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Stable isotope constraints on the transport of water to the Andes between 22° and 26°S during the last glacial cycle

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Abstract

The modern climate over much of the Andes between 22° and 26°S is very dry. Dated sediment cores from desiccated lake beds contain saline deposits (salars) that have halite fabrics that indicate during previous, less arid climates saline lakes existed at Salar de Hombre Muerto (northwest Argentina, Andean plateau) and Salar de Atacama (northern Chile, west flank of Andes). Paleoclimate conditions are reconstructed from the stable isotope composition of paleo-saline lake waters trapped in fluid inclusions in lacustrine halite. Models of isotopic steady state are applied to estimate the isotopic composition of inflow (meteoric) water to the paleo-lake and paleo-atmospheric water vapor. The two salars' climate records differ. The timing of Atacama saline lakes is similar to lake level highstands on the Altiplano to the northeast with the deepest lake occurring between 24 and 19.8 ka. The modern meteoric water source for Atacama and the Central Andes is currently the tropical Atlantic, via the Amazon Basin, and stable isotopic evidence indicates the same source of water for the paleo-lakes in the Atacama. In contrast, to the southeast, at Hombre Muerto, the lakes that intermittently occupied the salar became progressively smaller since 45 ka. Water isotope composition today reflects atmospheric recycling by evaporation–condensation, as it did between 24 and 20 ka, whereas water transported to the earlier lakes does not indicate significant isotopic recycling. Using knowledge of modern-day atmosphere/oceanic circulation and forcing mechanisms, we hypothesize that the shifts in moisture transport to these Andean sites are directly tied to equatorial and South Atlantic atmospheric and oceanic surface circulation.

Keywords: South America; paleoclimate; precipitation; isotopes; salars

1. Introduction

The synchroneity of abrupt climate events identified in Greenland ice cores, North Atlantic deep sea sediments (Bond et al., 1993) and Antarctic ice cores (Bender et al., 1994) demonstrates that climate change can be propagated rapidly on a global scale. The similarity in timing of climate change events in the southern hemisphere to variability in northern hemisphere insolation has led to the hypothesis that long-term changes in cli-

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mate may originate in the northern hemisphere (Broecker et al., 1985; Broecker and Denton, 1989; Imbrie et al., 1992). These changes may be transmitted through the tropics via heat exchange associated with surface currents in the tropical Atlantic, and with the atmosphere. Alternatively, some global climate changes (such as the Younger Dryas) may be generated within the tropics (McIntyre and Molfino, 1996; Curry and Oppo, 1997; Hostetler and Mix, 1999; Cane, 1998; Clement et al., 2001; Charles et al., 2001; Yin and Battisti, 2001). However, in some areas of the southern hemisphere, notably in South America, the intensity of glaciation does not necessarily follow the timing or magnitude of northern hemisphere glacial activity (Clapperton et al., 1995; Espizua, 1999). The Pole–Equator–Pole transect of paleoclimate reconstruction in the Americas (PEP-1; Markgraf et al., 2000) is one of the growing data sets that is well suited to address the nature of inter-relations between northern and southern hemispheric climate change. A better understanding of how moisture transport and temperature shifted through glacial cycles is required in order to extract the forcing mechanisms from the climate records. The dual roles of moisture and temperature are especially evident in the large area of the South American continent that is semi-arid to arid (Bobst et al., 2001; Klein et al., 1999).

The majority of records of climate change that strive to reconstruct the isotopic composition of meteoric water use either oxygen or hydrogen, rarely both. Consequently, difficulties arise if only one isotope is measured because the effects of isotopic enrichment due to evaporation obscure the initial meteoric water composition. Exceptions to these records are those that are derived from analyses of the precipitation itself, such as ice cores, groundwaters and fluid inclusions. Ice-core records from mid- or low-latitude mountain glaciers tend to be short, extending at most to the last glacial maximum (LGM; e.g. Thompson et al., 1995). The longer records are restricted to the polar regions (Lorius et al., 1985; Dansgaard et al., 1993; Petit et al., 1999). Less continuous records can be extracted from dated groundwaters (e.g. Plummer, 1993). Paleoclimate records based on the isotopic analysis of both hydrogen and oxygen in fluid inclusions are rare (Horita, 1990; Yang et al., 1995). In this paper, a paleoclimate record has been produced from oxygen and hydrogen isotope compositions of lake waters trapped in fluid inclusions in halite over the last glacial cycle for two locations in South America, the Salar de Atacama in northern Chile and the Salar de Hombre Muerto in northwestern Argentina (Fig. 1). Isotope records are only available for relatively wet climate states, which represent roughly 50% of the time since 85 ka. Comparison of the isotopic composition of precipitation between these discrete wet climate states, and the modern dry state, may provide insights on the causes of the changes in the moisture budget in the arid section of the Andes.

2. Moisture in the southern tropics of South America

The three main precipitation regimes in South America are shown in Fig. 2. Moisture brought onto the continent from the Atlantic by the South Atlantic high and tropical easterlies produces summer precipitation in the tropics and subtropics of South America. Heating leads to intense convection over the Amazon Basin and rainout effects are reflected in the isotopic composition of precipitation over the annual cycle (Rozanski et al., 1993). Evapotranspiration across the Amazon Basin leads to a very small isotopic gradient from the coast inland to the base of the Andes (Gat and Matsui, 1991). Flow across the Amazon becomes northwesterly along the flanks of the Andes and orographic uplift of this air brings moisture onto the Altiplano. Isotope studies of snow in Bolivia and precipitation in northern Chile show that the source of precipitation is consistent with an Amazon source (Thompson et al., 1995, 1998; Aravena et al., 1999). The amount of moisture that reaches the crest of the Andes and the western edge of the Altiplano appears to be related to the strength of westerly flow: when westerly flow is strong, moist air from the east fails to reach the Andean crest (Garreaud, 1999). Moist air reaching the Altiplano helps sus-

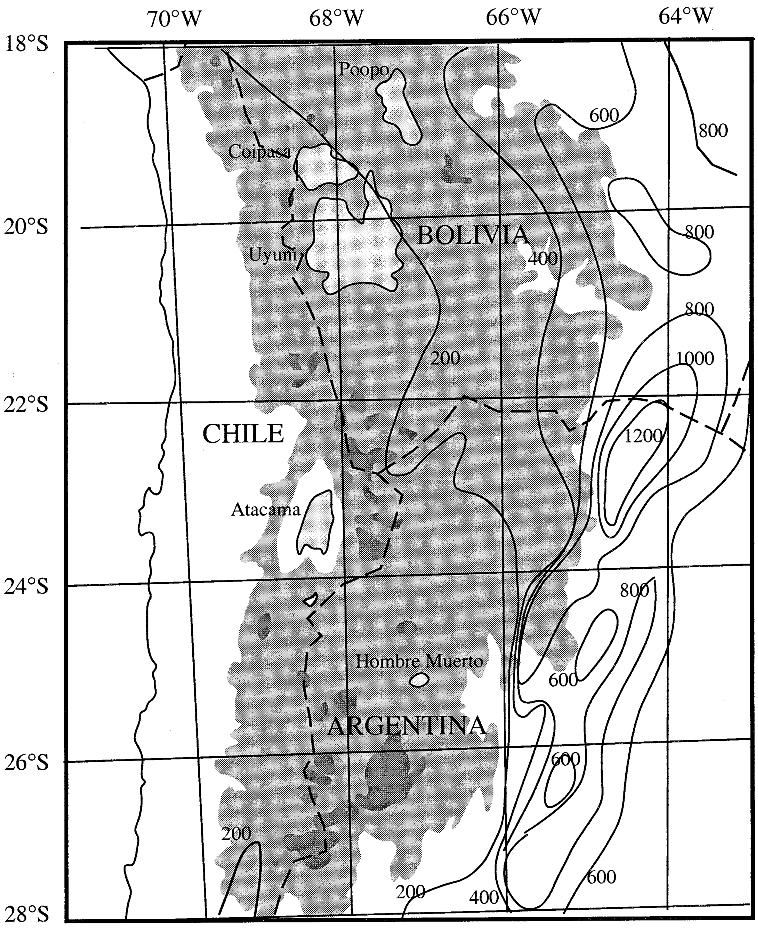

Fig. 1. Location of the salars of Hombre Muerto and Atacama in the central western part of South America. The shaded sections are land areas over 3000 m and 4500 m elevation. Annual precipitation contours (mm/yr) from the WMO/UNESCO Climate Atlas for South America have been overlaid.

tain the second area of intense summer convection. Centered at 19°S, 65°W over the Central Andes, this feature is known as the Bolivian high (Lenters and Cook, 1997). Northward and southward shifts in position of the Bolivian high are affected by several climatological phenomena including ENSO events, extratropical cyclones and changes in the E–W position and intensity of the South Atlantic Convergence Zone (SACZ) (Lenters and Cook, 1999; Vuille, 1999).

The SACZ is a region of high precipitation. Its northern end is part of the precipitation system of the Amazon Basin and it runs diagonally off the southeast coast of the continent. Satellite images indicate that the SACZ exists throughout the year over the ocean, but only develops over the continent as the land is heated. Station data from sites influenced by the SACZ (e.g. Ascuncion and Salta) show that rainout effects dominate the isotopic composition of precipitation (IAEA/WMO, 2001). Unlike stations within the Amazon Basin, Salta and Ascuncion have greater seasonality in temperature. The isotopic composition of precipitation that falls during winter cannot be distinguished from summer precipitation.

South of the SACZ is a NW–SE-trending arid belt in which rainfall typically is less than 250 mm/yr. Precipitation increases during the winter to the south and west of this arid diagonal. The isotopic composition of precipitation varies ac-

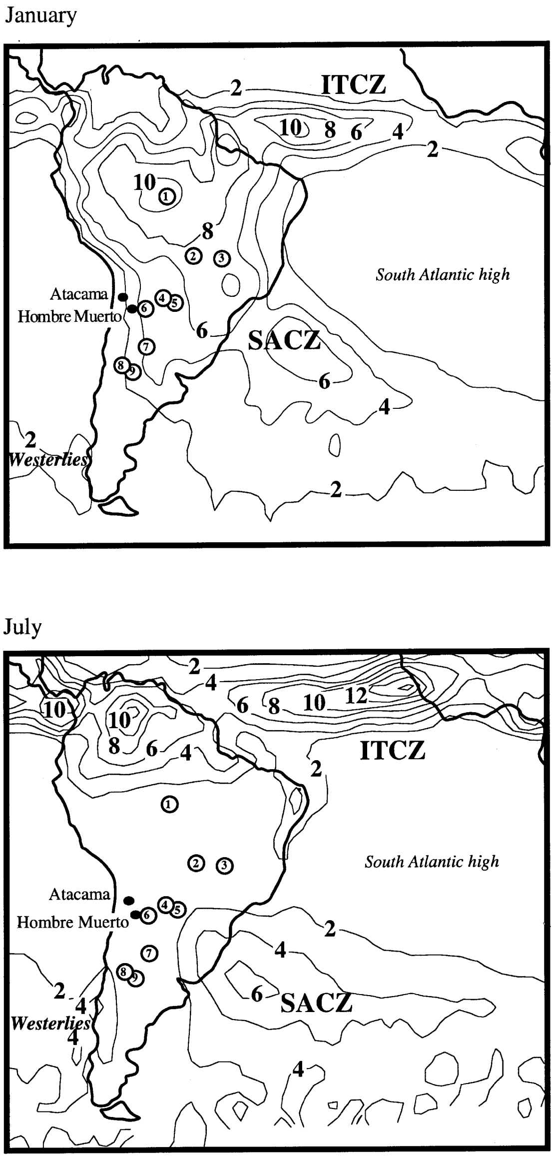

Fig. 2. The satellite-derived data of a 20-year average (1979–1998) precipitation field (PSG CLIM) for South America for January and July. Contours are in mm/day. The three major sources of precipitation are associated with the ITCZ, the SACZ and the westerlies. IAEA/GNIP stations are numbered: 1, Porto Velho; 2, Cuiaba; 3, Brasilia; 4, Asuncion; 5, Corrientes; 6, Salta; 7, Santiago del Estero; 8, La Suela; 9, Nacuñan.

cording to temperature, even in areas such as Nacuñan where monsoonal summer precipitation can equal winter precipitation (IAEA/WMO, 2001). Occasionally during the winter, cold air from the South Pacific travels northward as a front or cut-off into northern Chile and northwestern Argentina. While the cold fronts bring Pacific sourced moisture into the area, the cut-offs do not. Instead, the cold air interacts with moist Amazon sourced air to produce snow, particularly on the eastern side of the Andes and between 23 and 25°S (Vuille and Ammann, 1997; Vuille and Baumgartner, 1998).

The salars studied here are located in desert areas of the Andes with high surface albedos. Hombre Muerto is located 120 km west of Salta and at 2800 m higher elevation. It is influenced by occasional summer rain that reaches the Puna plateau (the extension of the Altiplano in Argentina) from the east, as well as rare winter snowfalls (meteorological data from Minera del Altiplano and Borax Argentina). Salar de Hombre Muerto (and Salta) lies within the area influenced by the SACZ. Salar de Atacama lies within the western foothills of the Andes at 2300 m elevation. The rare rainfalls are produced from moist air crossing the Andes from the Amazon, though it has been suggested that the Pacific may be a source of moisture for some low-altitude areas in northern Chile (Aravena et al., 1999). The vast majority of water reaching the Salar de Atacama does so through aquifers that recharge in the western cordillera of the Andes and possibly even further east (Magaritz et al., 1990).

3. Modern environments

3.1. Salar de Hombre Muerto

Salar de Hombre Muerto is located on the eastern side of the Puna plateau (25°20′S, 67°00′W) at 4100 m elevation. The salar lies in an internally drained basin and is surrounded by volcanoes and mountains that rise to elevations in excess of 5000 m. The 600 km^2 salar is located in the northern part of the 4000 km^2 drainage basin (Fig. 3). Much of the southern part of the basin is on

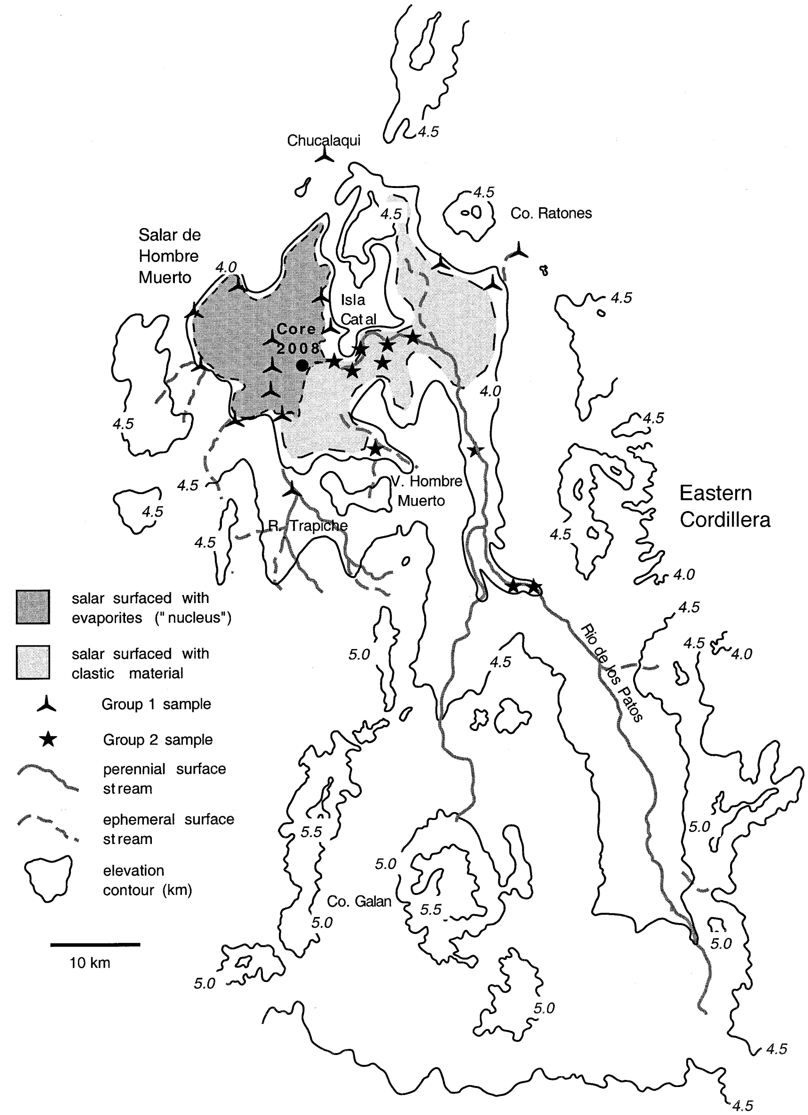

Fig. 3. Location of samples collected at Salar Hombre Muerto.

the flanks of Cerro Galan, a volcanic peak that reaches 5900 m. The principal stream feeding the salar, the Rio de los Patos, rises on Cerro Galan and has a catchment area of 2000 km^2. The Rio de los Patos empties into the eastern part of the salar where the clastic debris is trapped and, along with evaporite minerals, infills a relict valley to a depth of tens of meters (Jordan et al., 1999). Most years, the Rio de los Patos continues south and west to reach the western part of the salar that is filled with many hundreds of meters of halite (Jordan et al., 1999).

Meteorological data from two mines located next to Salar de Hombre Muerto show the following: (1) summer monthly mean temperature is 23°C, 15°C warmer than winter monthly means; (2) diurnal temperatures vary by 20–25°C; (3) precipitation occurs predominantly in the summer and falls as rain around the salar and as snow at higher elevations; (4) winter snowfalls are rare.

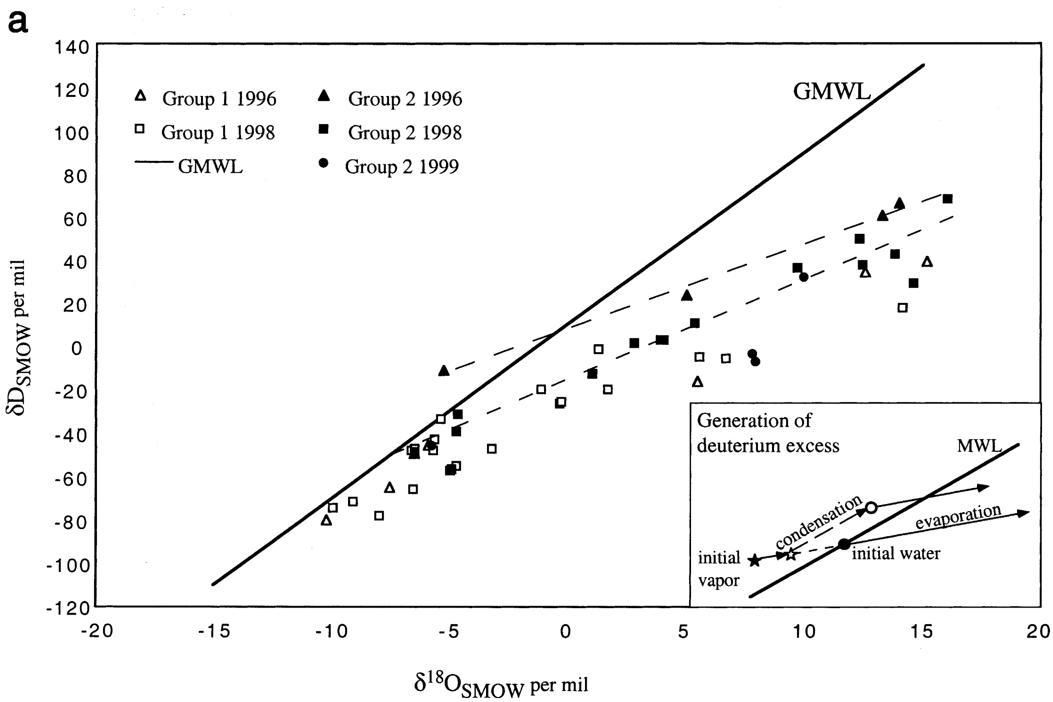

Fig. 4. (a) Stable isotope compositions (activities) of samples of fresh and saline surface waters, and subsurface brines at Salar Hombre Muerto. The inset shows how deuterium excesses can be generated by water recycling. ε is the isotopic enrichment factor for condensation. (b) 'String of lakes' isotope evaporation model for samples from the Rio de los Patos. Triangles are 1996 data and circles are 1998 data. The curves are fitted to the data from that year. Note that for $\delta^{18}O$, the curve fits data for both years. The input parameters for initial inflow waters and atmospheric water vapor and relative humidity (h') are given. The values in parentheses for the δD diagram are for 1996 data.

We collected samples of fresh and saline surface water and subsurface brine in March 1996, February 1998 and May 1999. Many of the samples have undergone isotopic evaporative enrichment. Streams and springs that rise in the northern and western parts of the drainage basin are isotopically the most depleted. The streams that were sampled in different years do not have different isotopic compositions. During the 3 years it was sampled the Rio de los Patos was isotopically more enriched than the other streams although its catchment has the highest elevation (Fig. 4a). Unlike the other streams in the northern and western part of the basin, the isotopic composition of the Rio de los Patos is variable from year to year. Samples collected from the Rio de los Patos in 1996 that have undergone little evaporation (based on chemical composition and conductivity) have high deuterium excess (d_{xs}, where $d_{xs} = \delta D - 8\delta^{18}O$) of +30. High deuterium excess in precipitation in arid areas is not uncommon and occurs when evaporation occurs in low-humidity environments; the classic example is precipitation in the eastern Mediterranean region (Gat and Carmi, 1970). Re-evaporation of surface water in low-humidity environments also creates vapor masses with high d_{xs}. For example, mountain fog in northern Kenya has high d_{xs}, and Ingraham and Matthews (1988) explained this feature through the evaporation of surface waters in the hydrologically closed Chalbi desert to produce vapor that condenses onto vegetation in the surrounding mountains. A similar mechanism (though not involving fog) is plausible here. The limited surface waters from discharged groundwater and precipitation (most likely snowmelt), evaporate into a dry atmosphere that would have lost water vapor during orographic uplift

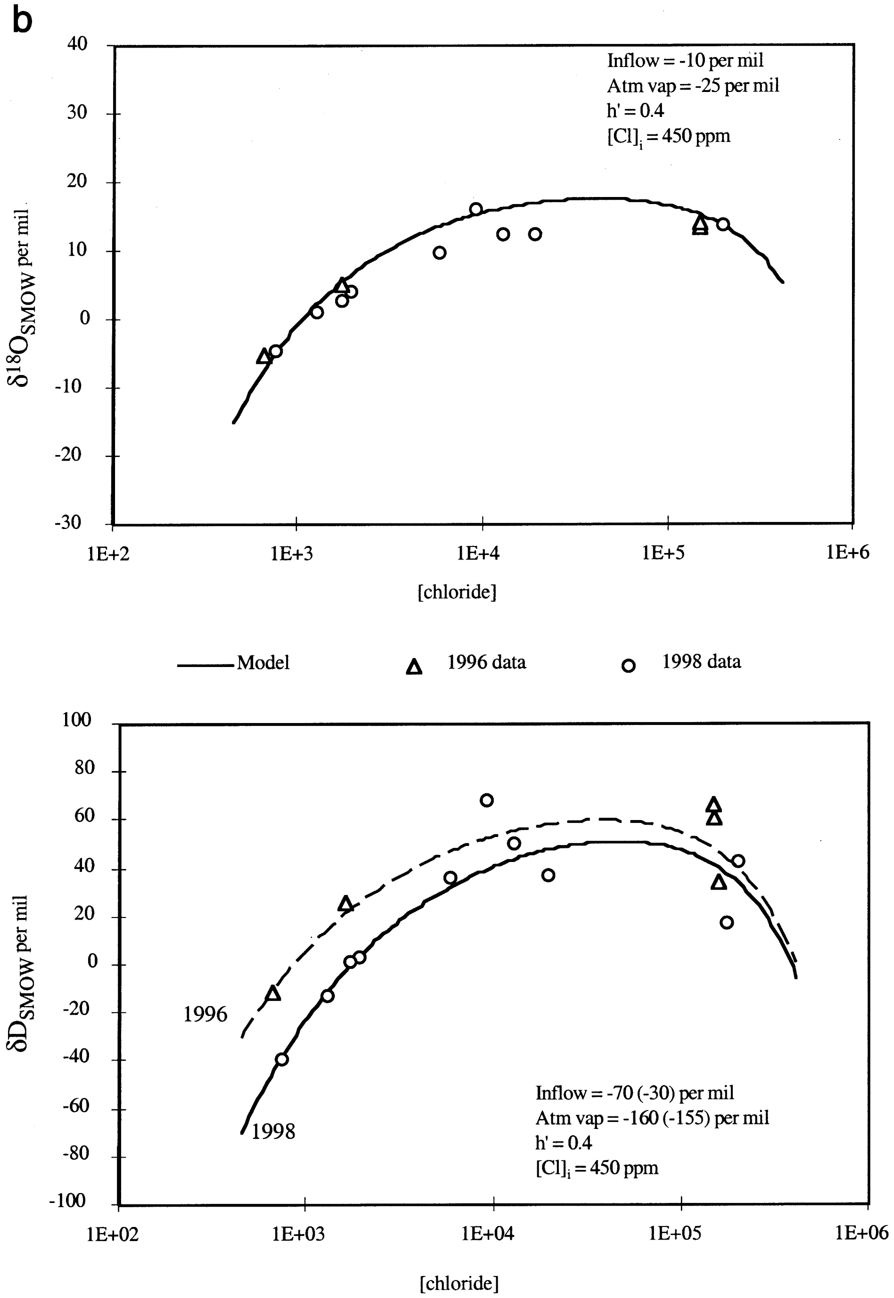

Fig. 4 (*Continued*).

over the eastern cordillera. This new vapor source mixes with existing vapor in the atmosphere and condenses at the elevation of the 0° isotherm. This precipitation has high d_{xs} and will be more enriched in ^{18}O and ^{2}H than the surface waters that evaporated.

Samples of atmospheric water vapor were not collected, but its isotopic composition can be estimated from evaporation models such as the string of lakes model (Gat and Bowser, 1991). The basic concept of this model is that a stream is divided into a series of reservoirs from which some water evaporates. The change in isotopic composition of the water as some of it evaporates is determined (Gonfiantini, 1986), the remaining water flows into the next reservoir. In order to estimate the amount of evaporation that takes place, the isotopic variation of the stream water is compared to a conservative tracer, and here we use chloride concentrations (Fig. 4b). Initial isotopic and chloride compositions are used from our data, and different values of atmospheric water vapor compositions and relative humidity are used to find those that give the best fit to data for the Rio los Patos (the most extensively sampled stream). The relative humidity is only allowed to vary between values (10–45%) that have been recorded at the salar by the two mining companies there (Minera del Altiplano and Borax Argentina). From both models we estimate that the atmospheric water vapor has a $\delta^{18}O$ composition of −25‰ and a δD composition of −155 to −160‰. The $\delta^{18}O$ composition is similar to estimates for the atmosphere vapor composition at Lake Titicaca (−25‰ to −27.4‰), 400 km to the north in the Andes (Fontes et al., 1979).

3.2. Salar de Atacama

Salar de Atacama in northern Chile (23°30′S, 68°30′W) lies in a closed drainage basin at 2300 m elevation at the western foot of the active volcanic arc of the Andean cordillera (Figs. 1 and 5). The total area of the drainage basin is about 15 000 km^2 and the salar is about 3000 km^2 in area. The northern, eastern and southern topographic edges of the drainage basin reach elevations of 6000 m, whereas the western side, bounded by the Cordillera Domeyko, just exceeds 3000 m. Marginal zones of the salar, which contain clastics and efflorescent evaporite crusts, represent 55% of the total area, and are dominantly in the northern sector. The southern part is dominated by the thick halite in the salar 'nucleus' (Bevacqua and Chong, 1995).

The largest surface stream, the Rio San Pedro, enters the salar from the north, as does the second-largest surface stream, the Vilama. Use of the water from these streams for irrigation accelerates evaporation, and these surface streams are of negligible importance as sources of water to the halite nucleus today. The slopes of the Andean volcanoes are covered by Pliocene ignimbrites and, closer to the salar, by alluvial fan deposits. These ignimbrite sheets contain many sheeted aquifers, including many perched aquifers, that recharge at high elevations in the Andes (Fritz et al., 1978). Water in these aquifers is old: bomb-produced tritium cannot be detected at these lower elevations and ^{14}C ages range from a few thousand to 20 000 years (Fritz et al., 1978). These aquifers provide the salar with two to five times more water than surface water sources, and the isotopic composition of the subsurface brines in the salar reflects these aquifers.

Mean annual precipitation on the center of the salar is about 10 mm/yr (personal communication SQM Salar). Greater precipitation falls on the Andean peaks to the north, east and south (100–350 mm/yr in the north) (Aravena et al., 1999; Fritz et al., 1978). Isotopic studies of precipitation in northern Chile show that the range is large. The local meteoric water line (LMWL) $\delta D = 7.8\delta^{18}O + 9.7$‰ is similar to that of the wet season Amazon and for the Bolivian and Peruvian Altiplano (Aravena et al., 1999). In April of 2000, we collected samples of recently fallen and older snow from the cordillera immediately east of the salar (C. Purico; Fig. 5) at an elevation between 4800 and 4900 m asl (above sea level). They have $\delta^{18}O$ values in the narrow range of −9.7 and −12.8‰ (Table 1 and Fig. 6).

The $\delta^{18}O$ composition of samples taken in 1998 from freshwater wells in the eastern alluvial fan deposits display a narrow range (−7 to −8‰; Fig. 6), similar to data collected during the 1970s (Fritz et al., 1978). The narrow range of isotopic values of samples from the freshwater wells reflects the long residence time of water in the aquifers that supply these wells. The isotopic composition of the freshwater wells lies close to the LMWL. The isotopic compositions of many of the freshwater springs are similar to the wells, but some lie below the LMWL because of evap-

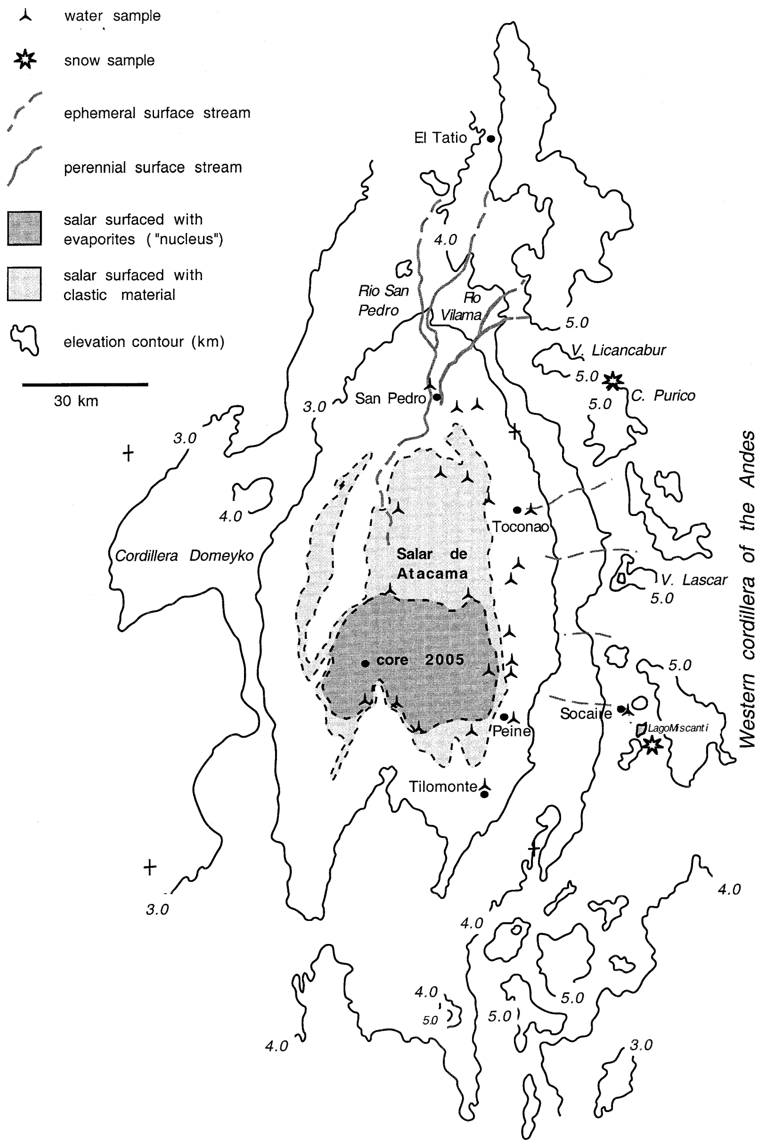

Fig. 5. Location of samples collected at Salar de Atacama.

Table 1
Snow samples from the Cordillera immediately to the east of Salar de Atacama

Location	Elevation (m)	Date	Time	Depth (cm)	$\delta^{18}O_{SMOW}$ (‰)	δD_{SMOW} (‰)
Honor	4800	4/7/00	15:50	3	−11.24	−64.8
Honor	4800	4/7/00	4:00	0	−10.28	−60.9
Saire bench	4900	4/9/00	15:30	8	−9.68	−45.6
Saire bench	4900	4/9/00	15:30	20	−12.84	−75.6
Saire bench	4900	4/9/00	15:30	75	−12.552	−74.4

orative enrichment. Where springs and their resulting streams were both sampled, it is possible to determine the slope of evaporation paths. Compositions of solitary evaporated samples may be projected back to the LMWL using these evaporation slopes.

The freshwater springs with the isotopically lightest compositions are located close to Socaire (Fig. 5). Immediately east of Socaire there are many high peaks, including the crest of Cordon de Puntas Negras, which exceeds 5600 m. Precipitation collected between 4000 and 4500 m elevation is isotopically much more depleted (Aravena et al., 1999) than any of the springs and wells we sampled. Isotopic enrichment of precipitation along the LMWL before it becomes groundwater must occur. Ablation and condensation processes within penitentes (ice pinnacles) proceeds along the LMWL (Peña, 1987), and the snow we collected may have already undergone isotopic enrichment during ablation, like the penitentes. Enrichment of 3–4‰ for $\delta^{18}O$ of meltwater relative to overlying ice was also measured on Volcan Parinacota at 5450 m to the north of Atacama (Peña et al., 1985). Alternatively, groundwater that is now being discharged was recharged under different climate conditions.

4. Fossil meteoric waters: fluid inclusion stable isotopes

Chemical sediments have the capability of preserving the water they precipitated from by trapping water in fluid inclusions. Halite either precipitates on the bottom of a halite-saturated pond or as rafts on the surface. In the former, the crystals form fluid inclusion-rich bands in stacked chevrons, in the latter, the crystals are cubes that have fluid inclusion-rich bands that are parallel to the crustal faces. Primary fluid inclusions are small (>1 to <100 μm) and cubic. Fluid inclusions that form from groundwater in voids below the surface are rare and are usually large and irregularly shaped. In addition, the halite is usually very clear because of the absence of the numerous small primary inclusions. Thus layers of lake-precipitated halite can be identified from

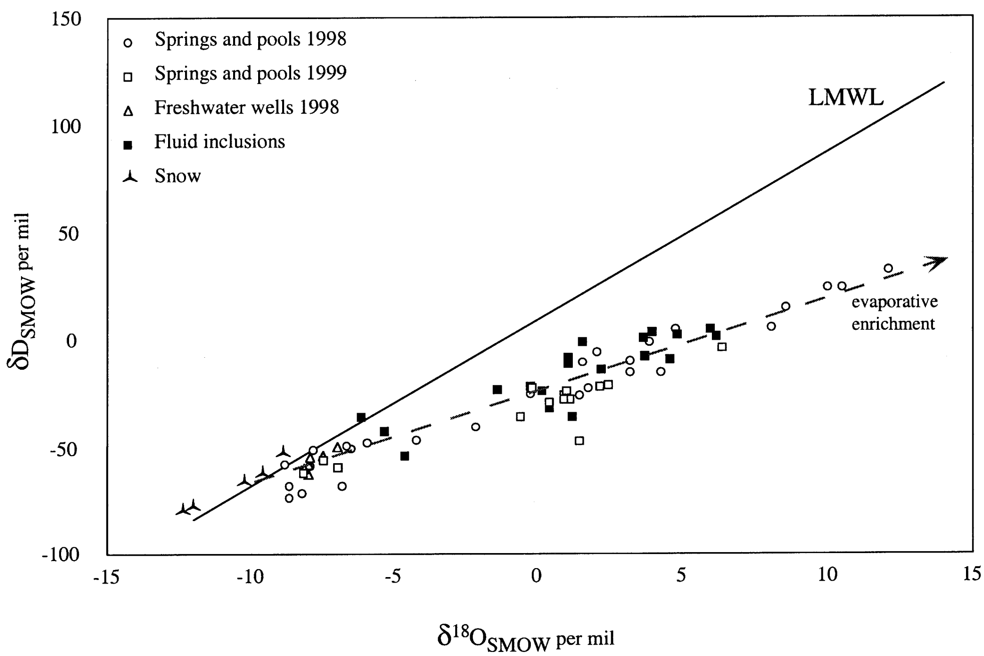

Fig. 6. Stable isotope compositions of samples of fresh and saline surface waters at Salar de Atacama. Data for fluid inclusions in primary lake halite are included and demonstrate the isotopic similarity for modern- and paleo-brines.

their textures and nature of the fluid inclusions. These primary halite layers can be dated using U–Th methods (Ku et al., 1998) and the records of moisture budgets (lake halite represent wet periods, clear secondary halite represent dry times) are very similar to conventional records based on local pollen records or carbonate layers in nearby, less arid basins (Baker et al., 2001a; Betancourt et al., 2000).

Samples of lake-precipitated halite were fragmented and pieces containing abundant fluid inclusions picked. Sections of these halite pieces that contained either detrital material or other evaporite minerals were cleaved and discarded. The halite was then washed with ethanol and dried overnight in an oven. The samples, weighing between 100 and 500 mg, were put into a quartz tube on a gas extraction line and evacuated. Once a stable vacuum had been obtained, the halite was melted and condensable gases collected under liquid nitrogen. The $\delta^{18}O$ composition of the water was determined using a micro-equilibration technique (Kishima and Sakai, 1984) and the δD on the same water measured using the zinc reduction method (Coleman et al., 1982). Measurements were made using a Finnigan Delta S mass spectrometer.

Models exist that use multiple samples from a single lake-halite layer to yield estimates of the isotopic composition of inflow water and atmospheric water vapor as well as an estimate of relative humidity (Horita, 1990). The model that is applied to our data is that of a terminal lake. The lake is maintained at isotopic steady state by the isotopic flux entering the lake being balanced by the isotopic flux out of the lake. The only flux out of a terminal lake is through evaporation. The equation describing isotopic steady state of a terminal lake is (Horita, 1990):

$$\delta_{ss} \approx (\alpha^*)^{-1}\{(\delta_A - \delta_{F(a)} - C_k)h' + \delta_{F(a)} + \varepsilon * + C_k\}$$

where α^{*-1} is the equilibrium isotope fractionation factor between the water vapor and liquid; h' is the water activity-normalized relative humidity; $\varepsilon = \varepsilon^* + \Delta\varepsilon$ where $\varepsilon^* = 1 - \alpha^*$ and $\Delta\varepsilon = (1-h')C_k$ where C_k is the kinetic isotope fractionation factor; δ_A is the isotopic composition of atmospheric water vapor and $\delta_{F(a)}$ the isotope activity ratio of the inflow water. We have used a temperature of 20°C to define α^*. This temperature is based on fluid inclusion homogenization temperatures that indicate no change in temperature at these locations for the last 80 ka (Bobst et al., 2001).

There are too many degrees of freedom to allow a unique solution of the above equation, but it is possible to compare regression lines of data from a single lake layer with the extremes of 0% and 100% h'. The intercepts of the data regressions with the locus lines of minimum δ_{ss} (when $h' = 100\%$) and maximum δ_{ss} ($h' = 0\%$) give δ_A and $\delta_{F(a)}$, respectively (Horita, 1990). The composition for the atmospheric moisture can be determined from the minimum δ_{ss} from the expression $\delta_{ss} = (\alpha^*)^{-1}(\delta_A + \varepsilon^*)$, and the inflow water from the maximum δ_{ss} using the expression $\delta_{ss} = (\alpha^*)^{-1}(\delta_{F(a)} + \varepsilon^* + C_k)$ (Horita, 1990). The ranges in modeled values for inflow waters and atmospheric water vapor are determined from 1σ error bands on the least-squares fit for data from Figs. 8 and 10. Humidity can be approximated from the relative position of data points to the extremes of normalized humidity (0% and 100%).

4.1. Salar de Hombre Muerto

Textural studies of the 40 m long core show that saline lakes occurred at numerous depths (Fig. 7). The thickness of the lake halite layer and the absence of any suggestions of desiccation in the lower layers indicate that these were the volumetrically largest lakes that occupied the salar. The isotopic composition of the trapped lake waters (Fig. 8) is less variable than surface water in the modern desiccated lake (Fig. 4a), which is consistent with models that indicate that the greatest isotopic enrichment occurs in isolated pools (Horita, 1990). The compositions of the trapped lake waters in the different lake horizons form three arrays shown in Fig. 8. The values of $\delta^{18}O$ and δD for the inflow waters and model-derived atmospheric water vapor for the three arrays are given in Table 2.

The first point to note is that any change in atmospheric water vapor compositions during the last 85 ka is beyond the capabilities of this method to detect. The second is that the inflow

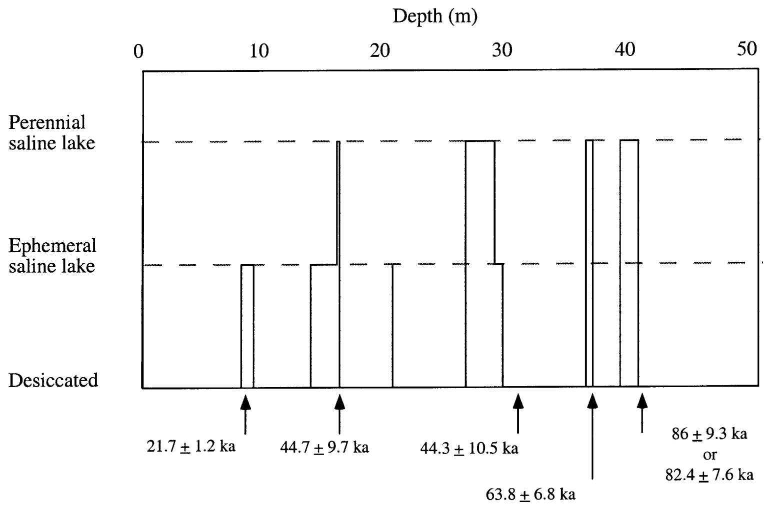

Fig. 7. Core 2008 stratigraphic column showing paleo-environments and U-series dates, Salar de Hombre Muerto.

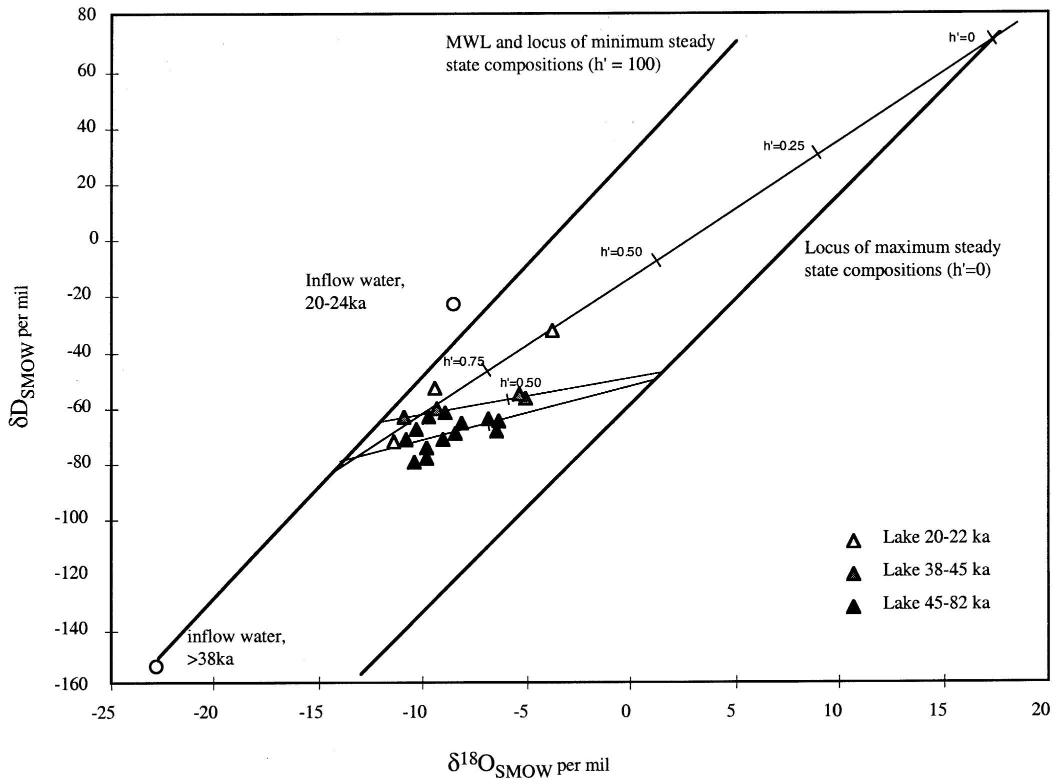

Fig. 8. Stable isotope compositions of fluid inclusions in primary lake halite intervals from core 2008 with the results of the terminal lake steady state model (Horita, 1990).

Table 2
Comparison of modeled isotopic compositions of inflow water to the salars of Hombre Muerto and Atacama to ice core records (Thompson et al., 1995, 1998) and modeled atmospheric water vapor

Location	Age	$\delta^{18}O$ (‰)	δD (‰)
Inflow waters			
Hombre Muerto	modern	−10	−70 (−30)
	20–24 ka	−1 to −9	27 to −43
	38–82 ka	−22 to −23	−146 to −157
Atacama	modern	−10	−70
	5.4–53 ka	−5 to −7	−37 to46
Sajama (Bolivia)	modern	−16.8	no data
	LGM	−22.1	no data
Huascaran (Peru)	modern	−18.5	−132.5
	LGM	−22.9	−172
Atmospheric water vapor			
Hombre Muerto	modern	−25	−155 to −160
	5–8 ka	−22 to −24	−147 to −172
	5.4–53 ka	−19 to −20	−150 to −156

Value in parentheses is from 1996.

water to the lake that existed between 20 and 22 ka was isotopically very similar to water that currently flows in the Rio de los Patos in years characterized by high d_{xs} and high proportions of recycled surface water in precipitation. The other two isotope regressions based on lakes that existed prior to 22 ka indicate that their inflow water was isotopically depleted relative to today by as much as 10‰ in $\delta^{18}O$, yielding compositions similar to glacial ice on Sajama in Bolivia and Huascaran in Peru (Thompson et al., 1995, 1998). This difference in inflow water compositions (i.e. meteoric waters) cannot be explained by temperature depressions. The temperature drop is too large (> 15°C) to be consistent with any other data sets based on the position of the 0°C isotherm, pollen or isotope compositions of ice (Klein et al., 1999; Thouret et al., 1996; Thompson et al., 1995). Instead, it is necessary to look at the alternatives such as the absence of secondary evaporation contributions to water vapor, an increased continental gradient and increased rainout, a change in moisture source region or a change in seasonality (Fernández et al., 1991).

4.2. Salar de Atacama

Textural studies of a 100 m core indicate the presence of saline lakes at different times during the last 65 ka (Fig. 9). The occurrences of the two Holocene lakes coincide with periods of increased summertime precipitation around the salar and increased spring outflow (Betancourt et al., 2000), but the deepest, longest-lived lake (27–16 ka, deduced from halite textures) does not coincide with interpretations derived from either the midden or spring data. It is most likely that the discrepancy arises because lakes in the salar were fed by re-

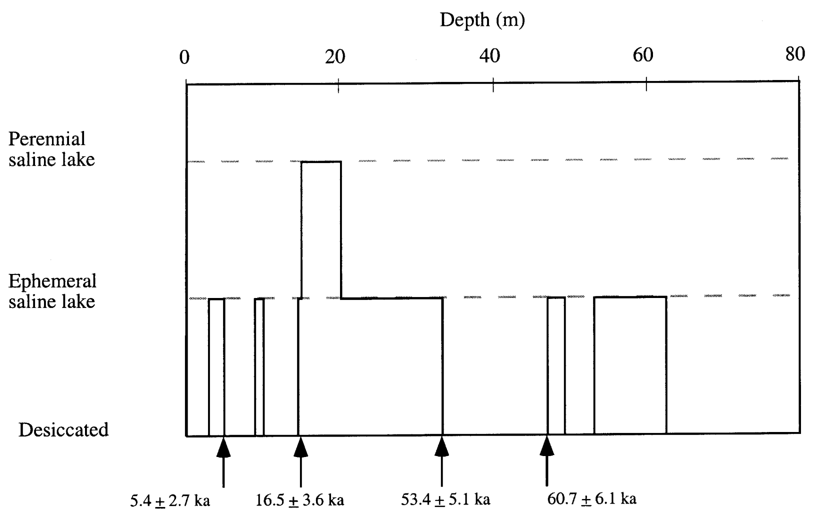

Fig. 9. Core 2005 stratigraphic column showing paleo-environments and U-series dates, Salar de Atacama.

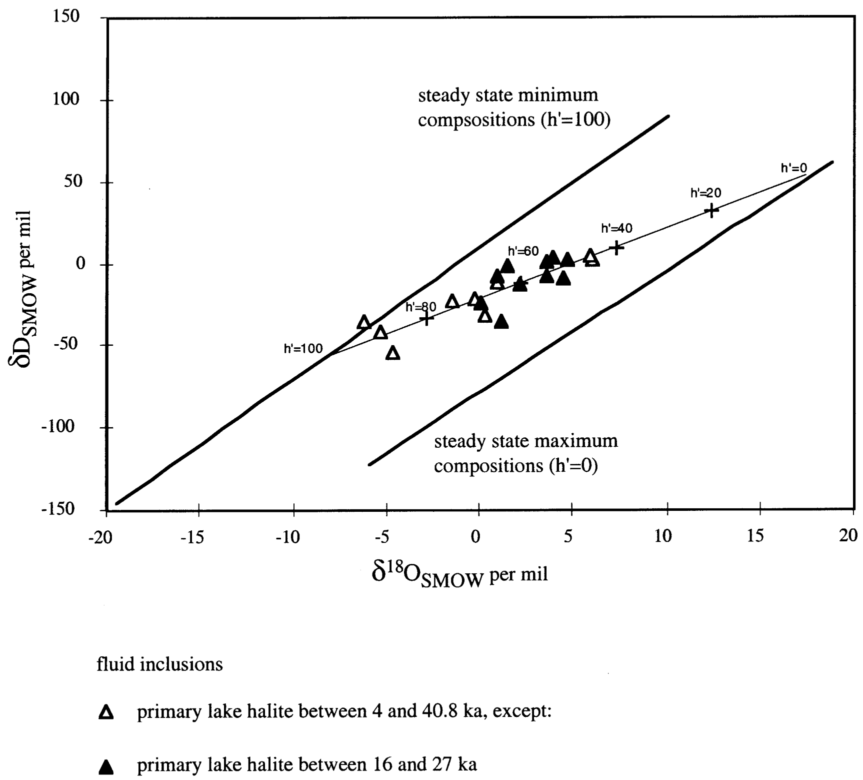

Fig. 10. Stable isotope compositions of fluid inclusions in primary lake halite from Salar de Atacama core 2005 with the results of the terminal lake steady state model (Horita, 1990).

gional groundwater rather than local precipitation that would affect vegetation and springs fed by small perched aquifers common amongst the sheeted ignimbrites flanking the western cordillera (Betancourt et al., 2000). The similarity between the record of the hydrologic budget at Atacama and at Uyuni, 120 km to the north, is consistent with a regional groundwater flow model that shows that areas as far north as Uyuni and east of the western cordillera can act as recharge areas for regional groundwater flow that is focused into the topographic depression of the Salar de Atacama (Jordan et al., unpublished data). Thus the record of isotope composition of trapped lake waters from the Atacama probably represents a record of changes in isotope composition of groundwater that discharges into the Salar de Atacama and recharges north and east of the salar.

The range in isotope compositions of lake waters trapped in fluid inclusions (Fig. 10) overlaps that of modern surface waters (Fig. 6) and forms a single array that, using the model of Horita (1990), indicates inflow water (i.e. meteoric water in the recharge area) and atmospheric water vapor has not changed within the error of our method during the past 41 ka. Springs in the Pampa Del Tamarugal basin, 300 km north of the Atacama, also recharged from the western flank of the Andes, have the same $\delta^{18}O$ and δD compositions, but variable ^{14}C ages (Fritz et al., 1981). The lack of isotopic change with groundwater age supports constant isotope compositions of rain and snow over long periods of time (Magaritz et al., 1989). Because volcanic CO_2 makes it virtually impossible to accurately ^{14}C-date groundwater discharging today (Fritz et al., 1978), comparisons of modern and glacial groundwater in the Atacama may have problems. However, the similarity of the hydrologic budget at Atacama and Uyuni (which is surface-fed; Baker et al., 2001a) suggests that groundwater residence time at Atacama is on the order of a few thousand years rather than tens of thousands of years. Regardless, meteoric water in the recharge area and atmospheric water vapor at the salar where evaporation and formation of the halite occurs has not changed during the past glacial cycle.

Finally, it should be reiterated that data for inflow water and atmospheric water vapor at both salars are only valid for periods of increased precipitation and groundwater discharge. There are no records for the conditions during previous dry periods. The only data we have for those are the modern environments. The record of moisture budgets of Salar de Hombre Muerto and Salar de Atacama are similar in that the modern climate is in a dry state and that during the LGM both salars were occupied by a standing body of water. The isotopic composition of the precipitation that provided water to the LGM lakes and the atmospheric water vapor is similar to modern compositions. Prior to the northern hemisphere LGM the water budget and isotope records from the two basins were quite different.

5. Implications of variations in the isotopic composition of meteoric water in the past

In the arid parts of the Andes, snowline depressions are generated by additional moisture, not by lower temperatures (Klein et al., 1999). Consequently, the presence or absence of lakes in the arid Andes is an indicator of glacial state rather than temperature variations. According to the halite record, the largest paleo-lake occurred during the LGM in the Salar de Atacama. This makes the climate history of the Atacama similar to that of Uyuni and indeed to records obtained in many places both north and south of the Equator, in marine and continental settings. The climate history of Hombre Muerto is different. The LGM-age lakestand was small compared to lakes that formed earlier, especially compared to lakes that were preserved at the bottom of the core during MIS 4 and 5a (60–85 ka). Not only was there more water in Hombre Muerto before 38 ka, but that water was isotopically different compared to modern and LGM precipitation. Instead of preserving the effects of re-evaporation and condensation through a dry atmosphere, the water forming these lakes had lower d_{xs} and was isotopically lighter ($\delta^{18}O = -22.5‰$ compared to $-10‰$), similar to LGM snow on Sajama and Huascaran (Thompson et al., 1995, 1998). If the atmospheric lapse rate of 5–5.5°C/km for northwest Argentina (Schwerdtfeger, 1976) was constant during the last glacial cycle, and rainout effects were smaller than temperature effects, a value of $-22.5‰$ for the MIS 3 and 4 lakes is reasonable, given a mean annual temperature of -5°C at an elevation of 5500 m (derived from the T–$\delta^{18}O$ relationships from the GNIP stations at Salta and Nacuñan, both on the eastern flank of the Andes in northwestern Argentina (IAEA/WMO, 2001)).

It is possible that the moisture delivered to Hombre Muerto before 38 ka was from the same source area throughout the last 85 kyr and the only difference was the relative intensity of moisture recycling. There are some issues that arise from this interpretation. Modern moisture (and presumably during the LGM) reaches the salar after crossing the Amazon Basin, being drawn into the SACZ, and then rising onto the Puna plateau. If this were also true of moisture fluxes before 38 ka, it is difficult to reconcile the large paleo-lakes at Hombre Muerto with the near-absence of lakes in Atacama at this time. It seems unlikely that the increased moisture flux to Hombre Muerto would pass the recharge area of the Atacama without affecting the moisture budget of that system. Instead, it seems more probable that moisture that formed the pre-38 ka lakes at Hombre Muerto followed a different track that avoided the more central areas of the Andes.

There are few continental climate records that extend further than 25 ka. However, marine cores that record changes in continental runoff and erosion products in addition to ocean conditions (temperature, paleoproductivity) over the last glacial period do exist in the equatorial Atlantic and parts of the South Atlantic. Changes in precipitation over Titicaca (Baker et al., 2001b), northern

Brazil (Arz et al., 1998), northern Venezuela (Peterson et al., 2000) during the LGM, the timing of the Heinrich-1 layer deposition and the Younger Dryas chronozone coincide with circulation changes in the western equatorial Atlantic and atmospheric circulation over the tropical Atlantic (Wefer et al., 1996; Arz et al., 1999; Harris and Mix, 1999; Rühlemann et al., 1999, 2001; Wolff et al., 1999; Vink et al., 2001). During periods of North Atlantic cooling (and increased precipitation over Titicaca), meridional sea-surface temperature (SST) gradients are inferred to have increased, leading to more intense trade winds, more zonal winds and a general southward shift of low-latitude wind systems, including the Intertropical Convergence Zone (ITCZ) (Rühlemann et al., 1999; Vink et al., 2001). At the same time, northern and southern equatorial currents in the tropical Atlantic are thought to have shifted southward with a weakening of the north Brazil current (NBC), related to an enhanced NBC retroflection and/or a stronger southward flowing Brazil Current (BC). Rühlemann et al. (1999) present evidence for an enhanced NBC retroflection during the LGM and Younger Dryas. Arz et al. (1999) have evidence for a stronger BC during the LGM. The absence of any change during the Younger Dryas may be due either to the event not occurring in the study area or because the event duration may not have been captured due to low sedimentation rates. It is not clear if a stronger BC always occurs with an enhanced NBC retroflection or whether it is linked to particularly strong southeast trade winds relative to the northeast trade winds.

The lakes at Hombre Muerto that existed prior to 38 ka coincide with a thickening of the western equatorial Atlantic warm water pool and with high Melosira concentrations in the western equatorial Atlantic (Melosira, a freshwater diatom, is transported from African lakes by the easterly trade winds) (Wefer et al., 1996; Pokras and Mix, 1985). The pre-38 ka lakes at Hombre Muerto occur during summer insolation minima in the southern hemisphere. With high southern latitude cooling, more intense zonal winds (stronger southeast trade winds) could have resulted, possibly favoring a strong BC. If the BC was strong, then warm equatorial water could have flowed further south along the eastern South American margin. Warm water off northern Brazil correlates with increased terrigenous supply and more humid conditions on the continent (Arz et al., 1998); likewise, during times of an enhanced BC, the associated warm water may have increased local continental humidity and runoff. An additional factor that would enhance the effect of warm water reaching further south on moisture reaching arid areas of northwest Argentina would be a likely spin-up and shift south in the South Atlantic high and the area of wind convergence over south America, scenarios suggested previously (Wefer et al., 1996; Villagrán, 1993). In comparison, the lake and precipitation history at Salar de Atacama is more similar to other areas in the Central Andes. The moisture flux to this area reflects upper-air circulation and the strength of westwind flow across the Central Andes which may be impacted instead by changes in tropical Pacific SST (Garreaud, 1999; Vuille et al., 2000; Garreaud and Aceituno, 2001; Garreaud et al., 2003).

6. Summary

The isotopic compositions of surface and subsurface waters have been measured in samples from Salar de Atacama in northern Chile and Salar de Hombre Muerto in northwestern Argentina. Moisture sources providing water to the Atacama come from the east via the Amazon Basin from the tropical Atlantic, consistent with other studies (Aravena et al., 1999; Fritz et al., 1978). Moisture reaching Salar de Hombre Muerto also comes from the east, but the isotopic compositions of streams indicate that the moisture is recycled through the atmosphere, isotopically enriching streams and increasing deuterium excess.

During the past glacial cycle, lakes existed in both salars. The lakes occupying the Salar de Atacama were probably groundwater-fed, and are isotopically indistinguishable from modern surface waters. The largest lakes in the Atacama occurred during MIS 2. At Hombre Muerto, the largest lakes occurred earlier, coiciding with

MIS 4 and 5a, and their isotopic compositions indicate that there was no recycling through the atmosphere. The very small lake that occupied the salar during MIS 2 was isotopically similar to modern surface brines – including the isotopic signal imparted by recycling water through a dry atmosphere. The occurrence of lakes at Hombre Muerto appears to be more closely related to changes in intensity of warm surface currents flowing southward along the eastern seaboard of South America than to ocean-wide changes in thermohaline circulation. There remains a possibility that there was a change in the seasonality of precipitation at Hombre Muerto, or rather that there were greater contributions of winter snow. The similarity of the modeled isotopic composition of inflow waters to the perennial lakes at Hombre Muerto to peaks in the Central Andes (Thompson et al., 1995, 1998) keep an easterly source of moisture appealing. However, an increase in cold cut-offs (Vuille and Ammann, 1997; Vuille and Baumgartner, 1998) during the winter, interacting with moist, easterly sourced water to produce snow could cause a sufficient increase in snow melt to create continuous inflow to the perennial saline lakes. This theory would agree with the observation of the modern–14 ka record of vegetation from the province of Jujuy (Fernández et al., 1991) and a change from cool and winter moisture to warm and summer moisture at about 10 ka. However, the record from Hombre Muerto presented here does not have data for this period, so a direct comparison is not possible. However, the data here do indicate a change in climate between 38 and 24 ka. If more winter moisture did occur at the time of the LGM, then there was a change in moisture fluxes that occurred before the LGM that had more profound effects on the hydrologic budget of Hombre Muerto.

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