NATURAL ISOTOPES IN THE GROUNDWATER OF THE TULÚM VALLEY, SAN JUAN, ARGENTINA

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ABSTRACT

The groundwater in the Tulúm Valley of Western Central Argentina is mainly recharged by water from the San Juan River. Both isotope and hydrogeological investigations of the region lead to this conclusion. A faulted buried ridge divides the valley into two basins. The northern section has deep groundwater that seems to be trapped by the upfaulted block. It has been shown by radiocarbon analyses that water from the upper aquifer flows with a velocity of 10 m/yr. South of the ridge the situation is more complicated; oxygen-18 and hydrogeological analyses indicate a contribution from local precipitation.

RÉSUMÉ

Dans la région centrale de l'Ouest Argentin les eaux souterraines de la vallée de Tulúm sont principalement rechargées par l'eau de la rivière San Juan. L'investigation isotopique et hydrogéologique de la région donne cette conclusion. La vallée est divisée en deux bassins par une arête souterraine. La section nord possède des eaux souterraines profondes qui semblent être retenues par l'arête. L'eau de l'aquifère supérieur s'écoule à la vitesse de 10 m/an, déterminée grâce aux analyses de radiocarbone. Au sud de l'arête la situation est plus compliquée et les analyses d'oxygène-18 et hydrogéologiques font penser qu'il y a un rapport entre les précipitations locales et les eaux souterraines.

INTRODUCTION

'Plan Agua Subterránea', a project officially called 'Groundwater Research in the North West of Argentina' and executed by the United Nations as part of the United Nations Development Programme, is being carried out in cooperation with the Argentine Government through the Consejo Federal de Inversiones with aid from the provinces of San Juan and Mendoza.

Preliminary results of the investigation of natural isotopes in the groundwater of the Tulúm (or Tullún) Valley in the province of San Juan are presented here. An earlier discussion of this study was presented in 1967 at the Heidelberg Colloquium on Isotopes in Hydrology (Lerman, 1967a).

In December 1966 six production wells were sampled under the auspices of the Argentine National Research Council and the Physics Laboratory of the University of Groningen, Netherlands. The isotope analyses and hydrogeological investigations allowed some characteristics of the aquifers to be assessed. The content of radioactive isotope ^{14}C and the content of the stable isotopes ^{13}C and ^{18}O provided information about age, flow rate and origin of the groundwater.

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TABLE 1

Description of the boreholes sampled in the Tulúm Valley

Well no.	Department or locality	Depth (m)	Filter depth (m)	Remarks
219	Chimbas	*ca.* 45	*ca.* 39–45	No log. Nearby wells show only gravel. Excellent conditions for surface water infiltration.
49	Pocito	72	57–72	Log shows only gravel. Excellent conditions for surface water infiltration.
749	Rawson	100	62–100	Flowing artesian wells. Confined by clay aquicludes.
747	Rawson	220	182–220	
28	Veinticinco de Mayo	220	195–220	
19	Sarmiento	256	229–256	Artesian but non-flowing. Confined by clay aquicludes.

Regional Description

The Tulúm Valley is situated at a latitude of 31° 30′ S, 200 km east of the Andes at an average elevation of 600 m (Figs. 1 and 2). The San Juan River drains the valley and discharges into a saline depression in the south east of the province. The average annual precipitation is one of the lowest reported for Argentina, about 80 mm a year.

Irrigation from the river was started over 400 years ago by the Huarpe Indians. It has been extended and improved to such an extent that today the flow of the river is almost completely used for irrigation, except at flood periods and in winter. Nowadays about 65,000 ha of vineyards and other crops are irrigated with water from the river and from approximately 4000 wells. Most of the wells have been drilled during the last 12 years to supplement the surface irrigation system during periods when the river flow is not sufficient. Another 200,000 ha of potentially rich desert land, now lying uncultivated mainly at the southern fringe of the irrigated area, could be brought into agricultural production if irrigation water were available.

Hydrogeology

The geological map (Fig. 2) shows two classes of rocks: non-water-bearing, and water-bearing. The non-water-bearing rocks are shown in patterns and range in age from Pre-Cambrian to perhaps Tertiary. The oldest generally form the mountainous areas to the east and west, but they are also found scattered in the valley. The north end of the valley is underlain by impermeable Tertiary sediments where a pediment has been cut and in which no groundwater movement is apparent. The valley floor is underlain by a Quaternary alluvial deposit having a thickness of 600 m or more. It consists of water-bearing sands and gravels (aquifers), as well as layers of silt and clay (aquicludes). Most of these materials were deposited by the former San Juan River flowing through the Zonda Canyon. The area is seismically active and after tectonic adjustments the river changed its course to its present position.

Geophysical studies brought to light the large Tulúm fault which crosses the central part of the basin (Figs. 2 and 3). Seismic information indicates a recent movement along the fault. The cross section shown in Fig. 3 is based on geophysical surveying by the resistivity method for most of the deeper parts of the basin. Where available, information from drilling was used as a control for the shallow portions. Two aquifer zones are shown on the left side of the cross section: the upper aquifer zone and the lower aquifer zone, separated one from the other by the lower aquiclude zone. South east of the Tulúm fault these aquifer zones contain some thin aquicludes as well as permeable sands and gravels where the upper and lower aquifer zones appear to meet.

As might be expected in an alluvial fan, coarser materials have been laid down in the forebay or phreatic area in the north west where the river emerges from the mountains. The materials become progressively finer to the south and south east until sand and gravel are scarce (about 5 per cent).

Most of the groundwater has to originate in the San Juan River since no infiltration occurs, because the small amount of rainfall is accounted for by evaporation. Recharge takes place mainly in the forebay area, where the irrigation water from the river can infiltrate. The movement of groundwater is towards the south and south east as shown by the equipotential map (Fig. 4).

An area of flowing artesian wells occurs north west of the fault due to three factors. First,

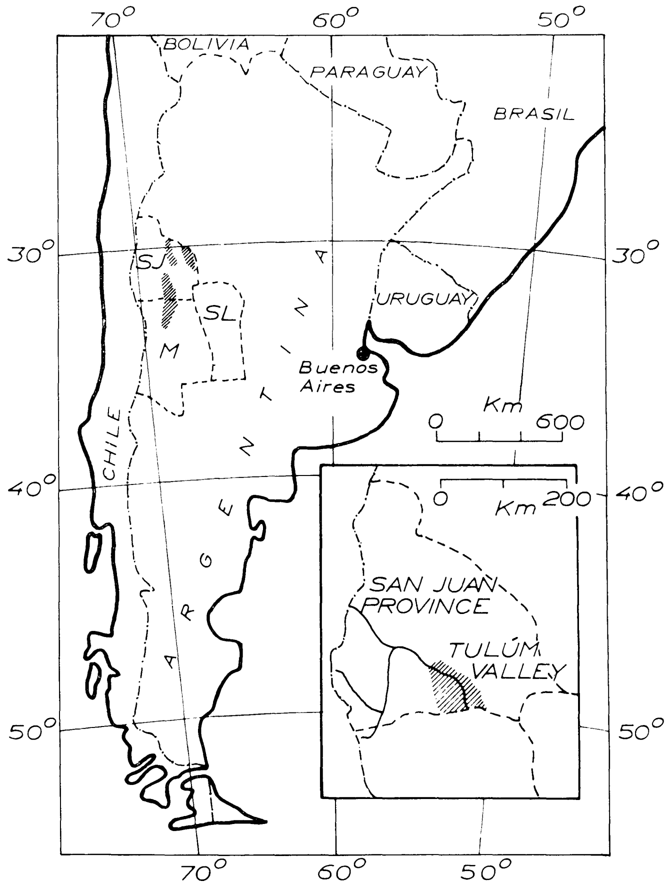


Fig. 1 — Location maps. The shaded area in the large map shows the regions where the project Plan Agua Subterrànea is operating. The shaded area in the inset is the Tulúm Valley studied in this article. (SJ: San Juan Province; M: Mendoza Province; SL: San Luis Province.)

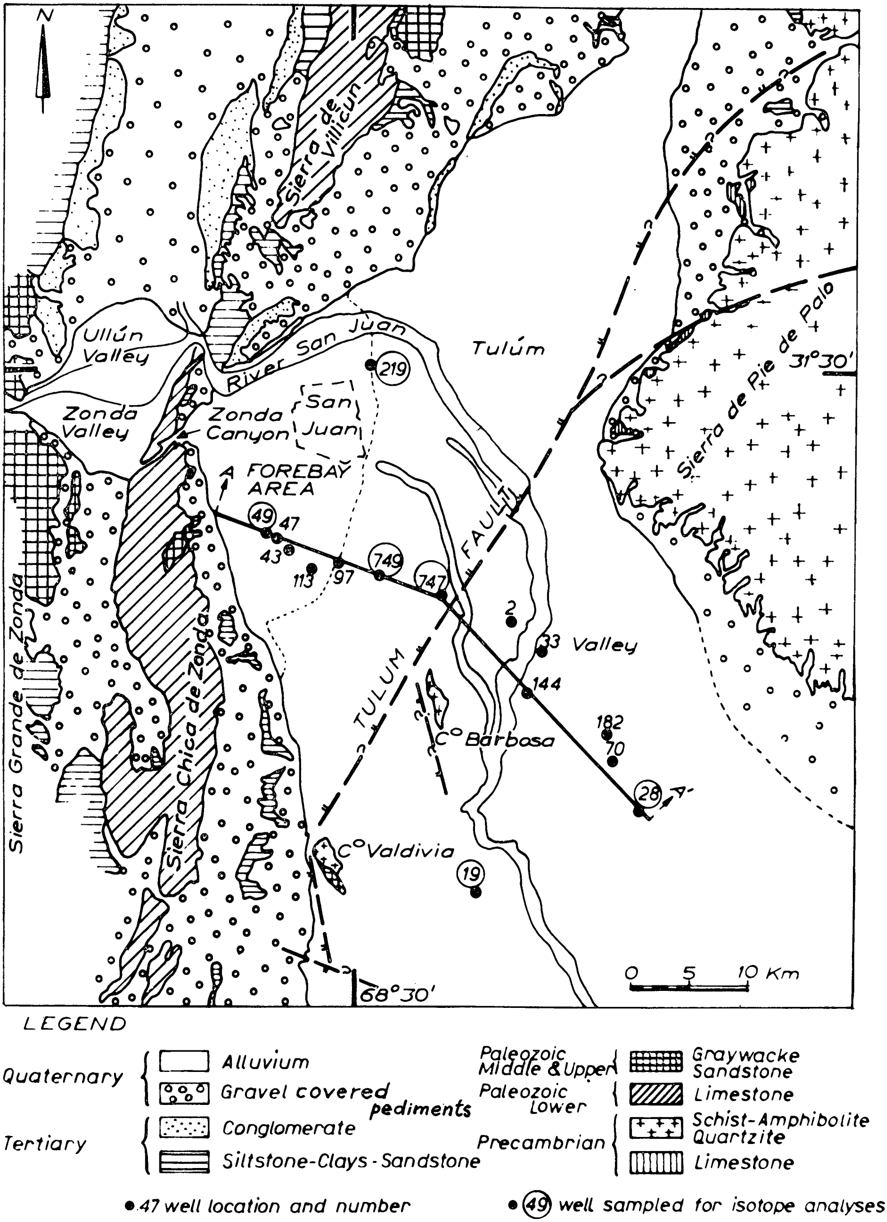


Fig. 2 — Geology of the Tulúm Valley. The line AA′ indicates the location of the cross section given in Fig. 3.

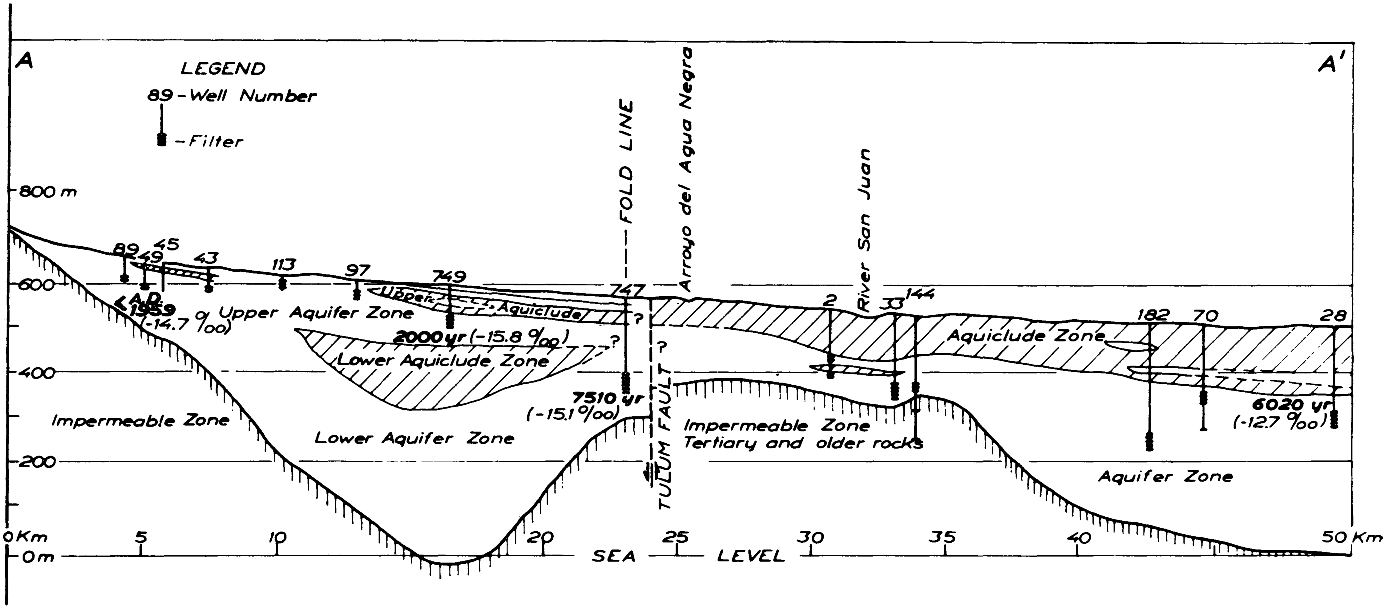


Fig. 3 — Geological cross section of the Tulúm Valley along the direction AA′ of Figure 2. The radiocarbon ages and the $\delta\ ^{18}O$ values (within brackets) of the sampled wells which lie on this section are indicated.

the materials are coarser in the forebay area, decreasing in size and permeability to the south east where confined conditions exist. Second, the ground surface north west of the Tulúm fault tends to be lower than it is on the downthrow side. Third, the fault lowers the transmissivity of the water bearing sediments to the south east where the aquifer section is reduced by the upthrown block (Fig. 3).

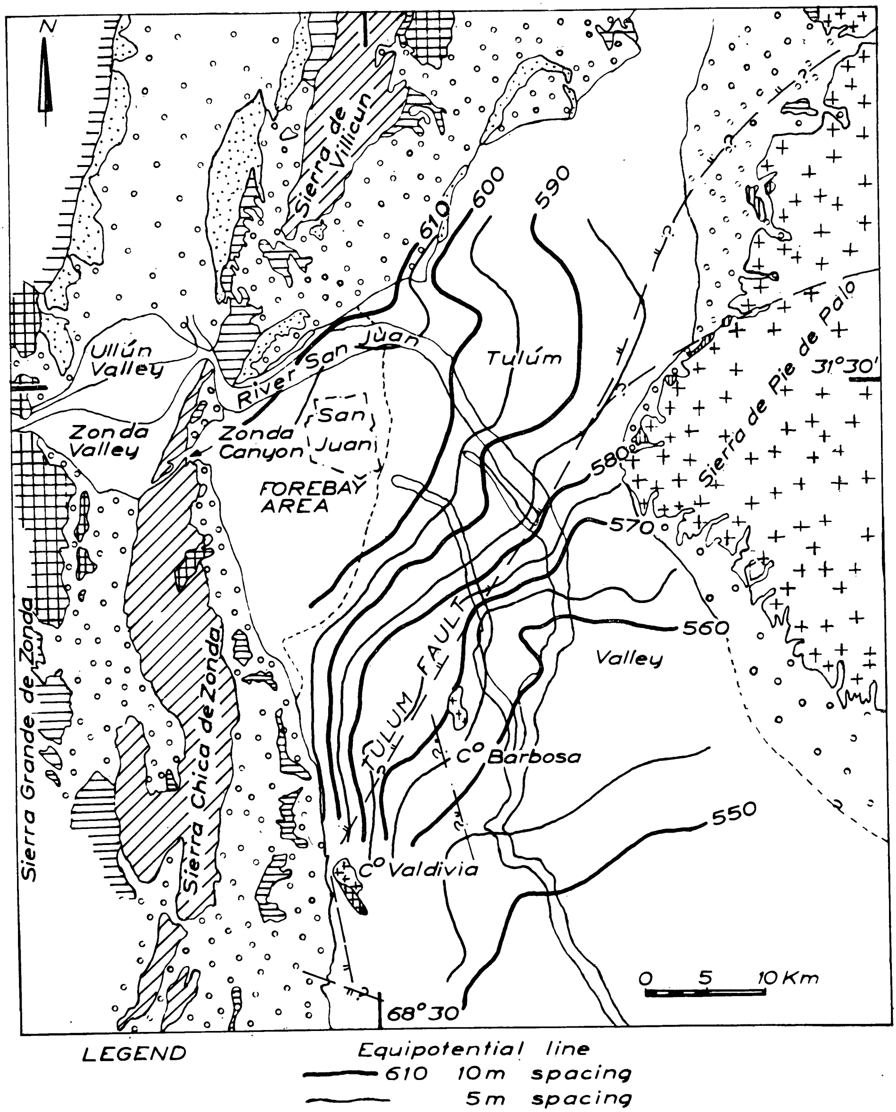
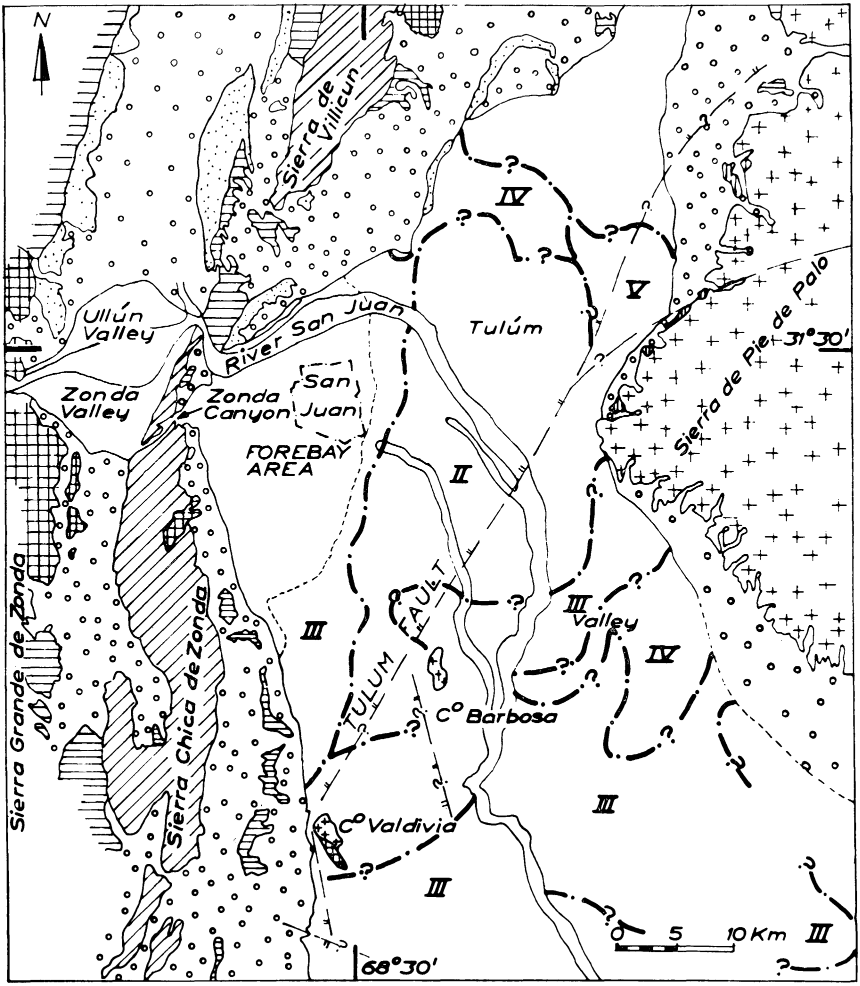


Fig. 4 — Lines of equipotential pressures in the upper aquifer of the Tulúm Valley on September 1967. See Fig. 2 for the explanation of geological symbols.



LEGEND —·—·— Limit between different qualities of water

—·—? —·—? Questionable limit

Class	Description	Sodium (Alkali) and Salinity Hazards C-S	B ppm	RSC epm
I	Excellent	C_1-S_1	< 1.00	< 0.63
II	Good	C_1-S_2; C_2-S_1; C_2-S_2	1.00-2.00	0.63 - 1.63
III	Fair	C_1-S_3; C_2-S_3; C_3-S_1; C_3-S_2; C_3-S_3	2.00 - 3.00	1.63 - 1.88
IV	Poor	C_1-S_4; C_2-S_4; C_3-S_4; C_4-S_2; C_4-S_3; C_4-S_4	3.00 - 3.75	1.88 - 2.50
V	Not Suitable	SAR > 30; EC > 5000 μ mhos/cm (3200 ppm)	> 3.75	> 2.50

Fig. 5 — Water quality map of the Tulúm Valley. The zones indicated correspond to the upper aquifer during July 1967–July 1968. The class of water is governed in all cases by that of the four criteria which shows the poorest condition. See text for explanation and Fig. 2 for geological symbols.

TABLE 2

*Chemical analyses of Tulúm wells**

Analysis no.	Well no.	EC† at 25 °C (μ mho/cm)	DS‡ (ppm)	Cations (meq/l)	Boron (ppm)	[Ca^{++}] (meq/l)	[Mg^{++}] (meq/l)	[Na^{+}] (meq/l)	[K^{+}] (meq/l)	[HCO_3^{-}] (meq/l)	[$SO_4^{=}$] (meq/l)	[Cl^{-}] (meq/l)	SSP§ (%)	SAR‖	Class
193-0826	219 49	1100	750	12·50	0·25	8·73	1·32	8·35	0·10	5·20 5·7	6·50	1·72	18·8	1·0	III C_3–S_1
195-0458	749	450	296	4·70	0·22	2·44	0·62	1·57	0·07	1·82	2·04	0·54	33·4	1·3	II C_2–S_1
187-0460	747	534	368	5·17	0·37	2·10	0·35	2·65	0·07	1·05	3·18	0·87	51·3	2·4	II C_2–S_1
201-1464	28	1580	1100	16·51	0·93	5·94	0·56	9·83	0·17	1·00	10·66	4·85	59·5	5·5	III C_3–S_1
189-1538	19	1120	631	10·97	0·48	3·74	2·22	4·87	0·14	2·80	4·81	3·30	44·4	2·8	III C_3–S_1

* [$CO_3^{=}$] and RSC—residual sodium carbonate, both are zero for all analyses of this table.
† EC—Electrical conductivity.
‡ DS—dissolved solids.
§ SSP—soluble sodium per cent.
‖ SAR—sodium adsorption ratio.
All these parameters are as defined by Richards (1954).

Water Chemistry

The classification of water quality that was employed is given in Fig. 5. This classification of irrigation water is that used in the US Agriculture Handbook No. 60 (Richards, 1954) with the addition of the criteria for boron and residual sodium carbonate. Samples were examined for their electrical conductivity (EC), sodium absorption ratio (SAR), residual sodium carbonate (RSC), and boron content (B) and their overall classifications were determined from the worst of these four characteristics; for instance, a sample with Class II EC, SAR and RSC but with a boron content of 3·5 ppm would be given an overall classification of IV (R.D. Flannery, pers. comm.).

On this basis the values of what is usually considered the upper aquifer (Fig. 3) have been drawn in on Fig. 5 to show the distribution of the different classes as they occur in the valley. Class II quality water occurs east of the forebay area, but the forebay area itself is now underlain by Class III groundwater in the upper aquifer. No doubt this water was previously Class II and has been degraded to Class III by the infiltration of irrigation water which has leached soil fertilizers and other materials.

The bicarbonate concentration (HCO_3^-) was determined at each borehole before the samples for isotope analyses were taken. Complete chemical analyses were carried out later at San Juan and the results are given in Table 2.

Isotope Analyses

(a) *Carbon-14*

Radiocarbon analyses of the inorganic carbon dissolved in the groundwater have proved to be useful for measuring the ages, and consequently the flow velocities of groundwater (Münnich and Vogel, 1960; Vogel and Ehhalt, 1963; Vogel, 1967, 1970). About 60 l. of groundwater were processed for each sample. The total carbon content was extracted and concentrated near the wells using portable equipment.

The 200 ml of sodium carbonate solution obtained were later analysed in Groningen by proportional counting of CO_2. The results of the radiocarbon analyses are given in Table 3. The reference activity for the ^{14}C determinations is the activity of the NBS oxalic acid standard

TABLE 3

Isotope analyses of Tulúm wells

Analysis no.	Well no.	$\delta\,^{18}O$ (‰)*	$\delta\,^{13}C$ (‰)*	^{14}C (%)	Conventional age (yr)	Corrected age (yr)
GrN-5096	219	−14·9	−10·8	103·6±0·9	−290±70	< A.D. 1960†
GrN-5064	49	−14·7	−13·3	95·7±0·5	350±40	< A.D. 1959†
GrN-5055	749	−15·8	− 5·8	66·3±0·6	3300±70	2000
GrN-5073	747	−15·1	− 7·6	33·4±0·8	8810±200	7510
GrN-5066	28	−12·7	−12·0	40·2±0·6	7320±130	6020
GrN-5057	19	− 8·7	− 8.7	16·5±0·3	14500±150	13200

* The precision of the stable isotopes analyses is better than 0·1 ‰.
† Means younger than the date given.

or recent activity (Radiocarbon, edit. stat.). The corrected age is calculated on the assumption that the initial concentration of ^{14}C in the infiltration water is 85 per cent of the recent activity. This assumption is based on experience with data from other aquifers. If the samples have ^{14}C concentrations considerably exceeding 85 per cent, it is assumed that radiocarbon produced by the nuclear weapon tests has already infiltrated into the aquifer. In those cases the minimum dates are deduced starting from the atmospheric ^{14}C concentration data from the Southern Hemisphere (Broecker and Olson, 1960; Rafter, 1965; Vogel and Lerman, 1969). The errors indicated (Table 3) correspond to one standard deviation (σ) of the activity measurement. The uncertainty of the age figures is mainly determined by the uncertainty of the initial ^{14}C content of the water which is probably not larger than 5 per cent or 400 years (Vogel, 1967) and can be expected to affect all samples in the same aquifer to a similar extent, thus reducing the error in the observed flow rate. Retardation of ^{14}C in the aquifer can introduce an error making the age appear a few per cent older and the velocities correspondingly smaller (Münnich *et al.*, 1967).

(b) *Carbon-13*

This isotope is used to provide information about the origin of the dissolved inorganic carbon and about the conditions of infiltration (Vogel and Ehhalt, 1963). Its content has been determined in all samples. The results (Table 3) are expressed as $\delta\ ^{13}C$ PDB, i.e. the (per mill = ‰) fractional deviation of the isotopic ratio $^{13}C/^{12}C$ from that of the PDB standard (Craig, 1957).

(c) *Oxygen-18*

The ratio of $^{18}O/^{16}O$ in groundwater provides information about the sources of recharge of the aquifers. The results are expressed (Table 3) as $\delta\ ^{18}O$ SMOW, i.e. the relative deviation (% σ) of the isotopic ratio $^{18}O/^{16}O$ from the SMOW standard (Craig, 1961). The isotopic composition of precipitation is dependent on the condensation temperature (Dansgaard, 1961, 1964). Thus, by comparing ^{18}O analyses of ground and surface water the possible localities of condensation of the recharged water can be determined. For this comparison, surface water samples, mainly of rivers representative of the Andean region, were also collected. Those results are to be discussed and interpreted in a general survey article (Vogel *et al.* in prep.).

Discussion

The chemical and isotope analyses in general agree with the hydrogeological evidence. The stable carbon isotopic results point to a 'normal' origin for the dissolved carbon i.e. from humus CO_2 and soil limestone. The relatively large ^{13}C content in the samples from wells no. 749, 747 and 19 might be explained by (a) a higher than 'normal' ^{13}C content in the soil CO_2 due to plants with an 'enriched' photosynthetic pathway (Lerman, 1970), or (b) a longer residence time of the water at the surface before infiltration (Mook, 1970). Thus the assumption of an initial ^{14}C content of 85 per cent seems justified.

The $\delta\ ^{18}O$ of water from wells 219, 49, 747 and 749 is about -15 ‰, which is similar to the composition of the Andean rivers recharged with high mountain precipitation. A spot sample of water from the River San Juan for instance gave a value of $\delta\ ^{18}O = -15{\cdot}7$ ‰ (Lerman, 1967b), while the average local precipitation at an elevation of 600 m in this area is estimated to have a $\delta\ ^{18}O$ value of about $-7{\cdot}5$ ‰. This agrees with the hydrogeological conclusions that the source of recharge of the aquifers is water from the River San Juan, either directly from the river channel or indirectly from its branches.

The cross section shown in Fig. 3 follows a line that joins four of the six sampled wells (see complete list in Tables 1, 2 and 3).

In wells 49 and 219 water was found which already contained atom bomb ^{14}C. This water must thus have infiltrated less than 20 years ago. Both wells lie in the forebay area where the gravel favours infiltration of irrigation water. The chemical analyses show a higher content of bicarbonate than in the other samples and suggest different chemical conditions during infiltration. Analyses of boreholes 747 and 749 show some differences between the characteristics of the upper and lower aquifers, Thus, the ages are about 2000 and 7500 years, respectively. Assuming infiltration of water from the river channel in the forebay area and movement in the profile plane, the approximate average flow velocities are:

upper aquifer = 10 m/yr,
lower aquifer = 3 m/yr.

Since the hydraulic gradient is 0·001, as calculated from Fig. 4 and the porosity can be taken as about 50 per cent judging from the boring logs in the forebay area, the specific permeability of the upper aquifer can be calculated. The value obtained by using the formulae and appropriate conversion factors (Todd, 1959, p. 57, p. 328) is about 16 darcy, which is compatible with preliminary calculations based on results of field pumping tests (cf. Todd's values for clean sands and gravel aquifers, p. 53).

The differences in age and chemical composition indicate that the upper and lower aquifers are independent. The greater age of the water in the deeper aquifer is attributed to the fact that the water is partially prevented from flowing beyond the faulted buried ridge between Cerro Barboza and Cerro Pie de Palo. On the other hand, this ridge is not so shallow as to entirely impede the water flow of the upper aquifer. The situation at the other borings that were sampled is more complicated. Although the water of well 28, as shown in the profile, has an age compatible with that of well 749, its $\delta\ ^{18}O$ is different. This could mean either infiltration from a different source or admixture of water of different origins, i.e. locally infiltrated surface water. Its bicarbonate concentration is also different, being lower than that of the upper aquifer (well 749).

Well 19 lies between the profile plane and Cerro Valdivia (Fig. 2). The water sample taken from this well is the oldest measured in the Tulúm Valley. Neither the age nor the bicarbonate content contradict the assumption of a flow from north to south, but the $\delta\ ^{18}O$ content is completely different from that of the Andean rivers. The ^{18}O content of this sample indicates that the precipitation from which it is derived was condensed at a lower altitude (higher temperature) than that feeding the River San Juan.

CONCLUSIONS

Although the Tulúm Valley aquifers are not simple to study, some of their more general hydrogeological features can be distinguished even on the basis of only six analyses of groundwater. For the part of the valley, north of the buried ridge, it is concluded, both from the isotopic analyses and from the hydrogeological survey, that the water originates from the River San Juan and infiltrates either directly from the river and the irrigation and drainage channels, or from seepage of irrigation water through the soil in the forebay area. The most active movement of groundwater occurs in the upper layers of the alluvial deposits, while a slower movement is observed in the deep aquifers in the bowl north west of the Tulúm fault where the water appears to be at least semi-trapped. The movement of water south of the ridge is obviously too complicated to be studied on the evidence of two samples. The ^{18}O analysis of water from well 19, however, supports the idea that precipitation from the west of the well infiltrates into this aquifer, probably through underflows in the limestones. In this preliminary analysis of subsurface flows well 28 so far remains unaccounted for. Additional samples taken north of the Tulúm fault would help to understand the of water flow in that region. An even larger number of samples should be taken south of the fault up to boundaries of Mendoza and San Luis in order to obtain dependable information about the groundwater movement from the north of the Tulúm Valley.

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REFERENCES

Broecker, W.S. and Olson, E.A. (1960) Radiocarbon from nuclear tests part II. *Science*, *132*, 712–721.

Craig, H. (1957) Isotopic standards for carbon and oxygen and correction factors for mass-spectrometric analyses of carbon dioxide. *Geochim. et cosmoch. Acta*, *12*, 133–149.

Craig, H. (1961) Standard for reporting concentrations of deuterium and oxygen-18 in natural waters. *Science*, *133*, 1833–1834.

Dansgaard, W. (1961) The isotopic composition of natural waters. *Medd. Grnl.*, *165*, (2) 1–120.

Dansgaard, W. (1964) Stable isotopes in precipitation. *Tellus*, *16*, 436–469.

Lerman, J.C. (1967a) Isotopic survey of aquifers in the arid west region of Argentina. *Presented to the International Colloquium in Hydrology*, *Max Planck Institut*, *Heidelberg*, *16-17 October 1967*. Translated version published as: Reconocimiento isotópico de aquiferos: región de Cuyo. *Cienc. e Invest.* (1968) *24*, 268–373.

Lerman, J.C. (1967b) Recharge and flow in the Bahia Blanca aquifer investigated with environmental isotopes. *Presented to the International Colloquium in Hydrology*, *Max Planck Institut*, *Heidelberg*, *16-17 October 1967*. Translated version published as: Agua subterránea en Bahia Blanca: Investigación con isótopos. *Cienc. e Invest.* (1968) *24*, 315–319.

Lerman, J.C. (1970) Discussion, in: *Isotope Hydrology 1970*, International Atomic Energy Agency, Vienna, p. 286.

Mook, W.G. (1970) Stable isotopes of carbon and oxygen of natural waters in the Netherlands. *Isotope Hydrology 1970*, International Atomic Energy Agency, Vienna, pp. 163–190.

Münnich, K.O., Roether, W. and Thilo, L. (1967) Dating of ground water with tritium and ^{14}C. *Isotopes in Hydrology*, International Atomic Energy Agency, Vienna, pp. 305–320.

Münnich, K.O. and Vogel, J.C. (1960) C-14 age determination of deep groundwater. *Proc. Assemb. int. Ass. Scient. Hydrol.*, *Helsinki*, *IASH Publ. 52*, p. 537.

Rafter, T.A. (1965) Carbon-14 variations in nature, part 2. Increase in ^{14}C activity in the atmosphere of the Southern Hemisphere from the testing of nuclear weapons. *N.Z. J. Sci.*, *8*, 472–493.

Richards, L.A. (1954) Quality of irrigation water, diagnosis and improvement of saline and alkaline soils. *Agriculture Handbook No. 60*, US Deparment of Agriculture, Washington, D.C., pp. 69–82.

Todd, D.K. (1959) *Ground Water Hydrology*, Wiley, New York.

Vogel, J.C. (1967) Investigation of ground water flow with radiocarbon. *Isotopes in Hydrology*, International Atomic Energy Agency, Vienna, pp. 355–369.

Vogel, J.C. (1970) Carbon-14 dating of groundwater. *Isotope Hydrology 1970*, International Atomic Energy Agency, Vienna, pp. 225–237.

Vogel, J.C. and Ehhalt, D. (1963) The use of the carbon isotopes in groundwater studies. *Radio-isotopes in Hydrology*, International Atomic Energy Agency, Vienna, pp. 383–395.

Vogel, J.C. and Lerman, J.C. (1969) Groningen radiocarbon dated VIII. *Radiocarbon*, *11*, 351–390.

Vogel, J.C., Lerman, J.C. and Mook, W.G. Natural isotopes in surface and ground water from Argentina (in prep.).