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Geology of the Azacualpa Geothermal Site, Departamento de Comayagua, Honduras, Central America

Field Report

The Azacualpa Site Geology Team

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PLATES

EXECUTIVE SUMMARY

Investigation of the Azacualpa geothermal site is part of a joint Honduras (Empresa Nacional de Energía Eléctrica)/United States (Los Alamos National Laboratory and U.S. Geological Survey) assessment of geothermal resources in Honduras. This assessment is part of the Central American Energy Resources Project being sponsored by the U.S. Agency for International Development.

Azacualpa was selected as one of the initial sites for detailed study on the basis of geothermal reconnaissance work done in Honduras over the last 10 years. The purpose of this geological study was to make a preliminary evaluation of the geothermal system to determine if further investigations by geochemical, geophysical, and drilling techniques are justified.

The geothermal site is located in the central part of western Honduras on the Río Jaitique, approximately 100 km northwest of Tegucigalpa. The site, which consists of several hot springs, is heavily forested with canyons up to 100 m deep. The earth's crust in this region appears to be highly fractured and thinned, possibly due to crustal extension, which would make the Azacualpa site similar to geothermal sites being developed in the western United States. The hot springs at the Azacualpa site rise to the surface along segments of the Zacapa fault (Finch, 1972, 1979). Base temperatures, reported by Goff et al. (1986) are 180°-190°C, and estimated thermal power output is ~4.4 MW.

Our findings indicate that Azacualpa has good potential for development as an electrical power source. We recommend that a detailed geophysical study be done to further define the subsurface geology, fracture systems, and location of potential geothermal reservoirs. This information will be used to site geothermal gradient holes. A determination of the feasibility of drilling an exploration well will be based upon information acquired from the geothermal gradient holes. The realistic energy potential of the site will be demonstrated only when an exploration well has been drilled and the characteristics of the reservoir tested.

GEOLOGY OF
THE AZACUALPA GEOTHERMAL SITE,
DEPARTAMENTO DE COMAYAGUA, HONDURAS, CENTRAL AMERICA

Field Report

by

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Los Alamos National Laboratory	Empresa Nacional de Energía Eléctrica	Tennessee Technological University
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ABSTRACT

Thermal waters at the Azacualpa geothermal site are surfacing along fractures in the Atima Formation associated with the main north-south-trending Zacapa fault and the subordinate north-south-trending splays of the main fault. Permeability appears to be related to these fractures rather than to formation permeability in either the limestone of the Atima Formation or the Valle de Angeles Group red beds. Attitudes of lower Valle de Angeles Group red beds do not vary appreciably with distance away from the Zacapa fault, suggesting that the fault system is not behaving like a listric normal fault at depth. The "Jaitique structure," as conjectured by R. Fakundiny (1985), does not appear to have any manifestation at the surface in terms of structures that can be seen or measured in the bedrock. Its existence is considered unlikely at the present time. Calorimetry calculations indicate that the thermal anomaly at the Azacualpa site is producing ∼4.4 thermal megawatts.

I. INTRODUCTION

The geology of the Azacualpa geothermal site was investigated by a joint team of Los Alamos National Laboratory, Empresa Nacional Energía Eléctrica (ENEE), and Tennessee Technological University, July 18-25, 1985. The objectives of the investigation were (1) to describe the thermal springs in the Azacualpa area; (2) to determine the presence and behavior of subordinate or sympathetic faults parallel to the Zacapa fault (Finch, 1972) upstream along the Río Jaitique from the main spring site (known as "La Cueva"); (3) to determine whether the Zacapa fault flattens at depth; (4) to determine if the "Jaitique structure," postulated by R. Fakundiny (1985), controls the course of the Río Jaitique and is responsible for the presence of subsidiary hot springs at the Agua Caliente site in the Río Ulúa and along the Río Gualcarque southeast of San Francisco de Ojuera; (5) to determine if permeability in the reservoir rocks is the result of formation properties or of fractures caused by young, normal faulting; and (6) to make recommendations for the geophysical investigations to be carried out in the spring of 1986.

A. Regional Setting (Adapted from Heiken et al., 1986)

The Azacualpa site lies in central Honduras on the northwest corner of the Caribbean plate, the Chortis block (Fig. 1). This block of Paleozoic and younger continental crust (Fig. 2) is bounded on the north by the Caribbean-America plate boundary, the sinistral Bartlett/Cayman trough system and its landward extensions, the Motagua and Polochic faults. To the west and south, the Cocos plate is moving northeastward from the East Pacific rise and is being subducted under the Caribbean and America plates along the Middle America Trench. The Chortis block is terminated on the east and south by a region of younger crust of oceanic affinities in Nicaragua (Malfait and Dinkelman, 1972; Case and Holcombe, 1980). A detailed discussion of the tectonic history of this region is beyond the scope of this report, but the reader is referred to Anderson and Schmidt (1983) and Burkart and Self (1985).

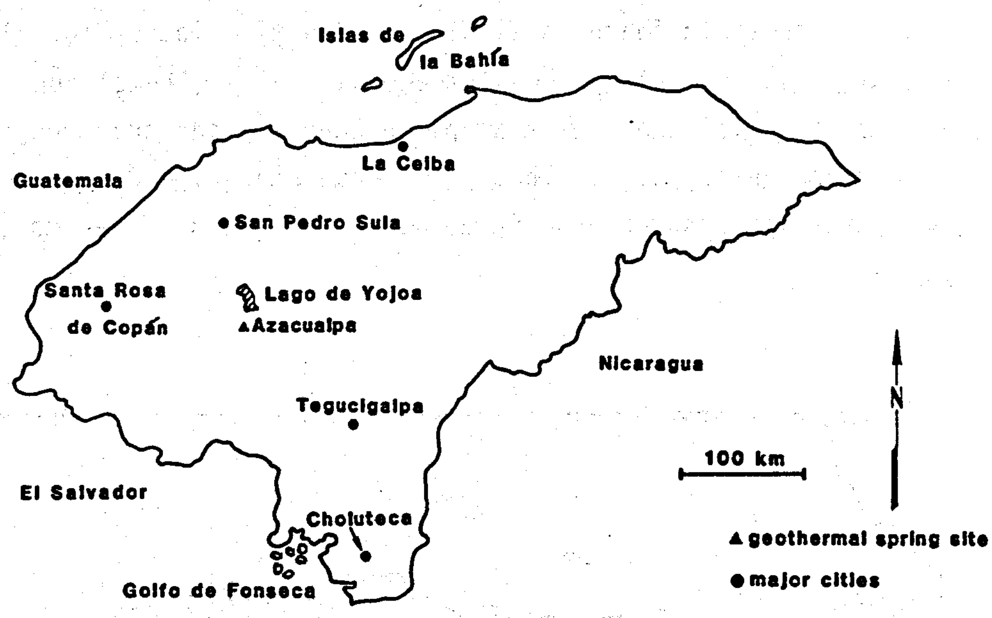

Figure 1. Location of the Azacualpa geothermal spring site.

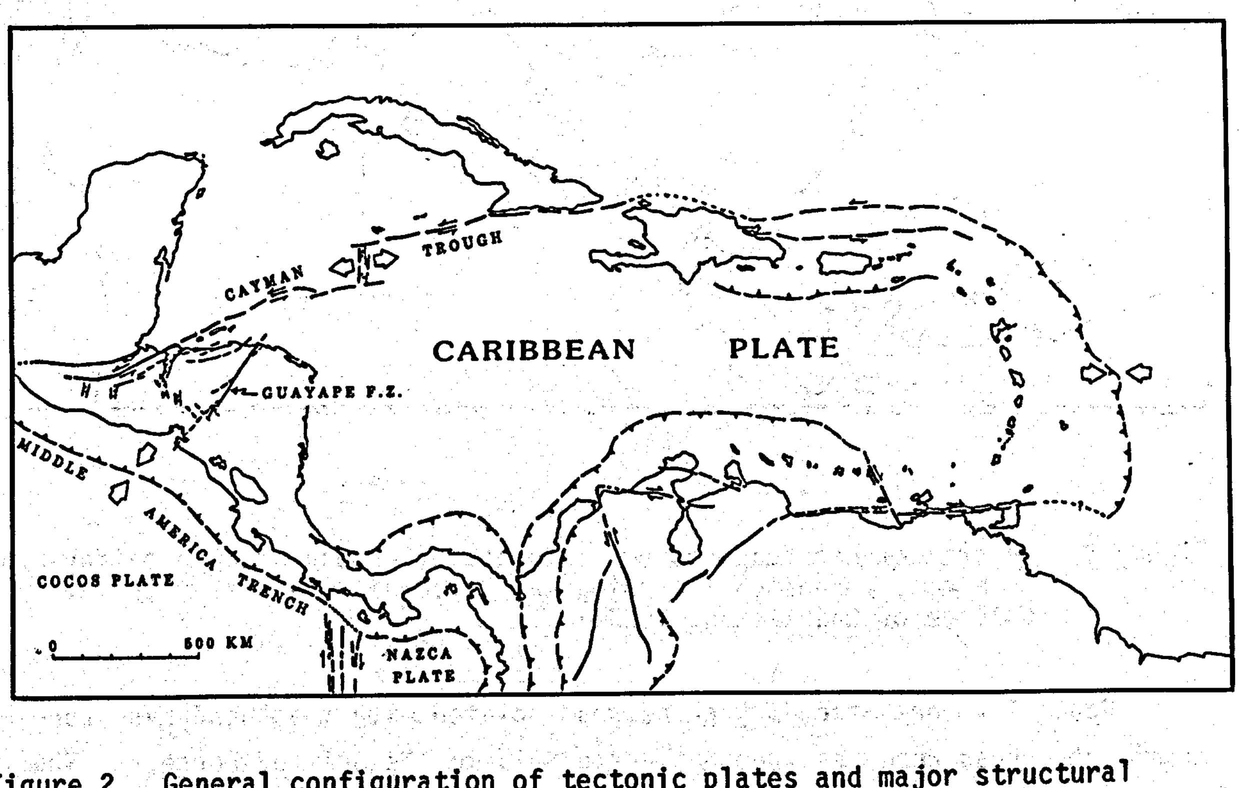

Figure 2. General configuration of tectonic plates and major structural features in the Caribbean Basin (modified from Case and Holcombe, 1980).

Principal tectonic features within the Chortis block (Fig. 3) include a number of east-west to east-northeast-trending faults (Chamelecón, La Ceiba, Aguán) that subparallel the sinistral plate boundary and are thought to be part of, or older analogues to, that plate boundary. The Guayape fault of eastern Honduras may also be associated with this group of faults (Ritchie and Finch, 1984).

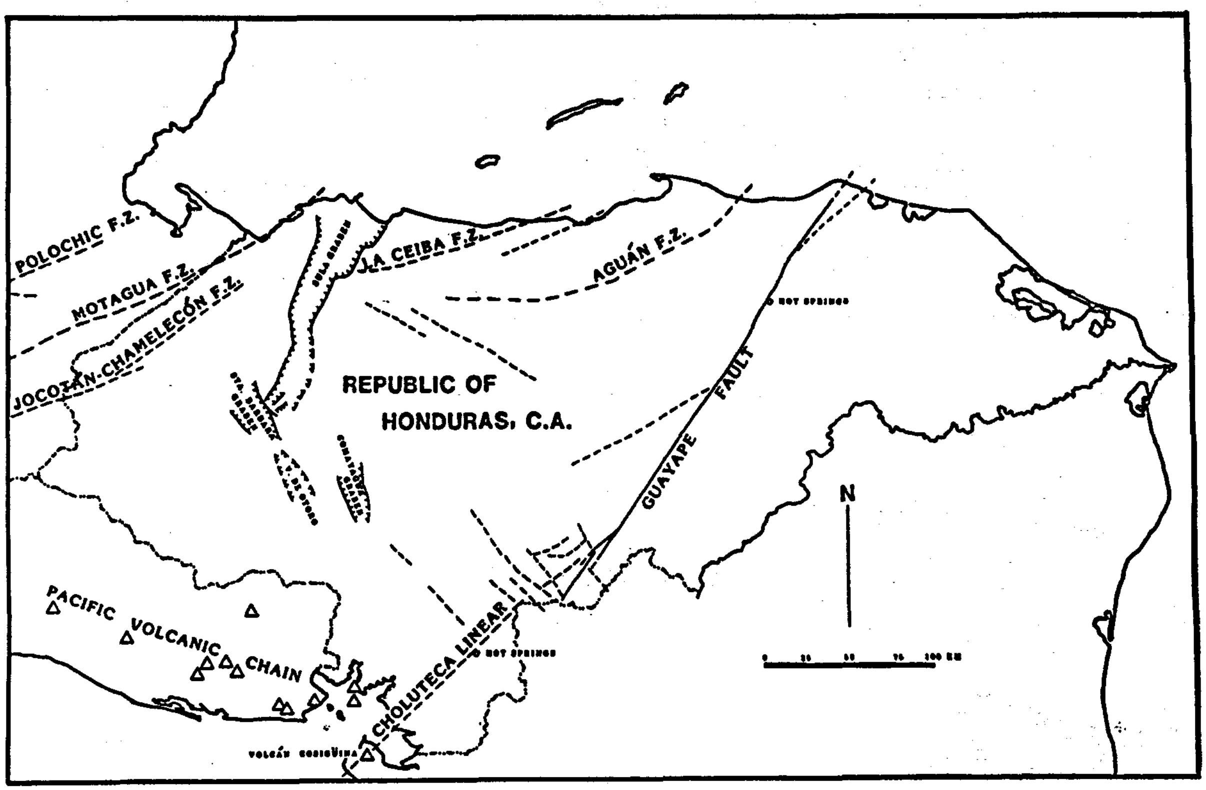

Figure 3. Major tectonic features of Honduras. (Personal communication from R. Finch, Tennessee Technological University, and A. Ritchie, College of Charleston, 1985.)

Generally north-trending grabens associated with the "Honduras Depression" cut across Honduras from San Pedro Sula to the Gulf of Fonseca. The faults bounding these grabens as well as a host of other faults throughout Honduras average a northerly strike but are stepped along northeast- and northwest-trending faults that are dominantly normal-slip but also have small strike-slip components. Plafker (1976) suggested that the northwestern corner of the Caribbean plate is fragmenting along north-trending extensional features of which the Honduras depression is the easternmost. This fragmentation results from this portion of the plate being pinned between the Cocos and América plates as eastward movement of the rest of the Caribbean plate continues (Fig. 2). The initiation and greatest movement of the graben faults are associated with the eruption of the Padre Miguel Group tuffs in the Miocene and Pliocene, although some minor adjustment on the faults may continue today. The east-west extension responsible for the graben implies north-trending relative maximum principal stress that suggests a sinistral component of motion on the associated northeast faults and a dextral component on the northwest faults. In addition to the graben and associated block faulting, this same extension has very likely produced crustal thinning in the region. This regional setting suggests an analogy to the Basin and Range province of the United States.

Finally, the Pacific volcanic chain lies well to the south of the Azacualpa site. Subduction along the Middle America Trench has been responsible for a long history of volcanism in Honduras, although there are no active volcanoes within the Republic. Mid-Tertiary basalts of the Matagalpa Formation were followed by the widespread and voluminous silicic tuffs of the Mid- and Late-Tertiary Padre Miguel Group. Some young, possibly Quaternary to Recent basaltic volcanism occurred in Honduras, principally along the Honduras Depression from Tegucigalpa to the north coast.

The Azacualpa site is clearly affected by faulting associated with the regional extension. In the 10 km^2 around the site, north-trending faults dominate the structure. Although northeast- and northwest-trending faults are common throughout the San Pedro Zacapa Quadrangle (Finch, 1979), the north-trending normal faults are the youngest and the most open. Northeast- and northwest-trending faults are generally somewhat older and also normal, but with a sinistral component of slip on the northeast and a dextral component on the northwest faults.

B. Stratigraphy

The details of the stratigraphy of Honduras are not well known principally because of poor bedrock exposure and closely spaced faulting. The best available description is that of Finch (1981), whose data, along with those of Mills et al. (1967), are reproduced as Fig. 4.

The oldest unit exposed on the Chortis block is a basement complex of low-rank metamorphic rocks consisting of dominant dark phyllite with lesser amounts of schist, quartzite, carbonate, and intrusive rocks. These rocks have been variously termed Cacaguapa Schist, Petén Schist, or simply "basement" and are generally assumed to be of Paleozoic age.

The basement rocks are overlain by a section of both red and non-red clastic units that underlie the Yojoa Group limestone. These strata include the El Plan Formation, the Todos Santos Formation, and the "Agua Fría Formation" (Horne and Finch, 1985). Horne and Finch (1985) propose the name "Honduras Group" for all clastic units on the Chortis block that overlie crystalline basement and predate the Aptian-Albian Atima Formation. Ritchie and Finch (1985) demonstrate a Jurassic age for at least part of the Honduras Group.

The Yojoa Group consists primarily of Atima Formation, up to 1400 m of dark, thick-bedded limestone, and locally the Mochito Shale and the Cantarranas Formation, a shaly limestone. The Atima Formation is an excellent marker, for it is the only thick limestone in the section and is a prominent ridge-former.

The Cretaceous-Tertiary Valle de Angeles Group consists of a great thickness of red clastic strata with conglomeratic layers common in the lower part of the unit and generally absent in the upper. Two relatively thin carbonate units are included in the Valle de Angeles Group and Yojoa Group limestones.

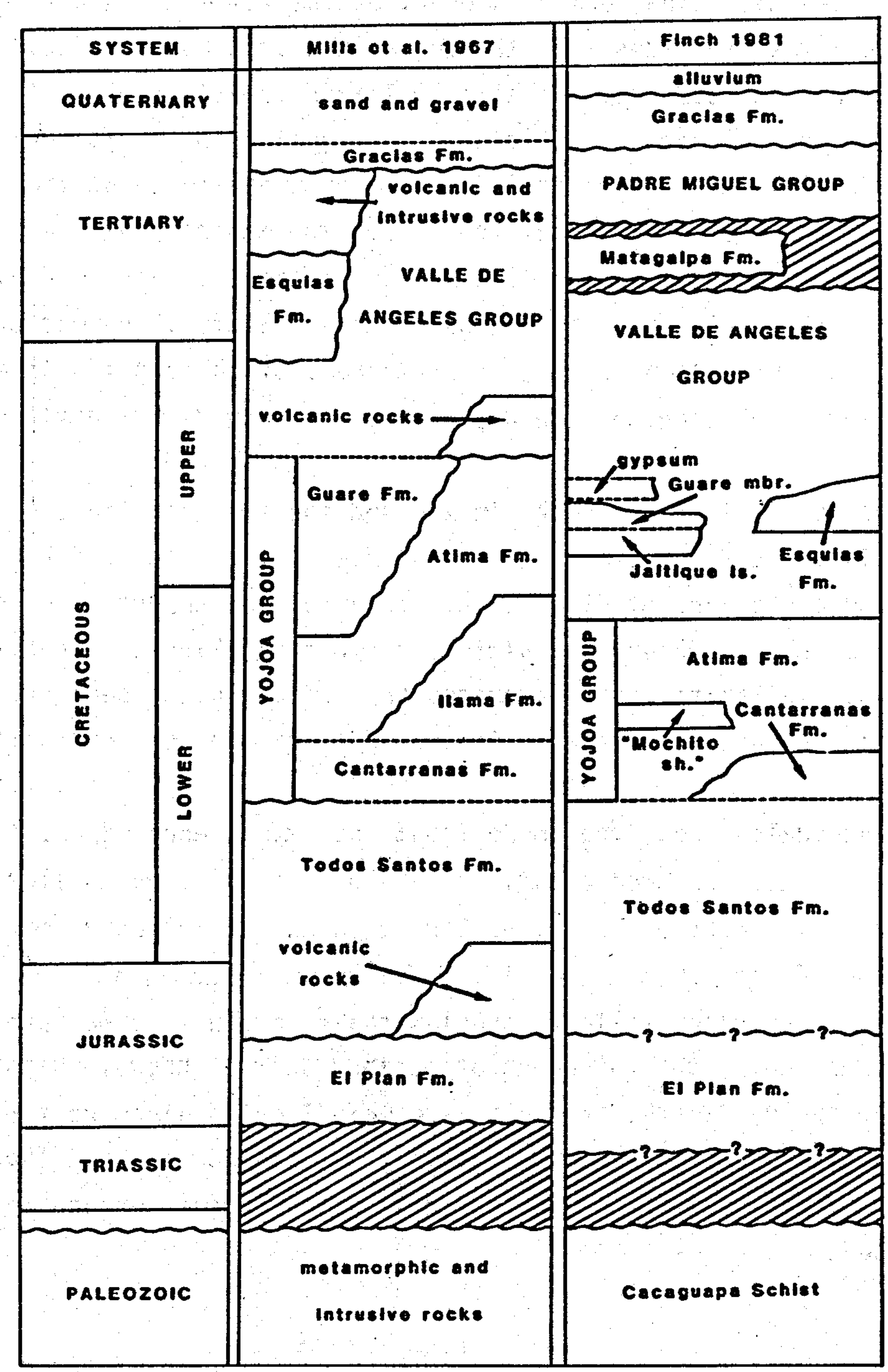

Figure 4. Generalized stratigraphic column for Honduras (after Mills et al., 1967, and Finch, 1981).

The Tertiary Matagalpa Formation overlies the Valle de Angeles Group. These basaltic lavas are widespread throughout Honduras but are locally absent from the section. At least some basaltic volcanism continued into the time of the eruption of the voluminous, silicic Padre Miguel Group tuffs and associated volcaniclastic sediments. There is some debate about the maximum and minimum ages of the Padre Miguel Group, but the majority of the tuffs appear to have been erupted in the Miocene and Pliocene. The Padre Miguel tuffs were erupted over a surface of considerable relief, which was undergoing active block faulting. As a result, the thickness of these tuffs is extremely variable, making projections of the depth to underlying strata difficult, if not impossible.

The youngest sedimentary rocks in the section are the Pliocene-Pleistocene clastic sediments and reworked tuffs of the Gracias Formation and alluvium in various stages of dissection. In a region subjected to long-term block faulting, such as Honduras, multiple periods of alluvial deposition are to be expected. Valley-fill conglomerates are common in the section, many as old as mid-Tertiary and associated with the initiation of the extensional faulting.

In the Azacualpa area, the predominant rock types exposed are limestones of the Atima Formation and red clastic strata of the Valle de Angeles Group, with minor volcanic rocks of Matagalpa Formation and an intrusive microdiorite of Tertiary age (Finch, 1972; see Table I for chemical analysis). Because of the juxtaposition of upper Valle de Angeles shales against Atima Formation along the Zacapa fault, the thickness of neither unit is known. With one exception, the springs in the Azacualpa area are located along north-south faults or are exiting from fractures within the Atima Formation. The sole exception is at spring site AC-2, which forms a travertine terrace on Valle de Angeles red beds.

TABLE I. Chemical Analysis of Sample AC-1 [from the Unit Mapped by Finch (1972, 1979) as Lavanderos Diorite]

Species	Input Weight (%)	Calculated Cation (%)	Normalized Weight (%)	Mineral	Cation (%)	Weight (%)
SiO_2	68.14	65.37	70.24	QZ	27.83	29.01
TiO_2	0.37	0.27	0.38	CO	2.80	2.48
ZrO_2	0.00	0.00	0.00	ZN	0.00	0.00
Al_2O_3	15.76	17.82	16.25	OR	16.77	16.19
Cr_2O_3	0.00	0.00	0.00	PL	45.30	41.94
Fe_2O_3	0.73	0.52	0.75	AB	32.27	29.36
FeO	1.52	1.22	1.57	AN	13.03	12.57
MnO	0.03	0.02	0.03	HY	5.81	5.46
MgO	1.53	2.19	1.58	EN	4.38	3.81
CaO	2.64	2.71	2.72	FS	1.44	1.64
Na_2O	3.47	6.45	3.58	MT	0.79	1.05
K_2O	2.74	3.35	2.82	IL	0.53	0.70
P_2O_5	0.08	0.06	0.08	AP	0.17	0.19
TOTAL	97.01	99.98	100.00	MT	0.79	1.05
$-H_2O$	97.01			SALIC	92.69	89.61
				FEMIC	7.31	7.40
					100.00	97.01

QZ-NE-DP Diagram

Weight percent:	QZ = 66.33	NE = 21.33	KP = 12.34
Molar percent:	QZ = 82.87	NE = 11.27	KP = 5.86

AN-AB-OR Diagram

Weight percent:	AN = 21.63	AB = 50.51	OR = 27.85
Molar percent:	AN = 20.99	AB = 52.00	OR = 27.01

A-F-M Diagram

Weight percent:	ALK = 62.16	FE = 22.53	MG = 15.31
Molar percent:	ALK = 57.17	FE = 17.32	MG = 25.51

II. STRUCTURAL GEOLOGY OF THE AZACUALPA THERMAL SITE

A. Introduction

Basic geologic mapping of this area done by Finch (1972, 1979) shows that the principal spring site "La Cueva" (AC-1) is located on the intersection of the Zacapa fault trace with the Río Jaitique. The Zacapa fault is a north-northeast-trending, down-to-the-west normal fault forming the eastern margin of the Santa Bárbara graben (Finch, 1972, 1985). The total displacement is unknown, but it very likely exceeds 1000 m inasmuch as the fault places upper Valle de Angeles red beds in the hanging wall in contact with limestone of the Atima Formation on the footwall. One objective of our investigation was to determine more precisely the nature of the Zacapa fault; a second objective was to ascertain whether the Zacapa fault is the sole structural control localizing the springs or if they occur at the intersection of the Zacapa fault with a more east-west-oriented structure suggested by R. Fakundiny and termed the Jaitique structure.

The regional structural setting is shown on the reverse of the Santa Bárbara geologic quadrangle map (Finch, 1985).

B. Zacapa Fault

The Zacapa fault produces a prominent topographic escarpment trending N20°E across most of the San Pedro Zacapa quadrangle. This fault-line scarp, primarily the result of differential erosion, is upheld by exposures of massive, bedded Atima Formation brought to the surface on the upthrown eastern side.

North some 9 km along the fault trace from the thermal area, in grid square 81/36, the Zacapa fault intersects with and is possibly offset by the La Boquita fault, which strikes more nearly northwest, causing a change in orientation of the eastern wall of the Santa Bárbara graben. The graben margin continues on to the north as the young Santa Bárbara fault. This fault lies along the southwest flank of the spectacular Montaña Santa Bárbara horst (Finch, 1973, 1985). This fault could be a direct continuation of the Zacapa fault that has recently been reactivated by uplift of the horst block that forms the second highest mountain in the Republic, which towers 2744 m above the surrounding region. The extremely crisp outline of the horst, faceted spurs along the Santa Bárbara fault, and the possible association of the horst with intrusive rocks at El Mochito Mine all argue for recent uplift of the horst block.

Southward from the thermal site, the Zacapa fault becomes difficult to trace because the Atima Formation disappears below the surface. Also the fault juxtaposes upper (hanging wall) and lower (footwall) Valle de Angeles clastic strata that do not uphold a sharply defined scarp and are prone to mass movements that obscure the fault trace. Failure of the fault to bring the Atima to the surface here suggests that the displacement decreases to the south. It is also likely that the fault breaks into splays of smaller displacement as suggested by the dashed lines on the published geologic map (Finch, 1979).

Where the trace of the fault is known with certainty, such as where the Atima Formation crops out along the base of the fault-line scarp, the Zacapa fault consists of a number of straight-line segments 1 to 3 km long, separated by smaller cross faults. The straight-line nature of these segments, which do not "vee" strongly into topographic depressions, implies that the Zacapa fault has a steep dip to the west. This conclusion is supported by dip measurements of 65°, 69°, 75°, and 85° observed in the fault plane and by subvertical measurements taken in several stream drainages along the fault trace.

The possibility that the Zacapa fault might be a listric normal fault was investigated by examining the beds in the hanging wall block for signs of rollover. Upper Valle de Angeles red shale and mudstone are exposed in the bed of the Río Jaitique for about 1100 m downstream from the fault. Thirteen strikes and dips measured in a traverse across these beds are recorded on the geologic map accompanying this report (Plate 1). All dips are to the southeast or south; the beds strike northeasterly toward the fault. There is no systematic increase in dip toward the fault, nor do the strikes become parallel with the fault. Therefore the beds exhibit no rollover, and the likelihood that the Zacapa fault flattens significantly at depth is not supported by the field data.

All available data support the original conclusion by Finch (1972) that the Zacapa fault is a high-angle normal fault (see cross section, Plate 2).

The dip of the main fault is probably about 75°W at the principal thermal site "La Cueva" (AC-1), as suggested by the fault plane in the Atima Formation, which is exposed on the north side of the Río Jaitique canyon. A dip of 69° westward was measured on the upstream splay of the Zacapa fault at grid coordinates 849/263 on the south wall of the river canyon.

Near the main fault, one surface of movement with an orientation of N10°W, 75°W, exhibits striations that rake southward at 29°, suggesting a component of oblique slip on some surfaces of movement on the Zacapa fault system. The only other field data that might imply significant strike-slip displacement on the Zacapa fault are changes in the strike of the Valle de Angeles beds as measured in the Río Jaitique. These attitudes change from generally east-northeast to east-west to west-northwest as the Zacapa fault is approached. This rotation could be interpreted as a broad drag feature resulting from dextral slip on the fault. However, strong and obvious drag in the Atima Formation limestone on the upthrown side of the fault is found only within a few meters of the main frontal fault and suggests mainly dip-slip motion. Accordingly, the broad zone of strike change in the Valle de Angeles is not thought to result from drag, and the motion on the Zacapa fault is believed to have been mainly dip-slip.

The displacement on the Zacapa fault, as mentioned earlier, is indeterminate but probably exceeds 1000 m near Quebrada Guajiniquil. Finch (1972, 1981) estimated the thickness of the lower Valle de Angeles here to be approximately 700 m and measured the Jaitique limestone elsewhere in the Zacapa area at 100 m. Below these strata on the upthrown block, at least 300 m of Atima Formation are exposed along the fault-line scarp, giving a sum of 1100 m of stratigraphic section exposed along the scarp on the upthrown block. On the downthrown side at Quebrada Guajiniquil, at least 100 m of Tertiary valley fill [TQd on the geologic map (Finch, 1979); Gracias Formation in this report] form the surface deposits.

The minimum vertical displacement on the Zacapa fault is the total of these exposed stratigraphic thicknesses, estimated at 1200 m. The total displacement might well be double this figure. The exact stratigraphic thicknesses of both the Matagalpa Formation and the upper Valle de Angeles strata--which should lie between the Gracias Formation at the surface and the

Jaitique Formation in the hanging wall subsurface--are unknown, but the thicknesses are certainly great and must be taken into consideration when estimating vertical displacement for the Zacapa fault.

Southward from Quebrada Guajiniquil, the throw on the fault decreases, but it could easily be as great as 900 m at the principal thermal site ("La Cueva," AC-1) where upper Valle de Angeles red shale and mudstone are downfaulted against the upper 100 m or so of the Atima Formation.

The age of the Zacapa fault is probably Pliocene or younger, constrained by the discovery near Zacapa of Pliocene(?) vertebrate remains in the valley-fill strata (Gracias Formation) preserved in the Santa Bárbara graben (Finch, 1972). These strata are in contact with the Zacapa fault east of the town of Zacapa and overlie eroded Matagalpa flow rocks. In the Santa Bárbara quadrangle, north and south of the town of Santa Bárbara, similar strata are mapped as Gracias Formation overlying Padre Miguel tuffs in the eastern portion of the graben (Finch, 1985). Although these two patches of Gracias Formation are separated by 16 km, it seems likely that they are remnants of a depositionally contiguous graben fill that accumulated as the graben developed. Around Zacapa these strata have been tilted 10 to 25° to the northeast, probably due to continued downsinking of the graben along the Zacapa fault. Erosion of these formerly more extensive deposits occurred more recently as the entire region underwent uplift, relative lowering of base level, and concomitant stream downcutting. As a result, only the two above isolated patches of the Gracias strata remain.

In summary, the Zacapa fault is a N20°E-trending, high-angle (70° to subvertical), down-to-the-west, primarily dip-slip normal fault. The throw decreases southward as the fault breaks into splays, with a 1200-m-minimum vertical displacement in the vicinity of the thermal site. The fault was active in Pliocene time and probably later. The Santa Bárbara fault, its presumed northern continuation, has certainly been active in fairly recent times. The main branches of the Zacapa fault and their subsidiary fractures serve as conduits for thermal waters surfacing in the gorge of the Río Jaitique.

C. East-West Jaitique Lineament

An east-west structural control influencing the several thermal sites in the Zacapa quadrangle was suggested by R. Fakundiny during the March 1985 Honduras geothermal reconnaissance trip. The suggestion was made on the basis of a suspected structural influence on the overall east-west course of the Río Jaitique and the remarkable line-up of the Azacualpa, Río Ulúa (AC-17), and Río Gualcarque (AC-18) spring sites.

The well-documented east-west-trending Taulabé anticline (Mills et al., 1967; Fakundiny and Everett, 1976; Curran, 1981) was mapped by Fakundiny and Everett in the late 1960s. The north flank of this structure forms a striking east-west linear feature that controls the course of the Río Tamalito (the reach of the Río Jaitique east of the town of Taulabé). Although the river continues a generally westerly course out of the Taulabé quadrangle into the Zacapa quadrangle, the Taulabé anticline is lost beneath Tertiary volcanic cover (Curran, 1981), and the actual stream course seems to have gradually shifted northward away from the projected flank of the anticline. That an east-west structure lies in the Tamalito valley north of the anticline is certain: the anticlinal rollover is well exposed in the Jaitique Formation, which dips steeply northward under upper Valle de Angeles red beds in the valley, then reappears 4 km to the north along a ridgecrest, overlying lower Valle de Angeles. The presence of a major east-west fault is thus established, but the fault location remains uncertain. Curran (1981) placed a northwest-trending fault contact between the upper and lower Valle de Angeles red beds about 1 km north of the Río Tamalito. If this structure is projected westward, it will not influence the course of the Río Jaitique.

Shorter, more eastwest-trending fault segments juxtaposing the upper Valle de Angeles with the Jaitique Formation and with lower Valle de Angeles strata are shown by Curran (1981) just south of the Río Jaitique near the border of the Taulabé quadrangle with the Zacapa quadrangle. Finch (1972, 1979) did not find evidence for these structures in the Zacapa quadrangle.

Members of the present field team who studied the 1:60,000 aerial photography were unable to detect any convincing east-west photolinears along the Jaitique drainage (which is cut by a number of more north-south linears). However, it must be noted that some sort of major faulting is required to the south of the Río Jaitique in order to bring south-dipping Jaitique limestone in the river gorge at 400-500 m up to 1000-1100 m at Cerro Cargamón 3 km south of the river. If we assume then that a major fault lies between the Río Jaitique and Cerro Cargamón, it must lie south of the Azacualpa thermal site and must not act as a control on the springs there. Alternatively, the alignment of thermal sites could be explained by postulating a second major limestone unit in the Valle de Angeles Group that has thus far gone unrecognized. Inasmuch as the area is known to be structurally complex, a structural explanation is preferred until post-Jaitique limestone members of the Valle de Angeles can be demonstrated.

The strongest argument for an east-west structural control on the thermal sites is not only the course of the Río Jaitique but also the remarkable, perfect alignment of the three thermal areas. From La Cueva (AC-1) at grid coordinates 843/162 to Río Gualcarque (AC-18) at grid coordinates 731/289, the distance is 11.6 km along a N76°W line. Río Ulúa (AC-17) at grid coordinates 777/274 lies only 400 m south of this line, certainly close enough to suggest that the three sites lie on a linear structure. But the Río Ulúa site, like the Azacualpa site, is related to northwest-trending faults of the Río Ulúa fault system (Finch, 1972, 1979). The Río Gualcarque spring issues from the base of a silicified knob (probably silicified limestone) completely surrounded by Tertiary volcanic rocks. No structural controls can be seen either in the field or on aerial photography. Although the alignment of the thermal sites is remarkable, no lineaments can be detected between these sites, and no evidence for such a structure was mapped by Finch (1972, 1979).

D. Description of Springs (see Fig. 5)

AC-1

AC-1 is the main site at Azacualpa (Fig. 6), called by us the "tunnel" but locally named "La Cueva." Springs occur over an elongated area approximately 55 by 190 m extending along a north-south-trending, unnamed stream valley 1.8 km east of Azacualpa. Most of the springs are located under a natural bridge ("tunnel") consisting of travertine and travertine-cemented

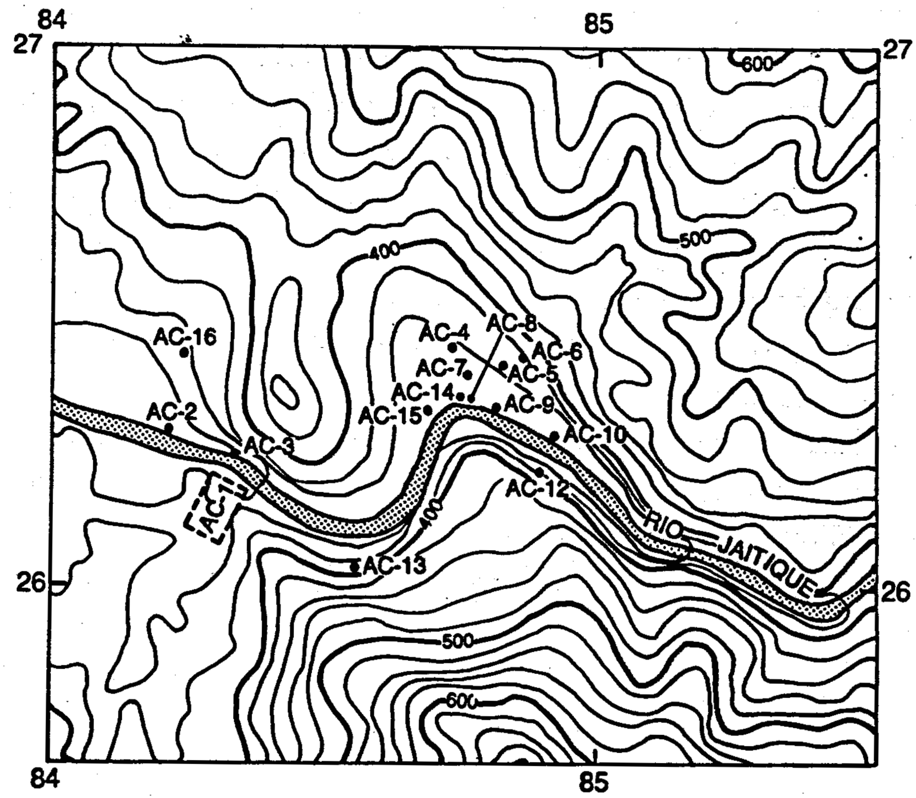

Figure 5. Azacualpa geothermal spring site. Described spring locations; 1:10,000 scale. Base map taken from the 1:50,000 San Pedro Zacapa topographic sheet.

alluvium (Figs. 6 and 7). This site is on the trace of the Zacapa fault. Estimated discharge and thermal power output are summarized in Table II.

<u>Spring Site 1</u>

This boiling pool is approximately 4 m wide by 8 or 10 m long, elongated in a northwest direction. Its depth could not be measured. The pool discharges at its northwest end into a channel that flows along the west wall of the tunnel for about 15 m through another area of boiling springs (Spring 3).

Temperature:	91°C (northwest end)
pH:	7.9
Discharge Rate:	>10 ℓ/min

TABLE II. Estimated Thermal Budget for the Azacualpa Site

Spring	ΔTemperature[a] (°C)	Flow (ℓ/min)	Thermal Output (kW)
AC-1	39	900	3822.0
AC-2	8	20	11.2
AC-3	64	30	134.4
AC-4	40	1	2.8
AC-5 to AC-7	30	45	94.5
AC-8	61	4	17.1
AC-9	55	4	3.9
AC-10	49	12	41.2
AC-11	Below river level		
AC-12	58	25	101.5
AC-13	59	10	41.3
AC-14	61	20	85.4
AC-15	42	10	29.4
AC-16	52	10	36.4
		TOTAL	4421.1
AC-17[b]	39	8000	21,840.0
AC-18[b]	20	300	420.0

[a] ΔT is the amount of heating that the thermal waters are assumed to have undergone during circulation through the geothermal system. An initial temperature of 35°C was assumed based on temperatures of normal streams in the area.

[b] Spring locations that are separate from the main spring site at Azacualpa. See text for details on location.

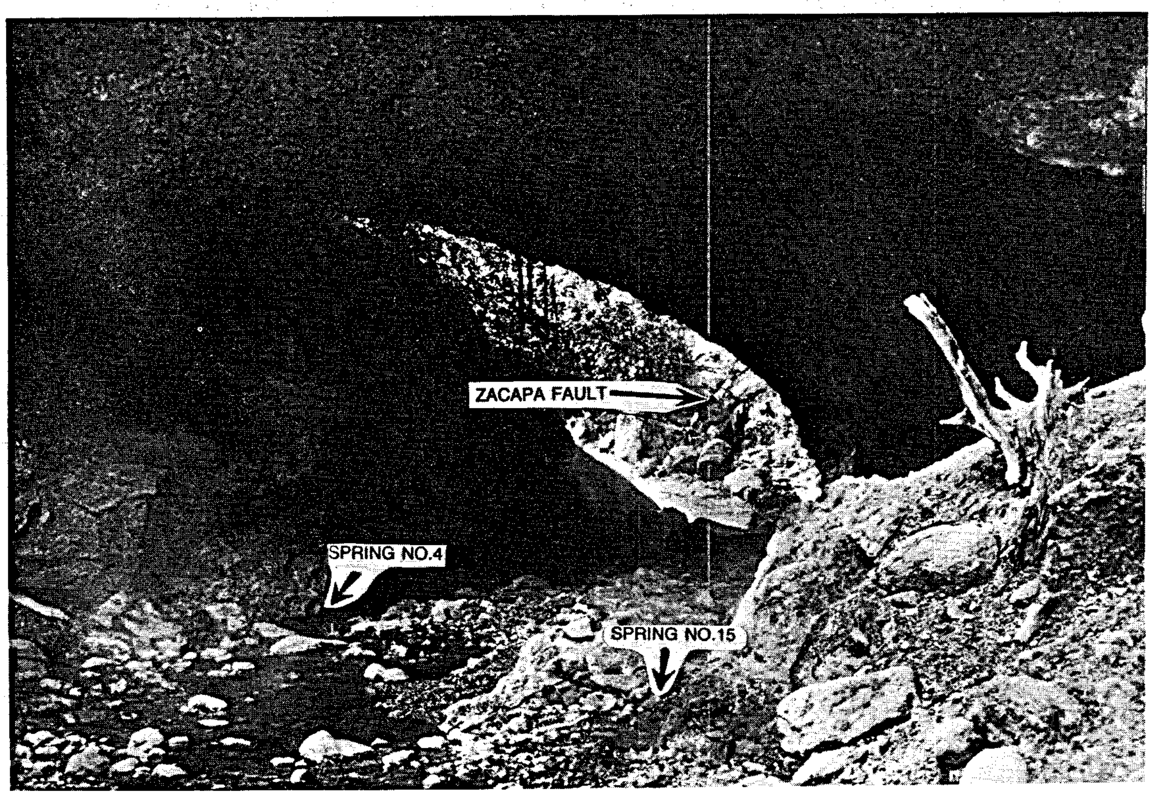

Figure 6. The tunnel at the AC-1 site.

Spring Site 2

This site is a 3- by 5-m area of small steam fumaroles and boiling springs that discharge through stream alluvium.

Temperature (spring):	98°C
Temperature (fumarole):	98.9°C
Temperature (ground):	96°C
Total Discharge Rate:	<1 ℓ/min

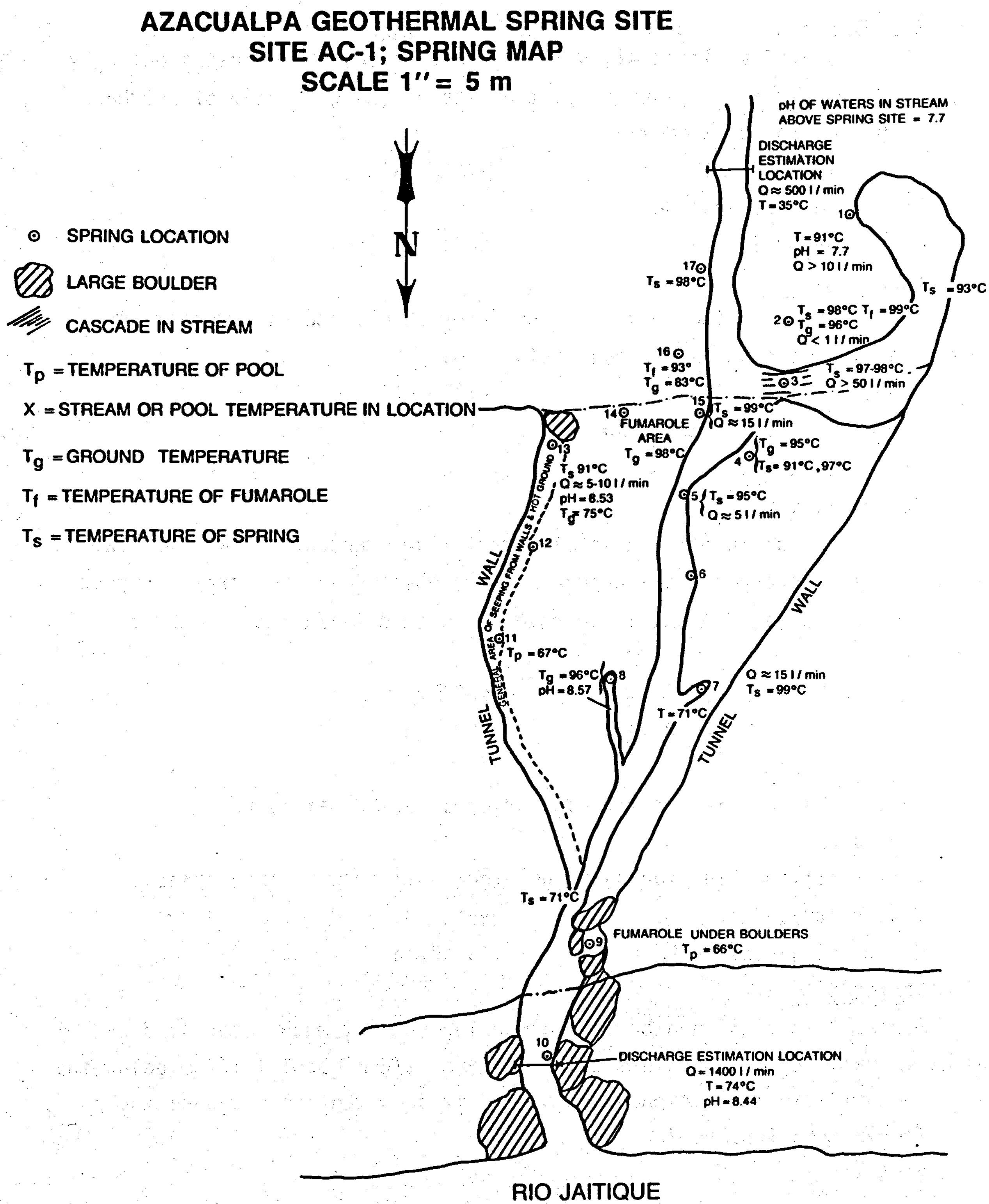

Figure 7. Azacualpa geothermal spring site AC-1.

Spring Site 3

This group of at least six boiling vents, lying in an area about 2 by 3 m, is covered by a pool that is part of the discharge stream of another boiling spring (Spring Site 1).

Temperatures (springs):	97°C, 98°C
Estimated Discharge Rate (pool and Spring 1):	50 ℓ/min

Spring Site 4

Three small boiling springs occupy about 2 m^2; the easternmost spring lies under the main stream through this site.

Temperatures (vents):	91°C, 97°C
Temperature (ground 1 m to northwest):	95°C

Spring Site 5

This small spring (1/3 m in diameter) flows through stream alluvium and has some gas discharge. Some carbonate is deposited in the stream leading away from the spring. A small fumarole is located 1 1/2 m southwest of Spring 5.

Temperature (spring):	95°C
Estimated Discharge Rate:	5 ℓ/min

Spring Site 6

This small, boiling spring discharges into the main stream.

Spring Site 7

This small, boiling spring issues from a fissure in travertine.

Temperature:	99°C
Estimated Discharge Rate:	15 ℓ/min

Spring Site 8

Spring 8 is small and boils vigorously, but not much water is discharged. Water collects in a small (1-1/2- by 1/2-m) pool 1 1/2 m below the vent. A small amount of carbonate is deposited on the rocks around the pool.

Temperature (ground in vent area):	96°C
Discharge Rate:	∿1 ℓ/min
pH (pool):	8.6

Spring Site 9

Spring 9 is a fumarole located in a crevice under the edge of a large rock, one of three surrounding a hot pool adjacent to the main stream. The pool is 1 m deep.

Temperature (pool immediately below the fumarole): 66°C

Spring Site 10

No data were collected because of discharge below water surface.

Spring Site 11

The small, 0.3-m-diameter pool, located at the edge of a tunnel adjacent to the wall, is not a spring; rather, it is made up of water from local seepage that collects in the pool. For 5 m or so to the north of this point and all the way to Spring Site 13, water seeps out of the lower 1-2 m of the wall. Active travertine is deposited all along this seepage zone. A small fumarole vent is located 3 m to the southwest of this point.

Temperature (pool): 67°C

Spring Site 12

Spring 12 is a fumarole along the lower part of the tunnel wall.

Spring Site 13

A fumarole and spring occur along a fissure (approximately 2 m wide) that extends about 5 m along the eastern wall of a tunnel. The fissure is 2 or 3 m deep, but low light prevents seeing very far into it. A spring issues from the tunnel wall about 5 m above the floor; water flows down the wall into the fissure. The fumaroles smell slightly sulfurous.

Temperature (spring):	91°C
Discharge Rate:	~5-10 ℓ/min
pH:	8.5

Spring Site 14

Spring site 14 is a small fumarole and an area of hot (58-78°C) ground. Ground temperatures range as low as 58° to 78°C to as high as 98°C 2 m uphill.

Spring Site 15

This boiling spring covers about 3/4 m^2.

Temperature:	99°C
Discharge Rate:	10-15 ℓ/min

Spring Site 16

A small fumarole bubbles up through muddy alluvium adjacent to the main stream. An area of steaming ground, 3 m north of the fumarole, extends 3 m or so up the alluvium bank. Travertine is deposited in this area.

Temperature (ground near fumarole):	93°C
Temperature (ground 3 m north of fumarole):	83°C

Spring Site 17

Several tiny, vigorously boiling springs cover approximately 1 m^2.

Total Discharge for AC-1 Site

The differential in the stream discharge above and below the tunnel suggests that the total discharge for the site is a minimum of 900 ℓ/min.

Temperature (differential):	+39°C
Estimated Discharge Rate:	900 ℓ/min

AC-2

This site, which consists of a single spring, is located on the north side of the Río Jaitique, west of site AC-1 (Fig. 5). Water issues from a limestone block (probably Atima Formation). About 10 m farther upstream (east), water discharge forms active travertine deposition onto Valle de Angeles shales.

Temperature (spring):	53°C
Temperature (10 m upstream from spring):	42°C
Estimated Discharge Rate:	20 ℓ/min

AC-3

This site consists of a group of boiling springs and fumaroles slightly above river level along the north side of the Río Jaitique across from the AC-1 site (see Figs. 5 and 8).

Spring Site 1

Spring 1 is a spouter approximately 1 m in diameter, which issues through talus.

Temperature:	92°C
Estimated Discharge Rate:	2-4 ℓ/min

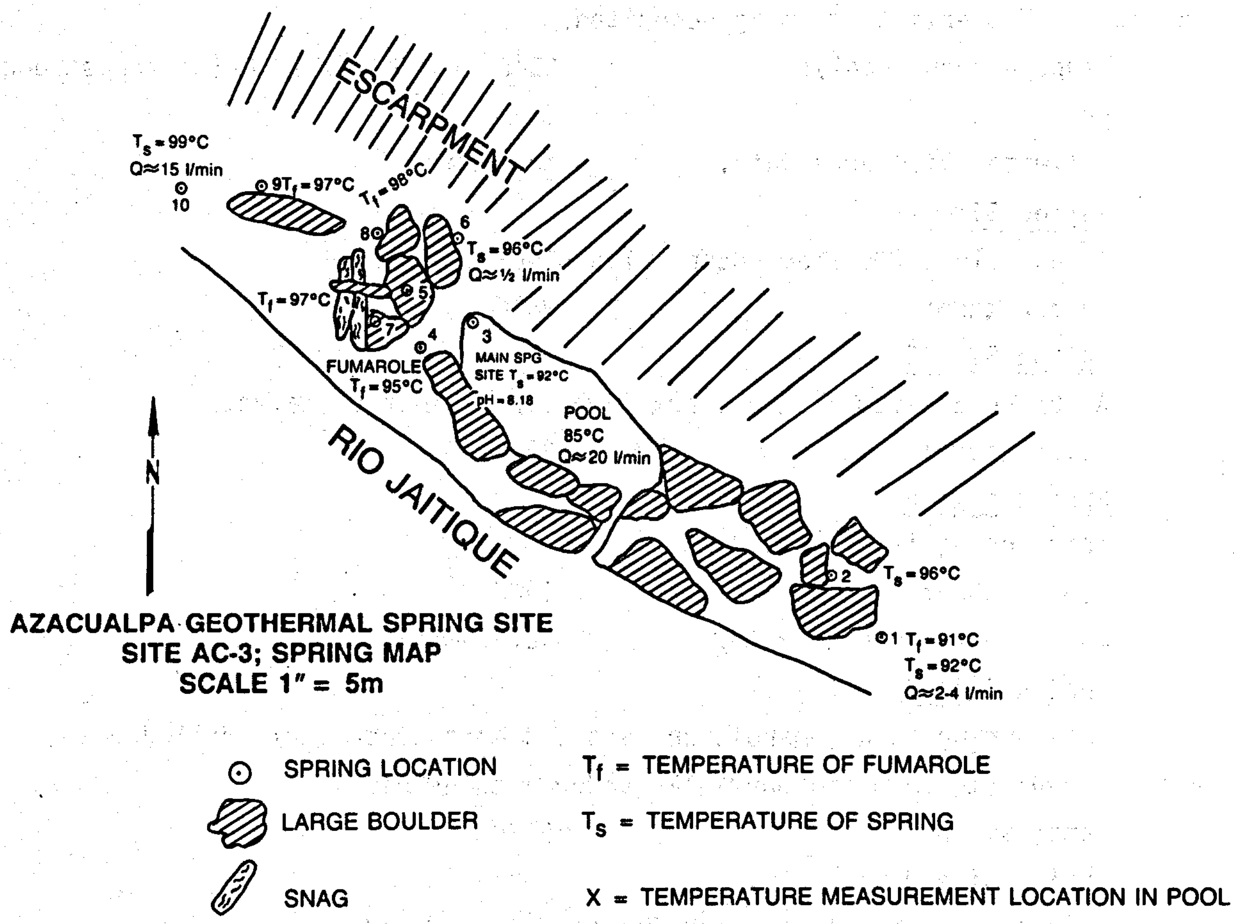

Figure 8. Azacualpa geothermal spring site AC-3.

Spring Site 2

This spring covers 3 to 4 m^2, where steam ascends from several places among talus blocks. At least one fumarole and possibly several occur here.

Temperature (crack between rocks where steam ascends): 96°C

Spring Site 3

Spring 3 is a hot pool 6 or 7 m long by 4 m wide by 1/2 m deep. A large boiling spring occurs at the northwest end of this pool, but water and gas also discharge at several places within the pool. Water seeps almost continuously up to a level of 4-5 m along an escarpment between this pool and Spring 1. Travertine is being deposited.

Temperatures (pool): 85°C (middle); 92°C (northwest end)
pH: 8.2
Estimated Discharge Rate: $\geq$20 ℓ/min

Spring Site 4

A fumarole exits from under talus blocks.

Temperature: 95°C

Spring Site 5

A fumarole exits from a crack in a large block of talus.

Temperature: 95°C

Spring Site 6

This spring is a spouter.

Temperature: 96°C
Estimated Discharge Rate: <0.5 ℓ/min

Spring Site 7

This spring is a fumarole where steam exits from a pit filled with sticks, mud, etc., and is partially under a talus block.

Temperature: 97°C

Spring Site 8

A fumarole exits from under leaves, etc., beside a talus block.

Temperature: 98°C

Spring Site 9

This spring is a fumarole and an area of small steam vents.

Temperature: 97°C

Spring Site 10

This is a boiling spring where water collects into a small pool. About 10 m west of this spring is a warm seep.

Temperature (pool): 99°C
Temperature (seep): 55°C
Estimated Discharge Rate (pool): ~15 ℓ/min
Estimated Discharge Rate (seep): 2-4 ℓ/min

AC-4 through AC-11, AC-14, and AC-15

Single springs or small groups of springs are located along the north side of the Río Jaitique, east of the high ridge composed of Atima Formation, near AC-1 (Fig. 5).

AC-4

Small seeps issue from among talus blocks of Atima Formation.

Temperature:	75°C
pH:	7.4
Estimated Discharge Rate:	<1 ℓ/min

AC-5 through AC-7

Sites all lie along a single warm stream. Site AC-6 lies at the head of this stream, and sites AC-5 and AC-7 lie farther downstream.

AC-5

A series of small seeps feed a warm stream. Seep discharge is too low for sampling. A slight smell of H_2S is noticeable in this seep area.

Temperature (ground in vicinity of one seep):	74°C
Temperature (stream above seeps):	21°C
Temperature (stream below seeps):	50°C
pH (stream where seep water enters):	7.2
Estimated Discharge Rate (stream):	40 ℓ/min

AC-6

A warm spring issues from Atima Formation at the head of a stream.

Temperature:	44°C
pH:	7.6
Estimated Discharge Rate:	10 ℓ/min

AC-7

Two warm springs 10 m apart issue from the north side of a small gully. Both springs issue from among float blocks of Atima Formation and drain into a small pool beside the stream. Because discharge is more abundant and temperatures are higher than expected, we think an additional hot spring is beneath a small waterfall in the stream near the head of the pool. A third spring is located among talus blocks of Atima Formation at the foot of the pool.

Temperature [first (eastern) spring]:	81°C
Temperature (second spring):	58°C
Temperature (third spring):	78°C
Estimated Discharge Rate (first spring):	5-10 ℓ/min
Estimated Discharge Rate (second spring):	<1 ℓ/min
Estimated Discharge Rate (third spring):	<10 ℓ/min
pH (first spring):	7.1

AC-8

A small seep issues from an outcrop of Atima Formation. Some carbonate deposition occurs around the seeps, and a faint H_2S odor is present.

Temperature:	96°C
Estimated Discharge Rate:	2-4 ℓ/min
pH:	7.7

AC-9

A pool (1- by 2-m) issues from the contact between a fine-grained, silicic, foliated dike rock and Atima Formation. A faint odor of H_2S is present.

Temperature:	80°C
pH:	7.2

AC-10

Two seeps 5 m apart issue from beneath talus blocks of Atima Formation. Although some carbonate has been deposited in the vicinity, none is deposited around the current spring or outflow channel.

Temperature (first seep):	93°C
Temperature (second seep):	84°C

Estimated Discharge Rate
(first seep): ∽2 ℓ/min

Estimated Discharge Rate
(second seep): ∽10 ℓ/min

pH (second seep): 7.2

AC-11

A high-temperature steam jet is located ∽20 cm below river level. It is manifested by a loud, low-frequency whistling noise and by forceful discharge of scalding water below the surface of the river. There is presently no gas discharge, presumably because flooding of the vent by the river causes condensation of steam before it exits to the surface.

AC-12 and AC-13

Sites are located south of the Río Jaitique, east of the high ridge of the Atima Formation that forms the hanging wall of the Zacapa fault.

AC-12

Two springs issue from under a block of Valle de Angeles red beds. A third spring is 60 m east of these two springs.

Temperature (first spring): 91°C

Temperature (second spring): 93°C

Temperature (third spring): 95°C

Temperature (ground): 45-60°C

Estimated Discharge Rate
(first spring): 5 ℓ/min

Estimated Discharge Rate
(second spring): 10 ℓ/min

Estimated Discharge Rate
(third spring): 5-10 ℓ/min

pH (first spring): 8.0

AC-13

Small hot springs issue from travertine-encrusted fractures in Atima Formation all along the south side of the Río Jaitique.

Temperature (two springs): 94°C

Estimated Discharge Rate
(individual seeps): 2-5 ℓ/min

AC-14

A small spouter comes from a fracture/bedding plane in the Atima Formation. In spite of a fairly high discharge rate, this spring is "blind;" i.e., it has no outflow stream. Water probably recirculates back into the rock and flows into the river at a lower level. A second spring occurs 5 m west of and 3 m lower than the spouter.

Temperature (first spring):	96°C
Temperature (second spring):	72°C
Estimated Discharge Rate (first spring):	10 ℓ/min
Estimated Discharge Rate (second spring):	5-10 ℓ/min
pH (first spring):	7.4

AC-15

A small spring issues from a fracture in the Atima Formation.

Temperature:	77°C
Estimated Discharge Rate:	5-10 ℓ/min

AC-16

A spring, issuing from Atima Formation, is depositing travertine on nearby boulders, which are quite hot.

Temperature:	87°C
Estimated Discharge Rate:	10 ℓ/min

AC-17

These springs, labeled "Fuentes Termales," are on the Río Ulúa, near the village of Agua Caliente. Their location is grid coordinates 776/274 on the Zacapa 1:50,000 topographic quadrangle. This site, the following site (AC-18), and the first group of sites (AC-1 through AC-16) along the Río Jaitique all lie along a single line trending N78°E. This site consists of numerous individual boiling springs that discharge from an active travertine deposit covering ~75 m^2. This deposit is built on a gravel bar in the river. Many springs discharge into an outflow channel leading out of the main area. The maximum temperature of these springs possibly indicates that they are diluted with river water percolating through the bar gravels. Additional springs are located to the south, southwest, and northwest of the main site, within a distance of 50 m. The total outflow from the entire site, including outlying springs, could be 3 to 5 times that of the outflow channel from the main travertine deposit.

Temperature (maximum measured in springs):	74°C
Estimated Discharge (outflow channel):	8000 ℓ/min
pH (springs):	6.8

AC-18

This hot spring, on the west bank of the Río Gualcarque, 2 km southeast of San Francisco de Ojuera Pueblo, Zacapa 1:50,000 topographic quadrangle, UTM grid coordinates 731/289, flows primarily from two orifices in limestone rubble. The first orifice is approximately 20 cm wide by 10 cm deep; the second orifice is 15 cm wide by 5 cm deep. The spring issues from the base of a silicified limestone knob about 100 m high. Pyrite and stibnite are visible in hand specimen; fluorite is visible in thin section (Finch, 1972).

Temperature (discharged water):	55°C
Estimated Discharge (first orifice):	~200 ℓ/min
Estimated Discharge (second orifice):	~80 ℓ/min
pH:	7.3

III. RECOMMENDATIONS FOR GEOPHYSICAL INVESTIGATIONS

Geophysical investigations of the Azacualpa site should concentrate on two main objectives: (1) determining the location of the reservoir supplying the hot water to the Azacualpa site and (2) delineating the relationship of the reservoir and its related conduits to the Zacapa Fault and the Atima Formation/Valle de Angeles Group contact. Of secondary importance is looking for any geophysical anomaly that suggests the existence, at depth, of the conjectured east-west Jaitique structure. Although field data do not support its existence, the presence of significant east-west structures to the east of the Azacualpa site (Personal communication, N. Ramos, 1985) argues that a final attempt be made to determine if the Jaitique structure is real.

To this end, we recommend that the following geophysical investigations be undertaken at Azacualpa, using as a starting point the model put forth in the accompanying cross section (Plate 2):

- Resistivity surveys along one north-south line and along one east-west line. The location of the north-south line has not been delineated, but it should be parallel to the Zacapa Fault in order to test for any anomaly associated with the Jaitique structure. The east-west line should be located as close as possible to cross-section line A-A' (Plate 2) to test east-west line validity.
- Geothermal gradient holes of both shallow (∿200 m) and intermediate (∿500-1000 m) depth to determine the geothermal gradient and to determine if there is any asymmetry to the shape of geothermal° gradient surface at depth [see, for example, Hill (1985), Fig. 3].
- Seismic surveying to delineate the behavior of the Zacapa fault and its subordinate splays at depth.
- Gravity surveying to determine the nature of the Atima Formation/Valle de Angeles contact west of the Zacapa fault, its relationship, if any, to the hot water reservoir, and its plumbing.

In planning the geophysical investigations of this site, we must recognize the pervasive nature of faulting exhibited in the Mesozoic stratigraphic section and the potential for an extremely complicated plumbing geometry. With this in mind, we also recommend that a hydrologist familiar with basin-and-range-type geothermal systems become involved in planning the geophysical investigations at the earliest possible date.

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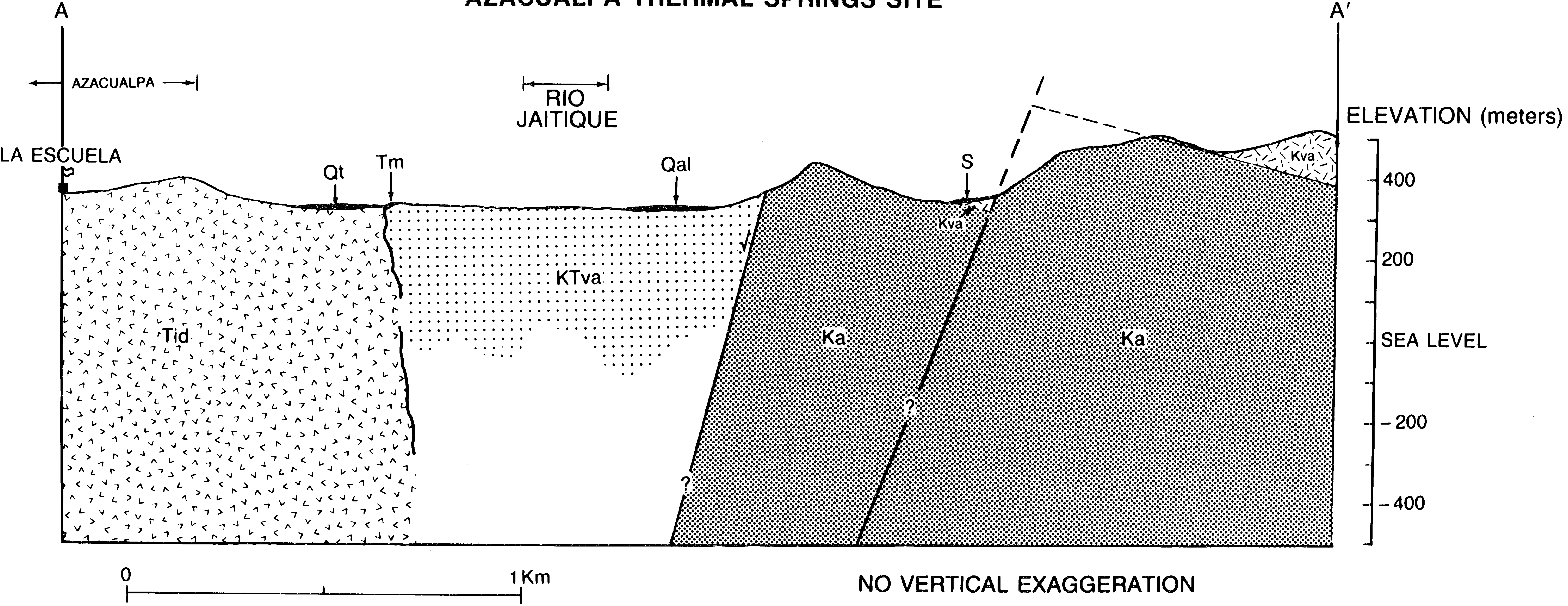
PLATE 2

AZACUALPA THERMAL SPRINGS SITE



NO VERTICAL EXAGGERATION

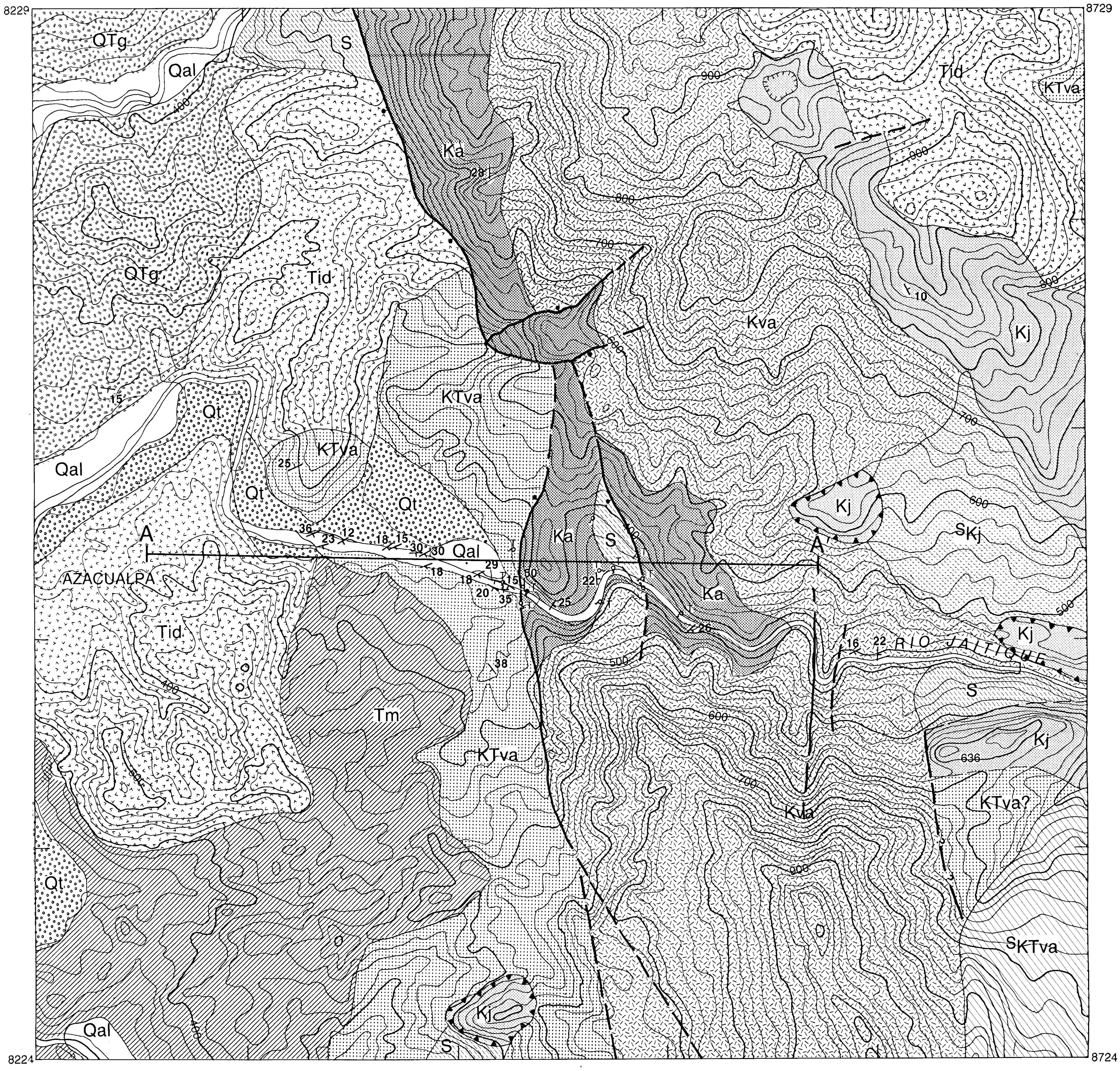
GEOLOGIC MAP OF THE AZACUALPA GEOTHERMAL SPRING SITE

4

LOS ALAMOS
S. Baldridge
D. Eppler
F. Perry
Geology in part after Finch (1979)

TENNESSEE TECHNOLOGICAL UNIVERSITY
R. Finch

EMPRESSA NACIONAL DE ENERGÍA ELECTRICA
W. Flores
R. Paredes



Base Map San Pedro Zacapa 1:50,000 A.M.S. Sheet #2560-II

Scale 1:10,000

0 — 1 km

MAP UNITS

RECENT DEPOSITS

QUATERNARY

Qal — ALLUVIUM

Qt — TERRACE DEPOSITS

S — LANDSLIDE

SKj — LANDSLIDE, (formation symbol shown is predominant rock-type in rubble).

OLDER ALLUVIAL DEPOSITS

?

Tm — VALLEY FILL DEPOSITS OF GRAVEL, SAND, AND REWORKED TUFFACEOUS SEDIMENTS

MATAGALPA FORMATION

TERTIARY

QTg — FLOWS OF ANDESITE, BASALT, AND LATITE

VALLE DE ANGELES GROUP

?

KTva / Kj / Kva — Ktva - UPPER VALLE DE ANGELES REDBEDS (including conglomerates, sandstones, mudstones, siltstones, and gypsum)
Kj - LIMESTONE OF THE JAITIQUE FORMATION
Kva - LOWER VALLE DE ANGELES REDBEDS

ATIMA FORMATION

CRETACEOUS

Ka — THICKLY-STRATIFIED LIMESTONE

INTRUSIVE ROCKS

Tid — LAVANDEROS DIORITE

SYMBOLS

FAULT, BALL ON DOWNTHROWN SIDE (dashed where inferred)

CONTACT

28 — STRIKE AND DIP OF BEDS

T — SPRING, ("T" indicates thermal spring with water temperatures higher than ambient).

LANDSLIDE BLOCK OF LIMESTONE

A — A' CROSS SECTION LINE

N