Perennial stream discharge in the hyperarid Atacama Desert of northern Chile during the latest Pleistocene

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A large fraction of the vital groundwater in the Atacama Desert of northern Chile is likely composed of "fossil" or "ancient" reserves that receive little or no recharge in today's hyperarid climate. Here, we present evidence for latest Pleistocene perennial streamflow in canyons from the hyperarid core of the Atacama Desert in northern Chile. Fluvial terraces in the Pampa del Tamarugal (PdT) basin (21°S) contain widespread fossil wood, *in situ* roots, and well preserved leaf litter deposits indicative of perennial surface flow currently absent in these channels. Nineteen radiocarbon dates on these deposits from four separate drainages within this endorheic basin indicate ages from 16,380 to 13,740 cal yr BP, synchronous with paleolake Tauca on the Bolivian Altiplano and other regional evidence for wetter conditions during the latest Pleistocene. Groundwater-fed riparian ecosystems and associated fluvial deposits abound today in the absence of direct rainfall in northern Atacama canyons with perennial discharge. Our relict riparian ecosystems from the PdT basin are indicative of conditions similar to these northern canyons. Given that discharge was higher than present during this time, we propose that these deposits represent the most important groundwater recharge events of the last 18,000 years. A lesser recharge event occurred during the Holocene, when phreatophytic trees also grew in these drainages between 1,070 and 700 cal yr BP, during the Medieval Climatic Anomaly. Taken together, our evidence lends further support for gradient changes in the equatorial Pacific as a major driver of hydrologic change in the Atacama on both centennial and millennial time scales.

central Andes | hyperaridity | riparian ecosystems | late Quaternary | fluvial terraces

The hyperarid Atacama Desert drapes across the western flank of the Andes Mountains, at the western extreme of central South America, including much of northern Chile. The extreme lack of precipitation is a feature that has remained stable over millions of years because of major coupled atmospheric and tectonic feedbacks (1–5). But short-lived times of increased precipitation exist in paleohydrological records at elevations above 2,000 m, reflecting millennial-scale variations in global climate. In particular, two major periods of increased precipitation are known to have affected groundwater tables and plant species distributions during the late Quaternary (6–10). The impacts of these wet phases in the lower elevation desert, expressed as either increased precipitation or variations in surface runoff and local groundwater table, have largely remained unstudied, although attempts have been made to understand current climate and the hydrologic system feedbacks (11–13). Increased surface flow over this region during predominantly late Pleistocene humid intervals may have modified the landscape and contributed to groundwater recharge.

Groundwater is a precious resource throughout the hyperarid and arid Atacama Desert for life (that of both native vegetation and humans) and industry. In particular, all aspects of copper production and the people that serve the industry rely on groundwater. Today, >23% of global copper is produced in the Atacama Desert (14), and in the year 2000, 16% of Chile's gross domestic product was derived from copper exports (14). Consequently, recognition of inputs and outputs to groundwater supplies is a vital part of Chile's economic planning. Nevertheless, few studies have assessed connections between water balances and past climates.

Here, we report on new evidence for latest Pleistocene recharge of major aquifers in the Atacama Desert, through the proxies of fluvial deposits and associated riparian ecosystems. This study is specific to the Pampa del Tamarugal (PdT), a low-elevation endorheic basin located 19°30′S to 22°S latitude at the base of the Western Andean Cordillera (WAC) in the hyperarid core of the Atacama Desert (Fig. 1). These fluvial sediments were deposited during humid climate "windows," in stark contrast to the Mio-Pliocene arid-hyperarid climates that preceded their deposition (7, 15) and the hyperarid conditions present today. Multiple terraced deposits inset into Neogene sediments along the eastern portion of the southern PdT display several aggradation and incision cycles along canyon walls, and connected surfaces of fans associated with the fluvial activity spread out from these canyons into the basin center. Although plantless today, these terraces and fans literally abound with Pleistocene fossil wood and leaf beds (Fig. 1 *C–E*), all of which are found *in situ* or have been transported only very short distances.

We use ^{14}C-dating (Table 1), sedimentological evidence, and macrofossil analyses to infer the latest Pleistocene drainage basin environment and paleoclimate by analogy to current climatic conditions and riparian ecosystems in the region. Our chronology establishes regional-scale connections between documented humid intervals to the east on the Altiplano, Western Cordillera, and Pre-Cordillera of the central Andes and our low-elevation fluvial record. We discuss the implications of our results for past freshwater recharge of the PdT basin, where groundwater is a major economic resource.

Modern Environment and Groundwater

The intense aridity of the Atacama Desert is brought about by a combination of long-term stable climatic factors. These include blocking of the mid-latitude Westerlies by the stable subtropical high-pressure belt, an orographic rainshadow generated by the Altiplano and WAC, and a strong coastal thermal inversion created, largely, by the cold, north-flowing Humboldt Current (3, 16). Austral summer rainfall between 18°S and 24°S occurs in the highlands (>2,000 m) when the intensified Bolivian High

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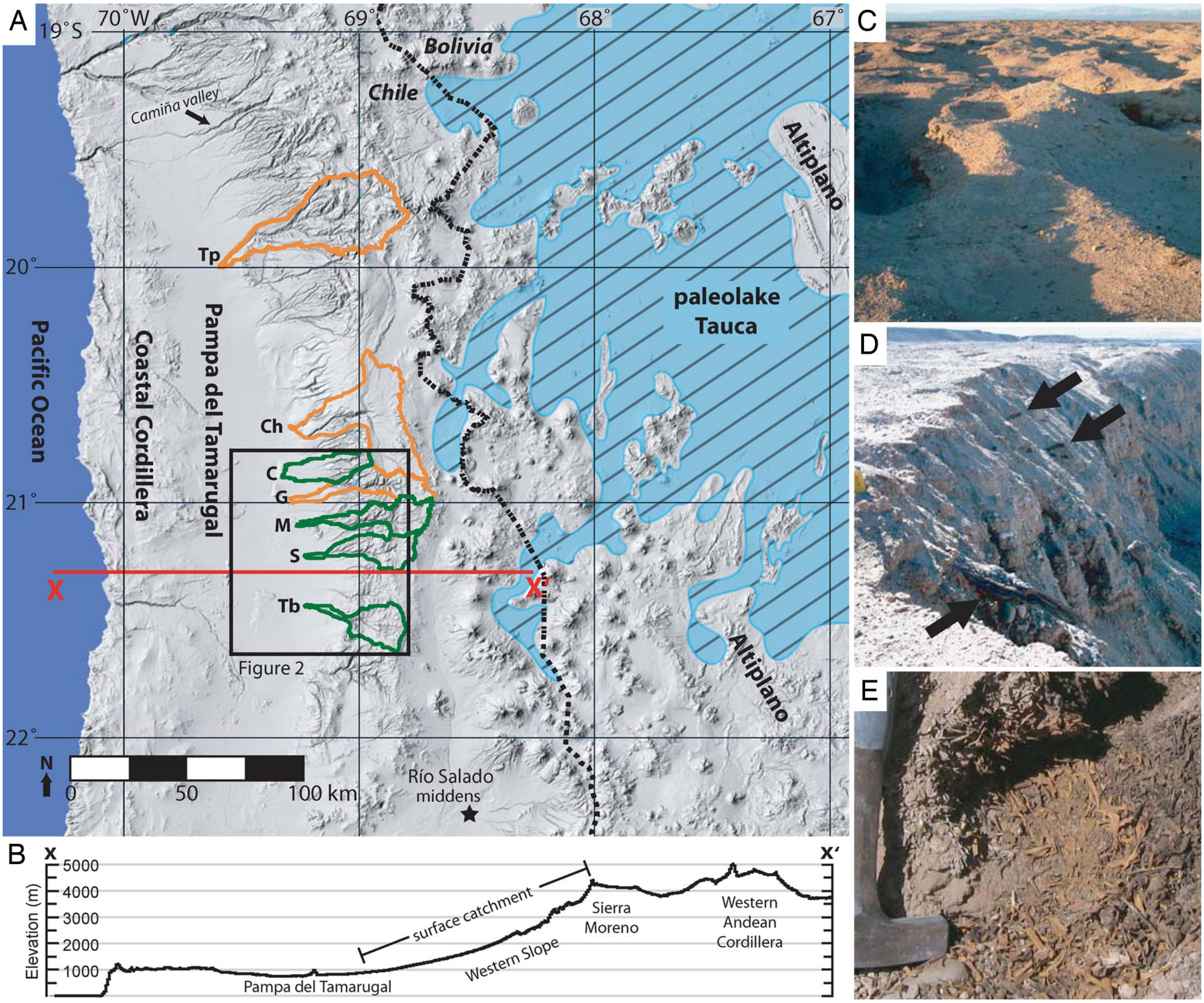

Fig. 1. Catchments and characteristic features of the late Pleistocene riparian systems. (*A*) Regional map of northern Chile showing study area in relation to the approximate maximum extent of paleolake Tauca. Green and orange lines enclose surface water catchments mentioned in the text (green where the trunk stream is ephemeral and bordered by late Pleistocene wood-bearing sediments; orange where the trunk stream is perennial). Tp, Tarapacá; Ch, Chacarilla; C, Chipana; G, Guatacondo; M, Maní; S, Sipuca; Tb, Tambillo. (*B*) Topographic cross-section (located along X—X′ in *A*). (*C*) Photograph of T2 surface at Tb. Note the numerous excavated ''mounds'' dotting the landscape, indicating the vast expanse of organic Pleistocene deposits. In *D*, black arrows indicate logs transported within late Pleistocene aggradational fill. (Notebook at left for scale.) (*E*) A *S. molle* leaf litter deposit at Tb.

advects moisture-laden Amazonian air masses over the Andes (17), occasionally as far west as the WAC and Sierra Moreno (SM). Westward transport of moisture is particularly strong during La Niña years, when the Bolivian High intensifies and migrates south over the Altiplano (18, 19), and, for the southern Altiplano, during years of anomalously high moisture delivery to the continent inboard of the South Atlantic (19). At these latitudes, annual precipitation amounts are a function of elevation on the Pacific-facing western Andean slope. From 1975 to 1991, annual rainfall below 2,000 m was <10 mm/yr, increasing to 120 mm/yr at 4,000 m elevation (13).

With a mean elevation of ≈1,000 m, the PdT is flanked to the west by the Coastal Cordillera and to the east by the Pre-Cordillera and SM, which rise to >4,000 m (Fig. 1). The westerly flowing surface drainages in the SM are completely disconnected from the Altiplano and WAC, which lie to the east (Fig. 1*B*). Baseflow originates from springs at high elevations within the surface water catchments (13, 20) and flows westward in widely spaced canyons. The eastern limits of groundwater catchments are not well defined (11, 20). Because today's rivers and groundwater display similar stable isotopic trends with altitude, both are likely derived from the same source (11).

A latitudinal change at ≈21°S from predominantly perennial (north) to ephemeral (south) streams correlates with a southward decrease in the area of the catchment basins [supporting information (SI) Table 2] rather than with a latitudinal climate gradient. Given that most of the western Andean slope drainage basins are located in the high-elevation WAC and SM (Figs. 1 and 2), and that a strong correlation of mean annual precipitation with elevation is known to exist (3), larger catchment areas correlate with greater discharge delivered to the trunk streams in this region (SI Table 2). For reference, the perennial Tarapacá River (≈150 km to the north of our study area; Fig. 1) had an average discharge of 0.303 m^3/s for the period 1984–1990,

Table 1. Sample locations and conventional or AMS ^{14}C dates of organic material

Sample no.	Laboratory code	Location, °S, °W	Sample ID	^{14}C yr BP	Cal yr BP (2σ)	$\delta^{13}C$, ‰
			Chipana canyon drainage			
1	UCIAMS-29216	20.90, 69.34	N05-21	13,055 ± 25	15,740–15,160	−22.7
2	UCIAMS-29221	20.90, 69.34	N05-22	12,160 ± 130	14,590–13,740	No data
			Maní canyon drainage			
3	CAMS-129007	21.09, 69.30	QM-2a	870 ± 30	910–700	−10.4
4	CAMS-129008	21.09, 69.28	QM-2e	960 ± 30	930–800	−22.7
5	CAMS-129009	21.09, 69.30	QM-3a	1,110 ± 30	1,070–940	−24.3
6	CAMS-131272	21.09, 69.32	QM-4	13,190 ± 35	15,960–15,300	−24.3
			Sipuca canyon drainage			
7	GX-32394	21.23, 69.19	QS-1a*	13,330 ± 80	16,250–15,420	−24.3
8	GX-32395	21.23, 69.20	QS-3†	13,400 ± 70	16,340–15,530	−24.4
9	UCIAMS-29222	21.23, 69.20	N05-10	14,470 ± 70	17,840–16,940	No data
			Tambillo canyon drainage			
10	GX-32396	21.43, 69.25	QT-1*	13,290 ± 80	16,180–15,370	−23.9
11	GX-32397	21.43, 69.25	QT-5‡	12,940 ± 150	15,840–14,870	−24.8
12	GX-32398	21.43, 69.25	QT-6†	13,310 ± 180	16,380–15,220	−24.5
13	CAMS-129367	21.44, 69.26	QT-8	13,280 ± 70	16,140–15,360	−24.0
14	CAMS-131273	21.44, 69.31	QT-9	13,220 ± 35	16,010–15,340	−27.1
15	UCIAMS-29220	21.44, 69.25	N05-11	13,080 ± 30	15,780–15,180	−20.5
16	AA62290	21.40, 69.42	N04-14a	12,244 ± 96	14,630–13,850	−28.1
17	UCIAMS-29218	21.40, 69.42	N05-12a	12,735 ± 30	15,250–14,840	−20.2
18	UCIAMS-29219	21.40, 69.43	N05-18	12,435 ± 30	14,820–14,190	−20.7
19	UCIAMS-29217	21.43, 69.46	N06-11a	10,170 ± 20	11,970–11,420	−21.7

Samples associated with levels of terraced deposits (explained in text): *, T2; †, T2.5; ‡, T2.7.

fluctuating between monthly averages of 0.159 m^3/s (November) and 0.438 m^3/s (February) (21). The Chacarilla perennial stream (≈20 km north of our northernmost site; Fig. 1) had a discharge of 0.015 m^3/s at the end of the 1999 dry season (13).

The drainages that enter the southern PdT in our study area have almost no surface flow in their trunk streams. Surface water that reaches the PdT through the canyons during an ≈5-yr-frequency storm event quickly infiltrates the unconsolidated streambeds (11, 13). These convective storms in the SM and WAC can produce ≈10–40 mm of rainfall per day at higher elevations (13, 22). Rough estimates determine that 5–10% of the precipitation that falls today within this drainage basin recharges underlying aquifers, with 90–95% being lost to evaporation (13, 21). The proportion of water infiltration to evaporation has been modeled to be much higher during extreme storm events (13).

Groundwater aquifers in the northern PdT and similar intermontane valleys of the Atacama Desert host many wellfields whose water is piped long distances to mines and municipalities. Some shallow (<50 m) PdT aquifers recharge locally (13, 22), but sparse ^{14}C data from the deeper aquifers (100–300 m depth), in conjunction with other evidence, suggest that some of the groundwater was recharged >10,000 years ago (11, 20, 21). Too few data exist to estimate what portion of the produced groundwater is fossil. For the southern PdT, only saline water aquifers are recognized.

Sediments deposited in the modern PdT reflect the asymmetry of its modern hydrologic environment. In the eastern canyons and on their alluvial fans, unsorted mudflow and debris flow deposits are widespread, emplaced by mass wasting triggered by the rare convective storms at high elevations (13, 22). In the western part of the valley where the water table nearly intersects with the land surface, its evaporation leads to precipitation of salts, forming salt pans (*salars*) (12, 13, 20, 22).

Direct rainfall in the PdT is negligible (absent for decades in some places), and the interfluves in the study area below ≈2,500 m elevation are entirely devoid of macroscopic life. In fact, large expanses of this "Absolute Desert" (23) are covered by highly soluble nitrate deposits (24, 25). Plant life only occurs today in perennial or intermittent channels and oases. Natural and planted forests of the phreatophyte *Prosopis tamarugo* (Mimosaceae) are extensive in the distal portion of the northern PdT where groundwater is within ≈10 m of the land surface. Occasional storm runoff supports sparse patches of halophytes in intermittent washes such as *Distichlis spicata* (Poaceae), *Cressa cretica* (Convolvulaceae), *Atriplex atacamensis* (Chenopodiaceae), *Loasa fruticosa* (Loasaceae), and *Tessaria absinthioides* (Asteraceae) (26).

Perennial watercourses are commonplace in major canyons with outlets to the Pacific Ocean north of 19°30′S (Fig. 1). These fertile oases support abundant riparian vegetation from their headwaters in the WAC and Precordillera through the low elevation hyperarid core of the Atacama Desert (26–30). Below 2,600 m, canyon floodplains are dominated by *Escallonia angustifolia* (Escalloniaceae), *Schinus molle* (Anacardiaceae), *Myrica pavonis* (Myricaceae), *Geoffroea decorticans* (Fabaceae), *Baccharis* spp., *Tessaria absinthioides* (Asteraceae), *Cortaderia atacamensis*, and *Phragmites australis* (Poaceae) (28–30).

Stratigraphy and Chronology of Latest Pleistocene Fluvial Terraces

Within the PdT, the canyons are incised into debris-flow-dominated alluvial latest Miocene relict terraced deposits (T1 in Fig. 3) that have seen negligible denudation during the past 5 Myr (31, 32). Late Pleistocene inset fill terraces are preserved between 1,200 and 1,550 m elevation in every major canyon connected to the SM from 20°30S to 21°30′S. We describe terraces and organic-rich deposits from the Chipana (C), Maní (M), Tambillo (Tb), and Sipuca (S) drainages (Fig. 2), each of which today hosts an ephemeral stream. Although well preserved late Pleistocene plant macrofossils were identified within multiple stages of terraced deposits at each location, the relationships of these deposits within and between Tb and S were specifically described for this study. In the perennial Chacarilla

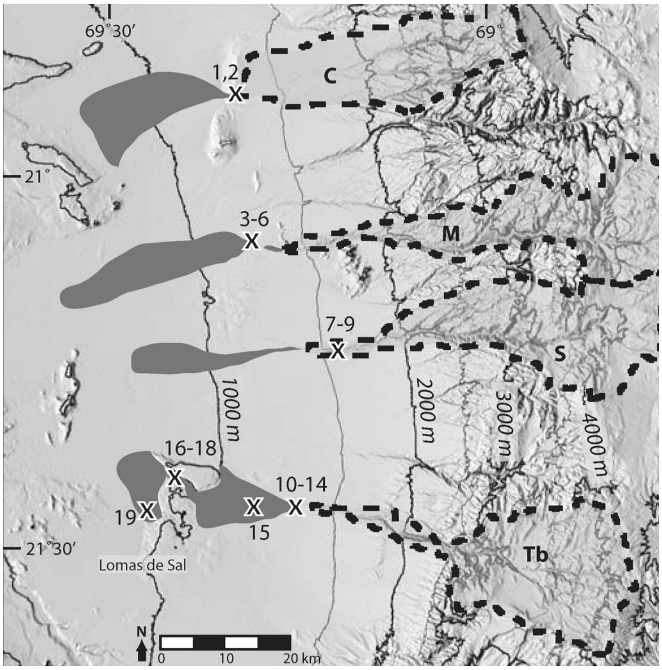

Fig. 2. Locations whose organic remains are reported here (marked by "X") in the lower sectors of ephemeral drainages (Fig. 1) where latest Pleistocene fluvial terraces line the canyons, and on alluvial fans spread westward from the mouths of the canyons across the floor of the PdT (contour interval = 500 m). Sample numbers correspond to Table 1. Gray shading indicates fans that also likely contain organic-rich deposits contemporaneous with dated material.

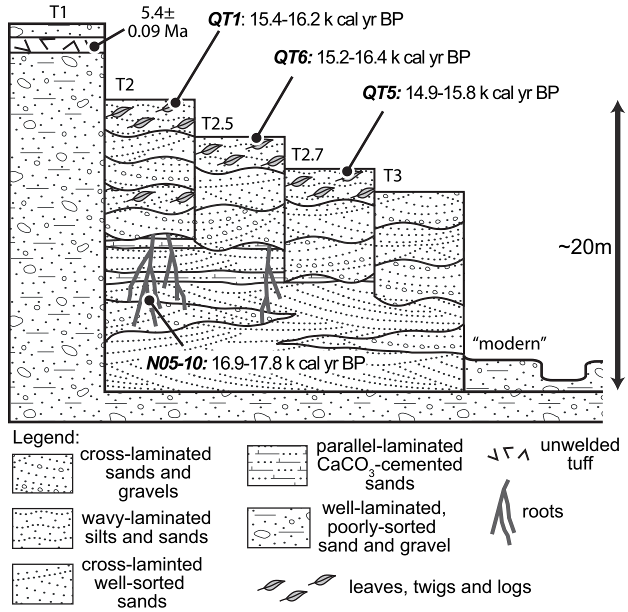

Fig. 3. Generalized stratigraphy of fluvial sediments inset within Upper Miocene alluvial deposits, combining observations from Tambillo and Sipuca canyons. All dated organic material was discovered *in situ* and taken from root material or leaf litter. Sample IDs are explained in Table 1. Ages listed are for single samples and denote the 2σ uncertainty. Horizontal distances are not to scale.

(Ch) and Guatacondo (G) canyons (Fig. 1), fluvial terraces occur in the same geomorphological positions as in C, M, S, and Tb but lack associated organic-rich deposits.

In descending order (to the modern channel), the different terraces recognized at Tb and S are T1, T2, T2.5, T2.7, T3, and "modern" (Fig. 3). At Tb, fluvial aggradational fill associated with terraces T2, T2.5, T2.7, and T3 reaches a thickness of 20 m. T2 is inclined more steeply than T1, intersecting at ≈1,200 m, west of which the fluvial fill spreads beyond the canyons to form alluvial fans. The modern channel (inset by 1–3 m into its floodplain) near 1,250 m elevation rests >10 m below T3 and continues as a confined channel for tens of kilometers downstream.

The oldest Pleistocene aggradational unit contains several horizons of a highly eroded, carbonate-bearing incipient paleosol. It consists of cross-bedded, well sorted, rounded to subrounded, medium- to coarse-grained sands, interbedded with weakly to prominently bedded pebble conglomerates containing Mesozoic to Neogene volcanic and sedimentary clasts. Interbedded horizontal carbonate hardpan layers reach stage II development. Unaltered roots (up to 20 cm in diameter) and rootlets are often preserved within $CaCO_3$ rhizoliths. A ^{14}C accelerator mass spectrometry (AMS) calibrated date of 17,840–16,940 cal yr BP (all dates at 2σ; calibrations according to ref. 33) on these roots gives the oldest age for the entire sequence (Table 1).

Aggradational fluvial deposits associated with the T2, T2.5, and T2.7 terraces are inset into either these oldest Pleistocene deposits or within the Miocene alluvial sediments. Practically indistinguishable from one another based on sediment and sedimentary structures, the terraces can only be recognized by the relative elevations of their upper surfaces and the sequence of fill deposits subdivided based on associated erosional bases and dated organic material. Reaching a thickness of ≈5 m, these aggradational fluvial deposits are very to moderately well sorted, well rounded to subangular, cross-bedded fine to coarse sands and pebbles. The topmost surfaces of these constructional terraces are dotted with mounds of extraordinarily well preserved organic matter that are surrounded by a small degree of rilling. These mounds contain abundant identifiable and datable organic material, and exhibit signs of extensive human wood "mining" activities since the early 1800s (34).

Apart from abundant wood and bark, these mounds abound with *in situ* leaf litter deposits. Leaves and fruits of the trees *E. angustifolia* and *S. molle* prevail. Pollen from Asteraceae, *Prosopis* sp., and Poaceae were also recovered (from Tb), as well as *Baccharis scandens* leaves and flowers, and seeds of the xerophytic annual *Cistanthe*. Poaceae and *Prosopis* pollen were detected in samples from S. AMS dates of these organic remains within the upper meter of deposits associated with the fluvial terraces range from 16,340 to 15,421 cal yr BP at S, to between 16,380 and 14,870 cal yr BP at Tb. Dates on organic deposits at M range between 15,960 and 15,302 cal yr BP.

Our ^{14}C-chronology of *in situ* organic remains (Table 1) present during each aggradational phase termination illustrates a systematic decrease in ages obtained from progressively lower terrace levels. At least three relatively rapid cycles of aggradation, abandonment, and incision are preserved. Terrace formation of T2.5 and T2.7 was short-lived, and three separate events (T2, T2.5, and T2.7) span from ≈16,000 to ≈15,000 cal yr BP (Fig. 3).

The deposits associated with the T3 terrace, inset beneath the T2.7 terrace, are also fluvial in origin, with moderately well sorted, well rounded to subangular, cross-bedded coarse sands and pebbles. They are indistinguishable in composition from the other deposits considered here, except that they are noticeably devoid of *in situ* organic material. As such, an upper age constraint does not yet exist for these deposits.

Fluvial deposits occur also ≈20 km west of the canyon T terraces within an incised ephemeral stream channel in Lomas de Sal (Fig. 2), a 50-m-high knoll of Mio-Pliocene evaporites

(14). The sediments contain fine- to coarse-grained, cross-bedded gravels and sands with abundant *E. angustifolia* leaves and logs of *S. molle* up to 40 cm in diameter. The organic material dates from between 15,253 and 13,850 cal yr BP (samples 16–18 in Table 1). These are a flood deposit and not *in situ*. Even more distant are fan deposits containing well sorted cross-bedded, fine- to medium-grained sands with abundant *in situ* and transported organic material. Sample 19 of *in situ* roots yields a ^{14}C AMS date of 11,974–11,415 cal yr BP, indicating a vegetative cover younger than the dated terraces located upstream.

Additionally, a late Holocene constructional terrace with organic mounds is also present along small side canyons that branch off from the M main drainage. Dated to between 1,070 and 700 cal yr BP (samples 4–6), these mounds contain almost pure *Prosopis* sp. remains, including seeds, pods, leaves, inflorescences, and wood. Archaeological remains (charcoal, bone fragments, flakes, and pottery) abound on the surface of this terrace. The most recent ("modern" in Fig. 3) deposits are debris-flow-dominated alluvial sediments, similar to those associated with the T1 late Miocene sediments.

Paleoenvironmental Interpretation and Regional Paleoclimate

At ≈1,250 m elevation, the latest Pleistocene section at Tb is the best preserved and used here for overall interpretation (Figs. 2 and 3). The array of species present at Tb reveals a blend of facultative phreatophytes and hygrophytic taxa analogous to riparian plant communities found in canyons with perennial rivers further north (e.g., Camiña Valley, 19°20′S; Fig. 1). *S. molle* is a xerophytic tree when local precipitation exceeds 200 mm/yr, becoming a facultative phreatophyte if precipitation drops below this threshold (35). Modern *Prosopis* trees are obligate phreatophytes that can pump water from depths of <10 m (36–38). The occurrence in these same deposits of the hygrophytes *E. angustifolia*, *C. atacamensis*, and *B. scandens* indicates perennial or seasonal surface riverflow. Today, these species are restricted to the bottom of perennial river canyons (29, 39), growing just a few meters from permanent watercourses. To reestablish any of the fossil species identified would not require an increase in local precipitation but rather the introduction of stream water or an outcropping water table. Hillslope (or zonal) taxa are notoriously absent from these deposits (except for a single seed of *Cistanthe* sp., a xerophytic annual). Taken together with the preservation of both a highly soluble surficial soil layer [or chusca (40)] and Miocene landforms (41), this lack of hillslope taxa implies that latest Pleistocene increased groundwater levels were not caused by enhanced local precipitation. Rather, enhanced water inflow to the PdT occurred through the canyons or by groundwater flow, from increased precipitation in the highlands further east, analogous to modern altitudinal variations in mean annual precipitation.

Preserved but undated fluvial terrace flights at similar heights above the modern floors of canyons Ch and G (Fig. 1) imply that the same wet intervals increased discharge into the PdT north of the dated deposits presented in this study. The lack of fossil organic debris on those terraces may indicate that stream power was greater or decomposition was more active, a situation with less potential to preserve plant debris.

Paleoshorelines on the Bolivian Altiplano attest to the former presence of large freshwater lakes during the late Pleistocene (42–44). Recent U-Th and ^{14}C dates for shoreline tufa deposits of paleolake Tauca (44), lying between 70 and 300 km east of PdT (Fig. 1), indicate enhanced precipitation (45) between ≈18,100 and 14,100 cal yr BP. PdT fluvial terrace deposits at low elevation are almost synchronous with these shoreline dates (44) for paleolake Tauca (Fig. 4). A second lake cycle "Coipasa" existed 13,000–11,000 cal yr BP (44) and corresponds with our most distal alluvial fan deposit. Deep groundwater at the western margin of former paleolake Tauca, dated between 17,500 and

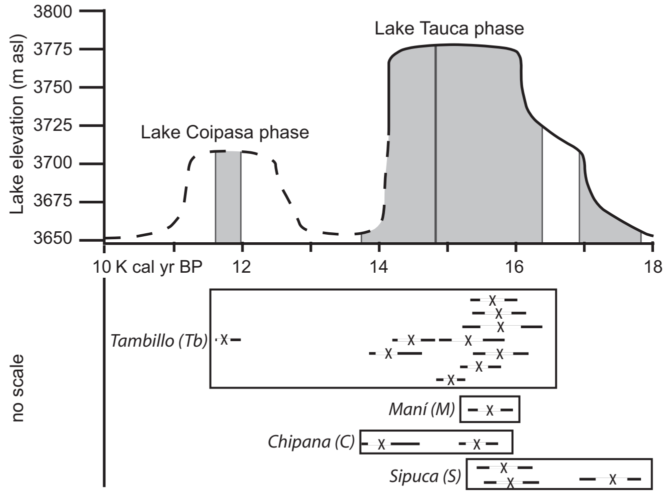

Fig. 4. Comparison of the Tauca and Coipasa lake cycles (44) with dated organic material from fluvial deposits of the PdT from four separate drainages as part of this study. X, median probability calibrated age. White and black bars represent 95% and 67% confidence intervals, respectively. The gray shading illustrates the 95% ^{14}C confidence intervals from our 16 Pleistocene dates. The dashed line indicates the portion of this lake level curve considered to be slightly less well constrained by the original authors (44).

11,000 cal yr BP (46), demonstrates the importance of recharge from these highstands.

Climate change is also recorded in regions that are now geographically and climatically analogous to the headwater regions of the PdT drainage basins. Plant species found in rodent middens from 3,000 m elevation, 130 km southeast of our study area near Río Salado (Fig. 1), are indicative of 2-fold precipitation increase at 17,520–16,270 cal yr BP with mean annual temperatures similar to modern (9). These ^{14}C-dates are coeval with both paleolake Tauca and with our PdT *in situ* riparian and phreatophytic vegetation. Middens formed 11,770–9,550 cal yr BP document another period of higher precipitation relative to today, correlative to the latter half of paleolake Coipasa and to the most distal PdT root-bearing fan deposit. Between 170 and 300 km SSE of our study area, middens collected from 2,400 to 3,200 m are interpreted to signify 200–500% more precipitation between 16,200 and 10,500 cal yr BP than today (6). Across the same area, paleowetland deposits signify higher groundwater tables from >15,400 to 9,000 cal yr BP at altitudes above 2,500 m (7).

Discussion and Conclusions

Consequences of increased precipitation during the latest Pleistocene at higher altitudes not only included the increased discharge through low altitude streams of the PdT, but also major paleoecological shifts at high-altitude midden sites, and of Altiplano lake highstands. Our new data demonstrate that there was enhanced stream discharge into the PdT during the time intervals of ≈17,750–13,750, ≈11,750, and ≈1,100–700 cal yr BP. Discharges were greatest between 16,500 and 13,750 cal yr BP, coeval with the Tauca lake phase on the Bolivian Altiplano, which has been related to ENSO-modulated amplification of westward drift of Bolivian High moisture during several millennia of pronounced equatorial sea surface temperature (SST) gradients [i.e., La Niña-like conditions (9, 44)].

Further evidence for the prominent role of the tropical Pacific in bringing about climate change comes from the younger terrace event at M, when groundwater must have been near the surface (<10 m) for *Prosopis* stands to have lived between ≈1,100 and 700 cal yr BP. This Medieval Climatic Anomaly (MCA) is of opposite hydrological impact (wet) to that of coastal Peru (dry), where lithic concentrations in a marine core document diminished strength of El Niño events during the MCA (47). Other proxies throughout the tropical Pacific (48–52) likewise are consistent with La Niña dominance during the MCA. Thus, a similar mechanism (a sustained SST gradient across the equatorial Pacific) operating at both centennial (MCA) and millennial (late Pleistocene) time scales may be responsible for increased precipitation in the central Andes and greater groundwater recharge.

The PdT terrace flights are interpreted to have been caused by multiple changes of climate-controlled stream power. Today's surface streams carry less water than the stream power needed for either the late Pleistocene aggradation of sorted gravel bars or the intervening stages of fluvial incision (32, 53). The near-total lack of water in the Holocene PdT led to the perfect state of preservation of latest Pleistocene and rare late Holocene organic debris.

Precipitation at high elevations brings to the PdT water that can recharge aquifers (11, 13, 20). The evidence in the PdT indicates only two major episodes of groundwater recharge during the last 18,000 years, millennial-scale pluvial events along the western portion of the central Andes. The smaller magnitude MCA recharge event indicates a century-scale oscillation of the groundwater table during the latest Holocene.

Even in the absence of incontrovertible direct dating of the groundwater stores, the physical and biological records reveal latest Pleistocene flow of water into the PdT, where it could recharge aquifers at a scale that has no match during the Holocene. Given the regional climatic consistency suggested by proxy evidence, latest Pleistocene fossil water may also be the dominant water resource in many other Atacama Desert basins. Although water managers might appropriately predict that decadal or century climate variation might return the region to conditions similar to those present during the MCA with modest increases in rainfall, there are no grounds to anticipate a return to latest Pleistocene levels of groundwater recharge possibly until the next global ice age returns.

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