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Re-evaluation of mid-Holocene deposits at Quebrada Puripica, northern Chile

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Abstract

During the middle Holocene (8–3 ka), wetland deposits accumulated in areas with emergent water tables in the central Atacama Desert (22–24°S), producing a stratigraphic unit (Unit C) that can be mapped and correlated across different basins and geomorphic settings. Wherever mapped, Unit C is located between 6 and 30 m above modern wetlands, and includes thick sequences of diatomite and organic mats. The origin, depositional environment, and paleoclimatic significance of Unit C is controversial and currently under debate. Grosjean [Science 292 (2001) 2391a] suggests the unit developed under a regime of falling lake and ground-water levels, whereas evidence presented here suggests that Unit C formed during a period of rising ground-water levels and increased vegetation cover. The debate is embedded in broader discussions about geomorphic processes in ground-water-fed streams, as well as the history and forcing of climate variability in the central Andes.

The central Atacama and Andes are remote, with few opportunities for different researchers to examine the same site. One exception is a sequence of mid-Holocene deposits at the confluence of Quebrada Seca and Río Puripica in northern Chile (23°S). Grosjean et al. [Quat. Res. 48 (1997) 239–246] initially suggested the deposits accumulated in temporary lake basins, which formed when recurring debris flows from a side canyon (Quebrada Seca) dammed the main channel (Río Puripica) during a period of drought and reduced stream flow. Upon our visit to the site, we found evidence that clearly demonstrates the deposits were not formed in temporary lakes, but rather were deposited in a wetland environment. Disagreement remains about the climatic interpretation of wetland deposits. Grosjean [Science 292 (2001) 2391a] now suggests that local ground-water levels rise and wetland deposits aggrade in deep canyon systems, such as Río Puripica, when stream power and channel erosion is reduced during prolonged dry spells. However, sedimentological evidence and the presence of Unit C in many depositional environments, not just deep canyons, indicate that it formed during a period of higher regional ground-water levels that were sustained by enhanced precipitation and recharge in the High Andes.

Keywords: wetlands; ground water; Atacama Desert; paleoclimate; middle Holocene

1. Introduction

Wetlands occur where the water table intersects

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the ground surface, resulting in the formation of seeps, flowing springs, wet meadows, and marshes. Wetlands produce a characteristic set of deposits, including diatomite, organic mats, and tufas, which can be mapped and dated to reconstruct past fluctuations in the heights of local water tables. Paleowetland deposits have been studied in arid and semiarid regions, including the Sinai Desert, Egypt (Gladfelter, 1990), Mojave Desert and Great Basin, USA (Haynes, 1967; Quade, 1986; Quade and Pratt, 1989; Quade et al., 1995, 1998), and Central Asia (Madsen et al., 1998).

In the central Atacama Desert (22–24°S) of northern Chile, modern wetlands and paleowetland deposits are found along ground-water flow paths that begin in the High Andes (>3500 m), where precipitation averages ~100 to 200 mm/yr, and end in basin aquifers in the hyperarid Atacama Desert (~2500 m), where precipitation is <10 mm/yr (Fig. 1). Wetlands are found primarily in two areas; in deeply incised canyons on the Pacific slope of the Andes, and near the base of the Andes where ground-water flow paths intersect basin aquifers.

We have identified and mapped paleowetland deposits at Tilomonte, Río Salado, and Río Loa (Fig. 1) in the central Atacama (Rech et al., 2002). Three main wetland units are present in these areas, and all follow the same general chronological pattern; Unit A – deposits that are beyond the range of ^{14}C dating and are located ~20 m above modern stream level at Tilomonte, Río Salado, and Río Loa; Unit B – deposits that are >15.4–9.0 ka and located in Tarajne at Tilomonte, an area that today does not support modern wetlands; Unit C – deposits that are 8.2–3.2 ka and located ~6–10 m above modern stream levels at Río Tulán, Río Salado, and Río Loa (Fig. 2); Unit D – deposits that are <3.2 ka and located ~2 m above modern stream level at Río Tulán and ~6 m above modern stream level at Río Loa at Quillagua. Here we focus on what we believe are additional outcrops of Unit C at Quebrada Puripica, previously described by Grosjean et al. (1997).

Quebrada Puripica is a deeply entrenched canyon on the Pacific slope of the Andes, located ~25 km northeast of Salar de Atacama, between the paleowetland sites of Tilomonte and Ríos Salado and Loa (Fig. 1). Grosjean et al. (1997) reported that mid-Holocene (7.1–3.3 ka) deposits formed as a result of recurring 'episodic debris flows from the low-elevation valley (Quebrada Seca) [that] dammed the Puripica River and created local ponds, shallow lakes, and wetlands upstream of the alluvial cone in the Puripica Valley' (Grosjean et al., 1997, p. 241). According to Grosjean et al. (1997), a generally dry climate and reduced stream flow allowed the debris flow dams to persist on the mainstem, forming an 'ecological refuge' for otherwise stressed Archaic human populations.

This interpretation of the Holocene deposits from Quebrada Puripica has been cited widely as evidence for mid-Holocene aridity in the central Atacama (e.g. Schwalb et al., 1999; Grosjean et al., 2001; Messerli et al., 2000). The Puripica deposits have also been used to constrain the age of lake chronologies (Grosjean et al., 1995), infer the relationship between climate variability and debris flow frequencies (Trauth et al., 2000), provide boundary conditions for climate models (Kull and Grosjean, 1998), and correlate advances in human technologies to climate (Grosjean and Núñez, 1994; Grosjean et al., 1997; Messerli et al., 2000).

Our investigation of the Puripica deposits was instigated by its synchroneity and apparent similarity to Unit C deposits that we have studied elsewhere (Betancourt et al., 2000; Rech et al., 2002). Of particular importance was to verify if the deposits were in fact the result of side-canyon damming and episodic lake formation as suggested by Grosjean et al. (1997), or were formed in wetland environments similar to those we had previously identified.

2. Methods

We surveyed Quebrada Puripica from its confluence with Quebrada Puritama (~3200 m) to an elevation of ~3600 m. We measured and sampled a series of sections from well-preserved outcrops along Quebrada Puripica to determine

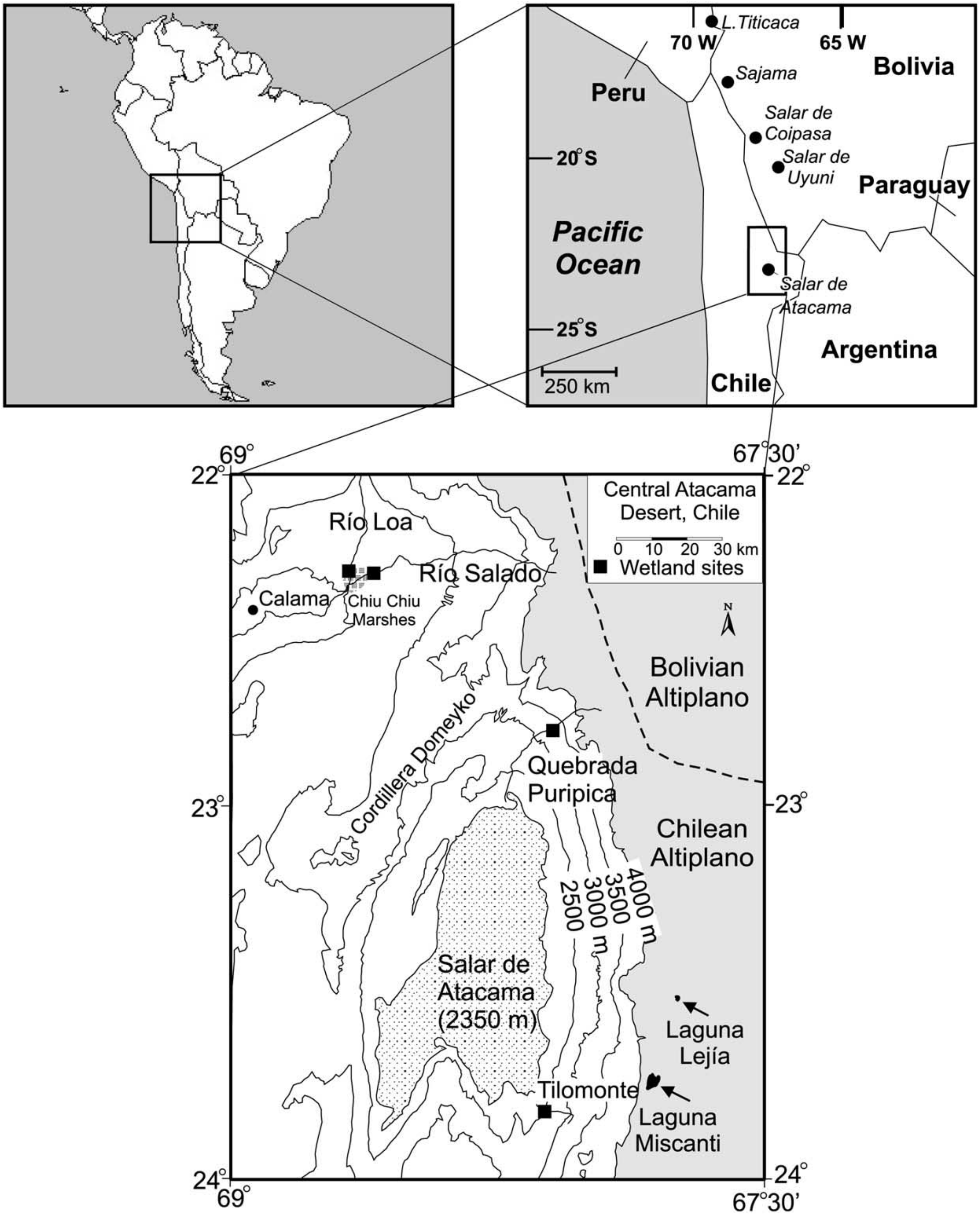

Fig. 1. Location of Quebrada Puripica, other wetland deposits, and key paleoclimatic proxy records in the central Atacama Desert (22–24°S), Chile, and central Andes.

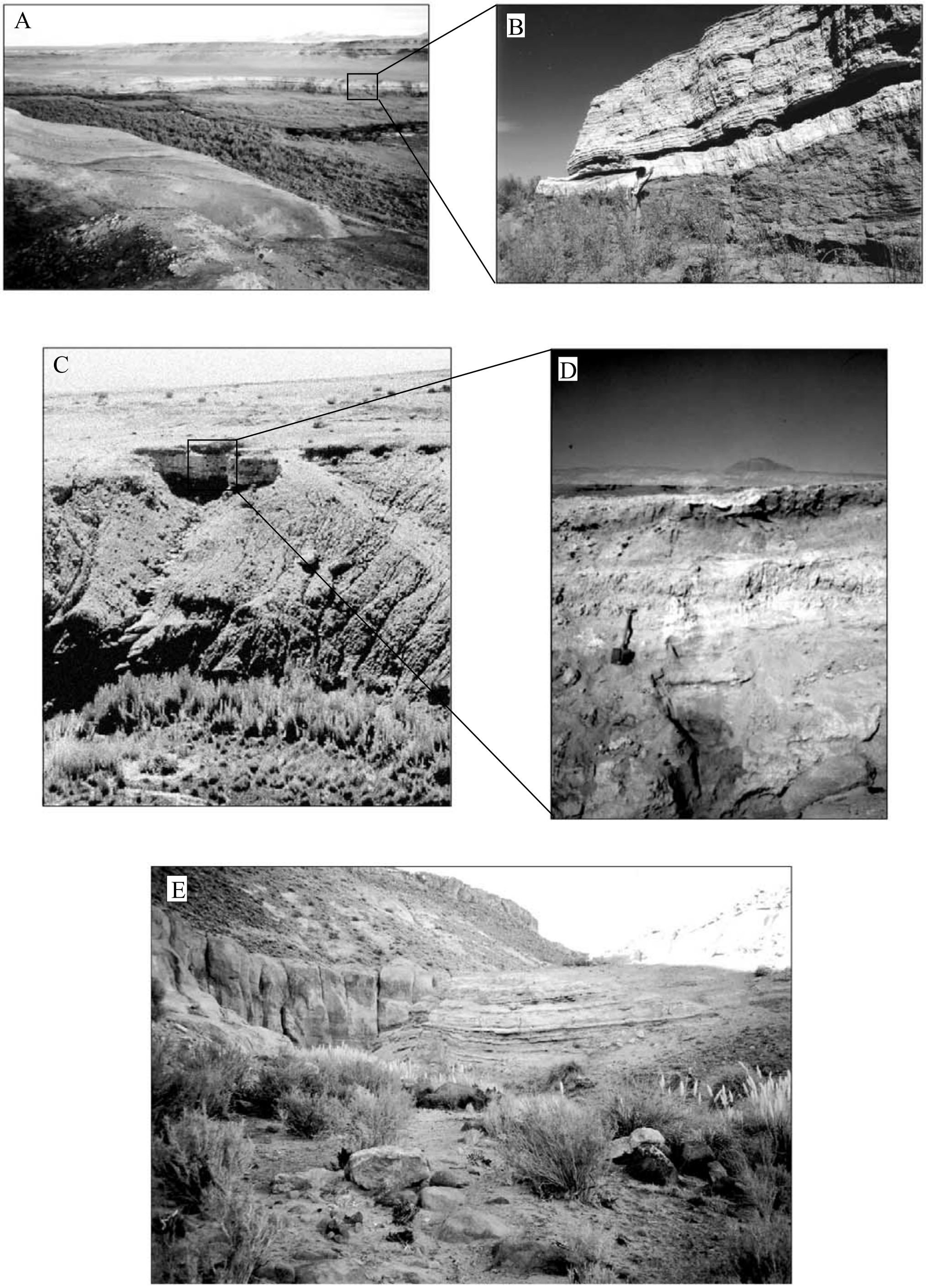

Fig. 2. Mid-Holocene (Unit C) wetland deposits from the central Atacama: (A,B) Río Salado – 7.1–4.3 ka in age and 6–10 m above modern stream level; (C,D) Río Tulán at Tilomonte – 8.2–3.2 ka in age and ~10 m above modern stream level; (E) Quebrada Puripica – 7.1–3.3 ka in age and between 4 and 32 m above modern stream level.

the spatial, temporal, and stratigraphic relations of the deposits. Geographic coordinates of station locations were determined with a hand-held GPS with a horizontal accuracy of ±10 m and a vertical accuracy of ±30 m. Station elevations and the longitudinal profile of the stream were determined by GPS elevations and checked against 50-m contour lines on topographic maps.

Samples for ^{14}C dating were collected from organic mats from near the top and the lowest exposed part of each section in order to constrain the age of the deposits. Both carbonized plant fragments (i.e. carbonized wood) and the humic acid fraction of bulk organic matter were dated at each station in order to test the ability of different organic fractions to return accurate ^{14}C ages, and to identify potential sources of contamination. Carbonized plant fragments are plant remains that have been partially reduced by geochemical and microbial activity in ground water (Cushing et al., 1986). They have not degraded completely into organic weathering products (i.e. humic acids) and thus retain some of their primary physical structure. Carbonized plant fragments appear much like charcoal, but are not as refractory, and go into solution more readily than charcoal of similar age during standard NaOH pretreatment of radiocarbon samples (Cook, 1964; Haynes, 1967).

Samples were processed by standard procedures at the University of Arizona's Desert Laboratory (Rech et al., 2002). Calibrated radiocarbon ages reported here were calculated using CALIB 4.3 (INTCAL 98 dataset), method A (Stuiver and Reimer, 1993; Stuiver et al., 1998) and include a 24-year Southern Hemisphere correction.

3. Results

3.1. Distribution of deposits

We identified Holocene deposits along a 6-km reach of Quebrada Puripica that runs from just upstream of the confluence with Quebrada Puritama (~3250 m) to ~2 km upstream of the junction with Quebrada Seca (~3580 m) (Fig. 3A). Deposits are discontinuous and are preferentially preserved on the interior of stream meanders. The deposits gradually thicken upstream, with the tops of sections only 2 and 5 m above modern stream level at stations 1 and 2, respectively, culminating in a height of 32 m above modern stream level at station 6 (Fig. 3B). The thickness of the deposits decreases upstream from station 6, with deposits 12 m (station 8) and 5 m (station 10) above modern stream level. Additional outcrops of deposits were observed upstream of station 10, but were not measured or sampled.

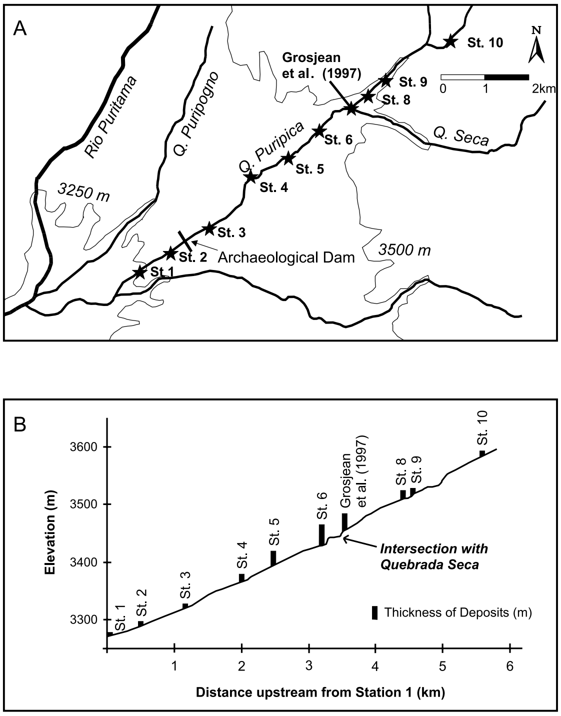

Fig. 3. (A) Topographic map of Quebrada Puripica study area with station locations, and (B) a longitudinal profile of Quebrada Puripica between ~3300 and 3600 m with a thickness of wetland deposits at each station.

3.2. Dating of different organic fractions

Matched pairs of carbonized plant fragments and humic acids displayed large differences in ^{14}C content (Table 1). Humic acids returned ages from 6300 ^{14}C years younger than to 4600 ^{14}C years older than associated carbonized plant fragments (Table 1). This indicates that there is significant, and variable, humic acid contamina-

Table 1
Quebrada Puripica radiocarbon dates

Lab. No.	Sample No.	Station	Depth[a] (m)	Material	δ^{13}C	^{14}C age	S.D.	Δ^{14}C[b]	Cal. years B.P.[c]
AA42522	AT 535A	1	−0.10	carbonized wood	−24.5	525	45		525
AA38735	AT 535B	1	−0.10	bulk humic acids	−25.6	740	50	+215	
AA42521	AT 534A	1	−0.80	carbonized wood	−22.8	490	45		510
AA38734	AT 534B	1	−0.80	bulk humic acids	−23.3	480	50	−10	
AA42516	AT 521A	2	−0.65	carbonized wood	−23.9	520	50		525
AA38726	AT 521B	2	−0.65	bulk humic acids	−23.5	5115	50	+4595	
AA38751	AT 519A	2	−1.55	carbonized wood	−22.6	7075	45		7900
AA38725	AT 519B	2	−1.55	bulk humic acids	−22.1	1550	40	**−5525**	
AA42518	AT 528A	4	0.10	carbonized wood	−24.6	2160	40		2120
AA38728	AT 528B	4	0.10	bulk humic acids	−21.5	3255	45	+1095	
AA42517	AT 522A-1	4	−6.10	carbonized wood	−25.9	6775	65		7600
AA38727	AT 522A-2	4	−6.10	carbonized wood	−23.5	2530	55		
AA42523	AT 536A	5	−2.80	carbonized wood	−23.8	1730	50		1580
AA38736	AT 536B	5	−2.80	bulk humic acids	−27.1	680	50	−1050	
AA42524	AT 537A	5	−18.80	carbonized wood	−22.4	6850	60		7670
AA38737	AT 537B	5	−18.80	bulk humic acids	−26.9	570	50	**−6280**	
AA42519	AT 529A	6	−0.10	carbonized wood	−24.5	2780	40		2850
AA38729	AT 529B	6	−0.10	bulk humic acids	−23.7	3570	50	+790	
AA42525	AT 538A	6	−19.00	carbonized wood	−24.6	4920	65		5610
AA38738	AT 538B	6	−19.00	bulk humic acids	−25.7	620	50	**−4300**	
AA42528	AT 547A-1	8	−1.20	carbonized wood	−24.3	1815	45		1710
AA38744	AT 547A-2	8	−1.20	carbonized wood	−24.1	1550	35		1410
AA42529	AT 548A	8	−9.20	carbonized wood	−23.9	3385	50		3610
AA38745	AT 548B	8	−9.20	bulk humic acids	−23.3	3790	40	**+180**	
AA42520	AT 530A	9A	−0.40	carbonized wood	−23.5	2695	40		2770
AA38730	AT 530B	9A	−0.40	bulk humic acids	−24.6	3000	45	+305	
AA38752	AT 533A	9A	−2.50	carbonized wood	−22.2	4275	45		4830
AA38733	AT 533B	9A	−2.50	bulk humic acids	−21.6	4365	40	+90	
AA42527	AT 542A	9B	−0.50	carbonized wood	−22.2	1435	40		1305
AA38740	AT 542B	9B	−0.50	bulk humic acids	−25.1	5965	45	+4530	
AA38753	AT 539A-1	9B	−2.75	carbonized wood	−23.2	2460	35		2390
AA42526	AT 539A-2	9B	−2.75	carbonized wood	−21.8	2510	45		2590
AA38739	AT 539B	9B	−2.75	bulk humic acids	−26.5	6835	65	+4350	
AA38742	AT 544A	10	−0.10	carbonized wood	−24.7	2950	40		3135
AA38743	AT 545A	10	−2.00	carbonized wood	−320.6	3240	40		3420

[a] Depth from the top of the section.

[b] ^{14}C age$_{\text{bulk humic acids}}$ − ^{14}C age$_{\text{carbonized plant fragments}}$; bold-faced ages indicate samples from the lower portion of the section.

[c] Method A (Stuiver and Reimer, 1993). A 24-^{14}C-year Southern Hemisphere correction was applied to all samples. The middle intercept was used when there were multiple intercept ages.

tion in organic material at Quebrada Puripica. In general, ^{14}C ages obtained from the humic acid fraction were younger than ages of carbonized plant fragments in the lower portion of the deposits (AT 519, 537, 538), and older than carbonized plant fragments in the upper portion of the deposits (AT 521, 528, 529, 530, 542) (Table 1). Young ages for the humic acid fraction of organic mats are likely the result of secondary contamination by humic acids transported during subsequent water table rises. The older ages of humic acids from the upper portion of wetland sections remain unexplained, but may be the result of secondary humic acids originating from older deposits. Due to the variability of the contamination in the humic acid fraction of organic matter at Quebrada Puripica, we limit our discussion to ages obtained from carbonized plant fragments.

Ages obtained from carbonized plant fragments are generally considered reliable, provided that humic acids are removed prior to analysis. There is also potential for the incorporation of older, reworked plant fragments into younger organic mats. This is unlikely, however, for two reasons. Firstly, carbonized plant fragments are fragile and easily disintegrate during transport. Secondly, organic mats are essentially wetland soils, forming under dense phreatophytic and hydrophyllic vegetation (Rech et al., 2002). Therefore, the vast majority of plant remains in organic mats are from vegetation growing at the soil site.

Radiocarbon ages obtained from carbonized plant fragments show good stratigraphic ordering and are in agreement with previously reported ages (Grosjean et al., 1997). Duplicate ^{14}C were determined on carbonized plant fragments at three stations. One sample (AT 539) yielded identical ages (2460 ± 35 ^{14}C years B.P., AA38753, and 2510 ± 45 ^{14}C years B.P., AA42526). A second sample (AT 547) yielded similar ages (1550 ± 35 ^{14}C years B.P., AA38744, and 1815 ± 45 ^{14}C years B.P., AA42528). A third sample (AT 522) yielded very different ages (2530 ± 50 ^{14}C years B.P., AA38727, and 6775 ± 65 ^{14}C years B.P., AA42517). The younger ages are likely the product of contamination by secondary rootlets, which can become carbonized during subsequent water table rises. Such contamination is indistinguishable (physically and chemically) from primary carbonized plant fragments.

3.3. Sedimentology and age of deposits

The deposits along Quebrada Puripica are composed of gravel, sand, silt, diatomite, and organic mats. Gravels are generally < 1 cm in diameter, are found in units between 2 and 10 cm thick, and comprise a small percentage of the deposits. Sand and silt units are common, range from poorly to well sorted, and are generally massive. Puripica deposits also contain abundant diatomite units, which comprise ~20–35% of the total deposits. The diatomite units are generally massive and range from a few centimeters to one meter in thickness. Organic mats are typically between 2 and 10 cm thick and commonly contain silt, sand, fossil plants such as *cortaderia* (Pampa grass), and abundant carbonized plant fragments. Bedding of the Puripica deposits is parallel to the slope of the stream along the entire 6-km reach surveyed.

We identified three time-stratigraphic units of deposits at Quebrada Puripica based on ^{14}C ages of carbonized plant fragments and the stratigraphic relations of the deposits: Unit C dates from ~7000 to 2700 ^{14}C years B.P., Unit D_1 dates from ~2500 to 1400 ^{14}C years B.P., and Unit D_2 dates to ~500 ^{14}C years B.P. (Fig. 4).

3.3.1. Unit C

Mid-Holocene (Unit C) deposits dating from 6200 to 3100 ^{14}C years B.P. were first reported at the junction of Quebrada Puripica and Quebrada Seca (Fig. 3) (Grosjean et al., 1997). We identified Unit C deposits at all localities except station 1 and possibly 3 (station 3 was not sampled) (Figs. 3 and 4). Several sections also have younger units that are inset against, or are overlying, Unit C deposits. This is clearly identified at station 9 (Fig. 5). At other locations, unconformities were not visible in field exposures, but are inferred from ^{14}C ages of carbonized plant fragments.

The base of Unit C dates to 7075 ± 45 ^{14}C years B.P. at station 2 (AT 519A), 6775 ± 65 ^{14}C years B.P. at station 4 (AT 522A), and 6850 ± 60 ^{14}C years B.P. at station 5 (AT 537A). The base of Unit C was either eroded or not exposed at other stations. The top of Unit C dates to 2780 ± 40 ^{14}C years B.P. at station 6 (AT 529A), 2695 ± 40 ^{14}C years B.P. at station 9 (AT 530A), and 2950 ± 40 ^{14}C years B.P. at station 10 (AT 544A).

3.3.2. Units D_1 and D_2

Evidence of two late Holocene deposits (Units D_1 and D_2) was also found at Quebrada Puripica. Unit D_1 is clearly exposed at station 9 (Fig. 5), where it dates to 2510 ± 45 ^{14}C years B.P. (AT 539A) at the base and 1435 ± 40 ^{14}C years B.P. (AT 542A) at the top. At other locations, Unit D_1

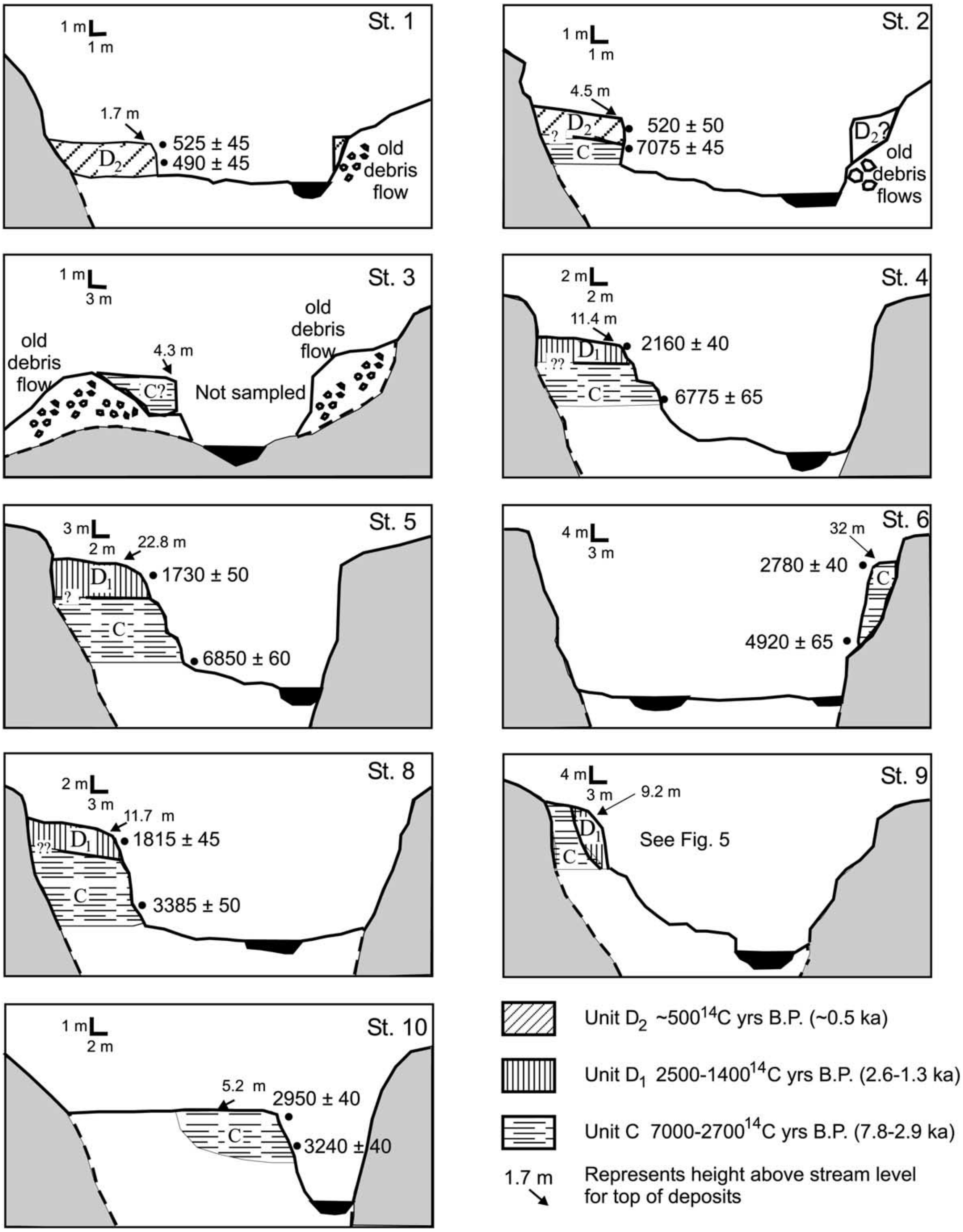

Fig. 4. Cross-sections of Quebrada Puripica at station locations with age and thickness of Holocene deposits. Note scale change at each station location. All ages are in ^{14}C years B.P.

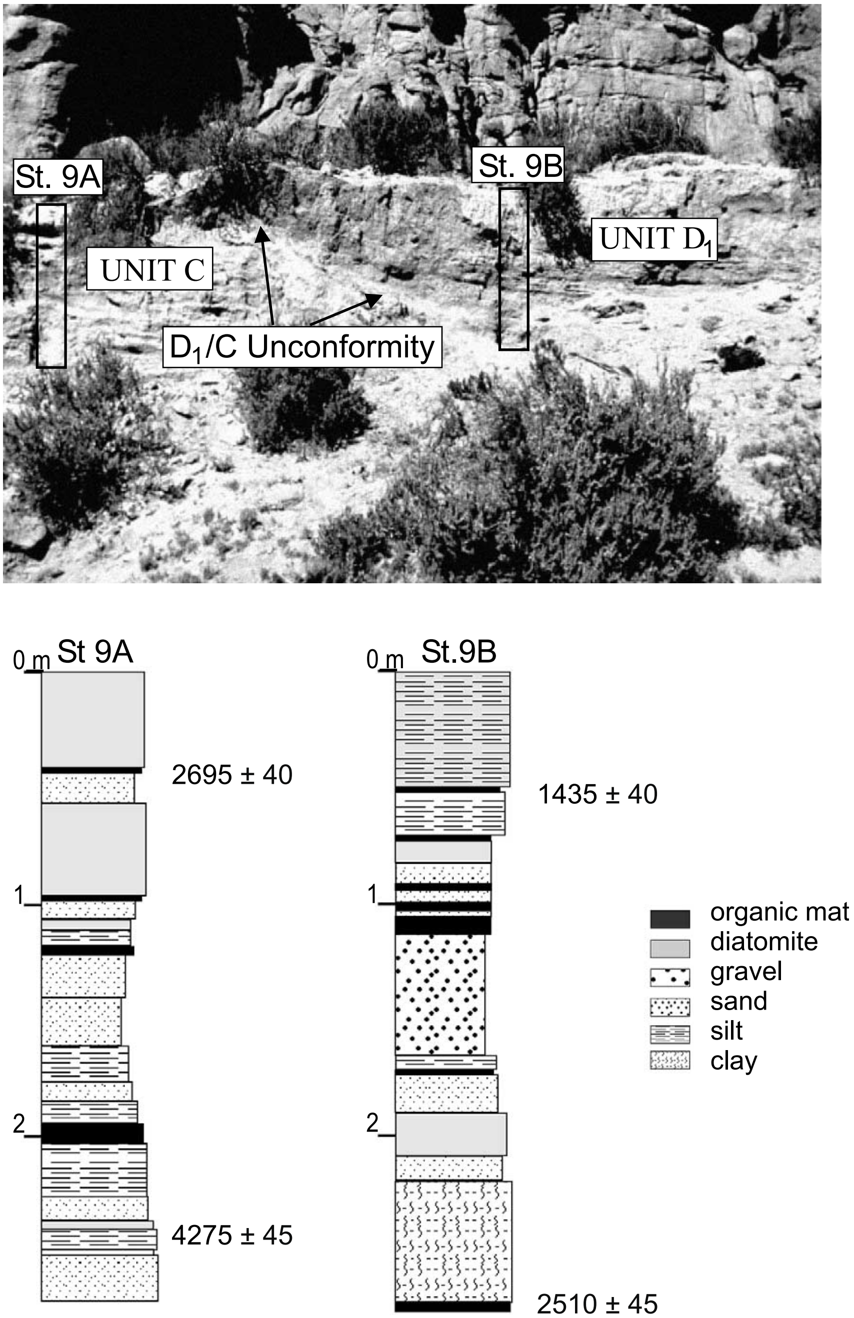

Fig. 5. Unit C and inset Unit D_1 deposits at station 9. Ages in ^{14}C years B.P.

is identified by ^{14}C ages of 2160 ± 40 (AT 528A), 1730 ± 50 (AT 536A), 1815 ± 45 (AT 547A-1), and 1550 ± 35 ^{14}C years B.P. (AT 527A-2), at stations 4, 5, and 8 (two samples), respectively.

Unit D_2 was identified in the lower reaches of Quebrada Puripica at stations 1 and 2, where it dates to ~500 ^{14}C years B.P. (AT 534A, 535A, 521A) (Fig. 4).

4. Discussion

4.1. The Puripica deposits

Our mapping and dating efforts at Puripica provide critical additional information about the age and spatial distribution of the deposits, which leads us to a fundamentally different view of their origin than that of Grosjean et al. (1997). The key difference is that we identified wetland deposits at several localities downstream of the intersection of Quebrada Puripica and Quebrada Seca. Grosjean et al. (1997) recognized thick wetland deposits just upstream from Quebrada Seca, which led them to suggest that recurring debris flows feeding out of Quebrada Seca blocked Quebrada Puripica and created small temporary lakes and marshes upstream from the intersection. The spatial distribution of the Puripica deposits, however, does not support this explanation. The presence of mid-Holocene (Unit C) deposits upstream and downstream of Quebrada Seca is clear evidence that Unit C was not formed by blocking Puripica at the proposed side-canyon damming location. In addition, the individual debris flow units identified by Grosjean et al. (1997) in Quebrada Seca were not thick enough to dam Puripica and create a temporary lake, nor is the canyon deep enough to create a closed basin encompassing the Holocene deposits upstream (Figs. 3B and 4). Furthermore, the origin of Unit D_1 (2500–1400 ^{14}C years B.P.) cannot be explained by side-canyon damming between 6200 and 3100 ^{14}C years B.P.

We consider the modern environmental setting at Quebrada Puripica, with wetlands along the main channel and dry alluvium in Quebrada Seca, to be an analog for the origin of the Holocene deposits. Today, active wetlands are present along the entire 6-km reach of Quebrada Puripica. The presence of Holocene deposits above and below Quebrada Seca, spanning 300 m in elevation, is best explained by elevated water tables over this entire area. The rise in the water table was not uniform across this entire area because the longitudinal profile of the stream is not graded. The Quebrada Puripica channel is most incised near station 6, which is just below a stream knickpoint. Thus, as the water table rose along the valley, the magnitude of the water-table rise was greatest at station 6 (Unit C water tables were 32 m above present) and more moderate elsewhere. The gradual thinning of wetland deposits upstream and downstream from station 6 is the result of the adjustment of Quebrada Puripica from a bedrock, non-graded stream to a sediment-filled, graded stream.

The current setting at the Puripica/Seca intersection (Fig. 6) is also the analog for the depositional environment of the Quebrada Seca deposits. As ground-water levels increased along Quebrada Puripica, local base level rose, causing Quebrada Seca to aggrade and deposit alluvial and debris flow sediments at this junction. The level of aggradation of the alluvial sediments was controlled directly by the elevation of the water table along Quebrada Puripica, and reached a maximum level of ~22 m above modern stream level at 3100 ^{14}C years B.P. (Grosjean et al., 1997).

Ground-water levels were highest during the deposition of Unit C, which began aggrading ~7000 ^{14}C years ago (7.8 ka) and reached a maximum level ~2800 ^{14}C years ago (2.9 ka). Water tables then dropped dramatically and Unit C deposits were incised. Although the full depth of incision is unknown, a drop in the water table of ~25% from the maximum mid-Holocene level is recorded at station 9. Water tables rose again during deposition of Unit D_1, beginning ~2500 ^{14}C years ago (2.6 ka) and reached a maximum level ~1400 ^{14}C years ago (1.3 ka). Unit D_2 represents a minor increase in water-table levels that occurred ~500 years ago at downstream locations.

4.2. Causes of changes in water-table elevations

Our view for the causes of aggradation and/or erosion of wetland deposits follows the 'base-level model' established in North America decades ago (Bryan, 1941; Antevs, 1954; Haynes, 1968; Karlstrom, 1988; Quade et al., 2001; Waters and Haynes, 2001). In wetland environments, dense vegetation and the cohesiveness of wet, fine-grained sediments make wetland deposits relatively resistant to erosion when water tables are high. The high resistance to erosion of channel

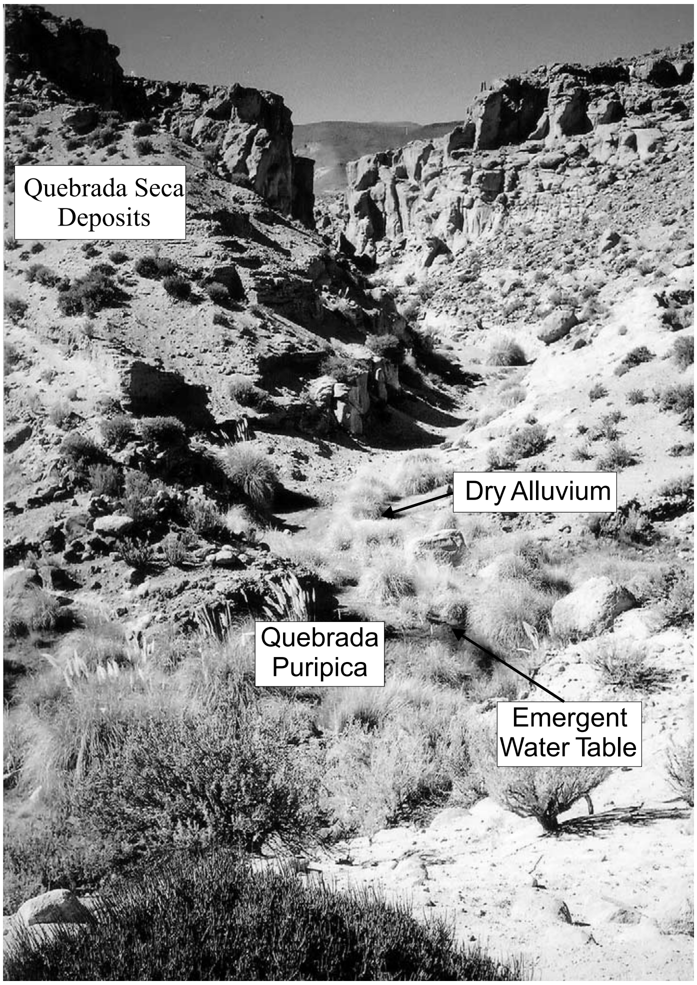

Fig. 6. Photograph (looking southeast) of the Quebrada Puripica/Quebrada Seca intersection. Note wetlands in Quebrada Puripica and dry alluvium in Quebrada Seca.

sediments with valley-floor vegetation has been demonstrated by flume experiments on swampy meadows covered with tussock and sedge vegetation in Australia (Prosser and Slade, 1994). In contrast, when water tables are low, valley-floor vegetation dies, rendering fine-grained, unconsolidated deposits much more susceptible to water erosion and deflation. Dry, loose material is easily incised, which channelizes water flow and increases the erosive power of the stream. This model is used widely in studies from the southwestern United States to interpret stratigraphic records from wetland environments (e.g. Quade et al., 1995, 1998; Waters and Haynes, 2001).

In contrast to the base-level model, others have suggested that an increase in size and frequency of stream discharge events results in increased stream channel erosion during wet periods (e.g. Hall, 1977). During dry periods, hillslopes are de-vegetated and soils are stripped from the landscape, causing sediment to accumulate in channels. Using this model, Grosjean (2001) postulated that deeply incised channels throughout the central Atacama were filled by alluvial sediments during an arid mid-Holocene, when the size and frequency of stream discharge events were diminished. Grosjean also argued that this allowed local, self-sustained aquifers that are disconnected from their surroundings to form in valley bottoms.

If this model is to be used to interpret mid-Holocene wetland deposits, it must be applied equally to wetland deposits of all ages in the central Atacama. Wetland deposits also formed within steep valleys during the late glacial/early Holocene (Quebrada La Higuera, Quebrada Guata Guata, and Quebrada Chaco; Rech, 2001) when Grosjean and others argue for wetter conditions than today (Grosjean, 1994; Geyh et al., 1999; Betancourt et al., 2000; Latorre et al., 2002; Rech et al., 2002).

Grosjean (2001) also argues that the rise in water-table levels occurred as a result of infilling of channels with alluvial sediments. Many wetland deposits in the central Atacama are composed predominantly of paludal and biogenic material, not alluvial sediments. These types of deposits form in situ and follow increases in the water-table level, rather than precede them. Depositional models for alluvial sedimentation, therefore, should not be applied to wetland environments, because the processes controlling the deposition or erosion of sediments are fundamentally different. Alluvial sedimentation in ephemeral streams is a complex process, with numerous factors contributing to the dynamic equilibrium of the system (Schumm and Hadley, 1957; Cooke and Reeves, 1976; Bull, 1997).

4.3. Comparison of mid-Holocene records in the central Atacama

Holocene environmental records from the central Atacama (22–24°S) come from sediment cores from the low-elevation (2350 m) Salar de Atacama (Bobst et al., 2001), the high-elevation (4140 m) Laguna Miscanti (Valero-Garcés et al., 1996; Grosjean et al., 2001), and rodent middens from 2500 to 3100 m (Betancourt et al., 2000; Latorre et al., 2002). These records provide important information for testing our model of accumulation of wetland deposits during wet intervals.

The Salar de Atacama is a 3000-km^2 salar (playa) located at the base of the Andes that is fed primarily by ground water, including ground water from Tilomonte, Río Tulán, and Quebrada Puripica (Fig. 1). Today, the water table in the Salar de Atacama is at or just beneath the surface of the salar. During the mid-Holocene (6.2–3.5 ka), the Salar de Atacama supported a perennial, shallow, saline lake. This interpretation is based on the presence of patchy primary halite in a sediment core (5.0–2.7 m; Bobst et al., 2001). This level dates to 5.4 ± 2.7 ka (1σ) based on a ^{234}U/^{230}Th isochron age on salt from a depth of 4.2 m and assuming constant sedimentation rates. Although similar to the timing of high water tables along ground-water flow paths as seen in our wetland sequences, the large uncertainty of the U/Th age makes comparison difficult.

Cores from Laguna Miscanti (Fig. 1) contain a record of lake sediments spanning the late Pleistocene and Holocene (Valero-Garcés et al., 1996; Grosjean et al., 2001). Clear evidence of low lake levels is present in one core in the form of aragonite, gypsum, and desiccation cracks (2.92–1.83 m; Valero-Garcés et al., 1996), and in a second core as gypsum and aragonite, and the absence of aquatic vegetation (3.75 to ~2 m; Grosjean et al., 2001). The age of this dry interval has been estimated to be 8.9–3.9 ka based on ^{14}C dating and by comparison with the Puripica record (Grosjean et al., 1995, p. 589).

Radiocarbon dating of lake sediments at Laguna Miscanti is problematic because terrestrial macrofossils are absent in the cores and the ^{14}C reservoir correction required for aquatic-based carbon is difficult to quantify. Valero-Garcés et al. (1996) identified a ^{14}C value of 45 percent modern carbon (pMC) for modern lake water from Laguna Miscanti, suggesting an apparent age of >6400 ^{14}C years B.P. A reservoir correction of 3000–4000 years was applied to the ^{14}C ages from this core. Grosjean et al. (2001) reported ^{14}C values of 80–85 pMC for dissolved inorganic carbon and living aquatic vegetation, which suggested a reservoir correction on the order of 2200–2500 ^{14}C years was necessary. Grosjean et al. (2001) applied reservoir corrections, between 0 and 4000 years, to measured ^{14}C ages by using a model of variable reservoir corrections based on water depths and lake levels.

The use of variable ^{14}C reservoir corrections is based on the assumption of enhanced lake water mixing with atmospheric CO_2 in shallow lakes and the diminished influence of atmospheric CO_2 in deeper lakes (Geyh et al., 1999; Grosjean et al., 2001). Greater reservoir corrections were applied during episodes of high lake level and lesser reservoir corrections were applied during periods of low lake level. This relationship is tenuous at best because shallow lakes in the Atacama are largely supported by ^{14}C-deficient ground water (7–50 pMC) (Fritz et al., 1978; Aravena and Suzuki, 1990). Lake waters remain ^{14}C deficient to varying degrees depending on the amount of mixing with the atmosphere. Therefore, accurate timing of lake-level fluctuations cannot be determined from these records.

Fossil rodent middens in the central Atacama have been used to identify past migrations of vegetation assemblages downslope in response to periods of enhanced precipitation (Betancourt et al., 2000; Latorre et al., 2002). The lower limit of vegetation in the central Atacama is strongly correlated with precipitation (Meserve and Glanz, 1978). Mid-Holocene vegetation assemblages from rodent middens at low-elevation sites (2500–3100 m) contain greater species abundances and grass percentages than middens of early and late Holocene age. These middens contain species such as *Junellia*, *Krameria*, and *Echinopsis*, which today are found between 3200 and 4000 m, representing a downslope migration of several hundred meters. Rodent middens contain numerous terrestrial plant macrofossils and therefore provide reliable radiocarbon ages that constrain the timing of vegetation migrations.

A comparison between changes in hillslope vegetation and the accumulation of wetland deposits shows that water tables are relatively high and wetland deposits aggrade during periods of enhanced precipitation as represented by high species and grass abundances in the midden record (Fig. 7). Wetland deposits stop aggrading and water tables drop following a sharp decrease in species and grass abundance in rodent middens. The difference in timing between changes in hillslope vegetation and the drop in water levels provides constraints on the response time of water-table levels to changes in precipitation. Response times should be considered *maxima* due to the discontinuous nature of the midden record, which only brackets the timing of major vegetation changes.

The most dramatic change in vegetation in the central Atacama, marked by a sharp decline in grass percent and species abundance in middens, occurred between 10.5 and 9.5 ka at low-elevation sites (Betancourt et al., 2000; Latorre et al., 2002). A subsequent drop in the water table at Tarajne occurred at ∼9.0 ka (Betancourt et al., 2000; Rech et al., 2002). This suggests a response time of 0.5–1.5 ka at Tarajne. Two other notable decreases in species and grass abundance occurred at 3.5 and 1.8 ka. Subsequent water-table drops occurred at ∼3.0 (Río Tulán and Puripica) and 1.3 ka (Río Loa, Puripica), respectively, suggesting response times of ∼500 years at these locations. A major water-table drop occurred at Río Salado at 4.5 ka. At present the cause for the early timing of the water-table drop at Río Salado as compared to the other mid-Holocene records is unknown. The response time of wetlands to changes in ground-water recharge is a function of the relative position of wetlands along the ground-water flow path. In general, wetlands at high elevations are more sensitive to changes in precipitation in recharge areas than those at lower elevations.

5. Conclusions

The accumulation of wetland deposits along Quebrada Puripica was the result of elevated ground-water levels, not side-canyon damming as previously reported by Grosjean et al. (1997). Three time-stratigraphic units of wetland deposits were identified, indicating separate episodes of increased water-table levels: Unit C – 7.8–2.9 ka; Unit D_1 – 2.6–1.3 ka, and Unit D_2 –∼0.5 ka. Units C and D_1 have been identified previously in the central Atacama (Rech et al., 2002) and are clearly regional phenomena. The distribution of Unit D_2 is unknown.

Carbonized plant fragments from wetland deposits at Quebrada Puripica yielded accurate radiocarbon ages. The ^{14}C contents of humic acids, however, were highly variable compared to car-

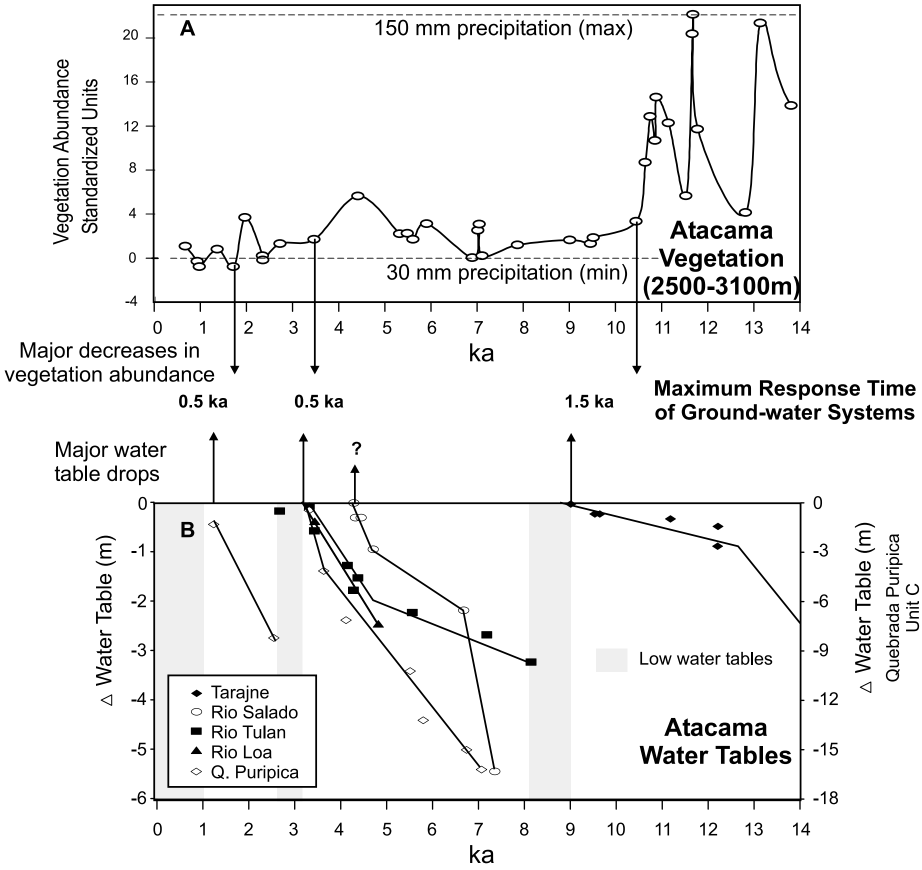

Fig. 7. Comparison between hillslope vegetation abundance (species and percent grass) from low-elevation (2500–3100 m) rodent middens (Latorre et al., 2002) and water-table fluctuations recorded by wetland deposits (Grosjean et al., 1997; Rech et al., 2002).

bonized plant fragments from the same level. This is in contrast to other wetland sites in the central Atacama, where humic acid fractions yielded reliable ^{14}C ages (Rech et al., 2002). The main difference between Quebrada Puripica and the other wetland sites is that Puripica was subject to several large water-table fluctuations during the Holocene. Humic acids transported during later periods of elevated water tables likely contaminated older deposits. Moreover, ^{14}C ages from humic acids were younger and older than the carbonized plant fragments, suggesting that multiple sources of humic acid contaminants may exist. The identification of such variability in the ^{14}C content of humic acids highlights the need for testing possible sources of ^{14}C contamination in all ground-water-fed hydrologic systems in the central Andes.

The mid-Holocene unit (Unit C) represents the highest water-table level at Quebrada Puripica, reaching a maximum of 32 m above modern stream level. Unit D_1 also represents a major rise in ground-water levels, >22 m above modern, yet it did not attain the maximum levels reached during the mid-Holocene. Unit D_2 represents a water-table increase of ~ 5 m compared to modern, but is limited to downstream locations.

We suggest that each of these periods of high water-table levels represent enhanced precipitation in the central Atacama, causing greater ground-water recharge and discharge, and that subsequent drops in water-table levels are associated with regional droughts. Water-table levels drop within 0.5–1.5 ka of major decreases in precipitation as inferred by grass percent and species abundance in rodent middens. Response times of ground-water systems to changes in precipitation are not confined to wetlands, but influence all paleoclimatic proxy records that are recharged by ground water, including perennial lakes and salars.

We agree with the conclusions drawn by Geyh et al. (1999) that hydrologic records indicate the late Glacial/early Holocene wet phase ended ∼9 ka and hyperarid conditions commenced at this time in the central Atacama. However, we disagree that this drought lasted until 3 ka (Grosjean et al., 1997; Geyh et al., 1999). Instead, we suggest the regional drought ended at ∼8 ka, and that climate during the mid-Holocene (8–3 ka) in the central Atacama was wetter than today and relatively stable. In contrast, the late Holocene was drier and subject to several regional droughts (e.g. at ∼3.0, 1.3, ∼0.5 ka). These results agree with other well-dated environmental records in the region.

At this time, the reasons for the large discrepancies between mid-Holocene records from the central Atacama and those from the northern region of the central Andes (e.g. Lake Titicaca; Wirrmann and de Oliveira Almeida, 1987) are unclear. Discrepancies may result from the sensitivity of various proxy records to climate change and/or differences in synoptic climatologies between the northern and southern portions of the central Andes.

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