ISOTOPE HYDROLOGY OF GROUNDWATERS IN THE PAMPA DEL TAMARUGAL, CHILE

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O. Suzuki
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ABSTRACT

The water resources in Northern Chile are extremely scarce and development is limited by these. This paper discusses the Isotope Hydrology of ground waters in the Pampa del Tamarugal--an area of extreme aridity (rainfall < 1 mm/year) on whose groundwater resources are mined for the town of Iquique, as well as industrial and agricultural purposes. The aim of the project was to obtain information on modern recharge and to delineate, if possible recharge environments. To obtain the necessary background information a precipitation survey in the high Andes, as wells as spring and surface water studies were carried out. The results show that: a well defined meteoric waterline exists where $\delta^{2}H = (7.8\ \delta^{18}O + 10.3)\ ^{0}/_{00}$, altitude effects depend on airmass movements and cannot be defined without a more regional and detailed sampling programme but ~~that~~ it is still possible to assign maximum altitudes of recharge to springs in the Andes and at the E. border of the Pampa del Tamurgal. Comparison of these data with groundwater compositions show, that these groundwaters originate from infiltrating surface water rather than directly infiltrated precipitation and a dependence of individual groundwater systems on specific quebradas (river valleys) is recognized. However, low ^{14}C activities indicate that most of the waters pumped today are essentially fossil and at least several hundreds to many thousands of years old. Some minor subsurface recharge does occur at the foot of the Andes, especially at Pica where high altitude waters discharge, but even their groundwater appears to be a diminishing resource.

1. INTRODUCTION

The Pampa del Tamarugal is a near desert area in Northern Chile (Figure 1) with no rainfall but some groundwater resources. Because of these the area has great importance for the regional development, and at present its aquifers supply water for the town of Iquique and other smaller communities. Other supplies are not available and, should these groundwaters represent a non-renewable resource water would have to be piped from the high Andes to the consumers. In the Andes rainfall becomes significant only at altitudes exceeding 3000 m - which coincides with appearance of a continuous plant cover.

It appears, however, that the climatic conditions during past centuries and millenia was different and that the region is becoming drier. There is archeological evidence of settlements daing less than 2000 years in areas where there is no water at all today. Even maps depiciting the situation after the colonization of the Spaniards show intermitten cultivated areas, rivers and continuous forest, where there are deserts and salars today. (Figure 2, O'Brien, 18). The desertification of this region was certainly aided by the ruthless nitrate industries of the late 1800 and early 1900's which consumed all natural vegetation of the region without any attempt to reforest or preservation. Where reforestation has been attempted during recent years the results were encouraging and distressing: it documented that the native tamarugo tree (Prosopis tamarugo) can grow very well in the very saline soils of the Pampa but that this was accompanied by significant drops in water level of the aquifers underlying the Pampa. Enhanced pumping for municipal and

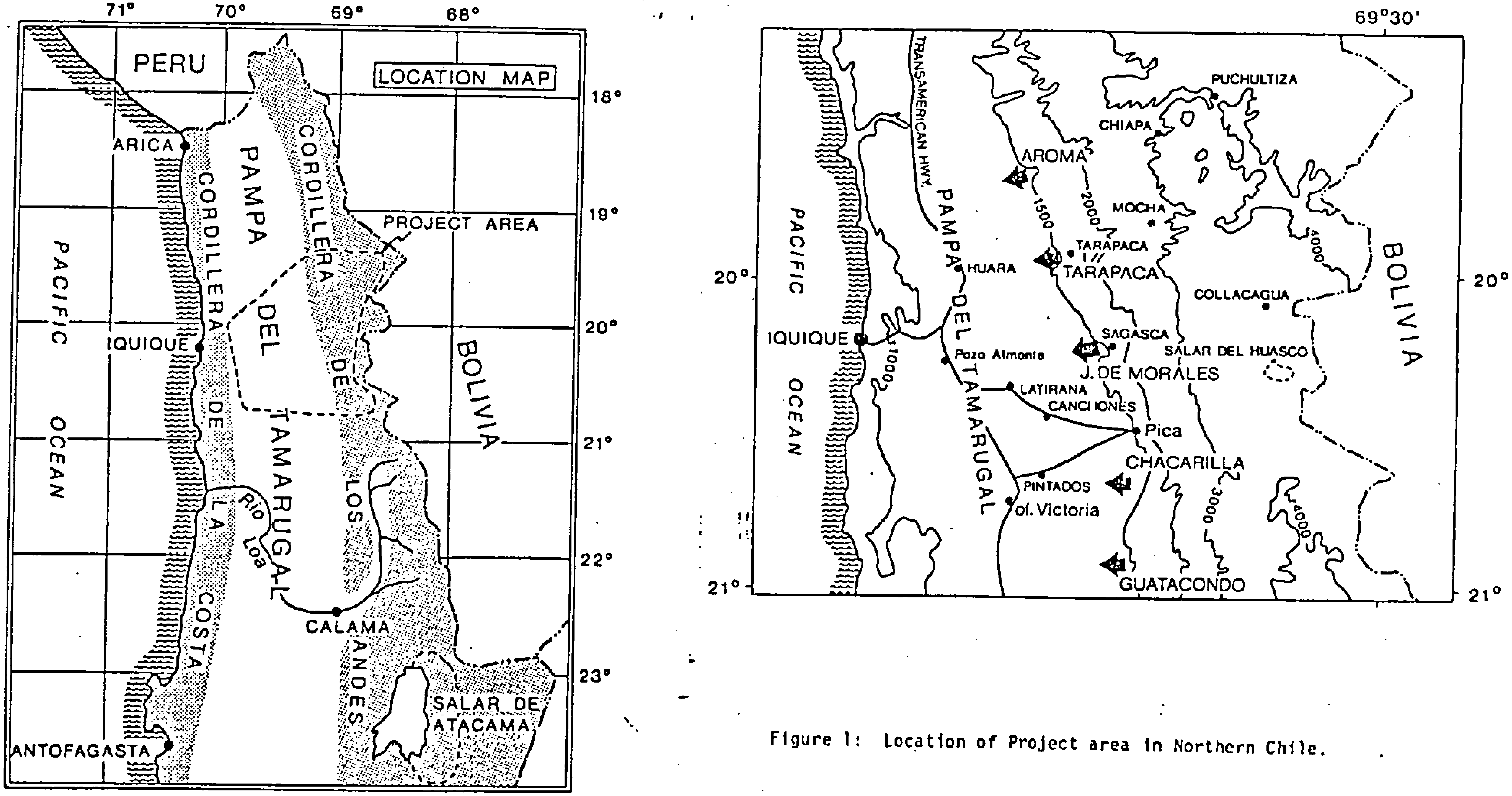

Figure 1: Location of Project area in Northern Chile.

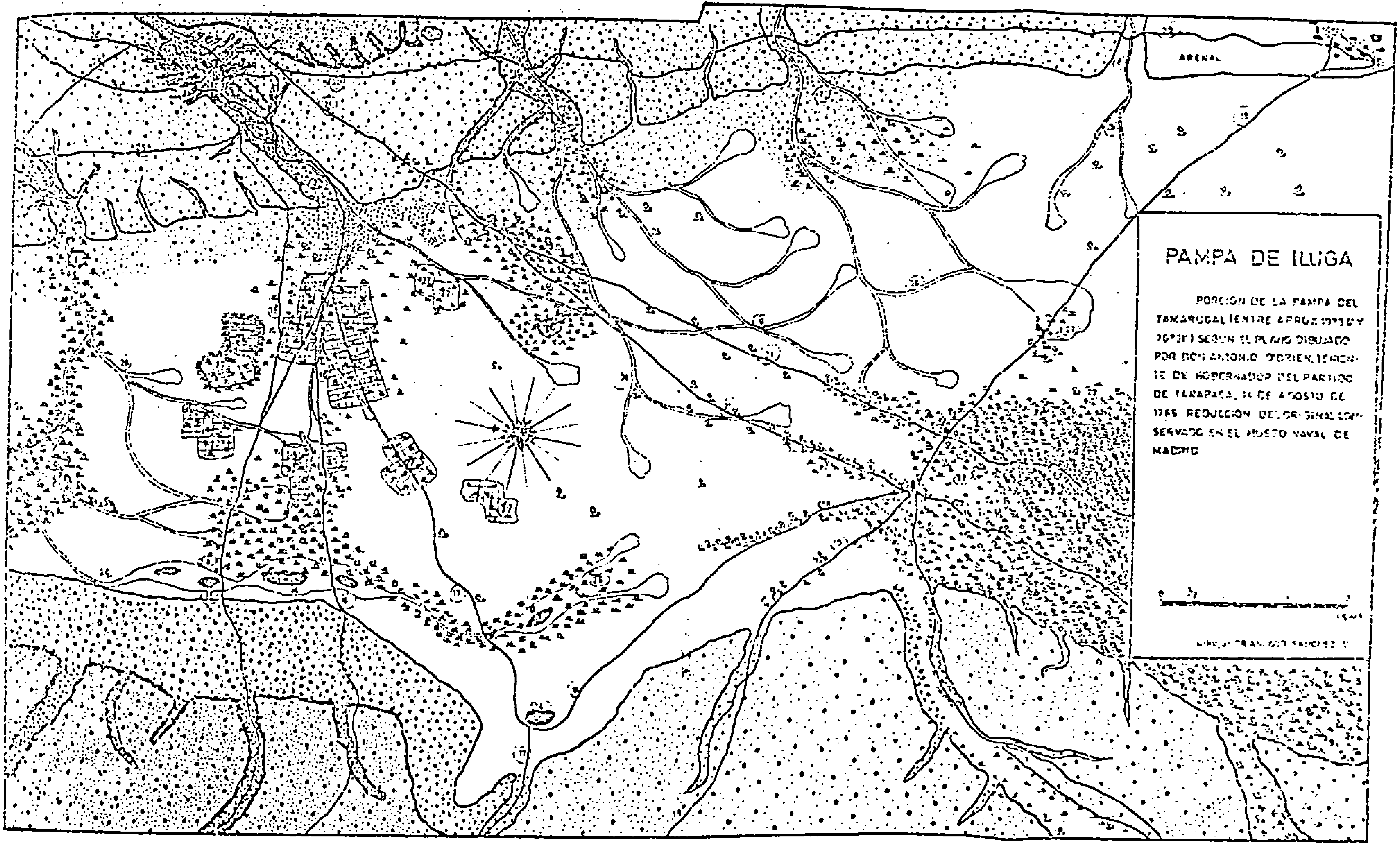

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Figure 2

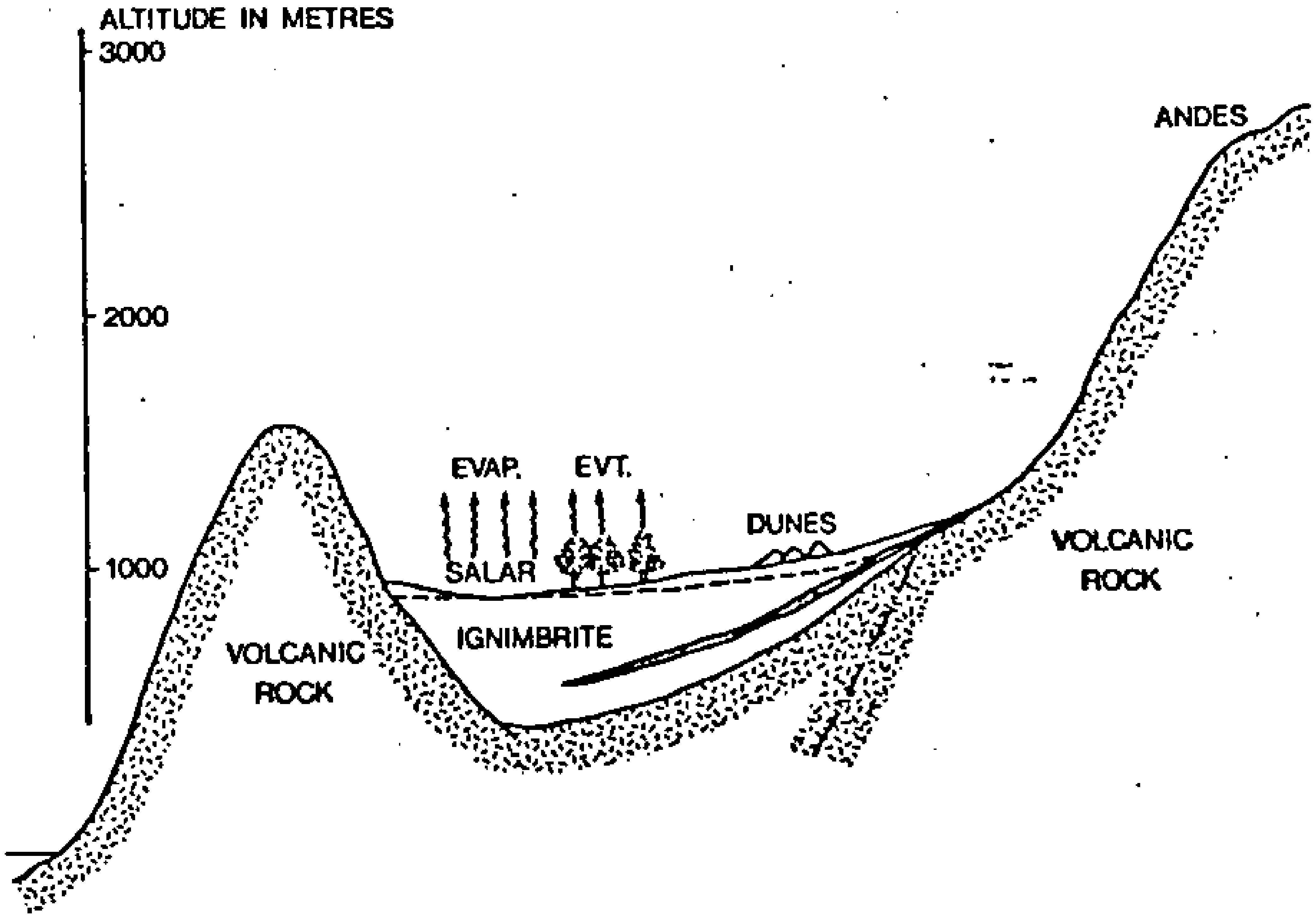


Figure 3: Simplified geologic cross-section through the volcanic rocks of the Front Ranges (Cordillera de la costa), the Pampa del Tamarugal and the rocks of the Andes.

materials from the Andes and several independent and closed sub-basins were established. The project area is located in one of these closed basins limited to the North by the Aroma valley which descends from the Andes and to the South by the Chacarillas valley and the Bellavista salar.

The aquifer within the basin are stratified with alternative lenticular clay-silt layers and coarse material of different permeabilities. The transmissivity of these deposits average 500 $m^3/d/m$, and in general they have a very low vertical permeability because of the interstratification of material with different contents of clay within the aquifers and the existence of the clay-silt layers. The main recharge to the aquifer must thus occur on alluvial fans at the mouth of the river valleys and in the river beds. At least two aquifers have been recognized and the general water movement is mostly from the North to the South, but East to South-West for the upper aquifer which begins just south of the Juan de Morales valley, crosses the Canchones region and terminates in the Salars near Of. Victoria. There the water table is close to surface and water is lost by evaporation from the salars. Going north and east the depth to water table can exceed 50 m.

3. SAMPLING PROGRAMME AND RESULTS

For the past twenty years or so a large number of chemical analyses were done on samples from the project area. Unfortunately this information has only qualitative importance because all hydrogeologic projects used chemical analysis only for water quality determinations. Very large variations in the chemical load of surface waters feeding these aquifers have been recognized and a detailed sampling and analytical programme is needed before a comprehensive interpretation is possible. Therefore, in this study, chemical analyses are only used to aid in the interpretation

Table 1: CHEMICAL ANALYSES

				DISSOLVED COMPOUNDS (mg/L)							
Location	No	^{o}C	pH	Ca	Mg	Na	K	Cl	SO_4	HCO_3	SiO_2
GROUNDWATERS											
Juan de Morales	G-2	27	7.7	153.0	5.4	90.0	19.0	114.0	376.0	71.0	54.0
Luzlali	G-5	17	7.8	153.0	19.2	--	--	210.0	304.0	105.0	84.3
Canchones Dos	G-6	26	7.9	52.0	6.0	152.0	10.0	80.0	290.0	99.0	76.0
Canchones Corfo	G-7	25	8.1	116.0	22.0	184.0	20.0	137.0	369.0	266.0	94.0
Cuminalla	G-8	25.5	7.5	96.0	9.4	176.0	13.0	117.0	413.0	88.0	73.0
Esmeralda	G-9	26	8.0	66.0	6.0	173.0	6.8	113.0	289.0	151.0	65.0
Chintaguay	G-11	31.5	7.6	23.0	0.1	56.0	1.6	52.0	52.0	84.0	44.0
Pintados A.P.	G-14	22.5	7.9	20.0	4.0	660.0	29.0	715.0	250.0	306.0	21.0
Pintados Cat	G-16	27	8.0	9.5	1.0	145.0	9.6	82.0	115.0	143.0	82.0
Victoria	G-17	25	6.9	30.0	8.5	222.0	19.0	210.0	197.0	120.0	87.0
SPRINGS											
Puchultisa	S-2	14	6.9	7.2	3.9	9.7	4.7	8.0	8.0	51.0	42.0
Checura	S-9	12	7.0	15.0	8.2	11.0	2.2	7.5	28.0	70.0	53.0
Chiapa 1	S-35	10.5	6.9	32.0	14.0	53.0	9.8	51.0	59.0	157.0	83.0
Chusmiza Cruce	S-10	10.5	7.2	31.0	0.2	150.0	4.5	59.0	279.0	44.0	66.0
La Batea	S-19	18	6.8	8.2	1.8	27.0	4.4	9.2	23.0	63.0	61.0
Sagasca	S-18	24	8.1	201.0	9.7	320.0	16.0	115.0	905.0	122.0	49.0
Miraflores	S-27	28	8.4	21.0	--	47.0	0.8	25.0	37.0	95.0	42.0
Puquio Nuñez	S-29	22	8.9	8.0	--	110.0	2.2	71.0	88.0	66.0	79.0
RIVERS											
Aroma at Curaña	R-1	16	8.48	144.3	18.9	--	--	1116.0	380.0	233.1	83.7
Tarapaca at Mocha	R-2	18	7.42	112.0	28.0	285.0	22.0	259.0	471.0	236.0	67
Piga	R-7	14	6.9	19.0	13.0	24.0	6.9	5.0	23.0	155.0	65
Collacagua	R-6	12	7.08	47.0	22.0	36.0	7.7	12.0	73.0	249.0	47

Table 2: ISOTOPIC CONTENT OF PRECIPITATIONS

LOCATION	NO.	PERIOD	PRECIPITATION mm	δ^2H $^o/_{oo}$	$\delta^{18}O$ $^o/_{oo}$
APACHETA TAPA	6	Dec/73-Jan/10/74	11.0	-72	-11.4
4350 m.a.s.l.		Jan/10/74-Feb/20/74	165.2	-136	-19.3
		Feb/20/74-Apr/11/74	35.7	-101	-15.5
		Wt. Means 1974	221.9	-121	-17.4
		Dec/16/74-Apr/12/75	83.0	-111	-15.5
		Wt. Means 1975	83.0	-111	-15.5
CHUSMIZA	8	Jan/9/74-Feb/20/74	107.3	-49	-7.7
3360 m.a.s.l.		Feb/20/74-Apr/11/74	29.6	-48	-8.1
		Wt. Means 1974	136.9	-49	-7.8
		Dec/18/74-Apr/15/75	174.9	-49	-7.3
		Wt. Means 1975	174.9	-49	-7.3
ALTO MOCHA	9	Jan/8/74-Feb/20/74	65.3	-44	-7.2
2590 m.a.s.l		Feb/20/74-May/18/74	2.5	-37	-5.4
		Wt. Means 1974	67.8	-44	-7.1
MOCHA	10	Jan/9/74-Feb/20/74	52.2	-35	-5.7
		Feb/20/74-Apr/15/74	27.1	-18	-3.4
		Wt. Means 1974	79.1	-29	-4.9
COLLACAGUA	12	Jan-1973	85.0	-87	-12.0
3915 m.a.s.l.		Feb-1973	100.1	-90	-12.2
		Wt. Means 1973	185.1	-89	-12.1
		Dec/73-Jan/10/74	14.0	-48	-7.1
		Jan/10-Feb/7/74	144.0	-117	-16.1
		Feb/07-Mar/20/74	Small Q.	-70	-10.4
		Wt. Means 1974	158.0	-111	-15.3
		Jan-1975	68.0	-144	-19.8
		Feb-1975	132.5	-118	-16.8
		Mar-1975	32.0	-90	-12.5
		Wt. Means 1975	232.5	-122	-17.1
HUASCO	13	Jan/9-Feb/7/74	54.8	-115	-16.3
3800 m.a.s.l.		Feb/7-Apr/9/74	44.6	-145	-18.3
		Apr/9-Dec/19/74	4.5	-110	-15.6
		Wt. Means 1974	103.9	-128	-17.1
INDIO MUERTO	14	Jan/10/74-Feb/7/74	43.9	-142	-19.2
4135 m.a.s.l.		Feb/7/74-Apr/9/74	11.0	-127	-18.2
		Apr/9/74-Dec/12/74	5.5	-118	-15.7
		Wt. Means 1974	60.4	-137	-18.7
		Dec/12/74-Apr/16/75	151.8	-127	-18.1
		Wt. Means 1975	151.8	-127	-18.1
TAMBILLOS	15	Jan/10/74-Feb/7/74	102.5	-50	-8.3
3300 m.a.s.l.		Feb/7/74-May/5/74	9.6	-64	-9.0
		Wt. Means 1974	112	-51	-8.4
		Dec/19/74-Apr/15/75	119.3	-49	-7.7
		Wt. Means 1975	119.3	-49	-7.7
APACHETA MAMA 4115 m.a.s.l.	16	Jul/30/73-Dec/74	77	-146	-19.9

Table 3: ISOTOPIC CONTENT OF SPRINGS

AROMA RIVER BASIN

NAME	LOCATION NO.	$\delta^{2}H\ ^{o}/_{oo}$	$\delta^{18}O\ ^{o}/_{oo}$	$\delta^{13}C\ ^{o}/_{oo}$	T.U.	^{14}C-pmC
PUCHULTISA 1	S-1	-83	-9.8			
PUCHULTISA 3	S-2	-97	-11.0			
TUJA	S-3	-92	-10.0			
PUCHULTISA 2	S-4	-94	-10.3			
SOTOCA (*)	S-6	-44	-6.9			
K[illegible]INA POTOSI (*)	S-8	-82	-11.4			
CHECURA	S-9	-89	-12.3		<0.5	
CHIAPA 2 (*)	S-34	-68	-9.3			
CHIAPA 1 (*)	S-35	-67	-8.7			
RIVER AT CURANA	R-1	-77	-9.0	-1.3	2.5±0.3	95.2

TARAPACA RIVER BASIN

NAME	LOCATION NO.	$\delta^{2}H\ ^{o}/_{oo}$	$\delta^{18}O\ ^{o}/_{oo}$	$\delta^{13}C\ ^{o}/_{oo}$	T.U.	^{14}C-pmC
CHUSMIZA TERMA	S-5	-69	-9.0			
CHUSMIZA CRUCE	S-10	-43	-5.8			
CHUSMIZA (*)	S-11	-64	-8.3			
GUARASINA (*)	S-12	-80	-9.3			
INDIO MUERTO 1(*)	S-13	-50	-7.7			
INDIO MUERTO 2(*)	S-14	-52	-7.2			
AGUAS CALIENTES	S-15	-104	-13.2			
AGUAS CALIENTES	S-16	-107	-13.5			
LAS CUEVAS	S-36	-100	-12.8			
TARAPACA	S-38	-80	-9.3			
RIVER AT MOCHA	R-2	-87	-10.7	-2.8	2.1±0.4	110.4
RIVER AT PACHICA	R-3	-87	-10.3			
RIVER AT GUARASINA	R-4	-84	-9.7			

(*) ONE SAMPLE

Table 3 (cont'd)

ISOTOPIC CONTENT OF SPRINGS

TAMBILLO - J. de MORALES BASIN

NAME		LOCATION NO.	$\delta^{2}H$ ‰	$\delta^{18}O$ ‰	$\delta^{13}C$ ‰	T.U.	^{14}C-pmC
SAGASCA		S-18	-49	-6.4	-7.2	1.2±0.5	85.7
MAMINA TERMAS	(*)	S-31	-66	-9.0		4.3±0.5	
MAMINA Mg	(*)	S-32	-65	-8.7			
MAMINA Ra	(*)	S-33	-68	-8.9			
RIVER AT SAGASCA	(*)	R-12	-49	-5.9			

SALAR DEL MUASCO BASIN AND PICA AREA

NAME		LOCATION NO.	$\delta^{2}H$ ‰	$\delta^{18}O$ ‰	$\delta^{13}C$ ‰	T.U.	^{14}C-pmC
L[illegible] BATEA	(*)	S-19	-101	-12.9			
CHALLAVINTO	(*)	S-20	-97	-12.6			
POTRERO		S-21	-99 ✓	-12.0		<0.5	
LAGUNA		S-22	-100 ✓	-12.2			
HUASCO LIPEZ		S-23	-102 ✓	-13.0			
SIN NOMBRE		S-24	-102 ✓	-12.9			
CONCOVA		S-26	-106	-13.1		<0.5	
MIRAFLORES		S-27	-106	-13.0	-5.8	<0.5	30.0
RESVALADERO		S-28	-105	-13.2			
CHARVINTO CREEK		R-5	-96	-12.5		15.3±0.8	
PIGA RIVER		R-7	-105	-12.8	-0.53	9.3±0.9	47.6
COLLACAGUA RIVER							
[illegible]T COLLACAGUA		R-6	-94	-11.5			
AT 5 Km FROM 6	(*)	R-13	-94	-10.3			
AT 15 Km FROM 6	(*)	R-8	-86	-9.3			

ORIENTAL EDGE

NAME	LOCATION NO.	$\delta^{2}H$ ‰	$\delta^{18}O$ ‰	$\delta^{13}C$ ‰	T.U.	^{14}C-pmC
LA CALERA	S-25	-57	-7.5	-8.4	2.3±0.5	47.5
PUQUIO NUNEZ	S-29	-90	-11.0	-6.9	<0.5	43.9

(*) ONE SAMPLE. All other samples are average values obtained on samples from more than one sampling.

Table 4:

ISOTOPIC CONTENT OF GROUNDWATER

PAMPA DEL TAMARUGAL

NAME	LOCATION NO.	δ^2H ‰	$\delta^{18}O$ ‰	$\delta^{13}C$ ‰	T.U.	^{14}C-pmC
DUPLIJZA	G-1	-79	-9.9	-8.4	--	62.3
J. de MORALES	G-2	-55	-7.0	-9.6	0.7±0.3	50.6
TIRANA FR	G-3	-78	-10.4	--	--	--
TIRANA DR	G-4	-80	-10.5	--	--	--
LUZLALI	G-5	-80	-10.1	-11.2	1.7±0.1	35.9
[illegible]CHONES DOS	G-6	-53	-6.7	9.51	<0.5	14.7
CANCHONES CORFO	G-7	-54	-7.2	-10.1	--	23.1
CUMINALLA	G-8	-56	-7.2	--	--	--
ESMERALDA	G-9	-89	-10.5	-12.1	2.4±0.3	96.8
CERVELINO	G-10	-80	-9.7	--	--	--
CHINTAGUAY	G-11	-105	-13.2	--	--	--
STA. ROSA	G-12	-72	-8.9	--	0.9±0.4	--
AURRERA	G-13	-87	-10.1	--	--	--
PINTADOS AP	G-14	-87	-10.5	-9.7	2.1±0.3	46.8
PINTADOS C	G-15	-86	-10.9	-12.9	--	22.3
PINTADOS CAT	G-16	-77	-9.2	-10.5	--	6.1
VICTORIA	G-17	-73	-8.6	--	--	--
P[illegible]UE VICTORIA	G-18	-74	-8.4	--	--	--
DUNOY	G-19	-68	-8.2	--	--	--
PICA DOS	G-20	-103	-12.5	-8.7	<0.5	94.8

1) The δ^2H and $\delta^{18}O$ data reported are average values of 3-10 samples per well collected between 1972 and 1977. All wells are isotopically stable and the standard deviation (1σ) for ^{18}O is below ±0.3 ‰ and for deuterium below ± 2.5 ‰. Samples for carbon isotope data and tritium analyses were colleced between 1976 and 1978 and are individual measurements.

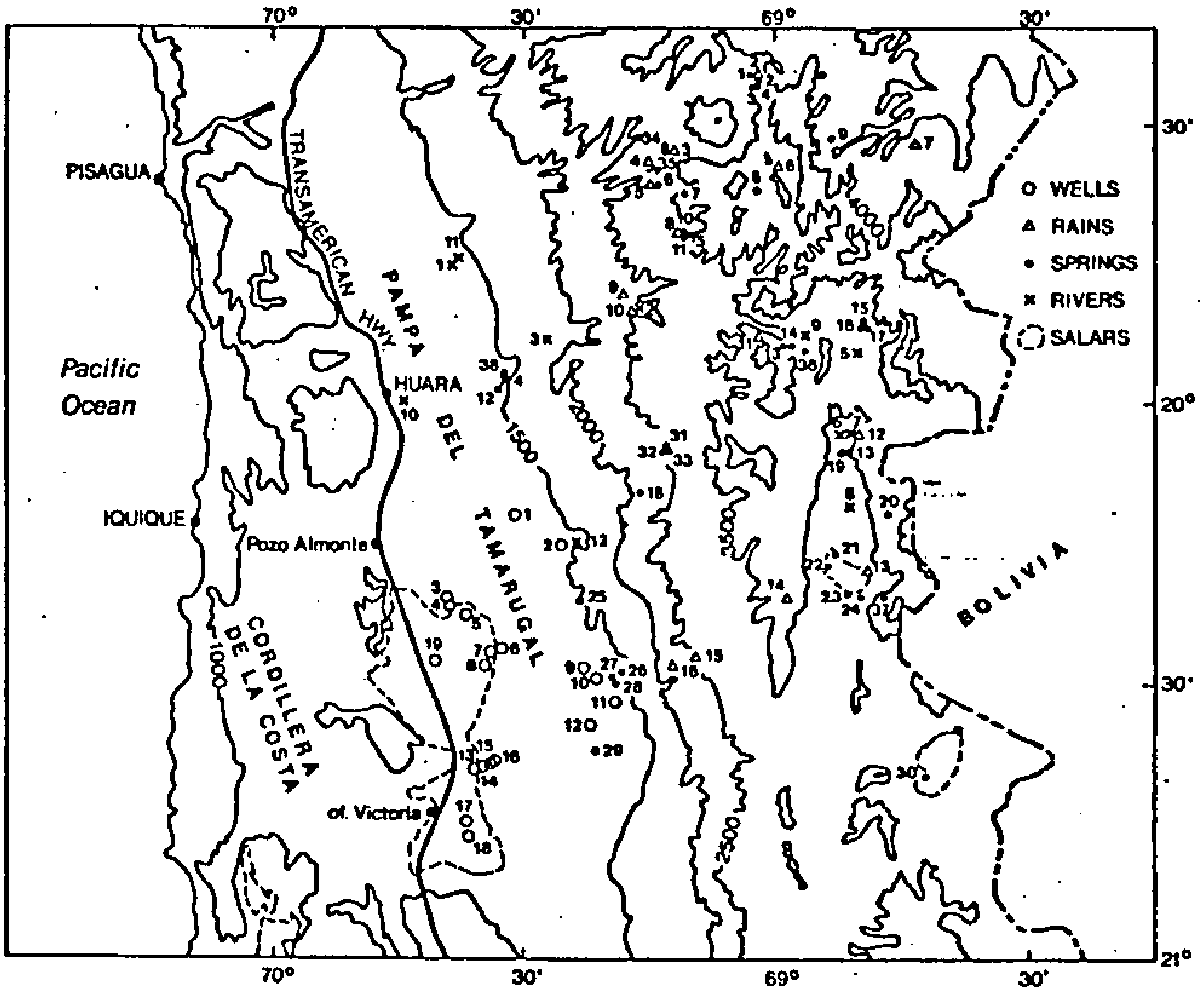


Figure 4: Sampling points in the project area. Note that on tables different types of water are given with a letter prefix which was deleted here for clarity.

of carbon-14 data and to provide a very basic picture of the geochemical evolution of these waters. A summary of the results is found in Table 1.

The sampling programme for ^{18}O, ^{2}H and ^{3}H determinations was initiated in 1972, and until 1974 was carried out in collaboration with the Geological Survey of Chile. Several hundred samples from wells, springs, rivers, salars and evaporation pans were analyzed. Also initiated was a precipitation survey using funnel-and-bucket arrangements with small amounts of liquid paraffin to collect seasonally integrated samples. Initially, much of the effort centered on the Salar del Huasco drainage basin (Figure 1) but the sampling programme was subsequently extended to cover a much larger area and then also included ^{13}C and ^{14}C sampling for attempts to date the groundwater occurrences in the Pampa. The precipitation sampling programme had to rely on one meteorological station for climatic data, otherwise the samples were simply placed at random throughout the project area. Sampling points for the recent environmental isotope programme are shown in Figure 4 and Tables 2-4 list the results of the environmental isotope analyses.

The ^{18}O and ^{2}H analyses are reported with reference to SMOW in the conventional δ $^{o}/_{oo}$ notations, all ^{2}H and part of the ^{18}O analyses we have done at CENA, Piracicaba, and most ^{18}O analyses were done in the laboratories at the Comision Chilena de Energia Nuclear. The overall precision is ± 0.15 $^{o}/_{oo}$ for ^{18}O and ± 1 $^{o}/_{oo}$ for deuterium. Tritium analyses were also done in this laboratory and are expressed in Tritium Units (T.U.). Carbon isotope analyses were mostly done at the University of Waterloo, and results of ^{13}C determinations are expressed with reference to the PDB standard with an analytical precision of ± 0.10 permil but overall reproducibility of about ± 0.7 $^{o}/_{oo}$. ^{14}C data are expressed as percent modern carbon (pmC) which is defined as 95% of the ^{14}C activity of the oxalid acid standard distributed by the National Bureau of Standards.

4. DISCUSSION

The hydrogeology of the project area is very complex, not only because the aquifers in the Pampa are still ill defined and, at present, cannot be sampled individually, but also because fracture flow over long distances may be important: springs which occur at the foot of the Andes must have their recharge areas at high altitudes, and water is probably transmitted through fractures etc. in tuffs and lava flows. Thus, the interpretation of many aspects of the hydrogeology of the project area is still incomplete although a broad picture does emerge.

4.1 Precipitation

The $\delta^{18}O$ and $\delta^{2}H$ values in precipitation show, in most areas of the globe a well defined relationship which depends largely on the history of the air masses (Craig, 1961). Thus it is important to note that the precipitation in the Andes of Northern Chile do not originate in the Pacific but come from the Bolivian Altiplano. Thus moisture should pass through the Amazonas basin and arrive as rain during the Bolivian winter (December to March) via the Altiplano (~ 4000 m in altitude) in Northern Chile. The history of these air masses is thus rather complex and one might expect some special $\delta^{18}O$ - $\delta^{2}H$ relationships. However, this is not the case and as Figure 5 documents a very well defined meteoric waterline is found where

$$\delta^{2}H = (7.8\ \delta^{18}O + 10.3)\ ^{o}/_{oo}$$

Precipitations from all altitudes are included (Table 2) and no evaporation

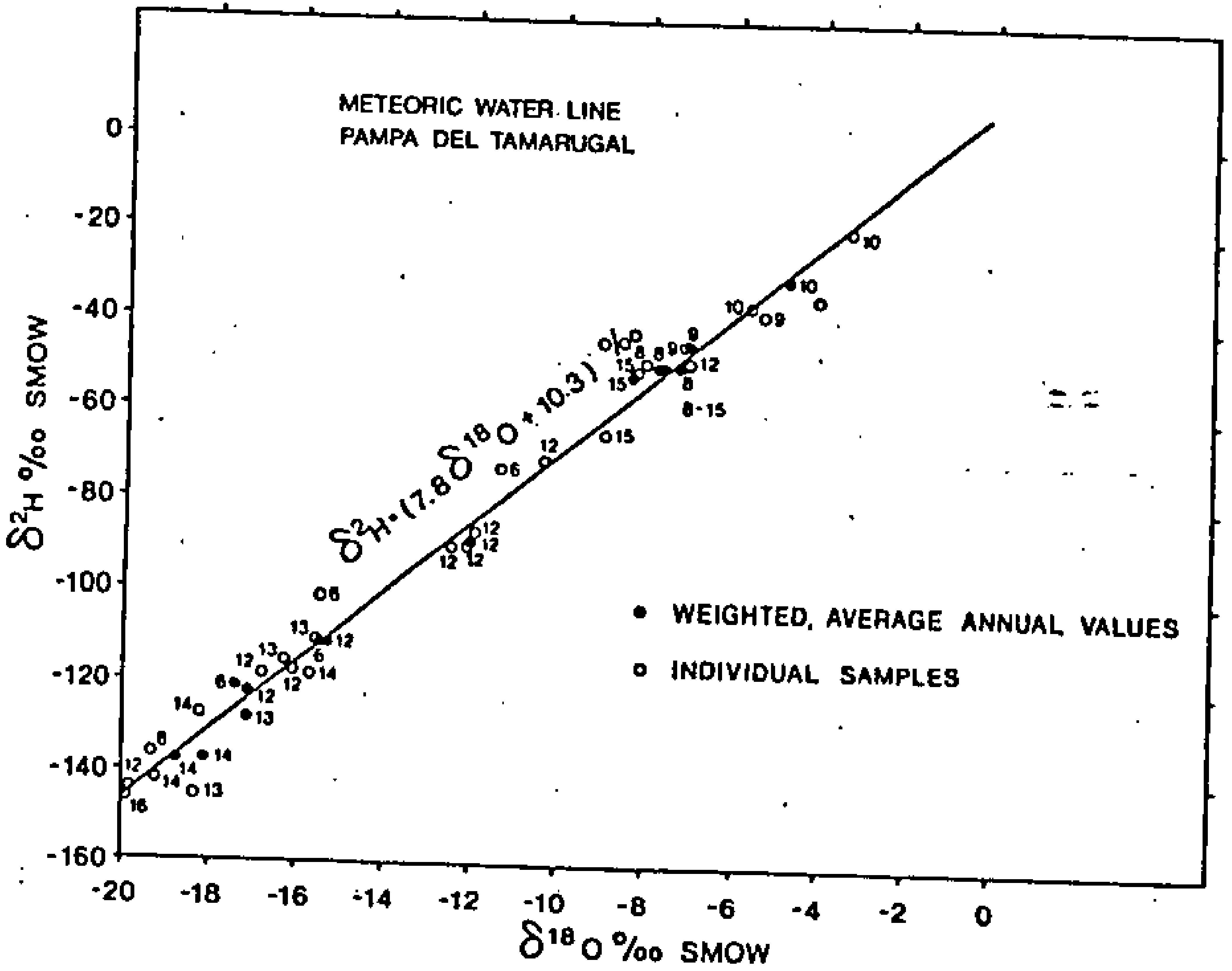


Figure 5: Meteoric waterline for all precipitation samples collected in the project area.

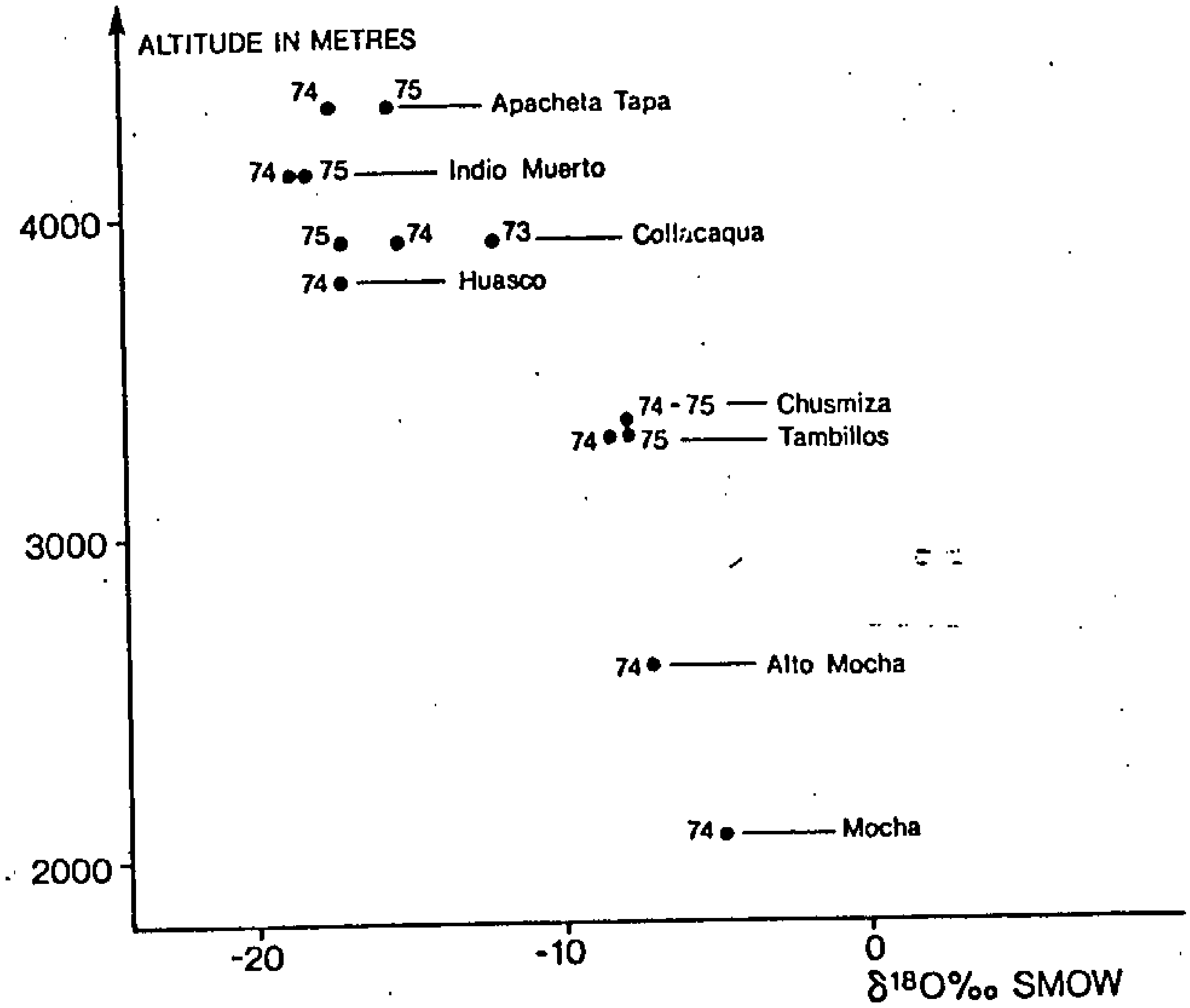


Figure 6: Oxygen-18 in average annual precipitation in the Cordillera de los Andes. Note the relatively weak altitude effect for springs between 2000 and 3000 m and the rigid decline in ^{18}O contents above 3500 m.

effects can be noted even for small rainfalls.

In a normal alpine environment, a decrease in heavy isotopes with increasing altitude is observed. For ^{18}O this amounts usually to 2-3 $^{o}/_{oo}$ per 1000 m rise and correspondingly higher values for ^{2}H. For example, Stowhas et al. (1975) find a decrease in $\delta^{2}H$ values of slightly less than 20 $^{o}/_{oo}$ in Central Chile. The recognition of these effects is important because they permit the use of ^{18}O and ^{2}H contents in groundwater and springs as indicators for the altitude of recharge. Figure 6 summarizes the data for this project area in Northern Chile and shows very significant altitude effects. They are, however, not well defined and seem to change with altitude. Thus little change is observed between 2000 and 3000 m or above 4000 m but a very major shift occurs at about 3500 m. This may be due to the limited number of sampling stations and also the fact that the average annual isotope content at every given station can show considerable variations. However, it also is a reflection of the complex history of these air masses which have already crossed the Andes before arriving in Northern Chile.

This has to be taken into account in any future project in these regions and it would be advisable to use a much closer net of precipitation stations, because it might well turn out that different sub-basins may show different but individually well-defined $\delta^{18}O$ - $\delta^{2}H$ relationship and altitude effects. An indication for this is seen south of the project area and was presented by Fritz et al. (1978).

4.2 Springs

The precipitation sampling programme experienced a number of difficulties and, therefore, it was decided to sample all accessible springs in the project area to obtain information about $\delta^{2}H$ - $\delta^{18}O$

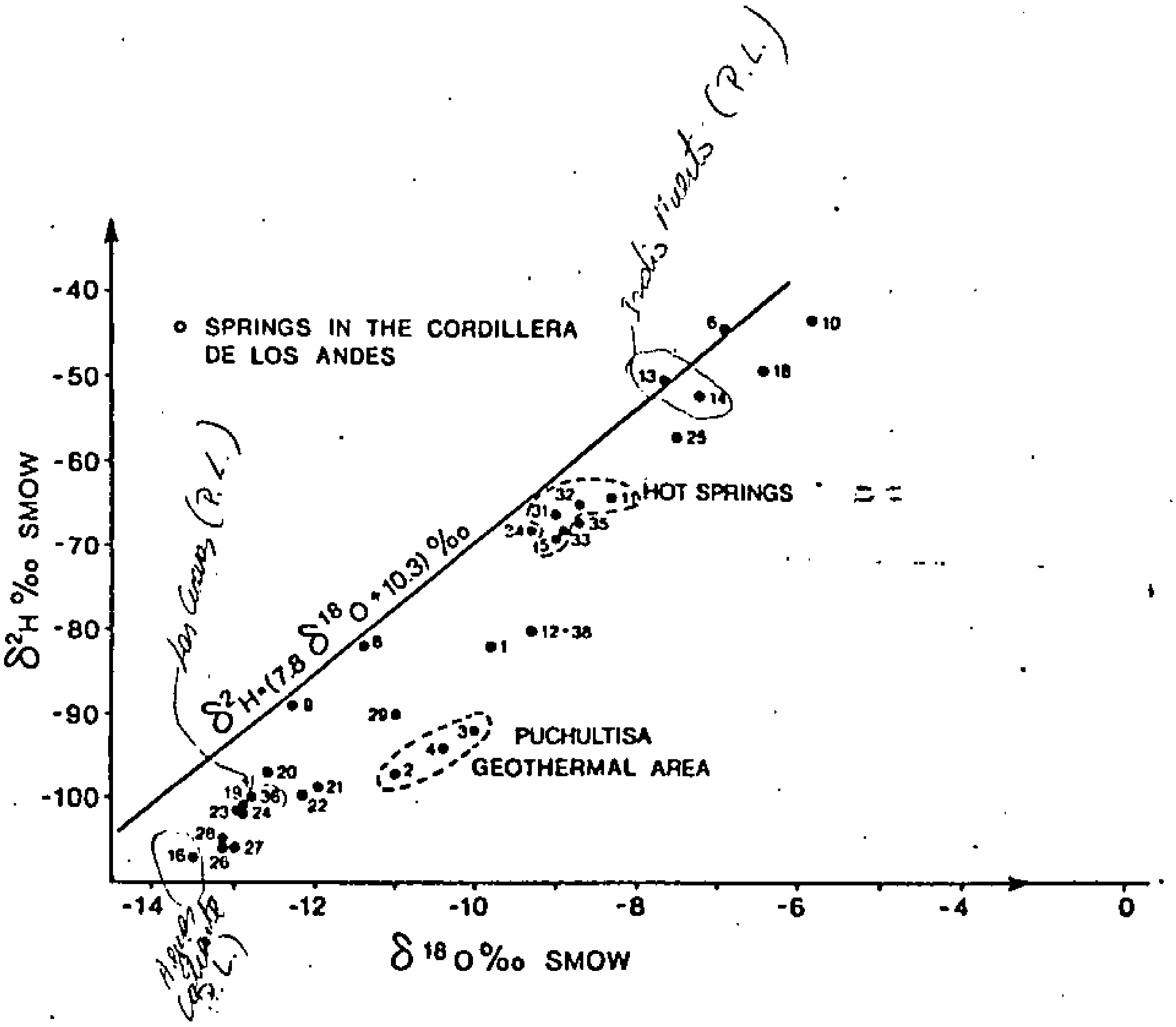


Figure 7. $\delta^{18}O$ and δ^2H values of springs in the project area. Note their displacement from the local meteoric waterline.

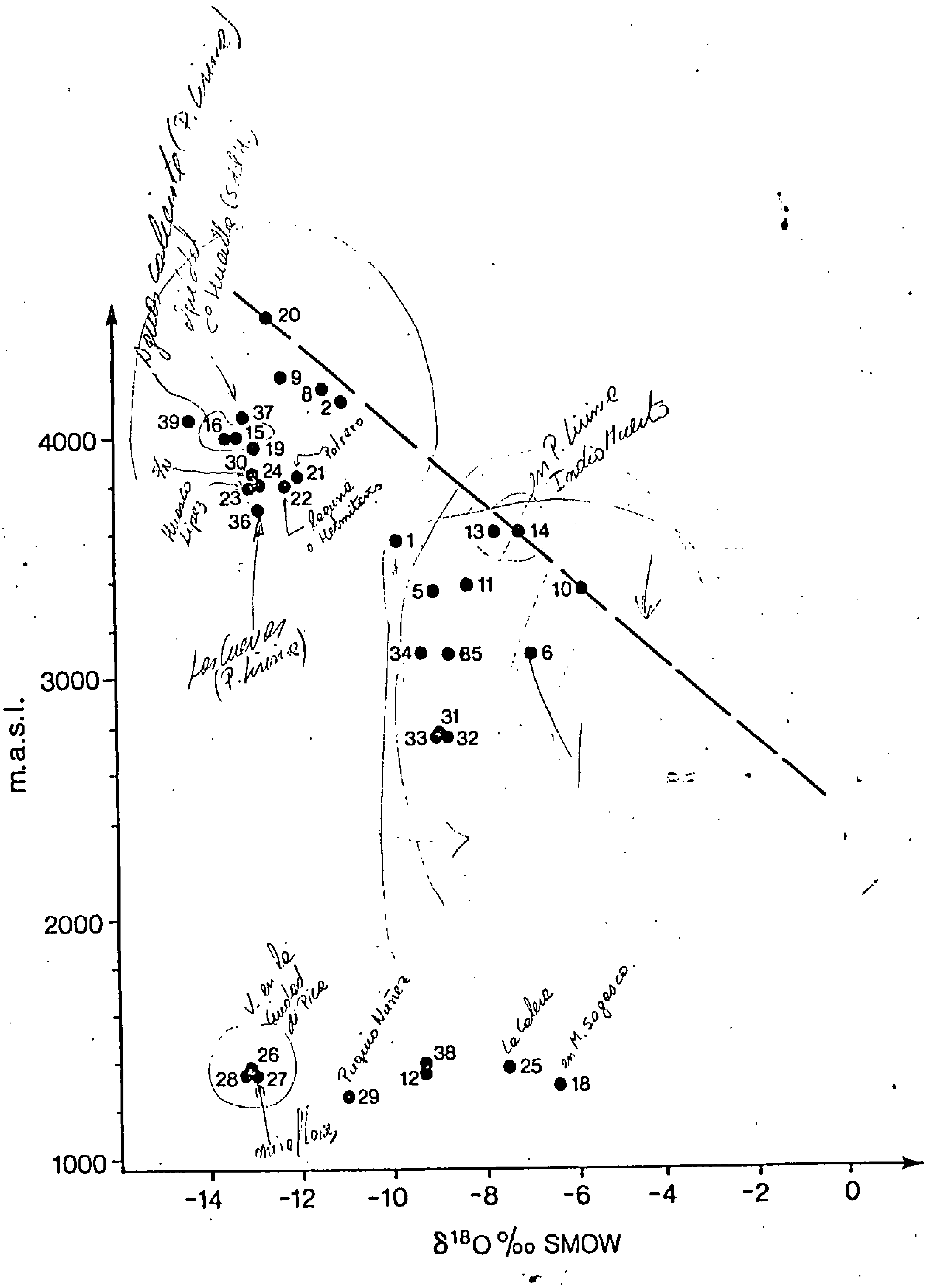


Figure 8. $\delta^{18}O$ values of springs are plotted versus altitude. The line above the sampling points denotes the approximate upper limit of recharge altitude. Note, that high altitude water can be found in springs at the foot of the mountains.

relationship in subsurface water, to derive approximate altitude affects and, with this, to obtain information about water movements in this terrain. δ^2H and $\delta^{18}O$ values of springs are shown in Figure 7, and Figure 8 compares the very variable $\delta^{18}O$ values with the altitude of discharge.

To deduct an altitude of recharge from these spring data the assumptions must be made that they represent the average isotopic composition of rainfall in the recharge area and show little or no seasonal variations. Analyses done on samples collected between 1972 and 1976 from the springs at Pica and the basin of the salar del Huasco show that these springs are isotopically very constant (± 0.3 ‰ for $\delta^{18}O$) and, therefore, the assumption is not unreasonable, especially if a large number of spring data can be compared.

The smoothing out of seasonal variations observed in local precipitations is an indication that many of these spring waters have a relatively long average residence time. Studies done in the Bavarian Alps (Homann et al., 1978) show that a complete disappearance of such variations can be expected with residence times exceeding about five years. Such long residence times are not unreasonable and are supported not only by the very low tritium concentrations (Table 3) but also the ^{14}C contents which vary between about 30 and 85 pmC.

Noteworthy is then also that only very few of these springs fall on the meteoric waterline which signifies that their water either has undergone evaporation before infiltration or is not related to modern precipitations in the area but reflect past climatic conditions during which precipitation data fell on a different meteoric waterline.

As will be shown below, evaporation from surface waters is an important process and affects not only the water balance of the local drainage basin but also the isotopic composition of its waters. However, most of the higher altitude springs cannot be related to infiltrating river water but are groundwater discharges from reservoirs which are replenished by infiltrating precipitations and possibly some snowmelt. This is supported by some ^{13}C analyses done on the aqueous carbonate of springs and rivers and for which negative $\delta^{13}C$ values were obtained for the spring waters but values close to 0 $^{0}/_{00}$ for the rivers. The latter reflects exchange with atmospheric carbon dioxide (see below) and the difference between the two can only be explained by infiltration through vegetated soil because no mechanism is known which could bring about a lowering of the $\delta^{13}C$ values in the subsurface.

Despite the relatively long residence times there is no real evidence to suggest that these spring waters are not related to modern precipitation but that their water infiltrated under somewhat different meteorological conditions during which precipitations had 5-10 $^{0}/_{00}$ less deuterium than modern waters, i.e. the meteoric waterline had a slope of ~ 8 but an intercept (d-value) of close to 0. The most simple explanation of the observed displacement from the meteoric waterline would be some evaporation before recharge. This would have to occur either from the soil surface (unsaturated zone) or during snowmelt. Such evaporation and associated enrichment has been observed in other arid environments (Verhaagen, 1975) and in soil column experiments (Leopoldo et al., 1974) and may also occur in the nearb basin of Rio Abaucan (N.W. Argentina) which was studied by Fontes and Molinari (1975) using environmental isotope techniques.

The $\delta^{18}O$ - altitude relationships in Figure 8 confirm, what has already been noted for the precipitation, namely that it is very difficult to deduce a well defined altitude effect from ^{18}O (or ^{2}H) data. Obviously, water which infiltrates at a certain altitude and discharges below this altitude difference may be variable. However, a maximum altitude of recharge based on the upper most points can be defined and is shown in Figure 8. This means the maximum value of ^{18}O found for a certain altitude, thus, the lower limit defines the minimum value of ^{18}O related to the altitude. Although it does not give a definite altitude of recharge for any spring it permits to put approximate limits on it.

Figure 8 shows springs which discharge in areas of possible recharge (above 3000 m) and springs which feed oasis at the foot of the Andes well below the potential recharge areas. For example, the springs at the oasis of Pica (S-26 to S-28) have the lowest $\delta^{18}O$ (and δ^2H) values of these lower springs yet their ^{18}O suggests that they recharged between 3800 and 4500 in altitude. These isotope contents are comparable to values found in the Salar del Huasco drainage basin which lies above 3800 m.a.s.l.

The springs of Sagasca (S-18) and Calera (S-25) have their recharge area close to or below 3500 m. Today, very little rainfall occurs at these altitudes and, therefore, they may belong to a dying hydrogeologic system which no longer receive any significant input. If this were the case, their yield would have to decrease with time. There are no records for any of these springs at the foot of the Andes to indicate whether indeed flow is decreasing. However, in other areas many contain large freshwater carbonate deposits around their discharge point which attests to higher flows during the past (Felsch, 1920; Fritz et al., 1978), able to support trees and other vegetation. No work on the carbonate sequences has been done yet but might prove to be quite interesting within a paleohydrologic investigation. Furthermore, all settlements had more cultivated areas in the past than today which is also an indirect indication that water supplies have decreased during the recent history of the project area.

The conclusion to be drawn from these spring data is then, that an altitude effect, although poorly defined, does exist and that a comparison is possible between springs discharging in the Andes with those delivering their water at the foot of the mountains. Also indicated is, that modern rivers do not feed and discharge in active spring systems and it is possible most of the water in today's springs recharged under slightly different climatic conditions.

Important to note is also that the ^{18}O and ^{2}H indicates that water movements within these volcanic rocks is significant and that even regional flow systems might exist--for example at Pica.

4.3 Surface Waters and Rivers

4.3.1 ^{2}H and ^{18}O

The Northern Chile is characterized by a great number of closed basins in which the terminal point of surface and sub-surface flows are the salares. (Stoerts and Carter, 19). Salares occur at all altitudes and only few rivers and creeks reach the foot of the Andes. The discharge of these is usually small (< 0.1 m^3/s). The study area in the Pampa del Tamarugal is the terminal point of one of the largest sub-basin in the project area and is fed by the rivers Aroma, Tacapaca, Juan de Morales, Quipisca, Quisma and Chararillas. Only the Aromas and Tarapaca reach the Pampa throughout the entire year, all others are seasonal and lose their water to the subsurface or by evaporation before they reach the Pampa. None flows through the Pampa, although, during major precipitation events all can flood significant portions of the Pampa. This, however, does not occur on an annual basis.

Water loss by evaporation is important in these arid or semi-arid environments and data to document its importance on isotopic compositions collected in the basin of the Salar del Huasco which is a closed basin in the Andean plateau. The Collacagua river fed by the tributaries Piga River and Charvinto creek reaches the salar during the rain season, were sampled between October 1972 and November 1975 at various points and the results are shown in Figure 9a. A significant deviation from the meteoric waterline is noted as a result of evaporation whose importance is further emphasized by the data from three sampling points along the Collacagua river where samples were taken during the same day. The sampling stations are about 5 km apart each.

The evaporative enrichment continues in the salar were samples were obtained from a shallow lagune. Results are plotted on Figure 9b and a very well defined δ^2H - $\delta^{18}O$ relationship can be as low as 4.1.

All rivers sampled in this study show a displacement from the meteoric waterline. In part this is due to the fact that most of these rivers are not fed by snowmelt or precipitation runoff but sustain their flow from groundwater (spring) discharges. Thus, the enrichment observed in the springs is also seen in the rivers. Additional isotopic enrichment does then occur within the rivers (see also Fontes and Molinari, 1975) and is responsible for the fact that no river sample in this study was close to the meteoric waterline. In all cases, the isotopic enrichments are much lower than those observed in the salares or the evaporation pans. This signifies that the disappearance of rivers is not due to total water loss by evaporation but mainly to infiltration into the subsurface. This is an important observation because the river water is thus not permanently lost but will appear somewhere else, either in the form of groundwater, for example in the Pampa del Tamarugal or as springs at the foot of the Andes.

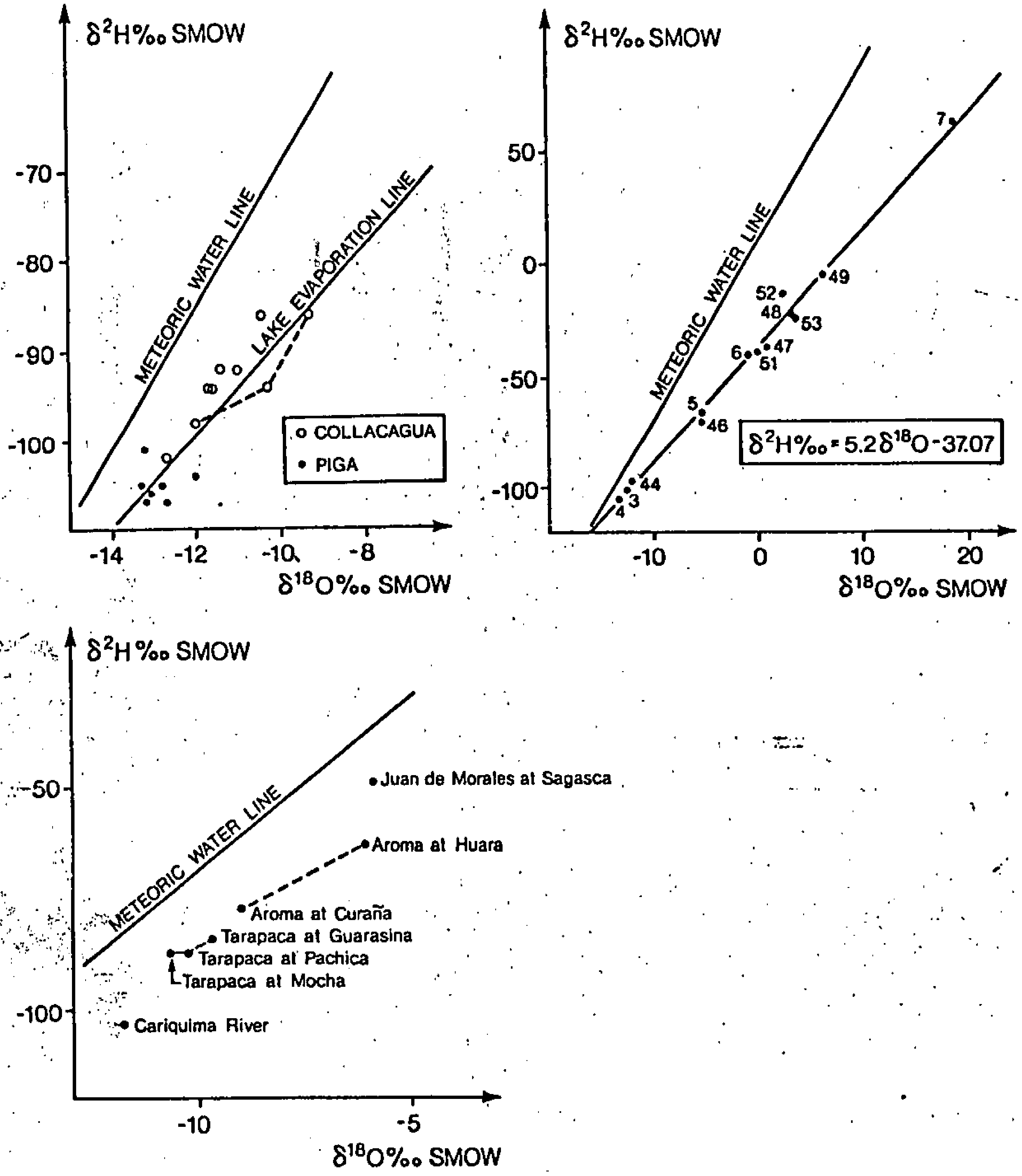


Figure 9. Isotope effects due to evaporation. a) Data from two creeks flowing into the Salar del Huasco b) evaporation in the Salar and c) evaporation effects in other rivers in the study area. The dashed line connects sampling points (same date) in the Collacagua river. Isotope enrichment by evaporation is clearly visible.

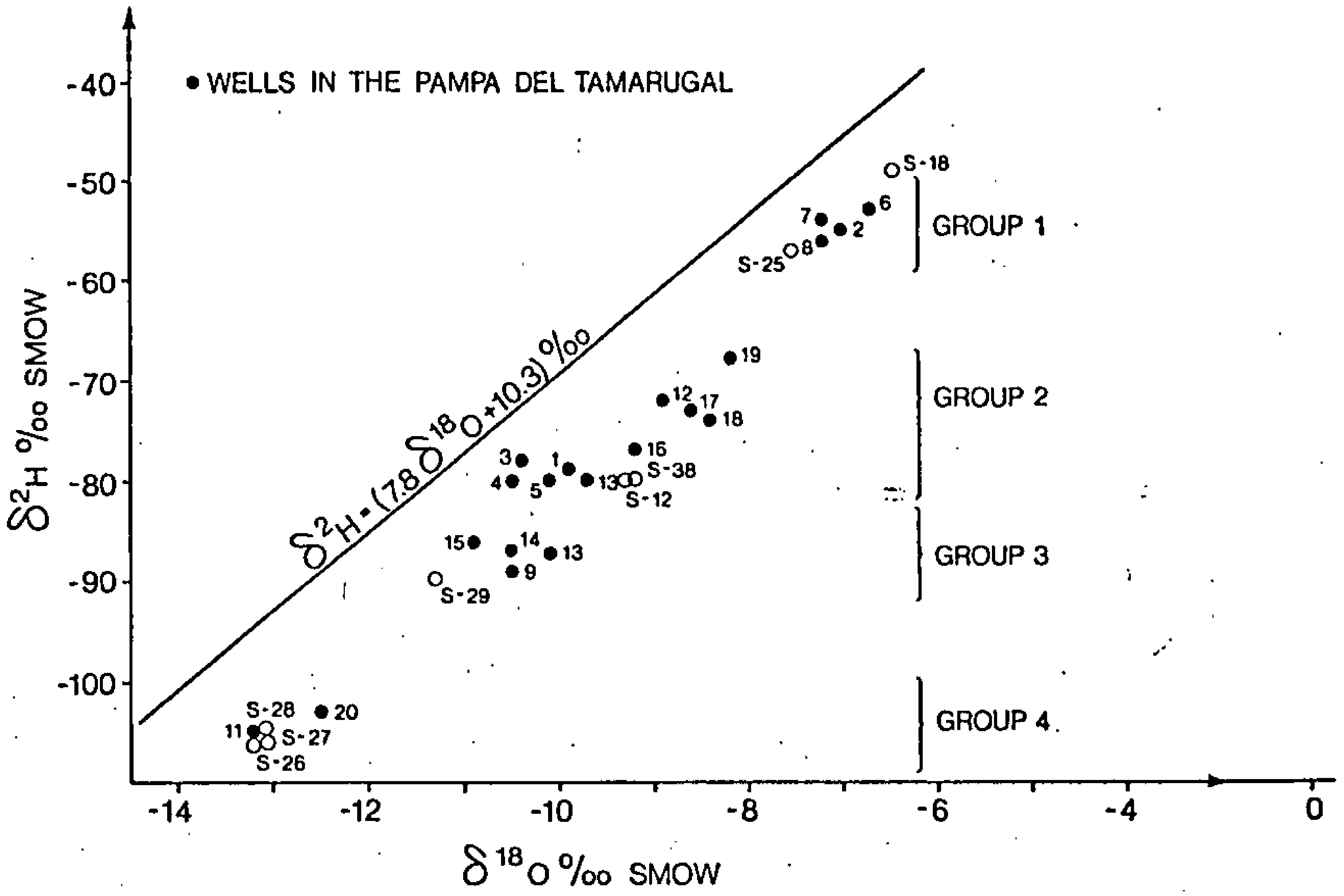
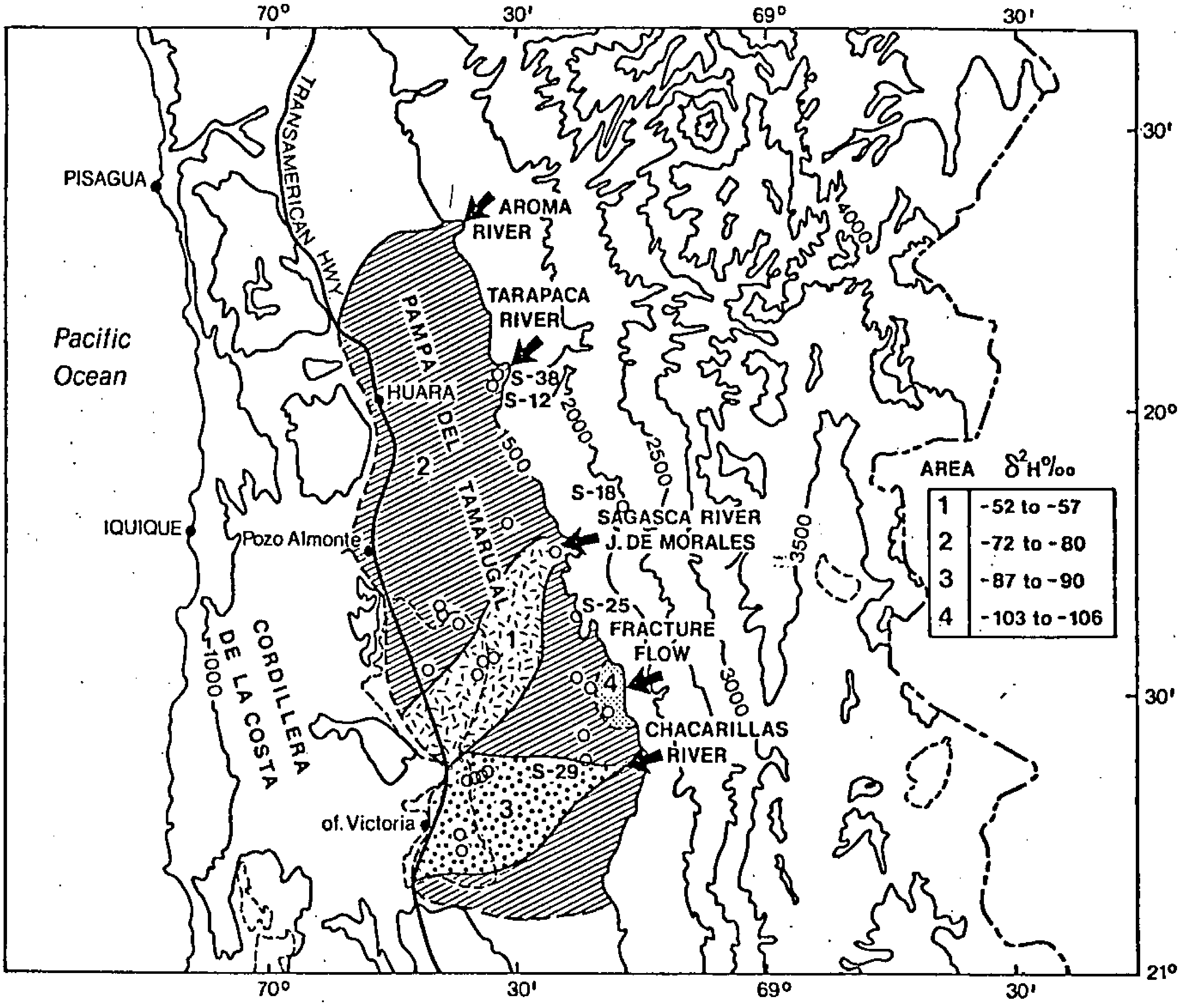


Figure 10. $\delta^{18}O$ and $\delta^{2}H$ values in groundwaters in the Pampa del Tamarugal



2H

Figure 11. Regional distribution of ^{18}O contents in groundwater of the Pampa del Tamarugal. The "regions of flow of a particular system" are drawn only approximately and need much refinement from additional boreholes.

4.2.2 Carbon Isotopes

To date groundwater with ^{14}C the initial ^{14}C activity of the infiltrating water has to be known. Since river water infiltration is potentially important for the groundwater reservoirs of the Pampa a number of carbon isotope determinations were made. The results are found in Table 3 and provide the following information:

Rivers in the high Andes are mostly fed by groundwater and close to the point of discharge the ^{14}C activity of the river reflects ^{14}C contents of the groundwater. Thus, the Piga River had at the time of sampling only 47.6 pmC. However, it also had measurable amounts of tritium, which then suggests that modern snow runoff was mixed with a groundwater which was either very old or lost its ^{14}C through exchange with volcanic CO_2 or carbonates (Fritz et al., 1978).

The carbon reservoir of a river exchanges then very rapidly with atmospheric carbon dioxide. This is seen in the Rivers Aroma and Tarapaca whose carbon isotopic compositions in the lower part is close to atmospheric equilibrium. Complete equilibration should result in a $\delta^{13}C \approx +2.0$ $^{o}/oo$ and a ^{14}C activity of ~ 130 pmC. The observed difference is due to incomplete equilibration and possibly some biologic CO_2 produced by algae etc. in the rivers.

A programme in progress is directed at elucidating the carbon geochemistry of Andean river system in this region and to describe isotope exchange processes which can affect their carbon isotopic compositions and tritium contents.

4.4 Groundwater

All isotope data obtained on groundwater samples from Pampa aquifers are listed in Table 4, ^{18}O and ^{2}H values are graphically shown in Figure 10.

4.4.1 ^{18}O and ^{2}H contents

Lack of precipitation in the Pampma del Tamarugal demands that the groundwater found today must have formed either much earlier under different climatic conditions or must represent the terminus of hydrologic systems whose origin is in the higher Andes. Regional groundwater flow through volcanic rocks, infiltration of river water and local recharge during periodic floods in the Pampa could thus replenish the groundwater resources of the Pampa. Against this background the very large spread in $\delta^{18}O$ and $\delta^{2}H$ values in these groundwaters is interesting. This spread excludes a single source and suggests that waters of different origin are found in these aquifers.

A comparison of $\delta^{18}O$ and $\delta^{2}H$ values in Figure 10 shows that also the Pampa groundwaters, like springs and rivers, do not fall on the local, present day meteoric waterline. This is a strong indication that rivers and groundwaters are genetically related and that disappearing rivers and periodic floods could contribute to the groundwater resources of the Pampa. It also could indicate that the Pampa groundwaters receive recharge at the present hydrological conditions.

In this context the regional distribution of $\delta^{18}O$ and $\delta^{2}H$ contents acquires a certain importance because it appears that different groundwater bodies or flow systems can be recognized. This is summarized in very general form in Figure 11. This regional distribution of isotope contents is rather surprising because a) sampling points in a borehole are not always well defined and some vertical stratification of aquifers does exist and b) if these waters are older than a few hundred years then the stable isotope contents of precipitations and river runoff may have been different from today's. However, no such shift is evident, although the available data may not suffice to recognize it as such.

The existence of at least two overlying aquifers has been recognized in areas where enough hydrologic drilling was done. Thus, Group 1 (Figure 10, 11) comprises wells of the Upper aquifer at Canchones (wells # G-6,-7,-8) and Juan de Morales (well # G-2) whose water probably originated in the Juan de Morales-Sacasca river valleys. Isotope data indicate that the precipitations feeding this system fell at altitudes below 4000 m.

Group 2 is not clearly defined and includes some deep wells. However, hydraulic data indicate flow from the Aroma and Taparaca Rivers towards the South West in an aquifer which underlies the shallow wells of groups 1a and 3. An example is well #G-16, Pintados Cat, whose isotopic composition distinguishes it from the other wells at this site. Surface discharge from this system occurs in springs at Guarasina (S-12) and Tarapaca (S-38). Figure 10 also shows well #G-9 (Esmeralda) as belonging to this group, although it is isotopically similar to group 3 samples. However, its origin is not clearly established because the well from which samples were taken could draw a mixture of group 2 and the isotopically depleated group 4 water.

Groupe 3, like group 2 is, because of lack of sampling points only approximately defined yet physiography, hydrological information and isotope data suggest that water entering the Pampa in or close to the Chacarillas River valley essentially moves in the area indicated for group 3. The spring at Puguio Nuñes is part of this system.

The groundwaters and springs at Pica form group 4 which is isotopically and chemically distinct; the total dissolved load does not exceed a few hundred mg/L and also the heavy isotope contents are the lowest of all waters analyzed in the project area. Their isotopic composition strongly indicates that they were generated at altitudes above 4000 m and were subject to the same type of evaporation noted already for all other surface and subsurface waters. Subsurface flow towards the springs at Pica from the high Andes must occur either as fracture flow or through porous volcanic strata.

4.4.2 Groundwater Dating

To verify the hydrogeological information a groundwater dating programme based on tritium and ^{14}C was initiated. Both, however, are only used in a qualitative manner because for tritium very little background information exists in this region and the carbon geochemistry of these waters is poorly understood.

Measurable amounts of tritium are found in a number of rivers and groundwaters, documenting that it is possible to recognize very young waters or waters which were exposed to the atmosphere during recent years. Isotope exchange during surface runoff or irrigation may well be the dominant mechanism which imparts tritium to these waters rather than direct runoff or infiltration of recent precipitations.

The importance of isotope exchange was already emphasized as an explanation for the high ^{14}C concentrations observed in rivers. Similarly the high ^{14}C contents in the wells at Esmeralda and Pica (96.8 and 94.8 pmC respectively) is almost certainly due to isotope exchange with atmospheric CO_2 during irrigation and return flow through vegetated soil and thus does not reflect the presence of young water. The observed ^{13}C contents ($-12.1\ ^{0}/_{00}$ and $-8.7\ ^{0}/_{00}$) respectively can be explained by open system exchange with soil-CO_2 at pH values between 7.0 and 8.5.

The soil-CO_2 composition has been measured at several localities and in different environments. From these measurements a value of $\delta^{13}C = -18 \pm 2\ ^{0}/_{00}$ was obtained in areas with vegetation whereas at one sampling point in the Pampa proper with very discontinuous vegetation a value of -12.0‰ was obtained. The results are in agreement with those reported by Fritz et al. (1979), for the Salar de Atacama.

For wells where irrigation-return flow is not evident the $\delta^{13}C$ values are similar to those mentioned above and the question arises whether their $\delta^{13}C$ contents too must be explained by open system equilibration with soil-CO_2, or whether closed system dissolution of carbonate minerals had occurred. No answer can be given, yet if open system equilibration would dominate the carbonate geochemistry of these waters then the measured ^{14}C activity would have to reflect actual water ages. These would range from approximately 4000 years at Dupliza to about 22,000 years in the deep well at Pintados (Table 4).

To evaluate groundwater ages, if closed system dissolution has occurred, an understanding of the geochemical evolution of these waters is necessary. Such information is, however, not available and correction models based on chemical data such as Ca, Mg, or Na concentrations are not applicable. The only approximation which could reflect the events is a carbon and ^{13}C balance. This approach was proposed by Ingerson and Pearson (1964) and results in the determination of an adjustment factor where

$$q = \frac{C_{initial}}{C_{final}} = \frac{\delta^{13}C_{DIC} - \delta^{13}C_{rock}}{\delta^{13}C_{soil-CO_2} - \delta^{13}C_{rock}} \text{ and } A_m = A_o . q . e^{-\lambda t}$$

with the underlying assumption that no addition of carbon occurs to the dissolved inorganic carbon (DIC) except through closed system dissolution of calcite or other carbonates ($\delta^{13}C_{rock}$) and that carbon is not lost from the system by any geochemical process. Whether these conditions are met or not is difficult to judge. However all groundwaters sampled are saturated and carbon loss in the subsurface is not impossible. The ^{13}C balance is thus the only adjustment procedure which may be applicable.

Assuming then that the $\delta^{13}C$ values of soil-CO_2 and rock carbon are -18%, and ±0.0% respectively, q can be determined. The thus adjusted ages are obviously much lower and would indicate that waters at Juan de Morales (well #G-2) are at best a few hundred years old, the shallow waters at Pintados (well #G-14) could be as old as 1000 years whereas the deep waters at this locality (#G-16) would be as old as 18,000 years.

How realistic these ages are is open to question. It is noteworthy, however, that all well waters for which contamination by irrigation return flow can be excluded have lower ^{14}C activities than the springs. This could be the result of geochemical dilution or decay. It is impossible to quantify either because the chemistry of the waters can vary significantly from one point to another within the same flow system as a consequence of soluble salts found in abundance throughout these deposits, especially as the western margin of the Pampa is approached.

5. SUMMARY AND CONCLUSIONS

The groundwater resources of the Pampa del Tamarugal are at present considered to be an integral component of the potential for future developments in this arid region. Municipal, industrial and agricultural expansions are based on these. However, the origin and future availability of these resources is in question because virtually no rainfall (< 1 mm/year) occurs in this region. The groundwaters thus either must be very old or recharge is maintained by water which arrives from the Cordillera de los Andes as surface or subsurface flow.

This study is a first attempt to use environmental isotope techniques to assess the origin and age of the groundwaters in the Pampa del Tamarugal. Background data based on analyses of precipitation samples, springs and surface waters in the project area have been accumulated since 1972 and the groundwater sampling programme was carried out between 1976 and 1978. Hydrogeologic information was assembled by the Departamentos de Recursos Hidraulicos del CORFO, Santiago and was available for this project. The conclusions reached in the present study agree to a large degree with those obtained from the hydrogeologic and geochemical investigations.

The ^{18}O and ^{2}H contents of precipitations in the project area show a well defined relationship which is described by

$$\delta^{2}H = (7.8\ \delta^{18}O + 10.3)\ ^{o}/oo$$

Also recognized are altitude effects which are, however, not clearly defined. Up to an altitude of about 3500 m the decrease in heavy isotopes with increasing altitude is similar to what is observed in a normal alpine environment or further to the South in the Cordilleras de los Andes in amounts to 2-3 $^{o}/_{oo}$ change for ^{18}O and correspondingly higher values for ^{2}H. However, above 3500 m a much larger decrease is noted. The reason for this is not evident and further precipitation surveys over a larger area are required before any firm conclusion can be reached.

The precipitation survey was paralleled by analyses of spring waters in order to obtain additional information about possible altitude effects, residence times of groundwaters and general information about the distribution of ^{18}O and ^{2}H in the subsurface waters of the higher Andes. Two remarkable observations were possible: a) the residence time of much of the waters discharging today at these springs exceeds several years, an observation supported by tritium and carbon isotope data and

b) regional groundwater flow in volcanic terraines is possible as documented by the springs at Pica. Furthermore, most of the spring waters were subject to some evaporation before infiltration. This process needs further investigation because it appears to occur in the unsaturated zone. This evaporative enrichment does not mark, however, altitude effects and it is possible to assign a maximum altitude of recharge to all springs.

Additional evaporation loss and isotopic changes as a consequence of it are recognized in all rivers which move within local drainage basins (e.g. the Salar del Huasco Basin) or which descend towards the foot of the Andes where they disappear in the alluvial fans at the eastern edge of the Pampa del Tamarugal. The isotope data show that infiltration rather than loss by evaporation is the principle reason for their disappearance.

Carbon isotope data show that exchange with atmospheric carbon dioxide dominates the aqueous carbon compositions of rivers--except where samples were collected close to their point of origin. This observation has importance for the interpretation of the carbon isotopic composition of groundwaters in the Pampa.

The range of $\delta^{18}O$ and $\delta^{2}H$ values noted in rivers and springs ($\delta^{18}O$ = -6 to -14 $^{0}/_{00}$) is also found in the Pampa groundwaters. Similarly the evaporation effects noted above is also observed in the groundwaters. This similarity and also the fact that these values do not vary at random throughout the Pampa but distinct flows related to specific springs or rivers are recognized, emphasizing that the groundwaters were recharged by surface and/or subsurface runoff from the Cordillera de los Andes. They are not the residual of a situation were direct precipitation recharge occurred in the Pampa during different climatic conditions.

Thus, recharge will also occur today, but probably in very limited amounts, although not enough information is available on subsurface recharge. Carbon isotope analyses strongly indicate, however, that all groundwaters sampled in this study infiltrated through vegetated soil and are not simply infiltrated river water. At present, such infiltration could occur in the quebradas or--if subsurface flow is dominant--in the higher Andes but in the past infiltration of surface runoff in the Pampa might have been possible.

Age determinations on these waters were attempted with ^{14}C and a range from modern activities to values as low as 6 pmC was obtained. The highest activities are observed in areas where isotope exchange with atmospheric CO_2 during irrigation and return flow through vegetated soil is possible. For others, the low ^{14}C activities are a strong indication that the waters are many thousands of years old. However, it is impossible to propose procedures which would permit the transformation of measured activities into water ages. The only approach taken is, therefore, based on ^{13}C analyses and yield adjusted ages between about 400 and 18,000 years. These age-estimates agree with hydraulic information, assuming that the present-day hydraulic gradients also existed in the past. Based on this information the groundwaters in the aquifers of the Pampa del Tamarugal must be considered as an essentially non renewable resource, although some minor recharge does occur along the foot of the Cordilleras de los Andes.

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