was strikingly abundant during deglaciation, re-emerges as an important taxon. That Poaceae representation and charcoal increase throughout this period is similarly consistent with the formation of a parkland-like habitat, subject to periodic fire, at the ecotone between forest and sub-*puna*. The increased occurrence of fire probably contributes to the decline of *Polylepis*.

The second interpretation could include a human element. Elsewhere in the Andes once the mid-Holocene drought ends, human populations expand rapidly and are engaged in landscape modification (e.g. Binford *et al.*, 1996; Brenner *et al.*, 2001). Local deforestation could also induce many of the above changes. No crop pollen was found in these assemblages, although the appearance of Cheno/Ams could represent the arrival of agricultural weeds or cultivation of quinoa (*Chenopodium quinoa*). However, in a site at a similar elevation where quinoa cultivation is thought to have occurred, at Marcacocha, Cheno/Ams pollen accounts for 10–25% and *Ambrosia*-type pollen, a common weed accompanying landscape disturbance, accounts for as much as 90% (Chepstow-Lusty *et al.*, 2003). At Laguna de Chochos, pollen abundance of these taxa rarely rises above 1%. The relatively low percentage of Poaceae pollen (ca. 20%) compared with >40% in many *puna* settings (e.g. Hansen *et al.*, 1984; Paduano *et al.*, 2003) suggests that forest patches are still important components of this landscape. The intermittent fire history, i.e. six samples with zero >100 μm charcoal versus eight samples containing some of this size fraction in the last 6000 yr, is consistent with occasional use of this site by humans. Tentatively, we infer that if people were present in this landscape their influence on it was modest prior to modern times.

Church (1996) excavated a rockshelter in the adjacent valley that contains Laguna Baja. His oldest dated material in the cave was charcoal from 12 000 cal. yr BP. Dated layers from ca. 4500 cal. yr BP contain stone tools, while numerous hearths were found in the cave at higher layers with dates from ca. 1300 to 4000 cal. yr BP. The deposits that were about 4500 yr old contained bones from large mammals such as deer and numerous *Festuca* seeds, suggesting hunting and the gathering of wild plants in the vicinity of the cave. The more recent layers included bones of small mammals such as guinea pigs and remains of cultivated plants. Church (1996) considered the toolkits and biotic remains and concluded that travellers were using the cave for short time periods. These activities are possibly recorded in the Chochos lake sediments with increased charcoal and minor amounts of weedy plant taxa pollen, and are consistent with our inference of low-intensity use.

By about 1500 yr BP, Lennon *et al.* (1989) and Church (1994) report evidence from dated archaeological sites that the montane forests near Chochos (sites known within 5 km) were inhabited. Anthropogenic influence of the deforestation that would have resulted is not apparent in the Chochos sediment record, but may have caused some of the fluctuations in relative abundances of the cloud forest taxa.

Fires set by people in the high elevation grasslands today promote the resprouting of the *Calamagrostis* and *Festuca* tussocks and favour the low-growing *Paspalum pallidum*, which are nutritious and sought after by cattle (Young, 1993a). The burning makes access in these dense grassland much easier for people and removes many of the woody plants, thus acting over time to keep treelines at lower elevations than would occur due to strictly climatic controls. The results can be seen today in landscape patterns of tree-less valley bottoms in places where forest patches dominated by *Escallonia* and *Weinmannia* are found on valley slopes and protected rocky places (Young, 1993b).

The pollen in the uppermost layer of the Chochos lake represents these landscape and land-use patterns, and is seen in decreased presence of cloud forest taxa around part of the lake, increased presence of Poaceae, and more input of *Huperzia* and *Alnus*, the latter due to pollen rain from trees at least 10 km away on the western side of the divide.

The uppermost sample of the core is quite different to those that precede it. Intensified fire regimes, promoting Poaceae and *Alnus*, and a substantial reduction in forest elements are reminiscent of pollen assemblages documented from the Inca occupation phase at Marcacocha (Chepstow-Lusty *et al.*, 2003). It seems very probable that intensified human land use is manifested in this sample. The effect of the clearance, and ecological simplification of the habitat, causes this uppermost sample to plot close to the Lateglacial samples in both the NMS and DCA analyses.

Again, these observations are entirely consistent with the Laguna Baja record that is interpreted to reflect occasional human use in the last 6000 yr with an abrupt increase in activity in the last 1200 yr (Hansen and Rodbell, 1995). From the greater percentage of Poaceae (ca. 40%) in the Laguna Baja record than at Chochos, it is inferred that the forest limit lay between these two sites for much of this time, although it cannot be discounted that the apparent gradient of openness was a function of human activity.

Mid-Holocene warm oscillations and cyclic forcing

The precessional periodicity of 19 000 and 22 000 years has been shown to be important to Andean lake levels (Baker *et al.*, 2001b) and the possibility that the mid-Holocene dry events are time-transgressive, tracking the nadir of January insolation, has been suggested (Abbott *et al.*, 1997b, 2003). In the Altiplano and Central valleys of the Andes, the length and intensity of the South American Summer Monsoon (SASM) is an important determinant of lake level. As SASM is so strongly reliant on convection, January insolation is a believable proxy for its strength. Both the peak of the early Holocene dry event and its termination are substantially earlier than those documented at Titicaca (5500–6000 cal. yr BP for the peak, and 4500 cal. yr BP for the termination (Baker *et al.*, 2001b)). Given that Titicaca lake-level response may be biased to its northern (wetter) catchment at 14 °S, the area that primarily determines its lake-level is separated from Laguna de Chochos by about 7 ° of latitude. Thus, if the peak of the event at Chochos is at ca. 9000 cal. yr BP and at about 5500 cal. yr BP at Titicaca, it would confer a ca. 2 ° latitude per millennium drift in the dry event. Such a rate of change is somewhat faster than the ca. 1 ° latitude per millennium suggested by the observations of Abbott *et al.* (2003) and is certainly worth closer investigation.

Despite that pattern, it is also important to note that all the sites documented by Abbott *et al.* are controlled by SASM, whereas the moisture flow to Lagunas de Chochos and Baja are due to diurnal cloud formation on the Andean slope and are not monsoonal in nature. It is probable, therefore, that these records could reflect a broader availability of moisture, or changes in the duration of diurnally forming cloud at the Holocene thermal optimum. Comparison of the Chochos record with other sites that are not wholly reliant on monsoonal precipitation would be especially valuable in determining regional patterns.

Shorter wavelength oscillations in the climate are also evident in the Laguna de Chochos dataset. The MS and organic carbon data from Laguna de Chochos were individually analysed for periodicity using wavelet analysis. As percentage carbon content is likely to be affected by inwash of mineral-rich clastics that have high MS values, and as the MS data offered a finer temporal resolution, the MS data are reported here.

The periodicities that were most significant were a 216-yr and 500–700-yr cycle. Both of these cycles waxed and waned in intensity during the Holocene with the 216-yr cycle strongest in the last 3000 yr and between 8000 and 10 000 cal. yr BP. This cycle is statistically indistinguishable from the 208-yr solar cycle (Baliunas and Jastrow, 1990) and may suggest that strong precipitation events under early Holocene and modern conditions are underlain by variability in solar output. This periodicity has previously been shown to be of importance in Central American precipitational patterns (Hodell *et al.*, 1995, 2001) but has not previously been identified in the Andes.

The longer cycle of ca. 500–700 yr could be an unidentified cycle, or may be a compounded signal of multiple shorter wavelength events, e.g. the 88-yr solar cycle. Such a cycle also fits with two hypothesised droughts in the Andes at ca. AD 600 (ca. 1350 cal. yr BP) and AD 1100 (ca. 850 cal. yr BP) (Chepstow-Lusty *et al.*, 2003). Similarly the periodicity that is revealed as a ca. 1600-yr cycle is probably a compounded signal, but suggests an intensification of climatic variability within the period from ca. 6000 to 10 000 cal. yr BP.

Conclusions

The Laguna de Chochos core provides a detailed record of the deglaciational and Holocene environments close to the upper forest limit on the eastern Andean flank. A high degree of correlation is evident between this record and a previously published record from nearby Laguna Baja, though the sensitivity of Laguna de Chochos to early Holocene climate change allowed us to confirm some of the more tentative conclusions reached by Hansen and Rodbell (1995).

The late glacial period was cool and moist, and vegetation was sparse on the glacial forelands. Once vegetation had established and productivity increased, a *puna* vegetation without exact modern analogue established at the site. Warming coincident with the termination of the Younger Dryas caused treeline to rise to above 3560 m above sea level (the elevation of Laguna Baja) at 11 500 cal. yr BP. A warm wet early Holocene was interrupted by a dry event that lasted from ca. 9500 to 7300 cal. yr BP. This event is considerably earlier than those previously recorded in the Altiplano and Central Andean valleys.

After the thermal optimum associated with the early Holocene, the upper forest limit appears to have been located between Lagunas Baja and Chochos, although anthropogenic clearance of forest on the *puna*/forest ecotone cannot be eliminated as a possibility. Although charcoal is unusually abundant for a forested setting in the Andes within the last 6000 years, its intermittent occurrence in the Laguna de Chochos record suggests low intensity, if any, use by humans. Only the uppermost samples show the marked simplification of the landscape that characterises modern human usage.

Pulses of inwashed clastics in the sedimentary record provided an MS record that probably reflects the 208-yr cycle in solar output. It is important to note that such forcing mechanisms are relatively subtle and can easily be masked by other events causing them to appear to come and go within the record.

Acknowledgements This research was funded by grants from the US National Science Foundation to D.T.R. (EAR-9418886 and ATM-9809229) and G.O.S. (EAR-9422424 and ATM-9813969), K.R.Y. (SES-8713237), and M.B.B. (DEB-0237573).

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