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EXPLORATION AND DISCOVERY OF THE MIRAVALLES GEOTHERMAL FIELD, COSTA RICA: A CASE HISTORY

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Introduction

The Republic of Costa Rica is located north of Panama and south of Nicaragua on the Central American isthmus. It is the second smallest in area and the smallest in population of the Central American republics. Population is approximately 2,000,000, in an area of only 23,000 square miles, for an average density of about 90 persons per square mile. Further, approximately two-thirds of the population live in an upland valley of some 3,000 square miles, the Central Valley.

Topographically, the country is characterized by a narrow Pacific Coastal Plain, changing abruptly to steep-sided mountains of the Central Cordillera. There are several important high valleys within this Cordillera, as well as many active or potentially active volcanoes. Of these, Arenal and Irazu are often in eruption; Rincón de la Vieja erupted last in 1963. East of the Central Cordillera is the broad flat Atlantic Coastal Plain.

Agriculture dominates the economic life of Costa Rica: coffee, bananas, beef cattle, rice, sugar, corn. Costa Rica receives abundant rainfall, averaging over 2,000 mm (80 inches). As a result, electric power generation is almost entirely by hydropower, with small oil- and gas-fired plants for reserve use. Electric power consumption grows at about 8% per year, demand thus doubling every 10 years.

Antecedents of the Exploration Project

In 1963, a reconnaissance survey by the United Nations identified several areas of interest for geothermal exploration. However, it was not until the period of severe increases in fuel costs beginning in 1973 that a geothermal project was deemed useful. In 1975, the Instituto Costarricense de Electricidad (ICE) was authorized by the government of Costa Rica to accept a loan from the Inter-American Development Bank (IDB) for a geothermal feasibility study of one of the areas nomiated 12 years earlier by the United Nations. ICE selected Rogers Engineering Co., Inc. of San Francisco, and GeothermEx, Inc. of Berkeley, California, to serve as its advisors in this project (figure 1).

This involved design of an exploration program, importation of equipment and materials, training of ICE staff in geothermal exploration principles and methods, supervision of exploration, and interpretation of results obtained. The exploration program is summarized in Figure 2. Phase I of work was completed in 12 months ending December 1976. This phase included intensive field data collection and preliminary interpretations, and resulted in preparation of a pre-feasibility report to the IDB, which triggered release of additional funds for Phase II. Phase II may be said to have begun in 1978, with selection of Foraky-Foramines, a Franco-Belgian drilling contractor.

Exploration

The region selected for exploration consists of some 500 km^2 of rolling to steep, deeply incised volcanic uplands, located on the lower flanks of volcanoes Rincón de la Vieja and Miravalles (from which the project takes its name), and ranging in elevation from about 300 m to over 1 km. Several major fumarole and hot springs complexes were found to be clustered in bunches along a 40-km-long line trending northwest-southeast, parallel to the volcanic trend, and located at the break in slope on their lower flanks. The 3 most important thermal areas are Las Hornillas, Las Pailas and Borinquen, all fumarolic.

The area was mapped geologically at 1:50,000 scale; selected areas were then mapped at 1:25,000 scale. Samples of waters and gases were taken from over 100 springs and wells, both cool and thermal, for complete chemical analysis. Some 10 samples were analyzed for ^3H; and about 30 for trace metals. Numerous rock specimens were analyzed chemically also; and several dozen samples were submitted for petrographic analysis. A dozen rocks were age-dated by K-Ar method.

Geologic study (figure 3) revealed a Quaternary and Late Tertiary section of wide local variation and intense (though variable) hydrothermal alteration. These factors combined to limit correlation from area to area with much assurance. However, a general stratigraphy was established, and has proven very adequate in interpretation of data from deep drill holes.

Principal findings include (1) recognition of a partially buried caldera located between Miravalles and Rincón de la Vieja; (2) age-dating of a widespread thick dacite tuff sequence (Bagaces Formation) as late Pliocene to Pleistocene; (3) tentative identification of eruptive vents for these tuffs; and (4) location of numerous areas of hydrothermal alteration that apparently were fumarolic in earlier episodes.

A reconnaissance gravity survey of approximately 1 station per km^2 was carried out over the same area, and modeled with the geology. Simultaneously, a series of Schlumberger resistivity soundings were run, beginning at the major fumarole areas and extending between and outward from them. A total of 16 lines have been run to date, with expansions at first reaching AB/2 = 1,000 m and more recently 2,000 m. Stations were established every 200 m along these lines.

Data collections and interpretation was very difficult for a variety of reasons. First, humid tropical conditions and rugged terrain resulted in limited life for parts and supplies. Second, rapid lateral variations in geology (faults and volcanic-clastic facies changes) were not always recognized in time to plan their avoidance. Third, regional resistivity is extremely low across much of the region, resulting in signals at millivolt levels for many important areas.

Despite these difficulties, extremely useful and revealing data were thus obtained. A major low is recognized at the surface resulting from hydrothermal alteration of the surface volcanic rocks. This low projects downward very precipitously, indicating probable fault control over the upwelling fluids. One sounding shows a multi-layer structure, with high resistivity in the shallow volcanic rocks above the regional water table; and an intense low extending to about 500 m beneath the surface zone. Beneath this, resistivity appears to increase, but not to extremely high levels. A second sounding shows that hydrothermal alteration has destroyed the shallow surface high, and has intensified the low at 300-500 m.

Hydrologic data were collected along with geochemical surveys, providing data on rainfall, runoff and evaporation, as well as on recharge and discharge paths of groundwater movement. From a study of the lithology of spring-discharge points, the Bagaces Formation was identified as a major regional aquifer, locally discharging thermal waters.

From these surveys it was possible to construct a powerful model of thermal and cool meteoric circulation. This in turn was correlated with geologic mapping and gravimetry models, both of which showed a north-south-trending graben or complex fault structure, intersecting the northwest structural trend at Miravalles volcano. The presence of the partially buried caldera at this intersection with the graben or half-graben appears to have localized the Las Hornillas thermal manifestations, perhaps as a result of a minor resurgent magmatic intrusion in post-caldera time.

However, it was temperature-gradient drilling that provided the greatest subsurface detail and most important information for siting of deep exploratory wells. During 1975-1978 some 38 gradient holes were drilled, to depths of 20 to nearly 300 m. Initially it was planned to drill at each of the important geologic-geochemical-geophysical anomalies; however, the difficulty of access to many areas, and the impressive nature of the Las Hornillas thermal and chemical anomaly, caused us to drill all but 7 gradient holes in the greater Las Hornillas area.

From this work, an intense and widespread gradient anomaly was identified at shallow depth, extending north-northeast-south-southwest, and having closure of over 400°C/km across at least 10 km^2. All holes were cored continuously to TD, because of lost circulation and other problems. Holes to over 200 m always encountered severe drilling difficulties, one blowing out from about 260 m. Several holes encountered temperatures of about 100°C. Two were significantly hotter: PH-27 (the blow out, at La Fortuna) was over 150°C at ∿250 m; PH-31 (at Las Hornillas) was 192°C at 285 m. The holes were 3.5 km apart, and within the high-gradient, low-resistivity anomaly.

Data for the first 27 holes in the greater Las Hornillas region are shown in figure 4. Thermal conductivity measurements were made routinely on cores, and heat flow was calculated for multiple intervals in most holes. A map of heat flow values for the Las Hornillas area (figure 5) shows contours to be almost identical to those of temperature gradient. Gradient values projected to an intersection with the boiling point curve by 500 or 600 m at depth; further projections yielded molten conditions 1.5 km or 2.0 km. It was, however, considered more likely that a hot water aquifer, was present, at a temperature below the boiling point for its depth, at perhaps 300 to 500 m, which depths were indicated by reversals in electrical resistivity soundings.

Geochemically, it was determined that likely reservoir fluid would be saline hot water (8,000-12,000 mg/l TDS) with temperature of 220°C or higher. The geochemical-hydrologic model inferred that upwelling of very hot water was occurring near Las Hornillas along an unmapped fault, perhaps from depths of 1.5 or 2.0 km, or even deeper, and was dispersed very rapidly north and south through permeable beds of the Bagaces Formation.

On this basis, sites were selected for 7 deep exploratory holes at Las Hornillas and vicinity. Depths of 600 m to 1.3 km were chosen. Well design was agreed upon, and the call was made for bids from drilling contractors.

While selection of a drilling contractor, contract negotiations and rig mobilization was accomplished, geochemical, geologic and geophysical exploration continued. Further resistivity lines were run, and selected stations were reoccupied to sound to 2 km depth. A comparison of wet season-dry season geochemistry was made, with results indicating that dilution of surface springs did occur, with a lag of perhaps 3 to 5 months after onset of rainy season. This resulted in a slight upward adjustment of estimated reservoir temperature.

Additional K-Ar age-dating of rock samples, detailed mapping of drill sites, construction of geologic cross-sections through the several proposed drill sites, and revision of the detailed local stratigraphy also was accomplished. Three additional gradient holes were drilled, to over 150 m each. These helped to extend and better define the boundaries of the high-gradient anomaly. Further modeling of the gravity and resistivity data was done also.

In April 1979, deep exploratory drilling began in hole PGM #1. Targeted depth was 1 km, with possibility of a fractured reservoir from 600 m, based on temperature gradient, resistivity and geochemical data. PGM #1 went to 1,300 m in depth, and was completed early in August 1979. The extremely long drilling period reflects serious troubles with the drill rig, and a difficulty in logging and testing the hole. Holes PGM #2 and #3 were drilled immediately after, during the period September 1979-March 1980. Thereupon, drilling was suspended, the rig released, and a period of well testing and data analysis was begun.

Results of the 3 holes are shown in figures 6 and 7. Each hole penetrated a very young section of lahar and andesitic lava, beneath which was encountered a thick set of lithic and crystal tuffs, with locally interbeddded silty sediment. The tuffaceous section is believed to be Bagaces Formation, which her is highly fractured and mineralized, and which serves as the geothermal reservoir. At varying depth into the Bagaces, each hole experienced total loss of circulation, which never was regained to total depth.

PGM #1 reached 1,300 m TD. #2 was 1,163 m, and #3 was 1,208 m in depth. Each bottomed in the same lithic tuff sequence, as far as can be determined from cores cut on bottom. Correlations made in figure 6 are tentative. Temperatures were expected to be high in each hole on the basis of gradients in shallow holes, and on the basis of the 192°C observed in PH-31, very close to the site of PGM #1.

Temperatures did indeed rise very rapidly in all 3 holes. However, in #1, there was a sharp reversal at about 320 m, just below the maximum depth reached in gradient drilling. This clearly illustrates the difficulty in utilizing gradient data exclusive of other parameters. All holes showed very slow temperature build-up in zones of massive lost circulation. For example, PGM #2 took 15,000 m^3 of fluid in the zone below 850 m. This zone to date is still making slow recovery in temperature.

Temperatures had reached a maximum of about 230°C in PGM #1 prior to inducing it to flow. This was essentially the value predicted by geothermometry. After flow began in September 1979, temperature downhole increased slowly to the present 238°C. PGM #2, as indicated above, has not reached temperatures as high as #1 or #3. The maximum reported is 212°C, in a zone at 850 m and again at TD (1,160 m). Not surprisingly, this hole has not yet been induced to flow continuously, despite repeated attempts to unload it. PGM #3 has recovered to 240°C over a 2- month period of intermittent testing.

PGM #1 is an unqualified success, flowing some 600,000 lb/hr of mass at about 150 psig. Flow temperature has risen slowly, to over 350°F at the surface. TDS is about 9,000 mg/1, very close to that predicted by geochemical-hydrological modeling. No scaling haw been observed. Long-term pressure drawdown tests are underway; no firm results are available. However, estimates of 6 MWe of electric power potential have been made.

PGM #2 probably will not be completed as a production well. It is unclear whether the hole was damaged during drilling and completion, or whether formation permeability is lower here than elsewhere. Considering the vast quantities of drilling fluid lost in #2, the latter appears unlikely. No -geophysical logs were run in this program, other than temperature surveys, for a variety of reasons having to do with cost. This, of course, has hampered our efforts to determine the true condition of PGM #2. Testing is continuing.

PGM #3 has been tested only intermittently; therefore, its flow characteristics are not known for certain. However, it appears to have as strong a potential as PGM #1. Certainly, it has recovered temperature as rapidly as did PGM #1.

From this drilling program, plus the continuing effort to model geologic, geochemical and geophysical data, a schematic representation of the geothermal system has been drawn (figure 8). A very hot aquifer is present at 200-300 m, with temperature of over 100°C (in PH-31, temperature reached 192°C in this zone). It appears to be fed by leakage upward along a major fault of fault set.

Background gradient of the region is approximately 35-40°C/km, as measured in numerous holes. This is slightly above what might be expected, but is not unusual for such youthful volcanic terrain as this. As one approaches the thermal system, gradient increases to about 100°C/km. This gradient would yield attractive temperatures at depths of 2 km, and is so indicated over an area of some 20-25 km^2.

The area above the presently defined geothermal field has an average gradient of over 400°C/km; this however is entirely due to the shallow hot aquifer, and is misleading in any attempts to model deep temperatures. Net gradients calculated to about 1 km from deep drilling are about 200°C/km, and yield temperatures just over 200°C at 1km depth. The shape of this 200°C isotherm at depth (figure 8) is uncertain. It may plunge steeply, as suggested by resistivity data; or it may extend horizontally for several km, sloping gently to reach 2 km in depth at a distance of several km from Las Hornillas.

The best estimate is that some 10-12 km^2 are underlain by potential geothermal reservoir at 1 km; and that out from this zone, drilling may encounter suitable temperatures at 1.5 to 2.0 km over an extensive area.

There are plans to drill additional wells into the 1 km section of the field after the financing for the next stage has been secured, and after a drill rig is imported for permanent use in Costa Rica. This may be early 1981. There are no present plans to test the 2 km zone. However, rig specifications call for 2 km depth capacity. A dozen sites have been selected for 1 km holes, and are to be prepared for drilling later this year.

Exploration is continuing in adjacent areas. Several gradient holes have been sited for drilling to 200 m at distances of up to 10 km from the present field. Hydrologic and geochemical monitoring are continuing. A microseismic network of 5 instruments has been installed, and has begun to collect data on regional seismicity. Geologic mapping will extend into adjacent areas also; and electrical resistivity lines are to be run into additional areas of promise.

After the testing program has been completed later this year, a technical and economic feasibility report will be presented to the lending agency, IDB. If reservoir potential is seen to be adequate, the first of what may be several power plants will be designed for construction. It is hoped to have the first geothermal power on line in 1984, the year in which reserve installed hydroelectric capacity will be exhausted by growing demand.

Reference

Koenig, James B. "Exploration of the Guanacoste, Costa Rica, Geothermal System," Geothermal Resources Council, Transactions, Volume 1, May 1977.

BRIEF HISTORY
MIRAVALLES GEOTHERMAL PROJECT

KEY PARTICIPANTS:

Instituto Costarricense de Electricidad, San Jose, Costa Rica (ICE)

GeothermEx, Inc., Berkeley, California

Rogers Engineering Co., Inc., San Francisco, California

Funded by Interamerican Development Bank (IDB)

MAJOR EVENTS:

Year Begun: 1975
- Loan Granted to ICE by IDB
- ICE & GeothermEx begin exploration work

1976:
- Field work completed, Phase I
- Feasibility report prepared for IDB for Phase II (Drilling)
- Training mission in USA for ICE geotechnical staff

1977:
- Drilling specifications prepared, bid
- Loan granted by IDB for Phase II
- Gradient drilling, other exploration continues

1978:
- Drilling contractor selected (Foraky-Foramines)
- Costa Rican government delays acceptance of Phase II loan
- Gradient drilling, other exploration, revised reports

1979:
- Costa Rican government approves Loan
- Drilling begins
- PGM #1 and #2 drilled, logged, tested

1980:
- PGM #3 drilled, logged
- ICE sets specifications for purchase of drill rig
- Feasibility report for 1st 30 MWe power plant

FIGURE 1

MIRAVALLES GEOTHERMAL PROJECT
EXPLORATION PROGRAM

1975: Geologic mapping, 1:50,000 500 sq. km.
Geochemical sampling begins, springs and fumaroles
Preliminary geoelectrical surveys - discontinued

1976: Geologic mapping completed 500 sq. km.
Geochemical sampling, analysis completed, some 100 springs, wells, fumaroles
Detailed geologic mapping + 1-m T surveys of fumarole areas, Las Hornillas, Las Pailas, Borinquen, etc.
Schlumberger soundings, 1 km maximum depth, 10 lines of average 5 km length, stations at 200 m.
Gravity survey, average 1 station per sq. km., 500 stations
Hydrologic-climatologic survey, data compilation
Temperature-gradient drilling, approximately 34 holes to dept of 20, 50, 100 and 250 m, in 3 major areas
(All of this material used in technical feasibility report on Phase I)

1977: Geochemical sampling of additional springs, wells; resampling for rainy-dry season differences
Temperature-gradient drilling of 3 additional holes, 150-300 m, major target area
Schlumberger soundings along 3 additional lines, to maximum depth of 1.5-2.0 km, station at 200 m., total 8 km.
Gravity survey remodeled using other programs
Radiometric age-dating of selected cores, outcrop samples
Continued geologic mapping, 1:20,000 scale, selected areas

1978: Geochemical-hydrologic modeling of Miravalles geothermal system
Temperature-gradient drilling of 1 additional hole, 150 m

1979: 1 additional Schlumberger sounding run in area of uncertain structure
1 additional temperature-gradient hole drilled, as fill-in
Microseismic network installed, begins data collection

1980-81: (planned): Temperature-gradient drilling, 3-6 holes, 150-250 m
Continued Schlumberger soundings to 2 km, along selected lines
Remodeling of geologic, geochemical and gravity data
Additional microseismic monitoring
Additional hydrologic monitoring, data compilation

FIGURE 2

GENERALIZED GEOLOGIC COLUMNAR SECTION
MIRAVALLES GEOTHERMAL AREA
(Thickness data) [age-dating]

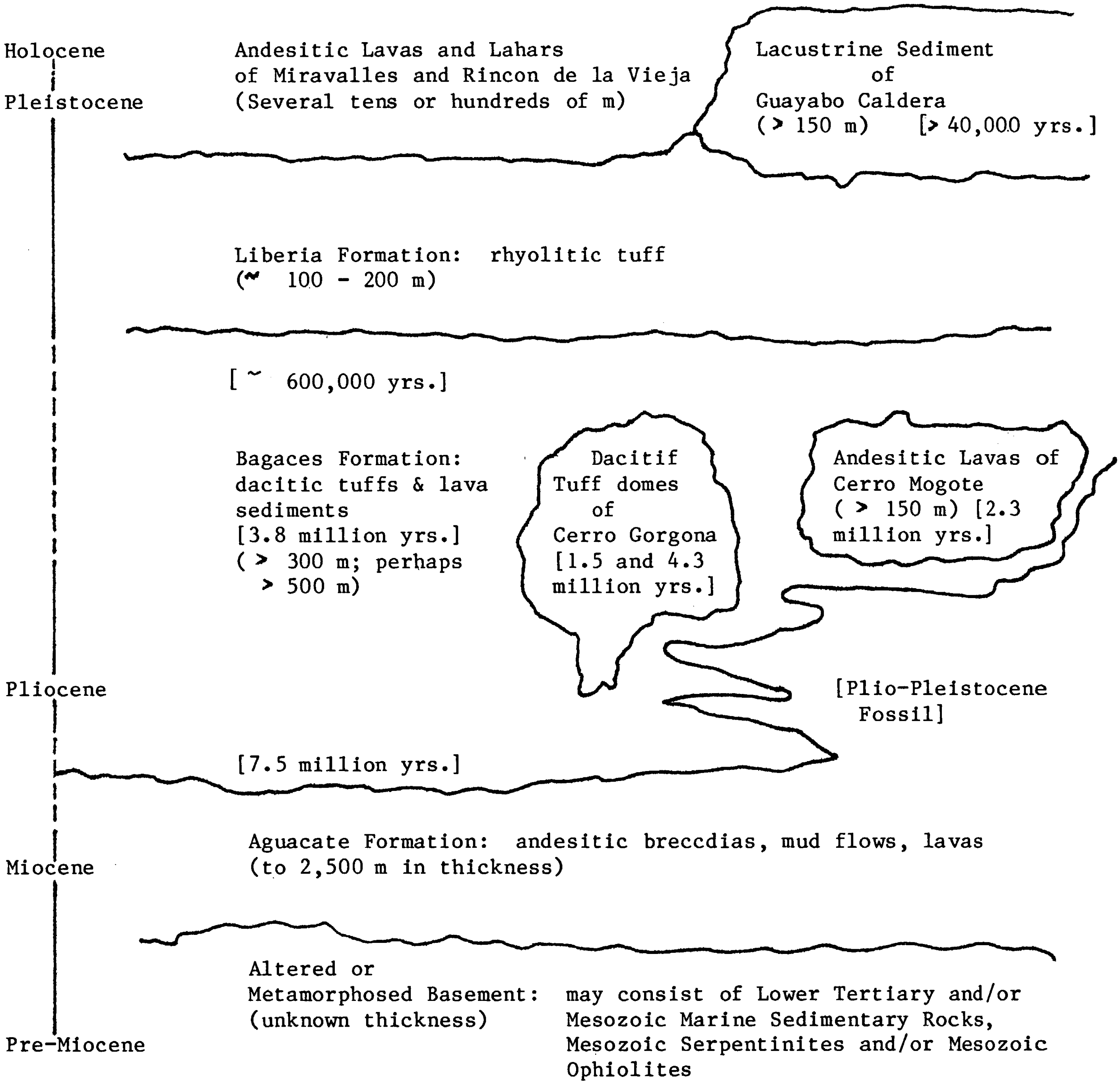


FIGURE 3

BASIC DATA FOR THE CALCULATION OF HEAT FLOW
IN THE ZONE MIRAVALLES GEOTHERMAL AREA

Well No.	Interval of Depth	Thermal Gradient	Thermal Conductivity	No. of Sample Analyses	Heat Flow in the Interval
	(meters)	(°C/Km)	(cal x cm^{-1} x $sec.^{-1}$ x $°C^{-1}$)	(Sample No.)	(cal x cm^{-2} x $sec.^{-1}$)
PH-1	0-15	20	* (2.0)	-	0.4×10^{-6}
PH-2	0-20	100	* (2.0)	-	2×10^{-6}
PH-3	0-20	1000	* (3.5)	-	35×10^{-6}
PH-4	15-50	20	3.13×10^{-3}	48	0.63×10^{-6}
PH-5	0-20	400	3.13×10^{-3}	86	12.50×10^{-6}
PH-6	10-30	280	-	-	-
	30-50	480	4.72×10^{-3}	17-92	22.66×10^{-6}
PH-7	30-55	55	2.07×10^{-3}	10-14	1.14×10^{-6}
	65-128	65	1.82×10^{-3}	9-11-12-13	1.18×10^{-6}
PH-8	0-20	275	1.90×10^{-3}	19	5.23×10^{-6}
PH-9	5-20	100	1.77×10^{-3}	34	1.77×10^{-6}
PH-10	7.50-20	135	1.77×10^{-3}	34	2.40×10^{-6}
PH-11	15-50	40	3.34×10^{-3}	33-35	1.34×10^{-6}
PH-12	5-35	105	4.18×10^{-3}	18-46-47	4.39×10^{-6}
PH-13	5-35	1200	3.69×10^{-3}	25-37	44.28×10^{-6}
PH-14	5-60	170	3.08×10^{-3}	23-27-28-29-30-31-58	5.24×10^{-6}
	30-110	255	3.37×10^{-3}	59	8.59×10^{-6}
	60-150	345	3.37×10^{-3}	59	11.62×10^{-6}
PH-15	20-40	200	2.85×10^{-3}	36	5.70×10^{-6}
	40-50	850	2.18×10^{-3}	26	18.53×10^{-6}
PH-16	0-35	50	3.53×10^{-3}	21	1.77×10^{-6}
PH-17	0-50	**	3.54×10^{-3}	15-16-20-61-62	
PH-18	0-30	315	3.32×10^{-3}	22-24	10.46×10^{-6}
PH-19	0-40	60	4.01×10^{-3}	55	2.41×10^{-6}
	40-70	200	3.26×10^{-3}	53-54	6.52×10^{-6}
	70-100	610	3.32×10	51-56	20.25×10^{-6}
PH-20	0-10	***	-	-	-
PH-21	0-30	2500	3.51×10^{-3}	52-57	87.75×10^{-6}
PH-22	10-35	678	3.73×10^{-3}	77-90	25.29×10^{-6}
PH-23	5-35	475	3.28×10^{-3}	65	15.69×10^{-6}
PH-24	5-100	**	3.40×10^{-3}	63-66	-
PH-25	0-40	460	3.17×10^{-3}	64-67-68	14.60×10^{-6}
PH-26	0-80	***	-	-	-
PH-27	0-190	700	3.63×10^{-3}	68	25.41×10^{-6}

FIGURE 4

MAP OF HEAT FLOW VALUES

Miravalles Geothermal Area

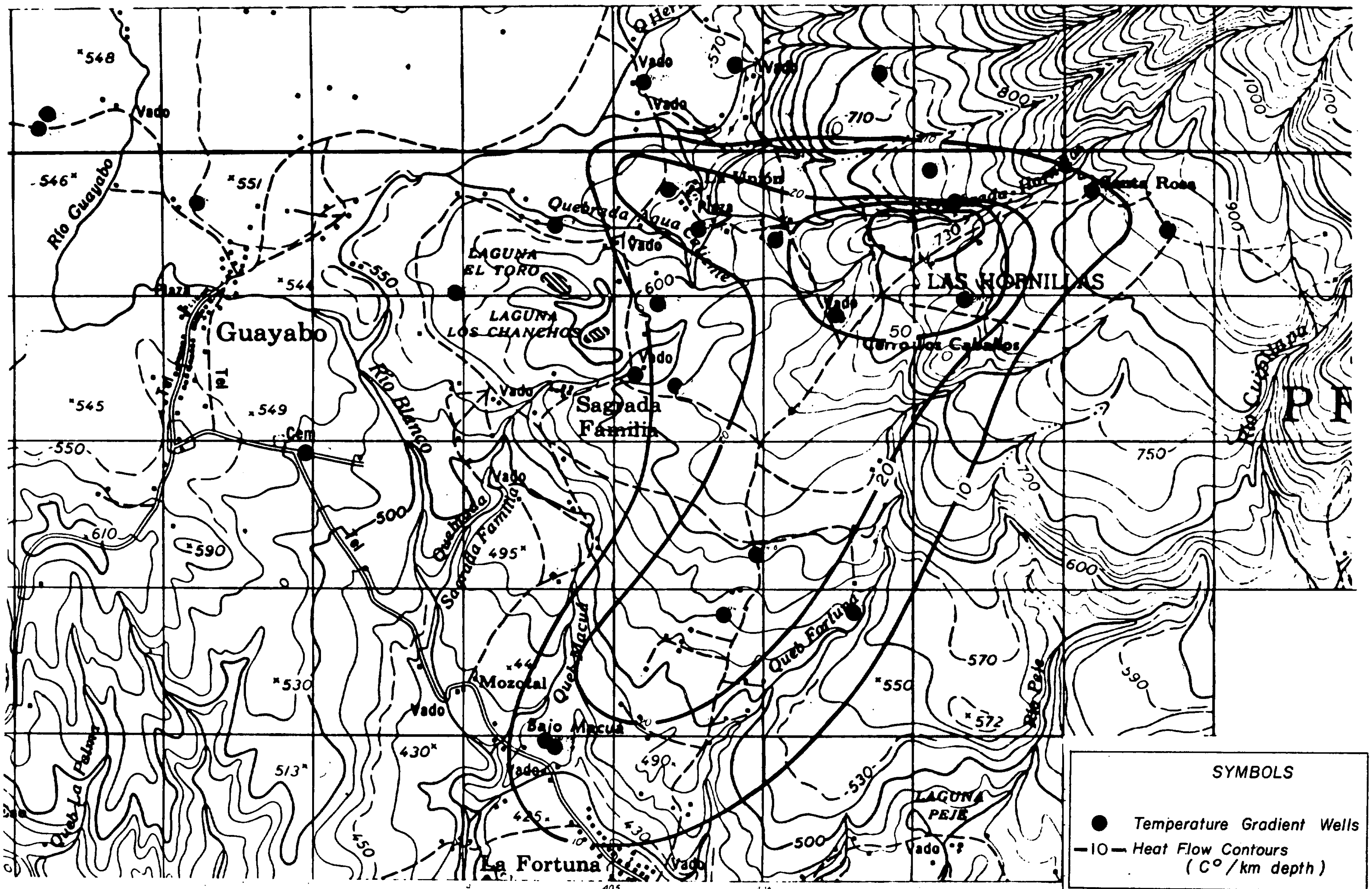
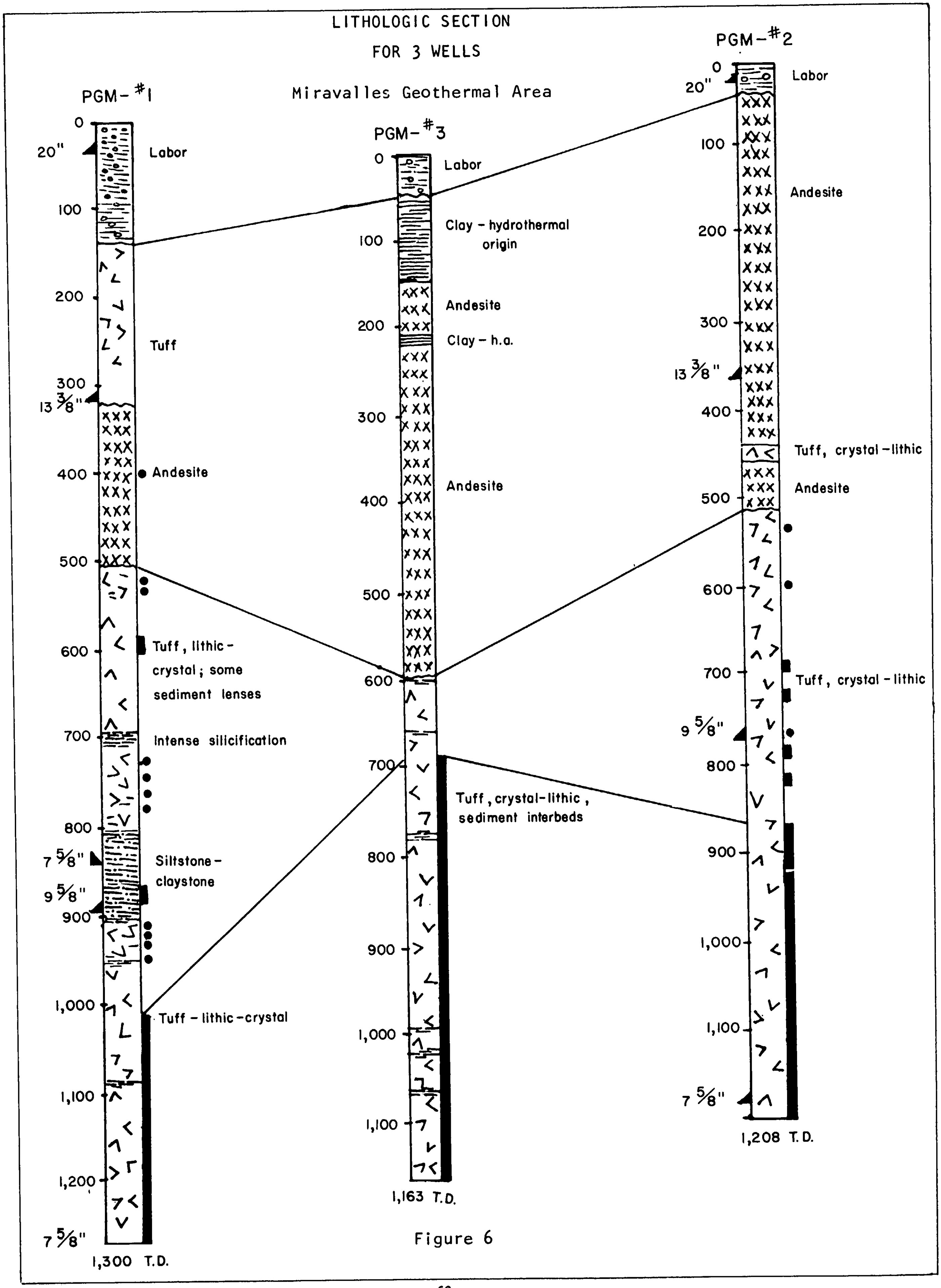
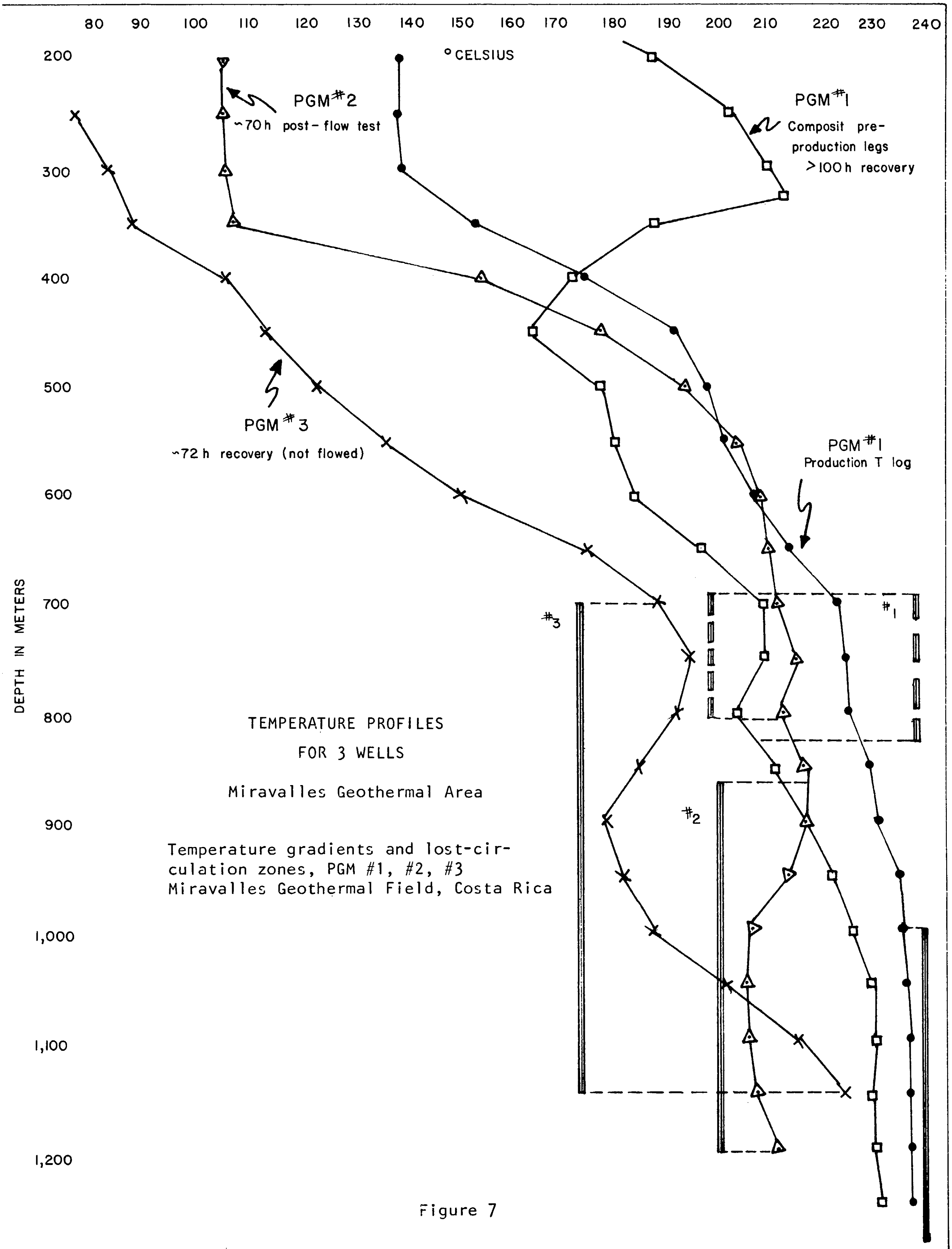


FIGURE 5


LITHOLOGIC SECTION
FOR 3 WELLS
Miravalles Geothermal Area
PGM-#1
PGM-#3
PGM-#2
Labor
Tuff
Andesite
Tuff, lithic-crystal; some sediment lenses
Intense silicification
Siltstone-claystone
Tuff - lithic-crystal
Clay - hydrothermal origin
Clay - h.a.
Tuff, crystal-lithic, sediment interbeds
Tuff, crystal-lithic
20"
13 3/8"
9 5/8"
7 5/8"
1,300 T.D.
1,163 T.D.
1,208 T.D.
Figure 6



Temperature gradients and lost-circulation zones, PGM #1, #2, #3 Miravalles Geothermal Field, Costa Rica

Figure 7

A SCHEMATIC OF THE
GEOTHERMAL SYSTEM

Miravalles Geothermal Area

1. Non-thermal background ~ 35°- 40° C/km (~ 100° C @ 2km)
2. Thermal halo of Las Hornillas ~100°-150° C/km (200° C @ 2km)
3. Very shallow hot aquifer ~ 300°->1,000° C/km (~100°-200°C @ 300m)
4. Shallow geothermal field ~ 200° C/km (~ 200°-240°C @ 1km)
5. Deep geothermal field ~ 125°-160° C/km (~ 240°-? C @ 2km)
6. Possible redrill or new well to tap deep geothermal field

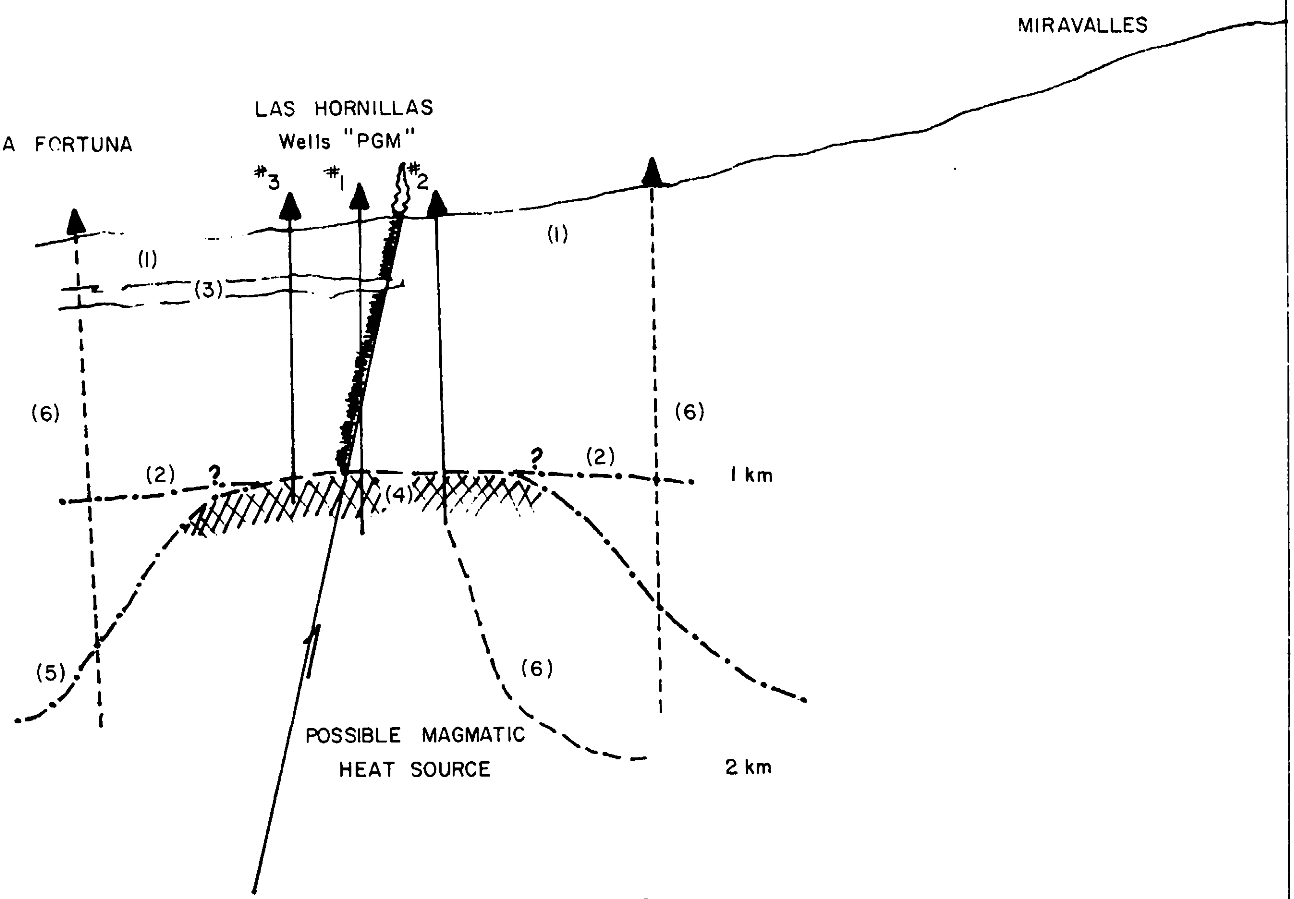


Figure 8