ABSTRACT

PALEOWETLANDS AND FLUVIAL GEOMORPHOLOGY OF QUEBRADA MANI: RECONSTRUCTING PALEO-ENVIRONMENTS AND HUMAN OCCUPATION IN THE NORTHERN ATACAMA DESERT

by Terry Workman

Quebrada Mani is a hyper-arid watershed in the southernmost Pampa del Tamarugal region of the Atacama Desert, Chile. Surficial geologic mapping and dating of a 4.3 km segment of Quebrada Mani was initiated to reconstruct past environments associated with a Paleoindian (ca. 12.8-11.6ka) and an early/late Formative (ca 2.5 to 0.7ka) archaeological site. Four distinct stratigraphic units were identified adjacent to the archaeological sites. Late Pleistocene paleowetland deposits comprise Unit $B_1$ (ca. 17,600-16,800 BP) whereas Unit $B_3$ (ca. 11,170-9,450 BP) has sedimentology indicative of fluvial over-bank deposits. Units $B_1$ and $B_3$ are separated by an unconformity and correspond with two regional pluvial phases, the Tauca and Coipasa, of the Central Andean Pluvial Event. Stream aggradation likely associated with more pluvial conditions occurred at 2,500-2,040 ($D_1$); 1,615–1,350 and 1,050–680 ($D_2$) cal yr BP, corresponding with evidence for early/late Formative human habitation. Past climate change likely facilitated the settlement of the Atacama by early hunter-gatherers and early/late Formative agriculturalists along fluvial drainages in an otherwise barren landscape.
PALEOWETLANDS AND FLUVIAL GEOMORPHOLOGY OF QUEBRADA MANI: RECONSTRUCTING PALEO-ENVIRONMENTS AND HUMAN OCCUPATION IN THE NORTHERN ATACAMA DESERT

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Introduction

The Atacama Desert is widely regarded as the driest region on earth, with much of the area receiving less than 20 millimeters of mean annual rainfall (Houston, 2005). Consequently, a barren landscape mostly devoid of life predominates. The Atacama extends across a high, nearly rainless plateau between the Andes Mountains to the east and the Pacific Ocean to the west. The desert stretches across an area of far western South America in northern Chile and southern Peru for some 1,600 kilometers in the north-south direction but only 150 kilometers in the east-west direction (Figure 1). The hyper-aridity of the Atacama Desert today is ascribed to many factors. The desert is situated in a sub-tropical high pressure belt (the Southeastern Pacific Anticyclone), and has an intense rain shadow effect provided by the Andes, which inhibits Amazonian moisture carried by easterly winds from reaching the area (Houston and Hartley, 2003; Vuille and Keimig, 2004). The Humboldt Current also produces a temperature inversion in the region, with cold air upwelling off the Pacific Coast creating thick fog banks along the western periphery of the Atacama. However, nearly all of this Pacific moisture remains as fog and does not lead to local rainfall as convection is repressed by the temperature inversion (Rech et al., 2001, Houston and Hartley, 2003, Houston, 2006).

Despite the extreme hyper-aridity of the Atacama Desert, many people live or lived within this barren desert. Indigenous populations lived and continue to live in many locations along perennial streams that drain from the Andean Cordillera. Although these drainages are generally deeply incised, indigenous groups use floodplains in these areas to grow crops and water animals for animal husbandry, utilizing extensive irrigation networks. There is also abundant archaeological evidence that suggest that humans previously occupied the region in the late Pleistocene/early Holocene as well as the late Holocene, though more work is still needed to understand the spatial and temporal record of humans in the Atacama Desert.

Quebrada Mani is a hyperarid watershed located in the northern Atacama Desert that today only sustains ephemeral stream flow and does not support seasonal or permanent human occupation. However, archaeologists have recently discovered a late Pleistocene Paleoindian site and an extensive late Holocene archaeological site (Latorre et al., 2011, Gayo et al., 2012) at Mani. Excavation of the late Pleistocene archaeological site (QM12c) unveiled a unique assemblage of artifacts that includes burned and cut bones, marine gastropods, pigments, plant fibers, lithics and reworked wood (Latorre et al., 2011). Seventeen $^{14}$C dates on this material date the Paleoindian site to ~12.8-11.6 ka, making QM12c one of the oldest Paleoindian sites uncovered in the Atacama Desert to date. Water availability and the paleoenvironmental context of the site are not well understood, however, making it difficult to understand subsistence strategies and whether the hyper-arid core of the Atacama was a barrier to human migration. The late Holocene archaeological site (ca. 2,300-700) is an early through late Formative agricultural site with a complex network of irrigation canals and floodplain agriculture (Gayo et al., 2012), yet today Quebrada Mani is an ephemeral stream. Does the presence of this archaeological site indicate wetter conditions and perennial stream flow in Quebrada Mani?

Causative relationships between environmental and cultural changes in the northern Atacama remain unclear although a plethora of information may be gained via the combined application of geologic and archaeological methods (Hodell et al., 2001; Nunez et al., 2002; Haug et al., 2003). Systematic mapping, interpretation of depositional environments, and radiocarbon dating of late Pleistocene and Holocene deposits within and around Quebrada Mani.
was undertaken to address key questions regarding the paleo-environmental setting in this area during human occupation and allow for a better understanding of human subsistence strategies. My specific research questions were as follows; (1) What was the depositional environment of the fine-grained deposits adjacent to site QM12C mentioned by Gayo et al., 2012 and is there evidence for perennial water at this locality during human occupation? (2) What was the paleoenvironmental setting during the late Holocene occupation of Quebrada Mani and is there evidence for perennial water during this time? (3) Are there links between climate and environmental change and human occupation of Quebrada Mani as well as other regions of the Atacama Desert?

**STUDY AREA**

The Atacama Desert

In northern Chile, precipitation in the High Andes (>3500m) recharges surface and ground-water systems that course down the Pacific slope through a series of drainages regionally referred to as Quebradas and replenish large aquifers in the hyperarid Atacama Desert. Wetlands, which are often situated along the base of the Andes, denote locations where the water table intersects the land surface. Elevated water tables result from increased groundwater discharge and ultimately from enhanced recharge in the Andes. Enhanced groundwater discharge is, as a result, thought to reflect an increase in the frequency and/or moisture content of South American Summer Monsoon (SASM) air masses that cross the Andes. Continental heating in summer drives deep convection over the Amazon Basin, bringing moisture into this region from the equatorial Atlantic via the trade winds. The trade winds are deflected southeast once they reach the Andes, creating a low-level northwesterly jet that transports tropical moisture from the Amazon toward the Gran Chaco region (lat 20–25ºS) (Nogues-Peagle and Mo, 1997; Zhou and Lau, 1998).

Quebrada Mani

The Quebrada Mani drainage lies in the southernmost portion of the Pampa del Tamarugal (PdT) (21º–21º450 S) and is flanked to the east by the Sierra Moreno, a Paleozoic-Mesozoic range that is part of the Arequipa-Antofalla craton and rises up to 4000m (Tomlinson et al., 2001; Ramos, 1988) (Figure 2). Quebrada Mani is an ephemeral canyon that rapidly grades into a narrow high-energy box canyon above 1400m above sea level (m.a.s.l.) characterized by episodic large flooding events. Perennial stream flow can be found in the tributaries of Quebrada Mani, but only above 3400m where rainfall is high enough to sustain shallow aquifers that feed perennial streams (Gayo et al., 2012). Today, Quebrada Mani is an ephemeral stream without surface water for the majority of the year. Quebrada Mani is positioned due south of the archaeological site QM12c and associated fine-grained deposits (Figure 3). The majority of the valley-fill deposits within the Mani drainage were deposited during periods in the past when discharge was much greater (Nester et al., 2007; Gayo et al., 2009). The most recent major pluvial period occurred throughout the central Andes during the last global deglaciation and is now identified as “Central Andean Pluvial Event” or CAPE (17,500–14,200 and 13,800–9,700 cal yr BP) (Quade et al., 2008; Latorre et al., 2006; Placzek et al., 2009). Phreatophytes such as *Prosopis alba*, *Schinus molle* and *Caesalpina aphylla* can occasionally be found growing within the modern channel in areas where the water table is close to the surface (Gayo et al., 2012) and near a local village that was abandoned in the 1980’s and
lies about 2km east of the archaeological site (Figure 4). At this location it is evident that traditional farming practices were in place, irrigating crops consisting of mostly corn in an area where the bedrock canyon narrows and groundwater is close to the surface.

**Regional and Site Archaeology**

**Pleistocene**

Increased rainfall during the CAPE led to increased perennial runoff and higher water-tables, as well as enabling riparian ecosystems and human cultures to flourish in the presently sterile landscape of the PdT (Santoro *et al*., 2011; Nester *et al*., 2007; Gayo *et al*., 2009). The archaeological survey undertaken by Latorre *et al*., 2011 revealed at least two phases of prehistoric human occupation along the Quebrada Mani drainage. A major occupational phase at site QM12c (21.09° S, 69.43° W) was discovered on the surface of the T₁ fluvial terrace (late Miocene; Nester *et al*., 2007) situated within the Quebrada Mani study area. Well-developed desert pavements along with weathered lithics are plentiful on this surface, which lacks ceramics or other evidence for agricultural activities. Latorre *et al*., 2011 document the latest Pleistocene age Paleoindian occupation of the Quebrada Mani archaeological site QM12c. Excavation of this site identified marine gastropods, pigments, plant fibers, burned and cut bones, lithics, and reworked wood coinciding with a prepared fire hearth. Seventeen ¹⁴C dates on this material date QM12c to 12.8-11.6 ka. The surface expression of site QM12c, with a surface area of ~1.6 km², contains lithic debris, bifacial tools, and bone shards. Surface lithic tool typologies at QM12c resembles those present at the Paleoindian site Salar de Punta Negra (SPN-1), located ~350 km further south (Quade *et al*., 2008). Among the most significant features, QM12c exhibits triangular stemmed points with prominent shoulders, a triangular preform that resembles the “Tuina” pattern, and the common “Patapatane” points (Latorre *et al*., 2011). Lithic artifacts were knapped from fine-grained quartzitic sandstone, opal, rhyolite, silicified limestone, and jasper. In contrast to artifacts constructed from local materials, other silicate materials were found in the final stages of preparation and are clearly allochthonous. They likely originated from a silicified limestone that outcrops 21 km north of Quebrada Mani and were transported to the site. Latorre *et al*., 2011 suggest that this evidence indicates that a wide array of activities occurred at QM12c over an extended time span (~1200 years). These included the final stages of lithic tool elaboration, hunting and food preparation (charred and cut bones), woodworking, and pigment preparation. Extra local lithic raw materials (found over 20 km away) and marine gastropods from the Pacific Ocean (>85 km away) indicate that the occupants were resourceful and very mobile (Latorre *et al*., 2011).

**Holocene**

Much of what we know about the Holocene habitation of Quebrada Mani comes from a study undertaken by Gayo *et al*. in 2012. Gayo and co-authors studied in situ organic deposits, rodent-burrows, and organic archaeological deposits found at Quebrada Mani. The vegetation reconstruction undertaken by Gayo *et al*., 2012 is based on radiocarbon dating and plant macrofossil analyses from eight in-situ organic-rich deposits and from eighteen ¹⁴C dated organic remains associated with archaeological artifacts. Remains of past human activities abound upon the T₂ terrace surfaces (Figure 3), including malachite beads, lithic and shell artifacts, rock engravings (petroglyphs), bones, ceramics, agricultural infrastructure (including terraced crop fields, irrigation channels and dams) and collapsed structures (Gayo *et al*., 2012).
In situ organic-rich deposits yielded datable and taxonomically identifiable fossil-plant remains with no signs of tissue decay and damage. Past shifts in the hydrologic budget at Quebrada Mani were inferred by considering the water requirements/adaptations and modern distribution ranges described for each taxa that occurs within a plant macrofossil assemblage (Gayo et al., 2012). Plant distributions were established by verifying the occurrence of taxa within four current well-defined plant formations developed from semiarid to hyper-arid zones along the western central Andean slope. Hygrophytes are plants growing in moist soils maintained by perennial bodies of water (such as those in wetlands). Phreatophytes are deep-rooted shrubs and trees that obtain water from a permanent groundwater supply. Mesoxerophyte plants are tolerant to prolonged droughts but cannot survive without two to three months of direct rainfall. Finally, xerophytes are plants that are tolerant to prolonged droughts, but survive by hydraulic-lift uptake and found in association with hygrophytes or Phreatophytes (Gayo et al., 2012). Plant macrofossils were utilized to determine both an age for associated archaeological remnants and to determine possible facies changes from perennial wetlands to a phreatic playa and to an ephemeral wash indicative of the modern drainage.

Twenty-six radiocarbon dates on late Holocene vegetation samples from Quebrada Mani exhibit three clusters of calibrated $^{14}$C ages of 1050–680, 1615–1350 and 2245–2230 cal yr BP, with important hiatuses at the intervals <680, 1350–1050 and 2230–1615 cal yr BP (Gayo et al., 2012). Gayo et al., 2012 interpret this distinct clustering of ecological-archaeological activity as episodes of amplified productivity brought about by wetter conditions. Nine $^{14}$C ages on leaf-litter deposits and rodent burrows indicate that between 960 and 680 cal yr BP, plants grew in situ upon the surface of T$_2$ terrace and sustained rodent populations. Likewise, radiocarbon dates from maize canes in life-position and organic materials in direct association with widespread farming vestiges suggest prolonged and intense agricultural activities within an extensive farming camp established along Quebrada Mani from 1050–730 cal yr B.P. (Gayo et al., 2012).

A preliminary analysis undertaken by Gayo et al., 2012 suggests that ceramic fragments associated with the farming vestiges preserved on the T$_2$ terrace have affinities with the Charcollo-Pica pottery type from the Pica-Tarapac’a complex. This cultural complex includes local farmer societies that inhabited perennial river canyons in the northern PdT basin between 1000 and 500 cal yr BP (Uribe et al., 2007). Evidence for extensive water dependent farming practices at Quebrada Mani (e.g., maize cultivation; Aubron and Brunschwig, 2008) support the notion that local exorheic hydrological patterns prevailed between 960 and 680 cal yr BP. Gayo et al., 2012 also provide evidence for earlier human occupation at Quebrada Mani that comes from nine $^{14}$C dates taken on buried charcoal and plant fragments from a section dug into a perched irrigation channel. These dates reveal two distinct periods of increased activities dated at 2,200 and 1,615–1,350 cal yr BP.

Gayo et al., 2012 show that wetter conditions prevailed at 2,500–2,040, 1,615–1,350 and 1,050–680 cal yr BP. The resemblance in timing of these hydroclimate changes in the low-elevation desert with other records from the western Andean slope argue for the existence of significant pluvial events on regional spatial scales for the past 2,500 years according to Gayo et al., 2012. Changes in the cultural history of the people that populated the PdT and the Atacama Desert in general can be better understood by the combined application of geologic and archaeological methods. The Atacama is a harsh environment where prehistoric populations ingeniously managed changes in water availability. In the case of Quebrada Mani, this included
the utilization of widespread agricultural fields, irrigated by a network of several kilometers of stone-lined canals dug into the $T_2$ surface.

RESEARCH METHODS

Field Methods

Late Pleistocene and Holocene surficial geologic deposits adjacent to Paleoindian site QM12c and the late Holocene archaeological site were described, mapped, and dated with radiocarbon dating. Outcrops were first examined during a surface survey of the archaeological material and Quaternary deposits in the surrounding region. Locations for detailed sedimentological descriptions were chosen based on the depositional facies present, the presence of wood or organic beds that could be used for radiocarbon dating, and the identification of clear stratigraphic unconformities. Outcrops of white, fine-grained sediments to the northeast of site QM12c were identified as being the most promising for understanding the late Pleistocene paleoenvironmental setting of the site and were the primary focus of this study. A 4.3 km stretch of Quebrada Mani just to the south of both of the archaeological sites was investigated to understand potential changes in stream flow and to reconstruct the history of aggradation and incision of Quebrada Mani at this locality. A surficial geologic map and 3 valley cross-sections were constructed for this reach of the stream from sedimentological descriptions, inset stratigraphic relations, and radiocarbon dating of wood included within the. Wherever possible, samples were collected from the top and bottom of stratigraphic units to constrain the ages of the deposits. The locations of outcrops used for the description of stratigraphic sections were established with a handheld GPS with a horizontal accuracy of ±10 meters. The ages of stratigraphic units were constrained by the mapping of stratigraphic relationships and by the radiocarbon ages of 16 samples of carbonized plant fragments and organic-rich sediments.

Laboratory Methods

Wood, carbonized plant fragments, and organic-rich sediments were converted into accelerator mass spectrometry (AMS) graphite targets for $^{14}$C dating and aliquots of carbon dioxide for $\delta^{13}$C analysis at Miami University during the fall of 2011. Samples were pretreated using the acid-base-acid method where samples were immersed in $2N$ hydrochloric acid overnight, rinsed with deionized water, treated with 2% sodium hydroxide overnight, rinsed with deionized water, treated with $2N$ hydrochloric acid overnight, and rinsed with deionized water until the resulting solution was of a neutral pH. Samples were evacuated of atmosphere on a vacuum extraction line and combusted at 700°C. The combusted gas was purified cryogenically and the resulting $CO_2$ was split into two aliquots. One aliquot was converted to graphite by catalytic reduction of $CO_2$ (modified after Slota et al., 1987) and submitted to the Arizona-NSF AMS facility for $^{14}$C analysis. The second aliquot was submitted for $\delta^{13}$C analysis in order to correct the measured $^{14}$C activity for isotopic fractionation. Radiocarbon ages are reported in $^{14}$C years and, after calibration, in calendar years. Conventional $^{14}$C ages were calibrated using the CALIB 6.0 (Stuiver and Reimer, 2009) to generate a median and a 2-sigma probability range for each $^{14}$C date in calendar years.
RESULTS

The age of the late Pleistocene and Holocene deposits was identified based on 9 radiocarbon dates from the fine-grained sediments north of the archaeological site QM12c and 16 radiocarbon ages from the Mani drainage south of the site. A series of stratigraphic columns were constructed and sedimentology was described for each of these deposits. Stratigraphy was separated into four major time-stratigraphic units from oldest to youngest; B_1, B_2, D_1, and D_2. Three valley cross-sections were constructed for the Mani drainage as well as for the fine-grained deposits to the north. A surficial geologic map was constructed showing the age and depositional environments of Quaternary sediments in and around the archaeological sites and showing the location of the archaeological sites, valley cross-sections, fine-grained deposits, abandoned agricultural village, abandoned irrigation canals, and terrace boundaries.

Surficial geologic mapping and description of measured sections identified late-Pleistocene paludal deposits northeast of Paleoindian archaeological site QM12c as well as several units of fluvial deposits within the Quebrada Mani drainage. The fine-grained paludal deposits are spread over an area of approximately 1km² (Figure 4). The deposits, labeled as Mani Wetland Station (MWS) 1-5, are situated from east to west with a downgrading slope from 1244m to 1227m in elevation. This ~17m of relief between the lowest and highest fine-grained deposit has many implications for the differences in sedimentation reflected between MWS 1 and MWS 5 which will be further discussed in the following sections. The location of the main stream channel, which is situated just south of the archaeological sites and fine-grained deposits, makes the aggradation and incision history a valuable tool for reconstructing the climate of both the Paleoindian archaeological site as well as the irrigation dependent early/late Formative cultures later inhabiting the T_2 surface (Figure 4). Here I first describe the age, stratigraphy, and depositional environments of the late Pleistocene paludal deposits, using the stratigraphic nomenclature of Rech et al., 2002 and Quade et al., 2008, then present similar results on the Quebrada Mani fluvial deposits.

**Time stratigraphic units**

**Fine-grained deposits**

Paludal deposits were identified just to the northeast of Paleoindian archaeological site QM12c (Figure 3). Outcrops of these deposits are generally a few meters thick, fine-grained, and light in color, making them contrast sharply with the dark, coarse-grained volcanic alluvial fan and fluvial deposits (Figure 5). Below I describe stratigraphic sections running from east to west along the study area and provide evidence that these deposits represent a wetland environment.

**Unit B_1**

Stratigraphic Unit B_1 includes the majority of fine-grained deposits situated just north of archaeological site QM-12C (Figure 4). At Mani Wetland Station 1 Unit B_1 is comprised of two beds. The lower bed is a light tan, massive, silty sandstone with large root voids that have orange/red Fe_2O_3 staining and CaCO_3 rhizoconcretions. This bed is overlain by a gray, calcareous, massive siltstone with small (1mm) root voids, Fe_2O_3 mottling, and CaCO_3 staining the surface. At MWS 1 a thin (~3 cm) organic mat is present in the upper siltstone (Figure 6d).
This organic mat yielded a calibrated radiocarbon age of 16,810 ±430 cal years BP (Table 1). Large tufas were observed in Unit B1 in the center of the deposits (near MWS-3), and thin beds of white sediments believed to be diatomaceous silts were observed in several locations. Multiple thin organic mats were also identified in Unit B1 deposits at station MWS-4, with two samples returning calibrated $^{14}$C ages of 17,600 ±410 and 17,490 ±450 cal years BP (Table 1).

Unit B1 is underlain by fluvial conglomerates associated with the T2 fluvial terrace. These conglomerates are visible cropping out below Unit B1 in the southwest portion of the deposits, just downslope from station MWS-1. Over much of the area where Unit B1 deposits are exposed, the upper surface of the deposits does not appear to be eroded (Figure 7). On the boundaries of the deposits, however, the upper section of Unit B1 has been eroded and the top of the B1 deposits are marked by a sharp, irregular unconformity with B3 deposits above the unconformity.

**Unit B3**

Unit B3 deposits overlie Unit B1 at a few locations and are stratigraphically inset at other localities. At Mani Wetland Station 1, Unit B3 overlies Unit B1 and infills a small channel that was incised within the B1 deposits. At this locality, Unit B3 is comprised of finely bedded (1-3mm) (laminar/horizontal) sand and silt and contains small root voids, though bedding is still well preserved. Overall, B3 is composed mostly of interbedded pink and tan silts. These interbedded fine silts and sands do contain woody debris in some locations. Wood from Unit B1 deposits at MWS-1 yielded a calibrated radiocarbon age of 11,170 ± 480 cal years BP (Table 1). The interbedded silts and sands of Unit B1 are interpreted as fluvial overbank deposits.

**Unit D2**

D2 is composed of poorly cemented silts and sands, with abundant organic material found throughout the unit. This unit consists of finely bedded silts, fine sand, and sheet wash deposits corresponding to early/late Formative age irrigation canals and agricultural practices (Appendix 1). Unit D2 has been identified at Mani wetland stations 2, 3, and 4 and has yielded three radiocarbon ages ranging from 750 ± 50 to 980 ± 80 cal years BP (Table 1).

**Fluvial Deposits**

Multiple stratigraphic units of fluvial deposits are visible within the modern incised channel of Quebrada Mani (Figure 9). I described channel cross-sections and collected wood for radiocarbon dating to constrain the age of these deposits and understand the recent history of aggradation and incision of Quebrada Mani. The identification of stratigraphic disconformities, the differences in relative heights above stream level, and differences in hardness and cementation allowed for the identification of several time-stratigraphic units during mapping in the field. Radiocarbon dating of these deposits indicated that there were a total of four inset stratigraphic units (B1, B3, D1, and D2) among the Quebrada Mani fluvial deposits (Figures 5 and 6). The valley cross-sections constructed in the field highlight the complex relationships of these inset units, especially as Units B3 and D1 are approximately the same height above the modern stream level (~5 m).


Unit B₁ and Terrace 2

Unit B₁, the surface of which is mapped as terrace T₂, is preserved along the northern bank of the study area as a thick, high (~10 meters above modern stream level), and nearly continuous terrace (Figures 5 and 6). The unit consist of late Pleistocene fluvial conglomerates with ridge and swale topography preserved on the surface. A weakly developed gypsic soil (~20 cm) caps the surface of Unit B₁. Clasts on the surface are shattered by salt weathering. Subsequent incision of Unit B₁ and deposition of inset units have stranded most of the outcrops of Unit B₁ farther away from the present incised stream channel, except in the far eastern end of the study area (near Station CS#3) where the stream currently is adjacent to Unit B₁ (Figure 3). The unit includes well-cemented silt, graded sand, and imbricated gravel lenses found down section, suggesting fluvial depositional processes (Figure 9c). Unit B₁ deposits are the oldest fluvial unit at Quebrada Mani based upon stratigraphic position, with Unit B₃ being inset within Unit B₁. Wood within Unit B₁ was identified at cross-section 3 and returned a calibrated radiocarbon age of (16,880 ±210 cal years BP) (Table 1). Pits on the surface of Terrace 2 (Unit B₁) where Pleistocene wood was mined for fire wood in the late 19th or early 20th Century (Figure 5)

Unit B₃

Vertical exposures of Unit B₃ are limited due to infilling by younger units. Unit B₃ unconformably overlies Unit B₁, but the top of the unit is approximately 5 meters above the active stream channel in most areas, considerably lower than the top of Unit B₁ (Figure 8). Unit B₃ is composed of mostly pink and tan silts, and poorly sorted conglomerates (Figure 9b). Reeds found within suggest perennial flow at least for a brief period.

Unit D₁

Unit D₁ is preserved as isolated patches throughout the study area on both sides of Quebrada Mani. The top of Unit D₁ varies in elevation throughout the area, but in some areas it reaches approximately 3-4 meters above the modern stream channel (Figure 9a). Unit D₁ is inset into Terrace 2 (Units B₁ & B₃). The unit is composed of poorly to moderately sorted gavels and silty overbank materials. Massive silt deposits with woody debris and floating gravels representing hyper-concentrated flows are also present. Eleven radiocarbon ages of wood from within Unit D₁ range from 2,760 ±50 to 1,320 ±30 cal years BP (Table 1).

Unit D₂

Unit D₂ is a well preserved low terrace about 2-3 meters above the active stream channel, proximal to the present channel. Unit D₂ is composed of poorly cemented silts and sands and is capped by hyper-concentrated mud flow deposits, with abundant woody debris found throughout the unit (Figure 9a). Unit D₂ is inset within Unit D₁, making it the youngest unit stratigraphically in the study area. 6 radiocarbon ages derived from plant macrofossils yield ages ranging from 700 ±30 to 290 ±20 cal years BP (Table 1).
DISCUSSION

Paleowetland Deposits

Paleowetland deposits between 18-26ºS in the Atacama Desert are found mainly around low-energy streams, springs, and within dry stream channels. These deposits can be used to reconstruct paleo-water tables and past ground-water discharge (Rech et al., 2001, Quade et al., 2008). A unique advantage of these deposits is that they often contain an abundance of terrestrial organic matter and thus can be easily dated, thus circumventing tribulations caused by carbon reservoir effects that are often problematic in lacustrine systems. Groundwater budgets in these systems are tied to precipitation and recharge rates in the central Andes (Rech et al., 2001).

Paleowetland deposits commonly consist of fining upward sequences of sand, silt, tufa (CaCO₃), sinter (SiO), diatomite, and organic mats. The presence of these latter, paludal sediments, indicate perennial water and can be used to reconstruct the past level of water tables. Paleowetland deposits often contain phreatic vegetation. Phreatophytes are deep-rooted shrubs and trees that obtain water from a permanent groundwater supply. They often occur inside active washes in the Quebrada Mani study area. Because these hydrologic settings are not endorheic basins, an amplification of water table height must be supported by enhanced ground-water discharge (Rech et al., 2001). Today Quebrada Mani exhibits groundwater levels of >70 meters below ground level (m.b.g.l.) (PRAMAR-DICTUC, 2007), much too low to support the formation of wetland deposits, though the identification of fine-grained deposits north of the archaeological site QM12c which are indicative of paleowetland deposits at Mani suggest that the water table once intersected the land surface.

The identification, mapping, and dating of paleowetland deposits at Quebrada Mani adds greatly to the base of knowledge regarding the timing and magnitude of pluvial events being compiled in the northern Atacama Desert. The presence of Units B₁ and B₃, separated by an unconformity and composed of diatomaceous silts with small (1mm) root voids, mottling, organic mats, and tufas, is consistent with elevated ground water tables that intersect the land surface i.e. wetlands. Having dated Unit B₁ deposits to 16,810 ±430 cal years BP at MWS 1 and 17,600 ±410 and 17,490 ±450 cal years BP at MWS 4, it can be concluded that Unit B₁ paludal sediments at Quebrada Mani were deposited coeval with the Tauca phase of the Central Andean Pluvial Event (17,600-13,800 cal years BP). Late Pleistocene wood found within the Quebrada Mani drainage, dating to 16,880 ±210 cal years BP, shows that the Unit B₁ wetland deposits were laid down contemporaneously with the late Pleistocene conglomerates. Unit B₃, unconformably overlying Unit B₁, has been dated to 11,170 ±480 cal years BP at MWS 1 corresponding with the Coipasa phase of CAPE (12,700-9,700 cal years BP). The presence of that the paleo-environment at this locality during the Paleoindian occupation at QM12c (12,800-11,600 cal years BP) was that of a perennially standing wetland coinciding with the Tauca phase of the Central Andean Pluvial Event.

Quebrada Mani Fluvial Deposits

Through the reconstruction of the aggradation and incision history of the Quebrada Mani fluvial deposits one can make interpretations that suggest that periods of aggradation coincide with periods of wetter conditions. Unit D₁, represented by eleven radiocarbon ages of wood ranging from 2,760 ±50 to 1,320 ±30 cal years BP suggesting a period of enhanced drainage
flow leading to Unit D₁ deposition. Gayo et al., 2012 suggest that wetter conditions occurred at 2500–2040 and 1615–1350 cal years BP coincident with D₁ deposition, on the basis of plant macrofossils found in situ with early/late Formative archaeological remnants including sophisticated irrigation canals and agricultural plots. Unit D₂ is represented by 6 radiocarbon ages derived from plant macrofossils yielding ages ranging from 700 ±30 to 290 ±20 cal years BP, once again suggesting enhanced drainage flow leading to D₂ deposition. Gayo et al., 2012 show that wetter conditions also occurred from 1050–680 cal years BP, coincident with Unit D₂ deposition and once again late Formative occupation of the T₂ terrace. Unit D₂ is capped by hyper-concentrated mud flow deposits suggesting the onset of ephemeral stream flow punctuated by large scale, episodic flooding events indicative of modern conditions.

**Comparisons to other regional wetland records**

To correlate these changes in wetland environments and stream aggradation at Quebrada Mani with climate the results obtained from Quebrada Mani must be compared to other regional paleowetland records from the late Pleistocene and Holocene (Figure 11). Various studies have radiocarbon-dated paleowetland and in-stream wetland/spring deposits throughout the region. Therefore, it is possible to determine whether the erosive and depositional trends at Quebrada Mani are localized or reproduced at a regional scale, indicating climate as a controlling factor in the development of cut-and-fill cycles.

Unit B deposits record the late Pleistocene/early Holocene wet phase in the Atacama and are present at Zapahuita Springs (3500m, 18.3ºS, 69.5ºW), Tilomonte Springs (2500m, 23.8ºS, 68.1ºW), and Quebrada Chaco (2650-3350m, 25.4ºS, 69.5ºW). This episode represents the wettest period in the Atacama over the last 40,000 years, and agrees well with other paleoclimate records in the region (Geyh et al., 1999; Betancourt et al., 2000). Unit D deposits represent a minor water-table rise during the late Holocene (Rech et al., 2001). In 2002, Rech et al., radiocarbon dated in-stream wetland units of >15.4-9.0 ka BP (Unit B₃) at Tilomonte Springs (approximately 150 km south-southeast of Calama). The youngest ages of Unit B₃ dated at Tilamonte Springs (9.0 ka BP) correlates with the ages obtained from the uppermost portion of Unit B₃ at Quebrada Mani (9.5 ka BP). Unit B₃ deposits were also dated at Quebrada Chaco (Rech et al., 2001) from sediments similar to those found at Quebrada Mani indicating the end of Unit B₃ deposition at ca 10.2 ka BP, corroborating well with Unit B₃ at Quebrada Mani. Deposits of in-stream wetland sediments identified as Unit C were dated from Tilamonte Springs (8.2-3.2 ka BP) (Rech et al., 2002), Quebrada Puripica (7.1-3.3 ka BP), (Grosjean et al., 1997; Rech et al., 2003), and Rio Salado (6.2-4.0 ka BP) (Rech et al., 2002), but were not dated at Quebrada Mani. Whether this is due to a lack of sampling resolution or erosional processes is yet to be determined. Unit D₁ (2.6-1.3 ka BP) and D₂ deposits (~500 years BP) dated at Quebrada Puripica (Rech et al., 2003) are equivalent with Units D₁ (2.8-1.3 ka BP) and D₂ (<1,000 years BP) deposits at Quebrada Mani, indicating regional depositional trends (Table 1).

This comparative record, while incomplete, suggests that cut-and-fill cycles from both in-stream wetland and paleowetland deposits respond to similar changes in climate. These paleowetland deposits only aggrade during periods of flowing water and corresponding water tables higher than the present day. The correlation between these deposits and in-stream wetland deposits suggests that the in-stream wetland deposits behave similarly, following the alluvial base level model (Tully, 2010).
The paleowetland (Figure 11) and drainage record (Figure 12) at Quebrada Mani can be compared with regional paleowetland deposits to better understand the relationship of climate and cut-and-fill cycles. These wetlands are not active today, and were only active in the past during periods of greater groundwater discharge. Quebrada Mani today exhibits groundwater levels of >70 m.b.g.l. (PRAMAR-DICTUC, 2007), much too low to support phreatic vegetation. Quade et al., (2008) revealed that elevated groundwater levels supported phreatic discharge into wetlands during two periods demonstrated by Unit B₁ (15,900-13,800) and Unit B₃ (12,700-9,700 cal years BP) at Salar de Punta Negra, which correlate with Unit B₁ and Unit B₃ in paleowetland deposits at Quebrada Mani (11,200-9,500 cal years BP). Dense concentrations of lithic artifacts confirm the presence of Paleoindians around the wetlands late in the second wet phase (11,000-9,700 cal years BP) at the associated archaeological site SPN-56 coincident with Paleoindian occupation at Quebrada Mani earlier in the second wet phase (12,800-11,600 cal years BP). The regional synchronicity of these changes points to an intensification of the SASM during the Central Andean Pluvial Event (Quade et al., 2008).

The abundance of flora contained within fossil rodent middens in the Atacama provides an exceptional independent proxy of regional climate (Betancourt et al., 2000; Latorre et al., 2003). The assemblages of vegetation contained within these middens records past migration of plant species down slope due to wetter climatic conditions. The rodent middens contain abundant plant macrofossils that facilitate the use of radiocarbon dating to constrain the ages of vegetation changes and species migrations. The inferred paleoclimate from the midden record (Latorre et al., 2003) suggests wet intervals from 11.7-9.6 ka cal years B.P., which correlates with Unit B₃ (11.2-9.5 ka BP) at Quebrada Mani. The midden record indicates drier conditions persisting until 7.6 ka BP. The midden record suggests hyper-arid conditions persist from 3.2 ka BP until the present day, excluding a briefly wetter period from 1.8-1.2 ka BP. Unit D₁ (2.7-1.4 ka BP) at Quebrada Mani may be correlated with this brief absence of aridity indicated by the rodent midden record as demonstrated by Gayo et al., 2012. The strong connection between the rodent middens and paleowetland records demonstrate that both systems are responding to climate, with aggradation at Quebrada Mani occurring during wetter intervals.

CONCLUSIONS

The first peopling of South America is one of the most widely debated topics in American archaeology (Goebel 2008, Dillehay 2000). Questions remain regarding the degree of interaction with extinct mega fauna, points of entry, migration routes taken (coastal versus inland routes) (Rothhammer, 2009), and the timing of initial human settlement. This is due in part to the presence of early (14,800-13,800 BP) archaeological sites such as Monte Verde in southernmost Chile, whereas no evidence of sites older than ~11,500 BP have been documented in the rest of Chile (Dillehay, 1989; Meltzer et al., 1997) until recently. QM12c represents an amazingly preserved Paleoindian archaeological site dated to 12.8-11.6 ka BP in the northern Atacama Desert. Utilizing a combination of geologic and archaeological methods a pluvial climate corresponding to the Coipasa Phase of the Central Andean Pluvial Event was reconstructed for the Paleoindian occupation of Quebrada Mani. While the Atacama today exhibits an unforgiving hyperarid environment devoid of vegetation and human occupation, paleowetland deposits radiocarbon dated to have been active at a time coeval with the second pluvial phase of CAPE (12,700-9,700 cal years BP) suggest that during the late Pleistocene Quebrada Mani constituted an attractive oasis to groups of hunter-gatherers in an otherwise barren landscape. Utilizing
paleowetland deposits as an indication of possible Paleoindian habitation sites, it is my belief that older archaeological sites lay undiscovered further and further north in South America lending credence to the possibility of a terrestrial migration route into the continent.

Having reconstructed the aggradation and incision history of the Quebrada Mani drainage it is clear that late Holocene human occupation of Mani is directly related to periods of greater Andean discharge and channel flow. These Holocene inhabitants were resourceful and demonstrated great ingenuity, having constructed elaborate irrigation canals that supplied water from the then perennially flowing drainage to extensive and flourishing agricultural fields. The Atacama is an extreme environment where changes in water availability were ingeniously managed by prehistoric populations. A preliminary analysis on ceramic fragments associated with the farming vestiges preserved on the T₂ terrace suggest similarities with the Charollo-Pica pottery type from the Pica-Tarapac’a cultural-complex, suggesting that once surface water becomes available at Quebrada Mani, human occupation becomes viable in this extreme hyperarid landscape creating a fertile oasis for economic human activities.
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Moreno, Ana. Santoro, Calogero M., Latorre, Claudio. (2009) Climate change and human occupation in the northernmost Chilean Altiplano over the last ca. 11,500 cal. a BP. *JOURNAL OF QUATERNARY SCIENCE* 24(4) 373–382


# Table 1: Summary of $^{14}$C Results

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<th>$^{14}$C age</th>
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<th>Calibrated age BP</th>
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# CALIB v. 6.0.0 (Stuiver and Reimer 1993). IntCal09.14C dataset (Reimer et al 2009); limit 50.0 calibrated ka B.P. Calibrated ages are reported as the midpoint of the calibrated range. Uncertainties are given at the 2σ(95%) confidence level and reported as the difference between the midpoint and either the upper or lower limit of the calibrated age range, whichever is greater. Multiple ages are reported when the probability of a calibrated age range exceeded 0.05.

* P* Probability of the calibrated age falling within the reported range as calculated by CALIB. CAPE Central Andean Pluvial Event Tauca Colpasas
Figure 1. Map of South America with the locations of the Atacama Desert, central Andes, the Quebrada Mani site (1), Quebrada Sipuca site (2), and Quebrada Tambillo site (3), Chile.
Figure 2. Aerial photograph displaying the many fluvial drainages and alluvial fan deposits that are recharged from the high Andes. Quebrada Maní study area is outlined.
Figure 3. Quebrada Mani study area demarcating the Paleoindian archaeological site QM12c, early/late Formative agricultural units, and historic (1970's) agricultural plots.
Figure 4. Surficial geologic map of Quebrada Mani in the northern Atacama Desert of Chile, with the watershed and study area outlined.
Figure 5. Northeastern view of extensive Mani paleowetland deposits. Outcrops of these deposits are generally 1 to 2 m thick, fine-grained, and light in color, making them contrast sharply with the dark, coarse-grained volcanic alluvial fan and fluvial deposits
Figure 6. Composite photo of Paleowetland deposits. a) diatomaceous sediments, b) diatomaceous silt layer, c) logs sticking out of unit, d) organic black mats, e) sampled paleowetland unit, f) late Holocene flotsam deposits with inset.
Figure 7. Generalized cross-section of Quebrada Mani Paleowetland deposits including selected radiocarbon ages expressed in Cal years BP.

Figure 8. Quebrada Mani active drainage. a) logs protruding from T₂ Pleistocene surface, b) D₁ Units facing east, c) recent mudflow deposit, d) T₂-T₄ terraces (D₂ units).
Figure 9a. Generalized cross-section at Quebrada Mani including selected radiocarbon ages, expressed in Cal years BP. *M2- Fossil wood, possibly washed in.
Figure 9b. Generalized cross-section at Quebrada Mani including selected radiocarbon ages, expressed in Cal years BP. *M19- Fossil wood, possibly washed in.

Figure 9c. Generalized cross-section at Quebrada Mani including selected radiocarbon ages, expressed in Cal years BP.
Figure 10. Quebrada Mani archaeology composite photo. a) Paleoindian site QM12c (12.8-11.6 ka). b) Paleoindian bifacial cleaver for butchering camelids. c) Paleoindian bifacially worked projectile point. d) Late Holocene agricultural plots. e) Late Holocene irrigation canals. f) Irrigation canals and adjoining agricultural plots.
Figure 11. Comparison of paleohydrologic records from the central Andes south of 18°S from: (a) paleowetlands from Quade et al., 2008, (b) rodent middens in point count abundance from Quebrada de las Zorras and Quebrada de Tocanar, and (c) the Poopo/Coipasa/Uyuni lake system (Placzek et al., 2006) with lake phases shown. (d) demonstrates radiocarbon ages on organics taken from Tambillo, Mani, Chipana, and Sipuca (Nester et al., 2007), (e) Radiocarbon ages from Mani paleowetland and fluvial deposits (this study), QM12c (Latorre et al., 2011).
Figure 12. Comparison of Holocene lake level, in-stream wetland, rodent midden, spring deposits, fluvial deposits, and archaeology records in the Atacama Desert. The shaded portions indicate periods of deposition.
APPENDIX I

Location: Quebrada Mani Wetland  Station: 1  Date: 7/3/11

<table>
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<tr>
<th>Depth (cm)</th>
<th>Lithology</th>
<th>TEXTURE (sorting, grain shape, matrix type, size)</th>
<th>NOTES (fossils, sediment structures)</th>
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Unit B₃

Massive siltstone filled with small (1mm) root voids, mottled, organic mat, CaCO₃ staining the surface, diatoms.

Fine sandy sandstone filled with large root voids and root casts. Fe₂O₃ staining throughout. Massive, hard.

Finely bedded (lamellar/horizontal) sand and silt (1-3mm) filled with small root voids, but bedding still well preserved.
Unit B₁


Unit B₃

Finely bedded (laminar/horizontal) sand and silt (1-3mm) filled with small root voids, but bedding still well preserved.

Major Unconformity
Unit B
Fine to medium sand with iron
 Massive discontinuities
 all with small root voids.

Unit B
(Fine) Flico medium sand
with CaCO cemented voids
and root casts.
Surface covered with tufa and popcorn tufa.

Silt and fine brown sand with iron oxide models and root voids with CaCO₃.

White diatomaceous silt

Fine sand with iron oxide staining.

Diatomaceous silt with pure diatomite layer on top and an organic black mat.

Massive silt with thin beds of sand up to 2cm thick. Silts filled with large and small root voids with iron oxide staining. Red silt at base.