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The Geothermal System of Araró, Mexico, as an Independent System of Los Azufres

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ABSTRACT

A new interpretation of the exploration results of the Araró, Michoacán, México, geothermal zone, and especially from one deep (1344 m) well drilled there, allows us to conclude there is evidence for a geothermal reservoir at this depth. The system seems to be a fracture zone reservoir fed by a deep, narrow conduit related to the Araró-Zimirao fault. It is probably a convection, liquid-dominant system, with sodium chloride fluids, medium to high temperatures (220-250°C), salinity around 3000 ppm as TDS, pressures close to hydrostatic, and low heat loss. The system appears to have been deepened over time by alternating episodes of self-sealing and hydro-fracturing, but still it is possible to expect commercially favorable temperatures and production conditions at depth. As suggested by the geochemical and isotopic data presented, the Araró geothermal system is an independent and genetically different system of the relatively nearby Los Azufres reservoir.

1. INTRODUCTION

Some years ago we prepared a comprehensive summary of the studies carried out by the Comisión Federal de Electricidad (CFE) in the Araró geothermal zone. This included the results of the hydrothermal alteration found in the deep exploration well Z-3 (Viggiano-Guerra and Gutiérrez-Negrín, 2001). One of the main conclusions of the paper was that there is an active geothermal system in the subsurface of the zone. It seems to be a fracture zone reservoir of a stock-work type, with sodium-chloride fluids and size limited to a narrow conduit, linked probably to the Araró-Zimirao fault at more than 2000m depth. Apparently, the system has been deepened from an original depth of ~300 meters to more than 2000 meters, by alternated episodes of self-sealing and hydro-fracturing.

This paper presents a brief recapitulation of the main geological and hydrothermal features of the Araró geothermal system, and discusses its possible relation to the relatively near system of Los Azufres.

Araró is a geothermal zone located in the central part of Mexico, inside the Mexican Volcanic Belt. It is at the northeastern portion of the Mexican State of Michoacán. The zone is around 40km northeast from the city of Morelia, and approximately 20km west from the Los Azufres geothermal field (Fig. 1). The main hot-springs area, known as Zimirao, is located at 19°53'54" North Latitude and 100°49'50" West Longitude. The hot springs are in the vicinity of the village of San Nicolás Zimirao (Fig. 2).

Araró was explored by the CFE from 1976 to 1981 and 1989 to 1991. In 1981, the deep exploration of well Z-2 was drilled in a place situated 5km west of the Zimirao area. In the second period new geological, geophysical and geochemical studies were carried out, including the drilling of five shallow (150-200 m) gradient wells and other deep exploration well (Z-3) located within the Zimirao area (Fig. 2). This well was programmed to reach a 2000m depth, but it was finished at a 1344m depth due to its low measured temperatures.

Fig. 1: Location of the Araró zone and the Los Azufres geothermal field.

2. GEOLOGICAL FRAMEWORK

The Araró geothermal zone is located within the Cuitzeo tectonic basin, which is a part of the regional Chapala Graben oriented in an E-W direction. Three normal faults are shown in Figure 2; all of them are in a general E-W trend: the Huingo fault at north, the Araró-Zimirao fault in the middle, and the El Caracol fault at south. These structures form an echelon system toward the north-northwest, slightly tilting toward the south-southeast (Departamento de Exploración, 1989).

Outcropping rocks can be grouped into three units (Fig. 2): basaltic andesites (Qpab) from Early Pleistocene, rhyolitic tuffs (Qtr) with an age between 1.2 and 0.9 Ma, and vitreous rhyolites (Qrv) with ages between 1.54 and 1.19 Ma, besides some alluvial deposits (Qal) (Departamento de Exploración, 1989; Casarrubias *et al.*, 1990).

Araró lies inside the Cuitzeo Lake hydrographic basin, which presents a shallow and wide aquifer. The Zimirao zone is around 100,000 square meters in extension (Fig. 2). There are around fifty hot springs, much of them have gas escape, and superficial temperatures between 48 and 99°C (average of 71°C). Their waters are composed of a sodium chloride composition with an average of 2340 parts per million (ppm) of total dissolved solids (TDS), from which 825 ppm in average are chlorides. Waters also contain up to 78 ppm of boron and 55.5 ppm in average (Table 1). Among the gases separated from some springs the main one is CO_2 with minor H_2S, H_2, noble gases (He, Ne, Ar) and hydrocarbons such as methane, ethane, and benzene. The water salinity and the gas composition suggest that the water of the Zimirao hot springs is coming from a mixing process of deep geothermal fluids with shallow fresh-water aquifers. This is also indicated by the application of conventional fluid geothermometers that gave deep temperatures in excess of 200°C (Departamento de Exploración, 1989; Tovar, 1991).

Beneath the Zimirao hydrothermal zone (Fig. 2) there seems to be a lacustrine-sediments bed that acts as a cap-rock. Where faults and fractures intersect this bed, it breaks allowing mixing of subsurface geothermal fluids with the aquifer water and gives place to a spring depositing sinter, calcite and NaCl. Thus, in this Zimirao zone the aquifer presents an average depth of around 1 meter and its water is mixed with those saline thermal waters from depth, which emerges to form hot springs with flows around 10 to 20 liters per minute (Departamento de Exploración, 1989).

Waters from the Zimirao hot springs are in equilibrium, since the H_2S and CO_2 rich waters have been neutralized by forming pyrite and calcite. HCl in these waters has been also neutralized due to deposition of NaCl on the surface surrounding some hot springs, Na coming from the Na-Ca plagioclases (Tello y Quijano, 1983; Tovar, 1991).

Waters from the nearby hot springs of Huingo and Cal y Canto, both located at the margins of the Cuitzeo Lake (Fig. 2), present a similar composition (sodium-chloride) but lower superficial (40-44°C) and deep (<200°C) temperatures. Other hot springs however, like those of San Bartolomé Coro and Atzimba, located east and south respectively from Zimirao (outside Figure 2), have waters of sodium-bicarbonate type with low salinity and chloride content between 3 and 15 ppm (Table 1). These hot springs do not seem to be related to any geothermal aquifer (Departamento de Exploración, 1989).

The Zimirao hydrothermal area (Fig. 2) seems to be the only fluid ascent from depth in the whole Araró zone. This up-flow does not emerge through other nearby places presumably due to peripheral self-sealing process. Taking into account the small surface extent of this zone, and the rather reduced flow of the hot springs, one can assume that the probable deep geothermal system appears to be also small.

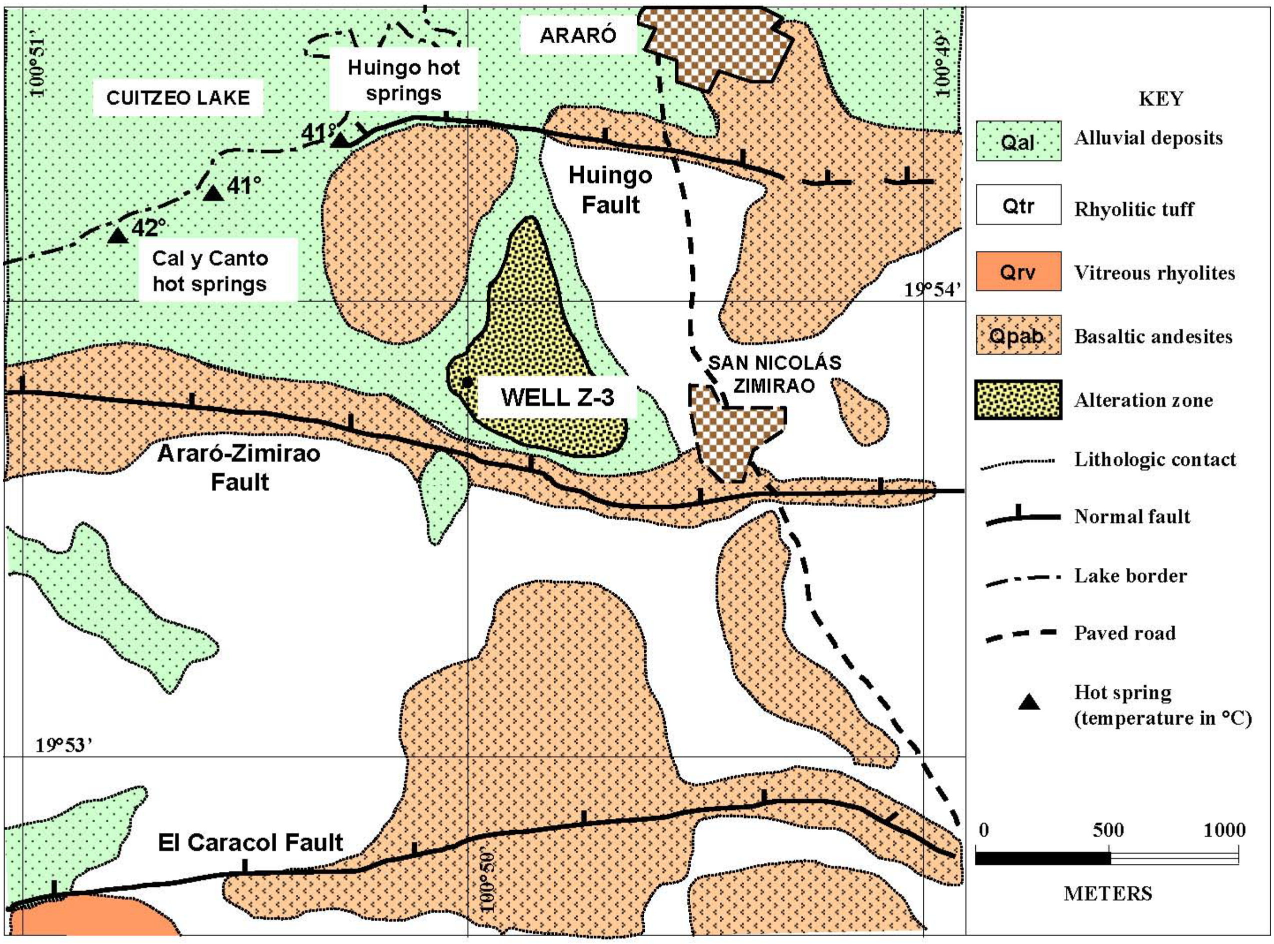

Fig. 2: Generalized geologic map of the Araró geothermal zone

Table 1: Results of chemical analyses of water-samples from the Araró geothermal zone.

Place	Date	T (°C)	pH	Na	K	Ca	Mg	Li	HCO_3	Cl	SO_4	SiO_2	B	Rb	Cs
Zimirao Zone(1)	Nov. 1990	71	7.78	693	47.5	31.7	2.0	5.4	165.4	825.3	102.5	207.5	55.5	0.62	1.35
Araró (Well 1)(2)	Nov. 1990	37	7.96	25.8	7.6	20.0	6.5	< 0.1	112.6	35.0	17.3	70.6	1.7	0.06	0.00
Araró (Well 2)(2)	Nov. 1990	36	8.23	16.3	8.3	14.3	5.2	< 0.1	100.1	20.0	5.7	77.0	0.0	0.03	0.00
Baños Huingo	Jan. 1983	41	6.80	316	30.0	27.0	2.2	2.5	189.0	293.0	60.0	187.0	< 0.1	0.20	0.20
San Bartolomé	Jan. 1983	29	6.60	27.0	4.2	13.8	5.6	0.5	104.0	15.0	0.8	120.0	< 0.1	0.00	0.00
San Bartolomé	Jan. 1983	32	7.10	21.2	4.8	13.8	4.8	0.5	129.0	10.1	0.0	120.0	< 0.1	0.00	0.00
Baños Atzimba	Jan. 1983	35	6.10	17.0	5.0	6.4	5.7	< 0.1	75.0	3.0	0.0	110.0	< 0.1	0.00	0.00
Well Z-3(3)	Oct. 1991	135-111	7.96	737	70.2	74.0	0.1	7.0	183.6	1064.0	158.6	--	71.4	0.70	2.20

(1) Average from 50 analyses.

(2) Wells 1 and 2 are groundwater wells.

(3) Average from 4 analyses, made by Tello y Moreno (1992). There is no data for SiO_2.

The November 1990 data are from Tovar (1991). The January 1983 data are from Tello and Quijano (1983).

SUBSURFACE FEATURES OF ARARÓ

According to the rocks cut by the well Z-3 in the subsurface of Araró, there is a thin layer (~3 meters) of a sinter deposit including lacustrine sediments with diatomeas, together with some andesitic clasts coming from depth and probably due to hydrothermal explosions. This seems to indicate a former superficial discharge of the system.

Underlying the sinter, there are around 33 meters of air-fall tuffs deposited in a lacustrine environment, belonging to the Qal superficial unit (Fig. 2), from a Pliocene-Pleistocene age. These tuffs are constituted by ash and lapilli clasts of plagioclase, biotite and pumice.

From a 36m depth there are intermediate and basic rocks represented by andesites and basalts, and one interval presenting pyroclastic rocks (lithic and vitreous tuffs). All of these rocks were grouped as belonging to the superficial unit Tpa, with no outcroppings in the Figure 2. Several intervals with hydrothermal breccias were noted in the well Z-3 (Viggiano-Guerra and Gutiérrez-Negrín, 2001).

Hydrothermal alteration minerals correspond to systems where sodium chloride of almost neutral pH hot geothermal fluids have interacted with the host rock. They include clay minerals (smectite-illite and illite), calcite, quartz (as crypto and micro crystalline), and minor amounts of chlorites (penninite at shallow depths), epidote (replacing plagioclases and augite) and pyrite (formed from epidote and often partially altered to hematite). Minerals even scarcer than those are zeolites (laumontite), amphiboles and talc, shown only at shallow depths and towards the bottom of the well (1340 meters). No wairakite was identified (Viggiano-Guerra and Gutiérrez-Negrín, 2001).

Water produced by the well Z-3 was analyzed (Table 1). It is of a sodium chloride type with 2740 ppm of total dissolved solids, 1064 ppm of chlorides, over 70 ppm of boron and around 0.1 ppm of magnesium. This composition is slightly higher than the average composition of the superficial hot springs. It is considered that this is so because the water of the well came from a deeper part of the aquifer and then was less boiled. The low concentration of magnesium suggests the water-rock interaction occurred at high temperatures (Tello y Moreno, 1992).

The water-rock equilibrium temperature was calculated to be between 220 and 240°C, after the Na/K and the H_2/Ar geothermometers. Graphical analysis of H_2/Ar against CO_2/Ar molar relationship suggests that gases are in equilibrium with the liquid phase at temperatures of about 200°C (Tello y Moreno, 1992).

Izquierdo (1991) studied some fluid-inclusions found in quartz and calcite crystals from 900-1080m depth in the well Z-3. The average homogenization temperatures obtained are presented in the Table 2, and they are in the rank of those calculated from liquid and gas geothermometry.

Table 2: Homogenization (Th) and ice-melting (Tm) temperatures from fluid-inclusions in the well Z-3.

Depth (m)	Crystal	Average Th (°C)	Average Tm (°C)	Salinity (as % wt. Eq. NaCl)
900	Quartz	247	+ 0.1	0.200
1000	Calcite	218	--	--
1080	Calcite	233	+ 0.2	0.370

The presence in the well Z-3 of minerals such as epidote, amphibole and talc implies an old temperature profile over 250°C in the interval between 200 and 300m depth. Relatively high temperatures (~230°C), more or less comparable, were encountered in fluid-inclusions trapped at around 1000m depth in hydrothermal minerals of the well. The liquid and gas geothermometry of the well fluids indicates also comparable temperatures (220-240°C), as well as some liquid geothermometers applied to the hot spring samples coming from the Zimirao zone.

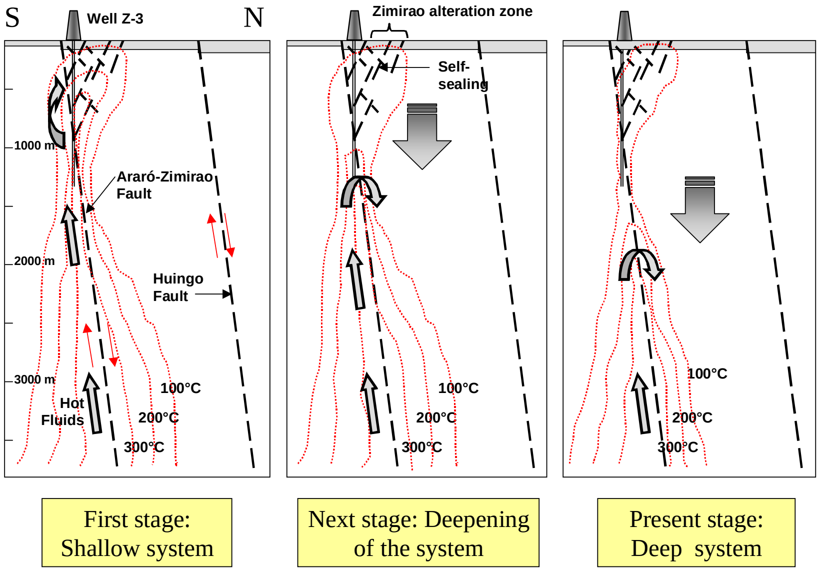

Fig. 3: Probable schematic evolution and deepening of the Araró geothermal system

However, the present temperatures measured in the well Z-3, both during and after drilling, are remarkable lower than the past ones: a maximum of 135°C at 550 meters, and 111°C at the well bottom (1344 meters depth). Temperatures indicated by the hydrothermal mineral assemblages and by the fluid-inclusions studies are actually old temperatures, which not necessarily have to match with the present ones, especially when the system has changed through time.

Instead the equilibrium temperatures indicated by the gas and liquid geothermometers are present temperatures, but evidently imply a deeper depth than those reached by the well.

A possible explanation for this, is the Araró geothermal system has cooled over time, due to self-sealing processes that probably have alternate with hydro-fracturing process, as indicated by the hydrothermal breccias. Under that assumption, it is probable that a high temperature (250°C or more) was present in Araró (especially in the Zimirao area) at shallow depths (around 300 meters) some time ago, as suggested by epidote, amphibole and talc. After a self-sealing process, this high temperature was deepened to depths of around 1000 meters, as the fluid-inclusions seem to indicate. By the now, a similar temperature would exist at even deeper depths (deeper at least than 1344 meters, perhaps more than 2000 meters), as suggested by the fluid and gas geothermometry (Fig. 3).

4. IS THERE ANY CONNECTION BETWEEN THE LOS AZUFRES AND ARARÓ SYSTEMS?

The Los Azufres geothermal field is one of the four Mexican geothermal fields under exploitation. With an electric installed capacity of 188 MWe, Los Azufres is located about 20 kilometers at southeast from Araró (Fig. 1). Some authors (Quijano, 1992; Tello y Moreno, 1992) have postulated the hypothesis that the Araró zone is just a distant, lateral discharge of the Los Azufres geothermal system, based upon the chemical and isotopic similarities between their fluids. Discussion of this hypothesis is important, because it brings the implicit conclusion that in the Araró subsurface there is none high temperature geothermal system susceptible to be tapped for electric generation.

One first objection to that hypothesis is the distance between Araró and Los Azufres. Certainly, twenty kilometers is a too long distance for the discharge of a geothermal system having the up-to-now known dimensions of Los Azufres. But regardless of the distance, following some other objections are discussed.

The Figure 4 is a sketch-drawing showing the approximate location of the Los Azufres field, including two exploration wells (EAZ-1 and EAZ-2) drilled at the periphery of the field, and the Araró geothermal zone. It also presents another hot springs zones of the surroundings, like those of Las Adjuntas, Atzimba and San Bartolomé Coro. Some villages and the Cuitzeo Lake are located too.

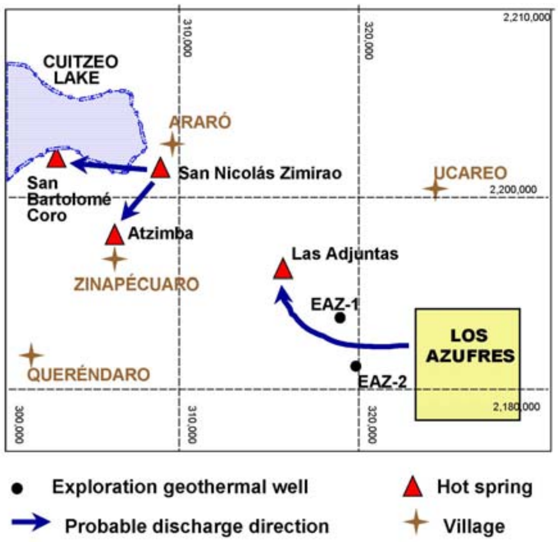

Fig. 4: Sketch showing the relative location of Los Azufres, Araró and other hot springs mentioned in the text. Arrows indicate the probable discharge direction of both Los Azufres and Araró geothermal systems.

On the other hand, the Table 3 presents some temperature and salinity data obtained from chemical analysis and fluid-inclusion studies on hot springs, well fluids and mineral samples, after information collected from Tello and Quijano (1983), Tello and Moreno (1992) and Viggiano (1996). Temperatures reported for wells EAZ-1, EAZ-2 and Z-3 are indeed the average homogenization temperature (Th) obtained from the fluid-inclusion studies done in those wells (Izquierdo, 1991; Viggiano, 1996). Temperatures reported for the hot springs of Zimirao, Las Adjuntas, Atzimba and San Bartolomé Coro are the average measured superficial temperatures, while the temperature reported for the fluid from the well Z-3 is the measured temperature at the feed zone of 550 meters depth.

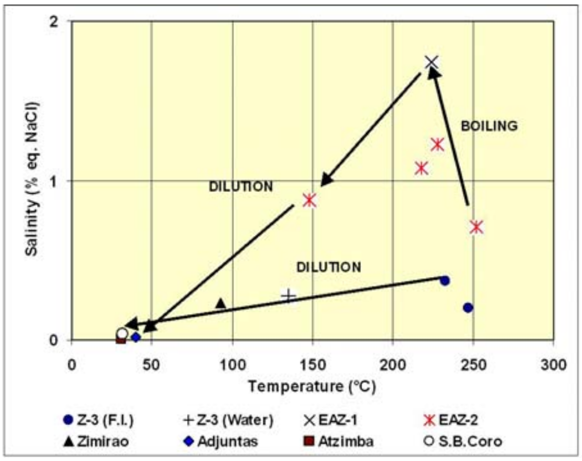

Fig. 5: Average temperature and salinity, expressed as weight percentage equivalent to NaCl, for fluids from the wells EAZ-1, EAZ-2 and Z-3, and from some hot springs. Data for Z-3 (F.I.) come from fluid-inclusions (Izquierdo, 1991), and from Z-3 (Water) from the chemical analyses of the water produced by Well Z-3.

For the wells EAZ-1, EAZ-2 and Z-3, the salinity reported in the Table 3 is the weight percentage equivalent to NaCl calculated from the ice-melting temperatures (Izquierdo, 1991; Viggiano, 1996). For hot springs and the fluids produced by the well Z-3, the reported salinity is the total dissolved solids (TDS) content determined by chemical analyses, expressed also as a percentage instead of parts per million. With those data of the Table 3 the Figure 5 was prepared. In this figure two distinct evolution paths are quite evident, one for the Los Azufres system and other for the Araró system. In Los Azufres it seems to be a boiling process starting at depth in the Well EAZ-2 towards the Well EAZ-1, and then a dilution process finishing in the Las Adjuntas hot springs. In Araró, the only process seems to be a dilution of the deep fluids in meteoric water at one or more shallow aquifers, which discharges in the Atzimba and San Bartolomé Coro hot springs. Arrows drawn in the former Figure 4 indicate the probable horizontal direction of both processes in Los Azufres and Araró.

It is assumed that the characteristics of the deep geothermal fluid (i.e., the parent fluid) in each system are those indicated by the primary fluid-inclusions studied. These inclusions had to be trapped small volumes of the original fluids at the first stages in both the Los Azufres peripheral system and the Araró system.

Thus, it is possible to see in the Figure 5 that similar temperatures (~250°C) were present in both systems, but the saline composition was different. In the case of the Los Azufres periphery, the parent fluid seems to have presented an average salinity of around 9700ppm (Well EAZ-2; see also Table 3). This salinity increased to ~17000 ppm when the fluid boiled (Well EAZ-1; Table 3), and then was highly reduced to ~200 ppm when the fluid mixed and diluted into shallow aquifers towards Las Adjuntas (Fig. 5 and Table 3). In the case of Araró, the parent fluid seems to be less saline (about 3700 ppm), and then is diluted to 350 ppm by mixing with shallow, meteoric aquifers towards the San Bartolomé Coro hot springs (Fig. 5 and Table 3).

Table 3: Measures and calculations of temperature and salinity in some wells and hot springs

Site (Depth)	Temperatures (°C) (1)	Temperatures (°C) (2)	Salinity (as % wt. eq. NaCl)
Well EAZ-1 (1988m)	224		1.74
Well EAZ-2			
(861m)	148		0.88
(1703m)	218		1.05
(1976m)	228		1.23
2200m)	252		0.71
Well Z-3			
(900m)	247		0.20
(1080m)	233		0.37
Water from well Z-3 (550m)		135	0.273
Araró hot springs (surface)		93	0.234
Las Adjuntas hot springs (surface)		40	0.021
Atzimba hot springs (surface)		32	0.008
San Bartolomé Coro hot springs (surface)		32	0.035

(1) Temperature of Homogenization.

(2) Measured Temperature.

Prepared with data from Tello and Quijano (1983), Tello and Moreno (1992), Izquierdo (1991) and Viggiano (1996).

According to this discussion, the geothermal system in Araró is not related at all to the peripheral geothermal system of Los Azufres.

Other interest aspect regards the isotopic composition. The Table 4 presents the isotopic composition of fluids from several geothermal wells of Los Azufres and from hot springs of Las Adjuntas, Araró (the Zimirao area), Atzimba and San Bartolomé Coro (for location to see Fig. 4). Deuterium and 18-Oxygen data come from previous published reports (Rodríguez *et al.*, 1984; Quijano *et al.*, 1987), and all of the analyses were done within a two-years period (April 1980-March 1982).

The isotopic results of Table 4 have been graphed in the Figure 6. In there are quit conspicuous two groups of isotopic compositions: one includes the fluids from the Los Azufres wells and the Araró (Zimirao) hot springs, and the other groups the fluids from the hot springs of Las Adjuntas, Atzimba and San Bartolomé Coro.

Table 4: Isotopic composition of water from some geothermal wells and hot springs.

Site		Date	Measured Temp. (°C)	ΔD (0/00)	$\delta^{18}O$ (0/00)
Wells of Los Azufres	AZ-1	Mar 82	300	-57.5	-3.67
	AZ-2	Mar 82	290	-62.9	-4.25
	AZ-4	May 80	300	-65.5	-4.36
	AZ-5	Jan 81	310	-62.9	-3.89
	AZ-6	Mar 82	257	-55.7	-5.02
	AZ-7	Apr 80	255	-65.5	-4.00
	AZ-8	Apr 80	285	-66.6	-4.44
	AZ-13	Mar 82	300	-57.5	-2.47
	AZ-16D	Mar 82	265	-59.1	-3.66
	AZ-17	Jan 81	260	-58.8	-5.60
	AZ-19	Mar 82	310	-64.5	-4.53
L. Adjuntas hot springs		Apr 80	39	-69.7	-9.74
Zimirao hot springs		Jan 81	92	-65.9	-5.87
		Mar 82	92	-58.6	-5.76
Atzimba hot springs		Apr 80	31	-72.2	-9.76
		Jan 81	31	-71.1	-9.81
S. Barolomé hot springs		Mar 81	32	-69.6	-9.22

Prepared with data from Rodríguez et al. *(1984) and Quijano* et al. *(1987).*

Now it is important to consider the geographic location of both groups (Fig. 4). If the Araró hot springs were a distant discharge of the Los Azufres system, the Las Adjuntas hot springs should present an isotopic composition more similar to those from the Los Azufres wells and Araró than those from the Atzimba and San Bartolomé Coro hot springs. It is to say, isotopic relationship of the Araró hot springs should be at the second group, and that from Las Adjuntas should be at an intermediate position between the Los Azufres wells and Atzimba and San Bartolomé Coro.

Again, data from the Table 4 and the Figure 6 seem to indicate that wells from Los Azufres and hot springs from Araró represent two distinct geothermal systems. Both systems presents a similar isotopic composition, but their respective discharges are the Las Adjuntas hot springs (for Los Azufres) and San Bartolomé Coro, and perhaps Atzimba (for Araró), more or less as indicated by arrows in the Figure 6.

5. CONCLUSIONS

There is enough evidence to support the presence of an active geothermal system at the subsurface of the Araró zone, as postulated before (Viggiano-Guerra and Gutiérrez-Negrín, 2001). The present temperatures of the system are lower and deeper than the old temperatures, as suggested by the hydrothermal mineral assemblages, the fluid-inclusions temperatures, the liquid and gas geothermometry and the measured temperatures in the well Z-3 and in the surrounding hot springs. This seems to indicate the geothermal system has been deepened over time, probably due to self-sealing of the shallow and more fractured zones. Nowadays, it is possible to expect temperatures over 220°C at greater depths than those reached by the well Z-3.

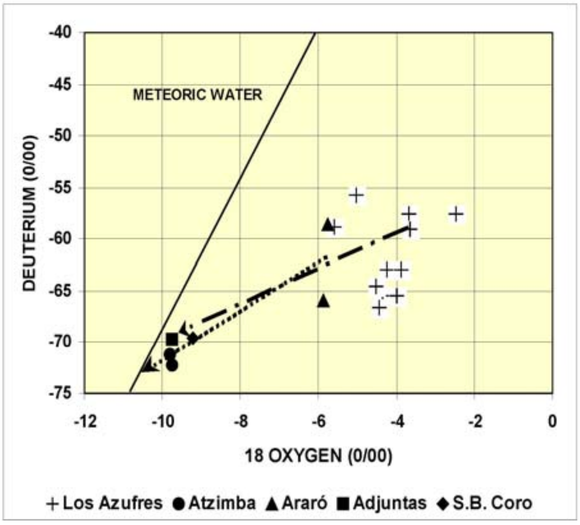

Fig. 6: Isotopic (Deuterium and 18 Oxygen) composition for water samples from several Los Azufres wells and from some hot springs, as presented in Table 4.

The Araró system looks like a restricted system probably constrained at depth by a narrow zone of fluid ascent. It seems to be a convection, liquid-dominant system, with sodium chloride fluids, mid to high temperatures (220-250°C) and low salinity (TDS of ~3000 ppm), quick discharge, pressures close to hydrostatic and low heat loss.

The Araró geothermal system is an independent and genetically different system of the Los Azufres reservoir, even though the geothermal fluids from both are of the same geochemical type (sodium chloride) and present similar isotopic compositions.

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