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CAMANCHACA AS A POTENTIAL RENEWABLE WATER RESOURCE FOR VEGETATION AND COASTAL SPRINGS ALONG THE PACIFIC IN SOUTH AMERICA

BY

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A N N E X

Exploitation of the Coastal Fog
(Translation of Text Received in Nairobi
from the Chilean Delegation attending the
UN Desertification Conference, September 1977)

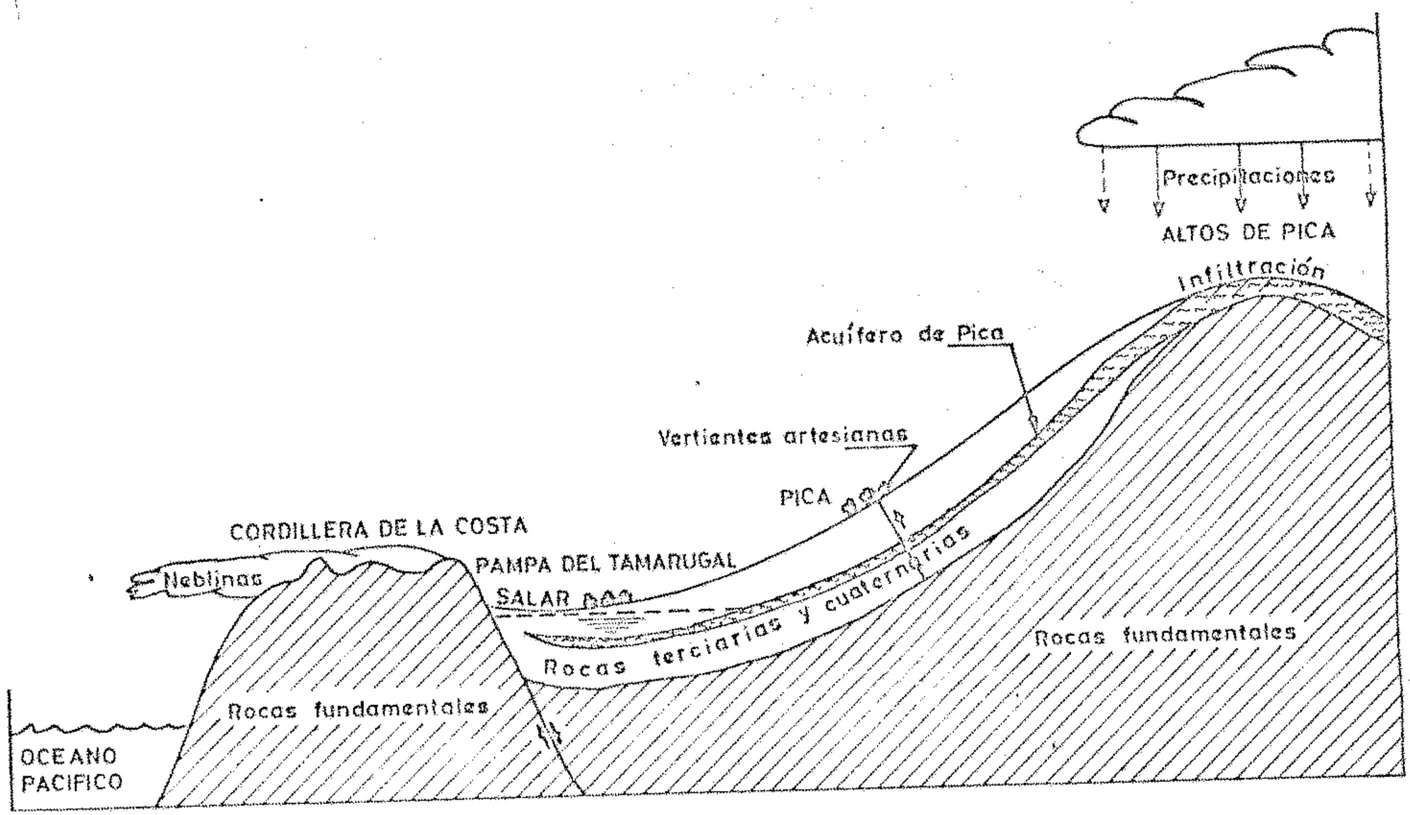
Camanchaca as a Potential Renewable Water Resource for Vegetation and Coastal Springs along the Pacific in South America

Introduction and Summary

Every hydrogeologist who has visited the impressive snow covered water divide between the Pacific and Atlantic Ocean in North Chile at only 200 to 300 km distance from the Pacific Coast, can not resist the idea that at least a small fraction of the melting waters may find its way somewhere through the subsoil to the Pacific Coast, this in spite of the extreme deserts separating the two mountain chains from the highest mountain range : the Coastal Cordillera with altitudes from 1100 to 2500 meters, and the Middle Cordillera with altitudes from 2500 to 4500 meters (Cordillera de Domeyko and its northern continuation Sierra de Moreno near Chuquicamata), which rise stepwise from the Pacific to the culminating Cordilleras de Los Andes with altitudes from 4800 to 6700 meters above sea-level. See Apollo photograph of Atacama desert (fig. 1), and tectonical interpretation of photo lineations in an active continental border (fig. 2).

This was the reason why the author after having participated to a stable isotope sampling programme of springs and mountain rivers in the higher areas between 2000 and 4300 meters, executed during the latter half of January 1971, started to collect on his own water samples of the sporadic springs in the lower coastal area from 0 to 1300 meters in the period from 13 May to 11 June 1971. This was during the time he was Acting Project Manager of the UN project (CHI-35) "Water Resources Development in the Norte Grande" in Chile.

The method used to find the origin of the scarce coastal spring waters was the examination of the stable isotope content of Oxygen 18. As no funds were allocated to finance the rather laborious analyses of the stable isotope samples, the author was glad to find Dr. W. G. Mook of the Physics Laboratory, University of Groningen, Netherlands, prepared to execute a part of the collected samples, while Dr. Eneas Salati of the Isotope Laboratory in Piracicaba near Sao Paolo, Brasil analysed some other samples as indicated in the list of the samples (Table I).



Perfil esquemático por los Altos de Pica (s. GALLI y DINGMAN, simplificado)

In contradiction with the expectations, the origin of the Pacific spring waters would appear to be from a local source. Since there is no precipitation (fig. 4) the only possible source is the cloud bank bounded at the upper side by a normally available temperature inversion layer (fig. 3 and fig. 5). This source of humidity is locally called "Camanchaca".

Although the data were discussed with Claudio Silva of the Chilean Nuclear Energy Commission also Scientific Organizer of the above mentioned sampling programme in the higher areas between 2000 and 4300 meters, and the sampling results were handed over to CORFO (Corporacion de Fomento de la Produccion, Chile) in November 1974, never a comprehensive report was produced on the matter. This was firstly due to the transfer in June 1972 of the author to the Unesco Regional Office of Science and Technology for the Arab States in Cairo Egypt were his occupations as Specialist in Environmental Sciences kept him busy, and secondly as no urgent reason existed to do so.

However, since the Chilean Government has the intention to make a constructive use of the waters contained in the Camanchaca or Nubes Rasantes which feed the low yield coastal springs, this last condition has changed (see annex 1 for Chilean proposal for the exploitation of the coastal mist). On the other hand also United Nations Environmental Programme UNEP has an interest in the subject, reason why as yet in November 1977 a report on the subject was written.

In the meantime also from the Chilean side already ongoing studies were continued and deepened mainly by Professor Hector R. Munoz and Professor Carlos Espinoza of the Universidad del Norte in Antofagasta. This should be seen as a complementary note to their fundamental studies which started as early as the sixties (see fig. 6 photo made before 1970 and used in 1c of the References).

II Principles of the Used Methodology

The heavy isotopes of hydrogen (H) and oxygen (O) naturally present in water molecules, namely the stable Deuterium (hydrogen -2) and stable oxygen -18, provide an excellent information about the origin of water.

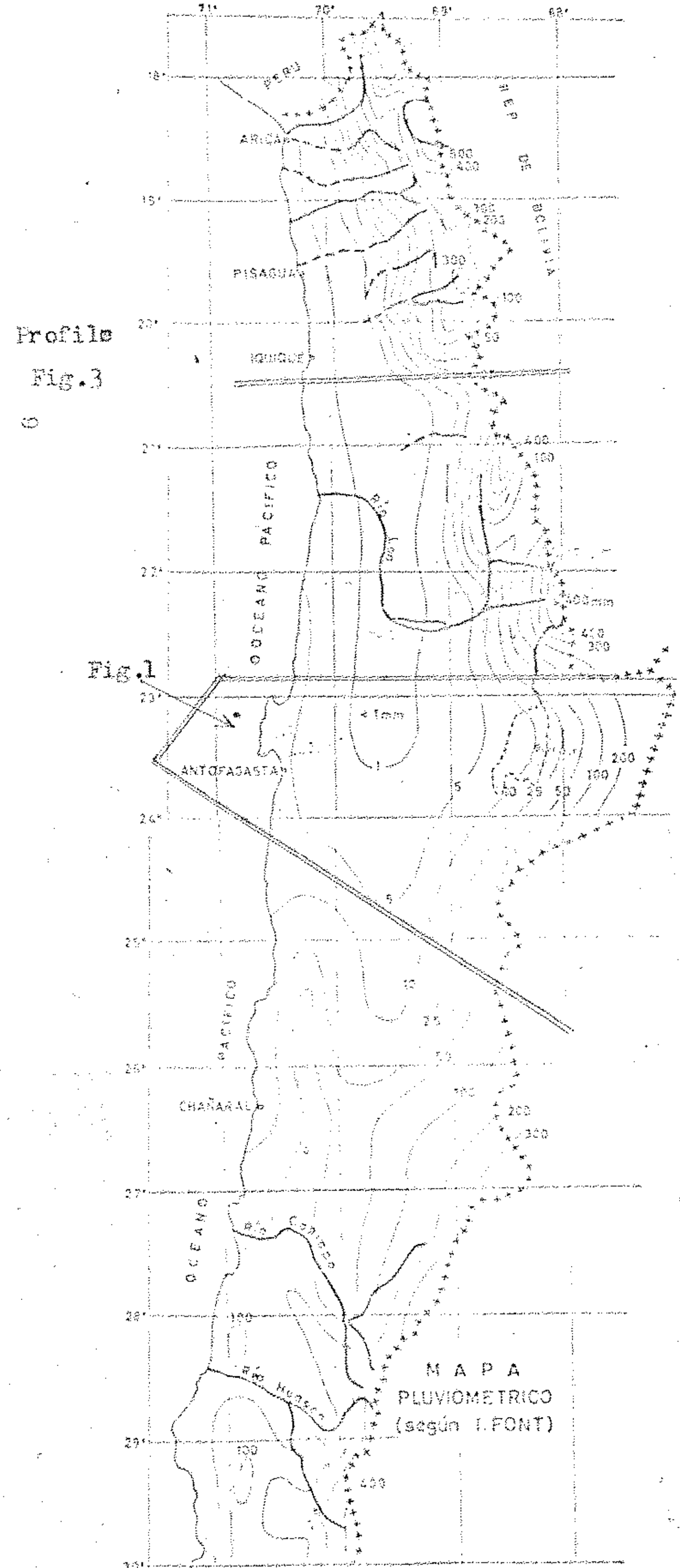


Fig.4

Pluviometric map of northern part of Chile (according to I Font) with location of Apollo photo fig.1 and profile fig.3.

Isotopes of an element contain the same number of protons and electrons but differ from each other in the number of neutrons. Hence the masses of isotopes of an element differ. Most elements consist of a mixture of isotopes; stable i topes and radioactive or unstable isotopes. The latter desintegrate with time under emission of radiation (Tritium, H-3;Carbon -14). The former stable isotopes content can only be determined by mass spectrometry.

In every million molecules of water, with normal isotopic composition $H^{16}O$ there are about 2000 molecules $H_2^{18}O$ containing the heavy isotope ^{18}C, and about 320 molecules $HD^{16}O$ in which one of the two ordinary hydrogen atoms is replaced by the heavy hydrogen isotope Deuterium (^2H or D). As long as 44 years ago it was realised by Gilfillan (1934) that the isotope ratio of water molecules in nature is not constant. Systematic investigation over the last 24 years revealed that the proportions of $H_2^{18}O$ and $HD^{16}O$ fluctuate within the ranges of 1880-2010 and 180-340 parts per million respectively. This is due essentially to the lower vapour pressures of $H_2^{18}O$ and $HD^{16}O$ as a result of which isotopic fractionation takes place during every phase transformation : evaporation, condensation, sublimation. Isotopic exchange, diffusion and dispersion ensure that isotopic fractionations, which initially take place at the phase boundaries, become measurable volume characteristics in a water sample. (See 2 of References).

The proportions in which the different isotopes occur represent an overall labelling of the water.

As the stable isotopes of a chemical element differ only in mass, the proportions in which they occur in nature are influenced by all processes on which gravity has a direct influence, including those related to changes in temperature as increase in temperature stimulates movement. A water molecule may overcome the force of gravity if sufficiently stimulated by heating which increases its velocity as a function of its mass. (Evaporation, sublimation or the reverse condensation).

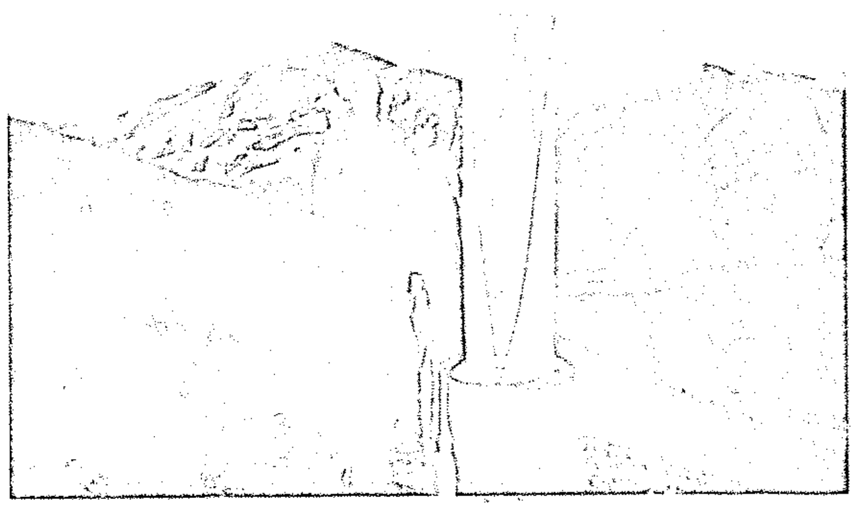
Most water will evaporate at the surface of seas and oceans and again with preference in the tropical zones. In compensation the oceans and seas will receive precipitation directly or indirectly, drained back through discharging rivers or groundwater. The overall effect combined with mixing through ocean currents etc.. provides ocean water with a very constant proportions of ^{18}O and ^{16}O or D and H, adopted by Craig (1961) as the SMOW standard (Standard

Photo by Hans Schneider

Fig. An oblique aerial view of coastal fog, the camanchaca, high against the flanks of the Coast Range in Antofagasta Province.

Photo by Rómulo Santana A.

Fig. . A fog trap (captaniebla) located in a pass of the Coast Range near Antofagasta. This is one of several experimental designs being tested by Professor Carlos Espinoza and others at the Universidad del Norte in the zone of the camancheca, or coastal fog.



Water sample analysis results for stable isotopes are always expressed as the relative deviation of the isotopic ratio $^{18}O/^{16}O$ or D/H from the SMOW standard or $\delta^{18}O\%$ SMOW in the following way :

$$\text{for } ^{18}O : \quad \delta^{18}O\% \text{ SMOW} = \frac{(^{18}O/^{16}O)\text{ sample} - (^{18}O/^{16}O)\text{ SMOW}}{(^{18}O/^{16}O)\text{ SMOW}}$$

The processes for deviation from the standard can be divided as follows :

- Latitude effect :

  Water vapour from the oceans, seas or lakes has a lower content of heavy isotopes than the surface water from which the vapour originates.

  In the Tropics the average temperature is highest. Therefore the fractionated distillation which would have no effect at the boiling point, causes only a minimum negative deviation. At higher latitudes the evaporated water will contain less ^{18}O as a consequence of the average lower temperatures at which evaporation takes place.

- Continental effect :

  In precipitations, the heavy isotope content decreases with increasing distance from the coast. A depletion of the heavy isotope content will take place as a function of the rainfall during the transport of vapour masses inland. (See also results of 11 with respect to those of 10 of References).

- Altitude effect :

  The humid air mass will successively become depleted in heavy isotopes as a function of precipitation when moved upward towards the culmination of a mountain range.

  The enormous difference in altitude over a relatively narrow stretch of land renders the altitude effect the most active agent for the differentiation of the collected samples. (See also 10 of References).

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III Interpretation of the Results

Table 1 consisting of 4 pages 7, 8, 9 and 10 gives the date, geographical location and type of the water occurence from which a sample was taken, in addition where possible, of the temperature of the water and its electrical conductivity during the sampling. The last column of table 1 gives the laboratory result.

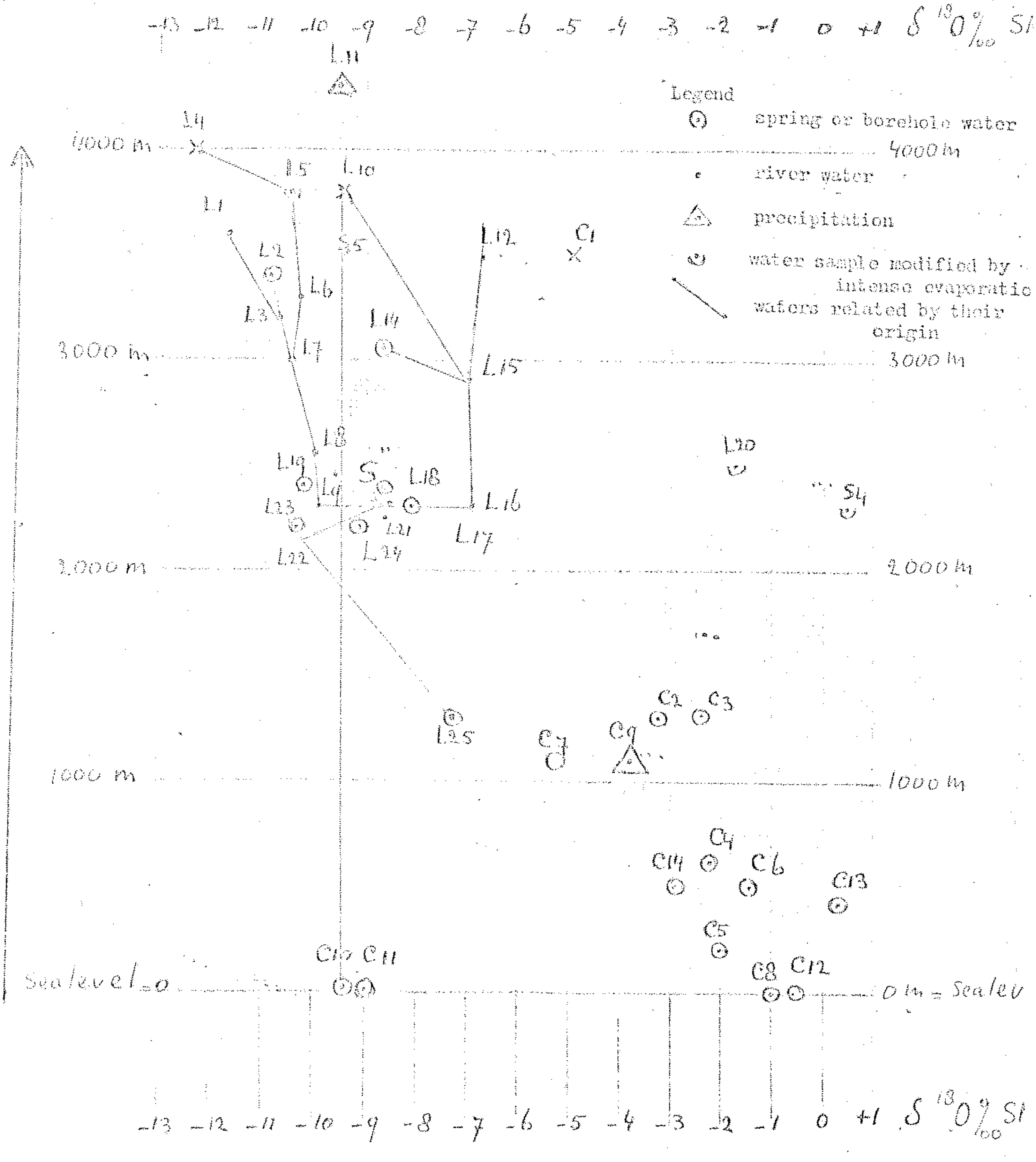
The range variations in ^{18}O content is from ^{18}O% SMOW = -13 to ^{18}O% SMOW = +0.5 (if sample L 13 of -17.21 is excluded as being little representative). This is quite an extraordinary variety of ^{18}O contents for such a relatively small area.

The samples originate from the following type of water occurences :

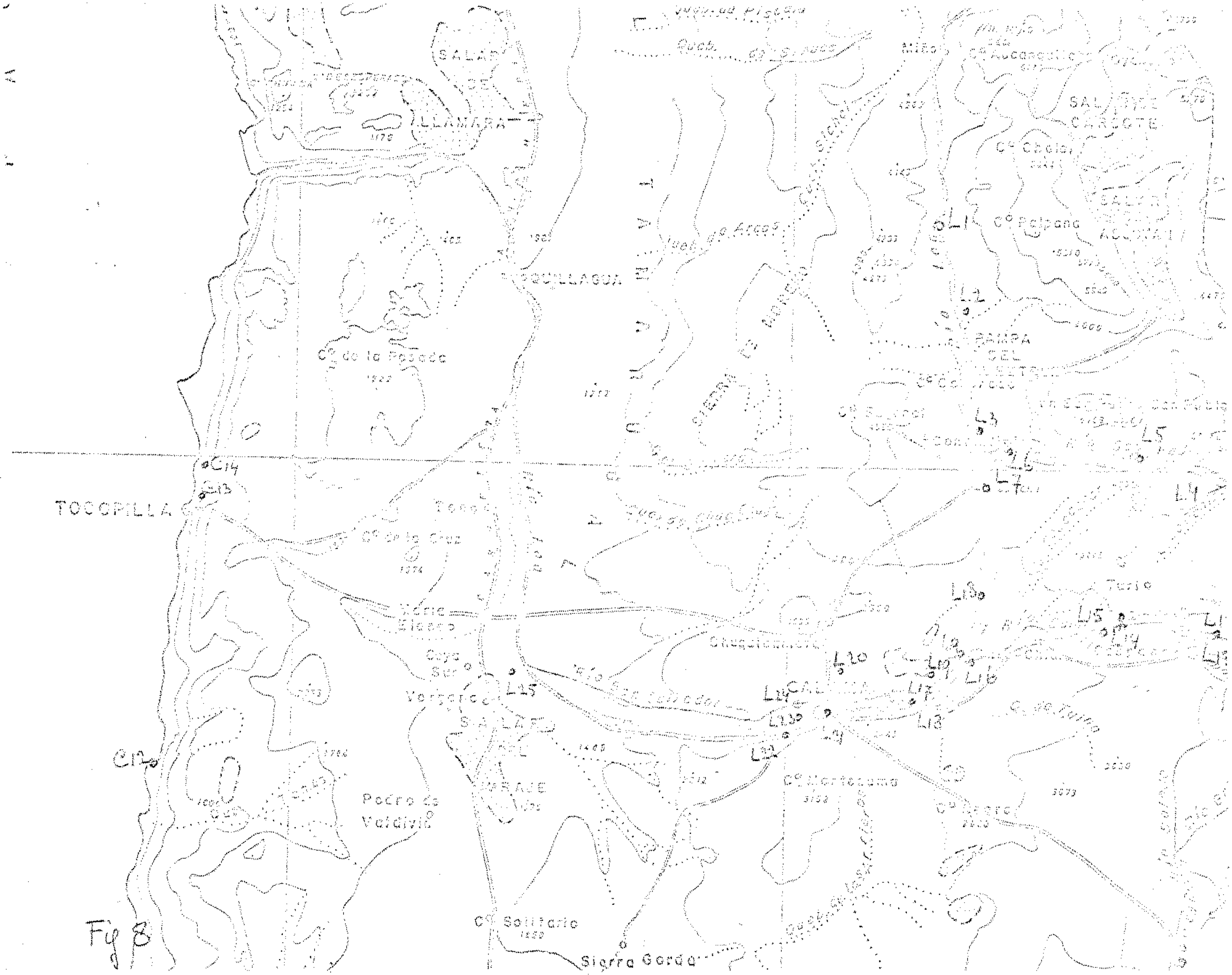
a, Precipitation (L 13, L 11 and C 9), with a rather individual character with the exception of the last one.

In arid or semiarid regions, only a heavy or consistent precipitation will fall in an environment with relative humidity of 100%. Small rains may loose part of their water to reevaporation of the rain drops by the surrounding air with unsaturated vapour pressure. On the other hand, intercepted standing rainwater may have become relatively enriched in ^{18}O due to evaporation after rainfall has ceased. Snow samples take more time before climatic influences may have changed the isotope content. However since snow falls at this latitude only at great, normally uninhabited altitudes, it may take many days after snow fall before a sample can be collected. In the case of L 11 this is different since Tatio is an inhabited settlement for the exploration and exploitation of the geyser field for geothermal power production.

The Camanchaca can only be captured during specific weather conditions and depends on the total surface of the "moist trap" (see chapter IV). Since the collected water is conducted to a closed container, evaporation cannot modify anymore the ^{18}O content. Only the temperature of the cloud or mist bank varying slightly with the seasons may influence the ^{18}O content. (See meteorological explanation of Camanchaca in chapter V).



.g.7 increasing proportion of Oxygen - 18 content



SALAR DE LLAMARA
SALAR DE CARCOTE
SALAR DE ASCOTAN
Cº Chela
Cº Palpana
QUILLAGUA
SIERRA DE MORENO
RAMPA DEL ABETRUZ
Cº de la Posada
Cº de la Cruz
TOCOPILLA
C14
C13
C12
Maria Elena
Coya Sur
Vergara
SALAR DEL MIRAJE
Chuquicamata
CALAMA
Río San Salvador
Pedro de Valdivia
Cº Solitario
Sierra Gorda
Cº Montecristo
Cº Turia
Turia
L1
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L21
L22

Fig 8

TABLE 1

1 No.	2 Date of collection	3 Location	4 Long. west	5 Lat. south	6 Type of sampling point with depth between () in meters.	7 Yield 1/sec.	8 Altitude meters	9 Temperature °C	10 Conductivity	11 $\delta^{18}O$%SMOW
						Order	of	Magnetude		
1	22.1.71	Coral Quemada	68°40'	20°37'	Rio Loa	522	3600		1230	-11.66
2	22.1.71	Fuentes de Tiara	68°37'	21°48'	Springs	875	3400	30°	5900	-10.85
3	22.1.71	Loa 2 a 4 km above San Pedro	68°37'	21°56'	Rio Loa	1350	3200			-10.64
4	23.1.71	Bocatoma Siloli	68° 3'	22° 1'	Rio Siloli	193	4000		295	-12.25
5	23.1.71	Ojo de San Pedro Outlet drain	68°19'	21°52'	Outlet Drain		3800			-10.46
6	23.1.71	Rio San Pedro at Crossing Carretera International	68°32'	21°52'	Rio San Pedro	370	3300			-10.23
7	22.1.71	Downstream Conchi Dam	68°38'	22° 3'	Rio Loa	1540	3000			-10.39
8	21.1.71	Loa above Lansana	68°37'	22°15'	Rio Loa	1600	2550	16°	2200	- 9.94
9	21.1.71	Loa above Rio Salado	68°40'	22°22'	Rio Loa		2300	21°5		- 9.90
10	30.1.71	Rio Toconce Linsor			Rio Toconce		3800			- 9.44
11	Winter 68	Snow Tatio	68°39'	22°20'	Snow		4300			- 9.5
12	24.1.71	Salado Chico above Tunnel Hojalar	68°12'	22°17'30'	Rio Salado		3450	11°	8000	- 6.76

+ Yield 1916 198 1/Sec. from SE
481 1/Sec. from NE at altitude 4100m, remarks from old Chuquicamata files.

Analysed in Isotope Laboratory Pirocicata, near San Paolo, Brazil.

1	2	3	4	5	6	7	8	9	10	11
L13	24.1.71	Standing Rain Water of 23 January			Rain Water		3400			-17.21
L14	24.1.71	Spring Aiguina	68°20'	22°17'	Spring		3050		2000	- 8.70
L15	24.1.71	Salado Downstream Road Crossing	68°22'	22°17'	Rio Salado	400	3900		5500	- 7.03
L16	21.1.71	Salado Above Rio Loa	68°40'	22°22'	Rio Salado	500	2300	14°	5800	- 6.91 ++
L17	25.1.71	Loa Downstream Salado at Angusturas	68°47'	22°27'	Rio Loa	2470	2300		2500	- 8.76 +++
L18	30.1.71	Salar de Isla Grande	68°46'	22°27'	Groundwater from Shallow hole		2300		7000	- 8.19
L19	21.1.71	Salar de Angusturas	68°45'	22°25'	Shallow hole		2400	14°	5500	-10.21
L20	25.1.71	Last Laguna Created by Waste Waters Chuquicamata	68°54'	22°24'	Laguna with PH-2		2500			- 1.76
L21	25.1.71	Drainage Water Irrigation Calama	68°56'	22°29'	Shallow hole (0.30) return flow irrig.		2250			- 8.64
L22	25.1.71	Salto de Chintorasto	69°00'	22°30'	Rio Loa	660	2150			-10.24
L23	25.1.71	Pozo VC. 61 between Loa and Opache	69° 2'	22°31'	Pozo (3.34m)		2200			-10.34
L24	25.1.71	Ojo de Opache 14km from Calama	69° 3'	22°30'	Spring	450	2200	13°	5900	- 9.14
L25	9.6.71	Pozo de Vergara	69°32'	22°26'30'	Pozo		1300			- 7.30

++ Yield 1916 over 2000 l/sec.

+++ Yield 1916 8.5km upstream Calam 3660 l/sec.

1	2	3	4	5	6	7	8	9	10	11
C1	3.6.71	Pipeline Agua Verde rom Sandon Y Sapo	70^{o} 0' (69^{o}17')	25^{o}25' (25^{o}14')	Pipeline		3500			-4.91
C2	3.6.71	Agua Verde	70^{o}08'	25^{o}25'	Borehole (105-187) (214-217)		1300			-3.37
C3	3.6.71	Agua Verde	70^{o} 0'	25^{o}25'	Open well(45- 60)		1300			-2.44
C4	3.6.71	Seepage above Taltal	70^{o}24'	25^{o}30'	Seepage		614			-2.22
C5	3.6.71	La Cochina	70^{o}27'	25^{o}26'	Open well		200			-2.06
C6	3.6.71	Los Perales	70^{o}27'20"	25^{o}01'	Spring		500			-1.46
C7	12.6.71	Maria Eugenio I Aguas Blancas	69^{o}55'	24^{o}10'	Borehole (24- 59)		1100			-5.29
C8	11.1.71	Spring Juan Lopez Cerro Moreno	70^{o}30'	23^{o}31'	Water dripping from roof of cave	0.5	4			-1.1
C9	4.6.71	Station Camanchaca No. 71040212	70^{o}18'	23^{o}30'	Condensation Water		1100			-3.78
C10	13.5.71	Intendencia Antofagasta	in Antofagasta		Seepage		10			-9.40
C11	13.5.71	Banco de Chile Antofagasta	in Antofagasta		Seepage		10			-9.01
C12	9.5.71	Cobija	70^{o}16'	22^{o}32'	Coastal Spring		4			-0.56
C13	11.6.71	Minita Depreciada Tocopilla	70^{o}10'30"	22^{o} 3'30"	Deep in mine		420			+0.30
C14	11.6.71	Aguada Manilla	70^{o}10'30"	22^{o} 0'30"	Spring		500			-2.92

1	2	3	4	5	6	7	8	9	10	11
S1	28.1.71	Tilopozo Casa	68°14'	23°46'	Spring		2315	29	4000	-8.60
S2	21.4.71	Pozo Tilomonte I	68°10'	23°48'	Borehole (69m)		2320			-8.84
S3	28.1.71	Laguna Peine	68° 8'30"	23°42'	Spring in Salar		2305	13	15000	-8.60
S4	28.1.71	End Laguna Peine	68° 8'	23°41'	Laguna fed by Springs S3		2303	30	20000	+0.51
S5	26.1.71	Quebrada Socaire	67°36'	23°36'	River Socaire	185	3500		1000	-9.39
S6	27.1.71	Quebrada Toconao	67°58'30"	23°11'	River Toconao	45	2580		350	-8.63
S7	27.1.71	Pozo 3 Corfo	68°10'	22°56'	Borehole (280)	68	2400		2000	-8.67
S8	4.1.72	Rio San Pedro at Entrance San Pedro de Atacama	68°13'	22°55'	Rio San Pedro		2450			-9.6 +

All samples are analysed in Croningen, Netherlands, except those marked by + analysed in Piracicaba. Brazil near Sao Pao

b. Spring or well water

They are both fed by groundwater and are more representative than category a. This water is directly recharged by precipitation or indirectly by melting water (see fig. 4). In this connection it should be mentioned that the area between the crests of the successive mountain chains is covered over large extensions by very permeable late Tertiary and Quaternary vulcanic tuffs, andesitic lavas, ignimbrites and alluvial fans, which have smoothed like an eiderdown the original much more capricious topography of the older geological formations. This has been proved by recent geophysical surveys (gravimetry, seismics and electrical resistivity). See 5, 6, 7, 8, 9 of the References.

These conditions cause that surface runoff is restricted to a minimum and water infiltrates near to the spot where it fell like precipitation to reappear at a lower location as a spring, in the bed of a mountain brook or in a "Salar" (Sebka) in a closed basin. Of course the drainage area of a spring is ill defined compared with the drainage basin of a river. One can only be sure that the water comes from an area of higher elevation than the spring in question. Due to the geological and geomorphological conditions groundwater may however cover large distances, sometimes undisturbed by geomorphological water divides. In this connection, it may be useful to consider the boundaries of the basins formed by the pre-Tertiary geologcial formations.

c. River water

The presently existing smooth relief between the mountain chains is especially in the higher part above 2000 m only interrupted by the canyons eroded by the fast flowing mountain brooks in the generally soft vulcanic and alluvial sediment cover (quebradas). The rivers are perennial with a surprisingly constant regime and consequently must drain the groundwater reserves. The yield of the most important rivers is artificially decreased by deviating the major part of the discharge through pipelines to the few population and mining centres in the area like Chuquicamata, Calama, Tocopilla, Antofagasta and Taltal to mention the most important ones.

L 4 has been collected from the intake of a pipeline of 365 km length supplying a part of Antofagasta with 30 l/sec.

L 10 is collected from the intake of a pipeline of 300 km length supplying Antofagasta with 430 l/sec.

C 1 is collected from the intake of a pipeline of 150 km length providing Taltal with 200 m^3/day of which a large part is lost due to its age (50 or 60 years). All these data apply only for the year of sampling as at present many works are in execution to improve the water supply of the area.

d. Samples like L 20, S 4 but also L 5 (for those who know the area) show obvious influences of heavy evaporation losses.

Categories a, b, c, and d are the differentiation of sampled water sources made in the diagram. For further differentiations is referred to table 1.

In the diagram the relative deviation in ^{18}O content of the sample from the SMOW standard, are plotted against the only approximately known altitudes of the corresponding sampling site. Considering the enormous variation in altitude, this approximation is sufficient for the purpose with exception perhaps for the area in the surrounding of Calama, where the hydrological situation seems to be complex.

The plotted points which have been connected by lines, represent sampled springs or river sections which provide obviously the main supply of down-stream sampled river sections. In the case of L 25, originating from a well, this well is most probably in connection with the Loa river as it is located at a few 100 meters from its course.

Three types of ^{18}O content modifications can be recognised :

1. At river junctions according to the original ^{18}O content of the tributaries and their respective discharges, the water down stream the junction will represent the mixture of the two original waters, according to the principle of weighted averages, or :

$$\frac{Q_1 \times \delta_1 + Q_2 \times \delta_2}{Q_3} = \delta_3$$

.../.

Q_1 - discharge of first river

Q_2 - discharge of second river

$Q_3 = Q_1 + Q_2$

δ_1 , δ_2 , δ_3 are relative deviations of ^{18}O content from the SMOW standard for the corresponding discharges.

2. The river water is locally used for irrigation as being the only water resource with the few springs in the region. Consequently, the irrigation water draining back to the river will become relatively enriched in ^{18}O content due to evaporation losses, eliminating with preference the lighter isotopes. This process, in spite of the fast flowing rivers, causes a gradual change to the right hand side of the diagram with lower altitudes.

3. Samples like L 22 confirmed to a certain extent by the near by groundwater occurence of L 23 and even more by L 24 from the largest spring in the area, however, with lower ^{18}O content, show an exception of the general tendancy of decreasing ^{18}O content with lower altitude. (Compare L 17 of the nearest upstream sampled river section of the Rio Loa, the only water course in the far surrounding that has eroded its way through the Cordillera de Domeyko and found its way to the Pacific).

   This exceptional behaviour can only be explained by a contribution of an unknown groundwater supply between the sampled river sections of L 17 and L 22 originating from a recharge area of about 3500 m altitude or higher.

If one compares the ^{18}O contents of the water drained towards the closed basin of salar de Atacama (fig.2), it is obvious that the origin of the brooks, groundwater and springs feeding the Salar are all the same and are afterwards modified by evaporation.

The only exception forms to a certain extent S 8 originating from the Rio San Pedro taken during the peak flow on 4th of January 1972, when the bridge collapsed. This is the only sample taken from a river with a surface runoff component in the discharge.

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If one considers the samples from the coastal region between 0 and 1300 meters, it appears that all samples concern ground water occurences (C 1 commented before not included).

Samples like C 2 and C 3 may be recharged from higher regions like C 1 but also by Camanchaca which can locally penetrate through mountain passes, and snow fall as the author observed ones on nearby mountain tops over 2000 m high. Similar conditions may explain water of the type of C 7. These samples were all collected in the Atacama desert separated from the Pacific Ocean by the coastal range.

C 9 and the samples of levels below 1000 m have been collected from the coastal region at different heights.

A special case form C 10 and C 11 collected from a water occurence in the basement of two government buildings in Antofagasta. Some people thought that these waters were provided by a far away source, however, the majority of people were correct who shared the opinion that these waters were derived from the leaks of the water distribution system supplied by the Toconce pipeline (see sample C 10).

Like C 10 and C 11 water originating from far inland would always be characterised by lower ^{18}O contents. Therefore, the large group of coastal water like C 4, C 5, C 6, C 8, C 12, C 13 and C 14 can only be explained as originated from Camanchaca water like C 9 with some modifications due to evaporation and the mixture of Camanchaca water of different seasons. A most convincing water occurence in this connection forms C 8, dripping from the roof of a cave underneath the about 1100 m high Sierra Morena on the peninsula of Mejillones opposite Antofagasta. Here Professor Espinoza recorded Camanchaca yields collected with standard "fog traps" of 6 liters a day. The site is separated from the mainland by a wide coastal plain being the only suitable location in the region for the large Antofagasta airport. The groundwater in the subsoil of this complete desertic plain is saline and from marine origin.

IV Previous experiments

Professor Hector R. Munoz and Professor Carlos Espinoza, of the Universidad del Norte, have studied the "Camanchaca" for many years. (See 1.c). Recordings have been made of the water collected from the "nubes rasantes" of

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over 100 standard moist collectors distributed over the coastal area of the Norte Grande and Norte Chico. This amount was obtained by regularly measuring the volume of these waters collected in 200 l. drums. A rectangular prism with base of 39 centimeters and length of 150 centimeters covered with resistant nylon mosquito netting and screwed on a drum, collects in the maximum case 6 liters per day over long periods (Cerro Moreno at 800 meters above sea level). However, 1 to 2 litres per day (measured over long periods) is an average case in the Camanchaca zone between 700 and 1,100 meters above sea level. A small pine tree which has been planted by Professor Espinoza in the Camanchaca zone above Antofagasta and was originally artificially watered, was in 1972 able to collect sufficient Camanchaca water to survive in a prosperous way in a surrounding without any further vegetation. An eye-witness reported that the tree had reached a height exceeding 2 meters in September 1976.

Generally, the Camanchaca zone can be recognized by the cacteceous vegetation in the coastal zone, sometimes with parasite plants which apparently collect water and do serve as food for the Huanacos (wild llama) living in this zone. However, in populated areas, this vegetation sometimes, and Huanacos always, have disappeared.

On the basis of the observations made by Mr. Munoz and Mr. Espinoza, it seems that the amount of water harvested by the plants from the Camanchaca is a function of the plants surface area, exposed to the clouds and not of the water need of the plant. Therefore a plant with a small water demand but large surface area can be a source of groundwater recharge, which in its turn could be the source of some coastal springs, The examined samples of the very small coastal springs recharged through the mediation of the cacteceous vegetation demonstrate this possibility.

V. Meteorological explanation of Camanchaca and applicability of its exploitation

Once it has been proved that not only vegetation can capture moist from clouds or mist banks for its own growth, but also that vegetation after its own needs are satisfied, can transmit the excess moist towards the soil as recharge, the conclusion can be drawn that afforestation will stimulate the increase of yield of the existing coastal springs and may most probably create new springs.

This new aspect makes the exploitation of the coastal fog (see annex) even more attractive. In this way, coastal deserts which, due to lack of water resources, are practically uninhabited could be opened up for modest development by harvesting the moist provided by the fog, either by natural vegetation or by artificial moist collectors, the most logic being the combination of the two.

In this connection, it is important to know where the meteorological and geomorphological conditions are such that this water resource can be exploited.

The South American Pacific coast from 30° southern latitude to near the Peruvian border with Ecuador, is noteworthy for the equatorwards extension of desert conditions, great uniformity and stability of weather, a high degree of atmospheric humidity in the morning during the entire year and last but not least a frequently uninterrupted cloud cover that hovers all the way down from far south of Antofagasta to 8° southern latitude covering a coastal zone that suffers an almost complete lack of precipitation. (See 1a and 1b of References).

The trade winds of the south eastern pacific create upwelling of the relatively cold ocean current "Humboldt current" along the steep pacific coasts of northern Chile and Peru, while the aridity of the climate is produced by a rather permanent high pressure zone, which can only be caused by subsiding air masses.

The combination of these effects in addition to the high mountain system of the Cordilleras de los Andes parallel to the coast creates the following situation :

> The trade winds blowing over the relatively cold ocean surface create a meteorologically cool and moist marine layer. The air above the marine layer is dynamically heated by susidence. The interface between these two layers varying in position between 700 and 1100 meter above sea level generates an inversion with a high degree of stability.

Clouds being raised above this interface between cool moist air and warm dry air, evaporates and so the inversion counteracts development of convective air masses which could otherwise produce precipitation. The overall result is a "dry" ocean and a desert coast.

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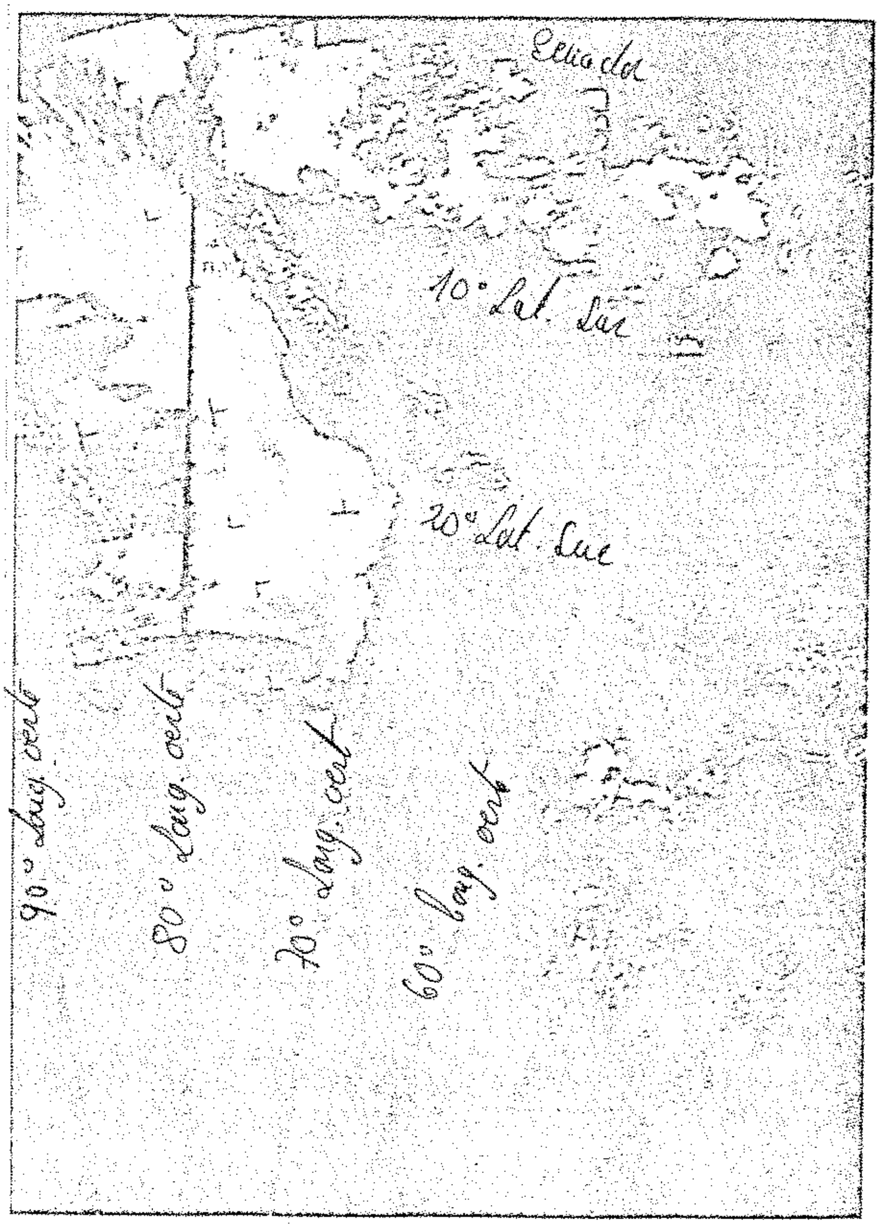


Fig. . West coast of South America as seen by Satellite ESSA 5, PASS 1381–1393, August 7, 1967.

In winter, the high pressure ridge over south America connects the south Atlantic and south Pacific anticyclones or high pressure areas. In summer the Cordilleras prevent the low pressure zone of the Amazon basin to penetrate in the area under consideration. Only some snow fall in the high mountains may occur (Bolivian Winter). (See also sample L 13 ?).

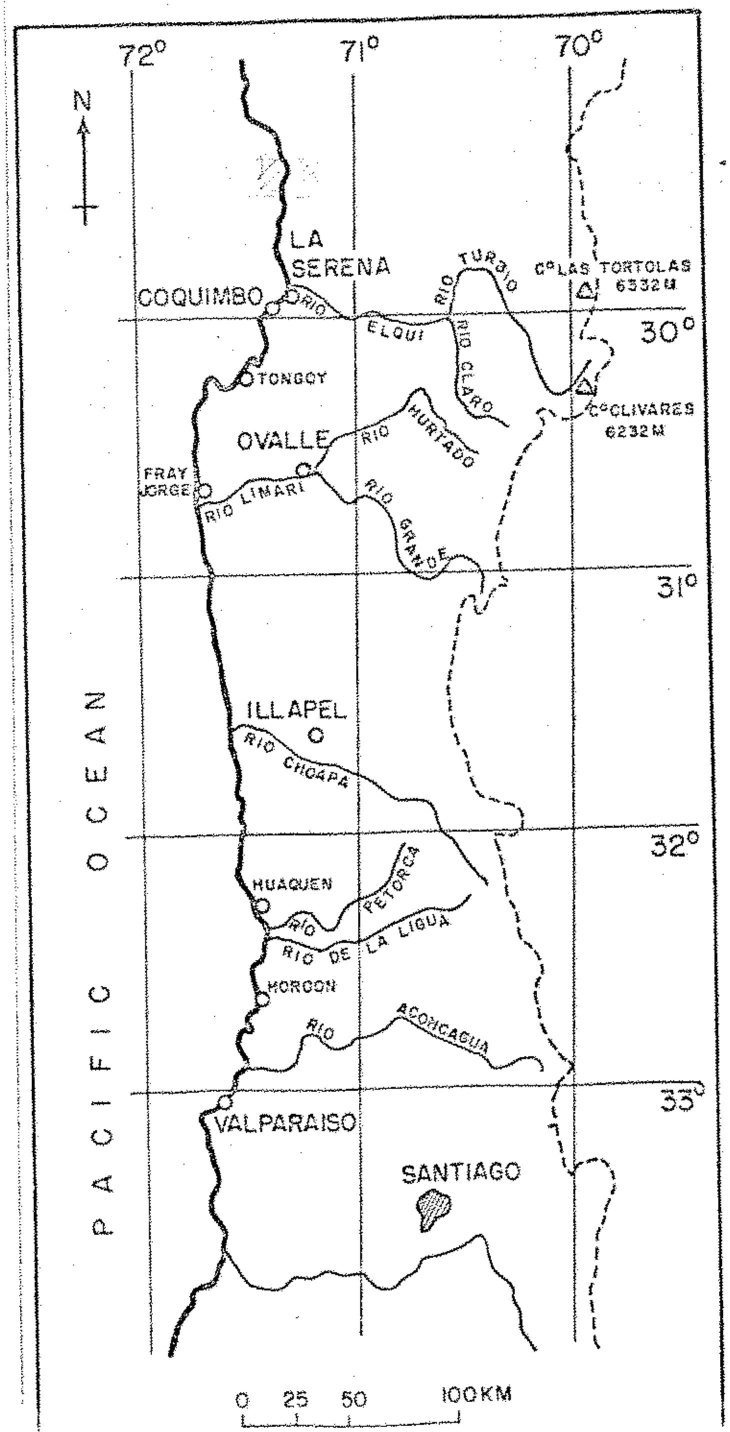
Atmospheric pressures in the southern winter are higher than during summer. That means more subsidence and higher temperature above the inversion in winter than in summer. The marine layer below the inversion has inverse annual temperature variations; in the winter colder than in summer. As a consequence in winter the inversion is more active and the stability reaches its maximum. The cloud cover may become more continuous in space and time, (see fig. 9 showing the west coast of south America as seen by satellite ESSA 5 on August 7th 1967. The cloud cover can be followed from 30° to 6° southern latitude).

In the extreme south of the area under consideration the "Norte Chico" between 33° and 30° southern latitude corresponding to the area of transition from the desert to the Mediterranean climate, climatic changes since the Pliocene period have left their mark in the form of remains of vegetation, paleosols, fossil land forms and deposits and fossilised mammels. (see l.d. of References).

The total precipitation varies here between 400 mm in the south to 100 mm in the north, while 85% of the precipitation falls between May and August as a result of the seasonal northward shift of the polar front. Changes in climate are of course first noticed in such transitional zones.

Roland Paskoff in his discussion of the Plio-Quaternary climatic changes along the semiarid seaboard of Chile arrives at the following conclusion :

a) The climate at the end of the Tertiary was probably of the warm humid tropical type, with a dry season of varying importance. It changed towards the Quaternary with a decrease in temperature and a reduction of rainfall.


72°
71°
70°
N
LA SERENA
COQUIMBO
RIO ELQUI
RIO TURBIO
RIO CLARO
C° LAS TORTOLAS 6332 M
30°
TONGOY
C° OLIVARES 6232 M
OVALLE
RIO HURTADO
FRAY JORGE
RIO LIMARI
RIO GRANDE
31°
PACIFIC OCEAN
ILLAPEL
RIO CHOAPA
32°
HUAQUEN
RIO PETORCA
RIO DE LA LIGUA
HORCON
RIO ACONCAGUA
33°
VALPARAISO
SANTIAGO
0 25 50 100 KM

b) "The Pleistocene period experienced an alternation between humid phases accompanied by a cooling of the atmosphere, and dry periods marked by a warming up".

About $20^{\circ}30'$ south in a surrounding of steppe-vegetation, the relict of the Fray Jorge forest still exists, comprising species of trees, ferns and lianas with reappear only about 1000 km further south in the evergreen forest of Valdivia.

The survival of this forest, extending over an area of about 800 ha. in the Altos de Talinay to the north and south of the mouth of the Rio Limari can easily be explained. Being situated on the flattened top of the raised coastal beach which directly faces the ocean at a height of 600 to 700 m the area benefits of the condensation of marine air. This "Occult Precipitation" increases the total annual rainfall almost ten times to about 1,500 mm (Kummerow 1962).

Whatever may be the reason of its origin, (large scale migration of the Valdivian forest during a glacial period or a relict of the Quaternary tropical flora) it shows a floral and physionomic likelyness to the Peruvian "Coja" vegetation.

The Fray Jorge forest is not unique. Other forest remains covering smaller areas, are found along the semiarid Chilean coast on mountain slopes facing the ocean.

The characteristics of such forest relicts are that ones destroyed, they do not regenerate naturally. In certain areas trees disappeared even in recent historical times, as the wood appeared indispensable as buttresses for the underground mining exploitation which flourished since the early Spanish occupation and even before (^{14}C examination on existing mine wood would probably reveal interesting results in this respects). In some areas, the deep soils which have developed during the period of vegetation may still exist. Such areas should be considered in the first place for afforestation with the help of artificial moist collectors providing water to the young trees until they are tall enough to become their own moist collectors. In this connection, traditional methods applied in other marginal desert areas of the world, may prove to be most useful. (See the authors actual work on the inventory of traditional water works in the Arab States).

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The exploitation of Camanchaca (or occult precipitation) as a renewable water resource being possible in Northern Chile, is a methodology which may find its application in many other areas in the world, where similar conditions prevail, such as parts of Lower California, the Moroccan coast where the Atlas Mountains approach the Atlantic, the steep coasts of Angola, and possibly the highlands of Yemen and Oman. On the Canary Isles, this method is already applied and in the region of Mount Kulal near lake Rudolf Kenya the possibility of increasing the spring yields in this way is at least under consideration.

There might exist many other sites where the renewable water resource could be used or improved if used already.

It is in complete agreement with the Chilean ideas to create a pilot project with a regional character to study the most efficient way of using this renewable water resource.

December 1977
CEG/ns/zm

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