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ANDEAN GLACIAL LAKES AND CLIMATE VARIABILITY SINCE THE LAST GLACIAL MAXIMUM

*Geoffrey O. Seltzer *, Donald T. Rodbell **, Mark Abbott ****

Abstract

Sediment cores from glacial lakes in the tropical-subtropical Andes provide a nearly continuous record of late glacial and Holocene paleoclimates. Basal radiocarbon dates from lakes and peats suggest that the last glacial maximum significantly predated the global maximum at 18 ^{14}C kyr BP. Most lakes have basal radiocarbon ages of <13 ^{14}C kyr BP, implying that there was a late-Pleistocene phase of glaciation that may have culminated about 14 ^{14}C kyr BP. Late glacial advances are recorded in several sediment records from lakes and by 10 ^{14}C kyr BP glaciers had retreated to within their modern limits. Mid-Holocene aridity is recorded in the stratigraphy from a number of lakes including Lago Titicaca. This phase of aridity was followed by rising lake levels and neoglaciation in the late Holocene.

Key words: *Paleoclimate, Glaciation, Lakes, Andes, Late Glacial, Holocene.*

LAGOS GLACIARES ANDINOS Y VARIABILIDAD CLIMÁTICA DESDE EL ÚLTIMO MÁXIMO GLACIAL

Resumen

Testigos de sedimentos de los lagos glaciares en los Andes tropicales/subtropicales proporcionan registros continuos de los paleoclimas del último glacial superior y del Holoceno. Dataciones del radiocarbón de los sedimentos profundos en los lagos y de las turberas indican que el máximo del último glacial fue antes del máximo glacial global con una fecha de 18 ^{14}C ka BP. La mayoría de los lagos tienen una antigüedad menor de 13 ^{14}C ka BP, lo que significa que hubo una fase de glaciación del Pleistoceno superior culminada alrededor de 14 ^{14}C ka BP. Los avances durante el glacial superior son indicados en varios testigos de sedimentos de los lagos y, después de 10 ^{14}C ka BP, los glaciares quedaron dentro de sus límites actuales. Una sequía durante el Holoceno medio está registrado en la estratigrafía de varios lagos, incluyendo el Lago Titicaca. Los niveles de los lagos estaban subiendo y había neoglaciación en el Holoceno superior después de la fase de sequía en el Holoceno medio.

Palabras claves: *Paleoclima, glaciación, lagos, Andes, Ultimo Glacial, Holoceno.*

* Dept of Earth Sciences, 204 Heroy Geology Laboratory, Syracuse University, Syracuse, New York 13244 USA, e-mail: goseltze@mailbox.syr.edu, FAX 315-443-3363.

** Dept of Geology, Union College, Schenectady, New York 12308, USA.

*** Limnological Research Center, 220 Pillsbury Hall, 320 Pillsbury Drive SE, Minneapolis, Minnesota 55455, USA.

LES LACS GLACIAIRES ET LA VARIABILITÉ CLIMATIQUE DANS LES ANDES DEPUIS LE DERNIER MAXIMUM GLACIAIRE

Résumé

Des carottages réalisés dans des lacs glaciaires des Andes tropicales et subtropicales ont fourni des registres paléoclimatiques continus couvrant le Dernier Maximum Glaciaire et l'Holocène. Des datations ^{14}C sur sédiments lacustres et sur tourbes indiquent que le maximum de la dernière glaciation s'est produit antérieurement au Dernier Maximum Glaciaire Global (18 ka BP). La plupart des lacs ont un âge inférieur à 13 ka BP, ce qui signifie que l'avancée des glaciers correspondant au Pleistocène terminal aurait culminé aux alentours de 14 ka BP. Des avancées durant le Tardi-glaciaire sont enregistrées dans plusieurs sites lacustres. À partir de 10 ka BP, les glaciers ont reculé au-delà de leurs limites actuelles. La sécheresse de l'Holocène moyen est repérée dans la stratigraphie de nombre de lacs, y compris le lac Titicaca. Cette phase d'aridité est suivie par une remontée des niveaux lacustres et une réavancée des glaciers à la fin de l'Holocène.

Mots-clés : *Paléoclimat, glaciation, lacs, Andes, Dernier Maximum Glaciaire, Holocène.*

INTRODUCTION

The glacial record of the tropical-subtropical Andes has primarily been established through the mapping of moraines and the radiometric dating of associated organic material (recent reviews provided by Clapperton, 1993a; Seltzer, 1990; 1992). This is an inherently discontinous record that is biased towards maximum phases of glaciation. Moraines from periods of less extensive glaciation are destroyed by subsequent and more extensive glacial advances. As a proxy for paleoclimatic conditions these data only provide insight for the time period over which the maximum-phase moraines formed. However, for these time periods the glacial evidence alone cannot provide a unique climate solution (Seltzer, 1994a).

Several important issues in the Quaternary paleoclimatology of the Andes can be addressed with lacustrine records from glacial lakes including: minimum age estimates for the timing of the last glacial maximum, the presence or absence of late-glacial climatic fluctuations that match similar events in the Northern Hemisphere, and the extent of mid-Holocene aridity. The timing of the last glacial maximum is significant when discussing the magnitude of snowline depression and the associated temperature reduction in the Andes. Recent work on low-latitude temperature change (Guilderson *et al.*, 1994; Stute et al., 1995) for the last glacial maximum (defined as 18 ^{14}C kyr BP by Imbrie *et al.*, 1984) appears to be overturning the hypothesis derived from the CLIMAP (1981) data that tropical-subtropical temperatures did not change significantly during the last glacial-to-interglacial transition. These new records of paleotemperature, which are based on the Sr/Ca ratio in corals and the noble gas content of continental groundwater, provide both more precise estimates of paleotemperature and better dated sequences. The climatic interpretations for late-Pleistocene snowline depression in the Andes have varied between reductions in mean annual temperature of 10° ± 1.9 °C (Fox & Bloom, 1994) to 3.5° ± 1.6 °C (Seltzer, 1992) with intermediate values of about 5°-6 °C (Seltzer, 1987; Rodbell, 1992a). All of the snowline studies have implicitly assumed that the maximum extents of glaciers were time synchronous throughout the region. What has been lacking is a precise definition of when the last glacial maximum occurred in the Andes. This timing is critical, however, in order to determine the nature of the discrepancy that exists among proxy records of paleoclimate (Seltzer, 1994b).

Besides the timing of the last glacial maximum the recognition of millennial-scale climatic changes in the Southern Hemisphere has also become important in the development of our understanding of the global nature of such events (e.g. Denton & Hendy, 1994; Broecker, 1994). If the Younger Dryas and other short-lived climate reversals such as the Heinrich Events (Bond *et al.*, 1992, 1993; Bond & Lotti, 1994) were global in extent, then the mechanisms that could link such changes between the hemispheres are not well understood. Given the time scales involved the mechanisms are unlikely to be associated with the orbital hypothesis for glaciation. Possible teleconnections may be related to the thermohaline circulation of the oceans (Broecker & Denton, 1989), an atmospheric dust veil (Clapperton, 1993a), or changes in the greenhouse gas content of the atmosphere (Sowers & Brook, 1995). Late-glacial readvances of glaciers in the Andes have been identified previously at the Quelccaya Ice Cap (Mercer, 1984), in central Peru (Rodbell, 1993), and in Ecuador (Clapperton, 1993b). What is lacking are well dated records that come from a number of sites to determine if these were synchronous advances responding to a common forcing or if they are random events that occurred in the late glacial (e.g. Markgraf, 1991).

Recent work on sediment cores from Lago Titicaca indicates that there was an extended phase of aridity in the mid-Holocene with a maximum decrease in lake levels of 50 m about 7250 ^{14}C yr BP (Wirrmann *et al.*, 1988). In Lago Huiñaimarca recent sedimentological studies show that many sediment cores have basal radiocarbon dates of about 3.6 ^{14}C kyr BP (Binford, pers. comm.), implying that much of the small southern basin of Lago Titicaca was dry until the late Holocene. Modern lake levels are closely tied to changes in precipitation in the region. A prolonged mid-Holocene drought could be related to changes in advected moisture associated with the easterly circulation.

1. METHODS

Minimum ages for deglaciation from various moraine stages have been obtained by coring lakes and peatlands that developed after glaciers retreated. Because of the dry climate of the high Andes and the limited vegetation it is difficult to find organic material buried beneath moraines to provide maximum limiting ages for glacial advances. Glacial lakes and peatlands in the Andes formed following deglaciation as end moraines dammed the drainage of high valleys. Basal dates from cores obtained at these sites provide minimum age estimates for deglaciation.

A square-rod piston corer (Wright *et al.*, 1984; Wright, 1991) was used from either a floating platform or peat surfaces to obtain continuous cores 5 cm in diameter. The cores typically penetrated the organic sediments of the Holocene and bottomed in inorganic silts and gravels indicative of glaciofluvial and glacial-lacustrine sedimentation. A radiocarbon date from the basal contact of the organic material provides a minimum age for the moraine that occupies the position immediately downvalley from the lake or peatland. Such a date also provides a minimum age for deglaciation of the site. Materials dated include bulk organic carbon, macrofossils, and humin and humic acid extracts (e.g. Seltzer, 1994c). Measurements that were made on these cores include: organic and inorganic carbon by loss-on-ignition (Dean, 1974) and coulometry (Engleman *et al.*, 1985), magnetic susceptibility, bulk density, and X-ray mineralogy.

2. RESULTS

The oldest glacial lake that we have located is Laguna Kollpa Kkota in the eastern cordillera of Bolivia (Fig. 1; Seltzer, 1994c). This is a small, closed-basin lake, that contains

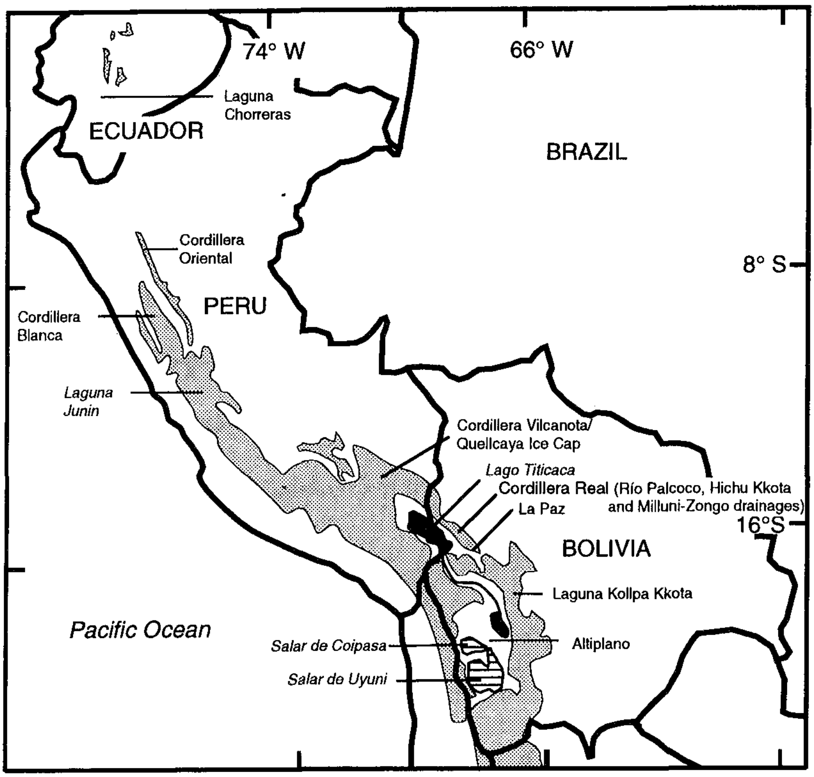

Fig. 1 - Map showing the location of sites mentioned in the text. The shaded area is >4 000 m a.s.l.

approximately 7-m of post-glacial sediment. Radiocarbon dates from the base of the sediment cores indicate that the site was deglaciated more than 20 ^{14}C kyr BP. The lake probably survived subsequent phases of glaciation because of the low elevation of the valley headwall (Fig. 2). Although other lakes that occupy such an altitudinal position have been identified, additional radiocarbon chronologies are lacking. At the Laguna Kollpa Kkota site no glacial features are found downvalley from the lake suggesting that the last glacial maximum is marked by the moraines that dam the lake.

Cross sections from the Río Palcoco and Milluni drainages in the Cordillera Real of Bolivia show the basal ages of peats nearly adjacent to the modern ice fronts are 9 to 10 ^{14}C kyr BP (Fig. 3). Thus, most of the moraines in these glacial valleys formed in the late glacial between 14 and 10 ^{14}C kyr BP, although their precise ages are unconstrained. Many of these late-glacial moraines may have been deposited during stillstands in an overall retreat of the glaciers, however, there is evidence that some of the moraines formed during glacier readvances.

Glacial lakes that have a continuous sediment record that spans the last glacial-to-interglacial transition (*ca.* 14 to 10 ^{14}C kyr BP) are critical for determining the climate response in this time interval. Laguna Chorreras in southern Ecuador is located at 3 700 m in a valley that has a maximum headwall elevation of 4 200 m (Fig. 1). The lake was deglaciated by

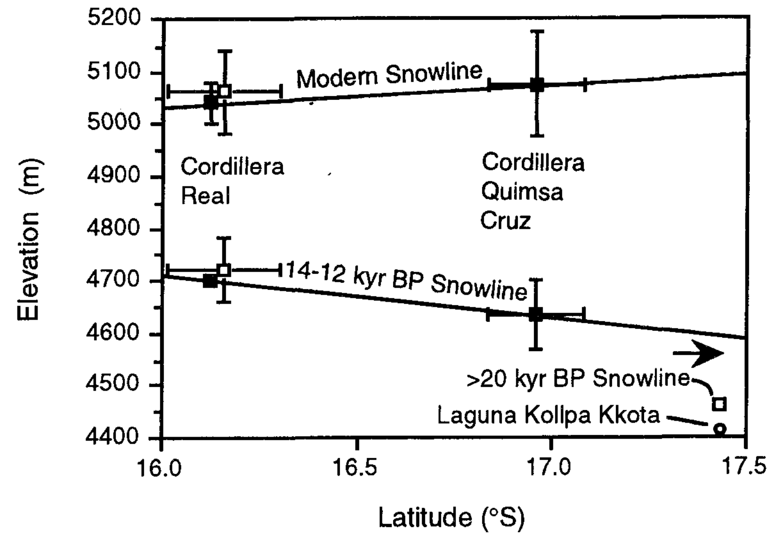

Fig. 2 - Modern and late-Pleistocene snowlines for the western slope of the Eastern Cordillera, Bolivia. The horizontal and vertical bars represent the latitudinal range of the sites and the variation in estimates of snowline, respectively. Snowline estimates are based on the accumulation area ratio (solid squares, AAR = 0,77) and the toe to headwall ratio (open squares, THAR = 0,37) methods (Müller, 1985; Seltzer, 1992). The arrow indicates the elevation of the crest of the headwall above Laguna Kollpa Kkota (after Seltzer, 1994c).

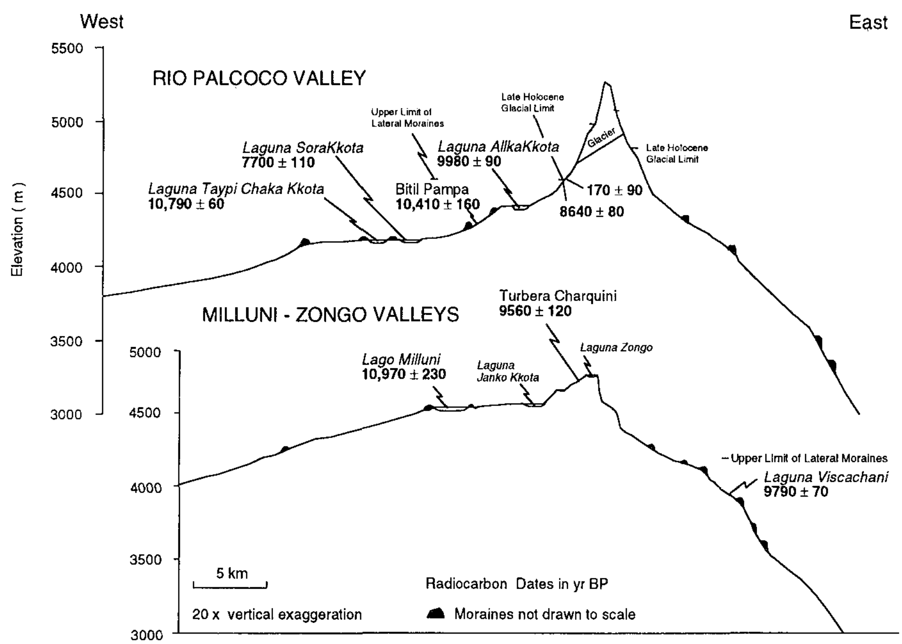

Fig. 3 - Longitudinal profiles of the Río Palcoco and Milluni-Zongo valleys with basal radiocarbon dates from lakes and peats.

12.5 ^{14}C kyr BP when organic-rich sediments began to accumulate (Fig. 4). There is a distinct inorganic interval, however, that dates to between 12,5 and 10,9 ^{14}C kyr BP. We believe that one mechanism that might produce this inorganic layer is glaciofluvial deposition during reoccupation of the cirques above the lake. A similar sediment stratigraphy in several lakes in the Cordillera Oriental of Peru has also been interpreted in this manner (Rodbell, 1993). If we assume the modern snowline in southern Ecuador is near the mean 0 °C isotherm, then reoccupation of the cirques today would require a snowline depression of ~1000 m. Such a snowline depression is 70% of the maximum snowline depression recorded for the area by the outermost moraines.

Most glacial lakes in the Andes have a continuous stratigraphy that spans the Holocene. In the Cordillera Real of Bolivia, Lago Taypi Chaka Kkota in the Río Palcoco drainage has a basal age of about 11 ^{14}C kyr BP (Fig. 5). A striking aspect of the stratigraphy in this lake and others like it is the initial rise in organic content of the sediment followed by an abrupt drop in the mid-Holocene. This general stratigrahpy is reproduced in Laguna Viscachani on the eastern side of the cordillera. It is also prevalent in other lakes in the Hichu Kkota and Río Palcoco valleys (Fig. 6). The relevance of these stratigraphic changes in organic carbon is uncertain given the number of processes involved in the production and preservation of organic carbon in the limnic enviroment. Factors that can influence the organic carbon content of the sediments include terrestrial and aquatic organic productivity and oxidation of the organic matter in the sediments. The timing of these changes corresponds with the arid phase as interpreted from sediment cores from Lago Titicaca (Wirrmann *et al.*, 1988).

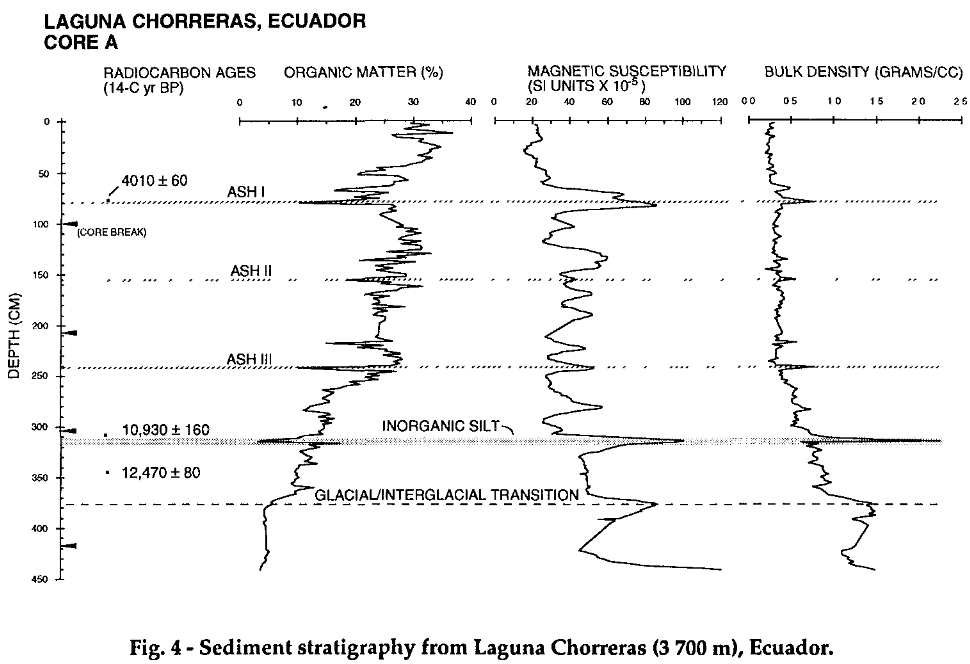

Fig. 4 - Sediment stratigraphy from Laguna Chorreras (3 700 m), Ecuador.

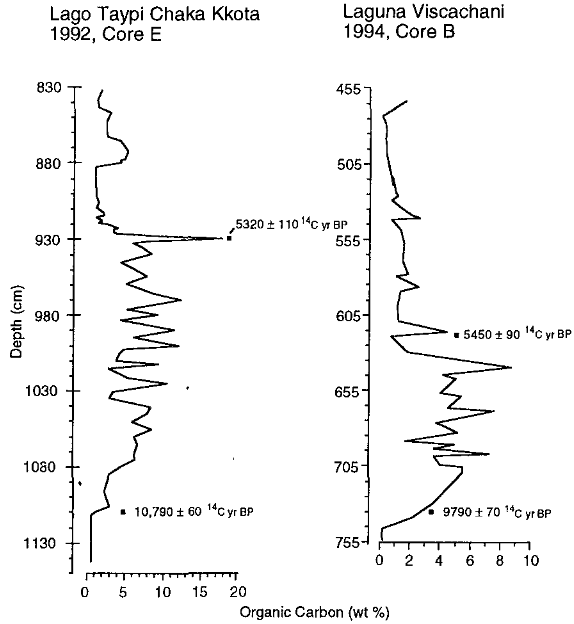

Fig. 5 - Organic carbon stratigraphy from L. Taypi Chaka Kkota and L. Viscachani, Cordillera Real, Bolivia.

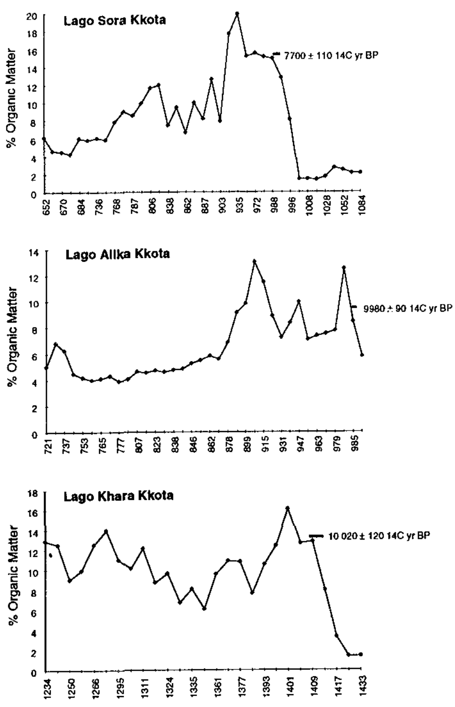

Fig. 6 - Organic matter profiles from lakes in the Cordillera Real, Bolivia.

3. DISCUSSION

The timing of the last glacial maximum in the tropical-subtropical Andes is constrained at relatively few localities (Table 1).

Table 1 - Select radiocarbon dates that provide minimum age estimates for the last glacial maximum in the tropical-subtropical Andes.

Location	Radiocarbon Control (^{14}C yr BP)	Reference
Sierra Nevada del Cocuy, Colombia	> 20,840 ± 140	van der Hammen *et al., 1981*
High Plain of Bogotá, Colombia	> 23,090 ± 270	Helmens, 1988
Junín Plain, Perú	23,980 ± 320 to 12,010 ± 110 or > 42,000	Wright, 1983
Cordillera Vilcanota, Perú	> 27,540 ± 970	Mercer, 1984
Cordillera Real, Bolivia	> 33,520 ± 460 and 33,650 ± 500	Argollo, 1980; 1982
Laguna Kollpa Kkota, Bolivia	> 20,140 ± 160	Seltzer, 1994c

The results from Laguna Kollpa Kkota suggest that the last glacial maximum clearly predated 20 ^{14}C kyr BP in Bolivia. However, other records from the region suggest that the last glacial maximum may be significantly older. Snowline reconstructions that are based on maximum moraine or cirque positions are probably sampling landforms that are late-Pleistocene and earlier in age. Certainly they predate the last global glacial maximum, which is defined as 18 ^{14}C kyr BP. Thus any temporal correlation between the CLIMAP results and the snowline proxy could be in serious error (Seltzer, 1994b). However, the geomorphic record of glaciation is inherently biased towards maximum phases of glacial advance. Records of less extensive glaciations are destroyed unless they occurred since the latest deglaciation. There may have been a glacial phase coincident with 18 ^{14}C kyr BP that was less extensive than late glacial advances of glaciers in the region. The geomorphic record of glaciation is inadequate for assessing climatic conditions at times other than relative glacial maxima for which there is no evidence at 18 ^{14}C kyr BP.

Late glacial advances of glaciers have now been documented at several sites. The correlation of these advances to events such as the Younger Dryas in the North Atlantic region remains uncertain. Mercer (1984) emphasized that the late glacial advance that is inferred from the sediment stratigraphy at Quelccaya predates the onset of the Younger Dryas at 11 ^{14}C kyr BP. This is similar to the observation that has been made at Laguna Chorreras in Ecuador. Given the limited data it is difficult to determine the regional extent of these events and current work is attempting to extend these data. The pollen record in Peru is also equivocal, where high resolution studies have been conducted only one site located near an ecotone records a vegetation change coincident with a potential late-glacial advance of glaciers (Hansen & Rodbell, in press; Hansen *et al.*, 1994). In contrast, in Colombia the El Abra stadial is clearly delineated in pollen spectra and is interpreted to be Younger Dryas in age (Kuhry *et al.*, 1993).

The signal for an extended period of mid-Holocene aridity can now be found in a number of lacustrine records. Most phases of neoglaciation in the Peruvian and Bolivian cordillera occurred during the late Holocene (Rodbell, 1992b; Seltzer, 1990, 1992; Seltzer & Wright, 1991; Gouze *et al.*, 1986), which supports the concept that the mid-Holocene was a relatively arid period with little glacial activity. It has also been suggested that the aridity restricted the development of raised-field agriculture around Lago Titicaca, which was important to the Tiwanaku Culture (Binford, pers. comm.).

4. CONCLUSION

Andean glacial lakes provide information on both the timing of glacial events and the nature of post glacial climate changes. Although the precise timing of most phases of glaciation remains uncertain it is clear from several basal radiocarbon dates that 18 ^{14}C kyr BP was not a maximum phase of glaciation in the Andes. There is also abundant geomorphic and stratigraphic evidence for glacier advances in the late-glacial. Whether these were random oscillations in the glacial-to-interglacial transition or a coherent signal across the region has profound implications for our understanding of the Younger Dryas. Finally, mid-Holocene aridity may have been associated with complete deglaciation of the valleys followed by renewed glacier activity and rising lake levels in the late Holocene.

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