ABSTRACT

HOLOCENE MEGA-DROUGHTS IN THE CENTRAL ATACAMA DESERT, CHILE

by Craig D. Tully

Mega-droughts are responsible for extreme changes in geomorphic processes and human-environment interactions. In many semi-arid environments, the frequency and magnitude of mega-droughts can be reconstructed with dendrochronology. In truly arid lands, however, it is generally not possible to use dendrochronology due to a lack of trees. In-stream wetland deposits may provide the necessary chronology to reconstruct past mega-droughts. Thirty-seven radiocarbon dates and five amino-acid racemization ratios provide excellent age constraint of cut-and-fill cycles of in-stream wetland deposits at Rio San Salvador, Chile. Corroboration of the geochronological history of these deposits with other paleohydrologic records across the Atacama Desert allows exclusive assumption of the alluvial base-level model of incision and deposition in arid lands. Periods of incision from 9.9-6.4 ka B.P., 3.5-2.7 ka B.P., 1.0-0.95 ka B.P., and 0.3 ka B.P. represent past mega-droughts. ENSO variability through the Holocene may drive these climatic changes.
HOLOCENE MEGA-DROUGHTS IN THE CENTRAL ATACAMA DESERT, CHILE

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by
Craig David Tully
Miami University
Oxford, Ohio
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Advisor:_________________________________________
Jason Rech

Reader:__________________________________________
Brian Currie

Committee Member:_______________________________
William Renwick
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INTRODUCTION

Mega-droughts, extreme droughts that persist for years to decades, can have a severe impact on water and environmental resources, biological communities, and human populations (Cooke and Reeves, 1976). Arid regions are especially vulnerable to mega-droughts, both due to the limitation of water resources and the large role climate has on geomorphic processes (Houston, 2005). There has been much work on the cause and frequency of mega-droughts over the last decade, initiated in part by the severe droughts that have affected the American Southwest and other arid regions (Forman et al., 2008; Waters and Haynes, 2001).

In many arid and semi-arid environments, the frequency and magnitude of mega-droughts can be reconstructed with dendrochronology (Stahle et al., 2005). In these regions, the history of mega-droughts can be used to assess the synoptic climatic controls leading to mega-droughts and to try and predict future mega-droughts. In truly arid lands, however, it is generally not possible to use dendrochronology to reconstruct mega-drought frequency due to a lack of available trees. Other proxies, such as records of isotope data derived from speleothems (Springer et al., 2007), vegetation diversity preserved in rodent middens (Betancourt et al., 2000; Latorre, et al., 2003), and dune field magnitude and orientation (Forman et al., 2009; Tripaldi and Forman, 2007), have been used to reconstruct mega-droughts in arid regions. However, these records are often sparse and incomplete, and many proxies are not readily available in all desert localities.

In-stream wetland deposits may provide a much-needed archive to reconstruct past mega-droughts in arid and hyper-arid regions. These wetlands occur in areas with an emergent water table, experience few large discharge events per year, and contain vegetation within the beds of incised streams (Zierholz et al., 2001). In-stream wetlands are resistant to erosion from major flood events due to in-situ vegetation “armoring” the streambed (Prosser and Slade, 1994) and reducing flow velocities in the active channel. Removal of streambed vegetation by either anthropomorphic means (such as plowing or livestock grazing) or environmental changes (such as a mega-drought) may initiate channel incision (Prosser and Winchester, 1996). A positive feedback between vegetation and channel incision can occur, with a loss of hydrologic connectivity from
decreased root structure resulting in a reduced erosive resistance capacity (Toledo and Kaufman, 2007).

Three different theories have described the erosional and depositional patterns in arid channels (Hereford, 2002). The first theory, the complex response model, does not identify climate change as a dominant factor, but states that temporally random processes within the catchment may cross intrinsic thresholds and promote aggradation or erosion (Schumm and Hadley, 1957; Schumm, 1977; Patton and Schumm, 1981; Boison and Patton, 1985; Waters, 1985; Patton and Boison, 1986; Elliot et al., 1999). The other two theories suggest that climatic changes within the catchment area directly control aggradation and incision. The stream power model suggests that periods of high discharge control aggradation and incision, with downcutting of the channel occurring during wetter periods with more available stream power, and filling of the channel during drier periods when there is less available stream power (Martin, 1963; Hall, 1977; Love, 1977). This theory does not apply to catchments that lack the appropriate amount of available stream power (due to a shallow gradient or small catchment area) to initiate channel erosion.

The third theory, the alluvial base-level model, implies that changes in the regional water table, or base level, control channel aggradation and incision. The lowering of base level during drier periods promotes downcutting and the rising of base level during wetter periods promotes aggradation (Bryan, 1941; Antevs, 1952; Cooley, 1962; Haynes, 1968; Euler et al., 1979; Karlstrom, 1988). Waters and Haynes (2001) determined that arroyos in the American Southwest are likely to initiate incision during drier climactic periods with low effective moisture.

In this study, I investigate the potential of using well preserved in-stream wetland deposits along the Río San Salvador, Chile, to reconstruct a history of mega-droughts that occurred in the east-central Atacama Desert during the Holocene. Radiocarbon dating of plant macrofossils and amino-acid racemization of aquatic gastropod shells are used to date well-preserved in-stream wetland deposits across erosional unconformities. Results are then compared with other regional paleoclimatic proxies to determine which stream model applies to the aggradation and incision history of Río San Salvador. I will argue that the alluvial base-level model controls the history of cut and fill cycles, and the
valley-fill deposits can be used to decipher a climate record through the Holocene. As in-stream wetland deposits are common in arid lands, this technique has great potential for elucidating the history and cause of mega-droughts in many arid regions worldwide. As modern climate change becomes an increasingly important concern regarding the availability of water resources in arid lands, it is important to understand the past variability of these systems to better manage future water resources (Milly et al., 2008).

**STUDY AREA**

*The Atacama Desert*

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, an extremely arid and barren landscape devoid of vegetation predominates. The Atacama extends across a high, virtually 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 hyperaridity of the present-day Atacama Desert is attributed to many factors. The desert is located in a high pressure sub-tropical belt (the Southeastern Pacific Anticyclone), and has a heavy rainshadow effect provided by the Andes which prevents 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 dense fog banks along the western margin of the Atacama. However, nearly all of this Pacific moisture remains as fog and does not lead to local rainfall as convection is inhibited by the temperature inversion. In addition to providing a rainshadow effect, the Andes Mountains impact the region by interrupting zonal circulation and altering the radiation balance at high elevations, which then increases evaporation.
The Calama Basin

The Calama Basin, located between 22°S and 23°S in the east-central Atacama, currently receives occasional moisture from three main sources. The South American Summer Monsoon (SASM) brings convective precipitation from the Amazon to the northeast and from the Gran Chaco to the southeast during the austral summer (Garreaud, 1999; Garreaud et al., 2003; Vuille and Keimig, 2004). Southwesterly air masses that originate from frontal precipitation associated with extra-tropical cyclones during the austral winter impact the Calama Basin, but diminish up the Pacific slope (Vuille, 1999).

The Calama Basin is particularly sensitive to El Niño/ Southern Oscillation (ENSO) variability (Houston, 2006). During El Niño events, diminished easterly winds couple with warmer surface ocean temperatures in the eastern Pacific Ocean to prevent the upwelling of nutrient-rich bottom waters and the creation of cool moist air near the coast. The reduction of this coastal temperature inversion allows some moisture into the western margin of the Atacama, but this moisture does not persist into the east-central desert (McKay et al., 2003). Strong westerly winds during El Niño events also deprive the eastern Atacama and Altiplano of moisture from the Amazon Basin, causing drought conditions in these regions (Houston, 2005). During La Niña conditions, on the other hand, precipitation is enhanced along the Andean Altiplano and eastern edge of the Atacama, as stronger easterly winds allow more moist air masses from the Amazon to cross the Andes and enter the eastern Atacama (Vuille and Keimig, 2004; McKay et al., 2003). The increased magnitude and frequency of El Niño events through the Holocene may have presented the region with more severe droughts and increased aridity (Moy et al., 2002).

Although the hyperaridity of the Atacama is substantial, there are some perennial streams sourced in the Andes that cross the Calama Basin westward to their discharge point in the Pacific Ocean. These streams are generally deeply incised up to a few hundred meters, and perennial discharge is maintained due to the exposure of surface aquifers in the Atacama Desert. The deep incision of many stretches of these rivers is attributed to tectonic uplift (Gregory-Wodzicki, 2000) and sea level change (Hallam, 1992) during the Pliocene, as well as variability in climate (Houston and Hartley, 2003).
However, most of these streams currently are underfit, with bankfull conditions and major flooding events rarely occurring (Houston, 2005).

**Río San Salvador**

Río San Salvador flows west from just north of the city of Calama to its junction with the Río Loa (Figure 2). The stream lies at a latitude of ~22.5°S and travels approximately 75 kilometers westward (69°W to 69.5°W longitude) across the hyperarid core of the east-central Atacama. The elevation of the channel ranges from approximately 2,200 meters near Calama to approximately 1,200 meters at the junction with the Río Loa, creating an overall stream gradient of 13.3 m/km. It is an atypical stream catchment, with nearly all streamwater sourced from groundwater recharge. The upper portion of the stream (which contains the study area) has a substantially lower gradient (6.3 m/km) than the downstream portion of Río San Salvador, which becomes deeply incised westward of the study area.

Río San Salvador was selected as a study area because of the excellent preservation of several fluvial terraces with in-stream wetland deposits, which is likely due both to the catchment being restricted to the hyperarid Calama Basin and the lack of large erosive localized floods. Plentiful carbonized plant fragments, organic-rich sediments, and aquatic species of gastropods preserved within the in-stream wetland deposits permitted high geochronological resolution. These favorable characteristics of Río San Salvador allow for investigation of the base-level model of cut-and-fill cycles, and deciphering the frequency of Holocene mega-droughts.

**RESEARCH METHODS**

*Field Methods*

A 4.3-km stretch of Río San Salvador was selected immediately downstream of Calama, Chile. A surficial geologic map of this section of the stream was produced from sedimentological descriptions and geochronology from 17 stratigraphic columns and 5 valley cross-sections. 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 37 samples of carbonized plant fragments and organic-rich sediments. Wherever possible, samples were collected from the top and bottom of each interpreted stratigraphic unit to better constrain the ages of the deposits. Five samples of aquatic gastropods (Hydrobiid sp.) were also collected for amino-acid racemization to establish ages for units that lacked organic material.

**Laboratory Methods**

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 Spring of 2008. Samples were pretreated using the acid-base-acid method where samples were immersed in $2M$ hydrochloric acid overnight, rinsed with deionized water, treated with 2% sodium hydroxide overnight, rinsed with deionized water, treated with $2M$ 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 900°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 (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 Fairbanks 0107 marine calibration dataset (http://radiocarbon.ldeo.columbia.edu/research/radcarbcal.htm; Fairbanks et al., 2005).

**RESULTS**

The surficial mapping and description of measured sections at Río San Salvador identified several inset units of fluvial deposits (Figures 3 and 4). All units contain fine sands, silts, diatomaceous sediments, and tufa deposits, which represent in-stream wetland conditions similar to the modern environment (Figures 5 and 6). A few units contain imbricated gravels and cross-bedded sands near the basal sections indicative of fluvial channel deposits at the onset of unit filling episodes. Valley-fill deposits
gradually thicken upstream (towards Calama) within the study area and end abruptly at the downstream terminus of the study area where the canyon becomes deeply incised into bedrock.

**Radiocarbon Ages**

A total of 37 radiocarbon ages processed from collected samples constrain the age of in-stream wetland units (Table 1). Thirty of the radiocarbon ages are derived from carbonized plant fragments collected from organic-rich deposits (Figure 7). Seven samples of bulk organic material were dated from organic-rich sediments as no plant fragments were identified in these samples. Radiocarbon ages of all units range from 11,095±95 to 320±55 years B.P., providing an excellent record of five distinct depositional episodes (Units A, B3, C, D1, and D2) and subsequent periods of incision throughout the Holocene. The episodes of unit filling correspond to the younger radiocarbon ages upsection in each stratigraphic unit, suggesting little secondary contamination or reworking of samples.

Two radiocarbon ages (samples 13 and 17) do not fit well within the sequence of aggradation relative to their respective time-stratigraphic unit (Table 1). Sample 13, a carbonized plant fragment, returned an age of 2310±40 years B.P., which is considerably older than other ages of approximately the same height above stream level in Unit D1. This erroneous older age may be the result of reworking of organic material from older stratigraphic units. Sample 17, an organic-rich sediment, returned an age of 3,600±60 years B.P., which is much younger than other samples of the same height in Unit C. This erroneous younger age may be due to contamination of this sample by younger sediments. It is also possible that these dates may indicate unconformities not identified in the field or errors in processing the samples.

**Amino acid racemization ages**

Organic material suitable for radiocarbon dating was not found in Unit A deposits. However, two gastropod samples (*Hydrobiid sp.*). were collected from Unit A for amino acid geochronology. Three additional samples of gastropod shells, also *Hydrobiid sp.*, were collected from Units C, D1, and D2 with firm age control to develop
an age model for the amino acid racemization rates at Río San Salvador. The relative age of Unit A is determined by amino acid racemization ratios consisting of plotted D/L aspartic acid (Asp) and D/L glutamic acid (Glu) values (Table 2). Based upon the extension of the age model, Unit A is determined to be at least 11,000 years old (Figure 8). Unfortunately, no gastropods were collected in Unit B3. As a result, the age model developed is of limited value. Nevertheless, the amino-acid racemization data confirm a comparatively older age for Unit A.

Time stratigraphic units

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 (Figure 9). Radiocarbon dating of these deposits indicated that there were a total of five inset stratigraphic units (A, B3, C, D1, and D2) within Río San Salvador (Table 1). The valley cross-sections constructed in the field highlight the complex relationships of these inset units, especially as Units B3, C, and D1 are approximately the same height above the modern stream level (~12 m) (Figure 10). These five distinguishable units adhere to the stratigraphic nomenclature used by Rech et al., (2002; 2003) and Quade et al., (2008) to describe in-stream wetland and spring deposits in other locations in the Atacama.

Unit A

Unit A deposits are the oldest of the valley-fill units at Río San Salvador based upon stratigraphic position, with Unit B3 (11,095 ±95 to 9,900 ±120 years B.P) being inset within Unit A. Supporting evidence from amino acid ratios indicate a late Pleistocene age for Unit A. The unit outcrops only along the southern bank of the study area, and is preserved as a thick, high (~18 meters above modern stream level), and nearly continuous terrace that unconformably underlies all younger deposits (Figure 11). Subsequent incision of Unit A and deposition of inset units have stranded most of the outcrops of Unit A farther away from the present incised stream channel, except in the far eastern end of the study area (near Station 11) where the stream currently is adjacent to Unit A. An excellent exposure of the basal section Unit A is located at Station 11 (Figure 11; see appendix). The unit includes well-cemented silt, graded sand, and interbedded
imbricated gravel lenses found downsection, suggesting fluvial depositional processes. Thinly bedded silt, sand, tufa, and diatomite deposits are found upsection, indicating a transition to a lower energy in-stream wetland depositional environment.

*Unit B₃*

Unit B₃ is the second oldest unit preserved at Río San Salvador, with four radiocarbon ages derived from plant macrofossils and organic-rich sediments yielding ages ranging from 11,095 ±95 to 9,900 ±120 years B.P. Unit B₃ is the most prevalent unit located in the study area (Figure 3), but good vertical exposures are limited due to infilling by younger units. Unit B₃ unconformably overlies Unit A, but the top of the unit is approximately 12 meters above the active stream channel in most areas, considerably lower than the top of Unit A. Unit B₃ is composed of mostly pink and tan silts and organic-rich sediments. Well cemented tufa is found toward the top of the unit in many sections, and numerous root casts are often present toward the central portion of the unit.

*Unit C*

Unit C is younger than Units A and B₃, yet older than Units D₁ and D₂. Twelve radiocarbon ages of plant fragments and organic-rich sediments from Unit C yield ages ranging from 6,425 ±35 to 3,505 ±45 years B.P. Unit C is found throughout the study area on both banks of Río San Salvador, and it is the stratigraphic unit most commonly exposed in vertical cuts in the southern portion of the study area. However, on the northern bank of Río San Salvador, Unit C is only exposed in the western portion of the study area. Many outcrops of Unit C reach approximately 12 meters above the active stream surface, and unconformably overlie Unit B₃. In-stream wetland facies are present, with well sorted silt and overlying imbricated gravels form the lower portion of Unit C, with silty sediments and numerous tufa layers occupying the upper portion of the unit.

*Unit D₁*

Unit D₁ is the second youngest stratigraphic unit, deposited after Units A, B₃, and C. Ten radiocarbon ages of plant macrofossils range from 2,740 ±15 to 1,090 ±45 years B.P. Unit D₁ is preserved as isolated patches throughout the study area on both sides of Río San Salvador. The top of Unit D₁ varies in elevation throughout the area, but in some areas it reaches approximately 12 meters above the modern stream channel. Unit D₁ is inset of both Units B₃ and C based upon local exposed unconformities (Figure 11).
Unit D₁ is easily identifiable from the other units at Río San Salvador due to the chocolate brown color of its sediments. The unit is predominantly composed of silty material consistent with in-stream wetland deposition, with pink tufa layers, sandy lenses, and root casts found throughout the sediments.

Unit D₂

Unit D₂ unconformably overlies Unit D₁, making it the youngest unit stratigraphically in the study area. Eleven radiocarbon ages derived from plant macrofossils yield ages ranging from 955 ±25 to 320 ±55 years B.P. Unit D₂ is a well-preserved low terrace about 2-6 meters above the active stream channel, proximal to the present channel. The unit noticeably thickens upstream, up to six meters thick eastward toward Calama (e.g. Station 11). Unit D₂ is composed of poorly cemented silts and sands, with abundant organic material found throughout the unit.

DISCUSSION

Synthesis of results

The amino-acid racemization data (Table 2; Figure 8) and thick exposures of Unit A (Figure 11) indicate a sustained period of deposition at Río San Salvador (Unit A) earlier than 11,000 years B.P. The radiocarbon data reveal another period of deposition during the late-Pleistocene and into the early Holocene, with aggradation occurring from 11,095 to 9,985 years B.P (Unit B₃) (Table 1; Figure 12). The presence of an unconformity above Unit B₃ corroborates with the lack of preserved units from 9,985 to 6,425 years B.P., indicating a period of erosive conditions for over 3,500 years during the early Holocene. Beginning at 6,425 years B.P., aggradation of Unit C continued for approximately 3,000 years corresponding with progressively higher levels of deposition above the modern stream level. An unconformity exists between Units C and D₁ from 3,505 to 2,740 years B.P., inferring another sustained period of erosive conditions. Unit D₁ preserves approximately 1,600 years of deposition from 2,740 to 1,090 years B.P. The unconformity between Units D₁ and D₂ omits only 150 years of the record; however, a sharp decrease in the water table is indicated between Units D₁ and D₂ (Figure 12). Unit D₂ records a period of deposition from 955 to 320 years B.P., with subsequent erosive conditions continuing to the present day. Most time stratigraphic units (Units B₃,
C, and D$_1$) are positioned with a maximum height of approximately 12 meters above the active stream channel, perhaps indicating a limiting threshold of aggradation in the Río San Salvador catchment.

**Comparisons to other regional wetland records**

In order to validate these assumptions of potential mega-drought conditions, the results obtained from Río San Salvador must be compared to other regional wetland records throughout the Holocene (Figure 13). Various studies of radiocarbon dating in-stream wetland and spring deposits have been conducted throughout the region. Therefore, it is possible to determine whether the erosive and depositional trends at Río San Salvador are localized or reproduced at a larger scale, indicating climate as a controlling factor in the development of cut-and-fill cycles.

Due to the poor age constraint of Unit A (~11,000 years B.P) in this study, it is difficult to correlate other regional Unit A deposits. In 2002, Rech *et al.*, radiocarbon dated in-stream wetland units of >15.4-9.0 ka B.P. (Unit B$_3$) at Tilomonte Springs (approximately 150 km south-southeast of Calama). The youngest ages of Unit B$_3$ found at Tilomonte Springs (9.0 ka B.P.) correlates with the ages obtained from the uppermost portion of Unit B$_3$ at Río San Salvador (9.9 ka B.P). Unit B$_3$ deposits were also dated at Quebrada Chaco (Rech, 2001) from sediments similar to those found at Río San Salvador (alluvial sediments progressing to in-stream wetland facies upsection) indicating conclusion of Unit B$_3$ alluviation at 10.2 ka B.P, corroborating well with Unit B$_3$ at Río San Salvador.

Deposits of in-stream wetland sediments identified as Unit C were dated from Tilamonte Springs (8.2-3.2 ka B.P.) (Rech *et al.*, 2002), Quebrada Puripica (7.1-3.3 ka B.P.) (Grosjean *et al.*, 1997; Rech *et al.*, 2003), and Río Salado (6.2-4.0 ka B.P.) (Rech *et al.*, 2002). These ages compare well with the ages obtained from Unit C at Río San Salvador (6.4-3.5 ka B.P.), indicating a period of regional aggradation. Unit D$_1$ (2.6-1.3 ka B.P.) and D$_2$ deposits (~500 years B.P.) dated at Quebrada Puripica (Rech *et al.*, 2003) are equivalent with Units D$_1$ (2.7-1.1 ka B.P.) and D$_2$ (<1,000 years B.P.) deposits at Río San Salvador, indicating regional depositional trends. The strength of age correlation between the various in-stream wetland deposits across the central Atacama allow for
Hereford’s first model (the complex response model) to be discarded, as the correlation between records indicate that climate is controlling the cycles of regional erosion and deposition.

The in-stream wetland record at Río San Salvador can be compared with regional paleospring deposits to better understand the relationship of climate and cut-and-fill cycles (Figure 13). These springs are not active today, and were only active in the past during periods of greater groundwater discharge. Quade et al., (2008) dated spring deposits from Unit B3 at Salar de Punta Negra with radiocarbon ages from 12-9.5 ka B.P., which correlate with Unit B3 in-stream wetland deposits at Río San Salvador (11.1-9.9 ka B.P.). A spring deposit identified as Unit C at Zapahuita Springs (Rech, 2001) was dated with radiocarbon ages from 4.9-2.8 ka B.P. These ages only corroborate loosely with Unit C (6.4-3.5 ka B.P.) in-stream wetland deposits at Río San Salvador, but both locations indicate periods of deposition during the mid-Holocene. This comparative record, while incomplete, suggests that cut-and-fill cycles from both in-stream wetland and spring deposits respond to similar changes in climate. These paleospring 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.

**Comparisons to other regional climactic records**

The abundance of flora contained within fossil rodent middens in the Atacama provides an excellent 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 downslope in response to wetter climactic conditions. The rodent middens contain numerous plant macro-fossils which 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 years B.P., which correlates with Unit B3 (11.1-9.9 ka B.P.) at Río San Salvador. The midden record indicates drier conditions persisting until 7.6 ka B.P. A wet interval recorded by the middens continues through the mid-
Holocene (7.6-3.2 ka B.P.) and is nearly synchronous with Unit C (6.4-3.5 ka B.P.) at Río San Salvador. The midden record suggests hyperarid conditions persist from 3.2 ka B.P. until the present day, excluding a briefly wetter period from 1.8-1.2 ka B.P. Unit D1 (2.7-1.1 ka B.P) at Río San Salvador may be correlated with this brief absence of aridity indicated by the rodent midden record. The strong connection between the rodent middens and in-stream wetland records demonstrate that both systems are responding to climate, with aggradation at Río San Salvador occurring during wetter intervals (the alluvial base-level model).

In another comparative proxy, sediment cores from the Salar de Atacama (Bobst et al., 2001) reveal a perennial, shallow, saline lake during the mid-Holocene (6.2-3.5 ka) based upon the presence of primary halite. The salar is a large (3,000 km²) playa located at the base of the Andes (about 120 km southeast of Calama) fed by groundwater recharged in the Altiplano. However, there is great uncertainty with regards to the $^{234}U/^{230}Th$ date (5.4 ± 2.7 ka) used to make the interpretation of a mid-Holocene lake. Although this interpretation coincides with the deposition of Unit C at Río San Salvador and other in-stream wetland locales, the imprecision of this $^{234}U/^{230}Th$ date makes it difficult to compare the paleolake and in-stream wetland records.

**Mechanisms for sustained mega-drought conditions**

The impact of ENSO variability on Holocene climactic fluctuations is difficult to relate to the east-central Atacama, for ENSO is defined oceanic-atmospherically (Trenberth, 1997) though it has far reaching global teleconnections. However, many studies regarding both the intensity and frequency of ENSO throughout the Holocene have been linked with regional paleoclimatic proxies. These studies are often conflicting, and the sheer variety of independent proxies has complicated comparisons between terrestrial and marine records.

Palmer and Pearson (2003) document La Niña-like conditions derived from an increase in pCO₂ levels in the late Pleistocene (16-11 ka B.P.) from boron isotopes. These La Niña-like conditions correspond with the deposition of in-stream wetland deposits in the Atacama (Unit B₁) (Quade et al., 2008). The inferred La Niña-like conditions persisting from 9.0-5.8 ka B.P resulting from analyses of mollusks at archeological sites
in Peru (Sandweiss et al., 2001) conflicts with a drop in the paleolake level of Lake Titicaca (Baker et al., 2001) and a period of incision reflected in the in-stream wetland record (Figure 13). El Niño-like conditions during the mid-Holocene derived from sea catfish (Galeichthys peruvianus) otoliths off the Peruvian coast (Andrus et al., 2002) does not match a prolonged period of aggradation demonstrated in the in-stream wetland record (which would imply La Niña-like conditions). However, Clement et al., (2000) indicate a drastic reduction of ENSO strength during the mid-Holocene through modeling, which is supported by evidence from Paupa New Guinea corals (Tudhope et al., 2001) and lake sediments from Ecuador (Moy et al., 2002). During this reduction in ENSO, Unit C in-stream wetland deposits were deposited at Río San Salvador and other locales, implying wetter (La Niña-like) conditions. Moy et al., (2002) demonstrate the strengthening of El Niño through the Holocene, which may be a primary driver of mega-droughts between the deposition of Units C, D1, D2, and the present (Figure 13).

These discrepancies between various proxies of ENSO variability may be subject to the annual magnitude and spacing of El Niño events. Some proxies may be skewed to record only large annual El Niño or La Niña related events. Even as continuous the in-stream wetland record is, it is impossible to preserve yearly fluctuations in ENSO variability. Pacific Decadal Oscillation (PDO) may present an alternative to ENSO variability as being the primary driver of Holocene climate change. PDO has a spatial distribution similar to that of ENSO but is persistent over much longer time scales (decadal to centennial) (Ruddiman, 2008). PDO events also see warm sea-surface temperatures in the eastern Pacific, potentially setting up an El Niño-like climatic regime with reduced precipitation in the Altiplano and eastern Atacama and the potential of sustained drought.

CONCLUSION

The Río San Salvador record indicates the presence of mega-droughts revealed by unconformities marking erosive periods between unit filling. As the regional water table is lowered during these mega-droughts, the vegetation armoring the active channel is removed, promoting incision by groundwater sapping. Stream power is not related to these processes, as a lack of flow velocity (due to a shallow gradient) and discharge
events (due to a small catchment area and lack of substantial local rainfall events) is apparent within the study area. The radiocarbon data express a record of incision and deposition of the in-stream wetland deposits solely based upon base level change. Periods of incision from 9.9-6.4 ka B.P., 3.5-2.7 ka B.P., 1.0-0.95 ka B.P., and 0.3 ka B.P. represent past mega-droughts.

By comparing the in-stream wetland record with other regional proxies, it is apparent that these deposits reflect past changes in climate throughout the Holocene. The congruity of the other regional in-stream wetland studies, as well as independent studies (such as paleospring deposits, vegetation found in rodent middens, and lake level fluctuations) confirm the response of the in-stream wetland system at Río San Salvador to changes in climate. The sensitivity of the in-stream wetland record may be valuable to determine the causes of sustained drought. The driver of these changes throughout the Holocene appears to be linked to the ENSO cycle, with the increased presence of El Niño years leading to sustained periods of aridity and mega-droughts. However, discrepancies in ENSO proxy data make it difficult to assume ENSO as the primary driver of Holocene climate change. Pacific Decadal Oscillation may be an alternative explanation for the persistence of these mega-droughts.

It is important to understand these past climatic drivers in order to predict the future of water resources in the central Atacama. The use of in-stream wetland deposits, such as the ones found at Río San Salvador, may provide the link from understanding past climate change to modeling future precipitation derived from ENSO or PDO variability.
REFERENCES


Table 1. Radiocarbon ages.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Sample</th>
<th>Station*</th>
<th>Lab Number</th>
<th>UTM Coord. - 1988 (Prov. S. Am. 1868)</th>
<th>Height (m)**</th>
<th>Material</th>
<th>$^1^3$C</th>
<th>$^1^4$C age (yr B.P.)</th>
<th>Cal. age (yr B.P.)</th>
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<td>16</td>
<td>AA79459</td>
<td>501057, 7517206</td>
<td>5.9</td>
<td>plant fragments</td>
<td>-18.5</td>
<td>500</td>
<td>35</td>
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<td>AA85617</td>
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<td>plant fragments</td>
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<td>25</td>
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<td>AA80175</td>
<td>500074, 7516994</td>
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<td>plant fragments</td>
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<td>35</td>
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<tr>
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<td>27</td>
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<td>plant fragments</td>
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<td>25</td>
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<td>501567, 7517251</td>
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<td>plant fragments</td>
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<td>30</td>
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<td>501927, 7517872</td>
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<td>plant fragments</td>
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<td>501030, 7517093</td>
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<td>15</td>
<td>11</td>
<td>AA79465</td>
<td>502444, 7517958</td>
<td>2.5</td>
<td>plant fragments</td>
<td>-24.7</td>
<td>1055</td>
<td>35</td>
</tr>
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<td></td>
<td>2</td>
<td>2</td>
<td>AA79462</td>
<td>500181, 7516411</td>
<td>1.4</td>
<td>plant fragments</td>
<td>-24.2</td>
<td>630</td>
<td>25</td>
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| Da   | 18     | 11       | AA80192    | 502444, 7517958                      | 11.9         | plant fragments | -8.8  | 1370 | 35 | 1290 | 15 |
|      | 44     | 24(11)   | AA79460    | 501066, 7517422                      | 10.7         | plant fragments | -20.8 | 1435 | 25 | 1325 | 20 |
|      | 3D+150 | 7        | AA85610    | 501153, 7517251                      | 9.7          | plant fragments | -13.4 | 1180 | 30 | 1090 | 45 |
|      | 13     | 9(11)    | AA79472    | 502008, 7517639                      | 9.6          | plant fragments | -12.6 | 2280 | 30 | 2310 | 40 |
|      | 26     | 15(7)    | AA79467    | 501030, 7517053                      | 9.5          | plant fragments | -14.0 | 1346 | 30 | 1280 | 15 |
|      | 2D+9.2 | 17       | AA85614    | 501598, 7517473                      | 9.2          | plant fragments | -16.7 | 1296 | 35 | 1245 | 40 |
|      | 3D+0   | 7        | AA85615    | 501153, 7517251                      | 8.2          | plant fragments | -25.8 | 2535 | 30 | 2685 | 65 |
|      | 6      | 5        | AA79463    | 500387, 7516534                      | 5.9          | plant fragments | -23.1 | 2390 | 40 | 2390 | 75 |
|      | 21     | 19(5)    | AA79465    | 502520, 7516506                      | 4.9          | plant fragments | -11.4 | 2210 | 30 | 2230 | 60 |
|      | 37     | 22(5)    | AA79465    | 502520, 7516506                      | 4             | plant fragments | -13.6 | 2610 | 30 | 2740 | 15 |

| C    | 36     | 22(13)   | AA79476    | 500529, 7516684                      | 11.7         | plant fragments | -13.1 | 3330 | 45 | 3560 | 60 |
|      | 23     | 13       | AA79466    | 500428, 7516625                      | 11.7         | plant fragments | -23.9 | 3625 | 30 | 3810 | 50 |
|      | 8      | 6(23)    | AA80188    | 501104, 7517152                      | 11.3         | sediments       | -13.1 | 3290 | 30 | 3505 | 45 |
|      | 40     | 23       | AA80190    | 500202, 7516994                      | 10.7         | sediments       | -22.9 | 3360 | 30 | 3600 | 40 |
|      | 4      | 3        | AA80187    | 500287, 7516466                      | 10.7         | sediments       | -23.8 | 3360 | 40 | 3600 | 50 |
|      | 20     | 19(13)   | AA8466     | 500252, 7516506                      | 10.2         | plant fragments | -21.9 | 4330 | 35 | 4870 | 35 |
|      | 36     | 13       | AA79475    | 500428, 7516625                      | 10.2         | plant fragments | -20.3 | 4330 | 35 | 4960 | 70 |
|      | 17     | 11       | AA80193    | 502444, 7517958                      | 9.4          | sediments       | -20.2 | 3360 | 50 | 3600 | 60 |
|      | 10     | 8(13)    | AA80191    | 501324, 7517362                      | 9.3          | plant fragments | -12.8 | 5380 | 30 | 6195 | 45 |
|      | 10     | 8(13)    | AA79464    | 501324, 7517362                      | 9.3          | plant fragments | -12.8 | 5380 | 40 | 6270 | 30 |
|      | 1      | 1        | AA80185    | 500006, 7516292                      | 4.7          | sediments       | -22.4 | 4690 | 45 | 5420 | 75 |
|      | 12     | 9(1)     | AA80189    | 500208, 7517839                      | 3.1          | sediments       | -22.8 | 9860 | 35 | 6425 | 35 |

| Bn   | 38     | 14(3)    | AA79477    | 500744, 7516894                      | 8.7          | plant fragments | -12.2 | 8870 | 60 | 9985 | 145 |
|      | 3      | 3        | AA80186    | 500287, 7516466                      | 4.2          | sediments       | -16.5 | 8830 | 40 | 9900 | 120 |
|      | 5      | 4(3)     | AA79470    | 500341, 7516493                      | 3.2          | plant fragments | -12.4 | 9425 | 40 | 10650 | 55 |
|      | 7      | 6(2)     | AA79471    | 501104, 7517152                      | 2.3          | plant fragments | -13.8 | 9660 | 40 | 11095 | 95 |

Notes:
* (parentheses) indicate corresponding stratigraphic column
** above modern stream level
Table 2. Amino acid racemization results.

<table>
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<tr>
<th>UAL</th>
<th>Site</th>
<th>14C age</th>
<th>material</th>
<th>DL Asp</th>
<th>DL Glu</th>
<th>DL Ser</th>
<th>DL Ala</th>
<th>L Asp</th>
<th>L Ser</th>
<th>L Ser/L Asp</th>
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<tr>
<td>7033 A</td>
<td>RSS1</td>
<td>510</td>
<td>single snail</td>
<td>0.240</td>
<td>0.114</td>
<td>0.266</td>
<td>0.151</td>
<td>4293</td>
<td>856</td>
<td>0.2</td>
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<tr>
<td>7033 B</td>
<td>14C = 510</td>
<td>510</td>
<td>single snail</td>
<td>0.237</td>
<td>0.101</td>
<td>0.265</td>
<td>0.157</td>
<td>5179</td>
<td>922</td>
<td>0.2</td>
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<tr>
<td>7033 C</td>
<td>510</td>
<td>single snail</td>
<td>0.238</td>
<td>0.104</td>
<td>0.259</td>
<td>0.121</td>
<td>6596</td>
<td>877</td>
<td>0.1</td>
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<tr>
<td>7033 D</td>
<td>510</td>
<td>single snail</td>
<td>0.216</td>
<td>0.088</td>
<td>0.217</td>
<td>0.114</td>
<td>7813</td>
<td>1037</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>7033 E</td>
<td>510</td>
<td>single snail</td>
<td>0.210</td>
<td>0.084</td>
<td>0.180</td>
<td>0.117</td>
<td>4999</td>
<td>949</td>
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</table>

average 0.228 0.088 0.237 0.132
stdev 0.014 0.012 0.038 0.020
CV 6.2 12.4 16.9 16.4

| 7034 A | RSS2 | 935     | single snail | 0.263  | 0.094  | 0.219  | 0.129  | 8398  | 1417  | 0.2         |
| 7034 B | 14C = 935 | 935     | single snail | 0.265  | 0.093  | 0.203  | 0.111  | 6739  | 1251  | 0.2         |
| 7034 C | 935     | single snail | 0.267  | 0.095  | 0.277  | 0.117  | 5181  | 977   | 0.2         |
| 7034 D | 935     | single snail | 0.277  | 0.091  | 0.263  | 0.119  | 5080  | 1026  | 0.2         |
| 7034 E | 935     | single snail | 0.261  | 0.100  | 0.292  | 0.143  | 7981  | 1169  | 0.1         |

average 0.268 0.087 0.261 0.124
stdev 0.010 0.006 0.038 0.010
CV 6.9 6.0 16.2 16.1

| 7035 A | RSS3 | 2390    | single snail | 0.378  | 0.121  | 0.482  | 0.201  | 2022  | 366   | 0.2         |
| 7035 B | 14C = 2390 | 2390    | single snail | 0.421  | 0.125  | 0.477  | 0.189  | 1536  | 411   | 0.3         |
| 7035 C | 2390   | single snail | 0.380  | 0.145  | 0.489  | 0.207  | 2138  | 439   | 0.2         |
| 7035 D | 2390   | single snail | 0.377  | 0.091  | 0.263  | 0.119  | 5080  | 1026  | 0.2         |
| 7035 E | 2390   | single snail | 0.385  | 0.143  | 0.506  | 0.221  | 1337  | 335   | 0.3         |

average 0.401 0.193 0.601 0.206
stdev 0.024 0.011 0.030 0.012
CV 5.0 8.0 16.0 6.8

| 7036 A | RSS4 | 5420    | single snail | 0.416  | 0.125  | 0.591  | 0.217  | 1648  | 395   | 0.2         |
| 7036 B | 14C = 5420 | 5420    | single snail | 0.396  | 0.113  | 0.425  | 0.183  | 1926  | 513   | 0.3         |
| 7036 C | 5420   | single snail | 0.435  | 0.128  | 0.562  | 0.220  | 1557  | 401   | 0.3         |
| 7036 D | 5420   | single snail | 0.429  | 0.164  | 0.463  | 0.272  | 1313  | 362   | 0.3         |
| 7036 E | 5420   | single snail | 0.404  | 0.114  | 0.515  | 0.209  | 2550  | 628   | 0.2         |

average 0.418 0.129 0.611 0.200
stdev 0.016 0.021 0.088 0.032
CV 3.9 6.1 12.4 14.7

| 7037 A | RSS5 | 34      | single snail | 0.612  | 0.396  | 0.327  | 0.664  | 1551  | 79    | 0.1         |
| 7037 B | no age   | single snail | 0.547  | 0.264  | 0.619  | 0.523  | 5077  | 89    | 0.0         |
| 7037 C | 34      | single snail | 0.523  | 0.360  | 0.263  | 0.664  | 1222  | 22    | 0.0         |
| 7037 D | 34      | single snail | 0.600  | 0.479  | 0.261  | 0.741  | 1227  | 72    | 0.1         |
| 7037 E | 34      | single snail | 0.609  | 0.469  | 0.320  | 0.741  | 1977  | 94    | 0.0         |

average 0.678 0.384 0.568 0.688
stdev 0.041 0.088 0.148 0.087
CV 7.0 22.3 41.7 13.0

| 7038 A | RSS6 | RSSA12.8 | single snail | 0.626  | 0.479  | 0.273  | 0.779  | 1000  | 69    | 0.1         |
| 7038 B | no age   | single snail | 0.608  | 0.389  | 0.311  | 0.705  | 1112  | 95    | 0.1         |
| 7038 C | RSSA12.8 | single snail | 0.597  | 0.393  | 0.341  | 0.700  | 1389  | 119   | 0.1         |
| 7038 D | RSSA12.8 | single snail | 0.624  | 0.406  | 0.257  | 0.762  | 914   | 81    | 0.1         |
| 7038 E | RSSA12.8 | single snail | 0.655  | 0.553  | 0.236  | 0.861  | 812   | 45    | 0.1         |

average 0.620 0.444 0.284 0.761
stdev 0.025 0.071 0.042 0.098
CV 4.0 16.0 14.9 8.8
Figure 1. Map of South America with the locations of the Atacama Desert, central Andes, and city of Calama, Chile.
Figure 2. Aerial photograph of the Calama, Chile area, with the Río San Salvador watershed and study area outlined.
Figure 3. Map of Río San Salvador with stratigraphic units, station locations, and cross section locations indicated.
Figure 4. Selected stratigraphic sections from Río San Salvador, Chile.
Figure 5. Photograph of a modern in-stream wetland at Río San Salvador.
Figure 6. Photograph of an in-stream wetland deposit. Note the alternating layers of tufa and silt.
Figure 7. Photographs of organic-rich layers at Río San Salvador with carbonized plant fragments.
Figure 8. D/L aspartic acid (Asp) and D/L glutamic acid (Glu) values plotted for six gastropod samples collected at Rio San Salvador. The sample ages are expressed in years B.P.
Figure 9. Generalized cross-section at Rio San Salvador including selected radiocarbon ages, expressed in years B.P.
Figure 10. Five valley cross-sections at Río San Salvador, Chile. See Figure 3 for cross-section locations.
Figure 11. Photomosaic of exposed sections of Units A, C, D₁, and D₂ with associated stratigraphic columns and radiocarbon ages at Station 11. The heights above the modern channel are expressed in meters, and radiocarbon ages are expressed in years B.P. Also refer to Figure 10, cross-section E-E’.
Figure 12. Radiocarbon ages (height above modern stream level) through the Holocene at Rio San Salvador. The best-fit lines demonstrate rising water tables through unit deposition, and the white areas represent periods of inferred mega-droughts.
Figure 13. Comparison of lake level, in-stream wetland, rodent midden, and spring deposit records in the Atacama Desert. The shaded portions indicate periods of deposition.
Location: Rio San Salvador, Chile
Station 1, Unit C
Date: 7/20/07

**Unit C**

- 7.0: pink and yellow tufa
- 6.5: interbedded silt and tufa
- 6.0: well-sorted yellow silt
- 5.5: pink tufa
- 5.0: organic material
- 4.5: yellow silt with thin clay layer at top
- 4.0: yellow silt with interbedded gravels
- 3.5: pink and brown silt

S1 - 5,420±75
S12 - 6,425±35
| Location: Río San Salvador, Chile | Station: D2, Unit D2 | Date: 7/28/17 |

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<tr>
<th>Scale (m)</th>
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<tr>
<td>2.0</td>
<td>pink silt with numerous root traces</td>
</tr>
<tr>
<td>1.5</td>
<td>rounded and imbricated gravel</td>
</tr>
<tr>
<td>1.0</td>
<td>organic-rich layer</td>
</tr>
<tr>
<td></td>
<td>poorly cemented tufa</td>
</tr>
<tr>
<td></td>
<td>tan silt with numerous root traces</td>
</tr>
</tbody>
</table>

S-2 535 ± 15
Unit C
- Pink tufa with interbedded silt and organic material
- Poorly developed organic material
- Well-cemented pink tufa

Unconformity

9.5
- Brown and pink silt with interbedded thin tufa
- Well-cemented silt

8.5
- Variegated silt with interbedded thin organic-rich layers
- Pink tufa
- Thick layer of organic material

Unit B3
- White and gray silt with numerous root casts
- Pink silt
- Well-sorted fine sand
- Organic material

S4 - 3,600±50
S3 - 9,900±120

S5 - 10,650±55
S7 - 11,095±95
Unit D:

- 7.0: poorly cemented tufa, cross-bedded well-sorted sand
- 6.5: brown and white silt with root traces
- 6.0: thick organic-rich layer, poorly cemented tufa, white silt with root traces
- 5.5: poorly cemented tufa
- 5.0: poorly cemented tufa
- 4.5: brown and pink silt with root traces
- 4.0: poorly cemented tufa
- 3.5: cross-bedded sand, poorly cemented tufa
- 3.0: poorly cemented tufa

Radiocarbon dates:
- S6: 2,390 ± 75
- S21: 2,230 ± 60
- S37: 2,740 ± 15
silty sand and gravel
silty fine sand
massive silt
coarse sand
massive silt with diatomite at base
silty fine sand
organic-rich material
interbedded diatomite and tufa
sandy silt
interbedded diatomite and tufa
organic-rich material

S3D+150-1,090±45
S26-1,280±15
S3D+0-2,685±65
silt and interbedded lens-shaped gravel

brown silt
diatomite
dark gray sand
diatomite
fine brown sand
variegated silt and sand
diatomite
interbedded silt, sand, and gravel
diatomite
pink silt and interbedded gravel
<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.0</td>
<td>well-cemented tufa</td>
</tr>
<tr>
<td>13.5</td>
<td>diatomite</td>
</tr>
<tr>
<td>13.0</td>
<td>well-cemented tufa with interbedded diatomite</td>
</tr>
<tr>
<td>12.5</td>
<td>medium-grained sand</td>
</tr>
<tr>
<td>12.0</td>
<td>diatomite with numerous root voids</td>
</tr>
<tr>
<td>11.5</td>
<td>medium-grained sand</td>
</tr>
<tr>
<td>11.0</td>
<td>diatomite</td>
</tr>
<tr>
<td>10.5</td>
<td>coarse gravel with interbedded cross-bedded</td>
</tr>
<tr>
<td>10.0</td>
<td>sand</td>
</tr>
<tr>
<td>9.5</td>
<td>tan sand and silt</td>
</tr>
<tr>
<td>9.0</td>
<td>dark brown sand and silt</td>
</tr>
<tr>
<td>8.5</td>
<td>sand and gravel</td>
</tr>
<tr>
<td>8.0</td>
<td>trough cross-bedded sand</td>
</tr>
<tr>
<td>7.5</td>
<td>pink silt</td>
</tr>
<tr>
<td>7.0</td>
<td>trough cross-bedded sand</td>
</tr>
<tr>
<td>6.5</td>
<td>pink silt</td>
</tr>
<tr>
<td>6.0</td>
<td>trough cross-bedded sand</td>
</tr>
<tr>
<td>5.5</td>
<td>pink silt</td>
</tr>
<tr>
<td>5.0</td>
<td>trough cross-bedded sand</td>
</tr>
<tr>
<td>4.5</td>
<td>gravel and silt</td>
</tr>
<tr>
<td>4.0</td>
<td>diatomaceous silt</td>
</tr>
<tr>
<td>3.5</td>
<td>cross-bedded sand</td>
</tr>
<tr>
<td>3.0</td>
<td>gravel and silt</td>
</tr>
</tbody>
</table>

Location: Rio San Salvador, Chile
Station: 11, Unit A
Date: 7/21/07
<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.0</td>
<td>organic-rich layer</td>
</tr>
<tr>
<td>11.5</td>
<td>repeating layers of thin organics and variegated silt</td>
</tr>
<tr>
<td>11.0</td>
<td>each layer is approximately 8 cm thick</td>
</tr>
<tr>
<td>10.5</td>
<td></td>
</tr>
<tr>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>9.5</td>
<td>unconformity</td>
</tr>
<tr>
<td>9.0</td>
<td>organic-rich layer</td>
</tr>
<tr>
<td>8.9</td>
<td>pink silt</td>
</tr>
<tr>
<td>8.0</td>
<td>poorly sorted yellow-tan sand</td>
</tr>
<tr>
<td>7.5</td>
<td>pink silt</td>
</tr>
<tr>
<td>7.0</td>
<td>very thin organic-rich layer</td>
</tr>
<tr>
<td></td>
<td>variegated silt</td>
</tr>
</tbody>
</table>

- Unit D:
  - S18 - 1,290±15
  - S44 - 1,325±20
  - S13 - 2,310±40
  - S17 - 3,600±60
Location: Rio San Salvador, Chile
Station 11, Unit D₂
Date: 7/21/07

Scale (m)
Lithology

Unit D₂

6.0
variegated silt

5.5
thick organic-rich layer

5.0
pink silt and sand

4.5
organic-rich layer
trough cross-bedded sand
variegated silt
well-sorted sand

4.0
variegated silt

3.5
thick organic-rich layer

3.0

2.5

S15- 955±25

S16- 510±10
well cemented tufa interbedded with thinner silty layers
pink silt with interbedded tufa
Unit B₃
pink silt with interbedded tufa
very hard organic-rich layer
gravel and silt
Location: Rio San Salvador, Chilé  
Station: 53, Unit C  
Date: 7/29/67

- Unit C

- Pink tufa with interbedded pink silt
- White silt with thin interbedded organic-rich layers
- Tufa with interbedded silt
- Gray silt with thick organic-rich layer at the top
- Silt and gravel

Layer: 12.0

- S36: 3.560±60
- S23: 3.010±50

Layer: 11.5

Layer: 11.0

Layer: 10.5

Layer: 10.0

Layer: 9.8

Layer: 9.0

- S29: 4.870±35
- S35: 4.950±70

- S10: 6.195±45
  6.270±30
Unit D$_2$: coarse sand with gravel lenses, lens of woody debris with organics, fine pink sand.
<table>
<thead>
<tr>
<th>Scale (m)</th>
<th>Lithology</th>
<th>Unit D₂</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
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<td></td>
</tr>
<tr>
<td>4.0</td>
<td></td>
<td></td>
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<td>4.5</td>
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<td>5.5</td>
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<td>6.0</td>
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<td>6.5</td>
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</tr>
<tr>
<td><strong>6.0</strong></td>
<td><strong>Unit D₂</strong></td>
<td><strong>S28- 525±15</strong></td>
<td>silt with interbedded organics</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>tufa</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fine sand</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>pink silt with interbedded organics</td>
</tr>
<tr>
<td></td>
<td><strong>Unit D₂</strong></td>
<td></td>
<td>yellow and pink silt with numerous root voids</td>
</tr>
</tbody>
</table>

**Notes:**
- Unit D₂ contains a variety of sediment types, including silt with interbedded organics, tufa, fine sand, and pink silt with interbedded organics.
- The yellow and pink silt with numerous root voids is present at the bottom of the section.
<table>
<thead>
<tr>
<th>Scale isp</th>
<th>Lithology</th>
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</thead>
<tbody>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>silt with numerous root voids</td>
</tr>
<tr>
<td></td>
<td>diatomite with organic-rich material</td>
</tr>
<tr>
<td></td>
<td>fine sand with numerous root voids</td>
</tr>
<tr>
<td></td>
<td>interbedded diatomite, silt, and tufa</td>
</tr>
</tbody>
</table>

**Unit D**

S2C+9.2- 1,245±40
<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Lithology</th>
<th>Comments</th>
</tr>
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<tbody>
<tr>
<td>4.0</td>
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<td></td>
</tr>
<tr>
<td>4.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Unit D2**
  - Poorly developed tufa
  - Organic-rich sediments
  - Interbedded silt and diatomite
  - Gravel
  - Interbedded silt, diatomite, and organic-rich sediments
  - Gravel

- S2D+0.35-935±25
- S2D+1.5-510±10
- S9-660±15

**Location:** Río San Salvador, Chile

**Station 17, Unit D2**

**Date:** 6/30/63
Location: Río San Salvador, Chile  
Station 30, Unit D2  
Date: 7/21/07

Unit D2

- brown silt
- organic-rich layer
- brown silt
- pink silt with interbedded gravel
- fine brown sand

S18- 540±25  
S15- 510±10
Location: Río San Salvador, Chile  Station: 23  Unit: C  Date: 7/28/87

- **Unit C**
  - Pink silt with interbedded tufa
  - Organic-rich layer
  - Pink silt
  - Poorly cemented tufa
  - Diatomaceous silt with root traces

- **S8**: 3,505 ± 45
- **S40**: 3,600 ± 40