Evidence for Contemporary Lakes and Glaciers in the Southern Altiplano During Late Glacial Time

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Abstract: Cosmogenic ^{36}Cl ages of glacial landforms on Cerro Azanaques are in the range 16.6-13.7 calendar ky. The equilibrium line altitude decreased by up to 800 m and air temperature decreased by up to 5°C. The glaciation was contemporary with the paleolake Tauca (18-13 ky, maximum at 16-14 ky), confirming that precipitation was a main factor controlling paleoclimate. But the initial glacial advance (before 16.6 ky) was caused by decreased temperature, and the final deglaciation (after 14.5 ky) was due to increased temperature.

INTRODUCTION

An outstanding problem in Quaternary geology and paleoclimatology of the Altiplano is the relationship between levels of paleolakes in closed basins and glaciers in the surrounding mountains. Understanding these relationships is important for reconstructions of paleoclimates because both lakes and glaciers respond to the same main climatic variables - precipitation and temperature. However, the current knowledge of ancient lakes and glaciers is incomplete, mainly because of difficulties in developing absolute chronologies for lake and glacial deposits. Paleolake shorelines are difficult to date because of possible large and uncertain reservoir effect in ^{14}C dating, and because of large corrections for excess Th in U-Th dating. Moraines in the arid environment of the Altiplano are difficult to date because of the absence of organic material datable by ^{14}C. Here, we use cosmogenic ^{36}Cl to date moraines and an outwash fan on Cerro Azanaques, to the east of Lake Poopó, and compare these ages with the previously-published chronology of paleolake Tauca.

STUDY AREA AND SAMPLING

The Altiplano of Bolivia (Fig. 1) contains abundant evidence of Quaternary climatic changes. In mountain valleys and in their foothills, moraines and outwash fans record former extent of glaciers. At the floor of the Altiplano, paleoshorelines of closed-basin lakes record varying lake levels. We developed a record of glacier advances and retreats in Lijunimayu Valley (Fig. 1), where a sequence of six moraines exists at elevations from 3900 m to 4700 m. An outwash fan (or a debris flow) is present at elevations between 3900 and 3800 m; at elevations below 3770 m, it becomes a glaciofluvial delta built into a paleolake level at an elevation of 3750 m.

Sampling was designed to obtain a complete glacial record preserved at the surface. Boulders were selected based on their size (large boulders were preferred), position on the moraine surface (horizontal tops were preferred), and preservation of glacial surface (striae, polish) or other indication of surface antiquity (varnish development, deep solution pits). In the field, for each sample we noted the following: boulder size (diameter and height) and shape (especially roundness), slope of the moraine surface, any indication of erosion of the matrix around the boulder, preservation of the boulder surface (including any indication of erosion of boulder tops), angle to topographic features, sample position on the boulder surface, and sample thickness.

METHODS

Samples were prepared following the procedures described previously (Zreda, 1994). Chlorine-36 was measured by accelerator mass spectrometry (Elmore et al., 1979) at Purdue University. Major elements were determined by X-ray fluorescence, B and Gd by prompt gamma emission spectrometry, U and Th by neutron activation analysis, all at a commercial laboratory. Chlorine was determined using combination ion-selective electrode following digestion of samples in teflon diffusion cells (Aruscavage and Campbell, 1983).

Cosmogenic ^{36}Cl dating uses the accumulation of ^{36}Cl *in situ* in erratics exposed to cosmic radiation (Phillips et al., 1990). Individual boulder ages were calculated using the production rates of ^{36}Cl determined by Phillips et al. (1996). These rates have been scaled to the latitude and elevation of sample sites (Lal, 1991), and corrected for the variable paleomagnetic field intensity (Shanahan and Zreda, 2000). Landform ages were calculated as weighted means of individual boulder ages.

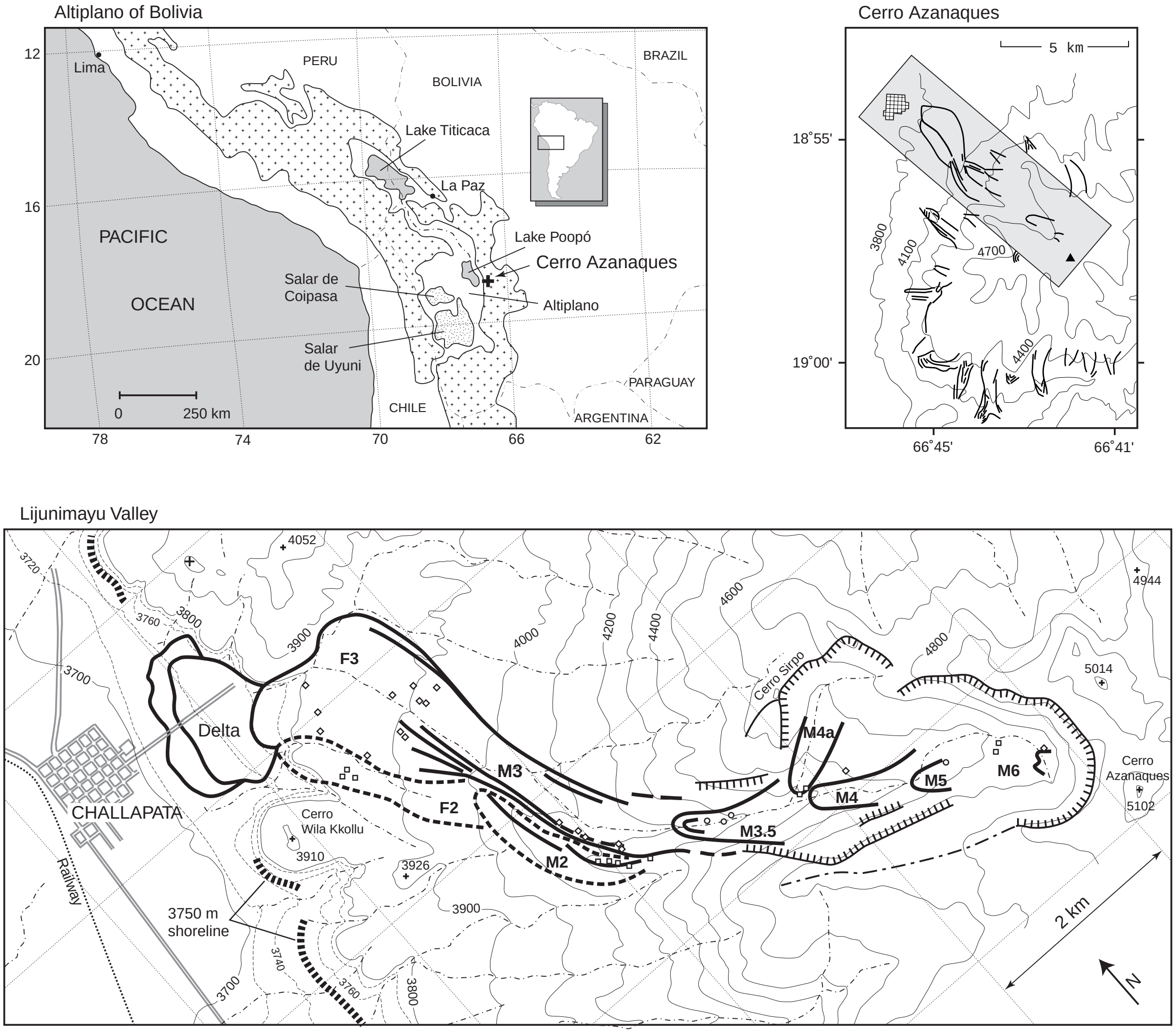

Figura 1 –*Study area and glacial deposits of the Lijunimayu Valley.*

Two methods were used to estimate paleo equilibrium line altitudes (paleo ELA or PELA): the toe-to-headwall altitude ratio (THAR), with the THAR ratio of 0.45 recommended by Klein et al. (1999), and the maximum altitude of lateral moraines (MALM). The two methods gave results consistent within 100 m. We report the ELA decreases calculated using the MALM method.

Paleotemperatures were calculated using the PELAs, the modern ELA of 5150 m, and the atmospheric temperature gradient (lapse rate) of 6.5°C/km. The temperature differences between today and glacial times is obtained under the assumption of paleoprecipitation rate similar to the modern rate (dP=0 in Table 1) and increased glacial-time precipitation rate by 200 mm/yr (dP=200 mm/yr)(Hastenrath and Kutzbach, 1985). We also assume that equivalent ELA changes are produced by 100 mm/y precipitation change and by 1°C temperature change (Hastenrath and Kutzbach, 1985).

RESULTS

Five moraines (M3, M3.5, M4, M4a and M6) and one fan (F3) were dated. The results are discussed below, and numerical results are compiled in Table 1 and shown in Figure 2.

The most extensive glacial advance (advance 3) is defined by a massive, tall, sharp-crested left lateral moraine (M3), whose surface contains numerous blocks 2-5 m in size, many with striated and polished surfaces. Five boulders gave consistent exposure ages.

Margin 3.5 is marked by three closely spaced, small, probably recessional moraines (M3.5), each composed of a single line of numerous, but small boulders, typically less than 1.5 m tall.

Table 1. Paleo ELA (PELA), ELA drop, and temperature drop for two different precipitation increases (dP) for Cerro Azanaques glaciers. Modern ELA of 5150 m and lapse rate of 6.5°C/km were used. Preferred values of temperature are shown in bold.

Surface designation	**Exposure age (ky)**	**Number of ^{36}Cl samples**	**PELA (m)**	**ELA drop (m)**	**Temperature drop (°C)**	
					dP=0	**dP=200**
M3	16.5 ± 0.5	5	4350	800	**5.2**	3.2
M3.5	14.5 ± 1.1	5	4500	650	4.2	**2.2**
M4	14.4 ± 0.9	5	4550	600	3.9	**1.9**
M4a	14.3 ± 1.2	2	4550	600	3.9	**1.9**
M5	undated	---	4650	500	3.3	**1.3**
M6	13.7 ± 0.7	2	4680	470	3.1	**1.1**
Mean M3.5 to M6	14.3 ± 0.5	16	---	---	---	---
F3	14.7 ± 0.4	10	---	---	---	

Advance 4 is defined by massive, tall terminal and lateral moraines in the main valley (moraine M4) and at the exit of a right tributary valley (moraine M4a). The moraine crests are littered with glacially rounded, polished and striated boulders up to 4 m in diameter and 2 m tall. The large size of moraines M4 and M4a implies a significant readvance of the Lijunimayu and the tributary glaciers and, therefore, an important climatic change. The mean ages of these two moraines are identical, as are their ELA depressions.

The two youngest moraines (M5 and M6) form well-defined loops near the head of the valley. Moraine M5 could not be dated because of the absence of well-preserved boulders. Moraine M6 marks the final stillstand or a short, minor readvance of the glacier before the final deglaciation. A single boulder from moraine M6 and three boulders from the outwash deposit in front of the moraine were combined to determine the mean age.

Ten boulders from the massive fan deposit (F3) gave consistent ages, with the mean of 14.7± 0.4 ky, correlative with moraines M3.5, M4 and M4a, M5 and M6, which have a combined age of 14.3 ±0 .5 ky.

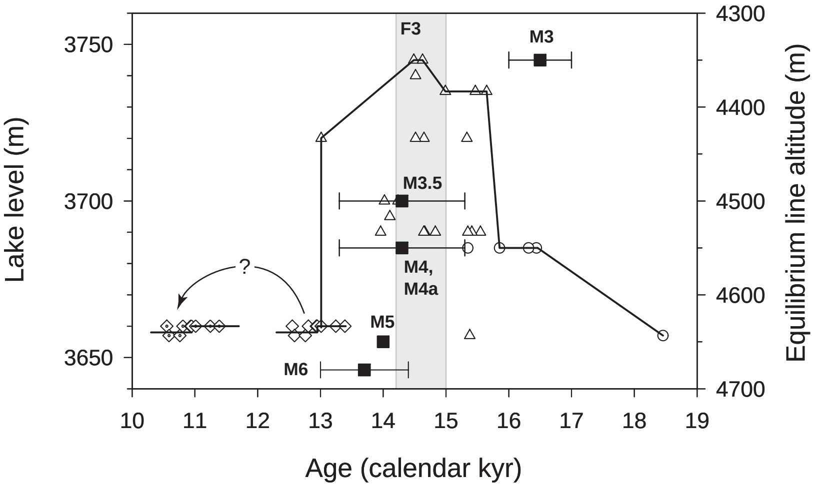

Figura 2. *Comparison of ^{36}Cl ages of Cerro Azanaques moraines (M3 through M6, squares, error bars are 1σ ; age of M5 is interpolated between M4 and M6) and fan (F3, gray bar, width is 1σ) with the ^{14}C chronology (open symbols) of paleolake Tauca (modified from Sylvestre et al., 1999).*

DISCUSSION

The ^{36}Cl data indicate that all moraines and the fan were deposited during Late-Glacial time, coevally with the paleolake Tauca (Fig. 2). Deposition of the most extensive moraine (M3, deglaciation age 16.5 ± 0.5 ky) coincided with the initial rise of the lake to approximately one-third of its maximum level (3685 m). The oldest ^{14}C age obtained for this lake level is 16.4 calendar ky. Together, these data suggest that the glacier that produced moraine M3 had existed before the lake filled up. Therefore, this initial glacial advance was probably due to decreased temperature rather than increased precipitation. Assuming that precipitation was not significantly different from the modern value, the temperature was about 5.2°C colder than today (Table 1). If similar glaciers at other locations around paleolake Tauca disintegrated at the same time, they might have been the cause of the initial increase of the paleolake level to 3685 m (the pluvial hypothesis). The deposition time of M3 coincides almost exactly with Heinrich event I (15.7-17.3 calendar ky), suggesting a global mechanism of climate change at the time.

All other moraines (M3.5 through M6) and the associated fan-debris flow (F3) were deposited at the time when the lake level was at or near its maximum. The high lake level indicates that the precipitation rate in the region was high, or/and that the evaporation rate was low (increased cloudiness). Consequently, the deglaciation at that time was most likely due to increased temperature. Assuming that the precipitation rate was higher than the modern value by 200 mm/y, the temperature was only 1.1-2.2°C colder than today (Table 1). This is supported by the unusually high temperature 15-14 ky ago inferred from the ^{18}O record obtained from Sajama ice (Thompson *et al.*, 1998). However, the same ice-core data indicate low accumulation rate, which is in an apparent conflict with our results. A possible explanation of this inconsistency is that due to the increased temperature, at Sajama site, most of the summer precipitation was in the form of rain, thereby contributing negligibly to the snow accumulation rate. Warm summer precipitation would also increase the rate of melting of glaciers around the southern Altiplano, causing favorable conditions for deposition of debris flow and fluvioglacial outwash.

The apparent absence of deposits that would correlate with the Last Glacial Maximum *sensu stricto* (about 21 calendar ky ago) shows that climatic conditions at that time were unfavorable for the development of sizeable glaciers. This is in agreement with other studies reporting apparent absence of LGM in South American lakes (Ledru *et al.*, 1998). This result confirms that LGM is not necessarily synchronous regionally or globally, and indicates that the common practice of correlating glacial deposits in absence of numerical chronologies can produce erroneous results and should be abandoned.

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