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The Geochemistry of the El Tatio Geothermal Field, Northern Chile

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ABSTRACT

Cold meteoric water, originating 15 to 20 km to the east or southeast of El Tatio, flows west and southwest toward the sea and is heated during transit through the Andes. The water is diverted upward as a result of heating and of the presence of permeable tectonic features, some of it being discharged as hot springs and geysers at El Tatio after a transit time of approximately 15 years.

The primary hot water entering the El Tatio basin at 800 to 1000 m has a temperature of 263°C, a high mineral content (9230 mg·kg^{-1} NaCl), is saturated with silica (quartz) and close to saturated with calcite, and contains appreciable concentrations of lithium (45 mg·kg^{-1}), cesium (15 mg·kg^{-1}), and arsenic (40 to 50 mg·kg^{-1}). Measured concentrations of carbon dioxide and hydrogen sulfide in well discharges reach 1.8×10^{-2} and 2.1×10^{-4} molal respectively, but indirect evidence suggests that carbon dioxide concentrations, in water below 800 m, could reach 8×10^{-2} molal.

During transit from depth to the surface the water is compositionally changed by boiling, dilution, rock-water interaction, and contamination from a deep brine. Recognition and interpretation of the chemical and physical parameters operating in the system, by geochemical techniques, have aided the siting of production wells.

INTRODUCTION

The El Tatio geothermal system lies at 68°01′ W, 22°22′ S about 80 km east of Calama, in Antofagasta Province, northern Chile. It is at an altitude of 4250 m, near the Bolivian border and is well known in Chile for its boiling springs, geysers, and fumaroles. From early times travellers have noted the high salinity of the spring waters, and the extensive flats covered with salt evaporates. Figure 1, taken from Trujillo (1974) and Mahon (1974) shows the location and topography of the area.

The thermal springs emerge in a basin lying between the volcanoes of the Andes and the Serrania de Tucle. A volcanic sequence of ignimbrites, tuffs, volcanic breccias, lavas, and interbedded sedimentary layers of Miocene to Recent age

rest on shales of Cretaceous age. The volcanoes rest on the other volcanics, which in the Serrania de Tucle are tectonically elevated and dislodged, the underlying shale also rising to a high level in the core (Healy, 1974).
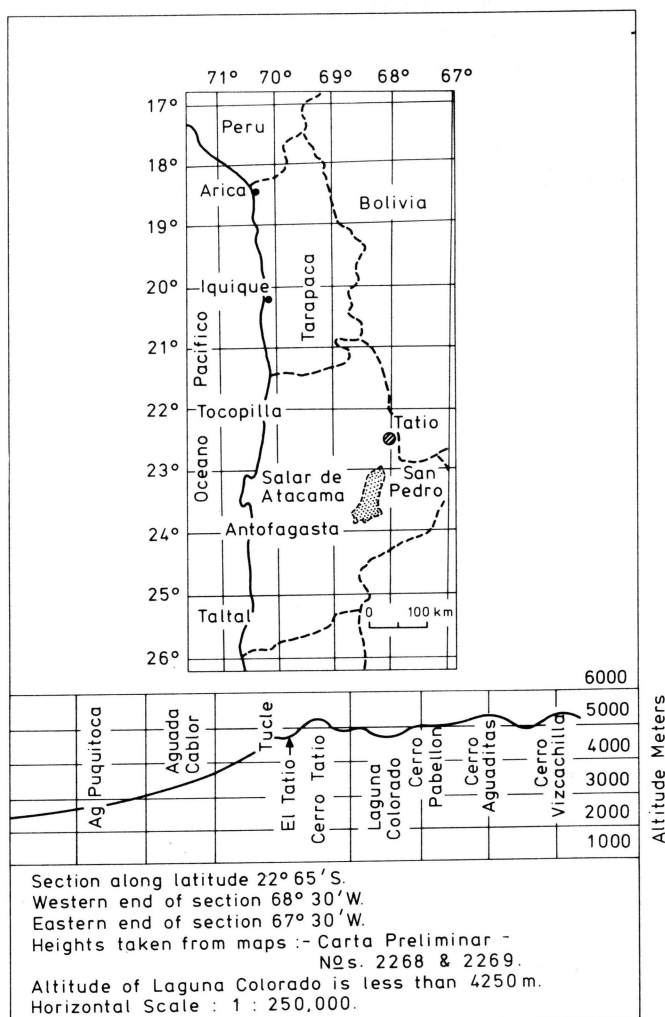

Figure 1. Location and topography of El Tatio.

Zeil (1956) and Trujillo (1968) carried out detailed surveys of the natural activity and noted and mapped some 200 surface features including geysers, hot springs, and fumaroles. Ellis (1969) and Cusicanqui analyzed and interpreted the compositions of a representative number of these features using the information to select sites for exploration wells. Simultaneously, Healy (1967, 1969), together with Chilean geologists, and Hochstein (1968, 1971) and Macdonald (1968), in association with Chilean geophysicists, selected exploratory well sites on the basis of geological and geophysical surface survey results.

Six exploratory wells of depths up to 740 m and seven production wells of depths up to 1821 m have been drilled into the system. Maximum temperature measured in any well (during discharge) was 263°C (Well 7). Detailed surface sampling of springs, fumaroles, and wells and downhole sampling of wells have allowed the chemistry of the fluids residing in the system and the physical processes occurring in the system to be evaluated.

CHEMISTRY OF SURFACE EMISSIONS

Figure 2 shows the numbers and localities of the hot springs, geysers, and wells at El Tatio which were sampled during the present survey. The natural activity occurs mainly in four geographic zones:

1. A zone in the wide northern part of the valley which has extensive salt flats and where the most active features are in a line of geysers and pools on the western margin.
2. A zone along the banks of the Rio Salado in the western valley.
3. A zone of sinter flats and pools continuing southeast from the northern area and into the southeastern valley and plateau.
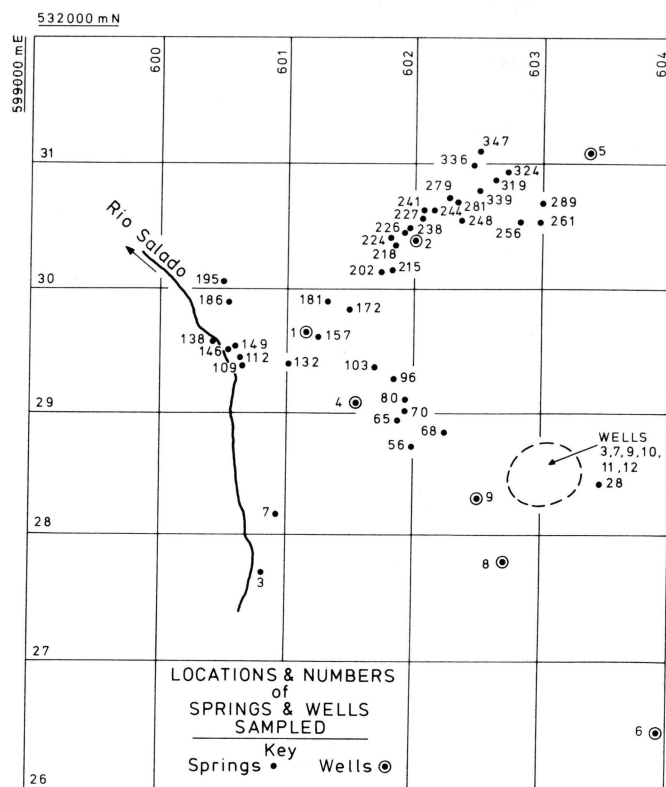
4. A zone approximately 2 km southeast of the main activity and at the base of the High Cordillera where steam-heated pools, mud pools, and fumaroles occur at the head of a stream.

Drainage from the Eastern Cordillera occurs through several westward-trending valleys and from the western complex mainly into the Rio Tucle, which joins the Rio Salado in the western zone of thermal activity. Most of the surface hot water discharges drain ultimately into the Rio Salado.

The very extensive sinter flats and a number of silica cones of extinct geysers, compared with the present-day low output of water, gives the impression that the activity at El Tatio was greater in the past. However, the high altitude and low humidity, with the consequent high evaporation rate, may be in part responsible for the extensive areas of sinter deposits. At the low atmospheric pressure of approximately 43.9 to 44.5 cm at 4250 m, water boils at a temperature of 85.5 to 86°C. The high evaporation rate causes salt incrustations about the edges of pools, and in general on all surfaces over which thermal water has flowed.

Warm springs occur in a valley northeast of Copacoya, and boiling springs, fumaroles, and hot water seepages occur east of the El Tatio basin close to the Chilean-Bolivian border at an altitude of approximately 4900 m. The latter natural activity is aligned in a general north-south direction and is notable for the growth of multicolored algae and extensive deposits of salt incrustations. Extensive hydrothermal rock alteration occurs throughout the zone particularly on the El Tatio volcano, and this feature, together with the deposits of salts surrounding hot water discharges, delineates the areas of high surface heat flow. The main cold water sink east of El Tatio is the Laguna Colorado which occurs at an altitude somewhat lower than the El Tatio basin (Figure 1).

Spring Chemistry

Table 1 gives the partial compositions of a representative group of spring waters; Table 2 gives some molecular ratios of constituents. Table 3 contains analyses of a selection of the waters for trace metals.

The spring waters are notable for their high mineralization (1350 mg·kg^{-1} NaCl), and the high content of cesium (15 mg·kg^{-1}), arsenic (45 to 50 mg·kg^{-1}), lithium (45 mg·kg^{-1}), and calcium (250 mg·kg^{-1}). The frequency distribution of values of certain constituents and ratios is shown in Figure 3. Apart from steam-heated or very dilute waters there is a very small range of values for the Cl:B ratio in El Tatio waters. It suggests that all of the chloride waters in the area rise from a common body of hot water. The constancy of values in the southern area at 13.0 indicates that the waters pass to this area either along one supply fissure, or through chemically very homogeneous rock. The scatter of results about a mean of 13.45 for the northern and western areas is a more usual distribution, showing small local contamination. The ratio of Na:Li also covers a restricted range of values. As lithium has a slight tendency to react with the country rock and can be absorbed as water cools, the distribution could be expected to be asymmetrical towards higher Na:Li values. The results are consistent with a common water source.

Figure 2. Locations and numbers of springs and wells sampled.

Table 1. Chemical composition of spring and well waters at El Tatio.

Concentrations mg·kg^{-1} at Atmospheric Pressure and Boiling Point

Spring no.	Temp. (°C)	pH (15°)	Li	Na	K	Cs	Mg	Ca	F	Cl	SO$_4$	HCO$_3$	CO$_2$	B	SiO$_2$	NH$_4$
65	85.5	6.70	28	2880	145	10.0	7.2	225	—	5236	42	88	18	123	177	—
80	84.0	6.93	34	3200	165	10.8	1.3	252	—	5878	50	44	5	139	174	—
109	85.5	7.70	34	3300	270	10.9	0.6	245	—	5874	37	19	1	134	123	2.0
149	85.0	7.78	34	3430	256	11.0	1.8	256	—	6011	32	12	0	136	137	—
181	84.5	6.90	—	2250	230	8.0	6.0	170	—	4009	36	114	21	91.1	122	—
186	83.5	7.00	34	3380	320	10.9	1.5	313	—	6062	35	35	4	115	142	—
202	85.5	7.25	33	3140	336	10.2	4.2	218	—	5628	37	41	3	127	137	—
218	85.0	7.30	37	3980	475	11.7	2.5	248	—	6638	35	40	2	149	174	2.3
227	85.0	7.40	47	4600	520	13.0	0.3	280	2.6	8220	38	39	2	187	256	2.9
238	85.0	7.32	45	4340	520	12.6	0.5	272	3.1	7922	30	46	1	178	260	3.8
244	85.0	7.30	46	4330	525	13.2	0.4	274	—	8126	27	41	1	183	269	2.7
339	82.0	6.22	46	4580	525	13.0	0.5	269	2.9	8037	32	36	22	182	221	3.6
Well No.																
1	—	7.46	30.2	4480	420	15.0	1.1	270	2.75	7943	64	29	1.8	173	400	1.4
2	—	7.36	42.0	5080	633	17.4	0.82	272	2.9	9134	49	53	2.0	195	452	2.17
3	—	7.65	31.1	3512	168	13.0	2.08	268	3.0	6160	60	12	—	139.5	238	—
4	—	7.45	28.0	4537	193	17.0	3.7	228	2.6	7774	62	81	—	172	338	—
5	—	7.4	44	5000	684	17	1.0	280	3.5	8360	45	65	3.5	203	460	1.5
6	—	8.2	17.1	1900	111	6.8	1.3	99	—	3048	177	111	0.6	77	184	—
7	—	7.0	45.2	4840	830	17.4	0.16	211	3.0	8790	30	40	5.4	203	766	2.3
10	—	7.05	43.9	4795	799	16.9	0.72	253	—	8986	31	40	5.5	206	740	—
11	—	6.98	44.9	4900	825	17.2	0.15	208	—	8716	32	41	5.2	202	748	2.5
12	—	7.56	45.1	4850	778	17.5	0.24	163	—	8450	62	69	2.2	181	655	—

Table 2. Molecular ratios of some constituents in El Tatio springs and wells.

	Molecular ratios						
	of Na to				of Cl to		
Spring no.	Li	K	Ca	B	SO$_4$	F	Cs
65	31	34	22.3	13.0	340	—	1960
80	28.5	19.5	22.0	13.0	320	—	2040
109	29.5	21	23.5	13.4	430	—	2020
149	30.5	23	23.4	13.5	510	—	2040
181	—	16.5	23.0	13.4	300	—	1880
186	32	18.0	18.8	16.0	470	—	2080
202	29	15.9	25.1	13.5	410	—	2060
218	32.5	14.2	28.0	13.5	510	—	2120
227	29.5	15.0	28.2	13.4	590	1690	2360
238	29	14.2	27.8	13.6	720	1370	2350
244	28.5	14.0	28.5	13.5	810	—	2300
339	30	14.8	29.6	13.4	680	1480	2310
Well No.							
1	44.7	18.1	28.9	13.8	335	1550	1980
2	36.5	13.6	32.6	14.3	505	1690	1965
3	34.1	35.5	22.8	13.5	280	1100	1775
4	48.9	39.9	34.6	13.8	339	1600	1715
5	34.3	12.4	31.1	13.5	540	1280	1980
6	33.6	29.1	33.4	12.6	465	—	1620
7	32.3	9.9	40.0	13.2	800	1570	1905
10	32.9	10.2	33.0	13.1	786	—	1995
11	32.9	9.9	41.0	13.2	740	—	1905
12	32.4	10.6	51.7	14.2	370	—	1806

Table 3. Trace metal concentrations in El Tatio springs (mg·kg^{-1}).

	Constituents									
Spring no.	Sr	Rb	Fe	Mn	Zn	Cu	Ag	Ni	Pb	Tl
65	1.00	2.26	0.55	0.43						
80	1.12	2.68	0.07	0.17						
109	1.30	3.62	0.06	0.30						
149	1.44	3.51	0.07	0.38	all less than 0.004	all less than 0.02	all less than 0.005	all less than 0.03	all less than or equal to 0.06	all less than or equal to 0.06
181	0.78	2.50	0.25	0.64						
186	1.19	4.22	0.03	0.16						
202	1.07	4.45	0.07	0.57						
218	1.15	5.38	0.06	0.49						
227	1.14	6.88	0.07	0.29						
238	1.14	6.65	0.10	0.41						

Figure 3. Distribution of values.

Figure 4. Chloride concentration in spring waters.
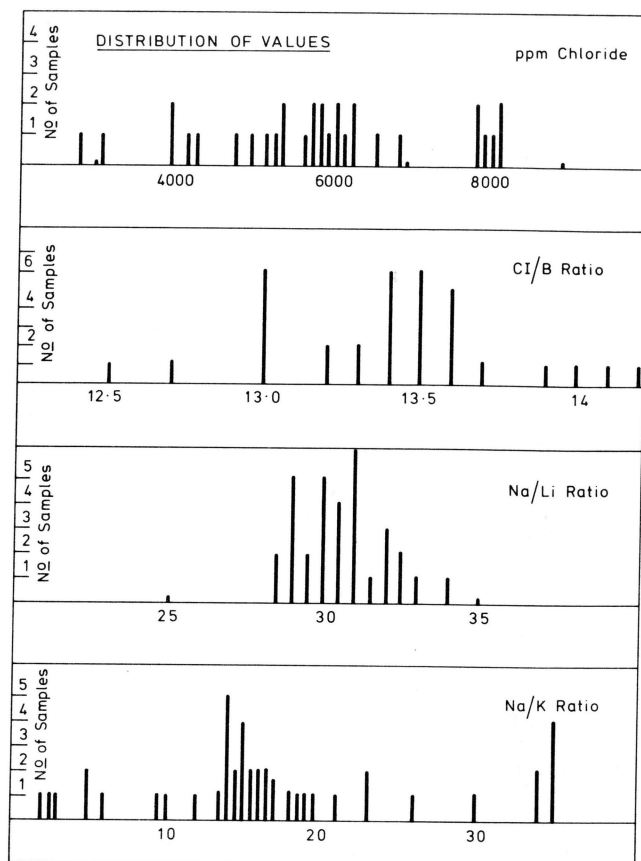
The variation in chloride concentration about the field can be seen in Figure 4. The distribution frequency (Fig. 3) shows major peaks at about 8000 and 6000 mg·kg^{-1}, which correspond respectively with the northern geyser area and parts of the western and southern areas. The near constant concentrations about 8000 mg·kg^{-1} for the northern geyser area suggest that these waters rise from depth without near-surface dilution. Silica concentrations and Na:K ratios suggest that the northern springs receive the most direct supply of deep hot water and that the minimum temperature of the deep aquifer is possibly 200 to 220°C.

The low fluoride concentrations of 2 to 3 mg·kg^{-1} found in the high chloride waters are as expected in the presence of the high calcium concentrations. The rubidium concentrations follow the trends in potassium concentrations. The ratio of Cl:Cs is almost constant over the field, within the errors possible in the determinations, pointing to a single water supply below the area. The rather high magnesium
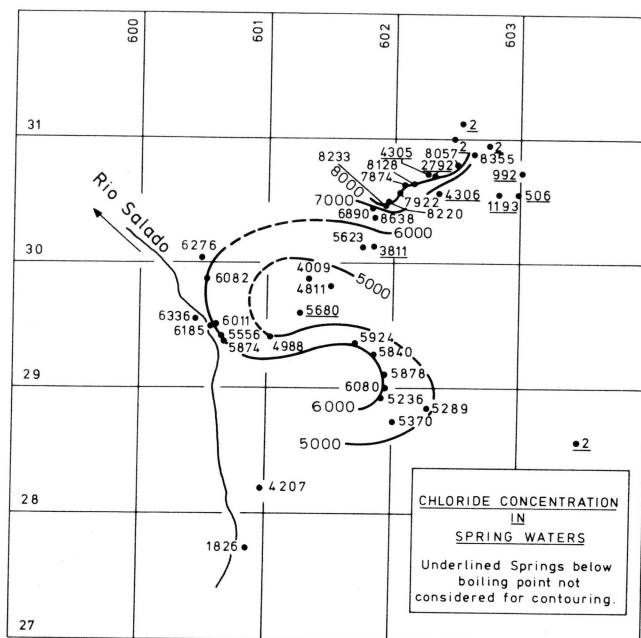
concentrations suggest that the water supply to the springs has a temperature less than 250°C but may also be partly due to the high salinity of El Tatio waters.

The general interpretation of the spring chemistry is that near-surface drainage from the east sweeps into a shallow hot aquifer underlying the western and southern areas, diluting the high chloride water which rises from deeper levels. The relatively high chlorides in the low-lying western area near the Rio Salado suggest a vigorous upflow of chloride water counteracting dilution effects.

The analyses of the northeastern springs shows that the water has the general characteristics of a much diluted El Tatio water. The eastern springs contain only minor chloride and it is apparent the hot waters in this area are steam-heated meteoric waters. However, at the altitude that these springs occur relative to that of the closest cold-water sink, it is unlikely that chloride water could ever reach the surface.

Fumaroles

A selection of fumarole results is shown in Table 4. The concentrations of gas in the steam are low in the northern and western fumaroles. In the southern and camp stream head fumaroles gas concentrations are approximately ten times higher, but this could to some extent be due to a concentration effect, as the rising steam partly condenses

Table 4. Analysis of fumaroles at El Tatio.

| Fumarole | Temp°C | Millimoles of gas per 100 moles water | | | | | | Molecular ratio CO_2:H_2S |
		CO_2	H_2S	N_2	O_2	CH_4	H_2	
266	86.6	75	0.6	9.8	5.2	0.02	0.0	125
233a	86.5	21	Nil	11.1	2.9	0.01	0.0	1000
140	86.4	28	0.03	7.9	2.1	0.00	0.0	1000
29	86.0	700	0.73	124	32	0.00	0.0	960
Head of camp stream	86.0	360	2.4	39	11	0.00	0.0	150

in heating the surface waters of these areas. High pressure steam at temperatures considerably above 100°C would also contain high gas concentrations and could be condensing into surface waters in these areas.

The large northern fumarole and the camp stream head areas have the lowest $CO_2:H_2S$ ratios, and the appreciable sulfide suggests that the steam originates beneath the depth of the oxidation or reaction layer which seems to underlie parts of the system. The southern areas (which are on elevated country) also contain appreciable sulfide and are presumably in a location where steam from deep levels can rise directly to the surface. Long lateral supply fissures to the southern zones are possible but the intense supply of steam to these areas may rise directly from a high-temperature aquifer immediately below.

Precipitates and Minor Elements

The major constituents of all the deposits are silica, calcium, arsenic, and antimony. Deposits rich in arsenic and antimony sulfides are often found in hot spring areas of neutral-pH, high-chloride waters. The strontium, rubidium, and cesium concentrations in the waters are about at the levels expected in comparison with other alkali ions. Iron and manganese are slightly higher than those found in dilute hot waters, such as Wairakei, New Zealand, but the high salinity at El Tatio could account for this. The

concentrations of base metals in the water are all at a low level.

Deuterium:Hydrogen and $^{18}O:^{16}O$ Ratios

Figure 5 shows the results obtained from a survey of the D:H and $^{18}O:^{16}O$ ratios in hot and cold waters in and around El Tatio. The hot high-chloride waters do not have δD values identical with local surface waters but follow a trend which suggests a mixing of deep hot water originating from outside the El Tatio environment with local surface water. The steam-heated, low-chloride waters are related to local meteoric waters by a line which is typical of waters in which deuterium and ^{18}O are concentrated by evaporation.

Samples collected from some distance east of El Tatio show a scatter of δD values and various degrees of evaporation. Although only a limited number of samples have been collected, the trend of δD and $\delta^{18}O$ is towards more negative values than those present in cold waters at El Tatio. The isotopic compositions of the waters discharged from wells at El Tatio suggest that the source water for the geothermal system could have δD and $\delta^{18}O$ values of -74 to -78 and -10.5 to -11.0 respectively. The eastern El Tatio cold waters trend towards these values and it appears that the source water for the El Tatio system originates some distance (15 to 20 km) to the east and southeast of the area.

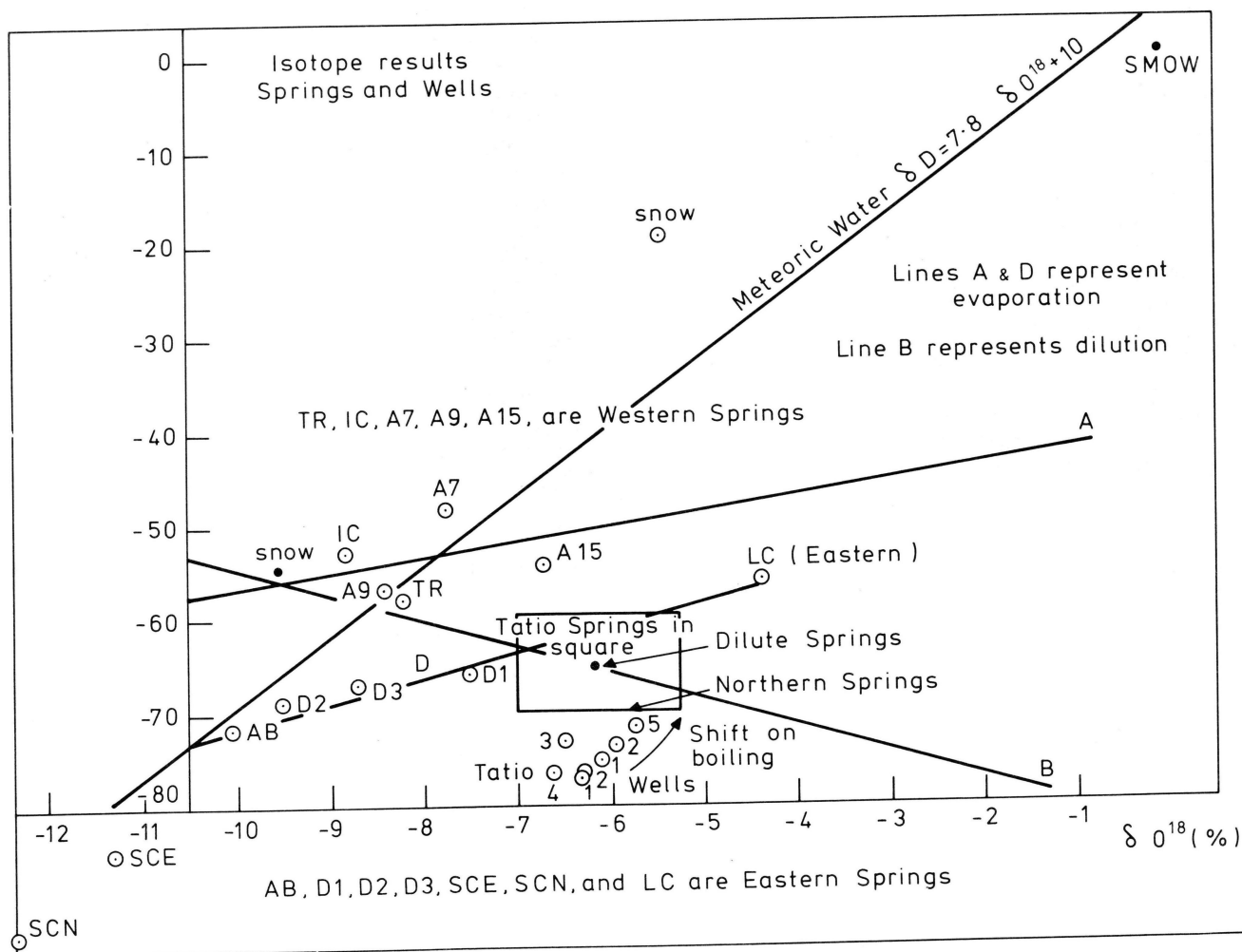The ^{18}O "shift" in the hot El Tatio waters is appreciable

Figure 5. Isotope results, springs, and wells.

and compares with those in other geothermal areas where rock permeability is limited, and/or where extensive rock-water interaction has occurred. Although the observed rock permeability at El Tatio is rather low, there is little evidence as to whether the large oxygen shift in this area is caused by this factor or whether it results from a long distance of travel from the source area. The topography of the area indicates that it is most unlikely that water would travel in a horizontal plane. Although the source water for the system may only be 15 km distant in a horizontal plane the actual distance travelled by the water may be twice this distance.

Tritium Content of El Tatio Water

Only preliminary data are available for the tritium survey of the El Tatio waters. The following interpretation can only be regarded as speculative at this point. The tritium content of undiluted El Tatio water is 3.2 T.U. $\pm$ 0.2 (1 T.U. = T:H 10^{-8}; the error represents one standard deviation). Assuming that the water entering El Tatio represents a constant supply in which the water fell as rain, entered the ground water supply, and moved to the sampling point without mixing with other water, its age on discharge would be about 15 years and almost certainly not greater than 17 years. From the source area indicated by the D:H ratios the rate of movement of water could be of the order of 1 km/year.

CHEMISTRY OF WELL DISCHARGES

General

The positions of the drilled wells at El Tatio are shown in Figure 2. Exploration wells are numbered 1 to 6 and production wells from 7 to 13. Physical data relevant to the wells are shown in Table 5.

Wells 1, 2, 4, 5, 8, 9, and 10, drilled in the western part of the system, pass through a temperature inversion at relatively shallow levels, 250 to 400 m. Wells 3, 7, 11, 12, and 13 in the eastern section of the field do not pass through the inversion, and temperatures at well bottoms are generally increasing. Well 6, drilled in the southeast, is too shallow to give much information about deep temperatures, but it increases in temperature at well bottom, 180°C at RL 3965 m.

The rock formations penetrated by the wells are in most cases nearly horizontal and only one major discontinuity has been recognized, the "Geyser Fault," in the northwest of the field. Many of the springs and geysers in the northern part of the field are aligned along the surface trace of the fault. The formations penetrated by the wells from the surface are: intermontane sands and gravels, Andean tuffs, Tatio ignimbrite, Tucle formation (lavas of dacite and rhyolite, siltstone and tuff, pumice breccia), Puripicar ignimbrite, Salado ignimbrite, and Salado breccias. In the western part of the field maximum temperatures occur in the Puripicar ignimbrite, at depths ranging from 250 to 400 m, while in the eastern wells maximum temperatures occur in the Salado breccias. Wells 8 and 9, which penetrate deeply into the Salado breccias, have temperatures of approximately 200°C at well bottoms, although temperatures appear to be rising very slowly at the drilled depths.
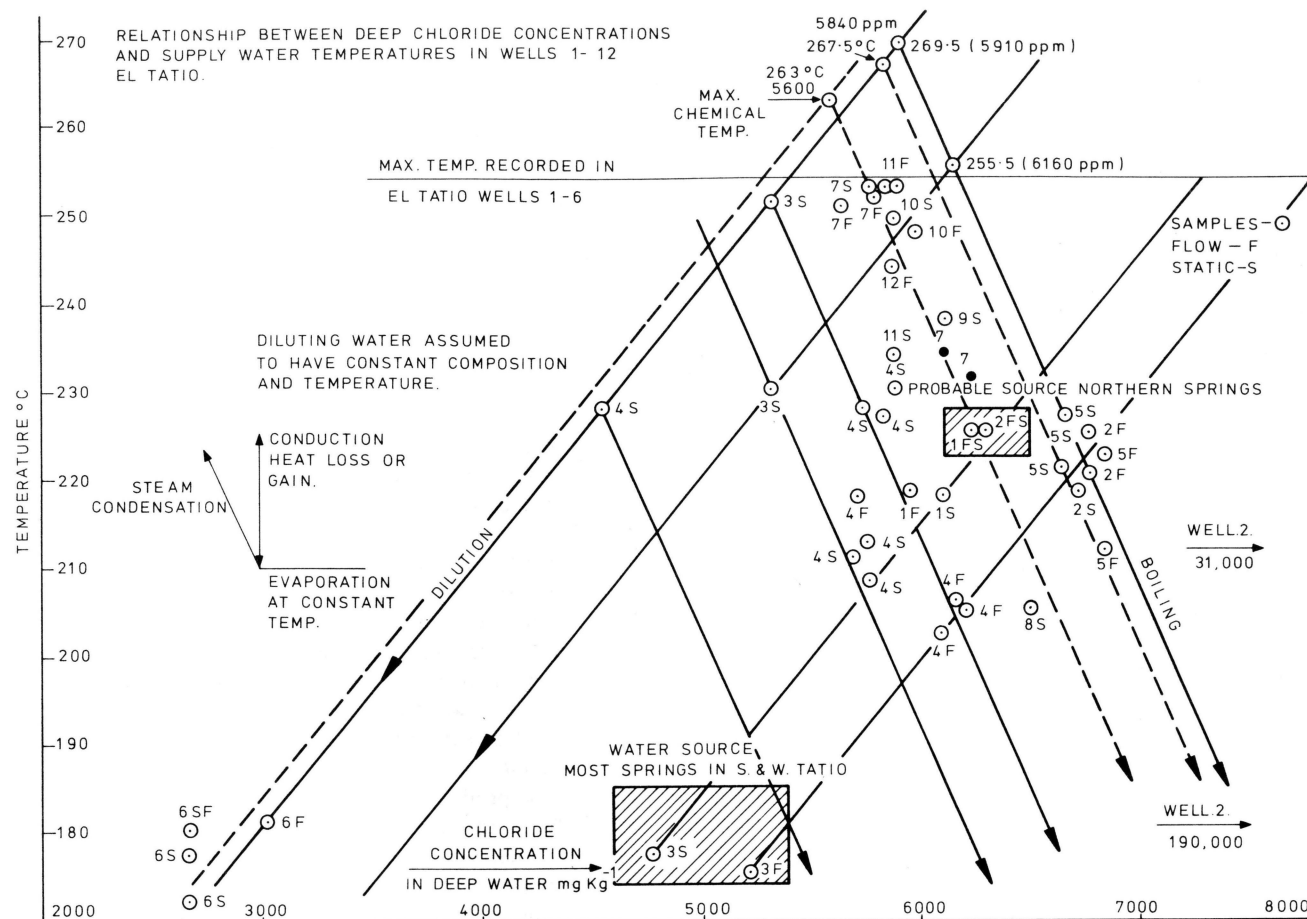
Water Chemistry

The chemistry of the water discharged from the wells is shown in Tables 1 and 2. There is some variation in the chemistry of individual wells with discharge but the results tabulated are reasonably representative of the waters present near the wells before drilling. The well waters are compositionally similar to the spring waters and can be related chemically to a single parent water. Waters with considerably higher chloride concentrations than were present in any of the spring waters were discharged from Wells 2 and 9 on initial opening. Well 9 did not produce long enough to follow chemical trends with time but the chloride concentration in Well 2 trended towards the northern spring values, after the well had been discharged for some weeks.

Downhole sampling of waters at different depths in the wells, before and after discharge, gave a detailed "in depth" chemical profile of the system. Of particular significance was the discovery of a saturated brine at a depth below approximately 600 m in Well 2. Evidence of this brine was also found in Well 5 at an approximately similar depth, and in Well 9, and possibly Well 10, at somewhat deeper levels (800 m).

The relationship between the chemistry of individual wells is shown diagrammatically in Figure 6, where supply water temperatures, estimated by silica and Na:K geothermometry and deep chloride concentrations obtained by surface sampling and downhole sampling are plotted. Trend lines showing

Table 5.   Wells—physical data.

Well no.	R.L., m	Depth m	Solid-cased m	Maximum temp. °C before discharge
1	4254.04	617	243	211
2	4262.41	652	295	226
3	4344.02	616	238	253
4	4263.96	733	247	229
5	4271.97	568	282	212
6	4478.99	551	401	180
7	4363.2	867	590	250
8	4335.9	1585	600	231
9	4323.3	1816	594	225
10	4343.5	1504	590	236
11	4341.4	894	575	240
12	4356.3	1410	595	247
13	4354.0	1010	501	?

Figure 6. Relationship between deep chloride concentrations and supply water temperatures in Wells 1 to 12, El Tatio.

the effect of boiling and dilution on the waters are shown together with the probable source waters for the northern, southern and western springs. The diluting water is assumed to have a uniform composition similar to that of the local surface cold waters.

Extrapolation of the most reliable chloride data and the maximum estimated chemical temperature suggests that the parent water entering the El Tatio system at approximately 800 m contains 5600 mg·kg^{-1} chloride and has a temperature of 263°C. Extensive physical testing on Well 7, including the measurement of deep temperatures during discharge, indicated that the water supplying the well was 261 to 263°C (R. James, personal comm.) although static measurements gave a maximum temperature of 250°C.

The composition of the water discharged from Well 7 is reasonably representative of the composition of the parent water. However, the Cl:B ratio of 13.2 is somewhat higher than found in a number of southern springs and in Wells 6 and 8 (also in the south), and may indicate that a small amount of brine contaminates the water. (The Cl:B ratio in the brine is 300.) The ratios of Na:Li, Na:Ca, Cl:SO$_4$ and Cl:Cs of 33, 40, 800, and approximately 1900 respectively in Well 7 are possibly present in the parent water.

The carbon dioxide and hydrogen sulfide concentrations in the water entering Well 7 are 1.8×10^{-2} and 2.1×10^{-4} molal respectively with a CO$_2$:H$_2$S ratio of approximately 90. Gas concentrations in the western wells are lower than these values, apart from Well 4, which had a carbon dioxide concentration of approximately 6×10^{-2} molal

(evidence suggests that a gas-rich steam phase enters this well at a shallow level). The CO$_2$:H$_2$S ratios in the western wells are considerably higher (3 to 15 times) than those in the eastern wells, suggesting fluid migration from east to west across the system.

There is evidence from downhole samples collected in Well 7 that the water entering the well during discharge boils before reaching the well. The steam escapes into higher formations and does not enter the discharge. From the amount of steam escaping and the known distribution of carbon dioxide between steam and water, an estimate of the original gas concentration in the deep parent water is possible. A value of 8×10^{-2} molal was obtained. Steam separating from water containing this concentration has a very high gas concentration (the actual concentration being dependent on the amount of separation). Steam discharged from the camp stream fumaroles and steam entering Well 4 at shallow levels contain high carbon dioxide concentrations of the order expected.

Carbon dioxide, the major gas present in the El Tatio waters, makes up over 99.5% of the total gases present. The nonabsorbable gases, consisting essentially of nitrogen with small amounts of methane and hydrogen, are present to the extent of 0.25% of the total gases.

EL TATIO BRINE

The presence of saturated brine in the central part of the El Tatio basin is very interesting. To the authors'

Table 6.   Comparison of constituent ratios in El Tatio brine with those of selected other sources.

Ratio	Brine El Tatio	Well 7 El Tatio	Crater Lake Ruapehu *†	White Island†	Well 11D–1 Salton Sea‡
Na:K	38.7	9.9	31.2	13.0	3.9
Na:Li	6 100	32.3	124	—	51.0
Na:Ca	29.8	40.0	2.1	5.2	2.3
Na:Rb	12 100	2 450	13 430	—	4 434
Cl:B	302	13.2	244	2 900	108
Cl:Cs	11 500	1 900	230 000	—	34 500
SiO_2	200	810	712	180	—

* Value on 20 August 1970
† New Zealand
‡ California, USA

knowledge this is the first time that a saturated brine has been identified in a geothermal system. The Salton Sea system in southern California contains a similar type of brine but is less concentrated.

The El Tatio brine has a pH of 2.0 at 25°C, a density of 1.2, a chloride concentration of 180 to 190 × 10³ mg·kg⁻¹ and exists in the rocks at a temperature of 180 to 200°C. The temperature of the brine is well below the boiling point for depth. The ratios of a number of constituents present in the brine and in Well 7 are shown in Table 6. Ratios present in waters of Ruapehu Crater Lake, New Zealand, in a fumarole condensate from White Island, New Zealand (an active andesitic volcano), and in the water discharged from Well 11D-1 at Salton Sea are shown for comparison.

There are considerable differences between the composition of the brine and the parent water entering El Tatio. Unfortunately the isotopic composition of the brine still requires elucidation, and its trace metal components have not yet been determined. Its origin therefore remains uncertain.

Of interest, however, is the negative temperature gradient through the brine and its high density. It appears that hotter, less dense fluids rising from deeper levels are diverted around the brine toward the eastern parts of the system.

INTERPRETATION OF EL TATIO CHEMISTRY

Cold meteoric waters, falling as snow or rain, to the east and/or southeast of El Tatio, within a distance of 15 to 20 km, penetrate down under the Andes to an unknown depth and move west and northwest under a hydraulic gradient toward the sea. The waters are heated by residual heat from the local volcanism, and as a result are diverted upwards through permeable tectonic features. The hot water reaches the surface in the El Tatio basin and steam, derived from the hot water, heats surface meteoric water just to the east of El Tatio. The travel time from east to west could be of the order of 15 years.

The hot water entering the basin below 800 to 1000 m is diverted initially to the east, around the brine, and then to the west following the direction of rock permeability. Within the basin the hot water is mainly confined to two aquifers, both of which are overlain by relatively impermeable rocks. The lower aquifer is the Puripicar and Salado ignimbrites which are overlain by the impermeable Tucle tuffs. In the center, south and southeast of the basin a second aquifer, the Tucle dacite is overlain by a relatively impermeable ignimbrite, the Tatio ignimbrite. The Tucle dacites are not present in wells 1, 2, 4, or 5 in the north and northwestern sectors of the basin.

As the hot water moves upward toward the base of the Tucle tuffs, boiling occurs as vapor pressure and gas pressure exceed the confining pressure. Upward movement of primary hot water occurs in the east of the Basin. The confining pressure (aquifer pressure) at the base of the Tucle tuffs is probably of the order of 25.5 kg·cm⁻², and temperatures at this zone are controlled within the limit of 215 to 230°C by this pressure. Water which has cooled by boiling moves horizontally under a pressure gradient and downward in zones where upward movement of hot water is limited or absent. The density difference between cold and hot water is significant, and the downward movement of the colder water may produce in part the well-defined temperature inversion in the west of the basin. Thermal equilibrium between rock and water is attained and maintained, the water temperature imposing the temperature gradient on the system in this aquifer. The steam and gas liberated from the hot water may move along the top of the ignimbrite with the water, or flow upwards, where permeability allows, toward the surface.

Little or no dilution occurs in this aquifer, particularly in areas where the upper Tucle dacite aquifer is absent. Waters move upward through permeable zones in the Tucle tuffs (localized permeability) and are discharged into the Tucle dacite or pass directly into the Tatio ignimbrite. The Tucle dacite contains cold water, originating from precipitation on the western flanks of the Andes, which mixes in with the rising hot water. The temperature of the composite water in the dacite is basically controlled by the quantities of hot and cold water and the temperature of these waters. Chloride concentrations and water temperatures in the central basin suggest that there is twice as much hot water passing up into the dacite as cold water moving through the dacite. The temperatures in the dacite are controlled by this mixing mechanism, but at equivalent depths in other parts of the basin temperatures are controlled by the permeability between the Puripicar ignimbrite and the surface and conductive heat loss. Dilution and the amount of cold water in the dacite increase in the southeast at Well 6.

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