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Geochemical Exploration at Cuitzeo Basin Geothermal Zone (Mexico)

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Abstract: Water samples from springs and wells from the Cuitzeo Basin (Michoacan state, Mexico) were studied to investigate the main geochemical features of deep waters assessing moderate temperature geothermal resources in Mexico for direct uses. Radon measurements were also performed. Waters were classified as bicarbonate, chloride and sulfate according to their origin. Partially equilibrated and immature waters were found with reservoir temperatures between 129 to 216°C. Silica temperature results indicate reservoir temperatures in the range 100 to 200°C. Those temperatures are useful not only for direct uses but also to generate electricity. The average ground water radon concentration values were relatively low indicating an efficient fluid circulation pattern.

Key words: Low-medium temperature geothermal resources, Cuitzeo, Michoacan, Mexico, water geochemistry, radon

INTRODUCTION

The central region of Mexico is characterized by a volcanic range where 14 active volcanoes can be found, together with lacustrine depressions where two of the main lakes in the country are located: Chapala and Cuitzeo. These lakes are part of the Lerma river Basin, crossing Central Mexico from east to west, starting in the center of the country and reaching the Pacific Ocean in the west. Around the Cuitzeo depression one of the main mountain heights is the Los Azufres range, where the second in electric production geothermal field in Mexico is found. The drainage basin of Lerma River has been recognized as one of the most polluted in Mexico due to the proliferation of industrial development and the use of fertilizers and pesticides in the agricultural local practices[1]. Recent studies of chemical, radioisotopic and bacteriological concentration levels in different wells and springs belonging to the Upper Lerma river basin have shown that the recharge zone is complex[2,3].

Due to the neighboring of Los Azufres geothermal field, geochemical surveys were performed around Cuitzeo Lake since the early eighties[4,5]. These surveys showed four zones interesting for geothermal uses.

In Mexico low temperature geothermal resources are slightly used for direct applications in spite of its availability in rural zones, in this study an analysis of the possibilities of low-medium geothermal resources around Cuitzeo Lake is presented together with a geochemical and radon data interpretation.

MATERIALS AND METHODS

Cuitzeo Lake is located in the northern part of Michoacan state. Recent volcanism has occurred at this state, where the youngest volcano, Paricutin, was born in 1943 (Fig. 1). The main regional geological formations are from Tertiary and Quaternary periods. Michoacan hydrology is composed by upper Lerma River, the central lake zone and the Balsas River. The Cuitzeo basin having 3977 km^2 is one of the largest lakes of the zone. The main landform of the sampling zone is formed by the Cuitzeo depression. The southern region of the lake has been reported to have neutral-alkaline groundwater type; the recharge zones are located at the border of the hills at the east of Zinapecuaro and west of Morelia. The qualitative direction of underground flows, deduced from chemical water composition are from south to north in the southern part of the Cuitzeo Lake while at Querendaro, in the southeastern part of the lake, the flow is southeast to northwest following the local faulting[6,7]. The weather is moderate with summer rains (May-October) giving an

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Table 1: Physico-chemical composition of the water samples from the sites around Cuitzeo Lake. Sampling temperatures (T) are given in °C. Concentration values for Na, K, Ca, Mg, HCO_3, SO_4, Cl, B and SiO_2 are given in mg kg^{-1}

Site	CODE	T (°C)	pH	Na	K	Ca	Mg	HCO_3	SO_4	Cl	B	SiO_2
Jeruco	J	25.0	8.2	130.7	17.7	58.9	45.14	414.3	99.4	52.3	0.3	68.3
Cuitzeo 2	C2	26.5	8.4	56.2	14.1	37.5	37.67	372.8	41.3	08.0	0.2	67.5
Cuitzeo 3	C3	27.0	8.4	29.2	7.4	32.9	32.13	303.8	3.9	04.3	0.1	64.2
Copandaro	CO	26.0	7.7	68.9	9.3	74.3	31.69	319.8	47.2	108.0	0.2	69.4
Panteon	PA	28.0	7.3	45.7	7.7	45.7	21.05	303.4	1.5	4.3	0.1	81.8
El Salitre	ES	32.0	8.0	150.7	11.5	20.6	13.70	212.1	42.7	166.5	2.2	79.9
Los Baños	LB	36.0	8.0	99.6	2.0	11.9	0.55	172.5	16.1	58.9	1.0	46.8
San Agustin del Pulque	SAP	75.0	8.0	406.0	11.0	33.0	0.20	262.0	591.0	95.8	3.0	241.0
San Juan Tararameo 1	SJT-1	30.0	7.7	76.4	11.2	29.7	24.28	284.8	46.1	21.3		
San Juan Tararameo 2	SJT-2	52.0	7.4	583.0	34.0	78.0	2.40	798.0	1001.0	137.0	0.1	247.0
San Juan Tararameo 3	SJT-3	82.0	8.9	774.0	30.0	1.0	0.28	525.0	947.0	280.0	4.6	270.0
San Agustin del Maiz	SAM	89.0	7.3	542.0	27.0	14.2	0.40	623.0	591.0	130.0	3.9	250.0
Araro 1	AR-1	60.0	7.8	691.3	55.5	26.5	0.50	134.0	138.8	1046.8	65.2	134.0
Araro 2	AR-2	60.0	7.7	756.5	60.6	32.6	0.50	158.5	153.6	1290.2	80.4	257.5
Mariano Escobedo	ME	26.0	7.7	390.8	21.1	68.1	31.56	716.8	355.6	199.7		
Santa Rita	SR	37.0	8.5	92.0	4.1	11.2	0.96	214.4	12.1	7.7		

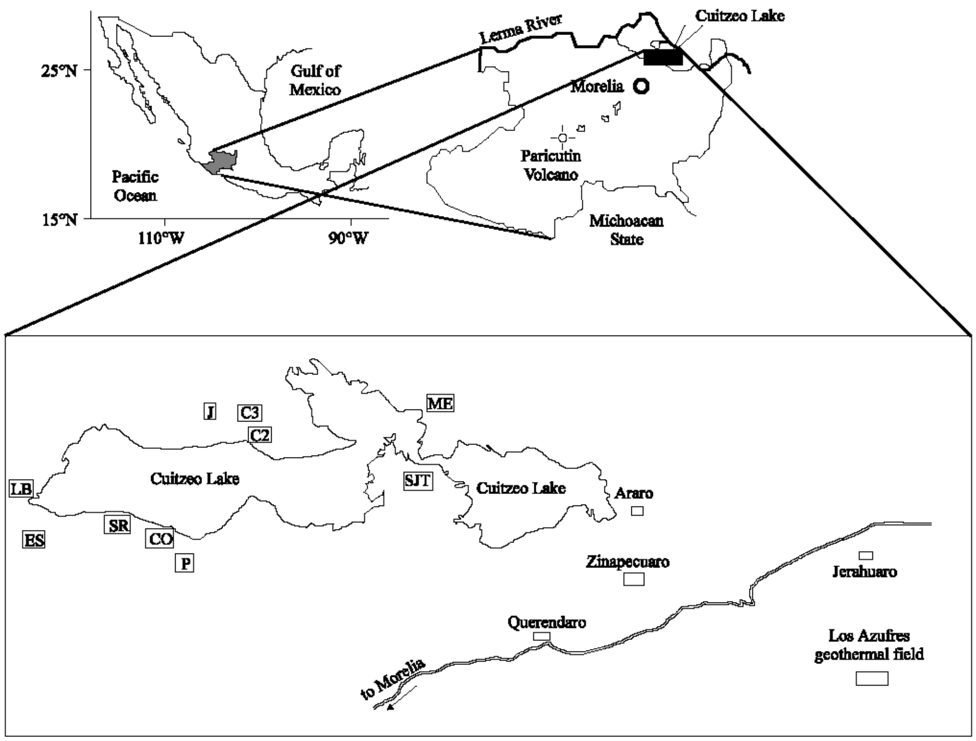

Fig. 1: Location of Cuitzeo Lake including several studied sites

average annual precipitation of 906 mm and the environmental temperature ranges from 10 to 28°C.

The western part of the Cuitzeo Lake is located about 30 km from the Los Azufres geothermal field. The geochemical and radon data were obtained from sites around the Cuitzeo Lake and Los Azufres (100°39'-101°20' W and 19°46'-19°59' N) at an average altitude of 1850 m. Data from Jeruco (J), Cuitzeo (C), Copandaro (CO), Panteon (PA), El Salitre (ES), Los Baños (LB), San Agustin del Pulque (SAP), San Juan Tararameo (SJT), San Agustin del Maiz (SAM), Araro (AR), Mariano Escobedo (ME) and Santa Rita (SR) (Fig. 1 and Table 1).

Data from 1983, 1990, 2001 and 2003[2,4,5,8] were analyzed to investigate the main geochemical features, the radon behavior and the estimation of reservoir temperatures.

The chemical data were classified and plotted on a Schoeller diagram[9] to see through the shapes of the curves if the samples are or are not related to each other.

The Giggenbach[10], Cl^{-}-HCO_3^{-}-SO_4^{2-} and the Na-K-Mg triangular plots were also obtained for the studied sites in order to classify the waters according to the dominant ions and to estimate reservoir temperatures. The Cationic Composition Geo-thermometer (CCG) was included in the Na-K-Mg plot[11,12]. The silica mixing model was used to investigate the fraction of hot water in the samples.

Isotopic data from some samples were compared to the global meteoric water line and to the composition of the Los Azufres geothermal wells considering data for the natural state reservoir fluids.

Groundwater radon data were obtained during field campaigns performed each three months in 2001 and 2003 at ten monitoring stations located at the sites indicated in Fig. 1.

RESULTS AND DISCUSSION

Chemical composition of samples is given in Table 1. Neutral to alkaline pH values were measured. Relative Cl-SO_4-HCO_3 compositions for the samples indicate that only Araro samples (AR-1, AR-2) are located in the area related to mature waters. Steam heated waters were found at San Agustin del Pulque (SAP), San Juan Tararameo 2 (SJT-2) and San Agustin del Maiz (SAM). All the other samples are located on the bicarbonate region and they are known as peripheral waters due to the absorption of deep CO_2 and to the mixing with shallower waters (Fig. 2).

Figure 3 shows the relative Na-K-Mg content for the samples[11]. Ground waters and springs are usually found close to the Mg corner while geothermal weir box samples are found on the full equilibrium line. As shown in the Fig. 3, only samples SAM, SAP, SJT-3 are in full equilibrium considering the CCG full equilibrium line, while AR-1, AR-2 and SJT-2 are in partial equilibrium. All the other samples correspond to immature waters. A mixing trend is observed among the samples indicating reservoir temperatures between 150 and 220°C, considering Giggenbach equilibrium line[11] which corresponds to 120 to 190°C with respect to CCG[12] equilibrium line (Fig. 3).

According to Schoeller diagram (Fig. 4) the studied waters show different salinity and two main patterns regarding the Mg content. Low Mg waters correspond to SAM, SJT-2, SJT-3, SAP, AR-1, AR-2 and SR indicating their geothermal character. The high Mg content is related to mixing with cooler and shallower waters. A wide range of SO_4, Cl and B concentration values were observed among the samples. In almost all the samples the low Mg content corresponds to high chloride and boron contents.

Results for different geo-thermometers: K/Na, K/Mg[11]; Na/K, Na-K-Ca with Mg correction[13], Cationic

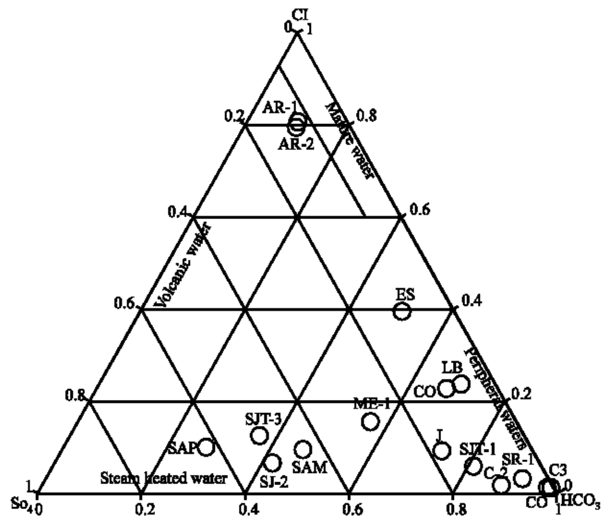

Fig. 2: Relation Cl-SO_4 HCO_3 composition of the samples

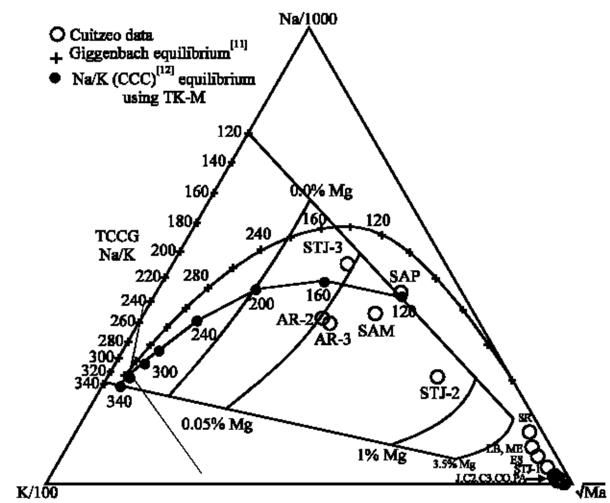

Fig. 3: Relative Na-K-Mg content for the samples. The Giggenbach[11] and CCG[12], equilibrium lines are also indicated

Composition Geo thermometer (CCG)[12] and SiO_2[11,13] are given in Table 2. Temperature (T°C) calculations in Table 2 were performed as follows (c means concentration in mg kg^{-1}): T (K/Na)[11] $= [1390/(1.75\text{-}\log(c_K/c_{Na}))]\text{-}273$; T (K/Mg)[11] $= [4410/(14.0\text{-}\log(c_K^2/c_{Mg}))]\text{-}273$; T (Na/K))[13] $=[1217/(1.483\text{-}\log(c_K/c_{Na}))]\text{-}273$; T(Na/K/Ca)[13]$=[1647/(\log(c_{Na}/c_K)+\beta(\log(c_{Ca}^{0.5}/c_{Na})+2.06)+2.47)]\text{-}273$; $\beta = 4/3$ for $T < 100°C$, $\beta = 1/3$ for $T > 100°C$, c in this case is given in moles kg^{-1}; T(Na/K/Ca))[13]$= [1178/(1.47+\log(c_{Na}/c_K))]\text{-}273$, this expression was used for samples SJT-2, SJT-3, SAM, AR-1 and AR-2 containing a %Mg < 3.5; T CCG[12] $= [10080/(5\ \log(c_{Na}/c_K)+2\log(c_{Ca}/c_{Na}^2)\text{-}\log(c_{Mg}/c_{Na}^2)+16.65)]\text{-}273$, this expression was suitable for

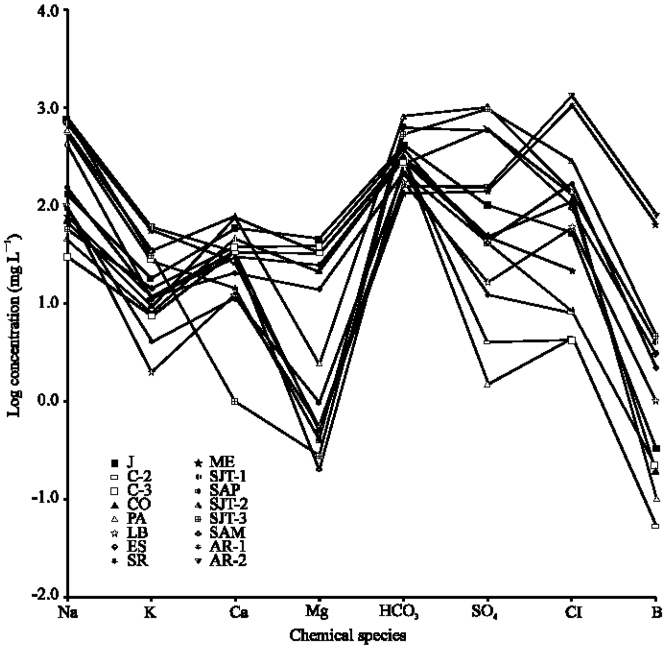

Fig. 4: Schoeller diagram for the samples

Table 2: Reservoir temperatures (T°C) estimated by different geo-thermometers: T (K/Na)[11], T (K/Mg)[11], T (Na/K)[13], T (Na/K/Ca)[13], T CCG[12], T SiO_2[13], T SiO_2[11]

Code	T (K/Na)[11]	T (K/Mg)[11]	T (Na/K)[13]	T (Na/K/Ca)[13]	T CCG[12]	T SiO_2[13]	T SiO_2[11]
J	258	62	243	91	38	117	99
C2	318	59	309	89	38	116	95
C3	319	47	305	63	32	114	92
CO	258	52	244	64	30	118	96
PA	278	53	266	64	30	127	106
ES	212	66	195	164	42	125	105
LB	129	62		58	79	99	74
SAP	146	120		125	132	194	188
SJT-1	265	59	252		38		
SJT-2	193	117	175	158	163	196	191
SJT-3	167	147		181	136	202	199
SAM	182	138	164	167	152	197	192
AR-1	216	159	199	192	186	156	140
AR-2	215	162	199	191	186	199	194
ME	188	70	169	153	42		
SR	175	72	156	81	105		

samples LB and SR. T CCG[12] = $[16000/(3\log(c_{Na}/c_K) + 3\log(c_{Ca}/c_{Na}^2) - \log(c_{Mg}/c_{Na}^2) + 44.67)] - 273$, this expression was used with samples: J, C-2, C-3, CO, PA, ES, SJT-1 and ME. T CCG[12] = $[11140/(6\log(c_{Na}/c_K) + \log(c_{Mg}/c_{Na}^2) + 18.3)] - 273$, this expression was used with sample SAP. T SiO_2[13] = $-42.198 + 28.831\,S - 3.6686E\text{-}4\,S^2 + 3.1665E^{-7}\,S^3 + 77.034\log S$ where S is the SiO_2 concentration of the sample; T SiO_2[11] = $(1000/(4.55 - \log c_{SiO2})) - 273$.

Cationic geo-thermometers provide a wide range of temperature values, which is due to the different rates of re-equilibration of chemical constituents in the water-rock reactions occurring at depth. Cationic geo thermometers that include Mg usually give low reservoir temperatures because Mg has a fast re-equilibration rate, this is the case of the following geo thermometers: K/Mg, Na-K-Ca with Mg correction and CCG for samples where the Mg content is higher than 3.5% (samples J, C-2, C-3, CO, PA, ES and ME). In addition, cationic geo thermometers are more suitable when samples are classified as mature waters, as in samples AR-1 and AR-2, in which the estimated temperatures (Table 2) seem to be more consistent, in spite of using geo thermometers based on Mg. Cooling processes when ascending the waters to the surface should be considered in order to assess which geo thermometers are more reliable to estimate reservoir temperatures from spring data. Such cooling processes sometimes imply the mixing of deep hot waters with shallower and cooler (Mg rich) waters. Considering Na/K geo-thermometers qualitative results were as follows: Na/K[11] provided the higher temperatures compared to

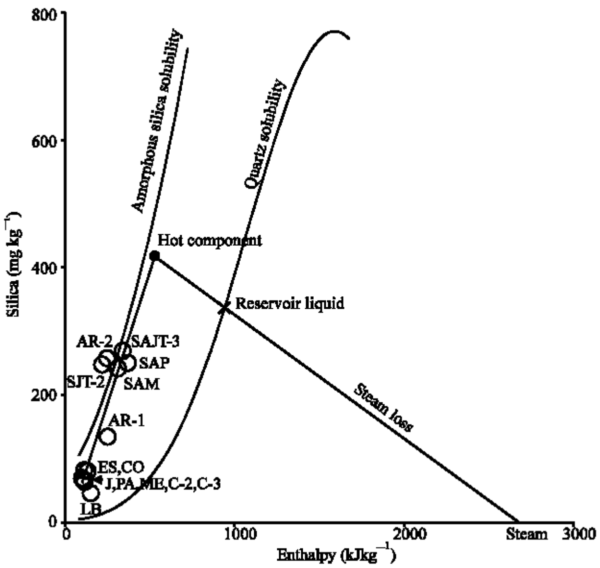

Fig. 5: Specific enthalpy (kJ kg^{-1}) vs silica (mg kg^{-1})

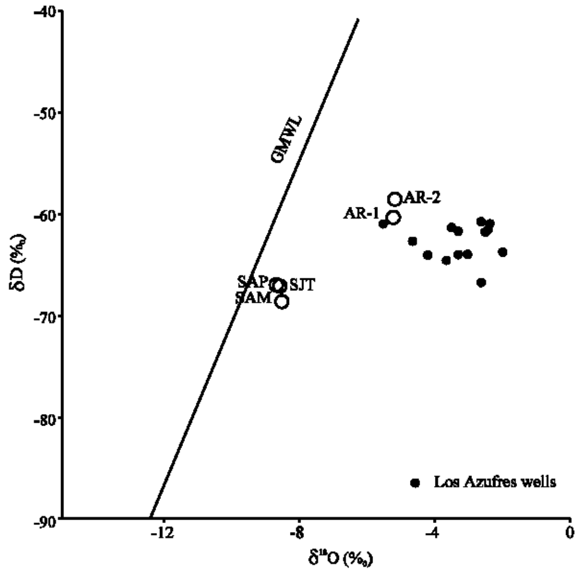

Fig. 6: Deuterium vs oxygen-18 (‰) of some samples

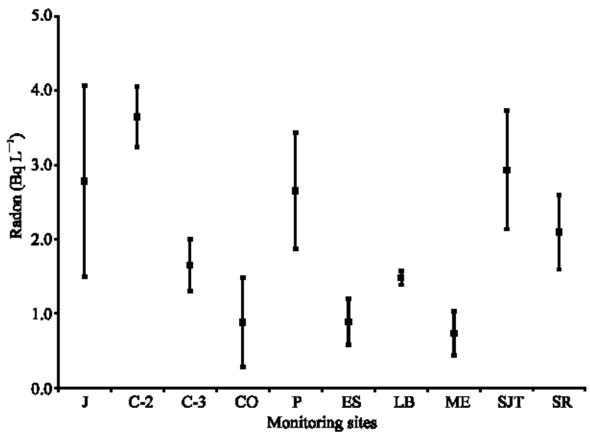

Fig. 7: Radon concentration values (Bq L^{-1})

Na/K[13] and these gave higher temperatures than those obtained using CCG[12]. In contrast, silica geo thermometers are based on silica solubility that depends only on temperature. Two expressions were used in Table 2 to estimate reservoir temperatures: T SiO_2[13] that considers equilibrium with quartz and T SiO_2[11] that considers equilibrium with chalcedony and is more suitable for spring data. Slightly higher temperatures are estimated with the quartz geo thermometer compared to the results obtained with chalcedony. As shown in Table 2 the silica temperatures indicate moderate reservoir temperatures between 90 and 200°C for all the sites.

Figure 5 is a silica versus specific enthalpy plot, where the samples have been represented as well as the amorphous silica and quartz solubility curves. A linear tendency for the samples is observed which shows the occurrence of a mixing process. The fitted straight line for the samples was calculated by the minimum square method. This line is explained by assuming that the reservoir liquid at 220°C is cooled to 131°C by boiling and subsequently is mixed with non-thermal waters to give the sample compositions. This boiling process is shown by moving the reservoir liquid point to the hot component point. The point for separated vapor is named Steam in the figure. From Fig. 6 the silica concentration for the reservoir liquid is estimated as 336.4 mg kg^{-1} and the specific enthalpy was 943.6 J g^{-1}. The fraction of hot component in the samples was estimated to be about 50% in AR-2, SJT-3, SAP and SAM and around 30% for AR-1, while the rest of samples are constituted by larger fractions of shallower cooler waters.

Isotopic results (δ^{18}O, δD) of some springs are shown in Fig. 6 where data for the Los Azufres reservoir fluids at natural state were included. All the samples show the oxygen-18 shift characteristic of geothermal fluids. Araro samples show a similar composition as compared to the Los Azufres fluids indicating a relationship between them. Tello and Quijano[4] indicated that Araro could be a discharge of the Los Azufres fluids, the present results seem to confirm this hypothesis.

The average and standard deviation of groundwater radon concentration values for each monitoring station are shown in Fig. 7. The average radon concentration values ranged from 0.88 to 3.66 Bq L^{-1}. These values, relatively low, indicate a rapid transit from recharge to the output of springs and wells[2,3] even if the stations are located in different geological environments around the

Table 3: Alternative uses of geothermal energy as a function of reservoir temperature as reported by Lindall[14]

Source temperature (°C)	Potential uses
180	Evaporation of highly concentrated solutions refrigeration by ammonia absorption, Digestion paper pulp, Kraft
170	Heavy water via hydrogen sulfide process, Drying of diatomaceous earth
160	Drying of fish meal, Drying of timber
150	Alumina via Bayer´s process
140	Drying farm products at high rates, Canning of food
130	Evaporation in sugar refining, Extraction of salts by evaporation and crystallization
120	Fresh water by distillation, Most multiple effect evaporations, concentration of saline solutions
110	Drying and curing of light aggregate cement slabs
100	Drying of organic materials, seaweeds, grass, vegetables, etc., Washing and drying of wool
90	Drying of stock fish, Intense de-icing operations
80	Space heating, Greenhouses by space heating
70	Refrigeration (lower temperature limit)
60	Animal husbandry, Greenhouses by combined space and hotbed heating
50	Mushroom growing, Balneological baths
40	Soil warming
30	Swimming pools, biodegradation, fermentations, Warm water for year-round mining in cold climates, De-icing
20	Hatching of fish, fish farming

lake. Effectively, stations Jeruco (J), Cuitzeo (C-2 and C-3) are located on pyroclastic flow deposits from local monogenetic volcanism at the northwestern shore of the lake. Station San Juan Tararameo (SJT), at the central part of the lake, corresponds to lacustrine deposits while Santa Rita (SR) and Copandaro (CO) are located on andesitic rocks in the southern part of the lake. However, all of them are associated to normal faulting that form the semi-graben of Cuitzeo Lake.

It is worth mentioning that the lower radon values in groundwater were found at El Salitre (ES), Copandaro (CO) and Mariano Escobedo (ME), three stations located on one of the main local geological faults. This behavior is explained considering that in such sites gas emanations occur. As radon is partitioned to the gas phase the liquid phase becomes depleted.

The higher radon values correspond to the sites where higher reservoir temperatures and gas emanations were found due to the high efficiency fluid flow that eventually transports the radon to the surface.

In Table 3 the possible alternative uses of geothermal energy as a function of reservoir temperature are given[14]. For the studied sites temperatures, there are many possible applications of geothermal fluids, including electric generation by conventional or binary cycles at Araro.

CONCLUSIONS

Analysis of chemical data from Cuitzeo wells and springs suggests that one or more geothermal reservoirs could occur. Araro waters are probably related to the Los Azufres geothermal fluids. Chemical geo-thermometers provided a wide range of temperatures for the reservoir, from 165 to 220°C which are able for electric generation and a wide range of direct applications. A model based on silica and enthalpy was obtained indicating a mixing process between hot deep fluids with shallower, cooler waters in different proportions. AR-2, SAM, SAP and SJT samples present about 50% of hot component in the mixture. Radon results indicated a high efficient fluid flow transport in the zones where higher reservoir temperatures were estimated.

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