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TEMPERATURE DISTRIBUTION OF UNDERGROUND WATERS IN THE LLANURA TUCUMANA GEOTHERMAL AREA, ARGENTINA

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ABSTRACT

This survey probes the geothermal resources of a large (50 by 170 km) area in the Tucumán province, Argentina. The main interpretive tools used are stable isotope compositions, and the Na-K-Ca/Mg and CCG cationic geothermometers. Forty-one water samples from 40 water wells and 1 river were collected and analyzed. ~~Our~~ results clearly indicate the presence of waters of geothermal origin, and widespread thermalism. Commercial-size "hot spots" with temperatures appropriate for most direct applications and for binary-cycle technology electric power production, are indicated by the survey results.

INTRODUCTION

The Llanura Tucumana Geothermal Area (LTGA) is located in the eastern part of the Tucumán province, Argentina. It covers the eastern part of the province, from the Sierra de Aconquija to the border with the province of Santiago del Estero. Thermalism, widespread in this area, is evidenced both by surface manifestations (e.g., Termas de Río Hondo, a popular spa in the southeastern border of the LTGA), and by discharge temperatures of many water wells.

This agricultural and industrial area is one of the most densely populated in the country. Important agricultural products include oranges and sugar cane. One of the biggest paper mills of the country, which processes waste sugar cane fiber, is located there. There is high potential for alcohol production from sugar cane. Concentrated orange juice and orange extracts are also produced. Winters, though relatively short, are cold, as attested by considerable investments in heating appliances throughout the area. Summers are long and hot. Thus, the potential for commercial geothermal heat utilization ranges from direct applications (e.g., heating and refrigeration of buildings, paper drying, concentration of orange juice, alcohol distillation, etc.) to electric power production.

Unfortunately, little is known about the temperature and distribution of the Area's geothermal resources. Jurío et al. (1975) reviewed geological, hydrogeological and discharge temperatures of water wells on a regional scale, including the LTGA, and analized the chemical composition of samples from 12 wells tightly grouped in the Termas de Río hondo area. They concluded that the regional underground heat flow is generally controlled by convection, that the highest temperatures are in the Termas de Río Hondo area, and that the equilibrium temperatures implied by the chemical composition of the fluids are significantly greater than the measured discharge temperatures. Miró and Méndez (1977) concentrated on the urban area of the Termas de Río Hondo city. They studied the discharge temperatures of 44 water wells and partial chemical compositions of samples from 9 wells; and concluded that underground heat flow is controlled by convection and influenced by secondary permeability due to local underground fracturing, and that the observed decline of discharge temperatures is due to exploitation. Baldis et al. (1983) interpreted their regional magnetotelluric results as indicating the existence of shallow magma and an associated geothermal area of about 200 km diameter coinciding roughly with the LTGA. Finally, Mon and Vergara (1987), in a brief paper containing no data, concluded that the Na-K-Ca/Mg geothermometer (Fournier and Potter, 1979) indicates deep temperatures higher than 200°C at several sites in the LTGA, and stressed the need for improved geothermometric studies.

This paper reports on a recent effort aimed at geochemical exploration of the LTGA. This effort is supported jointly by the Argentinian CONICET, the Mexican CONACYT, the Universidad Nacional de Tucumán (Argentina) and the Instituto de Investigaciones Eléctricas (México). Cationic geothermometry and stable isotope compositions were the main interpretive tools for this work.

HYDROGEOLOGICAL SETUP

The hydrogeological characteristics of the LTGA were described by Tineo (1987). Briefly, this area is a sedimentary basin with elevation ranging from 250 to 500 m a.s.l. To the North the basin is limited by the Sierras Subandinas. The Sierras de Aconquija, which rise abruptly to several thousand meters a.s.l., bound the basin to the West. The southern boundary is an outcrop of the Macizo de Ancasti basement rocks. And to the East the basin is bounded by the low (500-600 m a.s.l.) Sierra de Guasayán. Refraction seismic results indicate a maximum thickness of the sedimentary formations of about 2500 m, where the basement is deepest.

Precipitation on the Western border of the basin, in the high slopes of the Sierra de Aconquija, is high, exceeding 1800 mm/yr. Precipitation decreases rapidly with decreasing altitude to about 400-700 mm/yr in the basin. Aquifer recharge is believed to occur mainly in the lower slopes of the Sierra de Aconquija. There is a large artesian area in the basin, which is roughly within the 350 m a.s.l. contour line. The basin is pockmarked by thousands of water wells. These wells intercept good- to medium-quality aquifers to depths exceeding 650 m. Many wells have discharge temperatures in the range 30-50°C.

SAMPLING AND ANALYSIS

On the basis of a large data base of water-well drilling records, of the information reviewed in the Introduction and of budgetary constraints, we selected 40 wells for sampling.

The geographical distribution of these wells is illustrated in Fig. 1. The area covered by this survey is about 50 km wide by 170 km long (~ 8,500 km^2).

Each well was sampled once. The discharge temperature, pH and electrical conductivity were measured and recorded. Each sample was analyzed for Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, CO_3^{2-}, SO_4^{2-}, HSO_4^-, Cl^-, B and SiO_2. In addition, a sample of the Marapa river water was taken for isotopic reference. This sample was analized for the same ions.

Of the 41 samples, 18 were analized for ^{18}O and D. Due to logistic constraints, the sources of these 18 samples are located, without exception, in the southern portion of the surveyed area (Fig. 1).

STABLE ISOTOPES

These results are plotted in Fig. 2, in a δD - $\delta^{18}O$ diagram. The local meteoric line is also shown.

The diagram indicates the meteoric origin of the sampled waters, as expected. The grouping of the sample points in this diagram along lines of approximately constant δD values generally corresponds nicely with geographical location (see Fig. 1). The data points generally trend towards lighter isotopic compositions with increasing latitude, as if the recharge areas of the sampled aquifers were approximately at the same elevation. The deviations from this trend (notably Marapa river, Villa Monteagudo, El Arbolito) may be explained by variatons in latitude or elevation of the recharge areas.

The diagram also indicates the presence of geothermal waters in wells La Trinidad (1956), La Soledad, La Madrid, Talamuyo, Villa Monteagudo, El Espinal, Viltrán, Páez, Villa Pujio, Puesto del Medio, El Arbolito, Paloma, San Pedro de Guasayán and Taco Ralo. These waters present the characteristic oxygen isotope shift of geothermal waters (e.g., Craig, 1963). This indication is particularly strong for wells La Trinidad (1956), Talamuyo, La Madrid, La Soledad, Villa Monteagudo, Viltrán, El Arbolito, Paloma, San Pedro Guasayán and Taco Ralo.

GEOTHERMOMETRY

The total dissolved solids (TDS) of the water samples varies roughly from 180 ppm to 1600 ppm. The discharge temperatures are in the 20-50°C range. When applying cationic geothermometers to low-temperature, low-TDS waters as these, it is necessary to consider the concentrations of Ca^{2+} and Mg^{2+}, in addition to those of Na^+ and K^+. One should also keep in mind the possibility of dilution of thermal waters by fresher and cooler waters. Because of this, we chose to use the well-known Na-K-Ca geothermometer (Fournier and Truesdell, 1973) with its Mg correction (Fournier and Potter, 1979), and the Cationic Composition Geothermometer (CCG) (Nieva and Nieva, 1987). The CCG estimates aquifer temperatures from the Na^+, K^+, Ca^{2+} and Mg^{2+} concentrations and has low sensitivity to dilution. Furthermore, its accuracy is greater than that of the Na-K-Ca/Mg geothermometer, particularly in the $T<50°C$ and 150-210°C ranges (Nieva and Nieva, 1987).

Table 1 presents the measured discharge temperatures, and geothermometric calculations. There is good qualitative agreement between the Na-K-Ca/Mg and the CCG geothermometers. The former generally tends to predict lower temperatures. However, for the Marapa river sample, the Na-K-Ca/Mg prediction is too high, while the CCG prediction is much closer to the river temperature. For other cold, low-TDS samples, such as La Trinidad (1956), La Trinidad (1967), and Atahona, the same trend is observed, in agreement with

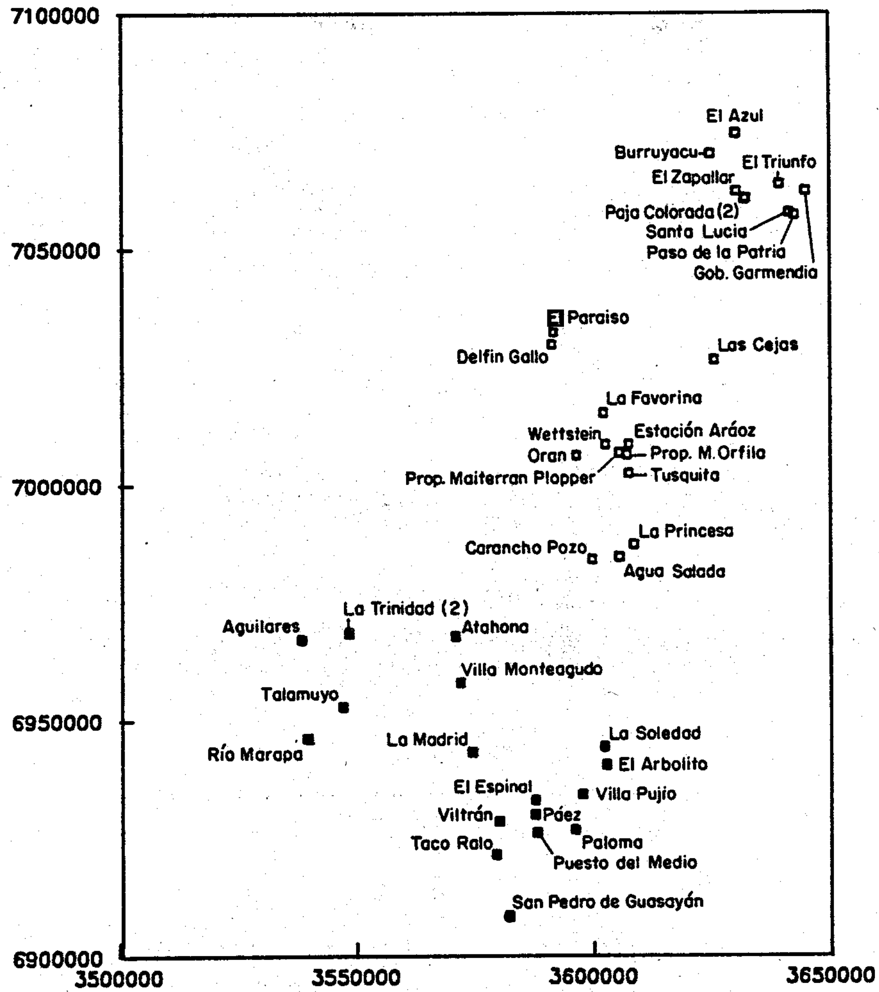

Fig. 1. Location of wells sampled in this survey. Filled squares indicate the location of the samples with isotopes analysis. The map is centered at 27° 07' 28''S, 65° 14' 15''W. Gauss-Krüger conformal projection; tick marks are at 50 km intervals.

the claim that for T<50°C the CCG geothermometer is generally more accurate than the Na-K-Ca/Mg geothermometer.

Of the 14 samples with isotopic indication of geothermal origin, 11 (Páez, Puesto del Medio, La Soledad, Viltrán, El Espinal, El Arbolito, Villa Pujio, San Pedro Guasayán, Talamuyo, Paloma and Villa Monteagudo) show qualitative agreement of Na-K-Ca/Mg and CCG results, which indicate thermalism (Table 1). But there is disagremment on the temperature estimates for La Trinidad (1956), La Madrid and Taco Ralo (Table 1). In the last 2 cases the CCG geothermometer indicates low-temperature waters. This is at odds with the considerable oxygen isotopic shifts of these samples. The discharge temperatures and Na-K-Ca/Mg estimates reinforce the notion that these are thermal waters. Furthermore, the Taco Ralo sample is Mg-rich, which may indicate a geothermal water that picked up excess Mg in its way to the surface (e.g., Fournier and Potter, 1979). The La Madrid sample is marginally rich in Mg. Assuming the origin of both samples to be high temperature geothermal waters, the CCG geothermometer predicts 204°C for Taco Ralo and 188°C for La Madrid. We provisionally conclude that the origin of these waters is geothermal, and that the originating aquifer temperatures lie somewhere between the Na-K-Ca/Mg estimates of Table 1, and the temperatures predicted with the CCG assuming high temperature origin.

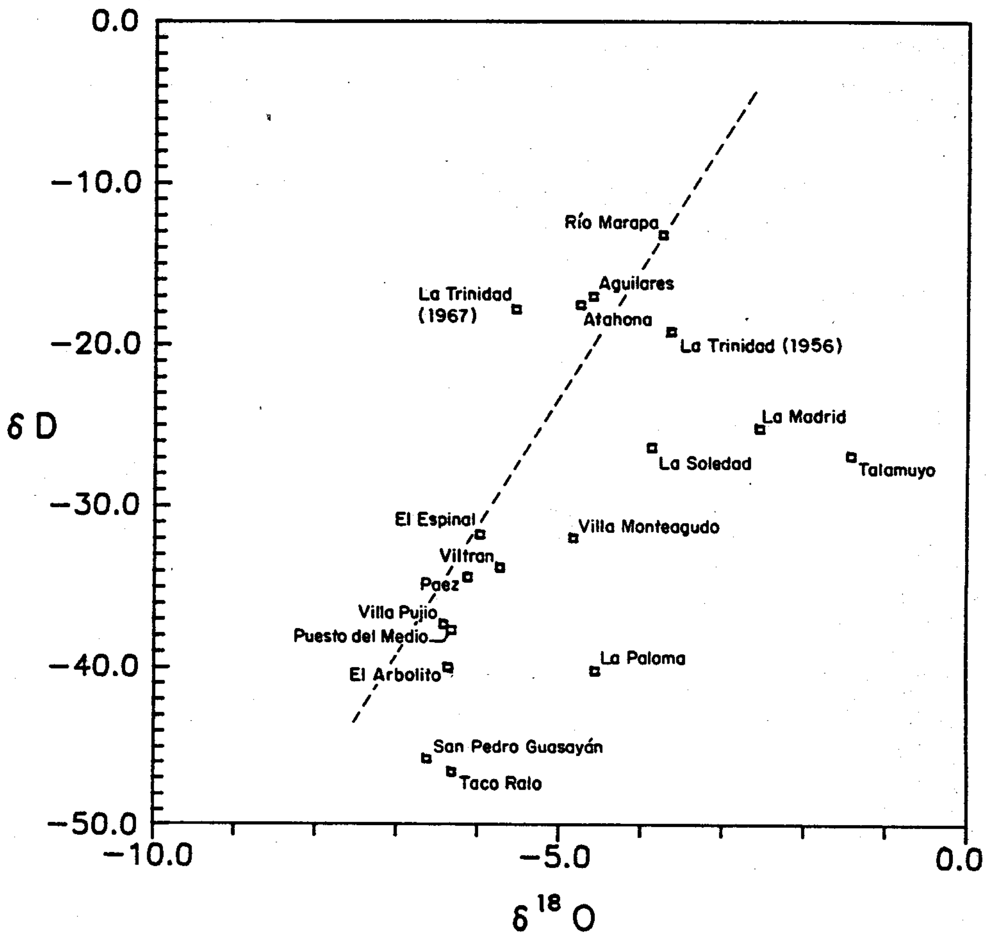

Fig. 2. Stable isotopes results and local meteoric line (dashed).

The sample from La Trinidad (1956) presents low TDS and discharge temperature, relatively high Mg concentration, high isotopic shift, and difering but relatively low reservoir temperature estimates from the CCG and Na-K-Ca/Mg geothermometers. The corresponding well is relatively shallow (86 m), and is located near the Río Medinas, a river whose sources are about 180 km away, high (~3500 m a.s.l.) in the Sierra Nevados del Aconquija. We interpret the ^{18}O isotopic shift as indicating evaporation, possibly of Río Medinas water.

Fig. 3 illustrates the Na-K-Ca/Mg results. These indicate the existence of several "hot spots" with typical linear dimensions exceeding 10 km. The hottest is in the La Paloma area, with temperatures of up to 143°C (Table 1). Next, in order of decreasing temperatures, is the Carancho Pozo area, with similar temperatures. To the NE of Carancho pozo there is a >95°C area centered in Las Cejas. And between these last 2 "hot spots" there is an extensive zone, in the neighborhood of Maiterran-Plopper, with temperatures in the 85-95°C range.

Fig. 4 illustrates the CCG results. Here the Taco Ralo and La Madrid estimated temperatures are kept as in Table 1. Several "hot spots" are also indicated. The hottest, with temperatures in excess of 145°C, is in the Maiterran-Plopper area. There are 2 other "hot spots" with temperatures exceeding 140°C, one to the W of Santa Lucía, Paso de la Patria and El Zapallar, and the other around Carancho Pozo. Finally, temperatures greater than 135°C and up to 154°C are indicated in the La Paloma area.

Fig. 5 incorporates the speculative high temperatures of Taco Ralo and La Madrid to the preceeding CCG picture. The Northern area isotherms remain, of course, unchanged. The main effects are to introduce an additional "hot spot" around La Madrid, and to displace and enhance the peak previously associated with La Paloma towards Taco Ralo. If the temperatures corresponding to Taco Ralo and La Madrid were intermediate between the high speculative values and those of the Na-K-Ca/Mg estimates, the peaks associated with these wells would be correspondingly lower.

Table 1. Sample temperatures

Sample	Temperature			
	Discharge	NaKCa	/Mg	CCG
Páez	50.2	143	143	146
Puesto del Medio	50.1	142	142	139
La Soledad	45.4	92	92	101
Viltrán	44.4	90	90	109
El Espinal	42.5	95	95	97
El Arbolito	42.5	87	87	100
Villa Pujio	40.6	81	81	95
La Madrid	40.0	88	88	32
San Pedro de Guasayán	39.5	90	90	115
Gob. Garmendia	39.0	98	98	126
Talamuyo	37.9	81	78	114
Paloma	37.5	150	142	154
Paso de la Patria	34.5	86	86	145
Santa Lucía	34.2	79	79	133
Agua Salada	33.6	99	99	126
El Triunfo	33.2	89	89	84
Las Cejas	32.5	97	97	136
Taco Ralo	31.7	93	90	34
El Azul	30.3	70	70	29
Aguilares	29.5	72	72	83
Carancho Pozo	28.4	141	132	142
Paja Colorada (Esc.)	28.0	78	78	30
La Princesa	27.7	93	93	140
Villa Monteagudo	27.6	65	65	101
Tusquita	27.6	88	88	146
Maiterran-Plopper	27.5	89	89	149
Paja Colorada (Argüe.)	27.1	74	74	29
Wettstein	27.1	88	88	149
Estacion Aráoz	26.0	150	87	36
El Zapallar	25.6	147	117	154
Orán	25.2	85	85	136
Atahona	25.0	52	52	20
Burruyacu	24.4	179	35	39
La Favorina	23.2	95	87	139
La Trinidad (1956)	21.5	61	61	29
El Paraíso	21.4	134	45	39
La Trinidad (1967)	20.2	55	55	26
Río Marapa	~20	48	48	25
Delfín Gallo	N.A.	92	75	108
Prop. Manuel Orfila	N.A.	91	91	149
Ea. La Argentina	~25	98	98	35

CONCLUSIONS

There is isotopic evidence of the geothermal origin of 14 samples of this survey.

The Na-K-Ca/Mg and CCG cationic geothermometers indicate widespread ocurrence of thermal waters in the surveyed area, with temperatures up to 140-155°C. Higher temperatures cannot be ruled out.

Our results indicate the existence of commercial size "hot spots", with temperature ranges >95°C to >145°C in the areas of La Paloma, Carancho Pozo, Maiterran-Plopper and El Zapallar.

The resource temperatures indicated by this survey would be adequate for most direct applications, and for electric power production with binary-cycle commercial technology.

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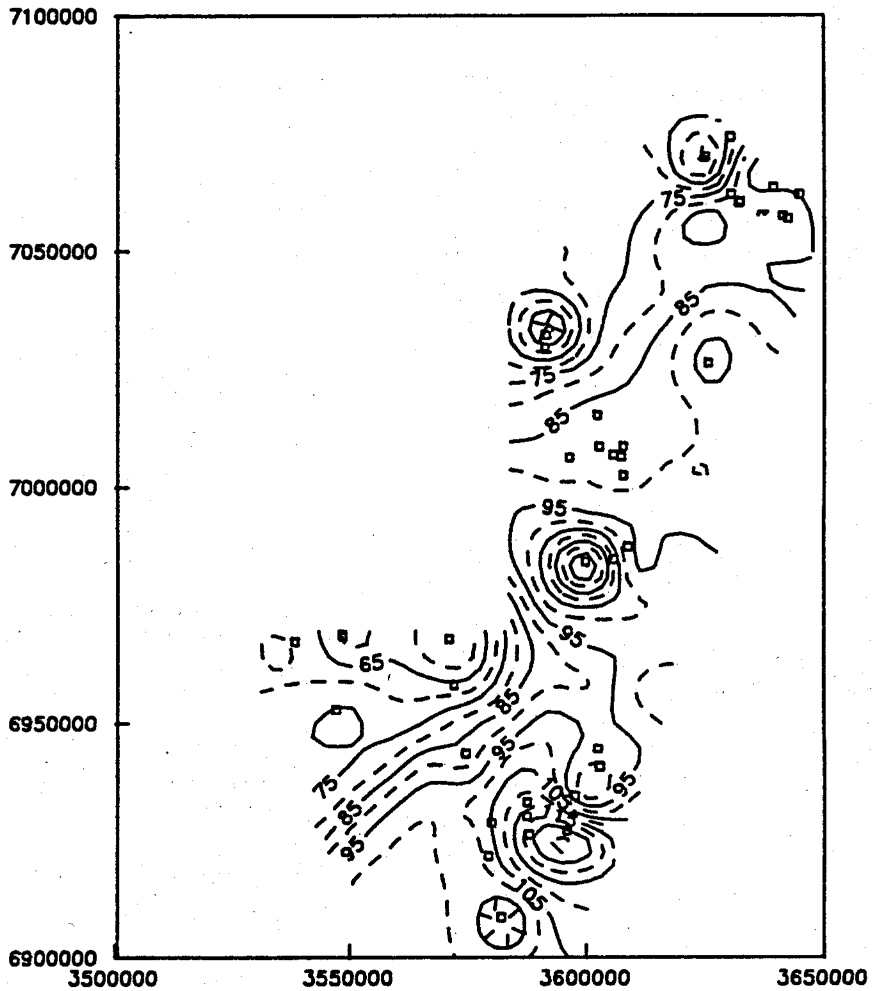

Fig. 3. Na-K-Ca/Mg isotherms.

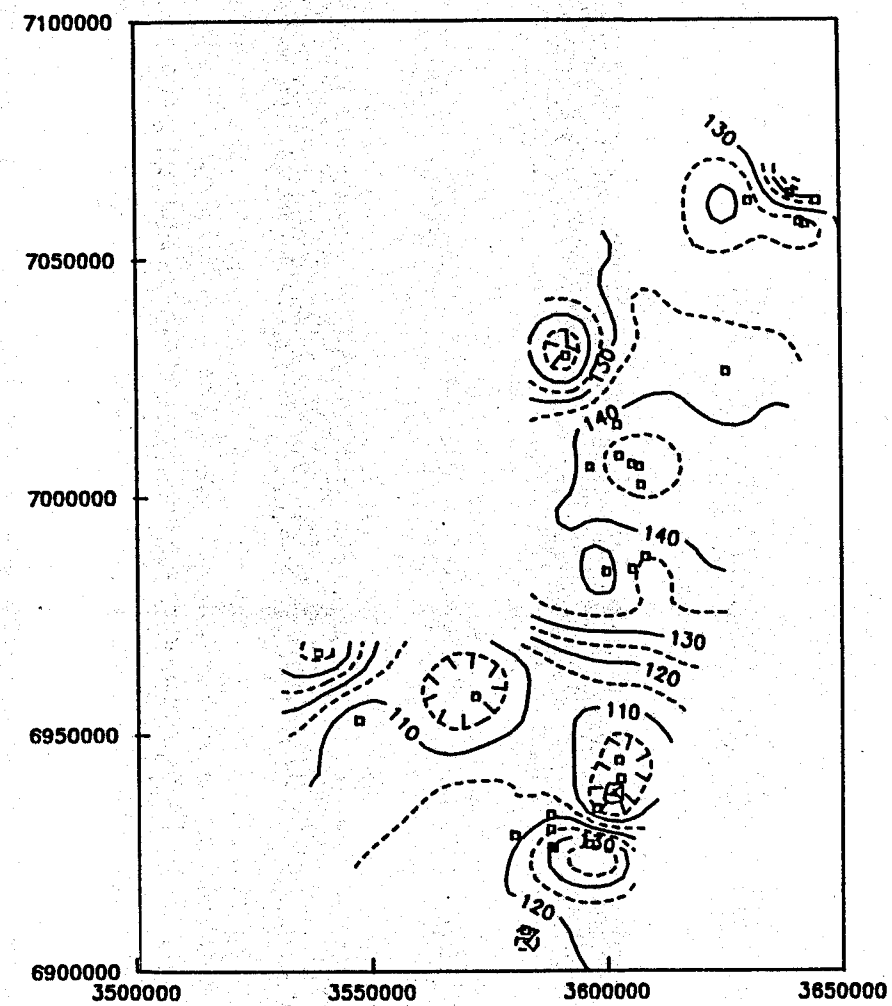

Fig. 4. CCG isotherms.

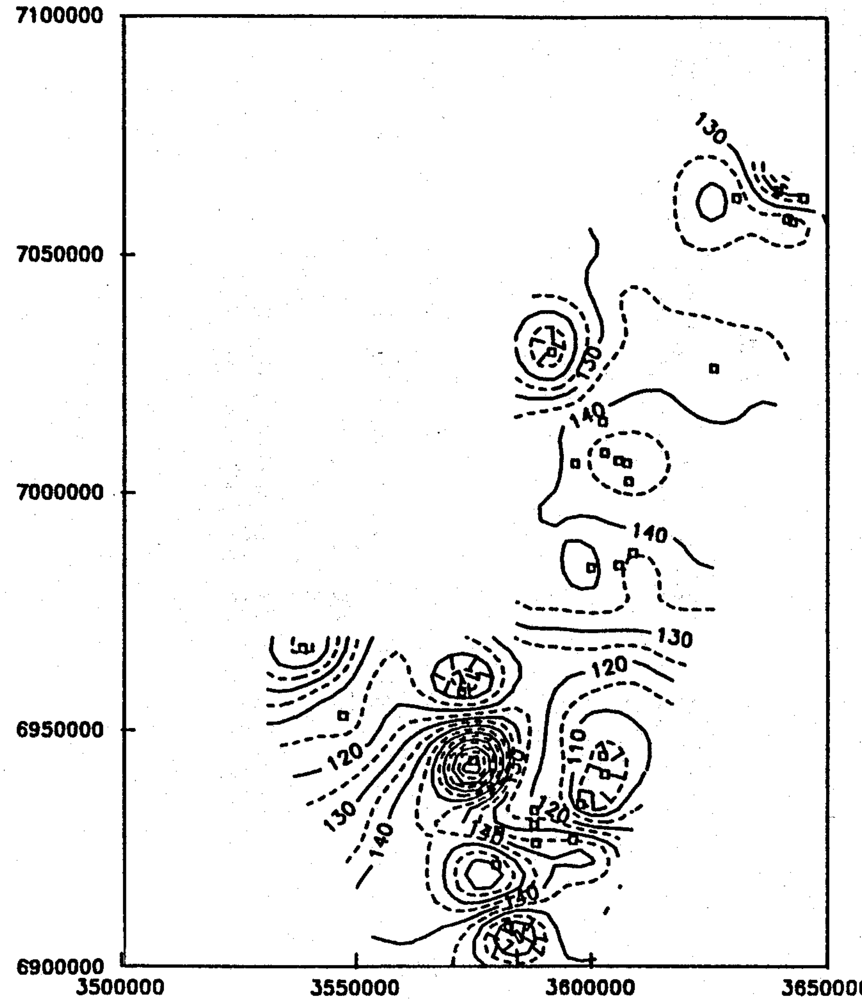

Fig. 5. Effect of the high speculative temperatures for Taco Ralo and La Madrid on the CCG isotherms.