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HYDROGEOCHEMICAL EXPLORATION OF THE TECUAMBURRO VOLCANO REGION, GUATEMALA

Fraser Goff[1], A. H. Truesdell[2], Cathy J. Janik[2], Andrew Adams[1], Alfredo Roldan-M.[3], and Kimberly Meeker[1]

[1]ESS-1, MS D462, Los Alamos National Laboratory, Los Alamos, NM 87545
[2]Branch of Igneous and Geothermal Processes, MS 910, U.S. Geological Survey, Menlo Park, CA 94025
[3]Unidad de Desarollo Geotermico, INDE, Guatemala City, Guatemala

ABSTRACT

Approximately 100 thermal and nonthermal water samples and 20 gas samples from springs and fumaroles have been chemically and isotopically analyzed to help evaluate the geothermal potential of the Tecuamburro Volcano region, Guatemala. Thermal waters of the acid-sulfate, steam condensate, and neutral-chloride types generally occur in restricted hydrogeologic areas: Tecuamburro-Laguna Ixpaco (acid-sulfate); andesite highland north of Tecuamburro (steam-condensate); Rio Los Esclavos (neutral-chloride). One small area of neutral-chloride springs east of the village of Los Esclavos has no relation to the Tecuamburro geothermal system. Neutral-chloride springs on the Rio Los Esclavos east and southeast of Tecuamburro show mixing with various types of groundwaters and display a maximum oxygen-18 enrichment compared to the world meteoric line of only about 1.5°/oo. Maximum estimated subsurface temperatures from liquid geochemistry are ≤200°C. In contrast, maximum estimated subsurface temperatures based on gas compositions in the Laguna Ixpaco area are about 300°C. The relation of neutral-chloride waters to the overall Tecuamburro geothermal system is not entirely resolved but we have suggested two system models. Regardless of model, we believe that a first exploration drill hole should be sited within 0.5 km of Laguna Ixpaco to tap the main geothermal reservoir or its adjacent, main upflow zone.

INTRODUCTION

The Tecuamburro Volcano region lies in southeastern Guatemala in the Central American volcanic arc. The region contains several volcanic centers of Pleistocene age that are associated with seismically active faults and a wide variety of hot springs and fumaroles. During July 1988 and February-March 1989, about 100 sample suites of thermal and nonthermal waters and fumarole gases were collected within 400 km^2 of the Tecuamburro region as part of a cooperative, AID-funded geothermal exploration effort among Institute Nacional de Electrification (INDE), U.S. Geological Survey (USGS), and Los Alamos National Laboratory (Los Alamos). This paper presents some preliminary results of the hydrogeochemical studies conducted in the region. Geological, volcanological, and geophysical investigations comprise other parts of this effort (Duffield et al., this volume; Hoover et al., USGS, unpub. data). Brief geothermal reports on the area have been previously completed by OLADE (unpub.) and Giggenbach (1988).

GEOLOGIC AND HYDROGEOCHEMICAL SETTING

Tecuamburro Volcano is a composite andesitic stratovolcano of Pleistocene age whose eruptions span a time period of about 0.1 to ≤0.04 Ma (Duffield et al., this volume). Currently, an abandoned sulfur mine in the summit area contains active fumaroles and a 2,900 year old phreatic crater about 0.5 km in diameter (Laguna Ixpaco) contains vigorously degassing acid-sulfate hot springs and mud pots (Fig. 1).

The main area of geothermal exploration occupies a 15-km wide, north-trending structural graben extending from the volcano north to the northwest-trending Jalpatagua fault zone (see Duffield et al., this volume). Between this fault zone and the volcano, and within the structural graben resides a broad highland of andesitic and basaltic rocks comprising a volcanic center that was active from at least 1.2 to 0.8 Ma. Rocks in this highland display local zones of intense hydrothermal alteration and the highland is characterized by steam-heated hot springs. Infernitos is the only hot spring of this type that is boiling.

Along the Jalpatagua fault zone is a Pleistocene cinder cone field of predominately basaltic rocks that has one eruption dated at 0.036 Ma (Duffield et al., this volume). The Jalpatagua fault is a strike-slip fault with Pleistocene movement whereas the east fault of the structural graben is a normal fault that had apparent seismic activity in 1979-1980.

We have examined three areas of neutral-chloride hot springs in the Tecuamburro region. The most impressive area of 35° to 97°C springs occurs near Colmenares along a 7 km stretch of the Rio Los Esclavos east-northeast of Tecuamburro Volcano. The southern boundary for springs of the Colmenares group occurs where a major east-west-trending fault crosses the Rio Los Esclavos (Fig. 1). A second area of small warm springs 30° to 42°C discharges on the north side of the Rio Los Esclavos about 4.5 km east of the village of Los Esclavos (east of Fig. 1). The

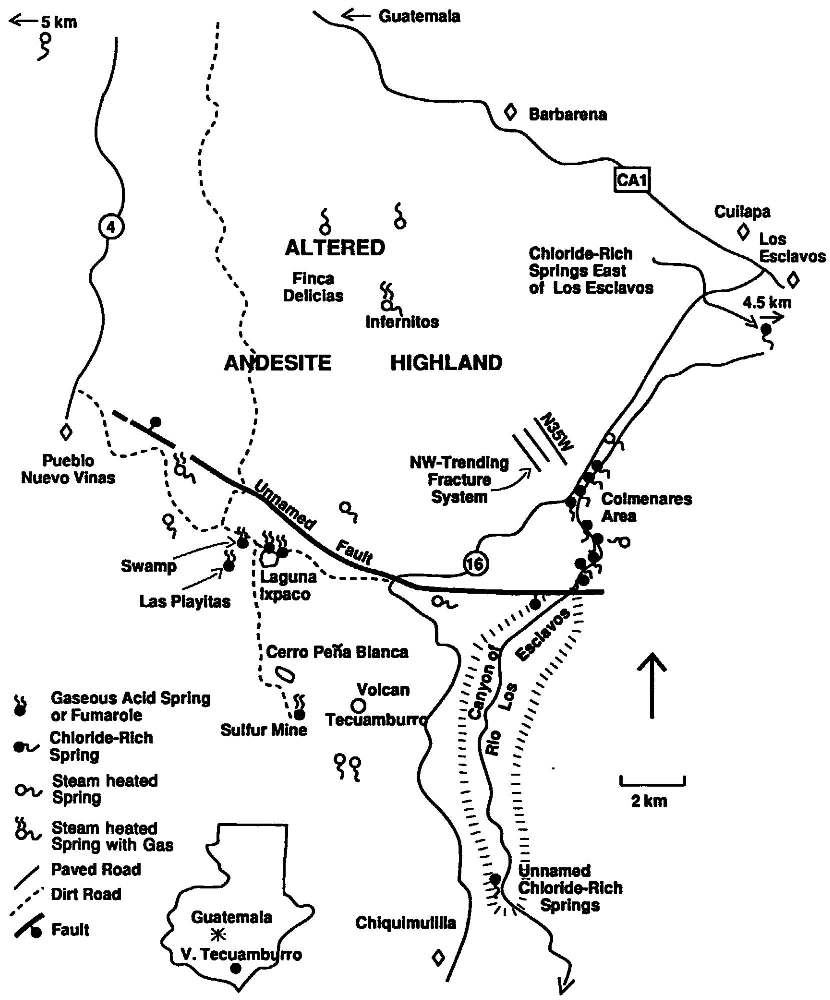


Fig. 1. Location map of Tecuamburro Volcano region, Guatemala.

third area comprises a broad seep and one 39°C spring south-southeast of Tecuamburro Volcano on the west side of the Rio Los Esclavos. Although we spent several days trekking through the deep canyon of the Rio Los Esclavos directly east of Tecuamburro Volcano (Fig. 1), we found no more neutral-chloride springs. It is clear, however, that the river controls the discharge elevation of all neutral-chloride springs in the region.

FLUID GEOCHEMISTRY

Several thermal water types discharge in the Tecuamburro region as mentioned above (Table 1). Steam-heated waters occur primarily in the altered andesitic highland north of Tecuamburro Volcano. Compositionally, they are relatively dilute with low concentrations of anions and trace elements commonly associated with high temperature equilibration such as As, B, Br, and Li (Fig. 2). Isotopically, they plot on or near the world meteoric line (Fig. 3) and have variable tritium contents (Fig. 4). Gases from these springs are relatively low in H_2S and relatively high in air components (N_2, O_2, Ar) (Table 2). Thus, "steam-heated" waters are composed primarily of near-surface groundwaters of varying age heated either by condensation of steam from a boiling reservoir below and/or by high subsurface heat flow.

Acid-sulfate springs occur only adjacent to Laguna Ixpaco and at two small sites to the west. Compositionally, they are relatively low in pH (≤3), have very high sulfate concentrations, have moderate concentrations of volatile to partly volatile components such as B and NH_4, and have low concentrations of Cl, Li, Br, and As. Contents of Ca+Mg are greater than Na+K. Isotopically, acid-sulfate springs display a typical evaporation trend of increasing δD and $\delta^{18}O$ and have tritium contents of 1 to 3 T.U. indicating that a large fraction of the water is young meteoric water, probably shallow groundwater. Presumably, the volatile components and steam originate from boiling of a high temperature reservoir at depth.

Acid-sulfate springs are associated with fumaroles and gas seeps with very high concentrations of H_2S. Gas seeps west of Laguna Ixpaco are similar in composition except that H_2 values are considerably lower and CH_4 values are slightly higher. Gases of similar composition issue at

TABLE 1. CHEMISTRY OF SELECTED SPRINGS, TECUAMBURRO REGION, GUATEMALA (values in mg/kg except where shown).[a]

Sample No.	Description	Temp. (°C)	Field pH	SiO_2	Na	K	Li	Ca	Mg	As	HCO_3	SO_4	Cl	F	Br	B	NH_4	$\delta^{18}O$ (°/∞)	δD (°/∞)	^3H (T.U.)
Cold Springs																				
GT-88-23	Near summit, Tecuamburro	20.0	5.5	48	5.5	2.1	0.01	10.9	2.2	<0.05	49	12.5	2.5	<0.05	<0.1	<0.02	0.07	-8.49	-59.5	5.55
GT-88-35	Finca La Pastoria	23.4	6.0	90	10.6	10.8	0.01	8.3	3.1	<0.05	76	3.1	4.3	<0.05	<0.1	<0.02	0.49	-6.93	-46.9	8.29
Steam-Heated Springs																				
GT-88-34	Finca San Lorenzo	42.0	5.5	55	39	7.2	0.01	43.1	8.7	<0.05	186	109	1.3	<0.05	<0.1	0.02	0.06	-8.26	-55.7	0.18
GT-88-38	East of Finca El Chorro	57.6	5.0	85	25	9.0	<0.01	22.8	5.7	<0.05	30	165	1.1	0.19	<0.1	0.03	0.12	-8.40	-56.6	0.14
Acid-Sulfate Springs																				
GT-88-4	NE shore, Laguna Ixpaco	77.0	2.5	288	70	6.2	0.09	180	87.4	0.10	0	3560	<0.4	0.14	<0.4	0.31	13.9	2.55	-21.9	1.67
GT-88-24	Las Playitas	32.4	2.2	202	82	9.0	0.06	214	50.8	<0.05	0	5200	8.7	<0.05	<0.2	0.20	5.1	---	---	---
Neutral-Chloride Springs																				
GT-88-45	Rio Los Esclavos, near Colmenares	96.2	6.5	95	604	25.2	1.86	69	1.2	2.00	144	280	817	2.5	2.5	17.6	0.13	-6.72	-53.9	0.65
GT-89-74	Rio Los Esclavos, east of Los Esclavos	41.8	6.0	139	680	44	1.89	84	52.0	0.3	1220	178	530	0.5	1.2	5.4	0.09	W.	W.	5.95
GT-89-97	Rio Los Esclavos, SSE of Tecuamburro	39.2	7.0	141	436	37.6	0.58	79	64.5	0.8	763	121	519	0.4	1.2	11.0	0.17	W.	W.	1.00

[a]Chemical analyses by P. E. Trujillo and D. Counce (LANL); W. means waiting for results.

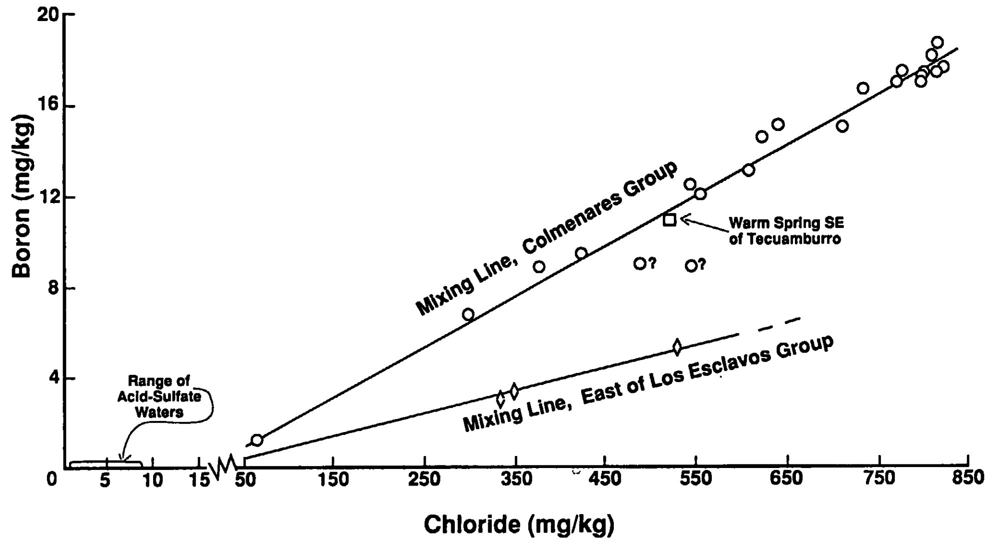
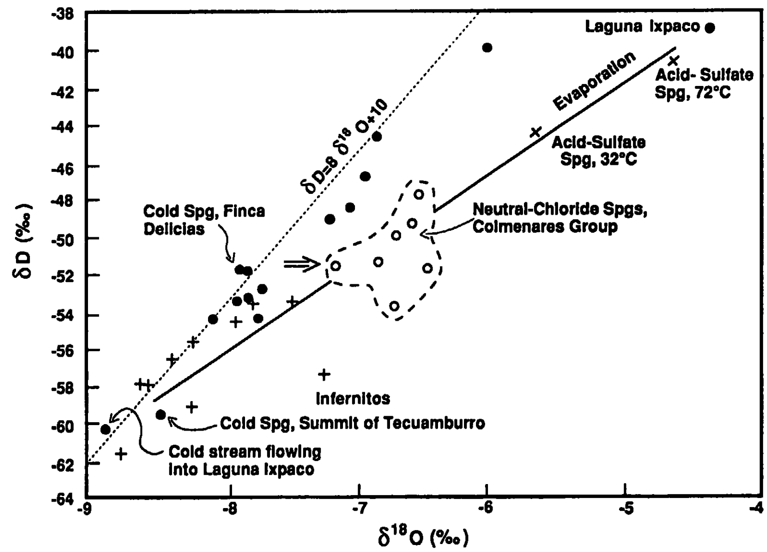


Fig. 2. Plot of boron versus chloride for thermal and nonthermal waters of the Tecuamburro region, Guatemala; circles = Colmenares waters, diamonds = east of Los Esclavos waters. Steam-heated waters and cold waters contain less boron than acid-sulfate waters.

Fig. 3. Plot of deuterium versus oxygen-18 for thermal and nonthermal waters of the Tecuamburro region, Guatemala (shows only data collected in July 1988); symbols same as Fig. 2 except x = acid-sulfate waters, + = steam-condensate waters, dots = cold waters. Analyses by Institute for the Study of Earth and Man, Southern Methodist University, Texas.



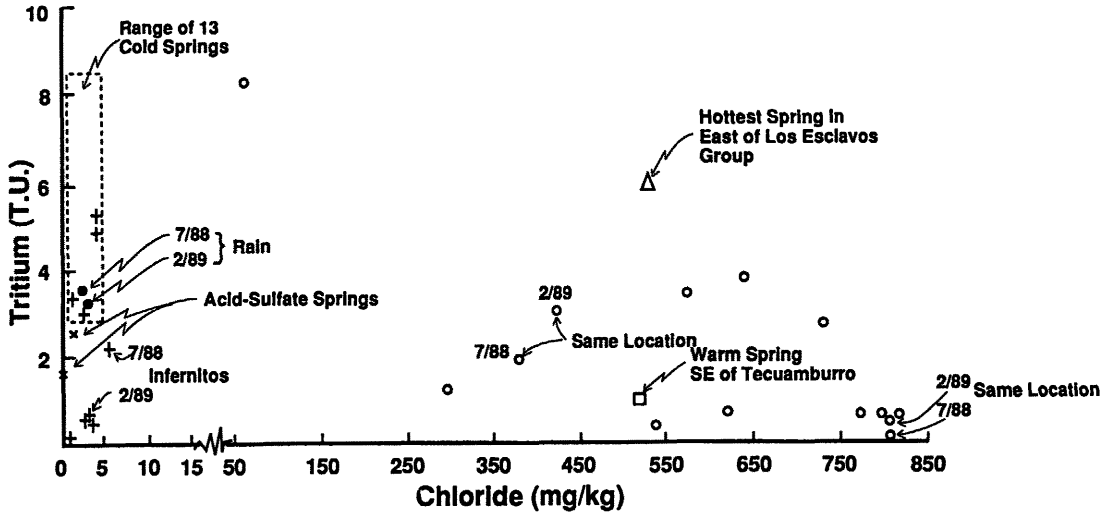


Fig. 4. Plot of tritium versus chloride for thermal and nonthermal waters of the Tecuamburro region, Guatemala; symbols same as Figs. 2 and 3. Tritium analyses by H. Gote Ostlund, University of Miami, Florida.

TABLE 2. GAS COMPOSITIONS FOR SPRINGS AND FUMAROLES, TECUAMBURRO REGION, GUATEMALA (values in mol-%, except where shown).[a]

Sample No.	Description	Temp. (°C)	CO_2	H_2S	H_2	CH_4	NH_3	N_2	He	Ar	O_2	$\delta^{13}C$-CO_2 (°/∞)
Laguna Ixpaco Area												
GT-88-4	NE shore, Laguna Ixpaco	77	88.0	7.86	0.906	0.012	0.004	3.196	0.0002	0.014	0.0021	-3.2
GT-88-5	NE shore, Laguna Ixpaco	85	87.1	9.38	0.616	0.0087	N.D.	2.836	0.002	0.012	N.D.	-3.0
GT-88-6	N shore, Laguna Ixpaco	71.5	88.1	8.84	0.111	0.0086	N.D.	2.924	0.0003	0.015	0.0020	-3.4
GT-89-82	Repeat of GT-88-4[b]	87.3	90.2	7.68	0.438	0.0054	N.D.	1.675	N.D.	0.004	0.0065	W.
GT-88-24	Las Playitas	33.0	89.6	7.22	0.0020	0.0288	0.002	3.133	0.0003	0.007	N.D.	-3.0
GT-88-32	Swamp, Finca Chintera	28.0	88.4	8.16	0.0006	0.029	0.001	3.384	0.0006	0.013	N.D.	-3.6
GT-88-33	Swamp, Finca Chintera	28.0	87.8	7.07	0.0006	0.043	0.002	5.077	0.0006	0.025	N.D.	-2.9
Summit of Tecuamburro												
GT-88-21(1)	Sulfur Mine	94.9	86.2	10.65	0.0015	0.0086	0.002	3.076	0.0003	0.013	N.D.	-2.7
GT-88-21(2)	Sulfur Mine	94.9	86.3	10.51	0.0015	0.0088	N.D.	3.086	0.0004	0.014	0.0016	-2.7
GT-89-80	Sulfur Mine[b]	94.8	87.8	9.68	0.0072	0.0061	N.D.	2.462	0.0079	0.014	0.0192	W.
Steam-Heated Region												
GT-88-34	Spring, Finca San Lorenzo	42.0	78.4	1.72	0.0008	0.976	0.003	18.73	0.0019	0.223	N.D.	-4.9
GT-88-42	Fumarole Infernitos	98.6	95.4	0.212	0.055	0.046	0.022	4.23	0.0010	0.033	0.028	-2.6
GT-89-101	Fumarole Infernitos[b]	98.7	95.4	0.002	0.079	0.035	N.D.	4.07	N.D.	0.036	0.272	W.

[a]N.D. means not detected; W. means waiting for results; analyses by C. J. Janik (USGS).
[b]Analyses by P. E. Trujillo (LANL).

the sulfur mine near the summit of Tecuamburro Volcano but these gases are not associated with permanent acid springs.

Neutral-chloride springs have relatively high concentrations of Cl, As, B, Br, and Li but only moderate concentrations of SO_4 and HCO_3. Compared to neutral-chloride fluids from drilled, high-temperature geothermal fields around the world (Fournier, 1981), the Tecuamburro examples contain only modest concentrations of SiO_2 (≤150 mg/kg) and relatively high concentrations of Ca+Mg suggesting either moderate temperatures of subsurface equilibration (<180°C) or mixing with cool dilute waters. A plot of B versus Cl reveals that mixing is an important hydrologic process for the large group of springs in the Colmenares area (Fig. 2). On the other hand, the cool fluids that mix with Colmenares thermal waters cannot be a single homogenous aquifer because both stable isotope and tritium data of mixed fluids show considerable variations with respect to recharge and relative age.

As of this writing, we only have stable isotope results for neutral-chloride springs of the Colmenares Group. Springs in this group form a cluster of points shifted about 1 to 1.5°/oo to the right of the world meteoric line. Such a shift would be indicative of high-temperature (≥200°C) isotopic exchange between water and rock. Curiously, the Colmenares points are shifted to the right with respect to cold springs such as Finca Delicias in the andesite highland (large arrow, Fig. 3) suggesting recharge from this area. The isotope data do not suggest recharge of the Colmenares springs from a source at Tecuamburro Volcano unless the reservoir has suffered substantially subsurface boiling at temperatures below 160°C. We do not see evidence of this in the zone between Ixpaco and Colmenares.

The single chloride-rich spring sampled south-southeast of Tecuamburro Volcano plots on the same B versus Cl mixing trend as Colmenares waters and has a few other chemical similarities to Colmenares waters (i.e., As/Cl and Br/Cl). On the other hand, the "SSE spring" is different from Colmenares waters in contents of SiO_2, Mg, HCO_3, and Na/K ratio. At this time, it is impossible for us to conclude if the two locations are hydrologically connected and chemically related or not. The spatial separation of the two sites and the abrupt hydrologic control of Colmenares springs by the east-west fault shown in Fig. 1 would argue that the sites are hydrologically separated.

Neutral-chloride springs issuing east of Los Esclavos are compositionally different than Colmenares waters in ratios of B/Cl (Fig. 2), Li/Cl, As/Cl, Na/K and in contents of SiO_2, Mg, and HCO_3. The former springs are also composed of at least 50% young meteoric water judging from their high tritium content (~6 T.U.). The springs east of Los Esclavos and those at Colmenares cannot be part of a single geothermal system.

All gases collected from the Tecuamburro region thus far have $\delta^{13}C$-CO_2 values clustered between -2.6 and -4.9°/₀₀. These values are heavier than those thought to be derived solely from CO_2 in volcanic/mantle sources (-5 to -8°/₀₀) but are similar to values found from marine limestones (Hoefs, 1973). Goff et al. (1985) found an extremely good correlation between the $\delta^{13}C$-CO_2 and $\delta^{13}C$-$CaCO_3$ in the gases and subsurface Paleozoic carbonate rocks in the 220° to 300°C geothermal system of Valles caldera, New Mexico. Paleozoic limestones are abundant in Central America north and east of Tecuamburro and a few scattered outcrops of these limestones are found south of the Jalpatagua fault zone east of Tecuamburro. Although we acknowledge that pH, fO_2, and temperature can effect carbon-13 systematics in geothermal reservoirs (Ohmoto and Rye, 1979), it appears that much of the CO_2 in the geothermal prospect region could be derived by thermal decarbonation of limestones in "basement" rocks buried by Tertiary volcanic rocks.

GEOTHERMOMETRY

Subsurface reservoir temperatures have been calculated for thermal fluids of the Tecuamburro region using a standard suite of chemical and isotope geothermometers (Table 3). Steam-heated waters yield widely varying estimates from 39° to 323°C reflecting their dilute chemistry and the fact that they have not equilibrated in a high temperature environment. The most accurate estimate is probably given by the Na-K-Ca (β=4/3) temperature of 54° ± 13°C that is roughly the mean of the range of discharge temperatures for this group. Estimates derived from gases sampled at two sites within this group suggest that a reservoir or source of steam at 140° to 150°C may underlie the altered andesite highland.

Gases from acid-sulfate springs and from the sulfur mine near the summit of Tecuamburro yield estimated subsurface temperatures ranging from 160° to 300°C. Gases from Laguna Ixpaco, the most vigorous area of fumarolic activity, consistently yield the highest temperatures. Gases from lower pressure vents with smaller gas volumes yield lower temperature values possibly due to chemical alteration of gas compositions in the near-surface environment.

Calculated reservoir temperatures for the neutral-chloride springs of the Colmenares group range from 130° to 165°C. Estimates based on the quartz geothermometer are lowest reflecting the fact that these springs are mixed. Cation geothermometers yield a very tight range of 145° to 150°C. Estimates based on the ^{18}O-SO_4 geothermometer are slightly higher. Calculated reservoir temperatures for the other two sites of neutral-chloride springs show more extreme variations than Colmenares waters; the lone sample from the "SSE spring" yields the highest estimated reservoir temperature (≤205°C) although we realize that this estimate may be unreliable.

Because all neutral-chloride springs show evidence of mixing, it is no surprise that estimates based on quartz are less than cation estimates. If we assume that waters of the Colmenares group and the "SSE spring" are derived from a 300°C reservoir underlying the Tecuamburro-Laguna Ixpaco area, then cation ratios, particularly Na/K, have reequilibrated drastically as waters have moved from the reservoir to the hot spring sites.

Based on the geothermometers, no reservoirs of high temperature underlie the neutral-chloride spring sites and only the Laguna Ixpaco area appears to have the estimated subsurface temperature, and other geothermal characteristics suitable for exploration drilling.

RESERVOIR MODEL

We present two alternative reservoir models at this time but neither model affects our choice of location for a first exploration well (described below). In the first model, we assume that a liquid-dominated source reservoir of about 300°C underlies the Laguna Ixpaco area and has a low-pressure vapor cap not more than a few hundred meters thick. This reservoir feeds a large fan of lateral flow systems of hot, chloride-rich water to the north, east, and south. We envision that these flow systems would be isolated by a combination of structural and stratigraphic controls and that the flow systems feeding the Colmenares group and the "SSE spring" have different evolutionary paths. Mixing and

TABLE 3. SUMMARY OF VARIOUS GEOTHERMOMETERS, TECUAMBURRO REGION, GUATEMALA (temperatures in °C).

Description	Temp. Range (°C)	Silica[a]		Cation			$^{18}O-SO_4$			Gas	
		Qtz-Cond,	Chal	Na-K[a]	Na-K-Ca[b]	Na-Li[c]	T_1[d]	T_2[e]	T_3[f]	D-P[g]	N-B[h]
Laguna Ixpaco Area											
Laguna Ixpaco, average of 4	87-71	---	---	---	---	---	---	---	---	277 ± 27	316 ± 12
Las Playitas	33	---	---	---	---	---	---	---	---	192	271
Finca Chintera, average of 2	28	---	---	---	---	---	---	---	---	166 ± 1	263 ± 10
Summit of Tecuamburro											
Sulfur Mine, average of 3	95	---	---	---	---	---	---	---	---	192 ± 14	318 ± 8
Steam-Heated Region											
Steam-heated springs, average of 12	33-70	130 ± 28	103 ± 30	323 ± 60	54 ± 13	39 ± 23[i]	127 ± 16[j]	118 ± 14[j]	119 ± 14[j]	---	---
Gas, Finca San Lorenzo	42	---	---	---	---	---	---	---	---	140	139
Gas, Infernitos, average of 2	99	---	---	---	---	---	---	---	---	145 ± 25	262 ± 7
Neutral-Chloride Springs											
Colmenares area, average of 9	60-96	132 ± 3	105 ± 3	150 ± 4	145 ± 2	149 ± 4	165 ± 7[k]	152 ± 7[k]	155 ± 7[k]	---	---
East of Los Esclavos, average of 3[l]	37-42	153 ± 6	128 ± 7	186 ± 6	167 ± 4	138 ± 3	W.	W.	W.	---	---
SSE of Tecuamburro[l]	39	157	133	205	177	92	W.	W.	W.	---	---

[a]Fournier (1981).
[b]Fournier and Truesdell (1973).
[c]Fouillac and Michard (1981).
[d]McKenzie and Truesdell (1977), conductive cooling.
[e]McKenzie and Truesdell (1977), single stage steam loss.
[f]McKenzie and Truesdell (1977), continuous steam loss.
[g]D'Amore and Panichi (1980).
[h]Norman and Bernhardt (1981).
[i]Average of 6 analyses.
[j]Average of 2 analyses.
[k]Average of 3 analyses.
[l]W. means waiting for results.

reequilibration cause the estimated subsurface reservoir temperatures of these springs to be lower than the true reservoir temperature.

In the second model, we assume that two reservoirs exist within the Tecuamburro region; one beneath the Laguna Ixpaco area and one beneath the altered andesite highland near Infernitos. The two reservoirs are separated from each other by the major east-west fault shown in Fig. 1. The former reservoir has a temperature of about 300°C and feeds the "SSE spring" by a lateral flow system (that suffers reequilibration) and the latter reservoir has a temperature of about 160°C and feeds the Colmenares group by a second lateral flow system. Three geologic arguments support such a model: 1) The entire region is tectonically active, has high heat flow, and has late Pleistocene volcanism; 2) a major structural boundary does restrict fluid flow on the south side of the Colmenares group; and 3) Colmenares group springs can be observed to issue from major fractures in andesite along the west bank of Rio Los Esclavos trending in a N35W direction toward Infernitos.

Neutral-chloride springs east of Los Esclavos are not part of the Tecuamburro "reservoir." They are related to fluid flow and heating adjacent to or within the Jalpatagua fault zone and its nearby cluster of basaltic cinder cones.

EXPLORATION WELLS

We have picked two sites for exploration drilling to verify temperatures and to test our models. Regardless of the model, the first well should be drilled very close to Laguna Ixpaco to a depth of at least 700 m to test temperatures, stratigraphy, and fluid types. If the first well is successful, we believe the second well should be drilled to a depth of 700 m just north of Laguna Ixpaco and the east-west trending fault to test whether or not there is one geothermal system with outflow in many directions or two separate systems.

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