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Early Warming of Tropical South America at the Last Glacial-Interglacial Transition

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Glaciation in the humid tropical Andes is a sensitive indicator of mean annual temperature. Here, we present sedimentological data from lakes beyond the glacial limit in the tropical Andes indicating that deglaciation from the Last Glacial Maximum led substantial warming at high northern latitudes. Deglaciation from glacial maximum positions at Lake Titicaca, Peru/Bolivia (16°S), and Lake Junin, Peru (11°S), occurred 22,000 to 19,500 calendar years before the present, several thousand years before the Bølling-Allerød warming of the Northern Hemisphere and deglaciation of the Sierra Nevada, United States (36.5° to 38°N). The tropical Andes deglaciated while climatic conditions remained regionally wet, which reflects the dominant control of mean annual temperature on tropical glaciation.

Maximum late-Pleistocene glaciation in the tropics was associated with an ~800- to 1000-m elevation lowering of glacier equilibrium-line altitudes in response to a 4° to 6°C reduction in mean annual temperature (*1–3*). The precise timing of the Last Glacial Maximum (LGM) in the tropics, however, remains uncertain, which makes comparisons among proxies of climate change in tropical and extratropical regions equivocal (*4*). To assess possible climatic teleconnections (*5*), it is necessary to determine whether climate change in the tropics at the last glacial-interglacial transition was synchronous with or preceded analogous change at higher latitudes. Hydrologic change in the tropics may have played a role in altering thermohaline circulation of the oceans (*6*) and atmospheric methane concentrations (*7*), which would also have affected the global energy balance. Characterizing the nature and timing of climate change in the tropics at the last glacial-interglacial transition is therefore critical for understanding this period of major global change.

In the southern tropical Andes, there is limited age control for the hundreds of moraines and cirques that typify the last glaciation. The best estimate for the age of the LGM comes from the basal sediments of Laguna Kollpa Kkota, Bolivia, where radiocarbon analyses of various organic fractions of the lake sediments indicate a minimum age for deglaciation of 23,000 to 20,000 calendar years before the present (cal yr B.P.) (*8*). Elsewhere in the southern tropical Andes, radiocarbon analyses of organic matter buried beneath moraines provide maximum ages for minor glacial advances between ~16,000 and 13,000 cal yr B.P. (*9–13*). The last of these advances culminated 12,800 cal yr B.P., at the onset of the Younger Dryas cooling in the North Atlantic region (*12*). Whereas glaciers in the circum–North Atlantic region expanded in response to cooling, the tropical Andean glaciers retreated rapidly throughout much of the remainder of the Younger Dryas. Here, we report records from two Andean lakes beyond the LGM ice extent that record not only the timing of deglaciation from the LGM but also regional paleohydrological conditions, allowing us to assess the nature of climate change at the last glacial-interglacial transition.

The continuous sediment accumulation in lakes situated beyond the limit of maximum glaciation in alpine regions can be used to determine the timing of glacial advance and retreat (*14–16*). The limit of maximum glaciation in the Andes extended nearly to the modern shorelines of both Lake Junin and Lake Titicaca (Fig. 1), but neither lake was overridden by glaciers, and there is no evidence that calving glaciers formed in these lakes (*17, 18*). At maximum glaciation, there were no intervening lakes or large floodplains for sediment storage between the glacial limit and Lake Junin or Lake Titicaca. High rates of inorganic sediment accumulation in these lakes during glaciation are associated with high magnetic susceptibility (Fig. 2, fig. S1), which is attributed to increased delivery of fine-grained magnetic minerals. In the cordillera surrounding both Lake Junin and Lake Titicaca, lakes formed behind terminal moraines as glaciers retreated from LGM positions (*17, 18*). These glacially formed lakes acted as upstream sediment traps, which enhanced the deglaciation signal reflected by a decrease in sedimentation rate and magnetic susceptibility in Lake Junin and Lake Titicaca. Both lakes have a modern radiocarbon reservoir effect of <250 radiocarbon years (*19, 20*), which we assume produced a minimal effect of old or "dead" carbon on radiocarbon ages (table S1) used to develop the age models of glacial sedimentation.

A decrease in organic carbon and an increase in magnetic susceptibility at ~30,000 cal yr B.P. record the onset of LGM conditions in the Lake Junin basin (Fig. 2, fig. S1) (*20*). The magnetic susceptibility of the sediments remained high until 22,500 cal yr B.P., when the sediments changed from an inorganic, carbonate silt to an organic-rich sediment as the LGM terminated in the region. The post-LGM organic sediments are dominated by the diatom *Cyclotella stelligera*, which is a planktonic diatom characteristic of moderately deep, freshwater conditions (fig. S3). These deep and fresh conditions persisted in the lake until ~16,000 cal yr B.P., when the lake began to accumulate authigenic carbonate (*20*) and the diatom stratigraphy indicates a shift to shallow, alkaline conditions and a flora dominated by benthic diatoms. Thus, the sediment stratigraphy from Lake Junin indicates that maximum glaciation in the Junin basin occurred from ~30,000 to 22,500 cal yr B.P. and that

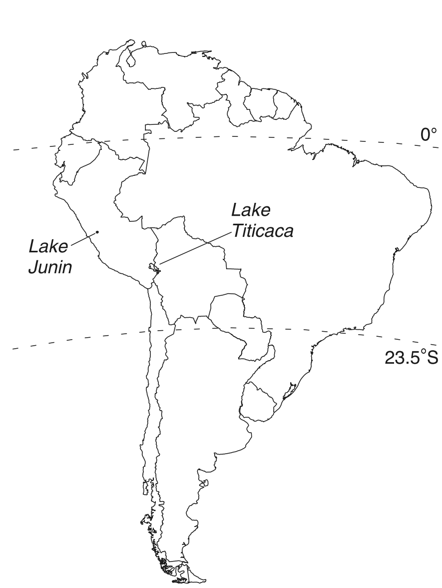

Fig. 1. Lake Titicaca and Lake Junin are located in the Peruvian-Bolivian Andes. Glaciers reached an elevation of ~4100 m above sea level in both watersheds, whereas Lake Titicaca and Lake Junin are located at elevations of 3810 and 4000 m above sea level, respectively.

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deglaciation occurred amid relatively wet climatic conditions.

In two piston cores from Lake Titicaca (NE981PC, 152-m water depth; NE985PC, 185-m water depth), magnetic susceptibility and sediment accumulation rates decreased between 24,000 and 19,500 cal yr B.P. (Fig. 2, fig. S1). In core NE981PC, magnetic susceptibility decreased 20,000 cal yr B.P. as organic carbon began to accumulate in the sediments (*21, 22*). Sedimentation rates decreased from ~0.6 to 0.2 mm/year at 20,000 cal yr B.P. (fig. S1). Similarly, in core NE985PC, magnetic susceptibility decreased

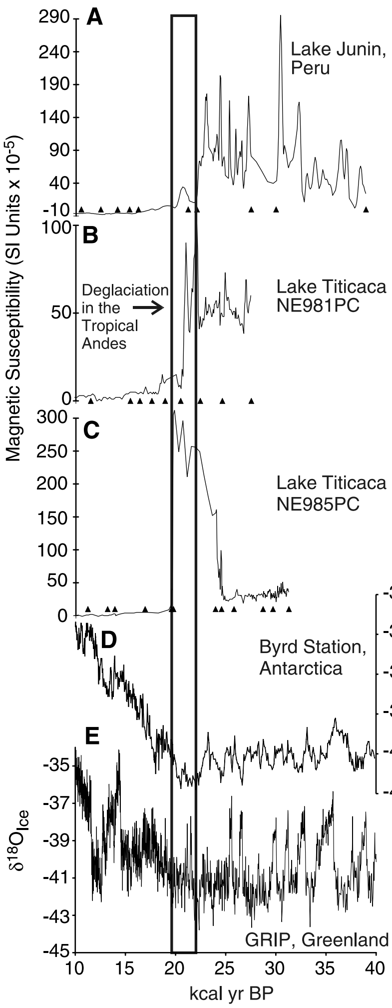

Fig. 2. Magnetic susceptibility of sediment cores from (**A**) Lake Junin (*20*) and (**B** and **C**) Lake Titicaca (*22*), measured with a Bartington MS2 meter. The black triangles indicate the calibrated radiocarbon ages used in developing the chronologies, and the boxed area indicates the timing of tropical deglaciation. Synchronized $\delta^{18}O_{ice}$ (the isotopic composition of glacial ice) profiles (*25*) from (**D**) Byrd Station (Antarctica) and (**E**) GRIP (Greenland). Deglaciation in the tropics represented by a drop in magnetic susceptibility predates the Bølling-Allerød transition in Greenland (~14,600 yr B.P.) and is more closely synchronous with early warming at Byrd Station. kcal yr BP, thousand calendar years before the present.

at 19,500 cal yr B.P., and sedimentation rates decreased from ~0.9 to 0.2 mm/year between 24,000 and 20,000 cal yr B.P. The difference in timing and magnitude of the magnetic susceptibility change may be attributed partly to the proximity of core NE985PC to the extensively glaciated Cordillera Real, Bolivia. Diatom and chemical stratigraphy from Lake Titicaca indicate that the lake was fresh and overflowing throughout the LGM until at least ~15,000 cal yr B.P. (*22*). Overflowing conditions persisted into the postglacial period, similar to the conditions at Lake Junin. This indicates that not only was the LGM in the tropical Andes associated with wet and cold conditions, but that wet conditions persisted throughout glacial retreat from LGM positions and into the post-LGM period. Farther south on the Bolivian Altiplano, a large, deep lake persisted from ~26,000 to 15,000 cal yr B.P. in what is today the Salar de Uyuni (fig. S3), adding further support to the hypothesis that the late Pleistocene in the tropical Andes was wet (*23*).

Sedimentary records from Lake Junin and Lake Titicaca show that the LGM in the tropical Andes occurred between ~30,000 and 20,000 cal yr B.P., then ended as glaciers retreated higher into valleys in the surrounding cordillera. Deglaciation occurred as snowlines rose ~1000 m in elevation in response to an increase in mean annual temperature during a climatically wet interval (*1, 3*). At the same time, summer insolation in the Southern Hemisphere was at a maximum because of orbital configuration (*24*), which may have contributed to deglaciation. Glaciers, however, remained in a diminished state, even as summer insolation reached a minimum at 10,000 cal yr B.P. When the timing of tropical deglaciation is compared with the methane-synchronized Byrd Station (Antarctic) and GRIP (Greenland Ice Core Project) ice-core records of temperature change (Fig. 2), the onset of deglaciation in the tropical Andes follows the record of Antarctic warming and precedes the Northern Hemisphere warming by several thousand years (*25*). If the timing of tropical deglaciation is compared to the Taylor Dome (Antarctica) ice-core record, which differs from other ice-core records from Antarctica in that it is highly correlated with the records from Greenland (*26, 27*), it is clear that the tropical Andes deglaciated several thousand years before higher latitude warming occurred. Ice-core records from the tropical Andes (*28, 29*) cannot be used to assess independently the latitudinal phasing of the end of the last glacial stage because of age model fitting to Northern Hemisphere records in this time period. However, sea surface temperature reconstructions from the tropical Pacific based on Mg/Ca ratios in planktonic foraminifera do show that early warming preceded a reduction in global ice volume change (mostly a Northern Hemisphere effect) (*5*). In contrast, maximum glaciation in the Sierra Nevada, United States (36.5° to 38°N), persisted until ~15,000 cal yr B.P. (*14*) (fig. S2), several thousand years after deglaciation had commenced in the tropical Andes. Thus, climatic warming in the southern tropical Andes preceded major temperature change in the Northern Hemisphere by at least 5000 years at the last glacial-interglacial transition. If early warming occurred throughout the tropics, this climatic change could have been transmitted both atmospherically and by ocean circulation processes (*30*) to produce deglaciation of alpine and continental ice sheets in the Northern Hemisphere.

References and Notes

1. A. G. Klein, G. O. Seltzer, B. L. Isacks, *Quat. Sci. Rev.* **18**, 63 (1999).
2. S. W. Hostetler, P. U. Clark, *Science* **290**, 1747 (2000).
3. S. C. Porter, *Quat. Sci. Rev.* **20**, 1067 (2001).
4. G. O. Seltzer, *Quat. Sci. Rev.* **20**, 1063 (2001).
5. D. W. Lea, D. K. Pak, H. J. Spero, *Science* **289**, 1719 (2000).
6. L. C. Peterson, G. H. Haug, K. A. Hughen, U. Röhl, *Science* **290**, 1947 (2000).
7. T. Blunier, J. Chappellaz, J. Schwander, B. Stauffer, D. Raynaud, *Nature* **374**, 46 (1995).
8. G. O. Seltzer, *Boreas* **23**, 105 (1994).
9. J. H. Mercer, M. O. Palacios, *Geology* **5**, 600 (1977).
10. J. H. Mercer, in *Late Cainozoic Paleoclimates of the Southern Hemisphere*, J. C. Vogel, Ed. (Balkema, Rotterdam, Netherlands, 1984), pp. 45–58.
11. J. D. Clayton, C. M. Clapperton, *J. Quat. Sci.* **12**, 169 (1997).
12. D. T. Rodbell, G. O. Seltzer, *Quat. Res.* **54**, 328 (2000).
13. A. Y. Goodman, D. T. Rodbell, G. O. Seltzer, B. G. Mark, *Quat. Res.* **56**, 31 (2001).
14. L. V. Benson *et al.*, *Science* **274**, 746 (1996).
15. J. L. Bischoff, K. Cummins, *Quat. Res.* **55**, 14 (2001).
16. L. Benson, in *Mechanisms of Global Climate Change at Millennial Time Scales*, P. U. Clark, R. S. Webb, L. D. Keigwin, Eds., vol. 112 of *Geophysical Monograph Series* (American Geophysical Union, Washington, DC, 1999), pp. 203–226.
17. H. E. Wright Jr., *Geogr. Ann.* **65A**, 35 (1983).
18. G. O. Seltzer, *J. Quat. Sci.* **7**, 87 (1992).
19. M. B. Abbott, M. W. Binford, M. Brenner, K. R. Kelts, *Quat. Res.* **47**, 169 (1997).
20. G. O. Seltzer, D. T. Rodbell, S. Burns, *Geology* **28**, 35 (2000).
21. M. J. Grove, thesis, Duke University (2000).
22. P. A. Baker *et al.*, *Science* **291**, 640 (2001).
23. P. A. Baker *et al.*, *Nature* **409**, 698 (2001).
24. A. L. Berger, *Quat. Res.* **9**, 139 (1978).
25. T. Blunier *et al.*, *Nature* **394**, 739 (1998).
26. E. J. Steig *et al.*, *Science* **282**, 92 (1998).
27. P. M. Grootes, E. J. Steig, M. Stuiver, E. D. Waddington, D. L. Morse, *Quat. Res.* **56**, 289 (2001).
28. L. G. Thompson *et al.*, *Science* **269**, 46 (1995).
29. L. G. Thompson *et al.*, *Science* **282**, 1858 (1998).
30. T. F. Stocker, *Science* **282**, 61 (1998).

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Supporting Online Material

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Figs. S1 to S3

Table S1

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