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Isotopic composition and origin of the precipitation in Northern Chile

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Abstract

A 3 a data set of isotopes in precipitation from northern Chile show a very distinct pattern, with $\delta^{18}\text{O}$ values ranging between -18 and -15‰ at high altitude stations, compared to $\delta^{18}\text{O}$ values between -10 and -6‰ at the lower altitude areas. The ^{18}O -depleted values observed in the high altitude area, the Altiplano, are related to processes that affect the air masses that originated over the Atlantic, cross the Amazon Basin (continental effect), ascend the Andes (altitude effect) and precipitated (convective effect) in the Altiplano. It is postulated that a second source of moisture, associated with air masses from the Pacific, may contribute to the ^{18}O -enriched values observed in the lower altitude areas. Similar isotopic patterns are documented in springs and groundwater indicating that the data presented in this paper are an accurate representation of the long term behavior isotopic composition of rain in northern Chile. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Groundwater is the main water source for cities, mining industries, and agriculture in northern Chile. The main aquifers are located in the Pampa del Tamarugal, a terminal basin of a drainage system originating in the high Andes. This basin is located between the Cordillera de la Costa and the Cordillera del Medio, at an altitude of 1000 m above sea level (masl) (Fritz et al., 1981; Magaritz et al., 1990). The hydrological cycle in this region is mainly a function of the precipitation regime above 2500 masl. This regime generates base flow fed mainly by springs in high altitude catchment areas and by runoff events related to precipitation in intermediate catchment areas. Some of this water is used for agriculture along the river valley, some is lost by evaporation from the river itself, some infiltrates the aquifers in the alluvial fans and finally, water is also lost by evaporation in the salares which

are located at the terminus of the groundwater flow system. During extreme rainy periods, flood waters from the rivers can inundate large areas of the Pampa del Tamarugal. However, due to the existence of clays and the extreme aridity of this region, most of this water is lost by evaporation (Peña et al., 1989).

The precipitation regime in the Altiplano of western Bolivia, southern Peru and northern Chile is related to the presence of a high reaching anticyclone in the upper troposphere during the summer. This system is thermally maintained by a combination of latent heat released during the precipitation events and to a lesser extent by sensible heat liberated from the Altiplano surface (Gutman and Schwerdtfeger, 1965). This meteorological regime causes summer to be the main rainy season in northern Chile. Twenty a of data indicate that more than 80% of the rains occurred during the December–March summer period (ICC-CONIC, 1982).

The strategic importance of groundwater in northern Chile has led to several studies aimed at evaluating these water resources (Campillo and Hojas, 1975; Karzulovic and Garcia, 1979; Fritz et al., 1981; Magaritz et al., 1989, 1990; Peña et al., 1989). Isotope geochemistry has been an important technique in meeting the objectives of these studies. One key parameter that must be evaluated for the application of isotope techniques in groundwater and surface water studies, is the isotopic composition of the meteoric water in the recharge and catchment areas. The first attempt to evaluate the isotopic composition of the rain in northern Chile was carried out as part of a study on the origin of the groundwater in the Pampa del Tamarugal aquifers (Fritz et al., 1981). Other studies in northern Chile have focused on the geochemistry of surface and groundwater, evaluation of evaporation rate from salares, and geochemistry and isotopic composition of runoff water (Magaritz et al., 1989; Grilli et al., 1989; Peña et al., 1989; Aravena and Suzuki, 1990). As part of this work, an extensive evaluation of the isotopic composition of the precipitation in conjunction with a study on the origin of the air masses was carried out in the study area. This paper presents isotopic data on precipitation collected during 1984 and 1986 and discusses the main processes influencing its isotopic composition. This analysis is supplemented by meteorological information on the trajectories of the air masses delivering the precipitation to the study region.

2. Materials and methods

Precipitation samples were collected using a network of rain gauges located at different altitudes along the western slope of the Cordillera del Medio and the Altiplano (Fig. 1). Since this area is difficult to access and is far from populated areas, sampling was done by local field operators. Therefore, it was extremely difficult to monitor the same network every year. Individual storms were sampled during the 1984 field season to evaluate the isotopic evolution of the rains during and between storms. Only bulked monthly samples were collected during the 1986 field season.

Stable isotope and ^3H analyses were performed at the Atomic Commission of Chile and the Institute für Hydrology (GSF), Germany, respectively. Stable isotope analyses are reported in δ units expressed as per mil (‰) deviations with respect to the international standard (VSMOW) and ^3H is reported in TU that corresponds to an abundance of 10^{-18} ^3H per ^1H atoms. The analytical error is $\pm 0.2\text{‰}$ for ^{18}O , $\pm 2\text{‰}$ for ^2H and ± 0.8 TU for ^3H .

3. Results and discussion

Isotope and precipitation data are presented in Table 1. Some of the rain stations do not have a complete record, but the absence of these data do not have a significant bearing on the general conclusion of this study (see discussion). The average weighted mean isotopic composition of the precipitation was calculated based on the total amount of rain collected during the rainy season (Table 2).

The data for 1984 represent rains collected during the summer (January–March) and winter (June–July). The summer rains show a significant spatial and temporal range in isotopic composition. Precipitation at high altitude stations is clearly more depleted in stable isotope content than rain sampled at low altitude stations. Temporal $\delta^{18}\text{O}$ variation is in some cases significant (e.g., -8.7‰ to -24.8‰ at Pampa Lirima, a high altitude station).

Summer rains in 1984 show a significant isotopic gradient with altitude (Fig. 2). The $\delta^{18}\text{O}$ values vary from -5.0‰ at the lower altitude stations to -19‰ in the Altiplano stations located at about 4000 masl. A similar isotopic relationship with altitude was observed in summer rains collected at different locations during 1974–75 in the study area (Fritz et al., 1981). These data are also presented in Fig. 2. Linear regression analysis on the 1974–75 and 1984 isotopic data with respect to altitude produced a regression coefficient (R^2) of 0.76 and 0.84, respectively. The $\delta^{18}\text{O}$ isotopic gradient with altitude for the summer rains of 1974–75 and 1984 is about $-1\text{‰}/100$ m, which is much higher than values reported in the literature. Altitude effects are typically $-0.2\text{‰}/100$ m for temperate zones and reach values as high as $-0.6\text{‰}/100$ m in polar regions (Dansgaard, 1964; Siegenthaler and Oeschger, 1980). Highly isotopically depleted rains in the range of -16‰ for $\delta^{18}\text{O}$ have also been reported in the Bolivian Altiplano (Stimson et al., 1993; Coudrain-Ribstein et al., 1995).

The rains collected during the summer of 1986 show a different pattern than the 1984 rains. They do not show a clear isotopic gradient with altitude and they are much more enriched in stable isotope content than the 1984 rains (Fig. 2).

The isotopic pattern of the summer rains could be classically interpreted as an altitude effect produced during the ascent of the Pacific air masses along the western part of the Cordillera del Medio. However, meteorological evidence do not support this hypothesis and, instead, indicate that the air masses originate from the E via the Amazon Basin.

Winter rains show a different isotopic pattern. Firstly, they are generally heavier in stable isotope content than the summer rains. e.g. the Coposa station shows a difference of 10‰ in $\delta^{18}\text{O}$. Secondly, no

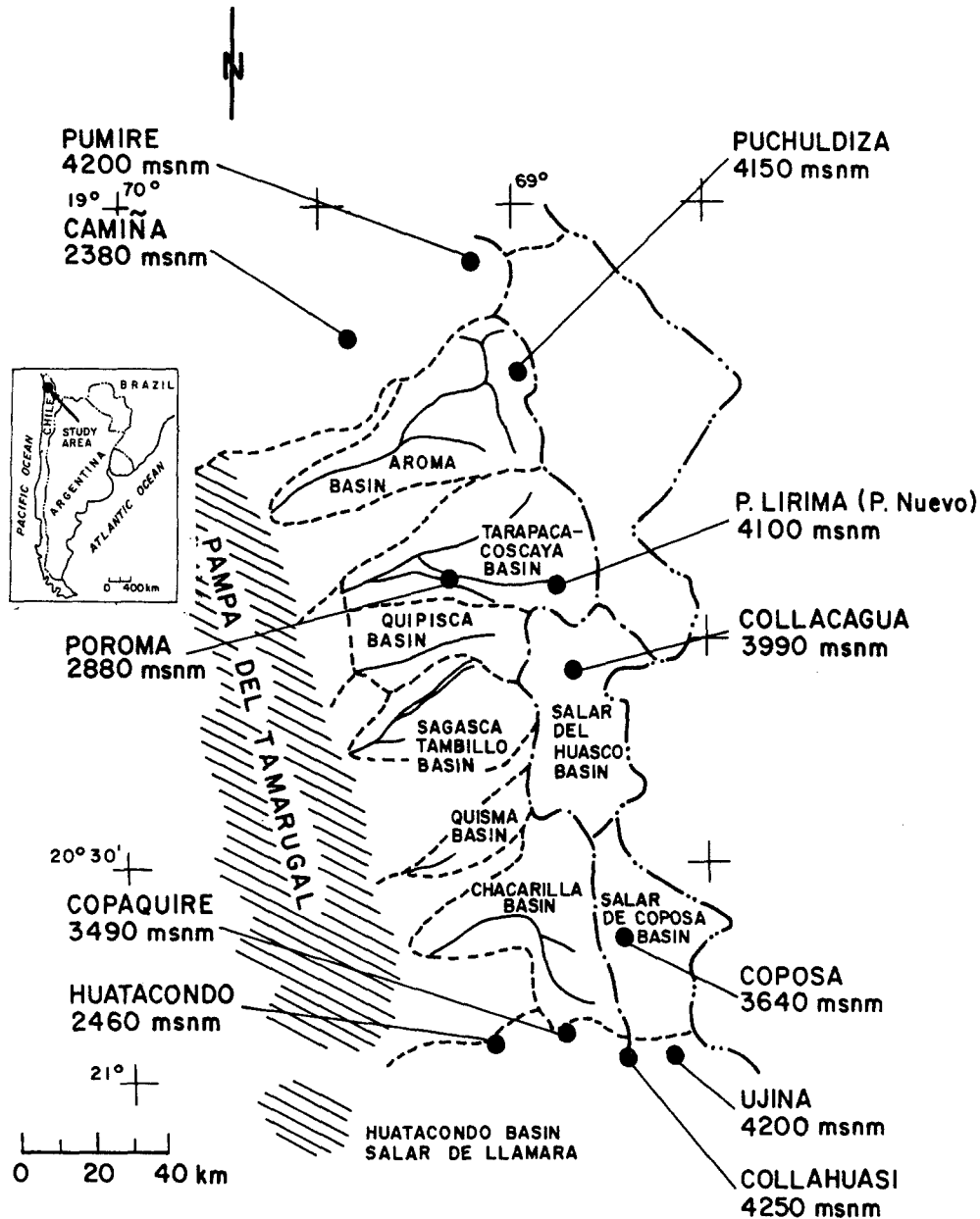


Fig. 1. Location of rain collectors in the study area.

strong relation is observed between altitude and isotopic composition (Fig. 2).

The summer and winter isotopic data from 1984 and 1986 are located on a well defined meteoric water line (Fig. 3) expressed by the following expression:

$$\delta^2\text{H} = 7.8 \delta^{18}\text{O} + 9.7(\text{‰})$$

This line is similar to the one reported by Fritz et al. (1981) for this area and is close to the global meteoric

water line (Craig, 1961). Isotope data for precipitation and surface water collected in the Bolivian and Peruvian Altiplano also plotted on the meteoric water line defined by the northern Chile precipitation (Stimson et al., 1993; Coudrain-Ribstein et al., 1995; Ruiz and Rojas, 1995).

The ^3H data range between 9.9 TU and 3.0 TU, with an average value of 6 TU. No difference is observed between the summer and winter precipitation.

Table 1. Isotopic composition of rains in northern Chile. 1984 data include individual storms and 1985–86 data monthly samples

Station	Altitude (m)	Sampling (Year)	Date (Month)	Period (hr)	Precip. (mm)	² H (‰ Smow)	¹⁸ O (‰ Smow)	<i>d</i>	³ H (TU)	
Collaguasi	4250	1984	5/Jan	17–22.1	14.0	–151	–21.0	17.0		
			17/Jan	16.2–19.2	8.0	–106	–15.8	20.4		
			12/March	19.1–22.3	2.0	–138	–18.9	13.2		
			Weighted Mean		24	–135	–19.1	17.8		
			1986	Feb		23.5	–150	–20	10	
				March		19.0	–72	–10.5	12	
Ujina	4200	1984	4/Jan	19.1–23.2	12.0	–152	–21.0	16		
			5/Jan	17.2–19.2	3.0	–151	–21.2	18.6	9.9	
			6/Jan	22.1–3.0	8.0	–151	–21.0	17		
			8/Jan	0.1–5.0	4.0	–150	–21.0	18		
			Weighted Mean		27	–151	21.0	16.9		
			1985	Nov		15.5	–57	–9.6	19.8	
				1986	Jan		28	–60	–8.2	5.6
			Feb			14.0	–53	–8.9	18.2	
			March			65.8	–78	–11.1	10.8	
			Weighted Mean		123.3	–68	–10.0	12.0		
			Puchuldiza	4150	1984	6/Feb	20.0–5.1	11.0	–90	–14.5
7/Feb	21.2–6.2	13.0				–137	–19.3	17.4		
8/Feb	24.0–5.2	6.0				–151	–21.3	21.0	5.8	
9/Feb	21.1–7.1	9.5				–118	–17.3	20.4		
10/Feb	15.0–15.3	3.0				–139	–19.7	18.6		
11/Feb	16.3–20.1	2.0				–69	–10.2	12.6		
Weighted Mean		44.5				–120	–17.6	20.0		
1985	8/Jun	nd				8.0	–80	–11.2	9.6	
	9/Jun	10.0–19.0				11.9	–78	–10.9	9.2	
	23/Jun	14.0–17.0				1.8	–79	–10.0	8.2	6.9
	24/Jun	8.0–20.0				6.5	–75	–10.9	12.2	
	25/Jun	nd				5.5	–78	–11.5	15.0	
	Weighted Mean					33.7	–78	–11.1	10.8	
1986	Dec					39.6	–94	–13.4	13.2	
	Jan					28.1	–73	–10.9	14.2	
	March		27.8	–148	–19.2	5.6				
	April		4.5	–113	–15.4	10.2				
	Weighted Mean		100	–104	–14.4	11.2				
	Pampa Lirima	4100	1984	1/Jan	17.0–5.0	6.0	–75	–11.0	13.0	
				2/Jan	20.3–9.3	22.5	–163	–22.1	13.8	
				3/Jan	16.1–11.0	20.5	–162	–22.6	18.8	
				4/Jan	ND	29.5	–199	–26.7	14.6	
				11/Jan	15.2–22.2	13.5	–116	–16.6	16.8	3.0
22/Jan				16.0–5.0	17.5	–137	–19.3	17.4		
23/Jan				7.3–8.3	13.0	–182	–24.8	15.4		
24/Jan				15.3–5.0	3.5	–126	–17.0	10.0		
5/Feb				23.0–10	4.5	–57	–8.7	12.6		
6/Feb				18.2–10.6	3.0	–69	–10.5	15.0		
11/Feb				0.5–9.3	4.5	–84	–12.5	16.0		
12/Feb				18.4–23.0	10.5	–151	–20.9	16.2	9.9	
13/Feb				19.5–8.4	17.5	–125	–17.6	15.6		
16/Feb				20.1–7.5	5.8	–156	–21.7	17.6		
4/March				19.2–22.2	3.0	–137	–18.8	13.4		
10/March	17.2–17.5	1.5	–77	–11.5	15.0					
17/March	4.0–10.0	1.8	–78	–11.5	14.0					
18/March	18.3–5.0	1.2	–124	–16.6	8.8					
26/March	18.1–18.3	1.2	–74	–10.3	8.4					
Weighted Mean		182	–147	–20.2	15.5					
1984	8/June	snow	4.0	–82	–11.1	6.8				
	18/June	snow	nd	–93	–13.6	15.8				
	19/June	snow	nd	–97	–14.2	16.6				
	25/June	nd	2.8	–67	–11.1	22.6				

	Weighted Mean				23.0	−81	−11.9	14.4		
Poroma	2880	1984	2/Jan	5.15–9.0	9.0	−36	−6.1	12.8		
			3/Jan	3.5–8.0	7.0	−70	−9.2	3.6		
			4/Jan	6.25–10.0	2.0	−32	−5.0	8.0		
			15/Jan	23.0–6.0	10.0	−16	−3.0	8.0		
			19/Feb	1.0–4.0	3.0	−35	−6.0	13		
	Weighted Mean			31	−41	−5.2	8.9			
	1985	Dec		10.1	−6	−2.5	14			
	1986	Jan		11.0	−25	−5.3	17.4			
		Feb		15.0	−24	−4.6	12.8			
		March		5.0	−37	−6.2	12.6			
	Weighted Mean			41.1	−21	−4.5	15.0			
Parca	2570	1985	Dec		3.5	−18	−4.4	17.2		
			1986	Jan		6.5	−34	−5.4	9.2	
			Feb		7.0	−58	−8.6	10.8		
			March		2.5	−43	−7.5	17.0		
	Weighted Mean			19.4	−41	−6.6	11.8			
Huatacondo	2460	1984	1/Jan	16.0–20.2	5.0	−15	−4.2	18.6		
			3/Jan	15.0–18.0	4.0	−15	−4.2	18.6		
			11/Jan	14.0–24.0	12.5	−48	−7.0	8.0		
			12/Jan	18.3–21.0	8.5	−9.0	−2.8	13.4		
			16/Feb	5.0–6.0	5.0	−29	−4.4	6.2		
			18/Feb	6.0–8.0	1.0	−26	−4.3	8.4		
				Weighted Mean			36	−27	−4.9	12.4
				1984	8/Jan	20.0–12.0	6.0	−61	−8.7	8.6
				8/Jan	nd	12.0	−85	−12.6	15.8	
				7/Jan	nd	3.0	−85	−12.6	15.8	
	11/Jan	nd	2.5	−75	−11	13.0				
	Weighted Mean			23.5	−78	−11.4	13.7			
	1986	Feb		4.0	−19	−2.7	2.6			
		March		11.0	−102	−14.6	14.8			
		Weighted Mean			15.0	−80	−11.4	11.2		
Camina	2380	1984	10/Jan	8.0–8.0	6.0	−20	−4.2	13.6		
			11/Jan	8.0–8.0	8.0	−20	4.1	12.8		
			22/Feb	17.3–8.0	6.0	−52	−8.2	13.6		
			9/March	24.5–6.4	26	−53	−8.3	13.4		
				Weighted Mean			46.0	−43	−7.0	13.3

Table 2. Weighted mean isotopic composition of rains in northern Chile

Station	Altitude (m)	Summer 1984			Winter 1984			Summer 1986		
		¹⁸ O	² H	Precip. (mm)	¹⁸ O	² H	Precip. (mm)	¹⁸ O	² H	Precip. (mm)
		(‰ SMOW)	(‰ SMOW)		(‰ SMOW)	(‰ SMOW)				
Collaguasi	4250	−19.1	−135	24				−15.8	−115	42.5
Ujjina	4200	−21.0	−151	27				−10.0	−68	123.3
Puchuldiz	4150	−17.6	−120	44.5	−11.1	−78	33.7	−14.4	−104	100
P. Lirima	4100	−20.3	−147	184	−12.5	−85	84.7	−11	−75	71
Collacagu	3990	−18.5	−134	66				−10.2	−69	146.6
Colchane	3965							−14.9	−106	207.6
Cancosa	3800							−13.7	−9.6	142.5
Huaytane	3720							−14.0	−99	161
Coposa	3640	−20.9	−154		−8.9	−58	28.9			
Copaquire	3490	−11.1	−76	74	−11.9	−81	23			
Poroma	2880	−5.2	−41	31				−4.5	−21	41.1
Parca	2570							−6.6	−41	19.5
Huatacon	2460	−4.9	−27	36	−11.4	−78	23.5	−11.4	−80	15
Camina	2380	−7.0	−43	46						

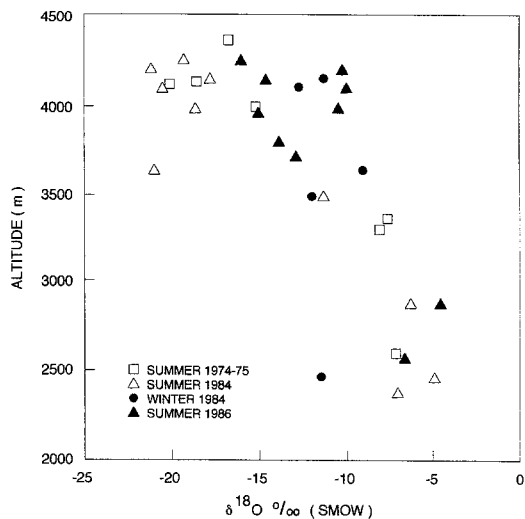


Fig. 2. Altitude vs. $\delta^{18}\text{O}$ in precipitation. 1974–75 data from Fritz et al. (1981).

Similar data have been reported for precipitation and surface water in the Bolivian and Peruvian Altiplano (Stimson et al., 1996; Ruiz and Rojas, 1995). The ^3H values are in the expected range for middle latitude areas in the southern Hemisphere (Albero and Panarello, 1980; IAEA, 1986, 1990).

Similar to the isotopic composition, the amount of precipitation shows a spatial distribution with a clear increase from W to E. The distribution seems to be a classic example of increasing precipitation with altitude (Fig. 4). However, in this case it is related to the location of the convective centers that are located in the

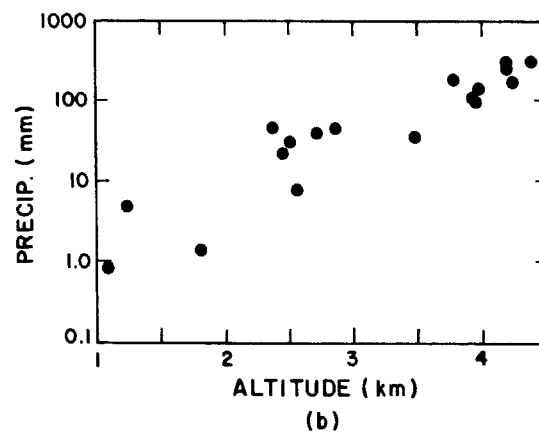
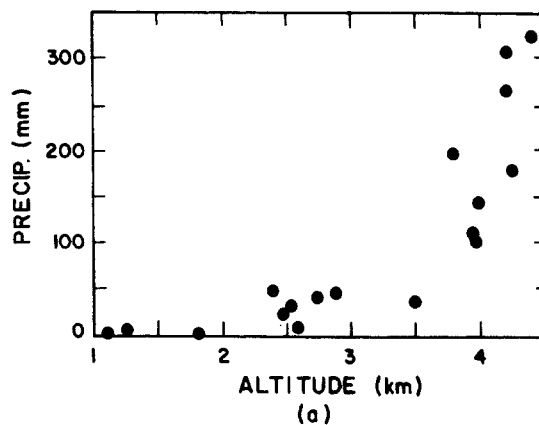


Fig. 4. Dependency of the amount of precipitation with altitude based on long term record of precipitation in northern Chile (from ICC-CONIC, 1982).

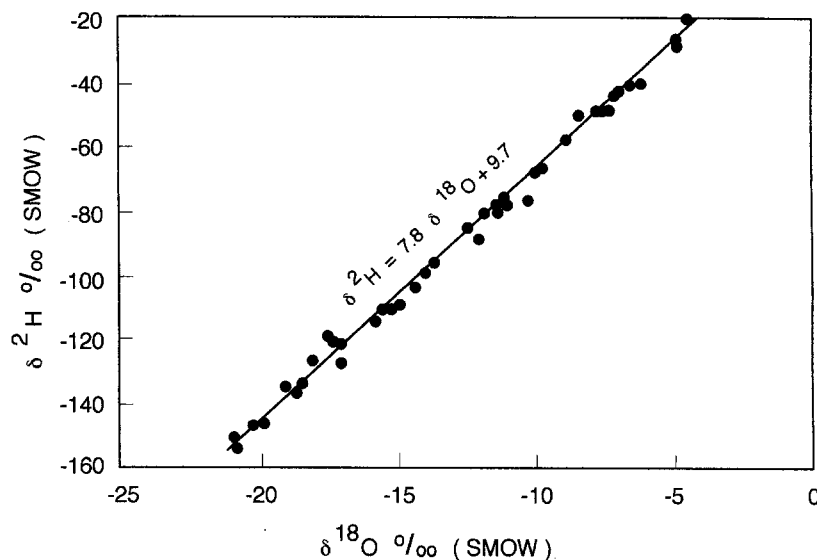


Fig. 3. Local meteoric water line for Northern Chile based on the 1984 and 1986 isotope data.

Altiplano region. The precipitation observed W of the Altiplano is generated by clouds located away from the convective centers.

4. Processes controlling the isotopic composition of the rains

4.1. Seasonal distribution

The isotopic pattern observed in the 1984 and 1986 summer rains and 1984 winter rains in northern Chile must be associated with the origin and history of the air masses that produced this precipitation. Observations from local inhabitants suggested that the summer rains are associated with easterly winds and winter with less frequent rains carried by northerly or westerly winds. Analysis of wind direction agreed with their observations (Fuenzalida and Rutland, 1986).

Analysis of isobaric trajectories of the air masses (Fig. 5 and Fig. 6) analyzed using satellite imagery (Fuenzalida and Rutland, 1986) resulted in the following conclusions: (a) the trajectories for the summer rains indicated that the air masses originated in the Amazon basin, (b) in cases where the air masses origi-

nated in the Pacific, no precipitation occurred (Fig. 5), and (c) the winter rains originated by the interaction of a polar front with air of tropical origin. The tropical air masses tracked at 700 mb originated in the Amazon basin, but at 500 mb, the principal component comes from the Pacific. This situation prevailed one day before the storm, but the air masses came from the Amazon basin and changed direction by a NNW turn toward the Altiplano during the storm (Fig. 6).

Meteorological evidence thus indicates that the main source of the air masses responsible for the precipitation in northern Chile is the Atlantic Ocean, via the Amazon Basin. These data also show that the spatial isotopic distribution observed in the summer rains in 1974–75 and 1984 cannot be related to a typical altitude effect occurring along the western slope of the Andes as this would require air masses from the Pacific.

Processes that may affect air masses during the transport from the Atlantic Ocean to the Altiplano region in northern Chile include hydrologic interaction within the Amazon basin, and isotope fractionation occurring during the ascent of the air masses toward the Altiplano and during precipitation at the study

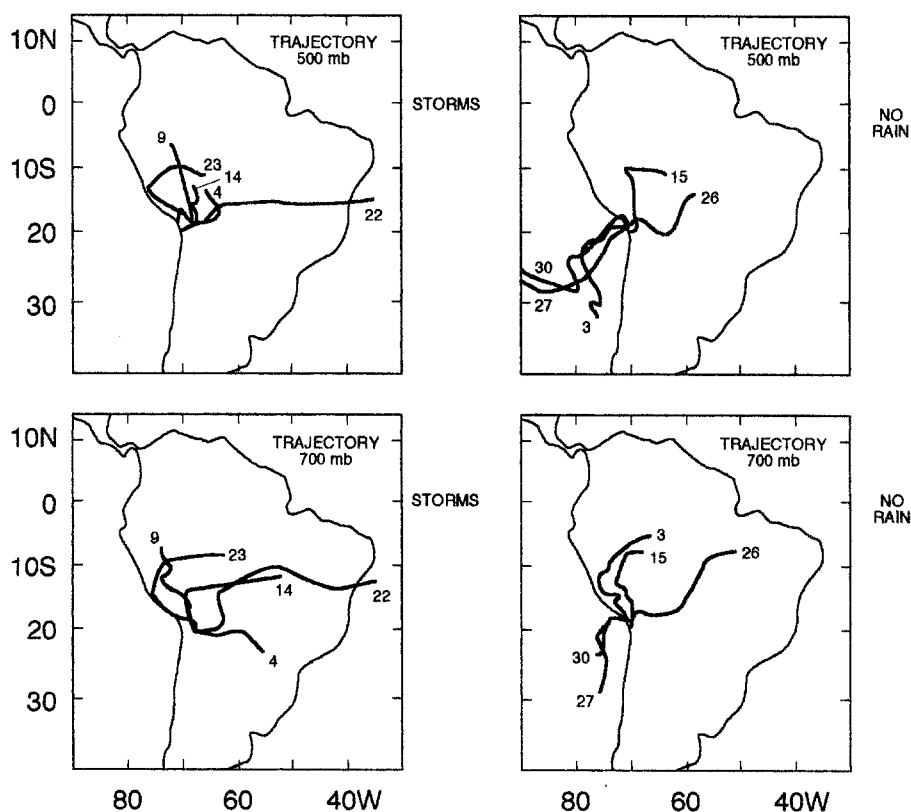


Fig. 5. Air mass trajectories of the main storms and days without rain during January and February of 1984.

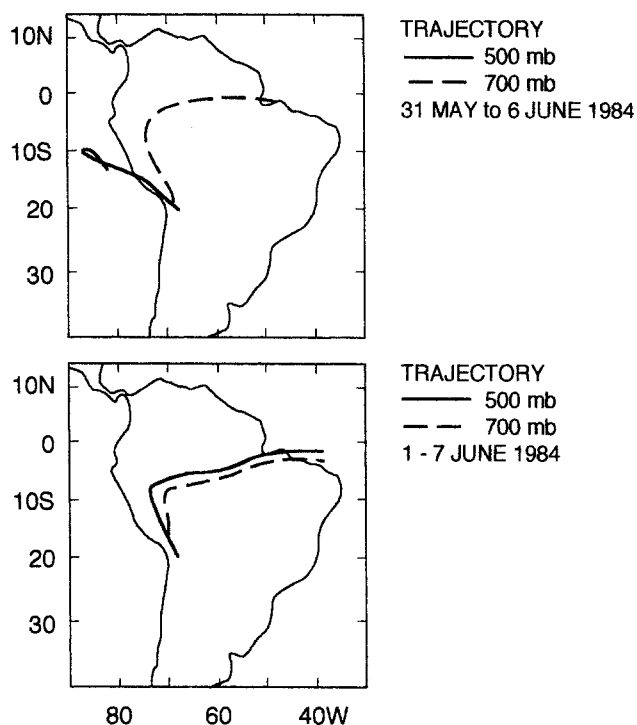


Fig. 6. Air mass trajectories for the winter storms in June of 1984.

area. The effects of these processes have already been analyzed by Grootes et al. (1989) in efforts to explain the ^{18}O record preserved in a 1500 a old ice core in the Quelcaya ice cap, located in the Peruvian Altiplano. This record shows a wide range in $\delta^{18}\text{O}$ values, varying between -8‰ and -31‰ . The enriched and depleted values are thought to be associated with snow precipitated during the dry (winter) and wet (summer) season, respectively. Isotope modeling suggests that a simple Rayleigh condensation equation combined with an 11‰ $\delta^{18}\text{O}$ -depletion associated with a change in altitude of 5.6 km reproduces these isotope values (Grootes et al., 1989). The calculations of the continental effect by Grootes et al. (1989) appears to represent extreme conditions and do not agree with the long term isotopic data in precipitation in this region, that shows a much smaller isotopic continental gradient (Salati et al., 1979; Victoria et al., 1991; Rozanski et al., 1993).

The significant isotopic variability observed in yearly precipitation in the study region can be associated with strong isotopic variation also observed in the precipitation (Matsui et al., 1983; Victoria et al., 1991) in the Amazon Basin (variable continental effect) and effects associated with the intensity of the convective storms. Isotopically less variable winter rains compared to the summer rains in 1984 (Fig. 2) may be related to there being no significant change in the isotopic composition

of the air masses during transport through the Amazon during the dry season (winter rains) compared to the wet season (summer rains) and the non-convective nature of the winter storms. This is consistent with the hypothesis used to explain the $\delta^{18}\text{O}$ values observed in an ice core collected in the Quelcaya ice field, Peruvian altiplano (Grootes et al., 1989). The $\delta^{18}\text{O}$ values between -8 to -10‰ represent snow precipitated during the dry season and the depleted $\delta^{18}\text{O}$ values ranging between -17 to -32‰ represent snow deposited during the wet season. The relatively more isotopically enriched rains observed in the wetter 1986 season, compared to the 1984 rains could be explained by rains produced by air masses that were less affected by isotopic changes during transport through the Amazon Basin.

4.2. Spatial distribution

The ^{18}O -enriched isotopic values documented in the lower western slope of the Cordillera del Medio compared to the more ^{18}O -depleted values in the Altiplano could be associated with (a) rain evaporation; (b) degree of convection, and (c) influence of air masses from the Pacific ocean.

Evaporation of the rain drops (in an unsaturated atmosphere) occurs during transport from the base of the clouds to the site of precipitation (Ehhalt et al.,

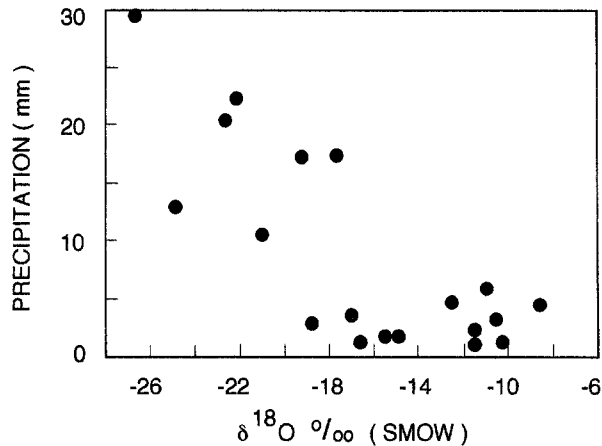


Fig. 7. Isotopic pattern of the precipitation during summer storms in 1984 on Pampa Lirima, a high altitude station.

1963). This effect is more likely to occur in the medium to low altitude areas of the Cordillera del Medio. Evaporation causes an isotopic enrichment in the residual water and this could explain, in part, the more ¹⁸O-enriched rains at lower altitudes compared to high altitudes. The process of evaporation causes the slope of the meteoric water line to decrease. The deuterium excess defined as: $d = \delta^2\text{H} - 8 \delta^{18}\text{O}$ can be used to evaluate the effect of evaporation in rains. “*d*” is determined by relative humidity and temperature conditions at the site of cloud formation (Merlivat and Jouzel, 1979). Rains affected by evaporation tend to have *d* values lower than 10 (Yutsever, 1975). The *d* values for the northern Chile rains range between 9‰ to 20‰, with no trend with respect to altitude (Table 1). Therefore, it seems that evaporation of rain is not significant.

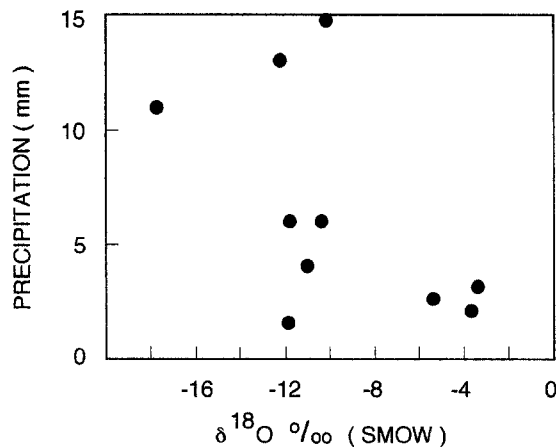


Fig. 8. Isotopic pattern of the precipitation during summer storms in 1984 on Copaquire, a low altitude station.

The possibility that convective activities influenced the isotopic composition of precipitation was evaluated through the analysis of individual storms sampled at one low and one high altitude station (Fig. 7 and Fig. 8). In general, these data show a trend toward depleted ¹⁸O values with increasing precipitation. This stratification was not observed during a low intensity rain (<3 mm) and probably is not a good example of the effect of the convective activity on the isotopic composition and amount of precipitation. It appears that the effect of convective activities on the isotopic composition of the rains is much more pronounced at the high altitude (reflected in the greater amount of precipitation) compared to the low drier altitude stations.

The other possible explanation for the more ¹⁸O-enriched values at the lower altitudes, is the contribution of isotopically enriched air masses from the W. Although meteorological studies indicate that the main source of moisture to the northern Chile region is the Atlantic Ocean, via the Amazon Basin, this information was obtained from evaluation of isobaric trajectories of the air masses at 500 mb (5600 masl, Fuenzalida and Rutland, 1986). Perhaps Pacific air masses that should be moving at lower altitude along the western slope of the Cordillera del Medio, were not detected in the study by Fuenzalida and Rutland (1986). This raises the question about the moisture content and the potential of Pacific air masses to produce precipitation. The only information available to evaluate this question was obtained during the winter season (Fuenzalida, unpublished data). Data collected at 1200 masl indicate a ratio of 3 to 4 g of vapor per kg of air and a relative humidity of 25%. If the air masses during the summer have 4 g vapor/kg air and a relative humidity of 30%, the air mass will require an ascent of about 2000 m to reach saturation. This is not unreasonable taking into account the steep altitude gradient in the study region. Therefore, we speculate that the ¹⁸O-enriched values observed at the lower altitude stations may be associated with the contribution of Pacific air masses ascending along the western slope of the Cordillera del Medio and gradually mixing with the air masses originated over the Atlantic Ocean.

4.3. Long term temporal distribution

One of the striking aspects of the isotopic pattern of the precipitation in northern Chile is that despite the variability observed in these data, attributed to a variable continental effect in the Amazon Basin and intensity of convective storms and possible contribution by the Pacific Ocean, the long term isotopic behavior follows a linear relationship similar to the meteoric water line defined for the wet season in the Amazon Basin (Victoria et al., 1991).

The $\delta^{18}\text{O}$ -altitude pattern reflected in the precipitation samples is also similar to values measured in spring water collected at different altitudes in the study region (Fritz et al., 1981; Magaritz et al., 1989). The spring waters range between -4% and -14% for $\delta^{18}\text{O}$ and between -50% and -110% for $\delta^2\text{H}$. In general, they are more enriched than the rains at similar altitude and they plotted below the local meteoric water line. This isotopic shift is also observed in the groundwater. This enrichment pattern compared to the rains is due to isotopic fractionation occurring during evaporation of the rain in the unsaturated zone of recharge areas (Magaritz et al., 1989). The streams represent a longer isotopic record than the precipitation data. The wide isotopic range observed in the precipitation and springs was also documented in the groundwater (Fritz et al., 1981; Aravena, 1996). Their isotopic composition ranges between -4% and -13.5% for $\delta^{18}\text{O}$ and -40% and -105% for $\delta^2\text{H}$. This finding has significant implications for the evaluation of groundwater resources. The very enriched isotopic values measured in some groundwater have to be associated with recharge areas located at lower altitude. The recent precipitation data show insignificant amount of rain in this region, implying no recent recharge is occurring in these areas. The isotopically enriched groundwater, then must have been recharged during a much wetter period in the past.

Concerning the climate regime responsible for the major recharge events in the past, the isotopic pattern in the precipitation can provide some insight about this aspect. Since this pattern is also preserved in old groundwater in the Pampa del Tamarugal aquifers (Fritz et al., 1981; Aravena, 1996), this suggests that the isotopic pattern observed in the short term rain data set presented in this paper is representative of the long term isotopic behavior of precipitation in northern Chile. This also implies that similar atmospheric conditions in northern Chile have prevailed throughout the Holocene.

5. Conclusions

Rain samples collected during the 1970s and the 1980s in the northern Chile region, show a wide range in isotopic composition. They vary between -5% to -30% in ^{18}O content. These data show that the most ^{18}O -depleted values are associated with rains collected at high altitude stations compared to low altitude stations. The local meteoric water line (LMWL) defined by these data $\delta^2\text{H} = 7.8 \delta^{18}\text{O} + 9.7$ is very similar to the LMWL for the Amazon Basin during the wet season, and the global meteoric water line. This relationship seems to be valid for the whole Altiplano region based on precipitation and surface

water data collected in the Bolivian and Peruvian Altiplano.

Meteorological evidence indicates that the origin of the air masses that produce much of the precipitation in northern Chile is the Atlantic Ocean via the Amazon basin. The very ^{18}O -depleted values observed in the northern Chile rains and the isotopic distribution with altitude are associated with the origin of the air masses and processes that affect their isotopic composition during transport from their source to the site of precipitation. These processes include interaction of the air masses in the Amazon basin that could deplete their isotopic composition by a maximum of -6% in ^{18}O , an altitude effect of 5 to 6‰ due to the ascent of the air masses along the eastern slope of the Andes, and a further isotopic depletion due to the convective nature of the storms in the Altiplano region. Moisture at lower altitudes may also be influenced by air masses originated over the Pacific Ocean.

The short term isotope data set presented in this paper illustrate the complexity of the processes that control the isotopic composition of rains in northern Chile. The rain data, however is an accurate representation of the long term behavior of the isotopic composition of the rain based on a comparison to a large isotopic data set from springs and groundwater in the study region.

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