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***Area Geotérmica de San Ignacio
(La Tembladera), Departamento de
Francisco Morazán,
Honduras, América Central***

Informe Geológico de Campo

Los Alamos Los Alamos National Laboratory
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**San Ignacio (La Tembladera)
Geothermal Site, Departamento de
Francisco Morazán, Honduras,
Central America**

Geological Field Report

The San Ignacio Field Geology Team

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PLATES

- Plate 1. Geologic Map of the San Ignacio (La Tembladera) Geothermal Site.
- Plate 2. Geologic Cross Section through the San Ignacio (La Tembladera) Geothermal Site.
- Plate 3. San Ignacio Geothermal Site - May 1985
Areas 1 and 4.

EXECUTIVE SUMMARY

Investigation of the San Ignacio 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 the geothermal resource potential of Honduras. This assessment is part of the Central American Energy Resources Project being sponsored by the U.S. Agency for International Development. San Ignacio 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 study is to evaluate the geothermal system of Honduras to determine if further investigations by geochemical, geophysical, and drilling techniques are justified.

The San Ignacio geothermal site is located in central Honduras on the north side of the Siria Valley near the village of Barrosa, ~100 km north of Tegucigalpa. Access to the site is excellent because it is located near a main road. The site has moderate relief with little vegetation, and has around 50 hot springs. Thermal manifestations appear to be related to large-scale thinning and fracturing of the crust in the region, possibly due to large-scale extension. In this respect, the area may be similar to many sites in the Basin and Range province of the western United States where geothermal energy is being developed.

The San Ignacio hot springs are located along several major faults that serve as conduits for the thermal waters. The measured surface temperatures range from boiling to $<50^{\circ}\text{C}$. Calculated reservoir base temperature, computed from geochemical surveys, is $\sim 185^{\circ}\text{C}$.

This study indicates that San Ignacio has good potential for development as an electrical power source; however, more information is needed before a complete determination can be made. It is recommended that limited geophysical studies be done to define further the subsurface geology and the nature of the geothermal system. These investigations will provide ENEE and Los Alamos scientists and engineers with the information necessary to site thermal gradient boreholes. Several boreholes will have to be drilled to a depth of several hundred meters to define the geothermal system and to

determine if drilling an exploration well is warranted. When such a well has been thoroughly tested and evaluated, the realistic energy potential of the site can be demonstrated. At that point, the information required to decide on the feasibility of using this geothermal site for electric power generation will be available.

SAN IGNACIO (LA TEMBLADERA) GEOTHERMAL SITE,
DEPARTAMENTO DE FRANCISCO MORAZAN, HONDURAS, CENTRAL AMERICA
Geological Field Report

by
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ABSTRACT

The San Ignacio (La Tembladera) geothermal site is located on the north side of the Siria Valley, Departamento de Francisco Morazán, near the village of Barrosa. Hot springs are located along a northwest-trending fault scarp at the edge of the valley and along north-trending faults that cross the scarp. The rocks in the area are primarily Paleozoic metamorphic rocks, overlain by patches of Tertiary Padre Miguel Group tuffs and alluvial deposits. Movement probably occurred along several faults during latest Tertiary and possibly early Quaternary times.

Four spring areas were mapped. Area 1, the largest, is associated with a sinter mound and consists of 40 spring groups. About half of the springs, aligned along a north-south trend, are boiling. Area 2 is a small sinter mound with several seeps. Area 3 consists of a group of hot and boiling springs aligned along a north-trending fault. The springs rise through fractured schists and a thin cover of alluvium. Area 4 is located at the intersection of several faults and includes one of the largest boiling springs in the area.

I. REGIONAL SETTING

A. Structure

The San Ignacio site lies ~100 km north of Tegucigalpa in the Department of Francisco Morazán (Fig. 1). It is located on a portion of the Chortis block, a block of Paleozoic and younger continental crust located in the northwest corner of the Caribbean plate (Fig. 2). The block is bounded on the north by the Caribbean-Américas plate boundary along the Motagua and Polochic faults (Fig. 3) and it 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). On the west, the block is bounded by the Middle America trench, where the Cocos plate is moving northeastward from the East Pacific rise and is being subducted under the Caribbean and Américas plates. 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).

Principal tectonic features within the Chortis block include a number of east- to east-northeast-trending faults (Chamelecón, La Ceiba, Aguán) that subparallel the sinistral plate boundary (Figs. 2 and 3). They are thought to be part of the plate boundary or part of older analogues to it. The Guayape fault of eastern Honduras may also be associated with this group of faults (Ritchie and Finch, 1984).

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 many other faults throughout Honduras generally strike northerly, but they are stepped along northeast- and northwest-trending faults that are dominantly normal-slip but 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 Américas plates as eastward movement of the rest of the Caribbean plate continues (Fig. 2). The initiation and greatest movement of the graben faults in the "Honduras Depression" occurred concurrently with the eruption of the

Figure 1. Location of the San Ignacio geothermal site.

Figure 2. Generalized plate tectonics of the Caribbean region (modified from Case and Holcombe, 1980).

Figure 3. Major tectonic features of Honduras (Ritchie and Finch, 1985).

Padre Miguel Group tuffs in the Miocene and Pliocene, although some minor fault movement may continue today. The San Ignacio site is clearly affected by faulting associated with regional extension. Northeast-, northwest-, and north-trending faults dominate the structure of the site. As indicated previously, the north-trending faults are normal, the youngest, and the most open to fluid migration. Northwest- and northeast-trending faults are generally somewhat older, also normal, but with a left-slip component on the northeast faults and a right-slip component on the northwest. In addition to the grabens and associated block faulting, this same extension has probably produced crustal thinning in the region. This, in turn, suggests a structural analogy to the geothermal sites in the Basin and Range province of the United States.

The Pacific volcanic chain lies well to the south of the San Ignacio site. Subduction along the Middle America trench has been responsible for a long history of volcanism in Honduras, although no active volcanoes exist within the Republic. Mid-Tertiary basaltic volcanism (Matagalpa Formation) was followed by the formation of widespread and voluminous silicic tuffs of

the mid- to late-Tertiary Padre Miguel Group. Some young, possibly Quaternary basaltic volcanism occurred in Honduras, principally within the "Honduras Depression" from Tegucigalpa to the north coast.

B. Stratigraphy

The details of the stratigraphy of Honduras are not well known, principally because of poor exposures and closely spaced faulting. Finch (1981) provides the best available description; his data, along with those of Mills et al. (1967), are shown in Fig. 4.

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

The basement rocks are overlain by a section of siliclastic units that include red beds and other clastic sediments, which underlie the Yojoa Group limestones. These strata include the El Plan Formation, the Todos Santos Formation, and the informally named "Agua Fria Formation." Finch and Horne (to be published) propose the name "Honduras Group" for all clastic units on the Chortis block that overlie crystalline basement and predate the Upper Cretaceous Aptian-Albian Atima Limestone. Ritchie and Finch (1985) demonstrate a Jurassic age for at least part of the Honduras Group.

The Yojoa Group is dominated by the Atima Formation, which is up to 1400 m of dark, thick-bedded limestone. This group also includes, locally, the Mochito shale and the Cantarranas Formation, a shaly limestone. The Atima Formation is an excellent marker because it is the only thick limestone in the section and is a prominent ridge-former.

The Cretaceous-Tertiary Valle de Angeles Group consists of thick red clastic strata; conglomeratic layers are common in the lower part of the unit and generally absent in the upper part. Two thin carbonate units are included in the Valle de Angeles Group: the Jaitique limestone and the Esquífas Formation. Care must be taken when mapping small patches of limestone to distinguish between Valle de Angeles Group and Yojoa Group limestones.

Figure 4. Stratigraphic columns for central Honduras (after Mills et al., 1967, and Finch, 1981).

The Eocene-Oligocene basalt flows of the Matagalpa Formation overlie the Valle de Angeles Group and are widespread throughout Honduras but are locally absent from the stratigraphic section. At least some basaltic volcanism continued into the time of the deposition of the voluminous, silicic Padre Miguel Group tuffs and associated volcanoclastic sediments. There is some debate about the age of the Padre Miguel Group, but the majority of the tuffs appear to have been erupted during the Miocene and Pliocene. The Padre Miguel tuffs were erupted over a surface of considerable relief that was undergoing active block faulting. As a result, the thicknesses of these tuffs are 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 rocks of the Gracias Formation and alluvium. It is common to find alluvial deposits in various stages of dissection within an area. 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.

At the Platanares site, there are outcroppings of Paleozoic age metamorphic rock from red beds made up of the Valle de Angeles Formation, tuff from the Padre Miguel Formation, and some alluvial deposits.

A detailed study showed that at the site there are no outcroppings of calcareous rock; nevertheless, a limestone clast was found in the Río Lara. It's not known whether this calcareous clast belongs to the Yojoa Group or to the Valle de Angeles Group. Next to the Platanares geothermal site there are only exposures of units belonging to Paleozoic bedrock, tuffs from the Padre Miguel Group, and alluvial deposits. Owing to the fact that the red beds of Valle de Angeles crop out nearby, it is probable that these can be found below the surface, possibly accompanied by the calcareous Yojoa Group.

In the immediate vicinity of the San Ignacio site, only Paleozoic metamorphic rocks, silicified Padre Miguel Group tuffs, and alluvial deposits are exposed. Because Paleozoic metamorphic rocks are exposed on both sides of the faults that pass through the geothermal site, it is unlikely that different rock units would be encountered in the subsurface.

II. FAULTS

A. Main Scarp and Border Faults

The main scarp on the north side of the Siria Valley has two major bends in it within the El Porvenir 1:50,000 quadrangle. The trend of the scarp changes from northwest to east, in the vicinity of UTM grid square 83/27, and then back to northwest, in the vicinity of UTM grid square 92/24 (eastern bend shown on Plate 1). The San Ignacio geothermal site is located at the eastern bend in the scarp. Simonson's (1977, 1981) map shows a border fault along the main scarp from the southern edge of the El Porvenir quadrangle (vicinity of 957/214) to Quebrada El Aguacate (vicinity of 928/244) and no border fault is shown between this quebrada and the western bend in the scarp.

The northwest-trending segment of the border fault in the map area is located very close to where it is depicted by Simonson (1981). However, the displacements of valley fill are not as he indicates. In Quebrada Grande, located immediately north of the village of Barrosa (the north side of this stream is in the extreme eastern corner of the 1:10,000 map), geologic relationships of the border fault and alluvium are well exposed. The augen schist member of the Cacaguapa Schist, which occurs as massive outcrops in the stream at the main scarp, extends downstream several tens of meters as a small exposure from the floor of the stream to approximately 1 m above the floor, and it terminates at the fault plane. At this location the fault is oriented N37°W, 60°S, and has two sets of slickensides that rake 4°N and 50°N. The slickensides with the larger rake appear to be younger than those with the smaller rake.

On the southwest side of the fault is old, moderately indurated alluvium, the top of which is continuous with the top of the augen schist. A thick (~3 m), younger, poorly indurated deposit of alluvium, with a basal bed of cobble-sized clasts, overlies older alluvium on the southwest side of fault and augen schist on the northwest side. Beds in the younger alluvium above the fault are not offset, indicating that the border fault has not moved since the alluvium was deposited. The fault does not cut the younger Quaternary alluvium as Simonson (1977, 1981) shows on his map.

The top of the augen schist and older alluvium exposures is an ancient geomorphic surface that developed after a period of major block faulting during Late Tertiary (syn- and post-Miocene?) time. A portion of the surface, located northeast of the fault, was a narrow (~100-m-wide) pediment, and located southwest of the fault was a bajada of undetermined size.

B. Arenal Fault

The Arenal fault is poorly exposed in the area that was mapped. It can be seen on the north side of Quebrada El Arenal near UTM grid coordinates 930/255 (Plate 1) and appears much as Simonson (1977, p. 78) described it, as "a narrow zone of closely spaced, anastomosing fractures." At this location the fault strikes approximately N80°E and dips steeply north. Bending of the schistosity in the augen schist member of Simonson (1977) along the fractures indicates that the north side is downfaulted. Simonson (1977) also concluded that the north side is down and inferred a left-lateral slip movement. To the west the fault disappears beneath alluvium of Quebrada El Arenal; however, a possible continuation of it can be seen on aerial photographs as an alignment of small topographic irregularities and differences in photographic tone on either side of the apparent trace. Although a border fault must be present in this area, the symbol for it on Plate 1 is queried as its existence cannot be proved. Regardless of whether this buried fault is a continuation of the Arenal fault, it must dip south rather than north like the exposed part of the Arenal fault. The main part of the San Ignacio geothermal site is located along this fault, and therefore it may be the most important structural element controlling hot spring activity (Plate 2).

C. North-Trending Fault

A north-trending fault extends from approximately UTM grid coordinates 911/246 to 909/255. A fault plane can be seen in schist outcrops in the stream that parallels its trend. The fault serves as a conduit for the water of several hot springs and appears to continue south to the Arenal fault and its projections.

Simonson (1977, 1981) shows a north-trending fault approximately between UTM grid coordinates 904/248 and 904/265. A southward continuation of this

fault would lie immediately east of a large area of silicified volcanic rocks (labeled Tsb on Plate 1) and would act as a structural boundary for that part of the main scarp. Aerial photographs of the area show no evidence of any buried fault south of 904/248, so the fault is terminated against the inferred trace of the buried border fault.

D. Northwest-Trending Fault

On the east side of hill 870 (UTM grid coordinates 916/253), a fault can be traced in the stream to a saddle at UTM grid coordinates 915/255. The fault plane, which is exposed on the east side of the saddle, is vertical and has horizontal slickensides. The south end of this fault probably terminates against the border fault. Regionally, most northwest- and northeast-trending faults and fractures possess some component of horizontal displacement.

E. Tectonic History

The stratigraphic record on the east side of the Siria Valley is too incomplete to determine the detailed history of major block movements. However, it is probably not unreasonable to assume that tectonism in the valley has been synchronous with deformation farther west in the Zambrano quadrangle studied by Dupré (1970). With this assumption some constraints can be placed on the time for the most recent faulting at the San Ignacio geothermal site.

Simonson (1977) indicates that the border fault along the main scarp probably began moving during the Miocene Epoch. In the Quebrada Piedras, a nearly vertical basalt dike approximately parallels the fault, indicating structural control. A sample from this dike yielded a K-Ar age determination of 108 ± 3 Ma, suggesting that the border fault was active by that time.

The Quebrada Grande, immediately south of the southeastern corner of the map area, is the best location for determining when the most recent movement on the border fault at the San Ignacio geothermal site took place. As previously stated, the border fault does not offset younger alluvium, which overlies the previously described paleogeomorphic surface; therefore, no movement has occurred along the fault since this alluvium was deposited. The (apparently) youngest slickensides along the fault indicate that its last displacement was right-oblique. The trend of these slickensides suggests that

the least principal horizontal stress (σ_3) was oriented west northwest-east southeast during most recent movements. This is consistent with the east-west regional extension currently taking place in Honduras.

Unfortunately, there is no way to determine the exact age of the younger alluvium, but its basal cobble bed is probably no older than early Quaternary.

No faults in the mapped area cut Quaternary alluvium or the sinter that is so prevalent throughout the geothermal site. However, the available evidence indicates that significant movement probably occurred on several of the faults during latest Tertiary and possibly early Quaternary times. Two surfaces have developed on Quaternary alluvium, which apparently formed in response to changes in base level in the Siria Valley. Repeated, recent changes in base level are, in part, related to post-Miocene block faulting and are common throughout most of Honduras.

III. SPRING DESCRIPTIONS

A. Area 1

Area 1 is the largest collection of hot springs at the San Ignacio (La Tembladera) geothermal site (Plates 1 and 3). They are located at the base of a sinter-covered, 140-m-high hill and rise through mostly siliceous sinter. The main spring area has little vegetation, in contrast with surrounding acacia brush. Rocks underlying the sinter are mostly agglomerates and conglomerates of valley-fill deposits. Flow estimates are just that--estimates. Elevation is ~700 m.

Spring Group 1

These springs are located near the road and are popular with neighbors for cooking, washing dishes, etc. Two springs have collars emplaced to form small pools. The springs are 2 to 4 m below the main terrace surface in a small stream. Five springs are aligned N50°W and rise through reddish conglomerate and siliceous sinter.

Temperatures (springs):	100°C (212°F), 98.3°C (209°F), 100°C (212°F)
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Flow Rate:	many tens of l/min
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Spring Group 2

All springs are along a N20°E trend and rise through sintered conglomerate.

Temperature (largest pool): 92.8°C (199°F)
Flow Rate: not established

Spring Group 3

Five springs, located along a line oriented N20°E, are in sintered valley-fill conglomerates. There is a faint H₂S smell.

Temperature (largest spring): 98.9°C (210°F)
Estimated Flow Rate: 10 l/min

Spring Group 4

This group, which covers 16 m², is located at a break in slope of the sinter terrace. There is no apparent orientation of springs. The largest pool has a surface area of 1 m².

Temperature (largest spring): 100°C (212°F)
Flow Rate: not estimated because the spring is located in a small stream.

Spring Group 5

This group is located at the highest point on the open (clear of vegetation) sinter terrace, about 12 m above the terrace base. Terrace here has a slope of 5°.

Temperature (springs): 95.6°C (204°F)
Estimated Flow Rate: 2 to 3 l/min

Spring Group 6

Two springs, along a N50°W trend, rise through the sinter terrace and a thin cover of colluvium.

Temperature (springs): 88.8°C (192°F)
Estimated Flow Rate: 2 to 5 l/min

Spring Site 7

Number 7 is a small spring that flows from a crack in the terrace sinter (N35°W). Fractures in the terrace surface are oriented N10°E, N30°W, and N70°W. There are many small seeps near Spring Site 7.

Temperature (spring): 92.2°C (198°F)

Estimated Flow Rate: 1 l/min

Spring Site 8

Spring Site 8 is located at a topographic break in the terrace, at a bedding plane between layers of conglomerate cemented by siliceous sinter. The springs (one pool hidden, one exposed) are issuing from an open space along the bedding plane and are capped by 1 m of sintered conglomerate.

Temperature (springs): 98.9°C (210°F)

Estimated Flow Rate: 10 l/min

Spring Site 8A

An elongate, boiling pool, located in a fracture in the terrace surface, appears to connect with Spring Site 8, which is 1.5 m lower than Spring Site 8A. Fracture orientation is N85°E.

Temperature (spring): 94.4°C (202°F)

Estimated Flow Rate: not measured

Spring Site 8B

Similar to Spring Site 8A, this small pool is in a 1.5-m-long fracture oriented N55°W. Spring Site 8B has no visible outflow, but it appears to be connected with Spring Site 8. Here, the sintered conglomerates lie flat.

Temperature (spring): 94.4°C (202°F)

Spring Group 9

This group consists of five hot springs and 8 m² of steaming ground. The springs rise through sinter deposits and thin colluvium; they lie along a line trending N45°W. Terrace sinter (bedded) slopes 5°SW.

Temperature (target spring): 98.9°C (210°F)

Flow Rate: not measured

Spring Site 9A

The spring is located at a break in slope on the terrace surface in fractured, bedded siliceous sinter.

Temperature (spring): 71.1°C (160°F)
Estimated Flow Rate: 5 to 6 l/min

Spring Group 10

This cluster of springs is located in a small creek and rises through recent alluvium along a N30°W trend. The cluster covers 0.75 m².

Temperature (springs): 92.2°C (198°F)
Flow Rate: not estimated

Spring Group 11

Group 11, which is similar to Group 10, covers 6 m² in partly sintered gravel. It is oriented generally northwest. This group forms an area of steaming ground; temperature and flow rate were not measured.

Spring Group 12

This patch of steaming ground, which is also similar to Group 10, covers 6 m² and is oriented approximately northeast.

Flow Rate: <2 l/min

Spring Group 13

This group occupies a 2-m² patch of steaming ground with an approximate northeast trend. The springs rise through partly sintered alluvium.

Estimated Flow Rate: <2 l/min

Spring Site 14

Spring Site 14 occupies 1 m² of steaming ground and consists mostly of vapor rising through alluvium.

Temperature (spring): 92.2°C (198°F), partly immersed
thermometer

Spring Site 14A

Rising through sintered valley fill, this spring is oriented N45°W.

Temperature (spring): 94.4°C (202°F)

Flow Rate: no estimate

Spring Site 14B

Two small springs, with a very low flow rate, are located below a break in slope of the sinter terrace.

Temperature (springs): 82.2°C (180°F)

Spring Site 14C

This spring issues from a bedding plane in massive sintered conglomerate at a break in slope of the terrace.

Temperature (spring): 87.8°C (190°F)

Estimated Flow Rate: 5 l/min

Spring Group 15

Eight springs issue at a break in slope of the terrace over a line 19 cm long, oriented N50°W. They are in bedded breccia, cemented by siliceous sinter.

Temperature (largest spring): 98.9°C (210°F)

Estimated Flow Rate: 10 l/min

Spring Group 16

Group 16 is an elongate cluster of springs, oriented N45°W; most are flowing from fractures between boulders in the sinter deposit.

Temperature (springs): 95.6°C (204°F), northwest end

97.8°C (208°F), southeast end

Estimated Flow Rate: >10 l/min

Spring Group 17

This line of small springs issues from a low mound of sinter oriented north-south and has a very low flow rate.

Temperature (springs): 93.8°C (201°F)

Spring Site 18

This large spring, which is in a creek bottom, issues from between boulders cemented by siliceous sinter.

Temperature (spring): 93.3°C (200°F)

Estimated Flow Rate: >20 l/min

Spring Site 19

This spring is a slow seep located at the top of the open sinter terrace. Seeps flow from bedding planes in bedded siliceous sinter.

Temperature (spring): 85.6°C (186°F)

Spring Site 20

This pair of seeps is similar to those at Spring Site 19. Fractures in bedded sinter are vertical, oriented N50°E, N10°W, east-west. Seeps are oriented N45°W.

Temperature (springs): 70°C (158°F)

Spring Site 20A

This placid spring is in hollow sinter (hole in capping bedded sinter). Flow rate is not measurable.

Temperature (spring): 67.2°C (153°F)

Spring Site 21

Spring Site 21 is a seep at the top of open sinter terrace.

Temperature (spring): 72.8°C (163°F)

Estimated Flow Rate: 2 l/min

Spring Site 22

Spring Site 22 is nearly identical to Spring Site 21.

Temperature (spring): 72.6°C (163°F)

Spring Site 23

Spring Site 23 consists of slow seeps located in bedded siliceous sinter.

Temperature (springs): 67.8°C (154°F)

Spring Group 24

Three seeps are located along a N45°W trend.

Temperature (springs): 73.3°C (164°F)

Estimated Flow Rate: <1 l/min

Spring Site 25

A pair of seeps, 0.5 m apart, are located in siliceous sinter.

Temperature (springs): 62.2°C (144°F)

Spring Group 26

A pair of springs are located in siliceous sinter.

Temperature (springs): 76.8°C (170°F)

Estimated Flow Rate: 3 l/min

Spring Site 27

This spring is located in siliceous sinter.

Temperature (spring): 76°C (169°F)

Flow Rate: no estimate

Spring Site 28

This spring is located in siliceous sinter.

Temperature (spring): 66°C (150°F)

Flow Rate: no estimate

Spring Site 29

This spring issues from sintered gravels at the head of the open terrace.

Temperature (spring): 75.6°C (168°F)

Estimated Flow Rate: 2 l/min

Spring Group 30

One hot spring and two seeps issue from a bedding plane in bedded siliceous sinter (very low flow rate).

Temperature (springs): 88.9°C (192°F)

Spring Group 31

This group is very low in the sinter terrace at the base of a sharp break in slope. Two springs, 1.5 m apart, issue from fractures and bedding planes in the sinter deposit.

Temperature (springs): 90°C (194°F)

Estimated Flow Rate: 10 l/min

Spring Group 32

The springs lie along a 5-m-long, north-south line, at a break in slope on the terrace.

Temperatures (springs): 66.7°C (152°F), 86.7°C (188°F)

Estimated Flow Rate: 5 l/min

Spring Site 33

Spring Site 33 issues from a fracture below massive silica sinter (cemented gravel) at a break in slope.

Temperature (spring): 86.7°C (188°F)

Estimated Flow Rate: <2 l/min

Spring Group 34

Springs here are difficult to identify; they are in a 5- x 4-m bog with numerous seeps.

Temperature (springs): 67.8°C (154°F)

Estimated Flow Rate: 5 l/min

Spring Site 35

Spring Site 35 is located at a break in slope and has a very low flow rate.

Temperature (spring): 75°C (167°F)

Spring Site 36

This spring issues from the base of a manmade wall and a small terrace. It is located at a natural break in slope along the lower part of the sinter terrace.

Temperature (spring): 83.3°C (182°F)

Estimated Flow Rate: 10 l/min

Spring Site 37

Spring Site 37 issues from the base of fractures and bedding planes in siliceous sinter (cemented boulder conglomerate).

Temperature (spring): 88.9°C (192°F)

Estimated Flow Rate: 10 l/min

Spring Group 38

This large boiling spring is located at a break in slope of the sinter terrace, in the creek bottom. Some reddish, valley-fill conglomerates are visible below the sinter deposit. The two lines of boiling springs are 3 m, north-south, and 3 m, east-west.

Temperature (springs): 92.2°C (198°F)

Estimated Flow Rate: >10 l/min

Spring Group 39

Groups 39 and 40 lie along a northeast-trending line between Areas 1 and 4, parallel to the extension of a fault exposed to the northeast. These springs are located in a 30-m² boggy area, overlying siliceous sinter.

Temperatures (springs): 51.1°C (124°F), 48.9°C (120°F),
61.1°C (142°F), 90°C (194°F), in
sintered ground

98.9°C (210°F), 76.6°C (169°F)

Flow Rate: no estimate

Spring Group 40

This group covers 100 m² and overlies siliceous sinter (cemented gravel). The area is elongate, trending generally northeast. All springs have very low flow rates.

Temperatures (springs):	88.9°C (192°F), 90°C (194°F), 86.1°C (187°F), 71.1°C (160°F), 76.7°C (170°F)
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Stream below Area 1

Temperature:	45.6°C (114°F)
Estimated Flow Rate:	1000 l/min

B. Area 2

Area 2 is an open mound of siliceous sinter, located 150 m west of Area 1. It is ~40 x 60 m (oriented east-west) and 5 m thick; it slopes south at 5° (Plate 1). Two warm springs are located at the west end, issuing through massive siliceous sinter. Small seeps are located across the mound top.

Temperatures (springs):	60°C (140°F), 68.9°C (156°F)
Estimated Flow Rate:	5-10 l/min, <1 l/min

C. Area 3

These springs are within an area ~50 x 400 m, located 400 m west of Spring Group 1 (Area 1) and 200 m west of Area 2 (Plate 1). These hot springs are located along a north-south fault that cuts through schists and is overlain by a thin deposit of valley-fill conglomerates. Springs are present at the north end of the area, in sheared schist in the base of the stream, at and below a waterfall that crosses the fault scarp. Access is along a road from Area 2.

Upper (Northern) Spring Group

This group of seven springs, aligned north-south over a distance of 20 m, rises through fractured schists and a thin cover of stream gravel and

sand. Joints in the schist are oriented N5°W, 80°E, and north-south, 80°E. There is a faint sulphur smell.

Temperatures (springs):	70°C (158°F), 68.3°C (155°F), 71.1°C (160°F), 66.1°C (151°F), 67.8°C (154°F), 53.3°C (128°F), 65.6°C (150°F)
Estimated Flow Rates:	10 l/min, 3-5 l/min, 2 l/min
Temperature (streams):	30°C (86°F), above springs 48.9°C (120°F), below springs
Estimated Total Flow Rate (streams):	230 l/min, below springs

Middle Spring Group

These springs cover 9 m², located 50 m above the waterfall. They rise through stream gravel. No flow has been estimated as they are in and near the stream.

Temperatures (springs):	65.6°C (150°F), 61.1°C (142°F)
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Lower Spring Group (Waterfalls)

A waterfall drops 10 m over a fault in schist. Many hot springs issue from and above the fault. A small dam and reservoir have been constructed at the top of the falls to divert hot water to nearby houses.

Schists exposed below the waterfall have a lineation of east-west, 25°W. They are broken by large fractures 5 to 40 cm apart, oriented north-south, 75° to 80°E. Springs in this face are issuing from fractures and foliations. Farther south, along the stream, a fault scarp is visible with the same orientation as the fracture sets.

Cliff surfaces are partly covered with deposits of siliceous sinter up to 0.5 m thick. Not all spring temperatures were measured because some springs were inaccessible.

Temperatures (springs):	93.3°C (200°F), 95°C (203°F), 76.7°C (170°F), 78.9°C (174°F), cliff face
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Temperatures (streams):	60°C (140°F), 63.3°C (146°F), base of waterfall
Temperatures (springs):	64.5°C (148°F), 76.7°C (170°F), 68.9°C (156°F), 70°C (158°F), 64.4°C (148°F), 73.3°C (164°F), 45.6°C (114°F), fault scarp (Progression is from the waterfall to 140 m south along the stream.)
Flow Rate:	not estimated

D. Area 4 (Spring Group 41)

Area 4 is the westernmost cluster of hot springs at this site. It is located in and adjacent to a north-south stream (Plates 1 and 3). Springs here rise through schist, overlain by valley-fill deposits (agglomerates and conglomerates consisting of angular schist clasts). Valley-fill agglomerates are partly cemented by siliceous sinter. Springs in Area 4 are sources for a hot creek that flows south-southwest.

Spring Site 41A

This spring is one of the largest at this site. According to a resident, a blast (phreatic?) occurred several years ago, and this spring began flowing after that blast. It is located near the bottom of a stream at the base of a deposit of sintered boulders. The spring is 0.25 m deep and has a surface area of 0.5 m².

Temperature (spring):	95.6°C (204°F)
Estimated Flow Rate:	>50 l/min

Spring Site 41B

This spring is on the stream floor, 3 m east of Spring Site 41A, at the valley-fill/schist contact.

Temperature (spring):	90°C (194°F)
Estimated Flow Rate:	5 l/min

Spring Site 41C

This spring issues at a break in slope from poorly cemented (sinter) ground.

Temperature (spring):	93.3°C (200°F)
Flow Rate:	not estimated

Spring Site 41D

Spring Site 41D is located at the top of a small terrace composed of massive siliceous sinter (with angular schist clasts).

Temperature (spring):	75.6°C (168°F)
Estimated Flow Rate:	10 l/min

Spring Site 41E

This poorly developed spring on the stream floor rises through stream gravel. It is associated with numerous seeps.

Temperature (spring):	97.8°C (208°F)
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Spring Site 42

The creek divides here, with a hot spring (Spring Site 42) 10 m above the divide to the east. The western branch has cool water. This hot spring rises through valley-fill agglomerates cemented by siliceous sinter.

Temperature (spring):	64.5°C (148°F)
Estimated Flow Rate:	many tens of l/min

Spring Site 43

These hot springs are located on the stream floor, 50 m south of Spring Site 42. They form a north-south trend and are 10 m apart.

Temperatures (springs):	58.9°C (138°F), 62.3°C (144°F)
Flow Rate:	no estimate

IV. RELATIONSHIP BETWEEN STRUCTURE AND HOT SPRINGS

Hot springs of the San Ignacio area are clearly fault controlled. Most significant of these faults are northwest- and northeast-trending normal faults that bound the Valle de Siria and crosscutting, relatively young north-south high-angle normal faults that parallel the regional "graben trend" (Fig. 5). Certainly, other faults have controlled the location of springs in the past. Many of the hills along the north side of the Valle de Siria are mantled by older sinter deposits generally at higher elevations than those near the active springs; also, the older deposits are more extensive, suggesting a long history of thermal spring activity. A brief description of each area follows:

A. Area 1

The active hot springs of Area 1 lie near an inferred N70°E fault, which is the southwestern extension of the Arenal fault. The hottest springs of this area lie along a north-south band on the western margin of the area, suggesting control by a north-south fault, which was not seen, but which may be responsible for the north-south ridges on the south flank of hill 870.

B. Area 2

Area 2 also lies along the inferred N70°E-trending fault that passes through Area 1 and along a north-south topographic alignment of ridges on the south flank of hill 870.

C. Area 3

A high-angle, north-northwest-trending fault lies in the unnamed stream that passes through La Tembladera. Hot springs lie along this fault; the hottest springs are located where the north-south fault intersects a N70°E-trending extension of the Arenal fault.

Figure 5. Orientations of linear groups of springs and the orientations of controlling fractures.

the hottest springs are located where the north-south fault intersects a N70°E-trending extension of the Arenal fault.

D. Area 4

Area 4 is structurally complex, but it appears to lie near the intersection of an extension of the Arenal fault with an inferred north-south to N30°W fault along the eastern side of hill 870.

V. RECOMMENDATIONS FOR GEOPHYSICAL SURVEYS

A. Dipole-Dipole Resistivity Surveys

The purpose of these surveys is to identify zones of fracture permeability along faults and beneath a thin cover of valley-fill conglomerates and sandstones. These surveys will be designed for a 1-km-deep penetration.

A total line length for the recommended surveys is 4.4 km. A-A' is an approximately north-south line that passes through Area 1 and out into valley fill. It is parallel to the cross section of the site included in this report. Access is fairly easy from the road and across open fields. About 100 m is through acacia brush.

B-B' crosses Areas 1 and 3, normal to a series of mapped (and inferred) north-south faults. It also crosses a N45°W fault (extended from the south-east); such a line will locate this fault (and others) beneath the valley fill to the east of Area 1.

C-C' is parallel to and 650 m south of line B-B'. It will identify the southern extension of north-south faults into the valley and the northwest extension of northwest-trending faults, and the fault lines can be projected into the hot spring areas. C-C' is along a new road that parallels the mountain front.

D-D' is a short line across Area 4 located at the intersection of multiple faults (northeast, northwest, north-south). Area 4 includes one of the most active springs at this site.

B. Thermal Gradient Drilling

After results from water geochemistry and resistivity surveys are complete, Los Alamos National Laboratory and the Empresa Nacional de Energía Eléctrica will meet to identify locations for thermal gradient holes. Access to the area is excellent, and bringing in a small drilling rig should not be difficult.

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GEOLOGIC MAP OF THE SAN IGNACIO (LA TEMBLADERA) GEOTHERMAL SITE

GEOLOGIC CROSS SECTION THROUGH THE SAN IGNACIO
(LA TEMBLADERA) GEOTHERMAL SITE