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AUTHOR(S): Fraser Goff,[1] Cathy Janik,[2] Lynne Fahlquist,[2] Andrew Adams,[1]
Alfred Roldan,[3] Mario Revolorio,[3] P. E. Trujillo,[1] and
Dale Counce[1]

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[1] Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, NM

[2] Branch of Igneous and Geothermal Processes, U.S. Geological Survey, Menlo Park, CA

[3] Unidad de Desarollo Geotermico, INDE, Guatemala City, Guatemala

MASTER

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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# A RE-EVALUATION OF THE MOYUTA GEOTHERMAL SYSTEM, SOUTHERN GUATEMALA

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[1]Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, NM
[2] Branch of Igneous and Geothermal Processes, U.S. Geological Survey, Menlo Park, CA
[3] Unidad de Desarollo Geotermico, INDE, Guatemala City, Guatemala

## ABSTRACT

Chemical and isotopic data from four fumarole sites combined with prefeasibility assessments obtained in the 1970s have resulted in a re-evaluation of the Moyuta geothermal system. Moyuta consists of an east-west trending complex of Quaternary andesite/dacite domes and flows cut by north-trending faults. Areas of fumaroles, acid springs, and bicarbonate-rich thermal springs flank the north and south sides of the volcanic complex. Chloride-rich thermal springs discharge along rivers at lower elevations around the Moyuta highland. The distribution of thermal features indicates that deep reservoir fluid rises convectively near the axis of volcanism. Geochemical data suggest that there are two subsystems having temperatures of about 210°C (north flank) and 170°C (south flank). Data extrapolations suggest a reservoir fluid containing about 2400 mg/kg Cl, with $\delta D = -48‰$, $\delta^{18}O = -6‰$, and a tritium content of 0.4 T.U. Exploration wells sited near the most northerly fumarole (Azulco) achieved temperatures of $\leq 113°C$ at 1004 m depth. We suggest the fumaroles occur above hydrothermal outflow plumes confined to vertical, fault-controlled conduits. Better drilling sites occur closer to the intersections of the north trending faults and the Quaternary volcanic axis.

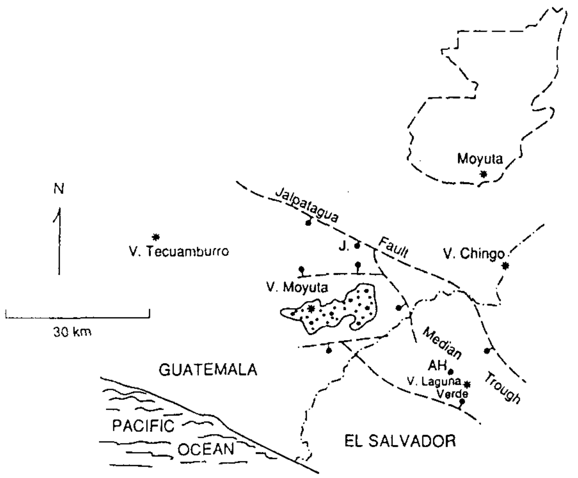

Fig. 1: Location map of Guatemala showing Moyuta volcano in relation to major tectonic features and adjacent Quaternary volcanoes; AH = Ahuchapán geothermal field; J = Jalpatagua.

## INTRODUCTION

In 1987 the Los Alamos National Laboratory (LANL), the U.S. Geological Survey (USGS), and the Instituto Nacional de Electrification (INDE) began a cooperative study of Guatemalan geothermal resources. Projects have included logging of existing production wells at Zunil I geothermal field (Adams et al., 1990), assistance with a DC resistivity survey at Amatitlán geothermal field, and a prefeasibility assessment of the Tecuamburro geothermal field (Goff et al., 1990; Heiken and Duffield, 1990). In 1990 INDE requested that the LANL-USGS hydrogeochemical team make a reconnaissance inspection of the Moyuta geothermal area to re-evaluate the geothermal potential and to suggest new sites for exploration drilling.

## BACKGROUND

The Moyuta geothermal area is located within the Central American volcanic arc in southern Guatemala (Fig. 1). Although Moyuta volcano has not erupted in historic time, it forms a prominent volcanic dome that is flanked by several hot spring and fumarole areas. Because Moyuta is the nearest Quaternary volcano in Guatemala to the producing Ahuachapán geothermal field in El Salvador and because the geologic setting of Moyuta is similar to Ahuachapán, Moyuta was the first geothermal area that was seriously explored in Guatemala (Einarsson, 1976). INDE and several foreign groups studied the Moyuta area through the mid-1970s (e.g., ELC, 1977).

Geology: Guatemala is located near a triple junction between the North American, Caribbean, and Cocos plates. In the Moyuta region, the Central American volcanic arc overlies a northeastward-dipping subduction zone between the Caribbean and Cocos plates. Differences in relative plate motions have created a complex, regional tectonic environment (Burkhart and Self, 1985). A series of right-lateral strike-slip faults define the boundary between the North American and Caribbean plates. Volcanism has been widespread and continuous since mid-Miocene time (Reynolds, 1987).

Moyuta volcano occurs on a highland that overlaps the southern boundary of the Jalpatagua Graben. This graben is the northwest extention of the Medial Graben (Central Depression) that stretches across the length of El Salvador on the northeast side of the volcanic arc (Ander et al., 1991). The northeast side of the graben is bounded by the Jalpatagua fault zone which has apparent right-lateral displacement and Holocene offsets further to the northwest (Duffield et al., 1989). Previous workers have stated that the Moyuta highland is a horst that is distinct from other structures southwest of the Jalpatagua Graben (ELC, 1976a).

Moyuta volcano lies in an east-west-trending belt of andesite/dacite domes and flows (Fig. 2). Because of the youthful morphology of this belt, Moyuta is thought to be late Quaternary in age although there are no dates on the volcanic products (Williams et al., 1964). Petrologic and geochemical studies show that these rocks are primarily porphyritic, two-pyroxene, calc-alkaline andesites although the latest domes are hornblende-bearing. A thick apron of andesitic tephra flanks the dome and flow complex. Because of the high rainfall in this area, tuffs are deeply weathered to saprolites and the steep terrain is covered with dense vegetation.

Beneath the Quaternary volcanic belt lies a thick sequence of volcanic rocks and associated laharic breccias, pyroclastic deposits, agglomerates, and sedimentary rocks of Miocene to Pliocene age. These rocks are predominately andesites and basaltic andesites. Beneath the volcanic rocks, isolated outcrops of Cretaceous limestones, shales, and granodiorites are exposed primarily near graben boundaries. Estimated depth to these basement rocks is roughly 1500 to 2000 m beneath Moyuta Volcano.

The youngest faults in the Moyuta area comprise a set of north-trending normal faults that cut across the Quaternary dome and flow complex. Locations of thermal features are apparently controlled by these faults. This is significant because other areas of geothermal potential in Guatemala (Tecuamburro, Amatitlán, Zunil) have normal faults of north and northeast trend that influence the boundaries and configuration of their geothermal systems (e.g. Foley, et al., 1990).

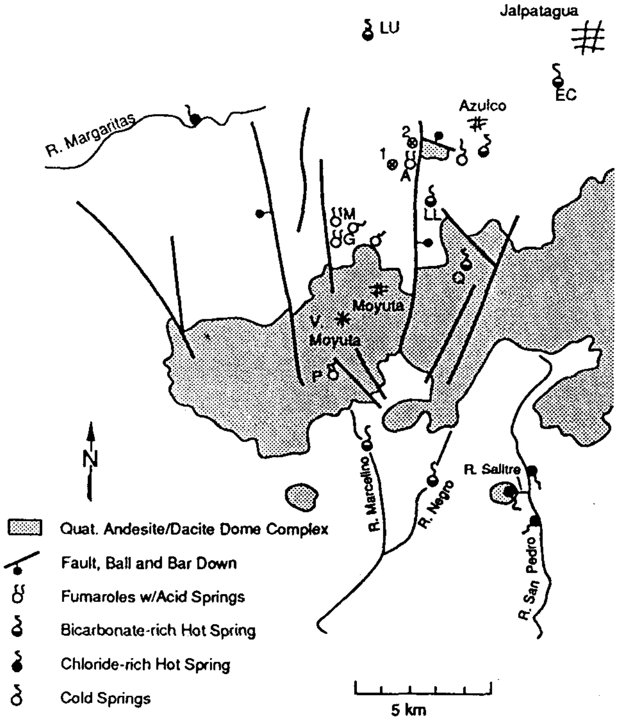

Fig. 2. Sketch map of Moyuta geothermal area (adapted from ELC, 1977) showing trend of east-west trending Quaternary dome and flow complex and faults cutting the Quaternary volcanics; A, G, M, and P = the fumaroles of Azulco, Guinea, Marcucci, and Padre Mariano, respectively; EC, LL, LU, and Q = bicarbonate-rich springs at El Cuje, Los Lomas, La Union, and Quebradona, respectively; 1 and 2 = exploration wells INDE-1 and INDE-2.

Thermal Features: The Moyuta dome and flow complex is flanked to the north and south by four areas of fumaroles and many areas of thermal, bicarbonate-rich springs (Fig. 2). Some springs in the fumarole areas are acid-sulfate, particularly at Padre Mariano. Low temperature, clay-rich alteration is abundant in these areas. Chloride-rich thermal springs are less common and occur only on the lower flanks of the Moyuta highland along rivers. The largest group of chloride-rich springs (30 to 80°C) discharges along the Rio San Pedro and tributaries several kilometers southeast of Moyuta.

The most impressive thermal feature is a large, slightly superheated fumarole at Azulco, the northernmost of the four fumarole areas. It is surrounded by an area of about two acres containing boiling springs that issue from a landslide in the side of a hill of hydrothermally-altered andesite (Fig. 3).

Fig. 3. Photograph of largest Azulco fumarole looking southwest; this feature apparently dominated the exploration efforts of earlier groups. Although slightly superheated, nearby INDE-1 was only 98°C at 1004 m depth.

Previous geochemical studies of Moyuta hot springs and fumaroles are difficult to use because of poor documentation of samples, poor location maps, and incomplete analyses (ELC, 1976b). Although all geothermal water types were recognized, no samples were analyzed for $SiO_2$, only sporadic data exists for B, Li, $NH_4$, and As, and few isotope samples were collected. Application of the Na-K-Ca geothermometer to the chloride-rich springs southeast of the volcano indicated subsurface temperatures of only 140°C. Thus, Azulco fumarole, with its impressive steam discharge and slightly anomalous concentrations of volatile components, looked like a good area for exploration wells.

Geophysics and Gradient Drilling: A gravity study (425 stations) covering an area of 200 $km^2$ was performed in the region between Moyuta and the Jalpatagua Graben, centered around Azulco fumarole (ELC, 1977). Data reduction used a density contrast of 2.67 $g/cm^3$. Modeling of the data was minimal. The gravity interpretation showed a series of east-west trending structures probably corresponding to buried, down-to-the-north faults marking the south side of the graben. These structures do not correspond with mapped faults or with thermal manifestations.

A variety of electrical methods were utilized, also centered around Azulco fumarole. Interpretation of this data indicated three small electrical resistivity lows generally overlying areas of fumaroles and bicarbonate-rich springs north of the volcano. The trends of these anomalies are northwest and northeast, and do not necessarily correspond with mapped faults. One of the anomalies occurs adjacent to the Azulco fumarole and the hills of exposed, altered andesite. These anomalies are probably related to shallow zones of clay-rich hydrothermal alteration.

Twelve shallow, thermal gradient wells (depth: 100 to 309 m, average depth: 170 m) were drilled north of Moyuta in an area of about 70 $km^2$ around Azulco fumarole. Gradients in ten of the wells ranged from 0 to 270°C/km with a maximum bottom-hole temperature of 73°C but the temperature profiles displayed many perturbations caused by shallow ground water circulation. Two wells were drilled in fumarole areas. At Azulco, well M-1 was isothermal at 114°C to a depth of 125 m because of superheated steam flow. At Guinea, well M-5 was 109°C at 134 m and had a bottom hole gradient of 870°C/km.

Exploration Wells: Two exploration wells, INDE-1 and INDE-2, were drilled in the area of Azulco fumarole from August 1976 to March 1977 in an attempt to discover a producible reservoir. INDE-1 was located about 1-1/4 km southwest of Azulco fumarole between two of the electrical resistivity lows and was drilled to a depth of 796.6 m. The well penetrated a sequence of andesitic flows, agglomerates, and associated sedimentary rocks displaying only mild hydrothermal alteration. Maximum temperature was 96°C at 675 m. Below this depth, temperature decreased. No significant fluid entries were encountered.

INDE-2 was drilled near gradient well M-1 in the immediate vicinity of Azulco fumarole to a depth of 1004.5 m. A similar sequence of andesite flows and agglomerates was penetrated and an andesite dike was encountered from about 900 to 965 m. Hydrothermal alteration was more pervasive but the rank was not high. Maximum temperature was 113°C at 200 m. Below this depth, temperature decreased to 75°C at 350 m. From this depth the temperature climbed gradually to 98°C at the bottom of the hole. Again, no major fluid entries were encountered.

A NE-SW cross-section from Azulco to Guinea using surface and well data was constructed by ELC (1977) and is reproduced in Fig. 4. The figure shows that hot fluids are confined to specific north-trending faults. Between these faults exist large regions of relatively cool rocks. The model used by ELC to explain these thermal features implies that a geothermal reservoir of 140 to 180°C exists at depths well below 1000 m. Fluids from the reservoir rise vertically up these faults and pool in the upper 200 m of rock to produce the "mushroom-shaped" isotherms drawn on the cross section. Based on the drilling results, development efforts at Moyuta ceased.

## RE-EVALUATION OF MOYUTA

Because of time and funding constraints our re-evaluation of Moyuta consists of interpretation of new data from samples collected at three cold springs and the four fumarole areas and integration of all available data into a more up-to-date model of the geothermal system.

Water Types: Thermal and non-thermal waters at Moyuta are easily subdivided into different types by their chemistry (Table 1). Non-thermal waters are dilute Ca-$HCO_3$ fluids with relatively low $SO_4$ and Cl, modest amounts of $SiO_2$ (from dissolution of volcanic glass) and low contents of trace elements (As, B, Br, and Li) that are usually enhanced in high-temperature reservoir waters. Anomalous concentrations of B and $NH_4$ are found in the cold spring at Finca El Pinto which is located a few hundred meters uphill (east) of Fumarole Marcucci.

Hot springs at the fumarole areas show all the variations common to such sites (White et al., 1971). Most springs are near boiling to slightly superheated and their discharge is small. Many of the springs, particularly the acid ones, are mud pots. Acid spring waters contain high $SiO_2$ and $SO_4$ concentrations. Generally speaking all springs have Ca + Mg > Na + K, low Cl, and low trace elements except for volatile species, $NH_4$ and B. Fumarole condensates are very dilute except for $HCO_3$ and, in one case, Na (probably from contamination).

Bicarbonate-rich thermal springs are abundant at Moyuta but, unlike the fumarole areas, they are only warm to moderately hot. Bicarbonate-rich waters are near neutral in pH, have $HCO_3 + SO_4 >> Cl$, and have Ca + Mg > Na + K. Except for a few B values that are slightly above background, no other trace element data are available.

It is now widely recognized that fumaroles, acid springs, and bicarbonate-rich springs like those found at Moyuta occur above liquid-dominated geothermal reservoirs and/or their outflow zones (Henley and Ellis, 1983). Where conduits are favorable, steam is boiled off the deep reservoir and rises to create fumaroles. Where conduits are less favorable, deep steam containing volatiles such as $CO_2$, $H_2S$, and $NH_3$ mixes with shallow groundwater to make acid-sulfate and bicarbonate-rich waters. Because near-surface reactions occur at temperatures ≤100°C, Ca + Mg commonly dominates over Na + K, particularly in volcanic host rocks of andesitic to basaltic composition. Trace element concentrations favored by high-temperature equilibration (As, B, Br, Li) are low in fumarole steam, acid-sulfate springs, and bicarbonate-rich springs of "steam-heated" origin.

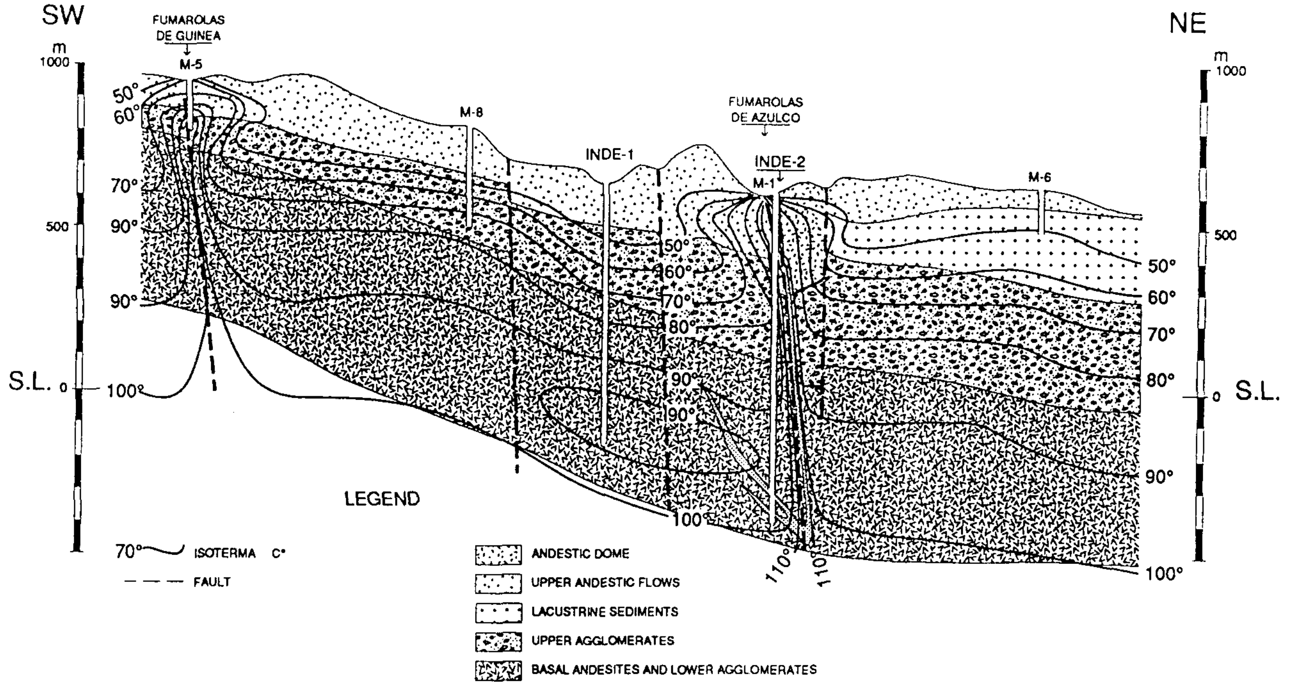

Fig. 4. Northeast-southwest cross section through the Azulco and Guinea fumarole sites; the isotherms imply that thermal fluids are confined to distinct, vertical, fault-controlled conduits (adapted from ELC, 1977).

Table 1: Chemical and isotopic data for selected cold springs, fumaroles, bicarbonate-rich springs, and chloride-rich springs, Moyuta geothermal area, Guatemala; values in mg/kg except where noted.

| Sample No. | Description | Temp (°C) | Field pH | $SiO_2$ | Na | K | Li | Ca | Mg | As | $HCO_3$ | $SO_4$ | Cl | F | Br | B | $NH_4$ | $\delta^{18}O$ (‰) | $\delta D$ (‰) | $^3H$ (T.U.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cold Springs[a] | | | | | | | | | | | | | | | | | | | | |
| GM-90-5 | South side of Pueblo Azulco | 25.0 | 5.9 | 61 | 6.8 | 1.7 | <0.01 | 11.4 | 4.1 | <0.05 | 76 | 1.2 | 1.7 | 0.03 | <0.05 | <0.05 | 0.13 | -7.49 | -47.4 | 3.91 |
| GM-90-6 | South side, Finca Buena Vista | 25.0 | 6.0 | 84 | 8.4 | 2.7 | <0.01 | 10.7 | 4.4 | <0.05 | 82 | 3.3 | 1.8 | 0.07 | <0.05 | <0.05 | 0.09 | -8.43 | -60.5 | 4.52 |
| GM-90-9 | Finca El Pinto | 29.0 | 6.5 | 71 | 10.0 | 4.6 | <0.01 | 10.9 | 4.5 | <0.05 | 76 | 11.3 | 2.6 | 0.13 | <0.05 | 0.64 | 0.41 | -6.99 | -51.0 | -- |
| Fumaroles[a] | | | | | | | | | | | | | | | | | | | | |
| GM-90-2a | "Frying Pan" Spring, Azulco[c] | 101.9 | 5.0 | 90 | 9.6 | 5.0 | <0.01 | 12.7 | 3.0 | <0.05 | 21 | 61.4 | 2.3 | 0.03 | <0.05 | 0.27 | 1.55 | -- | -- | -- |
| GM-90-2b | Condensate from above | 98.5 | 5.9 (ℓ) | 2 | 0.1 | <0.1 | <0.01 | 0.3 | 0.03 | <0.05 | 20 | 0.2 | 0.1 | <0.02 | <0.05 | <0.05 | 0.52 | -7.41 | -61.0 | -- |
| GM-90-3 | Spring M-46, Padre Mariano | 62.5 | 2.0 | 189 | 4.7 | 6.9 | <0.01 | 23.5 | 6.6 | <0.05 | 0 | 1125 | 1.5 | 0.06 | <0.05 | <0.05 | 5.86 | -1.94 | -39.0 | -- |
| GM-90-4 | Pool F-6, Padre Mariano | 48.0 | 3.5 | 113 | 18.3 | 4.1 | <0.01 | 37.6 | 11.4 | <0.05 | 0 | 220 | 1.8 | <0.02 | <0.05 | <0.05 | 1.88 | -4.78 | -43.3 | -- |
| GM-90-7 | Spring M-54, Guinea | 93.3 | 3.9 (ℓ) | 120 | 16.8 | 5.7 | <0.01 | 34.7 | 10.5 | <0.05 | 0 | 177 | 1.4 | 0.10 | <0.05 | <0.05 | 0.53 | -6.47 | -44.8 | -- |
| GM-90-8 | Fumarole Condensate, Guinea | 100.7 | 6.8 | 4 | 172 | 0.1 | 0.01 | 0.1 | 0.11 | <0.05 | 468 | 1.6 | 0.2 | 0.07 | <0.05 | 0.14 | 0.06 | -11.62 | -73.2 | -- |
| GM-90-10 | "Frying Pan" Spring, Marcucci[d] | 97.2 | 7.0 | 68 | 41.6 | 8.0 | 0.01 | 77.0 | 22.7 | <0.05 | 166 | 238 | 2.5 | 0.12 | <0.05 | <0.05 | <0.05 | -4.69 | -44.0 | -- |
| GM-90-11 | Fumarole Condensate, Marcucci | 98.6 | 5.5 | 3 | 18.1 | 0.1 | <0.01 | <0.1 | 0.02 | <0.05 | 60 | 1.9 | 0.2 | <0.02 | <0.05 | <0.05 | 0.21 | -7.67 | -55.5 | -- |
| Bicarbonate-Rich Springs[b] | | | | | | | | | | | | | | | | | | | | |
| M69 | Spring near Pueblo Azulco | 27 | 7.0 | -- | 52 | 3.6 | -- | 34 | 8.5 | -- | 310 | 4.0 | 11 | -- | -- | -- | -- | -- | -- | -- |
| HS120A | Spring near El Cuje | 40 | 6.0 (ℓ) | -- | 5.0 | 0.9 | -- | 88 | 4.1 | -- | 287 | 4.0 | 6.4 | -- | -- | 1.6 | -- | -- | -- | -- |
| M6 | Spring near Los Lomas | 42 | 7.5 (ℓ) | -- | 24 | 2.1 | -- | 90 | 16 | -- | 180 | 185 | 1.4 | -- | -- | 0.20 | -- | -- | -- | -- |
| M17 | Spring near La Union | 44 | 7.6 (ℓ) | -- | 22 | 7.3 | -- | 20 | 5.3 | -- | 131 | 17 | 1.2 | -- | -- | 0.20 | -- | -9.38[e] | -68.3 | -- |
| M9 | Spring at Quebradona | 61 | 7.0 (ℓ) | -- | 21 | 0.6 | -- | 114 | 26 | -- | 109 | 327 | 0.5 | -- | -- | 0.18 | -- | -- | -- | -- |
| 17M | Spring on Rio Negro | 39 | 6.6 (ℓ) | -- | 9 | 2 | -- | 97 | 30 | -- | 140 | 92 | 11 | -- | -- | -- | -- | -- | -- | -- |
| 22M | Spring on Rio Marcelino | 38 | 6.8 (ℓ) | -- | 24 | 7 | -- | 98 | 32 | -- | 180 | 74 | 11 | -- | -- | -- | -- | -- | -- | -- |
| Chloride-Rich Springs[b] | | | | | | | | | | | | | | | | | | | | |
| M35 | Spring on Rio Margaritas | 36 | 6.5 | -- | 50 | 17 | -- | 45 | 17 | -- | 64 | 29 | 64 | -- | -- | -- | -- | -- | -- | -- |
| 122R | Spring on Rio Salitre | 35 | 6.8 | -- | 140 | 19 | -- | 40 | 23 | -- | 89 | 12 | 220 | -- | -- | -- | -- | -- | -- | -- |
| ——[g] | Spring on U. Rio San Pedro | 75? | 7.2? | -- | 1010 | 33 | 1.50 | 22 | 6.7 | 4.9 | 306 | 214 | 1460 | 0.52 | -- | 29 | -- | -6.41[f] | -44.1[f] | 22 |
| ——[g] | Spring on L. Rio San Pedro | 67? | 7.2? | -- | 900 | 24 | 1.40 | 70 | 9.0 | 6.6 | 217 | 260 | 1370 | 0.49 | -- | 27.5 | 0.04 | | | 26 |

[a] Chemistry by P. E. Trujillo and D. Counce (LANL); stable isotopes by C. J. Janik, L. D. White, and L. Adami (USGS); tritium by H. Gōte Ostlund (U. Miami).

[b] Data from ELC (1976b).

[c] Steam from the largest fumarole at Azulco has T = 100.7°C, pH = 6.0, $\delta^{18}O$ = -11.6 ‰, $\delta D$ = -79.9 ‰ and $^3H$ = 0.39 T.U.

[d] The isotopic composition of condensed steam is $\delta^{18}O$ = -10.52 ‰ and $\delta D$ = -73.8 ‰.

[e] Average of three analyses; collection site of sample is unknown.

[f] Average of five analyses; collection sites of samples are unknown.

[g] Sample number, temperatures, and pH values for these samples are unknown; latter values are estimated from other analyses.

In contrast, the few chloride-rich waters of the Moyuta area are near neutral in pH but have Cl > $HCO_3 + SO_4$, Na + K > Ca + Mg, and anomalous concentrations of As, B, and Li. They are derivatives of neutral-chloride reservoir waters similar to those found in typical liquid-dominated geothermal systems. All chloride-rich waters in the Moyuta area are mixtures of reservoir water and various amounts of other groundwaters. They contain substantial Ca + Mg and tritium.

Gas Compositions: Major geothermal gas compositions listed in Table 2 are derived from duplicate samples collected in "caustic" gas bottles and analyzed at two different laboratories. Moyuta gases are typical of those evolved from geothermal reservoirs in volcanic host rocks. They are mostly $CO_2$ with lesser quantities of $H_2S$ and other components. $H_2$ and $CH_4$ contents are quite low. Air contamination occurs at both Azulco collection sites and at one Marcucci site. Even so, the air components at Azulco are unusual in that $N_2/O_2$ is much less than air. The reason for the relative $O_2$ excess is difficult to explain because $O_2$ is usually deficient due to greater reactivity.

Geothermometry: Standard chemical geothermometers cannot be used to evaluate the reservoir temperature of fluids from fumaroles, acid-sulfate springs, and bicarbonate-rich springs of steam heated origin because the fluids have not equilibrated with rock at high temperature (Fournier et al., 1981). For these areas, it is best to use the empirical gas geothermometer of D'Amore and Panichi (1980) who derived equations based on relative proportions of $CO_2$, $H_2S$, $H_2$, and $CH_4$ in drilled, high-temperature geothermal reservoirs. Calculation of subsurface equilibration temperatures yields 155 to 180°C (average = 167°C) for the Padre Mariano fumarole south of Moyuta and temperatures of 187 to 240°C for the three fumaroles north of Moyuta. Ignoring high and low values, the average temperature is 212 ± 6°C.

The warm springs on Rio Margaritas display extreme dilution and cannot realistically be used to evaluate source temperatures. Although silica values are not available, the high Na/K ratio (>10) indicates that the parent fluid of the Rio San Pedro springs is probably <200°C. Of the chloride-rich springs, valid calculations can only be made on the large group of springs along the Rio San Pedro. Using the data of ELC (1976b), 14 springs with discharge temperatures between 50 to 80°C yield an average subsurface equilibration temperature of 142 ± 15°C (range 120 to 170°C) using the Na-K-Ca($\beta = 1/3$) equation. The most concentrated spring on the Rio Salitre yields an estimated reservoir temperature of 188°C.

Springs of the Rio San Pedro group are southeast of Moyuta closest to the fumarole at Padre Mariano. Indicated reservoir temperatures from these two areas are in relatively close agreement. All fumaroles on the north side of Moyuta indicate reservoir temperatures that closely agree with each other and indicate a somewhat higher temperature than features on the south. Possibly, the Moyuta system contains two subsystems rising convectively on either side of the axis of late Quaternary volcanic vents.

Isotope Geochemistry: A plot of $\delta D$ versus $\delta^{18}O$ for Moyuta thermal and non-thermal waters is shown in Fig. 5. Only three cold springs from the area have been analyzed and two of them plot close to the world meteoric line. The third cold spring may be slightly evaporated but the chemistry indicates that it may be mixed with some condensed steam from Fumarole Marcucci. One bicarbonate-rich spring was analyzed by ELC (1976b) at La Union. It is

Table 2: Gas analyses of fumaroles, Moyuta geothermal area, Guatemala; values in mol-% dry gas.

| | Temp | | | | | | | | | | Total | $\delta^{13}C$-$CO_2$ | T(D-P)[a] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample No. | Description | (°C) | $CO_2$ | $H_2S$ | $H_2$ | $CH_4$ | $NH_3$ | $N_2$ | $O_2$ | Ar | He | (dry gas) | (‰) | °C |
| Analyses by C. J. Janik and L. Fahlquist | | | | | | | | | | | | | | |
| GM-90-1 | Largest Fumarole, Azulco | 100.7 | 74.07 | 1.815 | 0.223 | 0.011 | 0.103 | 18.03 | 5.521 | 0.386 | 0.00084 | 100.16 | -5.4 | 239 |
| GM-90-2 | "Frying Pan" Spring, Azulco | 101.9 | 48.21 | 1.003 | 0.110 | N. D. | 0.107 | 35.43 | 14.61 | 0.721 | N. D. | 100.19 | -6.0 | (213)[b] |
| GM-90-3 | Spring M-46, Padre Mariano | 62.5 | 95.62 | 0.027 | 0.036 | N. D. | 0.00048 | 4.3 | 0.024 | 0.013 | 0.00058 | 100.02 | -3.8 | (155)[c] |
| GM-90-4a | Fumarole near Pool F-6, Padre Mariano | 95.0 | 95.66 | 0.174 | 0.041 | 0.0019 | 0.0050 | 4.11 | N. D. | 0.0096 | 0.00056 | 100.00 | -3.55 | 177 |
| GM-90-4b | | 95.0 | 96.09 | 0.151 | 0.049 | 0.0085 | 0.0042 | 3.66 | 0.002 | 0.0074 | 0.00049 | 99.97 | -3.3 | 167 |
| GM-90-7 | Spring M-54, Guinea | 93.3 | 96.51 | 0.491 | 0.094 | 0.0015 | 0.00092 | 2.86 | 0.002 | 0.015 | 0.00038 | 99.98 | -4.0 | 209 |
| GM-90-8 | Fumarole, Guinea | 100.7 | 95.90 | 0.701 | 0.092 | N. D. | 0.0025 | 3.25 | N. D. | 0.024 | 0.00043 | 99.97 | -4.5 | (216)[d] |
| GM-90-10 | "Frying Pan" Spring, Marcucci | 97.2 | 96.08 | 0.638 | 0.132 | N. D. | 0.014 | 3.08 | N. D. | 0.036 | 0.00025 | 99.98 | -4.4 | (205)[e] |
| GM-90-11 | Fumarole, Marcucci | 98.6 | 90.76 | 0.846 | 0.135 | 0.0175 | 0.0079 | 7.12 | 0.975 | 0.110 | 0.00042 | 99.97 | -4.15 | 206 |
| Analyses by P. E. Trujillo and D. Counce | | | | | | | | | | | | | | |
| GM-90-1 | Largest Fumarole, Azulco | 100.7 | 84.66 | 0.834 | 0.248 | 0.109 | 0.022 | 10.52 | 3.309 | 0.242 | 0.067 | 100.02 | -- | 208 |
| GM-90-2 | "Frying Pan" Spring, Azulco | 101.9 | 71.99 | 0.521 | 0.082 | <0.01 | 0.031 | 19.62 | 7.22 | 0.398 | 0.313 | 100.18 | -- | (187)[b] |
| GM-90-3 | Spring M-46, Padre Mariano | 62.5 | 95.63 | 0.020 | 0.039 | 0.0013 | <0.0003 | 4.25 | 0.022 | 0.011 | 0.016 | 99.99 | -- | 156 |
| GM-90-4 | Fumarole near Pool F-6, Padre Mariano | 95.0 | 96.02 | 0.154 | 0.041 | 0.0011 | <0.0003 | 3.77 | 0.003 | 0.0027 | N. D. | 99.98 | -- | 179 |
| GM-90-7 | Spring M-54, Guinea | 93.3 | 96.31 | 0.820 | 0.097 | 0.0009 | <0.0003 | 2.75 | <0.0009 | 0.012 | 0.0083 | 99.69 | -- | 221 |
| GM-90-8 | Fumarole, Guinea | 100.7 | 95.89 | 0.954 | 0.099 | 0.0009 | <0.0009 | 3.00 | <0.0009 | 0.017 | 0.0073 | 99.93 | -- | 223 |
| GM-90-10 | "Frying Pan" Spring, Marcucci | 97.2 | 96.00 | 0.800 | 0.143 | <0.001 | 0.0041 | 3.04 | 0.0067 | 0.0195 | N. D. | 99.97 | -- | (210)[e] |
| GM-90-11 | Fumarole, Marcucci | 98.6 | 93.11 | 0.946 | 0.121 | <0.002 | <0.003 | 5.11 | 0.595 | 0.078 | N. D. | 99.96 | -- | (209)[e] |

[a] D'Amore and Panichi (1980) assuming $\beta = 0$ and $P(CO_2) = 1$ atm in all cases.

[b] $CH_4$ assumed to be 0.05 mol-%.

[c] $CH_4$ assumed to be 0.002 mol-%.

[d] $CH_4$ assumed to be 0.001 mol-%.

[e] $CH_4$ assumed to be 0.01 mol-%.

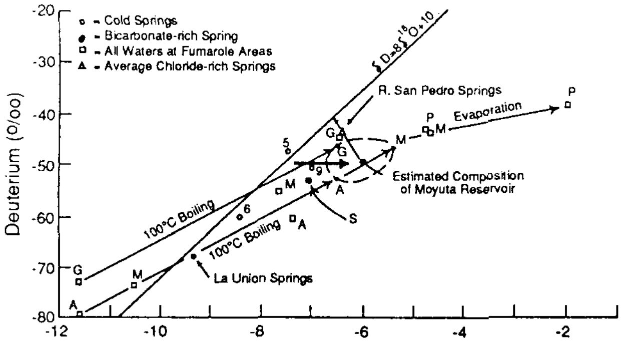

Fig. 5. Plot of deuterium versus oxygen-18 for thermal and non-thermal waters at Moyuta geothermal system, Guatemala; dark horizontal line shows approximate direction of isotopic shift of Moyuta reservoir water from local meteoric water. Point S represents the isotopic composition of the deep fluid if it is assumed that heat is lost by single-step steam separation by boiling during ascent from a reservoir at 210°C to hot springs at 100°C (see text). The vector from Moyuta reservoir water through R. San Pedro hot spring water is a mixing line.

isotopically depleted compared to the three cold springs yet La Union water also falls on the meteoric water line. This suggests that the water at La Union is recharged from a higher elevation than the cold springs or it contains a large component of condensed steam with an isotopic composition similar to condensates from the northern fumarole areas.

Waters from the fumarole areas show a wide range in isotopic composition. Some of the hot pools, like both samples from Padre Mariano and one sample from Marcucci, are enriched in $\delta^{18}O$ and $\delta D$ due to loss of water vapor by surface evaporation. Three of the fumarole condensates (from the north side of Moyuta) display extreme isotopic depletion by about the same magnitude. The composition of water in equilibrium with this steam can be estimated using fractionation data from Truesdell et al. (1977) and assuming single-step separation at 100°C. The dashed cloud represents the calculated range in composition of the residual water. Three other fumarole samples show less depletion indicating a complex mixture of surface water and steam from a deep source or from boiling surface water. If we assume conductive cooling of deep fluid from a maximum temperature of 210°C to near-surface temperatures of 100°C, the isotopic composition of the geothermal reservoir providing steam to the three fumaroles north of Moyuta is roughly -48‰ $\delta D$ and -6‰ $\delta^{18}O$. These calculations represent a modest oxygen-18 "shift" of up to +1.5‰ relative to local meteoric water. An alternative interpretation is to assume that heat is lost by single-step steam separation by boiling during ascent from a reservoir at 210°C to hot springs at 100°C. The isotopic composition of the deep fluid would be about -53.5‰ $\delta D$ and -7‰ $\delta^{18}O$ (point S in Fig. 5). The tritium content of the deep fluid by either interpretation, as measured in condensed steam from the Azulco fumarole, is 0.39 T.U.

As mentioned above, the chloride-rich springs on the Rio San Pedro are mixtures of deep reservoir fluid and near-surface groundwater. If we assume that the thermal fluid of the Rio San Pedro Springs is isotopically similar to our estimated reservoir fluid composition and if we assume conductive cooling and boiling, it can be seen from Fig. 5 that the cool groundwater involved in mixing is isotopically heavier than recharge water to the reservoir. Because the Rio San Pedro hot springs issue at significantly lower elevation than cold springs near the fumaroles, it is very likely that the cool component is derived near the discharge area of the springs.

Two Rio San Pedro hot springs were analyzed for tritium content in the early 1970s (ELC, 1976b). Both springs contained greater than 20 T.U. implying that the cool component involved in mixing is quite young. Tritium in Central American rain reached a maximum weighted mean value of about 60 T.U. in 1963 (Goff et al., 1987, p. 16) thus, the cool end-member of the Rio San Pedro hot springs is ≤10 y old. To estimate the chloride content of the source reservoir fluid, tritium content is plotted versus chloride of the hot springs (Fig. 6). The resulting line is extrapolated to a value of 0.4 T.U. (the tritium content of condensed steam at Azulco fumarole), and yields an estimated chloride content of the Moyuta reservoir fluid of about 2400 mg/kg. This value is typical of the chloride contents of geothermal reservoirs hosted in Quaternary volcanic centers (range about 400 to 10,000 mg/kg Cl, Fournier, 1981). Extrapolating the mixing line of Fig. 6 to O mg/kg Cl yields a tritium content of the cool end member of roughly 55 T.U.

Model of Moyuta Reservoir: Our model of the Moyuta geothermal reservoir is shown schematically in Fig. 7. It is based on the results of our work, the data of previous studies, and models developed for successfully exploited geothermal reservoirs in other Quaternary "arc" andesitic volcanos (Henley and Ellis, 1983). In this model the geothermal reservoir is recharged locally and heating of fluids to reservoir temperatures occurs near the axis of Quaternary andesitic vents forming the east-west trending dome and flow complex. Quite likely, a compound feeder dike exists at depth that utilizes a pre-existing structure for repeated eruptions of andesitic/dacitic magma.

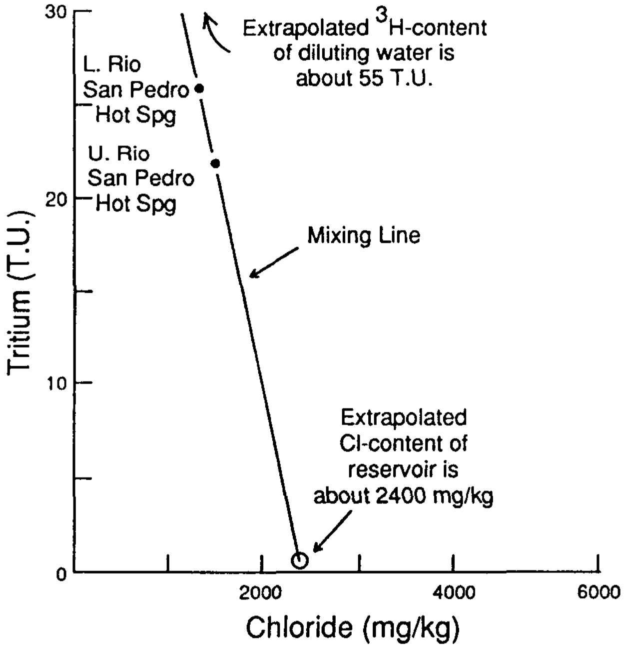

Fig. 6. Plot of tritium versus chloride content, Moyuta geothermal system, Guatemala.

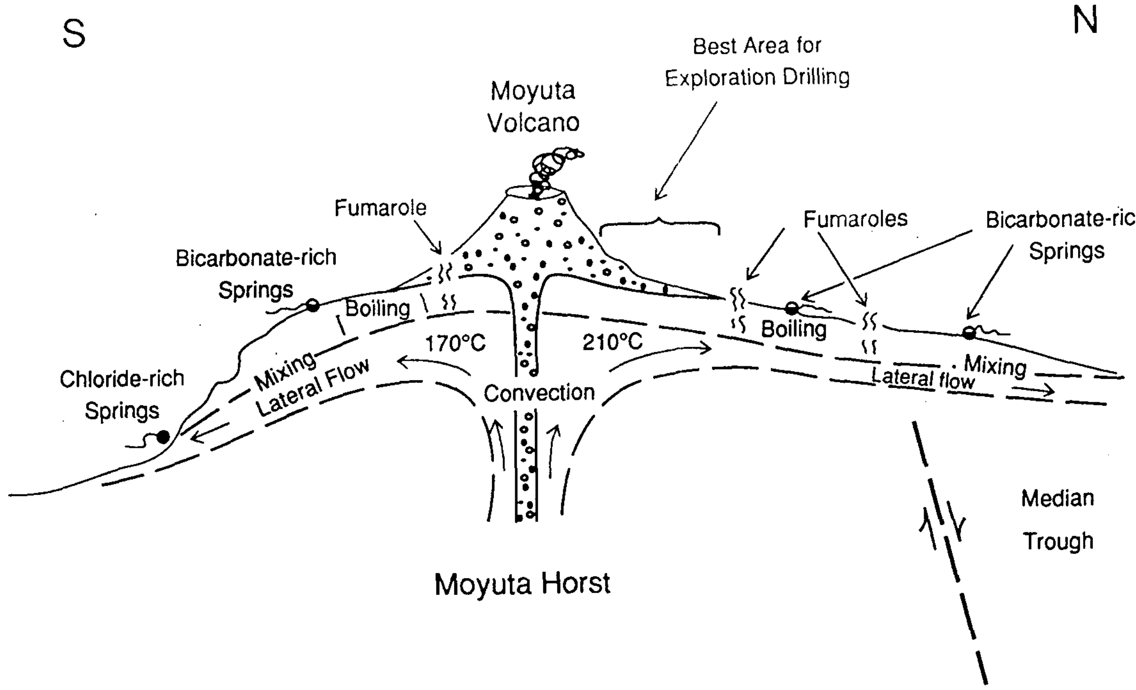

Fig. 7. Schematic cross section of Moyuta geothermal system showing configuration of reservoir and hot springs relative to the axis of Quaternary magma conduits and to major structural features; although lateral flow is an essential characteristic of the system it is apparently channeled along discrete, north-trending faults (see Figs. 2 and 4).

That the Moyuta "reservoir" lies on both sides of the dome and flow complex is difficult to deny. The distribution of fumaroles, bicarbonate-rich springs, and chloride-rich springs is "classic." These features are formed by subsurface boiling of reservoir fluids and condensation/reaction of steam and acid gases with near surface groundwaters. Convection and lateral flow of deep reservoir fluid occurs to the north and south (see also, Janik et al., 1983). Reservoir fluids in the outflow plumes mix with local groundwaters and discharge at lower elevations as chloride-rich fluids of mixed composition. Probably, there are at least two subsystems to the overall reservoir; one on the south at about 170°C and one on the north at about 210°C.

The schematic cross-section of Fig. 7 does not depict an important aspect of the northern subsystem that was discovered by earlier exploration drilling. Lateral flow is localized and directed along north-trending faults. Between these faults, fluid flow is minimal and local recharge is probable. Lateral flow of reservoir fluid along vertical, fault-controlled conduits is observed at other geothermal systems, such as Valles caldera, New Mexico and Bacon-Manito, Philippines (Goff et al., 1988). In such systems, isotherms are depressed rapidly on either side of the vertical conduit (e.g. Goff et al., 1988, Figs. 3 and 4). Clearly, the best drilling sites in such a system are near the axis or center of the heat source and/or along a fault between the heat source and the fumaroles. Although Azulco fumarole is the most impressive fumarole at Moyuta, it is furthest from the heat source and drilling penetrated the outflow of the reservoir.

## CONCLUSIONS

There are several conclusions that we wish to make regarding this re-evaluation of the Moyuta geothermal system:

1. The heat source of Moyuta is an east-west trending dome and flow complex that has resulted from several late Quaternary eruptions of andesitic to dacitic magma;
2. The configuration of thermal features is "classic" with fumaroles, acid springs, and bicarbonate-rich springs above the reservoir and with chloride-rich mixed springs at lower elevations near the terminus of the outflow plumes. The symmetry of the Moyuta system implies that it is comprised of two subsystems, one flowing north and one flowing south.
3. Evaluation of new and previous geochemical data indicates that the northern reservoir has equilibrated at about 210°C while the southern reservoir is equilibrated at roughly 170°C. Data extrapolations and calculations suggest that the reservoir fluid contains about 2400 mg/kg Cl and has $\delta D = -48‰$ and $\delta^{18}O = -6‰$. Analysis of fumarole steam yields a tritium value of about 0.4 T.U.
4. Although lateral flow is an essential element of the Moyuta geothermal system(s), fluids are confined to fault controlled vertical conduits much like the outflow plume of Valles caldera, New Mexico.
5. The best areas for exploration drilling are between the axis of the volcanic complex and the fumaroles flanking this complex. We would select sites along fault and fracture zones on the north side of Moyuta (Fig. 7) to intercept the hotter of the two subsystems.

6. The general characteristics of the Moyuta model are similar to many geothermal systems associated with Quaternary andesitic volcanoes. Within Guatemala both the Amatitlán system (Pacaya volcano) and the Tecuamburro system (Tecuamburro volcano) have similar configurations although structural features are different. Exploration drilling should follow a similar logic.

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