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

E.R. Iglesias*, A. Tinea#, M. Durán*, M. Verma*, J. García#
R.M. Barragán, J.C. Falcón#

*Instituto de Investigaciones Eléctricas,
Apdo. Postal 475, Cuernavaca, Mor., México
#Universidad Nacional de Tucumán,
M. Lillo 205, S.M. de Tucumán, Tuc. 4000, Argentina

ABSTRACT
This survey probes the geothermal resources of a large (50 by 170 km) area in the Tucumán province, Argentina. The main interpretable tools used are stable isotope compositions, and the Na-K-Ca/Mg and CCA cationic geothermometers. Forty-one water samples from 40 water wells and 1 river were collected and analyzed. Geochemical 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 south 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 in 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) to direct processes (e.g., 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. Jurio et al. (1975) reviewed geological, hydrogeological, and chemical data and analyzed 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 100 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 geothermal 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 interpretable 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 Quassyán. 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 arsien area in the basin, which is roughly within the 150 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 km²).

Each well was sampled once. The discharge temperature, pH and electrical conductivity were measured and recorded. Each sample was analyzed for Na+, K+, Ca²⁺, Mg²⁺, KCl, SO₄²⁻, HCO₃⁻, CO₃⁻, Cl⁻, B and I₂O₂⁻. In addition, a sample of the Marapa river water was taken for isotopic reference. This sample was analyzed for the same ions.

Of the 41 samples, 18 were analyzed for 18O 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 3δ - 6δ¹⁸O 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 4D 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 variations 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, Viltrín, Pätz, Villa Pujio, Puesto del Medio, El Arbolito, Paloma, San Pedro de Quassyán and Taco Ralo. These waters present the characteristic oxygen isotope shift of geothermal waters (Craig, 1961). This indication is particularly strong for wells La Trinidad (1956), Talamuyo, La Madrid, La Soledad, Villa Monteagudo, Viltrín, El Arbolito, Paloma, San Pedro Quassyán 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 Ca²⁺ and Mg²⁺ 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 Pottier, 1979), and the Cationic Composition Geothermometer (CCG) (Nieva and Nieva, 1987). The CCG estimates geotherm temperatures from the Na⁺, K⁺, Ca²⁺ and Mg²⁺ concentrations and has low sensitivity to dilution of thermal waters by fresher and cooler waters. Furthermore, its accuracy is greater than that of the Na-K-Ca/Mg geothermometer, particularly in the 30-50°C and 150-210°C ranges (Nieva and Nieva, 1987).

Table 1 presents the measured discharge temperatures, and geothermometric calculations. There is a 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', 26° 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 (Pérez, Puesto del Medio, La Soledad, Viltrán, El Espinal, El Arbólito, Villa Pujio, San Pedro Guasayán, Tamuyu, Paloma and Villa Monteagudo) show qualitative agreement of Na-K-Ca/Mg and CCG results, which indicate thermalism (Table 1). But there is disagreement 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.
The sample from La Trinidad (1956) presents low TDS and discharge temperature, relatively high Mg concentration, high isotopic shift, and differing but relatively low reservoir temperature estimates from the CCG and Na-X-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 Sífrra Nevados del Aconcagua. We interpret the δD isotopic shift as indicating evaporation, possibly of Río Medinas water.

Fig. 3 illustrates the Na-X-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 poz, 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 Lucia, 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 preceding 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-X-Ca/Mg estimates, the peaks associated with these wells would be correspondingly lower.
Table 1. Sample temperatures

<table>
<thead>
<tr>
<th>Sample</th>
<th>Temperature</th>
<th>Discharge Na-KCa/Mg</th>
<th>CCG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Páez</td>
<td>50.2</td>
<td>143 143 146</td>
<td></td>
</tr>
<tr>
<td>Puesto del Medio</td>
<td>50.1</td>
<td>142 142 139</td>
<td></td>
</tr>
<tr>
<td>La Soledad</td>
<td>45.4</td>
<td>92 92 102</td>
<td>101</td>
</tr>
<tr>
<td>Vultrán</td>
<td>44.4</td>
<td>90 90 109</td>
<td></td>
</tr>
<tr>
<td>El Espinal</td>
<td>42.5</td>
<td>95 95 97</td>
<td></td>
</tr>
<tr>
<td>El Arbolito</td>
<td>42.5</td>
<td>87 87 100</td>
<td></td>
</tr>
<tr>
<td>Villa Pujio</td>
<td>40.6</td>
<td>81 81 90</td>
<td>138</td>
</tr>
<tr>
<td>La Madrid</td>
<td>40.0</td>
<td>88 88 32</td>
<td></td>
</tr>
<tr>
<td>San Pedro de Quasayán</td>
<td>39.5</td>
<td>90 90 115</td>
<td></td>
</tr>
<tr>
<td>Gov. Garmendia</td>
<td>39.0</td>
<td>98 98 126</td>
<td></td>
</tr>
<tr>
<td>Talamuyo</td>
<td>37.9</td>
<td>81 78 128</td>
<td></td>
</tr>
<tr>
<td>Paloma</td>
<td>37.5</td>
<td>150 142 154</td>
<td></td>
</tr>
<tr>
<td>Paso de la Patria</td>
<td>34.5</td>
<td>86 86 145</td>
<td></td>
</tr>
<tr>
<td>Santa Lucía</td>
<td>34.2</td>
<td>79 79 133</td>
<td></td>
</tr>
<tr>
<td>Aguas Saladas</td>
<td>33.6</td>
<td>89 89 126</td>
<td></td>
</tr>
<tr>
<td>El Triunfo</td>
<td>33.2</td>
<td>89 89 84</td>
<td></td>
</tr>
<tr>
<td>Las Cejas</td>
<td>32.5</td>
<td>97 97 136</td>
<td></td>
</tr>
<tr>
<td>Taco Ralo</td>
<td>31.7</td>
<td>93 90 30</td>
<td></td>
</tr>
<tr>
<td>El Azul</td>
<td>30.3</td>
<td>70 70 29</td>
<td></td>
</tr>
<tr>
<td>Aguilares</td>
<td>29.5</td>
<td>72 72 83</td>
<td></td>
</tr>
<tr>
<td>Carancho Pozo</td>
<td>28.4</td>
<td>141 132 142</td>
<td></td>
</tr>
<tr>
<td>Peña Colorada (Esc.)</td>
<td>28.0</td>
<td>78 78 30</td>
<td></td>
</tr>
<tr>
<td>La Princesa</td>
<td>27.7</td>
<td>93 93 134</td>
<td></td>
</tr>
<tr>
<td>Villa Montaneagudo</td>
<td>27.6</td>
<td>65 65 131</td>
<td></td>
</tr>
<tr>
<td>Tusquita</td>
<td>27.6</td>
<td>88 88 146</td>
<td></td>
</tr>
<tr>
<td>Maiterran-Plopper</td>
<td>27.5</td>
<td>89 89 149</td>
<td></td>
</tr>
<tr>
<td>Peña Colorada (Argüe.)</td>
<td>27.1</td>
<td>74 74 29</td>
<td></td>
</tr>
<tr>
<td>Weltstein</td>
<td>27.1</td>
<td>88 88 149</td>
<td></td>
</tr>
<tr>
<td>Estación Aráoz</td>
<td>26.0</td>
<td>150 87 36</td>
<td></td>
</tr>
<tr>
<td>El Zapallar</td>
<td>25.6</td>
<td>147 117 154</td>
<td></td>
</tr>
<tr>
<td>Gar</td>
<td>25.2</td>
<td>85 85 106</td>
<td></td>
</tr>
<tr>
<td>Atahona</td>
<td>25.2</td>
<td>52 52 20</td>
<td></td>
</tr>
<tr>
<td>Burruyuscu</td>
<td>24.4</td>
<td>179 35 39</td>
<td></td>
</tr>
<tr>
<td>La Favorina</td>
<td>23.2</td>
<td>95 87 139</td>
<td></td>
</tr>
<tr>
<td>La Trinidad (1956)</td>
<td>21.5</td>
<td>61 61 134</td>
<td></td>
</tr>
<tr>
<td>El Páisí</td>
<td>21.4</td>
<td>134 41 84</td>
<td></td>
</tr>
<tr>
<td>La Trinidad (1967)</td>
<td>20.2</td>
<td>55 55 26</td>
<td></td>
</tr>
<tr>
<td>Río Murapa</td>
<td>-20</td>
<td>48 48 25</td>
<td></td>
</tr>
<tr>
<td>Delfín Gallo</td>
<td>N.A.</td>
<td>78 78 108</td>
<td></td>
</tr>
<tr>
<td>Prop. Manuel Orfila</td>
<td>N.A.</td>
<td>91 91 142</td>
<td></td>
</tr>
<tr>
<td>Ea. la Argentina</td>
<td>-25</td>
<td>98 98 35</td>
<td></td>
</tr>
</tbody>
</table>

Acknowledgements

This work was partly supported by the Consejo Nacional de Ciencia y Tecnología (CONACYT, México), and by the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET, Argentina). One of us (E.R.I.) acknowledges useful discussions with Dr. David Nieva at Instituto de Investigaciones Eléctricas.

References


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.