Water Resources in the Altiplano Region in Southern Peru, Their Isotope Composition and Origin

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Abstract

Isotope techniques were used on the Altiplano, the high plateau in southern Peru between the Pacific coast and Titicaca Lake, in order to clarify the origins of water resources which are to be used for supplying the dry coastal region. The results have shown a significant role of evapotranspiration in the water balance, and that the groundwater originates from fast infiltration of precipitation.

Introduction

The Altiplano in southern Peru is a plateau with an area of about 100,000sq.km. at altitudes between 3,500 and 4,600masl, and populated with 1.6 million inhabitants. The main activities are agriculture, cattle-breeding, and mining. The adjacent coast is a narrow strip of land with extended grounds suitable for agriculture and ranching but with a very arid climate.

The social and economic development of the region is limited due to various factors, among which the insufficiency of water resources stands out, a need which has limited agriculture as well as power generation.

The government of Peru, facing these limitations, has initiated various engineering projects, including channels, tunnels, and reservoirs for the accumulation and control of surface water and recently has intensified the exploitation of groundwater which occurs along the coast as well as on the Altiplano. The first results of these works have revealed the fragility of the hydrological balance. Problems of contamination from groundwater have also appeared.

The planning of water resources' development on a medium and large scale requires a good knowledge of the hydrodynamics of groundwater and the latter's relationship to surface and atmospheric water. This is why the IPEN (Instituto Peruano de Energía Nuclear), with the support of the IAEA (International Atomic Energy Agency) and the national institutions directly involved in the exploitation of water resources, has undertaken a thorough hydrological study, the first results of which are presented in this report.

Natural Characteristics of the Region

Topography

The Altiplano is a high plateau with smooth slopes at altitudes of between 3,500 and 4,600masl. It is flanked by the Andean mountain chains of the Cordillera Occidental and Cordillera Oriental, the summits of which exceed 5,400masl. The topography defines three basins: the basin of the Pacific Ocean, that of the Titicaca Lake, and that of the Amazon River (see map in Fig. 1).

Geomorphology

In the area studied, the Altiplano includes two distinct zones.

The transitional zone between the coastal margin and the Altiplano has a dissected topography, steep ridges, and narrow valleys with streams flowing only during rainy months, and consequently it is almost without natural vegetation.

The flat Andean zone or Altiplano has moderate slopes and is delimited by mountain chains and surrounding volcanic cones. It is covered with glacio-fluvial deposits forming pampas, which are exposed to fluvial erosion. In the depressions, marshy zones occur which are locally called *bofedales*.

Hydrography

The three hydrographic basins of the Altiplano are illustrated in the map in Figure 1.

The Pacific basin consists of small perennial streams which originate on the Altiplano and flow all the way to the coast.

The basin of the Titicaca Lake includes watersheds of streams which originate on the Altiplano and flow to Titicaca. These streams have a higher discharge which, however, fluctuates significantly.

The watershed of the Amazon River includes rivers which originate in the Cordillera Oriental de los Andes and flow to the Amazon River basin. They have the highest discharge of the region and their fluctuation is less pronounced.

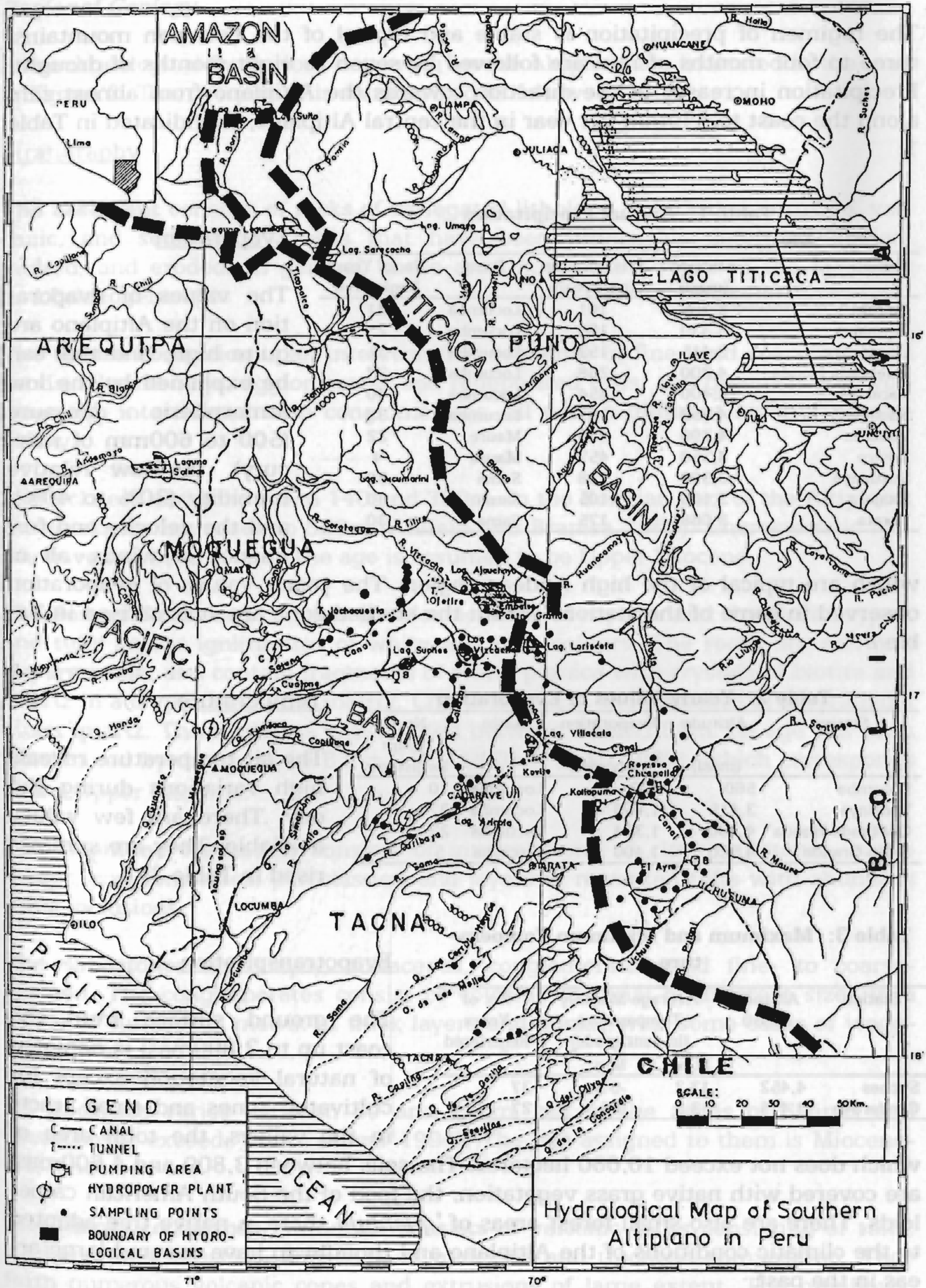

Figure 1: Hydrological Map of Southern Altiplano in Peru

Hydrology

Precipitation

The regimen of precipitation is stable and typical of the Peruvian mountains: three to four months of rain are followed by seven to eight months of drought. Precipitation increases in the direction towards the Altiplano from almost zero along the coast to 840mm per year in the central Altiplano, as indicated in Table 1.

Table 1: Annual Precipitation

Station	Altitude (masl)	Precipitation (mm/year)	Basin	No. of Years Registered
Cairani	3,205	101	Locumba	31
Camilaca	3,330	106	Locumba	23
Candarave	3,415	153	Locumba	31
Quebrada Honda	4,200	268	Locumba	27
Tacalaya	4,400	454	Locumba	40
Suches	4,452	381	Locumba	38
Vilacota	4,390	840	Maure	22
Kovire	4,350	457	Maure	4
Susupaya	3,390	188	Sama	30
Sitajara	3,100	105	Sama	30
Tarata	3,068	175	Sama	30

Evaporation

The values of evaporation on the Altiplano are quite high, and this can be explained by the low atmospheric pressure (500 to 600mm of mercury), the low relative humidity (30% to 40%), and the velocity and frequency of winds, all of which are typical of the high Andean region. The yearly values of evaporation observed in some of the stations within the studied zone are summarised in Table 2.

Table 2: Yearly Values of Evaporation

Station	Altitude (masl)	Evaporation (mm/year)	Basin	No. of Years Registered
Locumba	560	932	Locumba	10
Tacalaya	3,415	1,456	Locumba	37
Quebrada Honda	4,200	1,324	Locumba	27
Pasto Grande	4,520	1,400	Viscacha	5

Temperature

The air temperature reveals high variations during the day. There are few values available. They are summarised in Table 3.

Table 3: Maximum and Minimum Temperature

Station	Altitude (masl)	Average Monthly Temperature (in centigrade)		No. of Years Registered
		Max	Min.	
Suches	4,452	13.2	-5.9	37
Candarave	3,415	13.9	3.6	27

Evapotranspiration

The ground surface from the coast up to 3,800masl is depleted of natural vegetation except for cultivated zones and small tracts in the valleys, the total area of which does not exceed 10,000 hectares. The soils between 3,800 and 4,600masl are covered with native grass vegetation, the food of the South American cameloids. There are also small forest areas of '*quenhua* there, a native tree adapted to the climatic conditions of the Altiplano and thought to have covered large areas in the past.

The values of evapotranspiration were obtained analytically using published semi-empirical formulas, and are in the range of from 300 to 400mm/year.

Regional Geology

Several geological formations occurring on the Altiplano are indicated in the map in Figure 2. Their sequence is summarised as follows.

Stratigraphy

The basement consists of rocks of variegated lithology. It includes intrusive, volcanic, and sedimentary rocks that have been intensively deformed, folded, faulted, and eroded. In general, these are impermeable rocks of the Mesozoic and Palaeogene age.

The Maure Formation is an interstratified sequence of fine- and coarse-grained sands; silt and clays; agglomerates and redeposited tuffs; and greenish-grey volcanic ash intercalated with conglomerates, all with a different level of permeability.

Its thickness varies between 140 and 350m. In the Bolivian part of the Altiplano, the thickness increases to 500m (Ahlfeld and Branisa 1960). Characteristic fossils have not been found. The age is assumed to be Upper Miocene.

The Sencca Formation consists of volcanic rocks of rhyolite and rhyodacite types, and tuffs and/or ignimbrites of white and pink colours. The rocks are soft and impermeable, and contain fragments of white pumice with crystals of biotite and quartz in a cryptocrystalline matrix. Characteristic is the presence of bipyramidal violet quartz. The thickness is estimated between 10 and 80m. Its age has been determined by dating to be 6.5 ± 0.3 Ma (Clark et al. 1990), which corresponds to the Upper Miocene.

The Capillune Formation consists of intercalations of clays, siltstones, sandstones, conglomerates, pyroclastics, and layers of reworked tuffs with abundant lithic inclusions.

The sandstones are clayey, tuffaceous, conglomeratic, and fine- to coarse-grained. The conglomerates consist of volcanic material of different sizes in a sandy or tuffaceous matrix in thick layers and banks, with some cases of wedging.

Its thickness varies between 80 and 200m, but in the zones of Salinas and Vizcachas it exceeds 400m (Tovar 1994). The age assigned to them is Miocene-Pliocene.

The Volcánico Barroso Formation consists of volcanic rocks consisting of tuffs, agglomerates, breccias, and lavas of andesitic and trachytic composition. They form numerous volcanic cones and extrusions of large extent. The mudflows, lava flows, pyroclastics, etc occur in thick banks fractured into irregular blocks

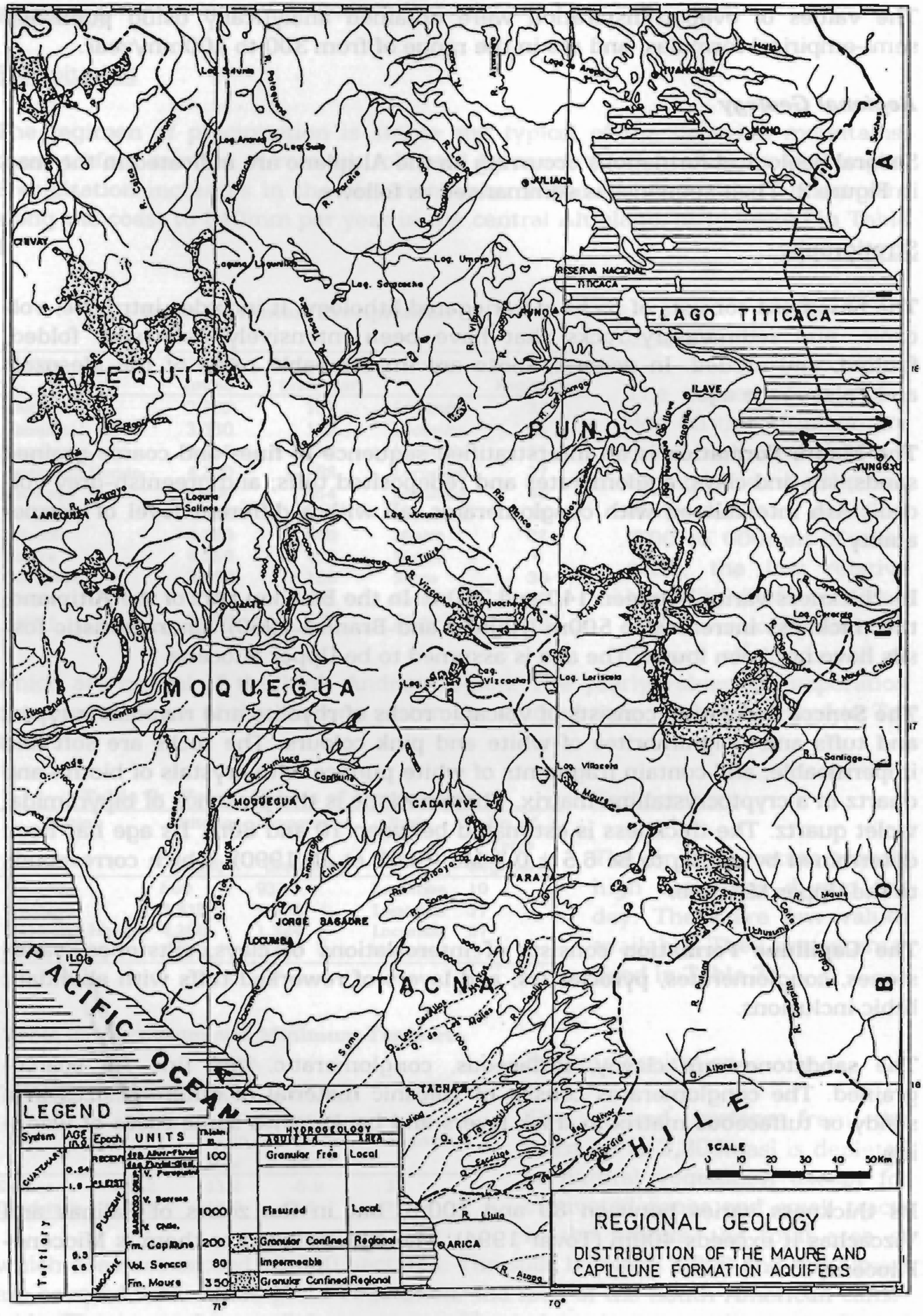

Figure 2: Regional Geology:Distribution of the Maure and Capillune Formation Aquifers

that may feature initial columnar jointing which gives them a certain permeability.

The Barroso is comprised of the volcanic formation of Chila, Barroso, and Purpurini. These volcanic formations are lying on different erosional surfaces and cover Mio-Pliocene rocks down to the fluvio-glacial sediments.

Its thickness varies, and in volcanic cones it may be as much as 1,000m. The volcanoes of the Barroso are very frequent on the Altiplano. The age of the Barroso is considered to be Plio-Pleistocene.

Quaternary deposits consist of unconsolidated clastic sediments deposited from the Pleistocene till the Recent. They are of different origins: the earliest, consisting of till, are related to the Quaternary glaciation, further to volcanic ashes, and finally to fluvial and alluvial sediments. They are very permeable.

Structural Geology

Structurally, the Altiplano has undergone three important events.

The tectonics of the basement: It originated during the epeirogenic phases, perhaps following the Pliocene, and affects the formations Maure, Sencca, and Capillune, causing folds, flexural folds of moderate inclination, as well as readjusting faults of local character which originated perhaps during the epeirogenic uplift of the Andes.

The tectonics of the cover: It developed during the volcanic activity of the Barroso, probably along weak zones. It affects the Tertiary strata as well as the volcanic formation; circular and radial faults originated in volcanic cones and their vicinity.

Neotectonics: It corresponds to the reactivation of some of the faults of the mentioned events. It has not left much contemporaneous evidence, and is perhaps related to the geothermal activity and to some springs.

The schematic cross section of the Altiplano (along line A-A as indicated in the map in Figure 1) is given in Figure 3.

Geological History

The basement consisting of Mesozoic and Paleogene rocks was folded, faulted, and eroded, resulting in a peneplain called 'Surface Puno'. This was exposed to tensional tectonic activities that created large basins and initiated a further process of erosion accompanied with the clastic fluvio-lacustrine deposition of the Maure Formation and concomitant volcanic activity that formed pyroclastic intercalations.

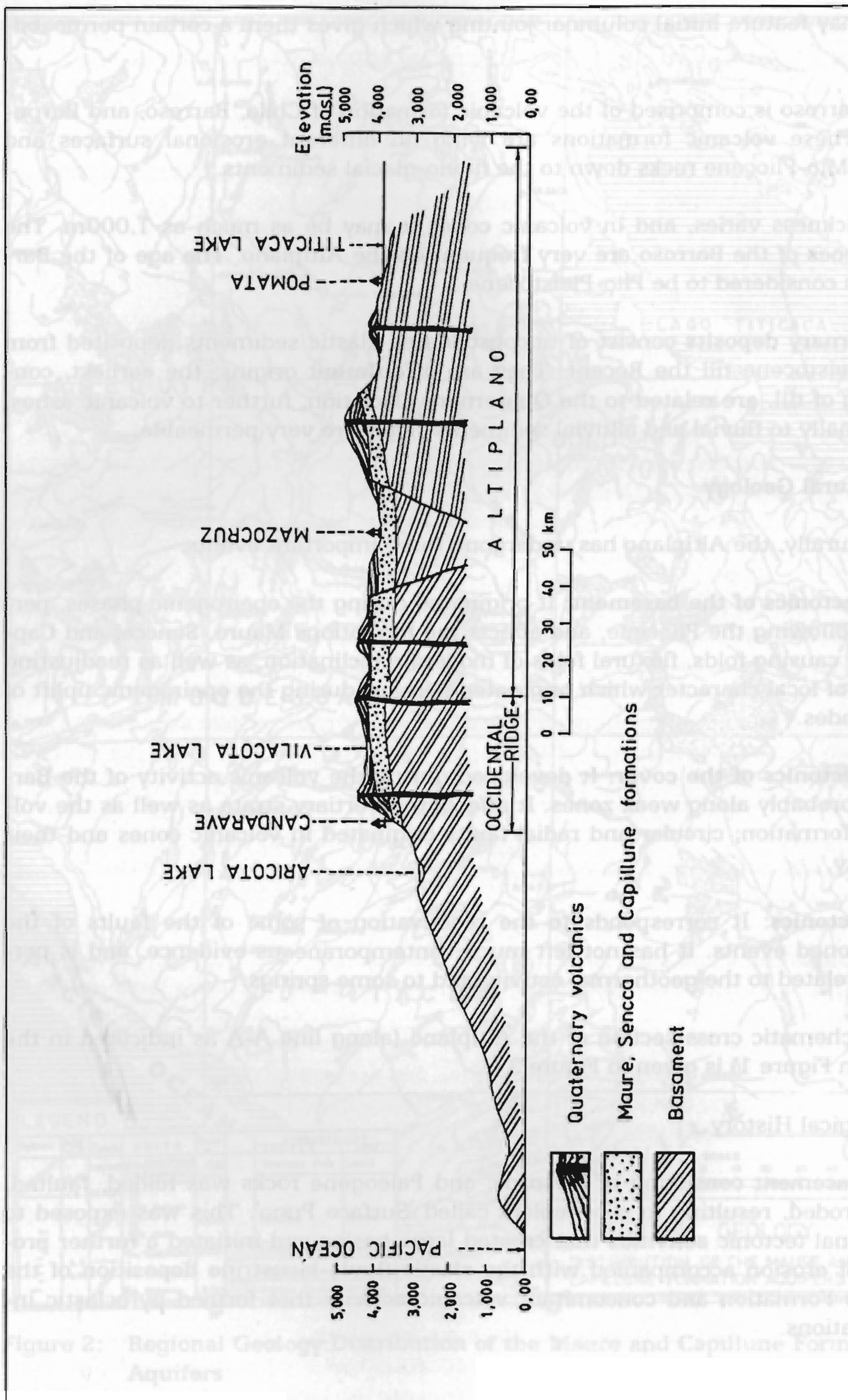

Figure 3: Geological Section Across the Altiplano in Southern Peru

The Maure shows flexural and monoclinal folds with a mild dip. It was exposed to another stage of denudation. The volcanic activity continued and increased, giving origin to the tuffs and ignimbrites of the Sencca (these are frequent on the Altiplano in general). This was followed by the accumulation of clastic and volcano-clastic sediments of the Capillune in a lacustrine environment. They were again exposed to folding, faulting, and denudation.

At the end of the Pliocene, another volcanic cycle followed within the weak zones, forming the Barroso volcanic Group with numerous volcanic cones. This volcanic activity moved from the east to the west, intensively modifying the drainage pattern and giving rise to the large endoreic basin of Titicaca Lake.

Towards the end, glacial activity affected a large part of the Barroso before the deposition of the volcanic materials of Purpurini and, finally, fluvial and alluvial activities modelled the Andean landscape into its present shape.

Application of Isotope Techniques

Isotope techniques present a valuable tool for hydrodynamic studies on a large scale by complementing the conventional hydrological methods. In the case presented, the remarkable variations of altitude and the intensive evaporation to which surface water is exposed permit the masses of water for which the dynamics are to be monitored to be characterised isotopically. With this aim, the studies undertaken involved the analysis of stable and radioactive isotopes in water: oxygen 18 (O-18), deuterium (D), and tritium. Samples of surface water, groundwater, and precipitation were taken and analysed from representative points of the studied zone, as indicated in Figure 1.

Results Obtained

Precipitation Water. The results are shown in Figures 4 and 5 and correspond to the relation of delta O-18 to delta D and of altitude to the delta O-18 (the latter being called the altitude gradient), respectively. The samples of precipitation were collected at 20 stations in the central Altiplano of Peru about 900km. north of the southern Altiplano (the study area) during the months of December 1994 and January to February 1995.

Surface Water and Groundwater. The results of isotope analyses are shown in Figure 6, where the values of delta O-18 are plotted against delta D, using Vienna Standard Mean Ocean Water (Vienna SMOW) as the reference sample.

Discussion of Results

In general, the stable isotope concentration in water samples is in the range corresponding to the altitudes of the sampling points, exceptions being lakes and thermal waters which show an isotope enrichment due to evaporation and isotope exchange with the rocks respectively. These differences in the isotope characteristics permit the movement of the masses of surficial water, groundwater, and precipitation to be correlated.

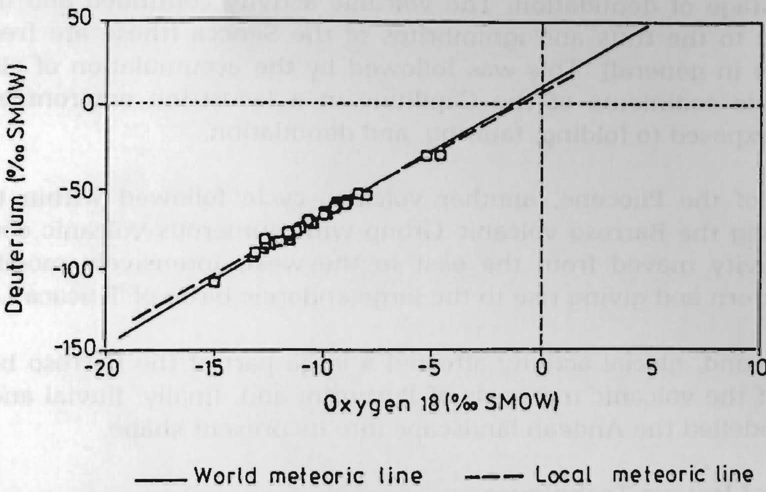

Figure 4: World and Local Meteoric Line: Central Altiplano of Peru

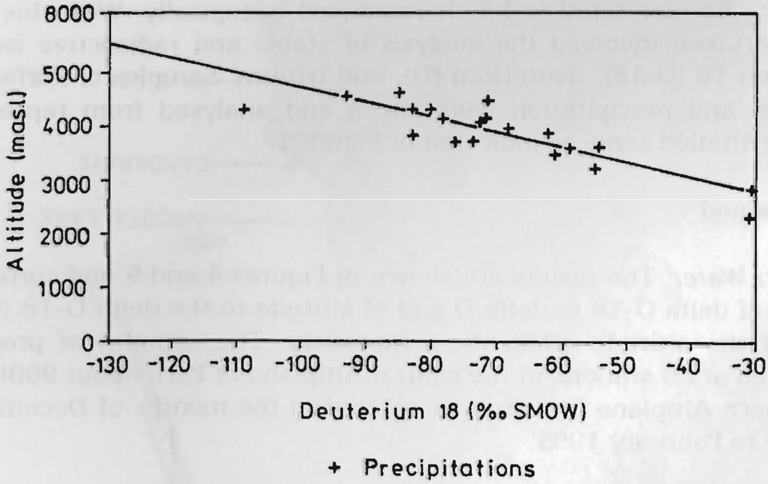

Figure 5: Isotope Altitude Gradient: Central Altiplano

The wide range of values of stable isotopes and tritium in springs and boreholes indicates that groundwater does not constitute a homogeneity body. In spite of occurring in two extensive regional aquifers, Capillune and Maure, the isotope values indicate that the groundwater forms a series of small bodies separated by impermeable barriers with little communication between each other, and which infiltrated rapidly. This idea is supported by the fact that the volcanic formation, Barroso, has formed numerous volcanic cones and flows which interrupt the continuity of the Capillune and Maure aquifers, giving rise to the smaller semi-independent aquifers.

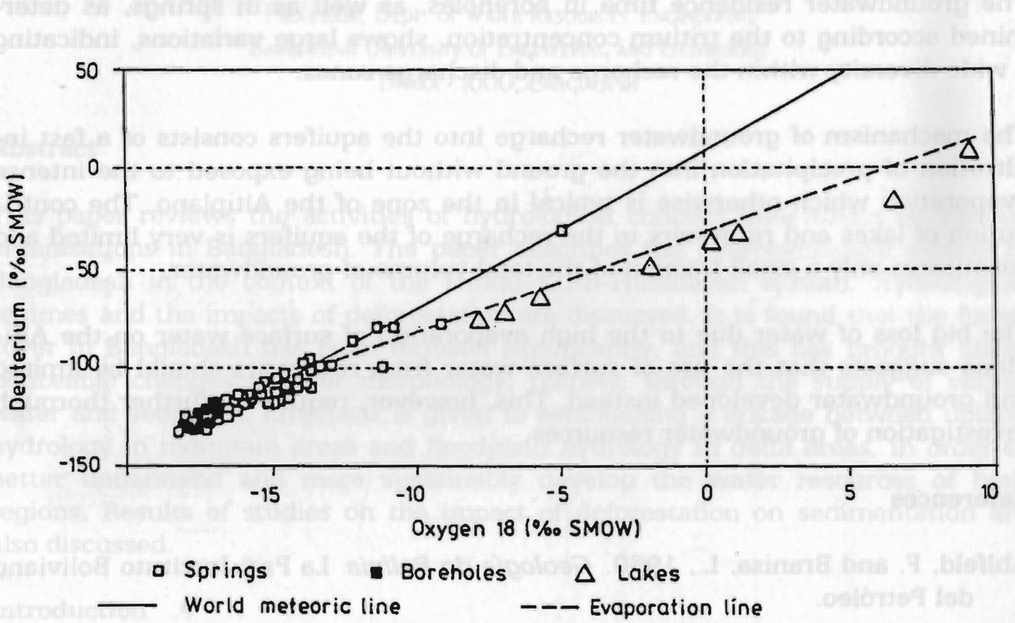

Figure 6: Isotope Composition of Water in the Area of the Proyecto Especial Tacna

The stable-isotope values of water in lakes and reservoirs show a dynamic process of evaporation which agrees with direct measurements of evaporation from pans in the field.

The values of tritium vary over a very wide range, too. The concentrations of tritium in springs and boreholes indicate a long groundwater residence time. It should be noted that some of the results are contradictory, as in the case of the spring, Cuchumbaya, which showed values of 0.1 T.U. (tritium units) and 4.0 T.U. in November 1992 and December 1993, respectively, and of the spring, Huaycata, which showed values of 0.5 T.U. and 4.1 T.U. in the same period. These differences may be explained in terms of a possible existence of two or more sources of recharge of the springs.

Conclusions

The stable isotopes O-18 and deuterium in precipitation in the central Altiplano near Lima show a local meteoric line with a similar and only slightly lower slope than the world meteoric line.

Groundwater in the southern part of the Peruvian Altiplano that occurs mainly in the aquifers, Capillune and Maure, does not seem to constitute a homogeneous body in regard to origin and hydrodynamics but is a cluster of small aquifers half-isolated from each other with relatively independent hydrodynamic systems.

The groundwater residence time in boreholes, as well as in springs, as determined according to the tritium concentration, shows large variations, indicating a wide diversity within the recharge and discharge zones.

The mechanism of groundwater recharge into the aquifers consists of a fast infiltration of precipitation into the ground without being exposed to the intense evaporation which otherwise is typical in the zone of the Altiplano. The contribution of lakes and reservoirs to the recharge of the aquifers is very limited and constitutes only a small fraction of the total volume of groundwater.

The big loss of water due to the high evaporation of surface water on the Altiplano suggests that the use of surface water from reservoirs should be limited and groundwater developed instead. This, however, requires a further thorough investigation of groundwater resources.

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