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Contrasting pollen histories of MIS 5e and the Holocene from Lake Titicaca (Bolivia/Peru)

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ABSTRACT: Two long sediment records (cores LTO1-2B and LT01-3B) from Lake Titicaca, Bolivia/Peru, are compared with a previously analysed Holocene record from this lake (core NE98-1PC). The Holocene records of LT01-2B and NE98-1PC are similar. There are striking differences, however, between the MIS 5e sections of the long cores and the Holocene records. In these records, temperature is probably the dominant parameter that determines the total fossil pollen concentration and is used to time the onset and termination of deglaciation. In contrast, the relative and absolute abundance of specific taxa (e.g. *Polylepis/Acaena,* Chenopodiaceae) are indicators of relative moisture availability. Although the Holocene contains a period of aridity between ca. 8000 cal. yr BP and 4300 cal. yr BP, it is a minor event compared with the more extreme aridity of MIS 5e. Core LT01-3B showed similar trends during MIS 5e when compared to LT01-2B, as did NE98-1PC when comparing Holocene records. MIS 5e and the Holocene are markedly different interglacials, depicted by shifts in pollen concentration and taxa representation over time. Copyright © 2005 John Wiley & Sons, Ltd.

KEYWORDS: fossil pollen; Chenopodiaceae; DCA; interglacial; Huiñaimarca.

Introduction

The comparison of our present interglacial with records from earlier interglacials may help improve our understanding of the overall climate system and whether or not the Holocene is a typical warm period. Of particular interest is whether, despite some orbital dissimilarities, Marine Isotope Stage 5e (MIS 5e) could be an approximate analogue for the Holocene without human landscape modification.

The suggestion that MIS 5e was radically different in terms of stability to the Holocene was first postulated after the recovery of the GRIP ice core (GRIP Project Members, 1993; Johnson *et al.*, 1995). This record, subsequently discounted (Bender *et al.*, 1994; Chappellaz *et al.*, 1997), was thought to show rapid climate fluctuations within the last interglacial period in contrast to a stable Holocene. Even though the MIS 5e portions of the Greenland ice core records are now considered to be unreliable due to disturbance in the stratigraphy, other records suggest that there was more climatic variation in MIS 5e than in the Holocene (Okuda *et al.*, 2002; Tzedakis, 2003).

The last interglacial is usually defined as lasting from 137 000–120 000 cal. yr BP (Jouzel *et al.*, 1993; Petit *et al.*, 1999; Shackleton, 2000; Tzedakis, 2003). In many of these records, MIS 5e started abruptly, peaked within 10 000 yr, and then after a sharp initial drop in temperature, transitioned into glacial conditions. At a global scale, the onset of the Holocene was very similar to that of MIS 5e, as in atmospheric CO_2 content rose from ca. 190 ppm during the preceding ice-age to ca. 260 ppm during the interglacial, and partial pressure of methane rose from 400 ppbv to 700 ppbv within a few thousand years (Petit *et al.*, 1999). Similarly temperature rose sharply at the onset of each event. Of particular interest is the peak in temperature during MIS 5e, which is generally thought to have been ca. 2 °C warmer than present (Lorius *et al.*, 1983; Barnola *et al.*, 1987; Genthon *et al.*, 1987; Jouzel *et al.*, 1987; Petit *et al.*, 1997, 1999).

Few terrestrial records are available to compare the vegetation and community composition of the Holocene with MIS 5e from within the same continuous record, this is especially true in the Southern Hemisphere. One of the few sites that does exist is the record from ODP Site 820, located 45 km off the coast of northeast Australia, but it is suspected that portions of the last interglacial are missing from this record (Moss and Kershaw, 2000). From the available material, Moss and Kershaw (2000) use fossil and modern pollen data to suggest that MIS 5e began abruptly, with increases in temperature and precipitation. Changes in pollen data occurred throughout the interglacial, and they found that the later portion of MIS 5e to be similar to the Holocene (Moss and Kershaw, 2000). In contrast to this picture of similarity, a record from the New Zealand lowlands shows elevated abundances of forest elements during MIS 5e, relative to Holocene (Okuda *et al.*, 2002). This is interpreted as indicating higher moisture availability during MIS 5e even though temperature is thought to be similar.

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Dissimilarities between interglacials are also found in the Northern Hemispheric Andes. The 650 000 yr Funza-I record from Colombia shows a warm and wet MIS 5e, inferred from the increased presence of sub-Andean elements in the pollen record (van't Veer and Hooghiemstra, 2000). No direct comparison can be made to the Holocene at this site, as the lake dried out during the late Pleistocene, and Holocene sediments were not deposited. Other cores that provide Holocene records from this section of the Colombian Andes characterise the current interglacial climate as warm but, in contrast to MIS 5e, dry (Mommersteeg, 1998; van der Hammen and Hooghiemstra, 2003).

The reasons and the extent of these differences is currently a topic of debate. One possible contributing factor is the postulated climatic teleconnection between the Altiplano and the Hill of Six Lakes (0° latitude) in northern Amazonia at the time of the Last Glacial Maximum (LGM). The Hill of Six Lakes provided an 170 000 yr record of precessionally driven lake level, in which January insolation was positively correlated with lake level (Bush *et al.*, 2004). During the LGM both the Hill of Six Lakes and the Altiplano (Baker *et al.*, 2001a) were deduced to be wet, but both experienced a multi-millennial dry event centred on 33 000 cal. yr BP (Bush *et al.*, 2004). The climatic linkage between these areas is provided by the Andean low level jet (LLJ) and the South American Summer Monsoon (SASM). The LLJ transports moisture south from equatorial latitudes in Brazil, and feeds the deep convection that drives wet season (austral summer) precipitation over Amazonia. As the SASM gains strength, some of this convected moisture is entrained to flow westwards over the Andes and thereby brings rain to the Altiplano.

The Salar de Uyuni, which lies south of Titicaca within the Altiplano, shows a pattern of high and low lake stands that appear to follow the variation of insolation maxima during the austral summer (January insolation at 16° S (Berger, 1992)). This precessional forcing apparently underlies lake level between 11 000 and ca. 70 000 years ago (Baker *et al.*, 2001a, 2001b; Fritz *et al.*, 2004; Chepstow-Lusty *et al.*, 2005). Prior to this time, the climate appears drier, or the basin tectonically different, so that although the sediments of the Salar de Uyuni pre-date MIS 5e, low lake levels and gypsum deposition predominate, and the precessional signal is lost.

Another potential teleconnection is the strength and periodicity of the SASM over the last 116 000 yr, supported by a speleotherm record from Botuverá Cave in subtropical Brazil (27°13′24″ S; 49°09′20″ W; Cruz *et al.*, 2005). Here a strong precessional cycle is evident in the δ^{18}O record, suggesting different sources of moisture to the cave. The timing of late Pleistocene lake stands on the Altiplano are explained by a precessionally forced SASM. As neither the record from Botuverá Cave, nor the precessional signal of the Salar de Uyuni extend back to MIS 5e, we hypothesise that if the teleconnection to northern Amazonia is preserved, the MIS 5e would have been dry on the Altiplano. Such a prediction emphasises that the long palaeoclimatic records from the High Plain of Bogotá in the northern Andes (4–5° N) and from Titicaca in the Central Andes (16–18° S) are hydrologically antiphased.

Palynological data from two Lake Titicaca (Bolivia/Peru) fossil pollen records, the main basin (LT01-2B) and Huiñaimarca (LT01-3B), and a Holocene record from the main basin NE98-1PC (Paduano *et al.*, 2003) provide evidence of both temperature and precipitation variation during the Holocene and the previous interglacial. These data allow us to investigate aspects of similarity and dissimilarity in the expression of these interglacials and whether the climatic teleconnections between Amazonia and the Andes had begun by MIS 5e.

Methods

Site description

Lake Titicaca (16° to 17.50° S, 68.5° to 70° W; 3810 m; Fig. 1) currently covers ca. 8500 km^2 of the Altiplano and separates

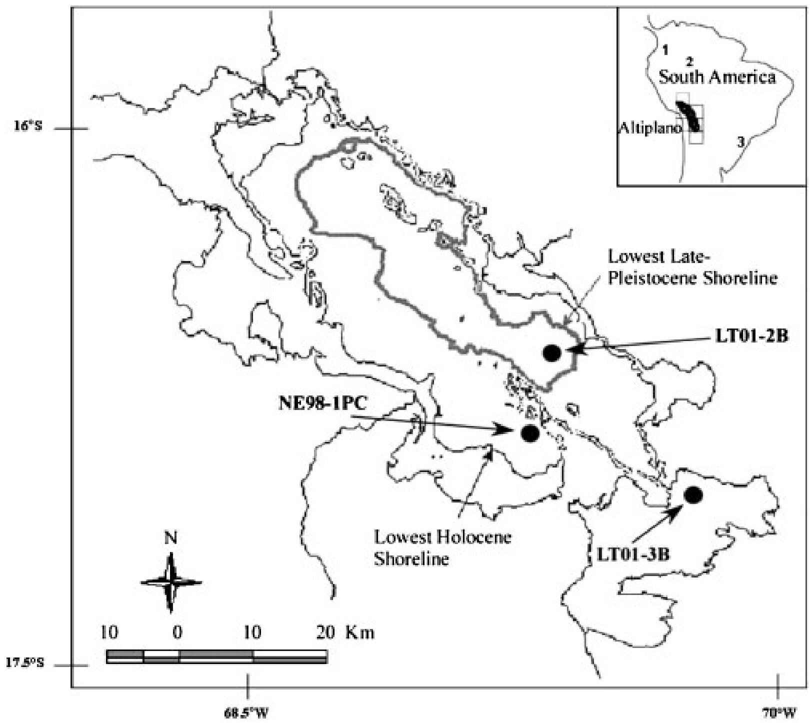

Figure 1 Map adapted from D'Agostino (1999) to show the coring locations with reference to changes in lake level. The Altiplano includes Lake Titicaca to the north and Salar de Uyuni to the south. South American sites discussed were included on the map for reference: Colombian sites (1), Hill of Six Lakes, Brazil (2), Botuverá Cave, Brazil (3)

the Cordilleras Oriental and Occidental, bordering Peru and Bolivia. Titicaca is considered to be a closed basin in most hydrological studies despite its outflow through the Rio Desaguadero south into Lake Poopó. Due to its vast volume relative to the small discharge, and that its discharge is contingent upon a lake highstand (Seltzer, 1990).

The Altiplano is semihumid to the north of Lake Titicaca, and increasingly arid to the south (Lenters and Cook, 1997). Beyond Lake Poopó in the southern Altiplano, the salars Uyuni and Coipasa are modern saltpans, though they supported lakes within the Late Pleistocene and early Holocene. Today the Andes exhibit low mean monthly temperature variation, but relatively high diurnal variation. Diurnal change could be as high as 25 °C in the southern Andes through the months of June, July and August (Seltzer, 1990).

Precipitation on the Altiplano generally occurs during the summer months, particularly December, January and February (DJF), because the moisture from the east is drawn in by strong convection. Due to upper air circulation (Ariztegui *et al.*, 1997), easterly flows favour wet conditions and westerlies favour dry conditions (Seltzer, 1990; Servant-Vildary and Mello e Sousa, 1993; Garreaud *et al.*, 2003; Servant and Servant-Vildary, 2003). As much as 65–78% of the 889 mm annual precipitation that regularly falls on Titicaca (829 mm on Huiñaimarca) is received in DJF (Roche *et al.*, 1992). The seasonality and intensity of precipitation at Titicaca appears to be influenced by the Bolivian High, the South American Summer Monsoon (SASM) and El Niño Southern Oscillation (ENSO).

The NSF/ICDP GLAD800 drilling rig raised a series of cores from Lake Titicaca in 2001. The two cores considered here, LT01-2B and LT01-3B, were raised from 236 m and 40 m of water, respectively (Fig. 1).

Core NE98-1PC was raised from 152 m water depth using a piston corer. The core is 11 m in length and spans the last 23 000 yr (Paduano *et al.*, 2003; Rowe *et al.*, 2003). A radiocarbon chronology was developed using 26 ^{14}C AMS ages.

An important distinction needs to be made about these various cores. Lake level at Titicaca varied considerably during the Holocene, and very possibly during MIS 5e. Within the Holocene, lake level lowered by as much as 90 m, with the effect of isolating the Huiñaimarca sub-basin completely. Thus for much of interglacial history core LT01-3B probably represents a small, isolated lake. Lowstands would also have caused the location of core NE98-1PC to have been closer to land. Such proximity would increase the proportion of local and shoreline pollen inputs, causing the record to resemble that of a small lake rather than a large water body. Core LT01-2B has probably remained part of a large water body, with strong regional pollen inputs throughout the period covered in this study.

Chronology

The LT01-2B age model was developed using a radiocarbon chronology for the upper 26 m of the core, which was extrapolated to a cluster of U-series ages at the top of the pre-Holocene lowstand (45.44 mblf). The mean age of 122 800 ± 7700 yr BP for four U-series dates during the penultimate lowstand was used for the age model (Fritz *et al.*, in review). The chronology beyond those dates was based on the Lake Titicaca calcium carbonate record tuned to the Vostok CO_2 chronology. The details of the radiocarbon and U-series dates and corresponding age model are presented elsewhere (Fritz *et al.*, in review).

Laboratory methods

Standard palynological methods were followed (Stockmarr, 1971; Faegri and Iversen, 1989). Sodium metatungstate (specific gravity 2.09) was used for density separation to concentrate pollen in clay-rich samples (Paduano *et al.*, 2003). Samples were mounted in glycerol and counted using a Zeiss Axioskop photomicroscope (400 × and 1000 ×). A total of 300 grains were counted per sample, or 2000 exotic *Lycopodium* in low-concentration samples. Pollen types were identified using the Florida Institute of Technology modern reference collection of >3200 South American pollen types, digital images of Titicaca pollen (Paduano, 2001), and pollen atlases (Markgraf, 1978; Hooghiemstra, 1984; Faegri and Iversen, 1989).

Pollen percentages, concentration per taxon and total concentration were calculated and graphed using C2 software (Juggins, 2003). To describe patterns in the pollen data between the cores, a detrended correspondence analysis (DCA) was calculated using data from core NE98-1PC (Paduano *et al.*, 2003), LT01-2B and LT01-3B using PC-ORD (Hill, 1979; McCune and Mefford, 1999). All default settings were used. The DCA was performed on the percentage data of the taxa represented in at least one sample with a >3% abundance (15 taxa).

Results

Chronology

The pre-Holocene low lake stand of Lake Titicaca is evident from the transition from inorganic muds to finely laminated sediments (Fritz *et al.*, in review). Both sedimentological characteristics (Baker *et al.*, 2001b) and pollen concentration data suggest a warm and dry period. Comparison of this section of elevated pollen concentration is appropriate, as the Holocene had similar shifts.

Evidence of an erosive surface within the MIS 5e zone of LT01-3B led us to postulate a hiatus in that core. The 11 000-yr duration of that hiatus is estimated by matching the adjacent pollen peaks with what appears to be a complete core from LT01-2B.

Pollen analyses

The pollen records reflect a transition into interglacial, full interglacial, and transition toward glacial conditions (Figs 2–4). The ordination of the fossil pollen data is used to define these episodes (Figs 5 and 6).

Rather than present a formal description of each pollen zone, we describe common patterns and divergences between the cores. At each site the onset of interglacial warming is marked by a rapid increase in pollen concentrations. In the NE98-1PC core pollen concentrations have been elevated above glacial levels by 10 500 cal. yr BP and become broadly stable (Fig. 2). The early Holocene has been characterised by a rise in Asteraceae ca. 13 000 cal. yr BP (Paduano *et al.*, 2003), and elevated *Polylepis/Acaena* ca. 6500 cal. yr BP as Cyperaceae declines into a mid-Holocene dry event (Fig. 2). The dry event occurred between ca. 9000 BP and 3100 BP and intensified between 6000 BP and 4000 BP. These same patterns are evident in the LT01-2B data, even though Cyperaceae pollen is not as abundant at this site because of its greater water depth. LT01-2B

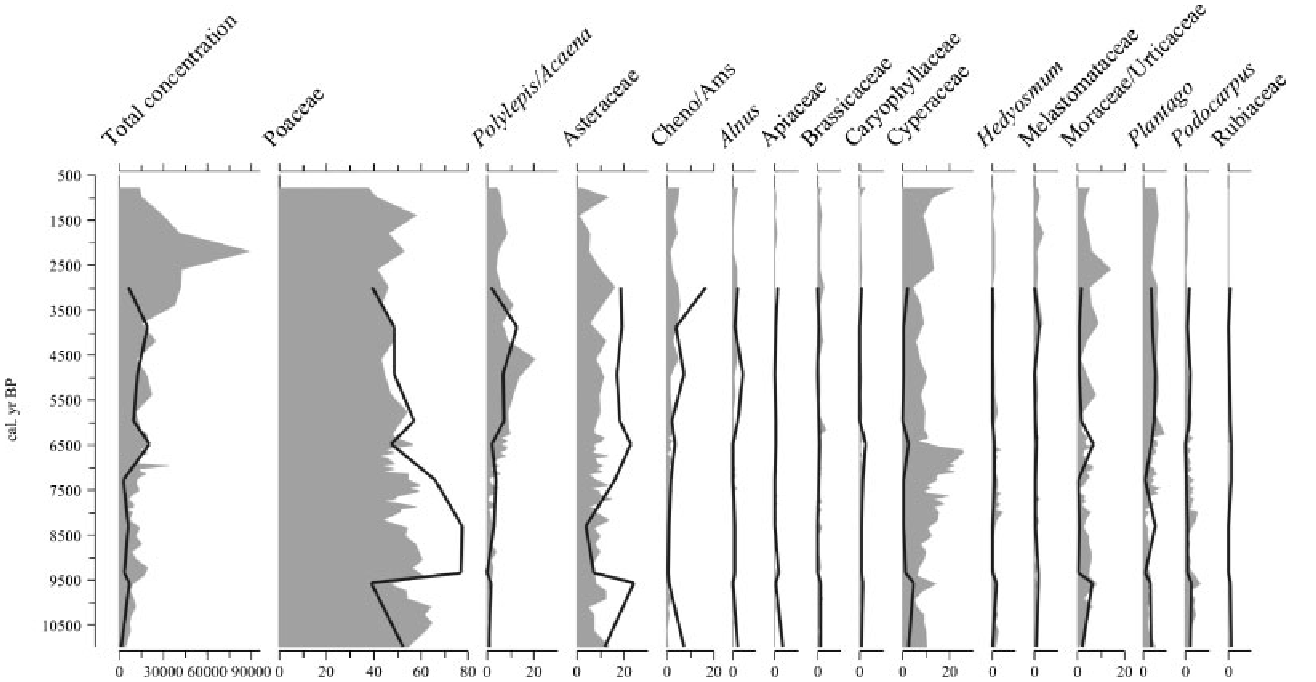

Figure 2 Holocene selected taxa percentage and total pollen concentration (grains/cm^3) diagram for core NE98-1PC. Core LT01-2B is superimposed on the diagram, indicated by the black line

Holocene was superimposed on the NE98-1PC diagram, and the overall pattern of suddenly increased pollen concentrations with Poaceae as an early dominant is evident from both records (Fig. 2). The relative increase in Asteraceae pollen in importance is not observed near the onset of the interglacial, but there is a very strong increase in *Polylepis/Acaena*, Moraceae/Urticaceae and *Podocarpus* pollen.

At the peak of the MIS 5e interglacial both of the records are exceptionally rich in pollen of Chenopodiaceae/Amaranthaceae (hereafter Cheno/Ams)—as much as 85% of the pollen sum (Figs 3 and 4). In the Holocene record the peak *of Polylepis/Acaena* pollen is followed by a much more muted rise in Cheno/Ams, never exceeding 20% of the pollen sum (Fig. 2). However, some uncertainty exists as to whether the LT01-3B captures the entire peak of MIS 5e, or whether there is a sedimentary hiatus within the Cheno/Ams pollen peak. Two factors are considered to tentatively suggest a gap between 131 000 and 120 000 cal. yr BP in the LT01-3B record: (i) there appears to be an erosion horizon at ca. 87.4 m depth just after the upper limit of the main Cheno/Am peak shown in the physical description of the core, and (ii) the upper peaks in Poaceae (>45%) and *Polylepis/Acaena* (>15%) correlate with peaks not found in the LT01-2B record until the latter part of 5e (Fig. 4).

The transition into the last glacial period, in both LT01-2B and 3B, is characterised by decline of Cheno/Ams to <10%,

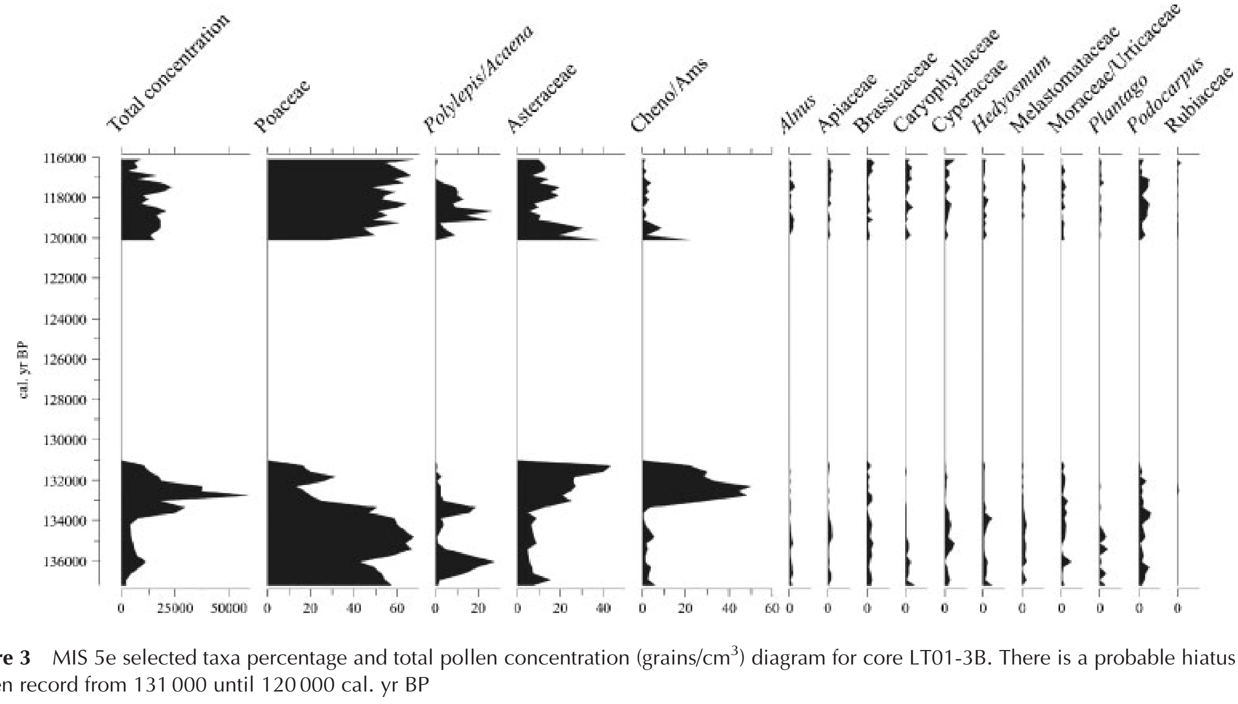

Figure 3 MIS 5e selected taxa percentage and total pollen concentration (grains/cm^3) diagram for core LT01-3B. There is a probable hiatus in the pollen record from 131 000 until 120 000 cal. yr BP

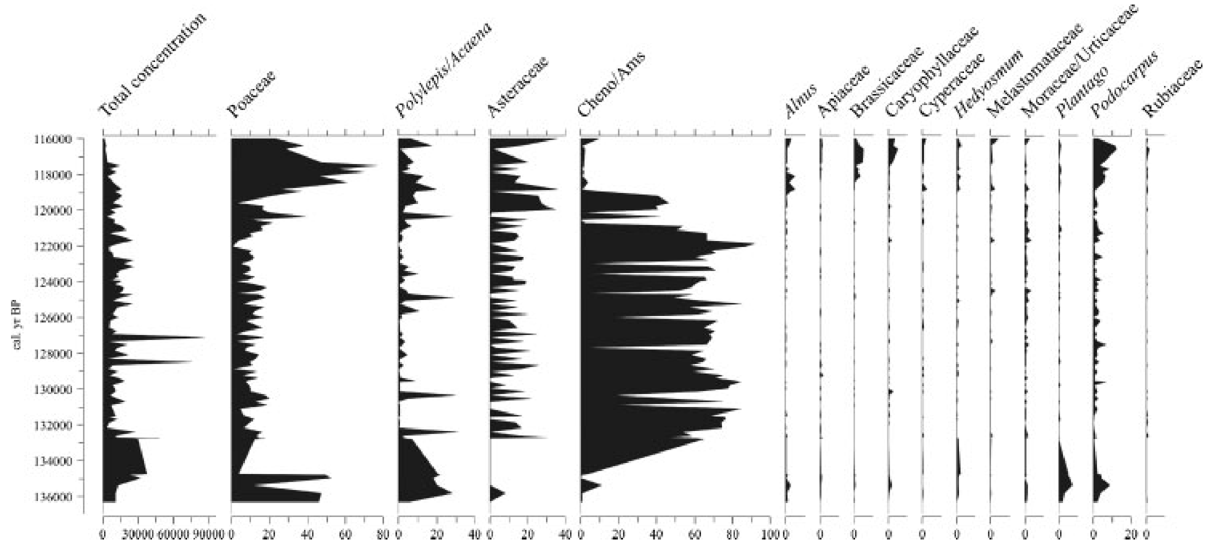

Figure 4 MIS 5e selected taxa percentage and total pollen concentration (grains/cm^3) diagram for core LT01-2B. MIS 5e is characterised by a high representation of Cheno/Ams

and sequential rises of Asteraceae, *Polylepis/Acaena* and Poaceae pollen abundances. No equivalent zone is seen in the Holocene.

The DCA ordination of core NE98-1PC paired with core LT01-3B provides the opportunity to compare two relatively small basins, one during the Holocene with one during the onset, peak and termination of MIS 5e (Fig. 5). In this analysis, Axis 1 represents a gradient characterised by Cyperaceae at the negative extreme and Cheno/Ams at the positive extreme. This gradient accounts for 53% variability in the dataset and cannot be readily attributed to a single variable. Cheno/Ams are generally indicative of oscillating lake margins, or saline marshes. Thus the axis probably reflects a gradient of increasingly strongly seasonal, warm conditions. Axis 2 separates the cloud of points at the positive extreme of Axis 1 and is characterised by *Polylepis/Acaena* at the positive extreme and Cyperaceae at the negative extreme (Axis 2 variance = 0.0639). This axis may represent a more straightforward gradient of declining moisture availability within samples that are less seasonally extreme.

The DCA analysis reveals an overlapping distribution of samples from the Holocene (NE98-1PC) and early MIS 5e (LT01-3B) on the first two axes (Fig. 5). However, the samples representing the peak conditions of MIS 5e plot separately (to the right of the diagram) from those of the Holocene, while the late interglacial (MIS 5d) once again overlap with those of the Holocene (on the left of the diagram).

When the samples from LT01-2B are introduced to the analysis the ordination pattern is still broadly similar (Fig. 6). Characterising species are the same on each axis as in the previous analysis (Axis 1 = 0.5582; Axis 2 = 0.0994; total variance = 0.9542). The peak interglacial samples from LT01-2B are seen to have even higher positive scores on Axis 1 than their temporal counterparts from the smaller waterbody represented by LT01-3B. The Holocene samples from LT01-2B plot near to, but not within, the cloud of samples from Holocene NE98-1PC but are statistically more similar to the early MIS 5e data from LT01-3B. The early and late MIS 5e samples from LT01-2B, like LT01-3B, show greater affinity with the Holocene samples on Axis 1 (Fig. 6).

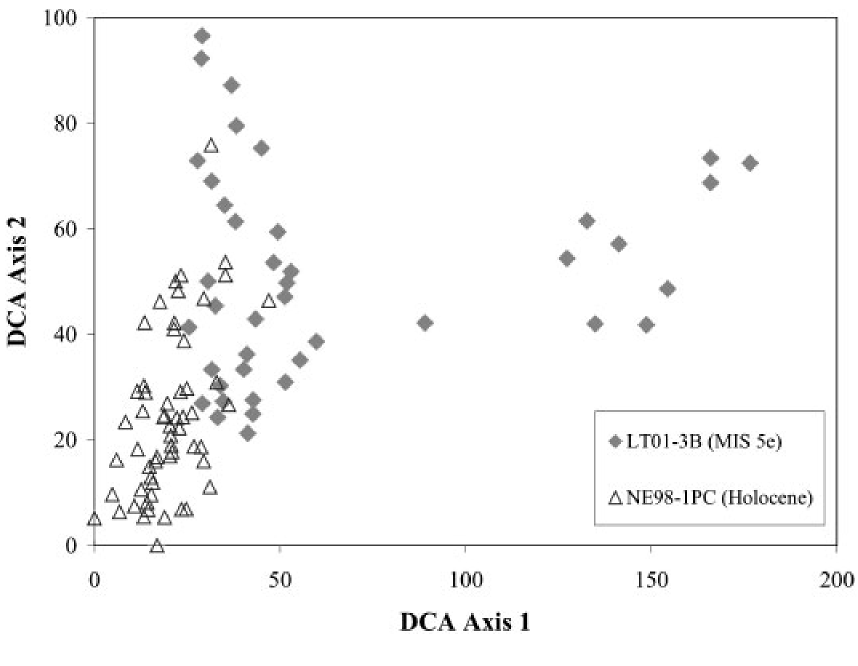

Figure 5 DCA ordination of percentage data of NE98-1PC and LT01-3B reveals an overlapping distribution of samples from the Holocene and early MIS 5e. Samples from the peak of MIS 5e are plotted separately on Axis 1

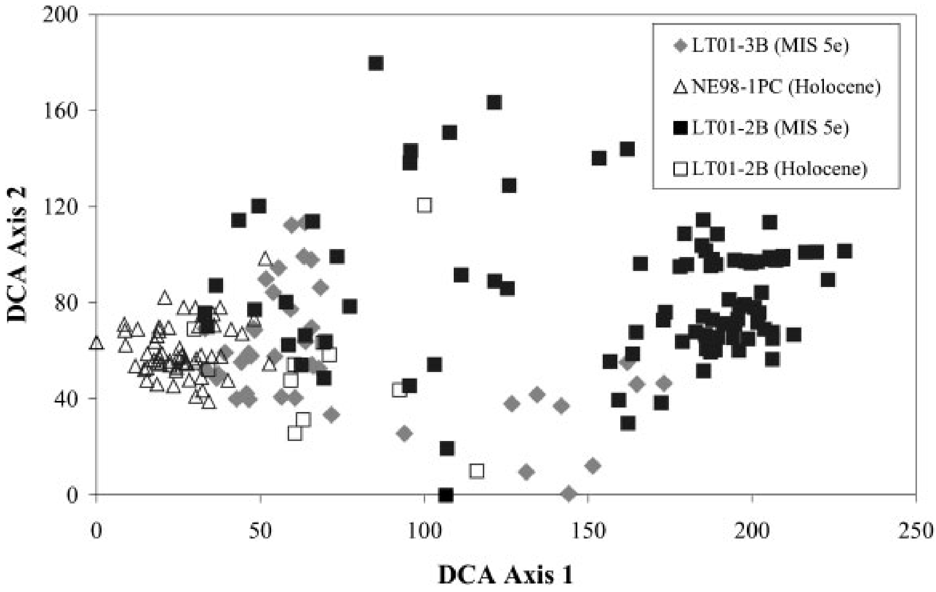

Figure 6 DCA ordination of percentage data with the addition of samples from LT01-2B reveals an overlapping distribution of samples from the Holocene and the early and late samples from MIS 5e. LT01-2B Holocene samples are similar to the early MIS 5e samples from LT01-3B

Discussion

The transition from glacial to interglacial conditions on the Altiplano was marked by a strong increase in pollen concentration, as glacial conditions are simply too barren to generate much pollen productivity. As conditions warmed, a threshold is exceeded that induced an initial jump in pollen production. Pollen concentrations continued to increase until the peak of the interglacial. Peak concentrations of Cheno/Ams suggest drought. On present evidence, it is not possible to determine if that drying was a product of increased temperature, decreased precipitation, or a combination of both.

The data from these three cores indicate that the trends in vegetation during the transition between glacial and interglacial conditions are broadly similar between locations of very different catchment size. The sequence of taxa that rise and fall in these transitions follow a trajectory of grassland components, e.g. Poaceae, *Plantago*, Cyperaceae, and other herbs. Within the interglacial phases wet interludes are marked by elevated abundances of Asteraceae. The trajectory continued from grassland through an open *Polylepis/Acaena* woodland, to an assemblage dominated by Cheno/Ams. This continuum represents an increase both in temperature and aridity. We infer that MIS 5e attained a Cheno/Am-dominated pollen spectrum for 14 000 yr between 134 000 and 120 000 cal. yr BP, and was so dry that the modern lake of Huiñaimarca dried out completely between 131 000 and 120 000 cal. yr BP. Similar results are supported by seismic data (D'Agostino *et al.*, 2002).

Unlike MIS 5e, the Holocene did not have a sharply defined boundary. Deglaciation began as early as 21 000 yr ago, and progressed fairly steadily. By 13 000 yr ago the pollen spectra are typically those of the Holocene in percentile terms, though pollen concentrations were a little low until ca. 10 500 cal. yr BP. Pollen concentrations rose until ca. 8000 cal. yr BP when a dry event led to a reduction in Cyperaceae and Asteraceae abundances and an increase in *Polylepis/Acaena* abundance. Thus, this early interglacial episode closely paralleled the transition into MIS 5e, but thereafter the records diverged. While MIS 5e progressed toward drier conditions, the Holocene became wetter after about 4300 cal. yr BP. The lake level of Titicaca and Huiñaimarca rose (Abbott *et al.*, 1997a, 1997b, 2000, 2003) at this time, and the pollen record of climatic change was largely subsumed by anthropogenic influences.

If the DCA Axis 1 scores of each interglacial are plotted against time since the start of their respective events a striking pattern is evident. The Holocene appears to have been slower to develop and to lack the aridity associated with MIS 5e (Fig. 7). The interpretation made that MIS 5e appeared to be drier and probably warmer than the Holocene fits both with the estimated conditions of the Salar de Uyuni at this time, the precessional teleconnection to Amazonia and long records such as Vostok.

Unfortunately, pollen analysis does not allow sub-family level identification among grasses or Cheno/Ams, and so there is plenty of opportunity for species turnover that is not apparent to the pollen analyst. *Polylepis/Acaena* type pollen could potentially include the genus *Acaena*, but as *Acaena* are restricted to cloud forests in this section of the Andes and *Polylepis* is found to an elevation of 4800 m, it is far more likely to be *Polylepis* pollen than that of *Acaena*. Thus while we recognise similarities between these glacial–interglacial stages we do not argue that the communities represented are analogues of one another.

Climatic variability within interglacials

A relatively wet Holocene at Lake Titicaca was interrupted by a multi-millennial dry event that lowered lake level between 8000 and 4300 cal. yr BP, possibly reaching its peak at ca. 5500 cal. yr BP (Abbott *et al.*, 1997a, 1997b, 2000; Seltzer *et al.*, 2000; Baker *et al.*, 2001b). Within this dry event there may have been wetter episodes, but none were of sufficient duration to be represented in the analysis of NE98-1PC, which has a temporal resolution of <100 yr (2 cm) between samples throughout this interval. In contrast, the MIS 5e record shows an overall stronger and longer dry episode, lasting from ca. 130 000 to 120 000 cal. yr BP with marked wet oscillations that are manifested by peaks of Asteraceae and *Polylepis/Acaena* pollen. The sampling resolution through MIS 5e in LT01-2B is ca. 330 yr (10 cm), and some of the wet events appear to last

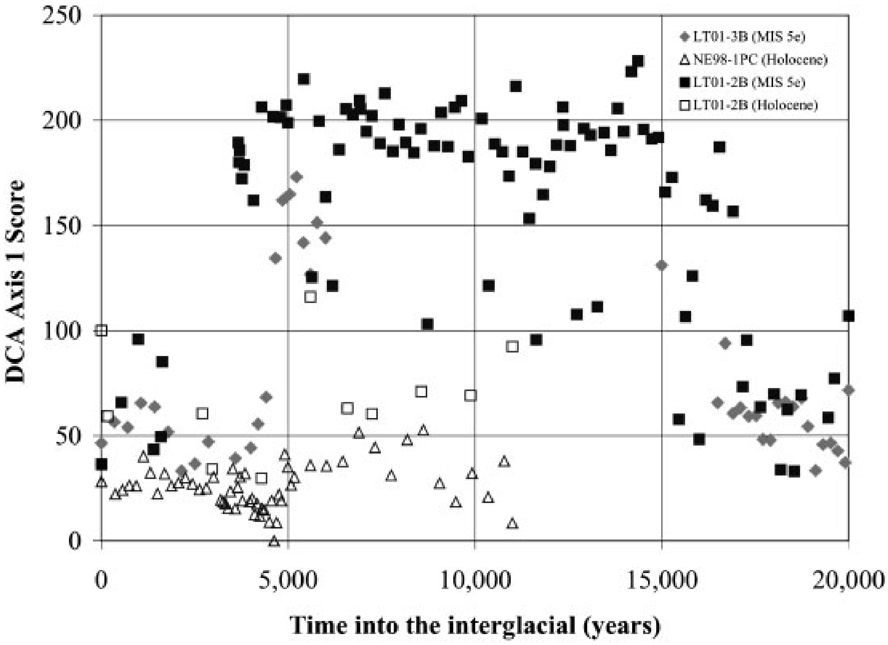

Figure 7 A comparison of the variation within the samples through the duration of an interglacial suggests the Holocene was slower to develop and lacks the aridity associated with MIS 5e

500–1000 yr. We cannot quantify this change in moisture availability, but note that there is no obvious Holocene counterpart.

Conclusions

The last two interglacials of the high Andes have been predominantly warm and dry, with MIS 5e being a more extreme event than the Holocene. At its peak MIS 5e caused even the deepest basin of Lake Huiñaimarca to dry out, and the main waterbody of Titicaca to become flanked by Cheno/Ams pollen type; the plants represented by this group typically can withstand considerable salinity and hydrological fluctuations. Consequently, while the transitional phases of MIS 5e and the Holocene share some commonalities, the peak of MIS 5e does not form an analogue environment in the absence of human activity in the Holocene.

The transitions into and out of the interglacials appear to reflect gradients of temperature and moisture availability. During those times *Polylepis/Acaena* emerged as a temporary but important floral component. Our data are consistent with the former widespread occurrence *of Polylepis* woodlands in the high Andes, but do not support the broader contention that this is the native interglacial flora of the Andes in the absence of human activity.

The apparent synchrony of precipitation between equatorial Amazonia, southeastern Brazil, and the Central Andes, supports the possibility that precessional forcing of the LLJ and SASM lies behind this teleconnection. These observations are also consistent with the observation that eastern Amazonia away from the influence of the LLJ and the northern Andes will not share this pattern of synchrony (Bush and Silman, 2004).

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References

Abbott MB, Binford MW, Brenner M, Kelts K. 1997a. A 3500 14C high-resolution record of water-level changes in Lake Titicaca, Bolivia/Peru. *Quaternary Research* **47**: 169–180.

Abbott MB, Seltzer GO, Kelts KR, Southon J. 1997b. Holocene paleohydrology of the tropical Andes from lake records. *Quaternary Research* **47**: 70–80.

Abbott MB, Wolfe BB, Aravena R, Wolfe AP, Seltzer GO. 2000. Holocene hydrological reconstructions from stable isotopes and paleolimnology, Cordillera Real, Bolivia. *Quaternary Science Reviews* **19**: 1801–1820.

Abbott MB, Wolfe BB, Wolfe AP, Seltzer GO, Aravena R, Mark BG, Polissar PJ, Rodbell DT, Rowe HD, Vuille M. 2003. Holocene paleohydrology and glacial history of the central Andes using multiproxy lake sediment studies. *Palaeogeography Palaeoclimatology Palaeoecology* **194**: 123–138.

Ariztegui D, Bianchi MM, Masaferro J, Lafargue E, Niessen F. 1997. Interhemispheric synchrony of Late-glacial climatic instability as recorded in proglacial Lake Mascardi, Argentina. *Journal of Quaternary Science* **12**: 333–338.

Baker PA, Rigsby CA, Seltzer GO, Fritz SC, Lowenstein TK, Bacher NP, Veliz C. 2001a. Tropical climate changes at millennial and orbital timescales on the Bolivian Altiplano. *Nature* **409**: 698–701.

Baker PA, Seltzer GO, Fritz SC, Dunbar RB, Grove MJ, Tapia PM, Cross SL, Rowe HD, Broda JP. 2001b. The history of South American tropical precipitation for the past 25,000 years. *Science* **291**: 640–643.

Barnola JM, Raynaud D, Korotevitch YN, Lorius C. 1987. Vostok ice core provides 160,000-year record of atmospheric CO_2. *Nature* **329**: 408–414.

Bender M, Sowers T, Dickson ML, Orchardo J, Grootes P, Mayewski PA, Meese DA. 1994. Climate correlations between Greenland and Antarctica during the past 100,000 years. *Nature* **372**: 663–666.

Berger A. 1992. Astronomical theory of paleoclimates and the last glacial–interglacial cycle. *Quaternary Science Reviews* **11**: 571–581.

Bush MB, De Oliveira PE, Colinvaux PA, Miller MC, Moreno E. 2004. Amazonian paleoecological histories: one hill, three watersheds. *Palaeogeography, Palaeoclimatology, Palaeoecology* **214**: 359–393.

Bush MB, Silman MR. 2004. Observations on late Pleistocene cooling and precipitation in the lowland Neotropics. *Journal of Quaternary Science* **19**: 677–684.

Chappellaz J, Brook E, Blunier T, Malaize B. 1997. CH_4 and d18O of O_2 records from Antarctic and Greenland ice: a clue for stratigraphic disturbance in the bottom part of the Greenland Ice Core Project and the Greenland Ice Sheet Project 2 ice core. *Journal of Geophysical Research* **102**: 26 547–26 557.

Chepstow-Lusty AJ, Bush MB, Frogley MR, Baker PA, Fritz SC, Aronson J. 2005. Vegetation and climate change on the Bolivian Altiplano between 108,000 and 18,000 yr ago. *Quaternary Research* **63**: 90–98.

Cruz FW, Burns SJ, Karmann I, Sharp WD, Vuille M, Cardoso AO, Ferrari JA, Silva Dias PL, Viana O. 2005. Insolation-driven changes in atmospheric circulation over the past 116,000 years in subtropical Brazil. *Nature* **434**: 63–66.

D'Agostino K. 1999. *Late Quaternary high resolution seismic stratigraphy of Lake Titicaca (Peru/Bolivia): implications for late Pleistocene–Holocene lake level lowstands*. MSc thesis, Syracuse University, Syracuse, NY.

D'Agostino K, Seltzer GO, Baker PA, Fritz S, Dunbar R. 2002. Late-Quaternary low stands of Lake Titicaca: evidence from high-resolution seismic data. *Palaeogeography, Palaeoclimatology, Palaeoecology* **179**: 97–111.

Faegri K, Iversen J. 1989. *Textbook of Pollen Analysis* (4th edn). Wiley: Chichester.

Fritz SC, Baker PA, Seltzer GO, Ballantyne A, Tapia P. (In review). Glaciation and hydrologic variation in the South American tropics during the last 370,000 years.

Fritz SC, Baker PA, Lowenstein TK, Seltzer GO, Rigsby CA, Dwyer GS, Tapia PM, Arnold KK, Ku TL, Luo S. 2004. Hydrological variation during the last 170,000 years in the southern hemisphere tropics of South America. *Quaternary Research* **61**: 95–104.

Garreaud R, Vuille M, Clement A. 2003. The climate of the Altiplano: observed current conditions and mechanisms of past changes. *Palaeogeography, Palaeoclimatology, Palaeoecology* **194**: 5–22.

Genthon C, Barnola JM, Raynaud D, Lorius C, Jouzel J, Barkov NI, Korotkevich YS, Kotlyakov VM. 1987. Vostok ice core: climatic response to CO_2 and orbital forcing changes over the last climatic cycle. *Nature* **329**: 414–418.

GRIP Project Members. 1993. Climate instability during the last interglacial period recorded in the GRIP record. *Nature* **364**: 203–207.

Hill MO. 1979. *DECORANA—a FORTRAN program for detrended correspondence analysis and reciprocal averaging*. Section of Ecology and Systematics. Cornell University, Ithaca, NY.

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.

Johnson SJ, Clausen HB, Dansgaard W, Gundestrup NS, Hammer CU, Tauber H. 1995. The Eemian stable isotope record along the GRIP ice core and its interpretation. *Quaternary Research* **43**: 117–124.

Jouzel J, Lorius C, Petit JR, Genthon C, Barkov NI, Kotlyakov VM, Petrov VM. 1987. Vostok ice core: a continuous isotope temperature record over the last climatic cycle (160,000 years). *Nature* **329**: 403–408.

Jouzel J, Barkov NI, Barnola JM, Bender M, Chappellaz J, Genthon C, Kotlyakov VM, Lipenkov V, Lorius C, Petit JR, Raisbeck G, Ritz C, Sowers T, Stievenard M, Yiou F, Yiou P. 1993. Extending the Vostok ice-core record of palaeoclimate to the penultimate glacial period. *Nature* **364**: 407–412.

Juggins S. 2003. *C2 Program version 1.4.* Department of Geology, University of Newcastle: Newcastle upon Tyne, UK.

Lenters LD, Cook H. 1997. On the origin of the Bolivian high and related circulation features of the South American climate. *Journal of the Atmospheric Sciences* **54**: 656–677.

Lorius C, Jouzel J, Ritz C, Merlivat L, Barkov NI, Korotkevich YS, Kotlyakov VM. 1983. A 150,000-year climatic record from Antarctic ice. *Nature* **316**: 591–596.

Markgraf V. 1978. *Pollen and Spores of Argentina*. University of Arizona, Tucson.

McCune B, Mefford MJ. 1999. *PC_ORD. Multivariate analysis of ecological data*. MJM Software Design, Gleneden Beach, Oregon.

Mommersteeg H. 1998. *Vegetation development and cyclic and abrupt climatic changes during the Late Quaternary: palynological evidence from the Colombian Eastern Cordillera*. PhD thesis, University of Amsterdam.

Moss PT, Kershaw AP. 2000. The last glacial cycle from the humid tropics of northeastern Australia: comparison of a terrestrial and a marine record. *Palaeogeography, Palaeoclimatology, Palaeoecology* **155**: 155–176.

Okuda M, Shulmeister J, Flenley JR. 2002. Vegetation changes and their climatic implication for the late Pleistocene at Lake Poukawa, Hawkes Bay, New Zealand. *Global and Planetary Change* **33**: 269–282.

Paduano G. 2001. *Vegetation and fire history of two tropical Andean lakes, Titicaca (Peru/Bolivia) and Caserococha (Peru) with special emphasis on the Younger Dryas chronozone*. PhD dissertation, Florida Institute of Technology, Melbourne, FL.

Paduano GM, Bush MB, Baker PA, Fritz SC, Seltzer GO. 2003. A vegetation and fire history of Lake Titicaca since the Last Glacial Maximum. *Palaeogeography, Palaeoclimatology, Palaeoecology* **194**: 259–279.

Petit JR, Basile I, Leruyuet A, Raynaud D, Lorius C, Jouzel J, Stievenard M, Lipenkov VY, Barkov NI, Kudryashov BB, Davis M, Saltzman E, Kotlyakov V. 1997. Four climate cycles in Vostok ice core. *Nature* **387**: 359–360.

Petit JR, Jouzel J, Raynaud D, Barkov NI, Barnola J-M, Basile I, Chappellaz J, Davis M, Delaygue G, Melmotte M, Kotlyakov VM, Legrand M, Lipenkov VY, Lorius C, Pepin L, Ritz C, Saltzman E, Stievenard M. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* **399**: 429–436.

Roche MA, Bourges JC, Mattos R. 1992. Climatology and hydrology of the Lake Titicaca basin. In *Lake Titicaca: A Synthesis of Limnological Knowledge*, Dejoux C, Iltis A (eds). Kluwer: Boston; 63–83.

Rowe HD, Guilderson TP, Dunbar RB, Southon JR, Seltzer GO, Mucciarone DA, Fritz SC, Baker PA. 2003. Late Quaternary lake-level changes constrained by radiocarbon and stable isotope studies on sediment cores from Lake Titicaca, South America. *Global and Planetary Change* **38**: 273–290.

Seltzer GO. 1990. Recent glacial history and paleoclimate of the Peruvian–Bolivian Andes. *Quaternary Science Reviews* **9**: 137–152.

Seltzer GO, Rodbell DT, Burns S. 2000. Isotopic evidence for late Quaternary climatic change in tropical South America. *Geology* **28**: 35–38.

Servant M, Servant-Vildary S. 2003. Holocene precipitation and atmospheric changes inferred from river paleowetlands in the Bolivian Andes. *Palaeogeography, Palaeoclimatology, Palaeoecology* **194**: 187–206.

Servant-Vildary S, Mello e Sousa SH. 1993. Palaeohydrology of the Quaternary saline Lake Ballivian (southern Bolivian Altiplano) based on diatom studies. *International Journal of Salt Lake Research* **2**: 69–85.

Shackleton NJ. 2000. The 100,000 year ice-age cycle identified and found to lag temperature, carbon dioxide and orbital eccentricity. *Science* **289**: 1897–1902.

Stockmarr J. 1971. Tablets with spores used in absolute pollen analysis. *Pollen et Spores* **13**: 615–621.

Tzedakis C. 2003. Timing and duration of Last Interglacial conditions in Europe: a chronicle of a changing chronology. *Quaternary Science Reviews* **22**: 763–768.

van der Hammen T, Hooghiemstra H. 2003. Interglacial–glacial Fuquene-3 pollen record from Colombia: an Eemian to Holocene climate record. *Global and Planetary Change* **36**: 181–199.

van't Veer R, Hooghiemstra H. 2000. Montane forest evolution during the last 650 000 yr in Colombia: a multivariate approach based on pollen record Funza-I. *Journal of Quaternary Science* **15**: 329–346.

