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***Hydrogeochemical Investigation
of Six Geothermal Sites in
Honduras, Central America***

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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LA-10785-MS

UC-66b

Issued: June 1987

LA--10785-MS

DE87 014713

Hydrogeochemical Investigation of Six Geothermal Sites in Honduras, Central America

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CONTENTS

EXECUTIVE SUMMARY	xv
ABSTRACT	1
I. INTRODUCTION	2
II. REGIONAL GEOLOGIC SETTING AND STRATIGRAPHY	2
A. Setting	2
B. Stratigraphy	5
III. REGIONAL HEAT FLOW	8
IV. REGIONAL ISOTOPES OF WATER	9
A. Stable Isotopes	9
B. Tritium	16
V. CHEMICAL CHARACTERISTICS OF THERMAL AND NONTHERMAL WATERS	22
A. Major Species in Nonthermal Waters	22
B. Minor Species in Nonthermal Waters	24
C. Major Species in Thermal Waters	24
D. Soluble Elements in Thermal Waters	28
E. Alteration of Thermal Waters	28
F. Thermal Water Compositions and Reservoir Rocks	29
G. Sulfate/Oxygen-18 in Cold Waters	32
VI. GEOTHERMOMETRY OF HOT SPRING DISCHARGES	35
A. Silica and Cation Geothermometry	39
B. Mixing Calculations	40
C. Isotope Geothermometry	42
D. Gas Geothermometry	43
VII. HOT SPRING DEPOSITS	43
VIII. PLATANARES SITE	47
A. Geology	49
B. Surface Features	50
C. Chemistry	52
D. Stable Isotopes	54
E. Tritium	57
F. Chemical Geothermometry	59
G. System Model	60
H. Power Output of the Hot Spring System	64

IX.	SAN IGNACIO SITE	66
	A. Geology	67
	B. Surface Features	67
	C. Chemistry and Stable Isotopes	70
	D. Tritium	78
	E. Chemical Geothermometry	78
	F. System Model	80
	G. Power Output of Surface Features	81
X.	AZACUALPA SITE	82
	A. Geology	82
	B. Surface Features	84
	C. Chemistry and Stable Isotopes	86
	D. Tritium	92
	E. Chemical Geothermometry	92
	F. System Model	93
	G. Power Output of Surface Discharges	94
XI.	CHOLUTECA REGION	96
	A. Geology	96
	B. Surface Features	98
	C. Chemistry	100
	D. Stable Isotopes	103
	E. Tritium	104
	F. Chemical Geothermometry	105
	G. System Model	106
	H. Power Output of System	107
XII.	LA CEIBA REGION	107
	A. Geology	107
	B. Surface Features	109
	C. Fluid Chemistry	111
	D. Stable Isotopes	112
	E. Tritium	116
	F. Chemical Geothermometry	116
	G. System Model	116
	H. Power Output	118
XIII.	EL OLIVAR SITE	119
	A. Geology	120
	B. Surface Features	121
	C. Chemistry	121
	D. Stable Isotopes	124
	E. Tritium	128
	F. Chemical Geothermometry	128

G. System Model	129
H. Power Output	131
XIV. CONCLUSIONS	131
XV. RECOMMENDATIONS	134
A. Site-Specific Geochemistry	134
B. Regional Geochemistry	135
C. Location of Thermal Gradient Hole at Platanares	135
D. Location of Thermal Gradient Hole at San Ignacio	135
E. Location of Thermal Gradient Hole at Azacualpa	136
ACKNOWLEDGMENTS	136
REFERENCES	137
APPENDIX A: HYDROGEOCHEMICAL DATA	143
APPENDIX B: TRITIUM CODES	164

TABLES

I.	Temperature, Silica Content, Chloride Content, and Rock Type of 19 Cold Waters in Western Honduras (see Fig. 5 for locations) . .	11
II.	Deuterium, Oxygen-18, and Tritium Analyses From Shallow Groundwaters, Streams, and Lago de Yojoa, Honduras	13
III.	Weighted-Mean Tritium Values From Precipitation in Selected Areas of Central America and the United States	17
IV.	Time Constants, Intercepts, and Correlation Coefficients For Exponential Curve Fits of the Tritium Concentration in Precipitation From Various Stations	21
V.	Carbon-13 Values of Rocks, Waters, and Gases from Honduras Geothermal Systems	33
VI.	Sulfate and Water Oxygen-18 Isotope Compositions and Calculated Equilibrium Isotope Temperatures	36
VII.	Chemical Geothermometers Used in These Investigations	38
VIII.	X-ray Diffraction Analyses of Spring Deposits, Cements, and Fracture Fillings at Platanares, San Ignacio, and Pavana Geothermal Sites, Honduras	45
IX.	Temperature, Calcium Content, and Bicarbonate Content of End-Member Thermal Waters	46
X.	Major Chemistry and Isotope Data for the Platanares Geothermal System	58
XI.	Calculated Geothermometers for the Platanares Geothermal System .	60
XII.	Calculated Geothermal Fluid in Quebrada Agua Caliente Downstream from all Hot Springs	65
XIII.	Major Chemistry and Isotope Data for the San Ignacio Geothermal System	71
XIV.	Calculated Geothermometers for the San Ignacio Geothermal System	77
XV.	Major Chemistry and Isotope Data for the Azacualpa Geothermal System	87
XVI.	Calculated Geothermometers for the Azacualpa Geothermal System .	94
XVII.	Major Chemistry and Isotope Data for the Choluteca Geothermal Region	102

XVIII.	Calculated Geothermometers for the Choluteca Geothermal Region .	105
XIX.	Major Chemistry and Isotope Data for the La Ceiba Geothermal Region	113
XX.	Calculated Geothermometers For Geothermal Systems in the La Ceiba Region	117
XXI.	Major Chemistry and Isotope Data for the El Olivar Geothermal Region	125
XXII.	Calculated Geothermometers For Geothermal Systems in the El Olivar Region	129
XXIII.	Summary of Averaged Geothermal Calculations (°C) for Geothermal Sites in Honduras (underlined values represent estimated reservoir temperatures)	133
XXIV.	Power Output of Surface Discharges at Six Geothermal Sites, Honduras	134

APPENDIX TABLES

A-I.	Location, Field Data, and Comments For Thermal and Nonthermal Waters of Honduras	144
A-II.	Major Element Analyses in mg/l for Thermal and Nonthermal Waters of Honduras	151
A-III.	Trace Element Analyses in mg/l for Thermal and Nonthermal Waters of Honduras	154
A-IV.	Isotope Analyses for Thermal and Nonthermal Waters of Honduras .	157
A-V.	Calculated Geothermometer Temperatures (°C) for Thermal Fluids of Honduras	160
A-VI.	Residence Times for Tritium Concentrations Under Well-Mixed and Piston-Flow Conditions in Central America (Base Year is 1985) . .	163

FIGURES

1. Map of Honduras showing locations of the six geothermal prospect areas described in this report.	3
2. Schematic cross section showing the relation of Tertiary volcanic rocks to Cretaceous sedimentary rocks and underlying metamorphic basement in Honduras (modified from McBirney and Weill, 1966)	3
3. Rotation of upper crustal blocks in northern Central America and attendant morphotectonic effects.	4
4. Stratigraphic nomenclature in Honduras (Finch, 1981)	5
5. Map of Honduras with sample site locations.	10
6. Map of North America showing contours of the approximate average δD values of meteoric surface waters (from Taylor, 1974) .	12
7. Plot of δD versus $\delta^{18}O$ for the cool groundwaters and surface waters of Honduras listed in Table II.	14
8. Plot of δD versus $\delta^{18}O$ for the geothermal waters and surface waters of Honduras (from data listed in various tables of text and in Appendix A).	15
9. Plot of logarithm (base 10) of tritium concentration versus time for all data presented in Table III.	20
10. Plot of mean residence time versus tritium concentration with curves representing the well-mixed and piston-flow models for Central America.	22
11. Schoeller diagram of cold waters of Honduras.	25
12. Schoeller diagram of waters from Platanares.	25
13. Schoeller diagram of waters from San Ignacio.	25
14. Schoeller diagram of waters from Azacualpa.	25
15. Schoeller diagram of waters from the Choluteca region.	26
16. Schoeller diagram of waters from the La Ceiba region.	26
17. Schoeller diagram of waters from the El Olivar area.	26

18.	Diagram showing B/Cl ratios (molar) of Honduras thermal waters compared with B/Cl ratios of selected geothermal waters around the world.	31
19.	Diagram showing total dissolved CO ₂ /Cl ratios (equivalence) of Honduras thermal waters compared with those of selected geothermal waters around the world.	31
20.	Diagrams showing log He and log NH ₃ (moles/mole dry gas) of Honduras hot spring gases compared with those of selected hot spring gases from geothermal sites around the world.	31
21.	Diagram showing N ₂ /Ar ratios (molar) of Honduras hot spring gases compared with N ₂ /Ar ratios of selected hot spring gases from geothermal sites around the world.	31
22.	Diagram showing carbon-13 in CO ₂ gas [‰ relative to Pee Dee Belemnite (PDB)] of Honduras hot spring gases compared with that of selected hot spring gases from geothermal sites around the world and with that from common carbon sources.	32
23.	Regional stratigraphy of Honduras related to location of thermal aquifers.	35
24.	Plot of silica versus temperature with curves representing the solubilities of various silica phases.	44
25.	Map of the Platanares geothermal area, Honduras, showing locations of various springs and faults.	48
26.	Photograph of waterfall in the Quebrada Agua Caliente looking northwest.	49
27.	Photograph of superheated hot spring PL-3 that issues from fractured silicified tuff on the northeast side of the Quebrada Agua Caliente.	51
28.	Plots of B, Li, and F versus Cl for thermal and nonthermal waters of Platanares, Honduras.	53
29.	Plot of spring temperatures versus Cl for thermal and nonthermal waters at Platanares, Honduras.	54
30.	Plot of SiO ₂ versus Cl for thermal and nonthermal waters at Platanares, Honduras.	55
31.	Plot of δD versus δ ¹⁸ O for thermal and nonthermal waters at Platanares, Honduras.	56
32.	Plot of δD versus Cl for thermal and nonthermal waters at Platanares, Honduras.	56

33. Plot of tritium versus Cl for the thermal and nonthermal waters at Platanares, Honduras.	59
34. Plot of enthalpy versus Cl for the thermal and nonthermal waters at Platanares, Honduras.	61
35. Plot of silica versus enthalpy for the thermal and nonthermal waters at Platanares, Honduras.	61
36. Schematic model of the Platanares geothermal system, Honduras. . .	62
37. Map of the San Ignacio geothermal area, Honduras, showing locations of various springs and faults.	66
38. Detailed map of the main spring area (Area 1), San Ignacio, Honduras.	68
39. Photograph looking due east of silica terrace at main spring area, San Ignacio, Honduras.	69
40. Photograph of hot springs at San Ignacio, Honduras.	69
41. Plot of δD versus Cl for thermal and nonthermal waters of San Ignacio, Honduras.	72
42. Plots of B, F, Li, and total HCO_3 (CO_3+HCO_3) versus Cl for thermal and nonthermal waters at San Ignacio, Honduras.	73
43. Plot of δD versus $\delta^{18}O$ for thermal and nonthermal waters at San Ignacio, Honduras.	76
44. Plot of Ca versus Cl for thermal and nonthermal waters at San Ignacio, Honduras.	76
45. Plot of tritium versus Cl for thermal and nonthermal waters at San Ignacio, Honduras.	79
46. Plot of silica versus Cl for thermal and nonthermal waters at San Ignacio, Honduras.	79
47. Schematic model of the San Ignacio geothermal system, Honduras. .	81
48. Map of the Azacualpa geothermal area, Honduras, showing locations of hot springs and faults.	83
49. Photograph looking north toward La Cueva and hot spring AZ-5, Azacualpa, Honduras.	85
50. Photograph looking north of hot spring AZ-8, which issues from faulted limestone in the gorge of the Río Jaitique.	86

51. Plots of B, F, and Li versus Cl for thermal and nonthermal waters, Azacualpa, Honduras.	88
52. Plots of Ca, SiO ₂ and NH ₄ versus Cl for thermal and nonthermal waters, Azacualpa, Honduras.	90
53. Plot of δD versus Cl for thermal and nonthermal waters at Azacualpa, Honduras.	91
54. Plot of δD versus $\delta^{18}O$ for thermal and nonthermal waters, Azacualpa, Honduras.	91
55. Tritium versus Cl for thermal and nonthermal waters, Azacualpa, Honduras.	93
56. Schematic model of the Azacualpa geothermal system, Honduras. . .	95
57. Map of the Choluteca region, southern Honduras, showing the approximate locations of the four areas that were sampled.	97
58. Map of the Pavana geothermal area, Honduras, showing locations of hot springs and a cold well.	99
59. Photograph looking east of hot spring PV-3 during gas sampling operations.	100
60. Photograph looking northwest of hot spring PV-9.	101
61. Plots of B, F, and Li versus Cl for thermal and nonthermal waters in the Choluteca region, Honduras.	103
62. Plot of δD versus $\delta^{18}O$ for thermal and nonthermal waters in the Choluteca region, Honduras.	104
63. Schematic model of the Pavana geothermal system, Honduras, based on geology of Duffield et al. (to be published), resistivity of Geonamics (1977), and geochemistry of this report.	106
64. Map of the La Ceiba region, northern Honduras, showing the locations of the three areas that were sampled.	108
65. Simplified structural map of northern Honduras showing the major strike-slip faults of the region.	109
66. Map of the Sambo Creek geothermal area showing locations of hot springs and the major east-west fault zone.	110
67. Photograph looking north of the hot creek formed by the thermal waters of the Sambo Creek geothermal area.	112

68.	Photograph looking west of hot spring SC-6 at La Labor thermal area, Honduras.	112
69.	Plots of B, F, and Li versus Cl for thermal and nonthermal waters in the La Ceiba region, Honduras.	114
70.	Plot of δD versus $\delta^{18}O$ for thermal and nonthermal waters in the La Ceiba region, Honduras.	115
71.	Schematic models of the Sambo Creek geothermal system, Honduras. .	118
72.	Map of the El Olivar geothermal region in the southern Sula Graben of Honduras showing locations of thermal sites at El Olivar proper and Laguna Agua Caliente.	119
73.	Map of the El Olivar area showing spring locations and a major normal fault.	122
74.	Photograph looking northeast of hot spring EO-2 and its travertine deposit at El Olivar.	123
75.	Photograph looking east of hot spring EO-6 at Laguna Agua Caliente, Honduras.	123
76.	Plots of B, F, and Li versus Cl for the thermal and nonthermal waters in the El Olivar area, Honduras.	126
77.	Plot of δD versus $\delta^{18}O$ for thermal and nonthermal waters in the El Olivar area, Honduras.	127
78.	Schematic model for the geothermal systems of the El Olivar region, Honduras, based on the geophysical studies of Zuniga (1975) and this report.	130

EXECUTIVE SUMMARY

Hydrogeochemical investigation of six geothermal sites in Honduras has been a cooperative effort between the United States of America (Los Alamos National Laboratory and the U.S. Geological Survey) and Honduras (Empresa Nacional de Energía Eléctrica). This investigation is part of the Central American Energy Resources Project being sponsored by the U.S. Agency for International Development. The sites were selected for geothermal exploration based on the previous work of GeothermEx (1980) and Geonomics (1977) and the purpose of the exploration activities was to evaluate each site for its geothermal potential. Using the hydrogeochemical and geologic data, we have ranked the sites according to their potential for the production of electrical power.

Our initial investigations of thermal sites in Honduras were focussed at Platanares, San Ignacio, Azacualpa, Choluteca region (Pavana), La Ceiba region (Sambo Creek), and El Olivar. Thermal waters, meteoric waters, and springs, which are mixtures of the two, were collected and analyzed. Mixing relationships, estimated reservoir temperatures, and characteristics of thermal fluids were determined for each site. Thermal waters in each area are near neutral, relatively dilute, $\text{Na-HCO}_3\text{-SO}_4\text{-Cl}$ fluids. None of the investigated areas is associated with Quaternary silicic volcanism and no area has acid-sulfate waters suggesting vapor-dominated reservoirs. Each thermal system is characterized by deep percolation of meteoric water, conductive heating at depth, and convective upflow along faults in extensional environments. Using chemical, isotopic, and gas geothermometers, reservoir temperatures were estimated for each thermal system: 225°C at Platanares, 190°C at San Ignacio, 185°C at Azacualpa, 155°C at Sambo Creek, 150°C at Pavana, and 120°C at El Olivar. Thermal output of surface fluids at the three best sites were calculated, with thermal output at Platanares being 45 megawatts (thermal), and those of San Ignacio and Azacualpa being 14 and 13 megawatts (thermal) respectively.

Based on estimated reservoir temperatures, geochemistry of fluids, geology, and surface discharge rates of thermal fluids, the Platanares, San Ignacio, and Azacualpa sites all demonstrate potential for electrical power

generation. However, the Platanares thermal site is clearly the best geothermal target of the six sites we investigated in Honduras.

From the data presented in this report, we have planned detailed hydrogeochemical studies to be performed at Platanares, San Ignacio, and Azacualpa in order to evaluate seasonal variations, mixing relationships, and accurately determine discharge volumes. Following these studies, thermal gradient holes should be cored in order to verify a high-temperature resource. At present, two core holes are planned for the Platanares site. The first hole will be cored through a fractured zone along which many boiling springs issue. The second proposed hole will be cored away from the main spring area in hopes of intersecting a lateral outflow plume containing fluids of mixed composition. Data that could be obtained from these core holes is required before a final determination can be made concerning the geothermal potential at Platanares.

HYDROGEOCHEMICAL INVESTIGATION OF SIX GEOTHERMAL SITES IN HONDURAS, CENTRAL AMERICA

by

The Hydrogeochemical Investigation Team

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ABSTRACT

We conducted detailed hydrogeochemical investigations at six geothermal sites in western Honduras: Azacualpa, El Olivar, Pavana, Platanares, Sambo Creek, and San Ignacio. None of the sites is associated with Quaternary silicic volcanism, although El Olivar lies adjacent to a small Quaternary basalt field and Pavana is part of a belt of hot spring activity parallel to and 35 km east of the Central American volcanic arc. None of the sites contains acid-sulfate waters indicative of vapor-dominated conditions. Thermal fluids are characterized by pH between 7 and 10, $Cl < 125$ mg/l, $HCO_3 > Cl$, $SO_4 > Cl$, $B < 17$ mg/l, $Li < 4$ mg/l, and $As < 1.25$ mg/l. Stable isotope analyses of the water show that recharge to the geothermal systems generally occurs from areas of higher elevation adjacent to the sites. Tritium contents of apparently undiluted thermal fluids range from 0 to 0.4 T.U., indicating residence times of fluids in the systems of more than 500 yr. Various geochemical indicators show that mixing of hot and cold end-member fluids occurs in the system at Platanares and, to a lesser degree, in the systems at San Ignacio and Azacualpa. No mixing is apparent in the fluids discharging at Pavana, Sambo Creek, or El Olivar. Boiling is the dominant process responsible for subtle

geochemical variations at Azacualpa and, possibly, San Ignacio. From comparisons of different chemical geothermometers, our best estimates of subsurface reservoir temperatures are 225°C at Platanares, 190°C at San Ignacio, 185°C at Azacualpa, 155°C at Sambo Creek, 150°C at Pavana, and 120°C at El Olivar. Including the discharge rates of surface features, the estimated power output of the three hottest sites is 45 thermal megawatts at Platanares, 14 thermal megawatts at San Ignacio, and 13 thermal megawatts at Azacualpa. The Platanares site is clearly the best geothermal target of the six sites we investigated in Honduras.

I. INTRODUCTION

These hydrogeochemical investigations are part of a coordinated effort among Empresa Nacional de Energía Eléctrica (ENEE), the United States Geological Survey (USGS), Los Alamos National Laboratory (Los Alamos), and United States university consultants to locate, evaluate, and develop geothermal resources in Honduras. Our initial studies have focused on six areas: Platanares, San Ignacio, Azacualpa, Choluteca region (Pavana), La Ceiba region (Sambo Creek), and El Olivar (Fig. 1). In addition to our geochemical efforts, Aldrich et al. (1986), Eppler et al. (1986), and Heiken et al. (1986) have completed geologic mapping at three of the sites and geophysical investigations are planned for the Platanares, San Ignacio, and possibly the Azacualpa sites. GeothermEx (1980a) and Geonomics (1977) have previously reported reconnaissance work on the geothermal potential of Honduras, and Gislason (1980) has presented short descriptions and maps of thermal areas showing spring locations. The present study combines detailed field observations with chemical and isotopic analyses of liquids and gases to estimate the temperature of underlying reservoirs, to define possible recharge zones and mixing relations among aquifers, to evaluate reservoir rock types, and to provide background data on regional isotopic distributions in Honduras.

II. REGIONAL GEOLOGIC SETTING AND STRATIGRAPHY

A. Setting

The regional geology of Honduras is characterized by a basement complex of Paleozoic metamorphic rocks and associated intrusive rocks that are

Figure 1. Map of Honduras showing locations of the six geothermal prospect areas described in this report.

Figure 2. Schematic cross section showing the relation of Tertiary volcanic rocks to Cretaceous sedimentary rocks and underlying metamorphic basement in Honduras (modified from McBirney and Weill, 1966).

overlain by deformed Mesozoic carbonate and clastic sequences (Fig. 2). These rocks are in turn overlain by an Oligocene andesite suite, an extensive Miocene volcanic sequence dominated by ignimbrites, and very localized Pliocene and Pleistocene andesite and basalt fields associated with the present graben systems of central Honduras (McBirney and Weill, 1966; Williams and McBirney, 1969).

Horne et al. (1976) discuss the pre-Mesozoic metamorphic-plutonic rocks of Honduras and their structural relations. The plate tectonic model of Burkart and Self (1985) describes the tectonic setting in Honduras during the past 10 Ma. Honduras lies on the northwest edge of the Caribbean plate and east of the Cocos plate (Fig. 3). Subduction of the Cocos plate beneath the Caribbean and North American plates has formed the Middle America trench, the parallel Central American volcanic arc to the east, and an associated

Figure 3. Rotation of upper crustal blocks in northern Central America and attendant morphotectonic effects. Inset shows three plates and their motions (open arrows). Subduction is in direction of teeth on Middle America trench. Main diagram shows flat-bottomed, Quaternary, pumice-filled basins (black) that suggest continuation of Jocotán and Motagua strike-slip fault system into western Guatemala. Morphotectonic response to counterclockwise rotation includes development of extensional basins (shown by hachured faults) south of plate-boundary faults. G = Guatemala graben; P = Ipala graben; CARIB = Caribbean plate; NOAM = North American plate; I, II, III, and IV are morphotectonic zones defined in Burkart and Self (1985).

northeastward-dipping subduction zone. The North American and Caribbean Plates are separated by the Motagua fault zone and associated left-lateral strike-slip faults that behave as a transform zone. Because of relative plate motions and the rotation of the Caribbean Plate around the southern tip of the North American Plate, western and central Honduras is being subjected to considerable east-west extension. As a result, north-trending graben systems that make up the greater Honduras Depression now cut pre-Miocene structures. These graben systems generally cut across the pre-Mesozoic structures, which are dominated by east-west trends (Horne et al., 1976). Faults bounding the grabens display Quaternary displacements, and the grabens are commonly filled with late Tertiary and Quaternary sediments and volcanics.

B. Stratigraphy

Figure 4 shows the basic stratigraphy of Honduras (Mills et al., 1967) as revised by Finch (1981). Major formations are described briefly, from oldest to youngest. In later sections we discuss the influence of rock type on the chemistry of thermal and nonthermal waters.

Pre-Mesozoic Basement (Precambrian[?] to Paleozoic). These basement rocks consist of undifferentiated sedimentary and volcanic strata regionally metamorphosed to almandine-amphibolite facies that have been intruded by intermediate-composition plutons (Rb-Sr age: 305 Ma). This

Figure 4. Stratigraphic nomenclature in Honduras (Finch, 1981).

complex is overlain by pelitic sedimentary rocks that underwent low-grade metamorphism in the pre-Jurassic (Horne et al., 1976). Fakundiny (1970) named the high-grade metamorphic rocks in central Honduras the Cacaguapa Schist. Similar high-grade rocks throughout Honduras are assumed to be correlative.

El Plan Formation (late Triassic and Jurassic). Deformed black shale and thin-bedded sandstone with a few calcareous beds rest unconformably on the metamorphic basement (Carpenter, 1954). This unit is best documented at the Rosario Mine near Tegucigalpa and is correlated with similar strata in eastern Honduras. Its extension into northwestern Honduras is variable, and its total thickness is unknown but may exceed 1000 m.

Todos Santos Formation (Jurassic and early Cretaceous). The Todos Santos Formation consists of deformed clastic red beds and conglomerates (Mills et al., 1967). Positive identification of this unit is difficult because it resembles the Valle de Angeles Group described below. The exact stratigraphic relation of this formation with the El Plan Formation is uncertain, and its exact thickness is unknown but may exceed 1000 m.

Yojoa Group (mid-Cretaceous). Deformed fossiliferous limestone with subordinate shale, conglomerate, and red beds composes the Yojoa Group (Carpenter, 1954). The upper part of the unit contains some petroleum-bearing shale and limestone. According to Finch (1981), the Yojoa Group is composed of three formations, of which the thickest and most widespread is the Atima Formation. This formation consists almost entirely of limestone, with local stringers of chert, and has a maximum thickness that may exceed 1000 m, as exhibited a few kilometers west of Lago de Yojoa (Finch, 1981). The Yojoa Group appears to conformably overlie the Todos Santos Formation.

Valle de Angeles Group (late Cretaceous and early Tertiary). The Valle de Angeles Group is predominantly deformed clastic red beds with subordinate limestone, conglomerate, shale, sandstone, and gypsum beds (Carpenter, 1954; Horne et al., 1974). Gypsum is most common in the upper part of the unit and is associated with petroleum-bearing limestone (see the description of the Guare Member of the Jaitique Formation in Finch, 1981). Rocks in the Valle de Angeles Group conformably overlie the Yojoa Group. The exact thickness of this group is unknown but may exceed 3000 m.

Intrusive Rocks (Cretaceous and early Tertiary). Stocks and batholiths of monzonite to granite composition intrude metamorphic basement, Cretaceous sedimentary rocks, and some volcanics of the Matagalpa Formation in northern and central Honduras. Potassium-argon ages from plutonic rocks of the Cordillera Nombre de Dios range from 93 to 57 Ma (Horne et al., 1976). Other intrusives are as young as Oligocene (Williams and McBirney, 1969).

Matagalpa Formation (Oligocene and Miocene). The Matagalpa Formation consists of discontinuous beds composed mostly of andesite and basalt flows and their fluvatile and laharcic derivatives (Williams and McBirney, 1969). Flows are commonly tilted and may be highly faulted, deformed, and hydrothermally altered by early Tertiary intrusives. This formation unconformably overlies the Valle de Angeles Group, and its thickness is highly variable and may locally exceed 2200 m.

Padre Miguel Group (Miocene). The Padre Miguel Group is an extensive volcanic unit consisting of tuffs, domes, and flows of rhyolite with subordinate dacite, andesite, and basalt (Burkart, 1965; Williams and McBirney, 1969). The unit also contains interbedded volcanoclastic sediments. Its rocks are tilted but generally not deformed. Padre Miguel rocks are most common in southern and central Honduras, where they usually cap mountain ranges and form a broad volcanic plateau. The thickness of this group may exceed 1000 m, and its volume exceeds 5000 km³. The unit unconformably overlies the Valle de Angeles Group and the Matagalpa Formation. Potassium-argon ages range from 19.1 to 5.2 Ma (Williams and McBirney, 1969; Duffield et al., 1986).

Basin Fill (late Tertiary). Grabens of the Honduras Depression are filled with volcanic and sedimentary rocks derived from older units and locally include associated lacustrine beds. The Gracias Formation (Olson and McDrew, 1941; Williams and McBirney, 1969) consists of pumiceous flood-plain and lacustrine deposits and marls filling an oval-shaped depression in southwestern Honduras. The thickness of various fills may exceed 1000 m.

Quaternary Volcanism. Relatively young volcanism associated with the Central American volcanic arc occurs only in the Golfo de Fonseca as islands of basaltic andesite. Small fields of Quaternary(?) basalt and andesite occur within or adjacent to grabens of the Honduras Depression (Williams and

McBirney, 1969). These rocks resemble some units of the Padre Miguel Group, and assigning an age to them is often difficult.

III. REGIONAL HEAT FLOW

No heat flow measurements have been obtained in Honduras. Heat flow has been measured in the Cordillera de Guanacaste of Costa Rica, which forms part of the Central American volcanic arc (Blackwell et al., 1977). Background heat flow in the Cordillera, composed mostly of Pliocene and Pleistocene andesitic stratovolcanoes and subordinate silicic caldera centers, is about 60 mW/m^2 , which is equivalent to 1.5 heat flow units (HFU). This value is common in island arc settings, where heavy rainfall and the presence of porous volcanic sequences favor downward circulation of meteoric water that masks true heat flow.

In contrast, a heat flow of 550 mW/m^2 (13 HFU) is associated with the hydrothermal system at Volcán Miravalles, Costa Rica (Blackwell et al., 1977). Similar heat flow anomalies are associated with the hydrothermal-convective systems at Momotombo, Nicaragua (Lopez et al., 1980), and Ahuachapán, El Salvador (Vides, 1976). Shallow geothermal gradients at these locations commonly exceed 500°C/km .

By analogy with the situation in Costa Rica, we would expect the segment of the volcanic arc in the region of Golfo de Fonseca in Honduras to display a heat flow of $<60 \text{ mW/m}^2$. On the other hand, we would expect most of western and central Honduras to have higher heat flow caused by Quaternary extensional tectonics, thin earth crust, and Quaternary basaltic volcanism. The abundance of hot springs in central and western Honduras suggests that this may be the case.

We have calculated the average heat flow for western Honduras using the method of Swanberg (1979) and Swanberg and Alexander (1979), in which regional heat flow is correlated with the silica content of cool groundwater. Heat flow, q , is calculated in milliwatts per square meter (mW/m^2) as follows:

$$q = \frac{T_{qtz} - b}{m}, \quad (1)$$

where b and m are empirical constants (13.2°C and $0.67^{\circ}\text{C m}^2/\text{mW}$, respectively), where

$$T_{\text{qtz}} = \frac{1309}{5.19 - \log_{10} \text{SiO}_2} - 273.15, \quad (2)$$

and where silica concentration is in milligrams per liter (mg/l). Based on the silica concentrations of 17 cold groundwater samples (Fig. 5 and Table I), the calculated heat flow is roughly 120 mW/m^2 , or approximately 3 HFU.

We caution, however, that the silica content of groundwater is partly correlated with rock type; for example, waters issuing from volcanic units generally contain more SiO_2 than do waters issuing from limestone. We also note that the number of data points used in our calculation is statistically small and that the constants, b and m , were derived from mathematical analysis of thousands of waters from the United States. Nonetheless, the value of 3 HFU is reasonable considering the volcanic and tectonic similarities between western Honduras and the Basin and Range province of the United States, where heat flow is about 2.8 HFU (Sass et al., 1981).

IV. REGIONAL ISOTOPES OF WATER

A. Stable Isotopes

Stable isotopes of water (D and ^{18}O) are used to identify recharge areas of geothermal systems and subsurface processes such as mixing and boiling in geothermal reservoirs (Craig, 1961; Truesdell and Hulston, 1980; Taylor, 1974). Also, normal meteorological processes and topographic effects cause variations in stable isotopes (Fontes, 1980). Isotopic values of precipitation vary with latitude, wind patterns, distance inland from the ocean, and elevation. Figure 6, a map of North and Central America, illustrates this variation by showing contours of the approximate average δD -values of meteoric waters (Taylor, 1974). We will discuss isotopic variations of meteoric waters before we discuss in detail the isotopic variations of thermal waters.

Honduras is a rugged, mountainous country whose highest elevations range from 2400 m in the north to 2850 m in the west. Mean annual temperatures,

Figure 5. Map of Honduras with sample site locations. The letter M represents Montaña.

TABLE I. Temperature, Silica Content, Chloride Content, and Rock Type of 19 Cold Waters in Western Honduras (see Fig. 5 for locations)

Location	Sample No.	Measured T (°C)	SiO ₂ (mg/l)	Cl (mg/l)	Rock Type
Azacualpa	AZ-3	28	34	3.5	Red beds
Pavana Area	PV-2	34	76	6.2	Alluvium; volcanics
	PV-6	29	79	5.7	Volcanics
	PV-12	33	56	27.3*	Volcanics
Platanares	PL-9	27	22	2.6	Crystalline rocks
	PL-12	35	39	7.2	Tuff
	PL-13	25	17	2.7	Tuff
	PL-16	28	48	3.3	Red beds; tuff
Sambo Creek	SC-4	31	33	9.9	Crystalline rocks
	SC-7	27	21	3.4	Crystalline rocks
San Ignacio	SI-11	28	25	8.6	Crystalline rocks
Miscellaneous	SF-1	35	74	6.0	Alluvium
	HN-1	24	67	5.5	Tuff
	HN-2	23	101*	6.2	Tuff
	HN-3	24	10	5.7	Limestone
	HN-4	27	103*	22.7*	Volcanics
	HN-5	25	57	5.6	Volcanics
	HN-7	29	34	5.8	Crystalline rocks
	HN-11	25	51	4.8	Volcanics
Average ^a		28.3±3.8	43.7±21.9	5.4±2.0	

^aError reported is standard deviation; silica and chloride averages do not include values followed by an asterisk.

affected primarily by elevation, average from 26–28°C along the Caribbean coastal plain to 16–24°C in the central highlands (U.S. Army, 1984). Because the prevailing winds of Honduras blow from north to south, the amount of local rainfall is strongly affected by the weather pattern and topography. Precipitation along the north coast exceeds 2000 mm/yr, whereas precipitation in the central highlands and along the south coast exceeds 1000 mm/yr with distinct wet and dry seasons (U.S. Army, 1984).

Figure 6. Map of North America showing contours of the approximate average δD values of meteoric surface waters (Taylor, 1974). Because of the linear relation between D and ^{18}O in meteoric waters, this figure can serve equally well as a $\delta^{18}O$ contour map if $\delta D = -30$ is replaced by $\delta^{18}O = -5.0$, etc.

During our investigations we collected 80 water samples for D and ^{18}O isotopic analyses. Included were 27 samples of cool groundwaters and streams and one sample of Lago de Yojoa (Table II). Previous geothermal investigations in Honduras (GeothermEx, 1980b; Geonomics, 1977) have not reported data for stable isotopes, nor are we aware of any isotopic data reported for hydrologic and environmental projects in Honduras.

Most of the D- and ^{18}O -values for surface and shallow groundwaters (Fig. 7) plot close to the world meteoric water line, $\delta D = 8 \delta^{18}O + 10$ (Craig, 1961). As expected, samples having lighter isotopic compositions originate at higher elevations (e.g., HN-1,* 1470 m), at greater distance away from the Caribbean Sea (e.g., all PV samples), or at both locations (e.g., HN-11, 730 m, sample taken south of Tegucigalpa). Waters from HN-9 and Lago de Yojoa

*Samples are identified by the region of their source: HN for miscellaneous Honduras, PL for Platanares, PV for Pavana, AZ for Azacualpa, EO for El Olivar, SI for San Ignacio, SF for San Francisco, and SC for Sambo Creek.

TABLE II. Deuterium, Oxygen-18, and Tritium Analyses from Shallow Groundwaters, Streams, and Lago de Yojoa, Honduras

Sample No. ^a	Name	Elev. (m)	Temp. (°C)	δD (‰) ^b	$\delta^{18}O$ (‰) ^c	3H (T.U.) ^d
Azacualpa Site						
AZ-3	Cold Stream*	350	28.0	-28.9	-4.83	7.62
AZ-10	Rfo Jaitique	380	--	-32.8	-5.03	4.83
Choluteca Region						
PV-2	Cold well, El Rosario*	50	34.0	-44.9	-6.30	--
PV-6	Cold well, La Castaña*	140	29.3	-38.9	-6.26	2.55
PV-11	Cold well, El Triunfo	60	--	-40.9	-6.29	--
PV-12	Cold well, El Obraje	50	32.6	-45.1	-6.09	--
El Olivar Site						
EO-4	Rfo El Potrero	55	--	-23.8	-3.88	--
EO-5	Tapwater, El Olivar	65	--	-38.6	-5.38	--
La Ceiba Region						
HN-7	Rfo La Masica	45	28.7	-14.7	-3.78	4.15
SC-4	Spring, Sambo Creek*	70	31.0	-19.2	-3.66	4.23
SC-7	Sambo Creek	20	27.2	-12.7	-3.80	3.45
Platanares Site						
PL-9	Quebrada del Agua Caliente*	800	26.7	-42.8	-7.01	5.50
PL-10	Spring*	740	38.4	-42.1	-6.51	--
PL-12	Spring*	735	35.1	-41.2	-6.53	5.14
PL-13	Spring*	800	25.3	-39.5	-5.92	--
PL-16	Rfo Lara*	700	28.0	-37.7	-5.95	7.24
San Ignacio Site						
SI-11	Spring*	780	28.0	-43.0	-6.58	0?
SI-14	Spring	700	28.0	-45.4	-6.47	--
Miscellaneous						
SF-1	Spring, San Francisco*	1000	35.0	-48.0	-6.92	1.54
HN-1	Spring, near Zambrano*	1470	24.0	-53.4	-7.65	4.92
HN-2	Spring, near Siguatepeque*	940	23.0	-46.1	-6.94	1.01
HN-3	Spring, Ojo Lajas*	610	24.0	-32.2	-5.11	7.01
HN-4	Cold well, Colonia San Antonio	700	26.7	-37.4	-5.60	0.89
HN-5	Spring, Agua Zarca*	1100	25.0	-41.2	-7.01	6.34
HN-8	Lago de Yojoa	640	--	-12.7	-2.44	--
HN-9	Cold stream	780	--	-10.4	-1.94	--
HN-10	Cold well, Rfo Abajo	1000	26.0	-43.5	-6.04	--
HN-11	Spring Los Chorritos*	730	25.0	-57.1	-8.44	--
	Tegucigalpa Rainwater (10/2/86)	975	--	--	--	2.63
	Tegucigalpa Rainwater (10/3/85)	975	--	--	--	3.36

^aSamples with an asterisk were used to calculate the meteoric water line of Honduras (see text).

^bPrecision is $\pm 1\%$; analysis related to SMOW.

^cPrecision is $\pm 0.25\%$; analysis relative to SMOW.

^dPrecision is $\pm 1\%$ relative.

Figure 7. Plot of δD versus $\delta^{18}O$ for the cool groundwaters and surface waters of Honduras listed in Table II.

are unusually enriched in D and ^{18}O , demonstrating the effect of evaporation. Probably Río El Potrero water has been similarly affected by evaporation. Samples from Sambo Creek and Río La Masica have $\delta^{18}O$ -values that are lighter than expected relative to their δD -values. Values for samples from El Obraje (PV-12) and Colonia San Antonio (HN-4), cold well waters, plot to the right of the meteoric water line and contain significantly higher Cl than expected for shallow groundwaters. We did not analyze samples AZ-10, PV-11, EO-5, SI-14, and HN-10 for Cl contents and, therefore, cannot verify that they are representative of background cold water. We excluded all suspect samples named above and found that the remaining 16 samples yield a linear regression equation of $\delta D = 7.76 \pm 1.13 \delta^{18}O + 8.29 \pm 7.32$ (95% confidence level) with a correlation coefficient (r^2) of 0.969. Because this line is very close to the world meteoric line, we will relate all data to the world line.

Although the data qualitatively show a correlation between isotopic depletion and increasing elevation, we do not have enough data from any one location to calculate the isotopic gradient. We know, however, that the isotopic gradient of ^{18}O for most climates is about -0.3‰ per 100 m (Fontes, 1980) and that Payne and Yurtsever (1974) calculated an isotopic gradient for ^{18}O of -0.26‰ per 100 m in their hydrologic investigation of Nicaragua.

Figure 8 shows the δD - and $\delta^{18}\text{O}$ -isotope compositions of Honduras hot spring waters with selected data on the meteoric waters. All hot spring data except those from El Olivar-Laguna Aguacaliente plot on or near the meteoric water line. Generally speaking, the hot spring waters that are the most depleted isotopically are either higher in elevation or the farthest away from the Caribbean, as observed for shallow groundwaters. The springs in the El Olivar region show a pronounced ^{18}O -enrichment that is probably caused by

Figure 8. Plot of δD versus $\delta^{18}\text{O}$ for the geothermal waters and surface waters of Honduras (from data listed in various tables of text and in Appendix A).

isotopic exchange between meteoric water and the limestone reservoir rocks, as discussed in more detail in Section XIII.

B. Tritium

Tritium is useful in determining the relative ages of groundwaters because it has a short half-life of 12.43 yr and because it was produced in copious amounts during atmospheric nuclear tests of the 1950s and early 1960s (Fontes, 1980). As a result of these tests, peak levels of atmospheric tritium occurred in 1963, and levels have been decreasing steadily since that time (see Table III). Tritium levels vary greatly by latitude; thus, in 1963 atmospheric tritium in the southwestern United States averaged 2800 tritium units (T.U.) (Vuataz and Goff, 1986), whereas in Veracruz, Mexico, it reached a maximum of only 65 T.U. (International Atomic Energy Agency, 1969). Atmospheric tritium also varies seasonally, with the highest levels occurring in the summer months and the lowest levels in the winter months. For example, at San Salvador, El Salvador, the tritium level in precipitation during August 1972 was 16.7 T.U., whereas the level in November of that year was only 4 T.U. (International Atomic Energy Agency, 1979).

Table III presents tritium concentrations in precipitation by year from stations in Veracruz, Mexico; San Salvador, El Salvador; Barbados; Miami, Florida; and the southwestern United States. These data are weighted-mean tritium levels, and the percentage of the annual rainfall used to calculate the weighted mean is presented in parenthesis.

During our investigations, we analyzed 16 samples from cool springs, wells, and flowing streams for tritium (Table II). The largest streams from the northern part of Honduras, where rainfall is very high (Sambo Creek, Río La Masica, and Río Jaitique), have an average tritium content of about 4.1 T.U. Presumably, these streams are recharged more by direct precipitation and run-off than by shallow groundwater flow. Based on the data from these large streams and on the discontinuous records from Veracruz and San Salvador, the present background tritium level for Honduras appears to be between 2 and 5 T.U. Two samples of rainwater collected in Tegucigalpa have tritium values of 2.63 and 3.36 T.U. Goff and Vuataz (1984) determined a background value of 4.46 T.U. for the Migny River on the island of St. Lucia in the Lesser Antilles, which is at the same latitude as Tegucigalpa.

TABLE III. Weighted-Mean Tritium Values From Precipitation in Selected Areas of Central America and the United States

Year	Veracruz ^a	San Salvador ^a	Barbados ^a	Miami ^a	SW USA ^b
1956					55
1957					108
1958					337
1959			12.86 (75)		975
1960					243
1961					216
1962	41.9 (57)				875
1963					2834
1964			95.36 (97)	167.00 (100)	1747
1965				58.4 (100)	822
1966			32.39 (98)	70.6 (100)	601
1967	30.02 (96)		20.52 (100)	35.68 (100)	366
1968	22.24 (98)	21.96 (76)	20.29 (100)	26.51 (100)	229
1969		19.98 (76)	15.53 (95)	29.52 (100)	253
1970	24.68 (74)	26.5 (98)	14.07 (74)	27.8 (100)	191
1971	19.4 (100)	19.57 (94)	12.62 (94)	24.4 (100)	194
1972	14.5 (74)	14.6 (94)	10.5 (100)	16.4 (100)	77
1973	10.7 (100)	10.2 (76)	7.9 (83)	13.0 (100)	97
1974	12.2 (99)	9.3 (66)	7.1 (72)	13.6 (100)	75
1975	8.6 (100)	9.0 (98)	7.6 (81)	8.9 (100)	73
1976					57
1977					56
1978					75
1979					32
1980					31
1981					41
1982					29
1983					15

^aNumbers in parentheses reflect the percentage of rainfall for which tritium data exist (International Atomic Energy Agency 1969, 1971, 1973, 1975, and 1979).

^bFrom Vuataz and Goff (1986).

The streams in the Platanares area contain levels of tritium slightly higher than our estimated background level. Therefore, the Rfo Lara (7.2 T.U.) and the Quebrada Agua Caliente (5.5 T.U.) must be recharged partially by shallow groundwater that was infiltrated a few years ago when tritium levels were higher. On the other hand, the spring used for bathing at

San Francisco near the Río del Hombre (SF-1, 1.5 T.U.), the spring near Siguatepeque (HN-2, 1.0 T.U.), and the well near Colonia San Antonio (HN-4, 0.9 T.U.) contain water whose average age is older because their tritium levels are substantially below the background level.

The six geothermal sites investigated apparently discharge end-member thermal water (undiluted and unboiled) containing between 0 and 0.4 ± 0.1 T.U. (see discussions in Sections VIII through XIII). To estimate ages of these hydrologic systems, we must consider the type of mixing that occurs in the system.

According to Pearson and Truesdell (1978), two models may be used to place limits on the mean residence time for groundwater: piston flow and perfect mixing. The piston-flow model assumes that there is no mixing of the water in the reservoir from the time of recharge to the time of discharge and that all molecules have the same residence time. The output tritium level depends upon the residence time and upon the tritium concentration in the recharge. The equation describing this model is

$$C_{out}(t) = C_{in}(t-\tau)e^{-\lambda\tau}, \quad (3)$$

where $C_{out}(t)$ is the tritium level in the discharge fluid at time t , $C_{in}(t-\tau)$ is the tritium level in the recharge fluid at the time of recharge, τ is the residence time, and λ is the decay constant for tritium ($5.576 \times 10^{-2} \text{ yr}^{-1}$).

The perfect-mixing model (or well-mixed model), on the other hand, assumes that the input to the groundwater reservoir is completely mixed with fluid already in the reservoir and that the discharge fluid has the composition of this mixed fluid. The equation that describes the perfect-mixing model is

$$\frac{dC(t)}{dt} = \frac{\dot{q}_{in}}{V} C_{in}(t) - \frac{\dot{q}_{out}}{V} C(t) - \lambda C(t), \quad (4)$$

where $C(t)$ is the tritium level in the reservoir (and the discharge) at time t , $\dot{q}_{in}$ and $\dot{q}_{out}$ are the recharge and discharge flow rates, and V is the fluid

volume in the reservoir. In the absence of information about the rates of recharge and discharge over time, we will assume that $\dot{q}_{in} = \dot{q}_{out} = \text{constant}$ and that $V = \text{constant}$. Equation (4) can be rearranged to give

$$\frac{dC(t)}{dt} + \frac{1}{\tau} + \lambda C(t) = \frac{1}{\tau} C_{in}(t) \quad , \quad (5)$$

where τ defined as $\frac{V}{\dot{q}}$ is the mean residence time. The solution to this equation is

$$C(t) = e^{-\left(\frac{1}{\tau} + \lambda\right)t} \left\{ \frac{1}{\tau} \int_0^t C_{in}(t) e^{\left(\frac{1}{\tau} + \lambda\right)t} dt + k \right\} \quad , \quad (6)$$

where k is a constant of integration. This constant is to be evaluated at the initial condition $C(0) = C_0$ where C_0 is the original tritium concentration in the reservoir before nuclear testing began. We take $C_0 = 0$ because the natural production of tritium before nuclear testing approaches zero and many of the thermal springs discharge fluid that has very low or no measurable tritium.

Table III presents some values for $C_{in}(t)$, but there is a paucity of tritium data for Central America before 1968 and after 1975. In Fig. 9 we plotted logarithm of the tritium concentration versus time for all the data presented in Table III (note that we plotted the data for the southwestern United States on a scale different from that used for the rest of the data). Figure 9 also shows exponential curve fits to various segments of the tritium concentration data.

Table IV presents time constants and correlation coefficients for the various curves. The table shows conclusively that a time constant of -0.5161 yr^{-1} fits the data from Barbados and the southwestern United States for the 1963-1967 period, whereas a time constant of about -0.1535 yr^{-1} fits the data from Veracruz and San Salvador for the 1968-1975 period. We will, therefore, estimate $C_{in}(t)$, where t is the time in years since 1963, as follows:

Figure 9. Plot of logarithm (base 10) of tritium concentration versus time for all data presented in Table III.

$$C_{in}(t) = 275 e^{-0.5161t}$$

for the period 1963-1967, and

(7)

$$C_{in}(t) = 26.51 e^{-0.1535t}$$

for the period 1968-present.

We can substitute Eq. (7) directly into Eq. (3) to obtain $C_{out}(t)$ for the piston-flow model and then in Eq. (6), which is then integrated to obtain $C(t)$ for the perfect-mixing model. Figure 10 presents results of these substitutions. Appendix B presents tables of values used in devising Fig. 10 as well as programs for performing these calculations on the HP-41C calculator. Note that these curves are valid only for spring samples collected in 1985. For years other than 1985, we can calculate tritium concentrations by following the procedure detailed in Appendix B. Tritium concentrations in the

TABLE IV. Time Constants, Intercepts, and Correlation Coefficients For Exponential Curve Fits of the Tritium Concentration in Precipitation From Various Stations

	Time Constant	Intercept (1963)	Correlation Coefficient
<u>1963-1967</u>			
Southwestern USA	-0.5161	2740.1	0.9858
Barbados	-0.5161	157.49	0.9984
<u>1968-1975</u>			
Veracruz, Mexico	-0.1505	57.04	0.8431
San Salvador, El Salvador	-0.1574	57.88	0.8270
Barbados	-0.1512	40.62	0.9506
Miami, USA	-0.1690	77.59	0.8820
Southwestern USA	-0.2028	737.91	0.8360
Veracruz and San Salvador	-0.1535	57.17	0.8301

two samples of rainwater collected on successive days in Tegucigalpa (Table II) plot very close to the calculated line in Fig. 9.

This analysis leads to several interesting conclusions. First of all, waters having a tritium concentration greater than 5 T.U. must have a piston-flow component whose residence time is between 12 and 22 yr. Examples of waters that fall into this category include Platanares Creek (PL-9), Rio Lara (PL-16), the cold spring at Azacualpa (AZ-3), and the spring at Ojo Lajas (HN-3). On the other hand, waters with tritium concentrations less than about 1.7 T.U. must be derived either from well-mixed aquifers having residence times greater than about 120 yr or from very poorly mixed aquifers having residence times greater than 25 yr. For systems that discharge large amounts of thermal fluid with relatively uniform composition over a large area, the well-mixed model probably approximates the behavior of the aquifer better than the piston-flow model does. In general, the "pure end-member" (undiluted) thermal waters from Honduras have tritium concentrations less than 0.1 T.U.,

thus suggesting maximum residence times on the order of 2000 yr (See Appendix A, Table A-VI).

V. CHEMICAL CHARACTERISTICS OF THERMAL AND NONTHERMAL WATERS

The general chemical characteristics of the thermal and nonthermal waters of Honduras that we analyzed are similar. These waters are dilute, with most samples containing <120 mg/l Cl (except for two waters), and they tend to be Na-Ca- HCO_3 - SO_4 -Cl waters.* Geothermal waters of Honduras resemble many of those from the Basin and Range province of the western United States, particularly Beowawe, Nevada (Garside and Schilling, 1979). Similarities include the high content of HCO_3 and SO_4 relative to Cl and trace element concentrations. The chemistry of thermal and nonthermal waters is apparently determined by reactions with the host rocks, temperature, and CO_2 pressure. Appendix A presents all chemical data.

A. Major Species in Nonthermal Waters

Nonthermal waters of Honduras are generally more dilute than are thermal waters (about one-tenth as concentrated). All nonthermal waters have HCO_3 concentrations that are 5 to 20 times higher than Cl or SO_4 concentrations. Most waters have greater concentrations of Ca than of Na, particularly where the springs issue from limestone. Chloride is relatively constant, ranging

*We have omitted valence of ions from the text except where necessary for clarity.

Figure 10. Plot of mean residence time versus tritium concentration with curves representing the well-mixed and piston-flow models for Central America. The analytical solution for the piston-flow model described in the text assumes that tritium concentration before 1963 is zero.

from 2.6 to 9 mg/l (excluding two high-Cl samples). This variation is small compared to variations in other constituents; thus Cl probably originates mainly from seaspray distributed by precipitation and only in small part from rock leaching. The low Cl concentration in the nonthermal waters issuing from marine sedimentary rocks suggests that connate seawater once present has been thoroughly leached by flow of fresh meteoric water. Relatively high concentrations of HCO_3^- (averaging 134 mg/l) suggest rock leaching by waters with high CO_2 contents, resulting in Na-HCO_3 or Ca-HCO_3 waters depending on rock type. Possible reactions include

and

The CO_2 partial pressures in the soil zone may be relatively high in tropical areas where warm average temperatures encourage both vegetative growth and oxidation of soil organic matter (roots, humus, and mobilized soluble organic acids). The high CO_2 pressures produce aggressive soil waters that leach minerals from soils and produce relatively mineralized, high- HCO_3^- , shallow groundwaters.

Two general chemical types of cold water are probably related to rock type. Some cold waters, possibly from shallow circulation in volcanics (the widespread Padre Miguel and Matagalpa volcanic and volcanilastic units that occur high in the section), have relatively high Na and K but low Mg and Ca. Other cold waters, possibly from deeper circulation in limestone-bearing sediments (the Yojoa and the Valle de Angeles Groups), have relatively high Ca and Mg but low Na and K. The Choluteca region is an exception, with high-Ca and HCO_3^- (but low-Mg and $-\text{SO}_4$) cold waters issuing from volcanics. Some cold waters within the thermal areas have roughly equal Na and Ca and must represent mixed fluids having small amounts of thermal water.

The concentration of bicarbonate produced in cold waters by reactions described in Eqs. (8) and (9) averages about one-fourth the concentration

produced in thermal waters. Bicarbonate in thermal waters originates from similar reactions but under substantially higher CO_2 pressures.

B. Minor Species in Nonthermal Waters

The range of Mg contents (0.04 to 20 mg/l) in nonthermal waters possibly reflects the range of Mg in rocks, with high-Mg waters related to dolomite or Mg clay-bearing rock. Cold waters are generally higher in Mg than are hot waters, particularly within a thermal area where the same source rocks are involved.

Other elements occurring in notably low concentration in cold waters include F, which is always below 1 mg/l and usually one-tenth to one-fiftieth the amount in associated hot waters; Li, which is always less than one-hundredth the amount in hot waters; B, which was either below detection (<0.02 mg/l) or less than one-tenth the amount in most hot waters (except those from Paleozoic schists); and NH_4 , which was much lower than in thermal waters associated with sediments but higher than in hot waters from schists and tuffs. The chemistry of cold waters is represented in a Schoeller diagram (Fig. 11) in which, for each sample, a line connects the logarithms of the concentrations of each constituent. Parallel lines between log constituent points indicate samples having the same ratio of those constituents. These concentration patterns may be compared with the patterns of hot waters given later.

C. Major Species in Thermal Waters

Thermal waters of Honduras generally resemble each other in chemistry (Figs. 12 to 17) but differ in detail, mainly as influenced by reservoir rock type and temperature. The waters from Platanares, San Ignacio, Azacualpa, and El Olivar have a strong sedimentary influence, shown by high ratios of B/Cl and total HCO_3/Cl (total HCO_3 is the sum of $\text{HCO}_3 + 2\text{CO}_3$). Pavana and Sambo Creek display an igneous/metamorphic influence with low B, HCO_3 , and NH_4 .

Chloride concentration in thermal waters in Honduras is relatively low compared with the concentration of most thermal waters in other countries. Platanares, Azacualpa, and Sambo Creek waters have <40 mg/l Cl, and San Ignacio and most Pavana waters have Cl <80 mg/l. El Olivar waters have

Figure 11. Schoeller diagram of cold waters of Honduras.

Figure 12. Schoeller diagram of waters from Platanares.

Figure 13. Schoeller diagram of waters from San Ignacio.

Figure 14. Schoeller diagram of waters from Azacualpa.

Figure 15. Schoeller diagram of waters from the Choluteca region.

approximately 120 mg/l Cl, and two waters in the Choluteca region have approximately 500 mg/l Cl. These Cl concentrations (except for the last mentioned) are lower than the concentrations that usually result from leaching of Quaternary volcanic rocks. Honduran thermal waters contain too much Cl for an atmospheric (seaspray) source and considerably less Cl than expected for connate water. Since connate water must originally have been present in the Cretaceous to early Tertiary marine reservoir rocks, these rocks must have been extensively

Figure 16. Schoeller diagram of waters from the La Ceiba region.

Figure 17. Schoeller diagram of waters from the El Olivar area.

flushed by meteoric waters during the past 60 Ma. However, the presence of high concentrations of B, Li, and F in the thermal waters and their near absence in nonthermal waters suggest that the leaching of these components from sedimentary sources must occur only at elevated temperatures. The continued generous supply of these elements and low Cl concentrations suggest that low-temperature leaching of Cl occurred before the latest tectonic events (i.e. east-west extension during the last 5 to 10 Ma) that initiated the thermal regimes.

The chemistry of waters at Platanares, San Ignacio, and El Olivar is dominated by Na and HCO_3 , suggesting that the CO_2 -rock-water reaction proposed earlier for cold waters also applies to thermal waters. The higher concentrations of Na and total HCO_3 suggest higher CO_2 pressures and more complete reactions at higher temperatures.

At Platanares, San Ignacio, and Azacualpa, Na concentrations are remarkably similar, ranging from 310 to 330 mg/l for the most concentrated waters. El Olivar waters are more concentrated (480-520 mg/l Na at El Olivar and 550-600 mg/l Na at Laguna Agua Caliente), whereas Pavana and Sambo Creek waters are less concentrated (230-240 mg/l Na at Pavana and 132-135 mg/l Na at Sambo Creek). Total HCO_3 is also relatively high at El Olivar (1200 mg/l) and at Platanares and San Ignacio (490-500 mg/l), moderate at Azacualpa (195-215 mg/l) and relatively low at Pavana (78 mg/l) and at Sambo Creek (105-130 mg/l). These facts suggest that higher pressures of CO_2 exist in the sedimentary reservoirs (El Olivar, Platanares, San Ignacio, and Azacualpa) so that larger amounts of Na and HCO_3 ions are produced by the reaction described in Eq. (8). The higher CO_2 pressure probably results from thermal metamorphism of limestone-bearing rocks in or below the geothermal reservoirs (see later discussion on carbon isotopes).

Almost all thermal waters have high concentrations of SO_4 (>100 mg/l), and thermal waters from Sambo Creek, Pavana, and Azacualpa have higher concentrations of SO_4 than of total HCO_3 . This suggests that at least in the sedimentary reservoirs the dissolution of gypsum and the precipitation of calcite produce SO_4 in place of part of the HCO_3 , perhaps by the reaction

The hot waters probably remain saturated with calcite and gypsum, maintaining Ca near 5-50 mg/l except where near-surface boiling and CO_2 loss increase CO_3 in solution and Ca is reduced by calcite precipitation (discussed later for San Ignacio). High concentrations of SO_4 at Pavana and Sambo Creek may have a different origin. Although volcanic and volcanoclastic rocks at Pavana could contain sulfate minerals, schist and intrusive rocks at Sambo Creek are unlikely to contain these minerals unless sulfates were deposited near the surface by an earlier fumarolic phase in which quantities of H_2S were oxidized. Alternatively, oxidation of sulfides such as pyrite may occur in the recharge to these areas.

D. Soluble Elements in Thermal Waters

Concentrations of Li, Cl, B, and F are probably determined by the total leachable concentrations of these elements in the reservoir rocks, and ratios of these elements are usually not affected by dilution and lower-temperature reactions (but see the later discussion of possible CaF_2 precipitation at Azacualpa and Pavana). These "soluble" elements behave conservatively in mixing, boiling, and rock-water interaction processes. This is evident from their constant ratios, shown in the mixing graphs, and from their constant relative positions (and parallel interconnecting lines) on Schoeller plots (Figs. 12 to 17). On these plots it is evident that K also behaves conservatively, suggesting that reequilibration of cations above the major reservoir of each area is limited by rapid fluid movement, silica-lined upflow channels (Fournier 1981), or increase of Ca, which keeps the solution more or less in equilibrium as temperatures decrease.

E. Alteration of Thermal Waters

In the absence of major boiling and CO_2 loss, more dilute, cooler waters should dissolve calcite from the sedimentary reservoirs (Valle de Angeles and Yojoa Groups) because limestone is ubiquitous and calcite solubility increases as temperature drops. Thus, the more altered waters show increased Ca concentrations. This process appears to occur at Azacualpa, Platanares, and El Olivar, where an increase in Mg concentrations (usually a reliable indicator of lower-temperature reaction or leaching) is coupled with an increase in Ca concentrations. It may also occur at San Ignacio, where many waters show an

increase in both Ca and Mg, but some show decreases in Ca, possibly related to boiling and calcite precipitation. Except at Pavana and Azacualpa, fluorite is probably undersaturated because F does not decrease as Ca increases. At Pavana, with increases in Mg and Ca, waters from the main area show a decrease in F, possibly because fluorite saturation is maintained as Ca leaching increases with decreasing temperature. At Azacualpa, on the other hand, decrease in F occurs with decrease in Ca, suggesting a more complex precipitation mechanism as discussed later.

The control on Ca in ascending waters at Pavana and Sambo Creek may be different from that described above for sedimentary reservoirs because there is no obvious supply of calcite. Possibly the feldspar-clay reactions that govern the Na-K-Ca geothermometer at higher temperatures continue to provide Ca to solution with decreasing temperature (Fournier and Truesdell, 1973). In these reservoirs the source of Mg is probably silicates (clays) rather than Mg-bearing carbonate.

F. Thermal Water Compositions and Reservoir Rocks

The thermal waters of the six hot-spring areas studied are generally similar, but they differ in certain characteristics that give strong indications of the type of reservoir rocks with which the water has equilibrated. In most of the areas there is little doubt as to the reservoir formation. Pavana springs issue from volcanics and volcanoclastics of the Padre Miguel Group; at Azacualpa the western springs issue from a fault zone between the Valle de Angeles Group and limestones of the Atima Formation of the Yojoa Group, but some springs to the east issue from only Atima limestone; the Sambo Creek springs issue from a basement complex of the Cacaguapa Schist and younger intrusives; and El Olivar springs issue from Atima limestone. At Platanares, the hot springs issue primarily from a section of Padre Miguel silicic tuffs. However, red beds of the Valle de Angeles Group, which underlie the tuffs to east and west, appear to govern the chemistry of Platanares waters. The chemical character of thermal waters at these five areas is generally consistent with equilibrium between the identified rocks underlying the springs and the reservoirs that are assumed to exist.

An incongruity between rock type and water composition occurs at San Ignacio; surface geology suggests a reservoir entirely in high-grade

metamorphic rocks of the Cacaguapa Schist. However, the water and gas chemistry is very similar to that of Platanares (a reservoir in sedimentary rocks) and quite different from that of Sambo Creek, known to issue from metamorphics. This difference can be seen in the high B/Cl ratio (Fig. 18), the high total CO_2/Cl ratio (Fig. 19), and the high NH_3 contents of gases (Fig. 20). These features of San Ignacio fluids resemble those of waters issuing from the Valle de Angeles Group and from sedimentary reservoirs elsewhere. The difference is also reflected in low He (Fig. 20) and low Ar (Fig. 21) concentrations, the latter indicated by an N_2/Ar ratio equal to that of air-saturated water. Thus, these San Ignacio gases differ significantly from the high He concentration and low N_2/Ar ratio of Sambo Creek gases, which must contain a radiogenic He and Ar component from old, high-grade metamorphic reservoir rock. From these indications we assume that San Ignacio has a sedimentary reservoir with limestone or calcite providing high CO_2 to react with rock and form high Na-HCO_3 waters characteristic of other Honduran systems with sedimentary reservoirs.

The $\delta^{13}\text{C}$ -values of CO_2 in hot spring and borehole gases may also indicate reservoir type (Fig. 22 and Table V). Systems with CO_2 from marine limestones have $\delta^{13}\text{C}$ -values of CO_2 near zero; those with CO_2 from oxidation of organic matter have low $\delta^{13}\text{C}$ -values (<-17); and those with pure volcanic CO_2 should have $\delta^{13}\text{C}$ -values near -5 to -8. Platanares, San Ignacio, and the part of Azacualpa that issues from the Valle de Angeles Group have $\delta^{13}\text{C}$ -values of CO_2 intermediate between those of limestone and organic carbon, whereas El Olivar, entirely in marine limestone of the Yojoa Group, has a $\delta^{13}\text{C}$ -value of CO_2 near -3. The $\delta^{13}\text{C}$ -value of the Azacualpa sample from Atima limestone is intermediate between the El Olivar and Platanares-San Ignacio values. Pavana has a $\delta^{13}\text{C}$ -value of CO_2 consistent with the presence of volcanic CO_2 , although a mixed source from lake sediments could be involved. A most puzzling $\delta^{13}\text{C}$ -value is that of the minor CO_2 (N_2 was the major gas) in gas from Sambo Creek, which is near -15, clearly consistent with an origin from organic carbon. Possibly the CO_2 from this spring was locally derived from oxidizing vegetation.

Using the chemical, gas, and isotopic indicators as well as the geologic relations, we have, in Fig. 23, assigned each thermal fluid to a particular

Figure 18. Diagram showing B/Cl ratios (molar) of Honduran thermal waters compared with B/Cl ratios of selected geothermal waters around the world. Ratios >0.1 generally indicate interaction with sedimentary reservoir rocks whereas ratios between 0.01 and 0.1 commonly indicate interaction with volcanic reservoirs.

Figure 19. Diagram showing total dissolved CO_2/Cl ratios (equivalence) of Honduran thermal waters compared with those of selected geothermal waters around the world. Ratios >1.0 generally indicate sedimentary reservoirs. An important exception is the system at Ngawha, New Zealand, which issues from metagreywacke.

Figure 20. Diagrams showing $\log \text{He}$ and $\log \text{NH}_3$ (moles/mole dry gas) of Honduran hot spring gases compared with those of selected hot spring gases from geothermal sites around the world.

Figure 21. Diagram showing N_2/Ar ratios (molar) of Honduran hot spring gases compared with N_2/Ar ratios of selected hot spring gases from geothermal sites around the world.

Figure 22. Diagram showing carbon-13 in CO₂ gas [‰ relative to Peedee Belemnite (PDB)] of Honduran hot spring gases compared with that of selected hot spring gases from geothermal sites around the world and with that from common carbon sources.

reservoir rock. We strongly believe that the reservoir at San Ignacio must be partly contained in a downfaulted section of the Valle de Angeles Group or in a similar type of sedimentary sequence that is buried by Tertiary and Quaternary basin-fill deposits.

G. Sulfate/Oxygen-18 In Cold Waters

The conventional use of ¹⁸O (SO₄) in geothermal studies is as a stable, slow-to-equilibrate geothermometer (McKenzie and Truesdell, 1979), and this has been its main use in our geochemical studies of Honduran springs. Sulfate oxygen isotopes can also be used as a tracer of the source of the sulfate. Although sulfate and water exchange oxygen isotopes rapidly at higher temperatures, the rate of exchange becomes negligible at low temperatures (McKenzie and Truesdell, 1977); thus, the δ¹⁸O (SO₄) in low-temperature waters should reflect the source of the sulfate. The cold water sulfate δ¹⁸O-value from sample AZ-3 (28°C, 2.6 mg/l Cl) is +12.9‰ (Table VI). This value is similar to that of most marine gypsum, which has remained near the present

TABLE V. Carbon-13 Values of Rocks, Waters, and Gases from Honduran Geothermal Systems

Sample No.	Type of Sample	$\delta^{13}\text{C}$ of Rock Carbonate (‰, PDB) ^a	$\delta^{13}\text{C}$ of CO ₂ (H ₂ O) (‰, PDB) ^a	$\delta^{13}\text{C}$ of CO ₂ Gas (‰, PDB) ^a
<u>Platanares Site</u>				
PL-1	Hot spring	--	-8.72	-10.80
PL-3	Hot spring	--	-7.69	-10.05
PL-7	Hot spring	--	-7.23	--
PL-8	Hot spring	--	-7.11	--
PL-9	Quebrada Agua Caliente	--	-8.48	--
PL-11	Hot spring	--	-6.77	--
<u>San Ignacio Site</u>				
SI-2	Hot spring	--	--	-11.75
SI-3	Hot spring	--	-7.11	-11.01
SI-7	Hot spring	--	-7.10	-12.80
SI-9	Hot spring	--	-7.37	--
SI-10	Mixed spring	--	-6.82	--
SI-12	Mixed spring	--	-8.15	--
SI-15	Hot spring	--	-8.10	--
<u>Azacualpa Site</u>				
AZ-1	Hot spring	--	-6.38	--
F85-19	Travertine at Spring AZ-1	-3.1	--	--
AZ-2	Hot spring	--	-5.26	--
AZ-4	Hot spring	--	-5.05	-12.63
AZ-6	Hot spring	--	-4.29	-7.04
F85-20	Atima Limestone	+3.8	--	--
AZ-7	Hot spring	--	-3.16	--
AZ-8	Hot spring	--	-7.01	--
AZ-9	Hot spring	--	-7.25	--

^aUncertainty is ± 0.25 ‰.

TABLE V. (continued)

Sample No.	Type of Sample	$\delta^{13}\text{C}$ of Rock Carbonate (‰, PDB) ^a	$\delta^{13}\text{C}$ of CO ₂ (H ₂ O) (‰, PDB) ^a	$\delta^{13}\text{C}$ of CO ₂ Gas (‰, PDB) ^a
<u>Choluteca Region</u>				
PV-1	Hot spring	--	-5.92	--
F85-22	Calcite from Spring PV-3	-2.8	--	--
PV-3	Hot spring	--	-5.86	-9.74
PV-4	Hot spring	--	-5.46	--
PV-7	Hot spring	--	-6.42	--
PV-8	Hot spring	--	-8.71	--
PV-10	Hot spring	--	-11.92	--
<u>La Ceiba Region</u>				
SC-1	Hot spring	--	-7.00	--
SC-2	Hot spring	--	-6.59	--
SC-3	Hot spring	--	--	-14.73
SC-5	Hot spring	--	-10.53	--
SC-6	Hot spring	--	-9.73	--
<u>El Olivar Site</u>				
E0-1	Hot spring	--	+0.47	-2.69
F85-16	Travertine at Spring E0-2	+5.0	--	--
E0-2	Hot spring	--	+0.07	--
F85-17	Atima Limestone	+3.0	--	--
E0-3	Hot spring	--	+0.07	--
F85-18	Old travertine	+3.3	--	--
E0-6	Hot spring	--	-0.11	--
E0-7	Hot spring	--	-0.75	-3.56

^aUncertainty is ± 0.25 ‰.

ALLUVIUM
GRACIAS FM., Volc. Sed.
PADRE MIGUEL GRP.
Rhyolite tuffs, domes
MATAGALPA FM.
Andesite, Basalt and
assoc. seds.

VALLE de ANGELES GRP.
Clastic Red Beds
Petroliferous Lmst.
Gypsum, Sh., Ss., Congl.

YOJOA GROUP
Atima Lmst.
Petroliferous Sh. and
Lmst. Congl., Red Beds

TODOS SANTOS FM.
Clastic Red Beds, Congl.

EL PLAN FM.
Black Sh., Ss.

Low-Grade Met.

CACAGUAPA SCHIST
High-Grade Met.

PAVANA

AZACUALPA
PLATANARES
SAN IGNACIO

AZACUALPA.
EL OLIVAR

SAMBO CREEK

Figure 23. Regional stratigraphy of Honduras related to location of thermal aquifers.

value of +13.5‰ since the Triassic (Claypool et al., 1980) and indicates that solution of gypsum is a possible SO_4 source. This cold water originates from the Valle de Angeles Group, which contains gypsum beds.

VI. GEOTHERMOMETRY OF HOT SPRING DISCHARGES

In exploration for geothermal energy, one method of investigation is the application of fluid geothermometers to hot spring discharges to estimate subsurface temperatures. Geothermometers depend on temperature-sensitive reactions between fluids and rocks or reactions within the fluid. These reactions must be sufficiently slow so that evidence of the equilibration temperature remains "frozen in" as fluids rise to the surface. The most

TABLE VI. Sulfate and Water Oxygen-13 Isotope Compositions and Calculated Equilibrium Isotope Temperatures

Sample No.	Date	Measured Temperature (°C)	Isotope Compositions		Calculated Isotope Temperatures ^a		
			$\delta^{18}\text{O}_{\text{SO}_4}$ (‰)	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$ (‰)	T ^{1b} (°C)	T ^{2c} (°C)	T ^{3d} (°C)
<u>Platanares Site</u>							
PL-1	5/17/85	99.5	+0.33	-6.14	248	220	227
PL-3	5/17/85	100.1	+0.12	-6.17	253	224	231
PL-7	5/17/85	98.5	+0.14	-6.12	254	224	231
PL-8	5/18/85	98.6	-0.02	-6.00	261	229	237
PL-11	5/18/85	70.8	+0.53	-6.09	245	209	219
PL-9	5/18/85	26.7	+10.88	-7.01			
<u>San Ignacio Site</u>							
SI-3	5/15/85	98.9	+0.05	-6.78	240	214	220
SI-7	5/15/85	98.0	+0.55	-6.75	229	206	212
SI-9	5/15/85	99.0	-0.15	-7.05	238	213	219
SI-12	5/27/85	72.0	-0.19	-7.06	239	205	214
SI-15	5/27/85	97.8	-0.41	-6.81	250	221	228
SI-10	5/15/85	30.9	+4.51	-6.42			
<u>Azacualpa Site</u>							
AZ-1	5/24/85	98.0	+2.92	-5.92	198	183	186
AZ-2	5/24/85	95.0	+2.83	-5.78	203	186	189
AZ-4	5/24/85	100.3	+3.13	-5.73	198	184	186
AZ-6	5/24/85	101.4	+3.25	-5.03	209	192	196
AZ-7	5/24/85	98.7	+2.95	-5.76	201	185	188
AZ-8	5/25/85	115.4	+2.77	-5.67	206	193	195
AZ-9	5/25/85	50.2	+7.44	-5.49	138	126	129
AZ-3	5/24/85	28.0	+12.91	-4.83			

^aTemperatures calculated using equations in McKenzie and Truesdell (1977).

^bNo steam loss (conductive cooling).

^cMaximum steam loss (adiabatic cooling).

^dContinuous steam loss.

TABLE VI. (continued)

Sample No.	Date	Measured Temperature (°C)	Isotope Compositions		Calculated Isotope Temperatures ^a		
			$\delta^{18}\text{O}_{\text{SO}_4}$ (°/..)	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$ (°/..)	T ^{1b} (°C)	T ^{2c} (°C)	T ^{3d} (°C)
<u>Choluteca Region</u>							
PV-1	5/29/85	90.6	+1.09	-7.46	203	186	189
PV-3	5/29/85	101.8	+1.25	-7.16	206	190	193
PV-4	5/29/85	92.6	+1.04	-6.97	214	194	198
PV-7	5/29/85	73.3	+1.39	-6.94	208	184	190
PV-8	5/30/85	82.0	+3.78	-6.69	171	159	161
PV-9	5/30/85	67.8	+4.40	-6.36	167	153	155
PV-10	5/30/85	81.1	+3.01	-7.23	175	161	164
PV-2	5/29/85	34.0	+4.64	-6.30			
<u>La Ceiba Region</u>							
HN-6	5/21/85	78.8	+5.60	+4.18	182	167	170
SC-1	5/21/85	99.9	+5.37	-5.05	172	163	164
SC-2	5/21/85	100.3	+5.70	-5.04	167	159	160
SC-5	5/22/85	87.7	+8.01	-4.09	149	142	142
SC-6	5/22/85	87.0	+7.36	-4.06	158	149	150
<u>El Olivar Site</u>							
E0-1	5/23/85	66.4	+8.22	-3.14	159	146	148
E0-2	5/23/85	72.3	+7.39	-3.59	164	151	154
E0-3	5/23/85	75.9	+7.36	-3.20	170	157	159
E0-6	5/23/85	77.4	+4.83	-3.17	215	191	196
E0-7	5/23/85	67.8	+5.21	-2.79	215	188	195
<u>Miscellaneous</u>							
HN-10	5/29/85	26.0	+6.00	-6.04			

^aTemperatures calculated using equations in McKenzie and Truesdell (1977).

^bNo steam loss (conductive cooling).

^cMaximum steam loss (adiabatic cooling).

^dContinuous steam loss.

TABLE VII. Chemical Geothermometers Used in These Investigations

Geothermometer	Equation ^a (Dissolved Components in mg/l; Gas Components in vol%)	Restrictions
a. Quartz (no steam loss)	$T^{\circ}\text{C} = \frac{1309}{5.19 - \log C} - 273.15$	$T = 0-250^{\circ}\text{C}$
b. Quartz (max. steam loss)	$T^{\circ}\text{C} = \frac{1522}{5.19 - \log C} - 273.15$	$T = 0-250^{\circ}\text{C}$
c. Chalcedony	$T^{\circ}\text{C} = \frac{1032}{4.69 - \log C} - 273.15$	$T = 0-150^{\circ}\text{C}$
d. Na/K (Fournier)	$T^{\circ}\text{C} = \frac{1217}{\log(\text{Na/K}) + 1.483} - 273.15$	$T > 150^{\circ}\text{C}$
e. Na-K-Ca	$T^{\circ}\text{C} = \frac{1647}{\log(\text{Na/K}) + \beta[\log(\sqrt{\text{Ca/Na}}) + 2.06] + 2.47} - 273.15$	$T < 100^{\circ}\text{C}, \beta = 4/3$ $T > 100^{\circ}\text{C}, \beta = 1/3$
f. Na-Li	$T^{\circ}\text{C} = \frac{1000}{\log(\text{Na/Li}) + 0.38} - 273.15$	$T = 0-300^{\circ}\text{C}(?)$ and $\text{Cl} < 7000 \text{ mg/l}$
g. $\Delta^{18}\text{O}(\text{SO}_4^{2-} - \text{H}_2\text{O})$	$T^{\circ}\text{C} = \left[\frac{2.88 \times 10^6}{1000 \ln \alpha + 4.1} \right]^{1/2} - 273.15$ where $\alpha = \frac{1000 + \delta^{18}\text{O}(\text{SO}_4)}{1000 + \delta^{18}\text{O}(\text{H}_2\text{O})}$	$T = 100-300^{\circ}\text{C}(?)$
h. Gas($\text{CO}_2\text{-H}_2\text{S-CH}_4\text{-H}_2$)	$T^{\circ}\text{C} = \frac{24775}{\alpha + \beta + 36.05} - 273.15$ $\alpha = 2 \log \frac{\text{CH}_4}{\text{CO}_2} - 6 \log \frac{\text{H}_2}{\text{CO}_2} - 3 \log \frac{\text{H}_2\text{S}}{\text{CO}_2} \quad \text{and}$ $\beta = 7 \log P_{\text{CO}_2}$ $\beta = \begin{cases} = 7 \text{ if } \text{CO}_2 < 75 \text{ vol } \%; P_{\text{CO}_2} = 0.1 \text{ atm} \\ = 0 \text{ if } \text{CO}_2 > 75 \text{ vol } \%; \text{CH}_4 < 2\text{H}_2; \text{H}_2\text{S} < 2\text{H}_2; P_{\text{CO}_2} = 1 \text{ atm} \\ = -7 \text{ if } \text{CO}_2 > 75 \text{ vol } \%; \text{CH}_4 > 2\text{H}_2; \text{H}_2\text{S} > 2\text{H}_2; P_{\text{CO}_2} = 10 \text{ atm} \end{cases}$	$T = 100-300^{\circ}\text{C}$
i. Gas($\text{CO}_2\text{-CH}_4$)	$T^{\circ}\text{C} = \frac{\log \frac{\text{CO}_2}{\text{CH}_4} - 0.237}{0.012}$	$T = 0-300^{\circ}\text{C}(?)$

^aC = concentration of dissolved silica, log = logarithm to base ten and ln = natural logarithm.

successful geothermometers depend on (1) solution of silica minerals, (2) cation exchange with feldspars, micas, and possibly clays, (3) equilibria of gases with rock minerals, and (4) isotopic fractionation between fluid constituents. Table VII lists the geothermometers used in this report, and White (1970), Truesdell (1976), Fournier (1981), and others have reviewed their application.

A. Silica and Cation Geothermometry

Silica geothermometers, depending on saturation with silica minerals (usually quartz at temperatures above 140°C and chalcedony at lower temperatures), equilibrate rapidly at moderate to high temperatures and are fully equilibrated in most geothermal reservoirs. However, they are affected by dilution and reequilibration during ascent of fluids to the surface. Silica geothermometers applied to spring samples usually do not indicate temperatures above about 220°C because solutions saturated with quartz at or above this temperature rapidly precipitate amorphous silica during ascent and cooling to surface temperatures.

Cation geothermometers include the Na/K and Na/Li ratios and the Na-K-Ca function (Ellis and Mahon, 1964; Fournier, 1981; Fouillac and Michard, 1981; Fournier and Truesdell, 1973). These geothermometers equilibrate only in the presence of feldspars or other alumino-silicate minerals. Their rate of reequilibration during ascent depends on the cation concentrations (dilute solutions equilibrate more rapidly than do concentrated ones), the flow rate and temperature during ascent, and the minerals encountered during ascent (if the upflow channels are lined with silica minerals, cation reequilibration is greatly slowed or prevented). In general, the Na/Li geothermometer reequilibrates slowly during ascent and may not be fully equilibrated in reservoirs whose temperatures are below 250-300°C.

Geothermometers based on Na/K ratios are generally similar to the Na-K-Ca geothermometer but can be applied only to low-Ca waters. For high-Ca waters these geothermometers give unreasonably high temperatures. Sodium-potassium geothermometers have the advantage of being little affected by dilution so long as the thermal water is much more concentrated than the diluting water. In general, the Na-K-Ca geothermometer gives satisfactory results with the widest range of water types. It does not have a sharp upper temperature

limit (like silica) but may partially reequilibrate in passage from higher-temperature reservoirs to the surface unless flow is extremely rapid within inert upflow channels and/or if there is no significant precipitation of calcite (and loss of Ca) caused by boiling. These conditions are probably met only in some geothermal wells but may be approximated by large flows of relatively high-Ca, low-HCO₃ water in silica-lined conduits that boils during ascent but deposits little CaCO₃ because of the limited supply of HCO₃. Waters that lose heat by conduction during moderately slow flow through silica-lined conduits and do not boil may also arrive at the surface unchanged in Na-K-Ca temperature. As we pointed out in the beginning of Section V, thermal waters of Honduras resemble many of those from the Basin and Range province of the western United States, and we note that Edmiston and Benoit (1985) found that the Na-K-Ca geothermometer predicts temperatures that are too high in this tectonic environment. Waters containing high Mg may give high-temperature indications and require an Mg correction (Fournier and Potter, 1979), but Mg is generally very low in waters whose temperatures are above 200°C, and it is not reasonable to correct for Mg that enters thermal waters during mixing. The Mg correction should, therefore, be used with caution.

B. Mixing Calculations

If cold, dilute water mixes with thermal fluid during ascent to the surface, it may prevent or reduce reequilibration and preserve evidence of deep temperatures. Several "mixing models" have been suggested by Fournier and Truesdell (1974) and Truesdell and Fournier (1976, 1977). Although useful formulas are available, these mixing models can most easily be used graphically. For warm (not boiling) springs, the enthalpy and silica content after mixing may be considered to be conservative components, and a mixing line can be drawn between the representative points. This mixing line may be extrapolated to the solubility curve of the silica mineral (usually quartz) that is thought to control concentrations of dissolved silica in the reservoir. The enthalpy at the intersection of the mixing line and the solubility curve indicates the reservoir temperature. This mixing model assumes no loss or gain of silica or heat either before or after mixing. Equilibration after mixing is assumed not to have occurred because the temperature is low and the reaction rate is very slow. Conductive cooling after mixing commonly occurs,

and the temperature indicated is then too high. This method should be used only for springs with high discharge volumes in which conductive cooling is unlikely. This method should also be used if cation geothermometer temperatures are much higher than quartz solubility temperatures.

The enthalpy-chloride plot is more generally useful because it can indicate original temperatures of waters that boil after mixing. On this plot the mixing temperatures are relatively high (140 to 200°C) so the geothermometer (silica or cation) is assumed to have equilibrated after mixing. It is also assumed that the mixed and nonmixed waters have cooled to surface conditions by boiling or conduction. To start, the surface Cl and enthalpy are plotted and lines are drawn from each point, either with constant Cl (if conductive cooling is assumed) or to the composition of steam (usually assumed to be at 100°C, i.e., zero Cl and 2680 J/g). Along each of these lines the enthalpy of liquid water at the temperature indicated by the geothermometer is marked. These chloride-enthalpy compositions are assumed to be those in the mixing chamber, and they may be connected with the enthalpy-chloride composition of cold water to form mixing or dilution lines. In cases where these dilution lines coincide, a single hot-water end member can be deduced. The nondiluted end-member water will have a reservoir chloride-enthalpy composition lying at the intersection of the dilution line with the cooling line of the highest-Cl surface water. The cooling line may be conductive with constant Cl, or it may be the boiling line drawn between the surface composition of the spring and that of steam. The deep temperature is calculated from the enthalpy at this intersection. It is possible that the nonmixed end member will not reach the surface, and without other information the water with the highest Cl (corrected to the same enthalpy) must be assumed to be nonmixed. If this water is in fact a mixture, the temperature indicated will be low. Dilution lines based on a single thermal water are suspect because they may not have equilibrated after mixing and may give temperature indications that are too high. Dilution lines drawn through multiple chloride-enthalpy compositions that extrapolate to reasonable cold-water and hot-water end members may be used with more confidence.

If mixing is indicated by silica-enthalpy or chloride-enthalpy plots, it should be sought in plots of conservative constituents, such as Cl-B and

Cl-Li, or by looking for constant ratios of these components. Correlation (constant ratios) alone may not indicate mixing because waters cooling conductively will be more dilute than the same waters cooling by boiling and steam loss and will have the same ratios of conservative constituents. The concentration difference between boiled and conductively cooled waters increases with reservoir temperature and is 20% for a 200°C reservoir. In general, if the variation exceeds 30-40% and conductive cooling is unlikely (boiling springs with large flows), mixing is indicated. More complicated cooling pathways may be shown by isotope diagrams in which not only the total temperature changes but also the temperature of steam loss will affect the final composition.

C. Isotope Geothermometry

A wide range of potential geothermometers originate from isotopic fractionation of an element between different compounds contained in geothermal fluids (Truesdell and Hulston, 1980). Some of these geothermometers require difficult analyses and unusually large samples. If samples are too small, fluids equilibrate too rapidly (indicating only collection temperature) or too slowly (either not equilibrating or equilibrating only at great depths below economical drilling). The most widely applied isotope geothermometer involves fractionation of oxygen between water and dissolved sulfate (McKenzie and Truesdell, 1977). This geothermometer completely equilibrates in geothermal reservoirs whose temperatures are above 150°C and reequilibrates only slightly in spring waters ascending at average velocities. Corrections must be made, however, for mixture with H₂O or SO₄ of different origin and for isotopic changes caused by boiling. The changes in water isotopes caused by boiling depend on the amount of boiling and the temperature of steam separation (Table VI). The maximum effect occurs if cooling is entirely by boiling and all steam separates at the surface (adiabatic cooling--T₂ in Table VI); there is less effect if steam separates as it is formed (continuous separation--T₃ in Table VI); and, of course, there is no isotopic change if the water cools conductively without steam loss (conductive cooling--T₁ in Table VI). This geothermometer may indicate temperatures somewhat higher than those indicated by chemical geothermometers but often similar to those found upon drilling.

D. Gas Geothermometry

Gas geothermometers are generally difficult to apply to hot spring and fumarole gases because most of the pertinent equilibria are pressure sensitive and competing gas reactions differ greatly in reaction rate. Gas pressures cannot be calculated without knowledge of the gas/total water ratio, which is usually unavailable for hot spring discharges. Despite these difficulties the empirical D'Amore-Panichi (1980) geothermometer has been surprisingly successful in a wide variety of systems. To understand this complicated geothermometer, read the original paper. Another empirical gas geothermometer has been developed by Norman and Bernhardt (1981), who have correlated the ratio of CH_4/CO_2 with the estimated reservoir temperature (Na-K-Ca) of hot springs in the state of New Mexico in the United States. This gas geothermometer has a smaller data base than the D'Amore and Panichi geothermometer and has been less successful.

VII. HOT SPRING DEPOSITS

Hot spring deposits can provide useful qualitative information on the subsurface temperature of geothermal reservoirs. For example, White et al. (1971) have proposed that hot springs depositing silica sinter probably have subsurface reservoir temperatures of at least 150°C . The basis of this proposal comes from the very high solubility of silica phases at higher temperatures (Fig. 24). For example, if we assume that a deep fluid at 250°C is saturated in silica with respect to the least soluble phase, quartz, then the fluid would contain 490 mg/l dissolved SiO_2 . If this fluid rapidly ascends to the surface to a boiling spring, it would then be supersaturated with respect to quartz and, in fact, all silica phases. If the water remains long enough at this temperature, precipitation of a silica phase would inevitably result. Precipitation may not occur if the water immediately mixes with cold water or if the water is undersaturated with amorphous silica. Because precipitation of crystalline phases is slow at low temperatures, a geothermal fluid can remain supersaturated with quartz for some time (otherwise, the quartz geothermometer would not work). Figure 24 also shows the case for a deep fluid at 150°C . Although this latter fluid would not be nearly as supersaturated as the one in the first case, it might be expected to

Figure 24. Plot of silica versus temperature with curves representing the solubilities of various silica phases.

precipitate amorphous silica upon reaching the surface, evaporating, and cooling below boiling temperature. Amorphous silica may deposit around spring orifices if water containing silica splashes on nearby rocks and evaporates.

Sizable silica sinter deposits occur at three geothermal sites in Honduras: Platanares, San Ignacio, and Sambo Creek. We also found amorphous silica in the spring deposits at the Pavana site and some quartz in the Azacualpa deposits (Table VIII). Consideration of the calculated reservoir temperatures, based on chemical geothermometry (Section VI above), would suggest that the presence of silica deposits requires a subsurface temperature of at least 130°C (which exists at the La Labor site).

In contrast to silica sinter, the presence of carbonate travertine indicates either that the hot spring system is equilibrated at temperatures $\leq 150^{\circ}\text{C}$ or that the hot spring waters are a mixture of a hot end member and a relatively Ca-HCO_3 -rich cold end member. This is because the solubility of CaCO_3 decreases as temperature increases. We can examine this relationship qualitatively by comparing the data in Table IX. All the Honduran systems are relatively rich in HCO_3 and CO_2 , and we see that the Ca concentration of the various hot end-member waters generally decreases as the temperature of the

TABLE VIII. X-Ray Diffraction Analyses^a of Spring Deposits, Cements, and Fracture Fillings at Platanares, San Ignacio, Azacualpa, and Pavana Geothermal Sites, Honduras

Sample No.	Location	Description	Mineral Phases (Most Abundant First)
F85-8	Platanares; sample just above northeast side of Quebrada Agua Caliente between springs PL-1 and PL-2	White, crusty, fracture-filling in silicified tuff	<u>Quartz</u> , illite, jaro-site, feldspar, gypsum(?), clinop-tilolite
F85-9	Platanares; sample from spring PL-5	White silica sinter	<u>Amorphous silica or opal</u> , quartz, feld-spar(?), smectite(?)
F85-10	Platanares; sample from spring PL-8	White, crusty fracture-filling in sheared Paleozoic schist	<u>Quartz</u> , illite
F85-12	Platanares; sample from spring PL-3	White crust on stream cobbles	<u>Quartz</u> , illite, amorphous silica, feldspar, kaolin(?)
F85-13	Platanares; sample near spring PL-3 along stream	Reddish cemented conglomerate	<u>Quartz</u> , feldspar, amorphous silica, smectite, illite(?), kaolin(?)
F85-21	San Ignacio; sample from 1 m above new spring SI-15 created in recent steam explosion	White massive traver-tine	<u>Calcite</u> , quartz, feldspar
F85-21P	San Ignacio; same sample as F85-21	White, platy crystals standing vertically ^b above massive sample	<u>Calcite</u> , quartz, smectite, illite
F85-23	Pavana; sample from spring PV-4	White fibrous mass of crystals in mas-sive travertine	<u>Calcite</u> , amorphous silica, feldspar, smectite
F86-7	Spring deposit at spring SI-9	Silica sinter	<u>Quartz</u> , feldspar, mica

^aBy S. Chípera, Los Alamos National Laboratory.

^bThinolite, CaCO₃ (Radbuch 1957).

TABLE VIII. (continued)

Sample No.	Location	Description	Mineral Phases (Most Abundant First)
F86-8	Old travertine deposit behind SI-9	Opaline sinter	<u>Quartz</u> , amorphous silica, mica, illite
F86-21	Spring deposit from Agua Caliente area, 30 km west of San Ignacio	Calcite travertine	<u>Calcite</u> , quartz
L86-2	Spring deposit at SI-21	Silica sinter	<u>Quartz</u> , mica, kaolinite, calcite
L86-3	Spring deposit at AZ-1	Travertine	<u>Calcite</u> , quartz
L86-5	Spring deposit at AZ-26	Travertine	<u>Calcite</u> , quartz
L86-8	Sample below waterfall at San Ignacio	Sinter	<u>Calcite</u> , quartz, mica, hornblende(?)

TABLE IX. Temperature, Calcium Content, and Bicarbonate Content of End-member Thermal Waters

Site	Hot End Member	Ca (mg/l)	HCO ₃ ^a (mg/l)	Temperature ^b (°C)
Platanares	PL-1	2.5	490	225
San Ignacio	SI-8	7.1	445	190
Azacualpa	AZ-4	8.4	159	185
Sambo Creek	SC-1	3.6	130	155
Pavana	PV-3	21.1	82	150
El Olivar	EO-3	38.0	1215	120

^aHCO₃ calculated as (2 x CO₃) + HCO₃.^bTemperature from chemical geothermometry.

system increases. Note that total HCO_3 concentration is not a good indicator of temperature.

We observed conspicuous deposits of travertine and/or prismatic CaCO_3 at three sites: Azacualpa, Pavana, and El Olivar. Interpretation of the geochemical data discussed in the site descriptions of following sections indicates that Pavana and El Olivar thermal waters do not show the effects of mixing; thus, it would appear that temperatures of these systems are $<150^\circ\text{C}$ at depth. In contrast, mixing is a phenomenon that affects some of the thermal waters at Azacualpa ($T_{\text{res}} \approx 185^\circ\text{C}$), and only springs having a Ca-HCO_3 -rich component (i.e., AZ-1 and AZ-11) are depositing carbonate travertine. Ancient hot springs of mixed composition may have deposited the travertine that forms La Cueva.

We observed a small amount of CaCO_3 displaying an unusual bladed habit (thynolite) on massive travertine 1 m above spring SI-15 at San Ignacio (samples F85-21 and F85-21P in Table VIII). No precise explanation for the presence of thynolite is available, but the crystals could have formed from a mixed fluid, from evaporation, or from boiling and loss of CO_2 . Silica sinter overwhelmingly dominates the deposits of the San Ignacio system.

Other mineral phases identified in the x-ray diffraction analyses of Table VIII do not indicate any particular temperature or pH environment. Gypsum and jarosite are sulfates common to many types of hot spring areas, particularly where evaporation may occur or where oxidation attacks sulfide minerals in the host rocks of the system. Clay minerals and feldspar probably originate from dirt or grit incorporated in the deposit or from wall rock adjacent to vein samples. Clinoptilolite, which was identified in sample F85-8 from Platanares (Table VIII), is a zeolite that commonly forms during diagenetic alteration of silicic tuffs (Hay, 1978). Some tuff adjacent to the vein was probably incorporated into the sample.

VIII. PLATANARES SITE

The Platanares site is located in the Quebrada Agua Caliente (Figs. 5, 25, and 26), just east of the villages of Platanares and San Andrés and

Figure 25. Map of the Platanares geothermal area, Honduras, showing locations of various springs and faults. The symbol X shows location of proposed 500-m core hole.

Figure 26. Photograph of waterfall in the Quebrada Agua Caliente looking northwest. Many hot springs discharge from the fractured and faulted tuffs near the waterfall.

about 16 km west of Santa Rosa de Copán (Santa Rosa de Copán sheet, UTM* coordinates 928/327). The region around Platanares is mountainous and deeply dissected. Elevations of nearby ridges exceed 1400 m, whereas the hot springs in the quebrada are at about 700 m. Platanares is reached by a rough dirt road from the south through the town of La Unión. An active gold mine is being worked at San Andrés. GeothermEx (1980a) and Flores (1980) have previously described the geothermal features.

A. Geology

Heiken et al. (1986) recently mapped the local geology of an area of about 12 km² at the Platanares site. Rocks in the area consist of Paleozoic

*UTM = Universal Transverse Mercator.

schist in the north, which is faulted against tuffs, and tuffaceous sediments and andesite of the Miocene Padre Miguel Group in the south. Triassic black shale of the El Plan Formation and late Cretaceous red beds of the Valle de Angeles Group have been identified west of Platanares by Dupré (1970). The latter unit underlies the Tertiary volcanic rocks only 2 km southwest of the Quebrada Agua Caliente (Heiken et al., 1986) and 1 km northeast of the quebrada. Quaternary terrace gravels cap the Paleozoic rocks near Platanares village, and patches of silica-cemented river gravels locally fill the canyon bottom near the springs.

Heiken et al. (1986) have described four sets of faults in the Platanares area. Of major importance to the spring system are a prominent northeast-trending fault that juxtaposes Paleozoic schist and Tertiary tuffs and north- to northwest-trending faults and fractures that control the positions of many springs and possibly the position of the quebrada (Fig. 25). The northeast-trending fault is apparently the northern boundary of the hot springs and probably of the geothermal reservoir.

B. Surface Features

Heiken et al. (1986) described and mapped most of the springs at Platanares. For convenience, we describe the springs in four groups: (1) a main boiling group in the lower Quebrada Agua Caliente, (2) a cool to boiling group in the central to upper Quebrada, (3) a small boiling group at La Bufa (uppermost quebrada), and (4) a small cool to intermediate group on the Río Lara. We estimate that there are more than 100 thermal springs and seeps in the Platanares area, varying from 35°C to slightly superheated. Although most thermal springs issue near river level, several were noted along canyon walls and in side arroyos up to 35 m above river level.

Lower Quebrada Agua Caliente. The group in the lower quebrada (Fig. 27) contains the greatest number of near-boiling to superheated springs (e.g., PL-3, >100°C, 30 l/min). This group is distributed along both sides of the quebrada over a distance of approximately 750 m, and the thermal waters discharge from fractured, silicified tuff, tuffaceous sediments, river gravel, and colluvium. Although no single spring has very large flow, the combined discharge of this group (above and below water level) is so great that the water in the quebrada adjacent to this group exceeds 40°C. In May 1985, the

Figure 27. Photograph of superheated hot spring PL-3 that issues from fractured silicified tuff on the northeast side of the Quebrada Agua Caliente. Spring spouts 0.5 m intermittently. Note white silica deposits around the spring orifice.

quebrada had an estimated flow of about 12,000 l/min. Several low-pressure steam vents occur along this reach of the quebrada primarily on the southwest side, from river level to roughly 25 m above river level. The odor of H_2S can be detected in steam from these vents and from the springs.

Most of the thermal springs are depositing silica sinter (e.g., sample PL-5 in Table VIII). Many fractures in the tuff are filled with solid to vuggy quartz and amorphous silica, no doubt from earlier spring activity. Patches of stream gravels are also cemented with reddish to whitish quartz and amorphous silica. These patches must represent in part periods of earlier spring activity although some may be associated with earlier silicification and hydrothermal activity resulting from emplacement of the gold deposit at San Andrés. Periods of high water and flooding probably strip sinter and cemented gravels from the canyon before they can accumulate to any appreciable volume. In addition to silica deposits, alteration minerals in the host rocks include jarosite, gypsum, clays, and clinoptilolite (Table VIII).

Central and Upper Quebrada Agua Caliente. From the vicinity of spring PL-3 upstream past the waterfall for a distance of about 1500 m, thermal springs tend to have low flow rates and cool to intermediate temperatures (e.g., springs PL-10 and PL-11, 38 to 71°C). Numerous thermal seeps issue from fractured tuff 250 m downstream from and in the cliff face of the waterfall. A small group of boiling springs occurs about 500 m upstream from the waterfall along the Quebrada. Gas discharges are uncommon and spring deposits less abundant than at the lower Quebrada, although the tuffs are silicified and altered and fractures contain veins of quartz and calcite.

La Bufa. About 1500 m upstream from the waterfall, at the point where a side canyon from San Andrés joins on the west, the Quebrada Agua Caliente bends sharply northeast following the trend of the major fault that juxtaposes Paleozoic schist and Miocene tuff. Upstream 100 m from this bend, approximately 10 to 15 thermal springs issue from fractured and sheared schist on both sides of the quebrada. The most obvious spring is La Bufa (PL-8, 99°C, 10 l/min), which spouts intermittently from a thin silica sinter surface on altered schist and river gravel. a larger spring discharges into the stream slightly upstream and opposite from La Bufa at the base of a ledge of schist. The steam at La Bufa smells of H₂S.

Río Lara. A small group of cool to intermediate springs and seeps flow from fractured, silicified tuff and river gravel in a narrow but shallow canyon on the Río Lara, about 1 km upstream from its junction with the Quebrada Agua Caliente. The largest spring in this group (PL-15, 54°C, 2 l/min) issues on the north side of the stream from behind large boulders. A few other seeps occur farther upstream as well as downstream. No gas emissions and spring deposits were noted although mineral crusts form around the evaporating seeps.

C. Chemistry

Thermal waters at Platanares are Na-K-HCO₃-SO₄-Cl in composition with significant trace concentrations of As, B, Cs, F, Li, and NH₄ (Table VIII). Boiling springs contain relatively small amounts of Ca and Mg. Concentrations of SiO₂ are the highest of any system studied in Honduras (up to 300 mg/l), although total dissolved solids (TDS) do not exceed 1070 mg/l. Boron exceeds Cl on a milliequivalent basis. High NH₄ concentrations are reflected in high concentrations of NH₃ in steam.

Significant mixing occurs between hot end-member fluid as represented by spring PL-1 and cooler groundwaters. The mixing relationship is best shown in the plot of B versus Cl ($r^2 = 0.995$) and plots of Li and F versus Cl (Fig. 28), but it is also observed qualitatively in the increasing concentrations of As and Cs with increasing Cl. In contrast, Ca and Mg contents decrease as Cl increases. Examples of mixed springs are PL-4, -6, -10, -11, -12, and -15.

In Fig. 29, we have plotted spring temperature versus Cl content to estimate the maximum temperature of the hot end-member thermal fluids before mixing. This can be done by extrapolating the mixing line to the value of the highest Cl content that was measured, which indicates a maximum temperature before mixing of about 120°C. The range of Cl in boiling springs is greater than could be produced by physical cooling processes and indicates that at least the lower-Cl spring waters are mixtures.

Figure 28. Plots of B, Li, and F versus Cl for thermal and nonthermal waters of Platanares, Honduras.

Figure 29. Plot of spring temperatures versus Cl for thermal and nonthermal waters at Platanares, Honduras.

Figure 30 shows a plot of SiO_2 versus Cl content. Here we see the mixing line trending toward boiling springs that have the lowest silica content. This plot reveals that some end-member thermal fluids are precipitating some silica during their ascent from the underlying reservoir before mixing in the near-surface environment. Spring PL-3 appears to be a mixture of water like spring PL-2 and a small amount of cold water, whereas other mixed waters such as PL-4, -6, -7, etc., contain a hot end member with lower silica.

D. Stable Isotopes

Figure 31 shows stable isotope compositions for thermal and nonthermal waters at Platanares. The Quebrada Agua Caliente, the Río Lara, and cold spring PL-13 plot on or close to the world meteoric water line, as expected. Examination of the local topographic map reveals that the average recharge elevation of the quebrada is significantly higher than that of the Río Lara or spring PL-13 (elevation ≈ 800 m). This higher elevation of recharge is reflected by the more isotopically depleted waters of the quebrada. Using the oxygen-18 gradient of -0.26‰ per 100 m, we find that the average recharge

Figure 30. Plot of SiO_2 versus Cl for thermal and nonthermal waters at Platanares, Honduras.

elevation of the quebrada is about 400 m higher than that of spring PL-13, or about 1200 m.

Hot end-member geothermal fluids (i.e., springs PL-1, PL-3, PL-5, and PL-8) plot in a cluster having about the same δD -value as the quebrada but showing a consistent oxygen-18 enrichment of 0.3 to 0.5‰ relative to the world line. The enrichment suggests high-temperature isotopic exchange between water and rock, whereas the similar δD -value indicates that the geothermal fluids are recharged at approximately the same average elevation as

the quebrada (1200 m). The only cold spring we sampled, PL-13, is too enriched in δD to be representative of the average recharge elevation, even though it issues just below the crest of the high terrace at the village of Platanares (at an elevation of about 800 m). Hot spring PL-15, a chemically mixed spring on the Río Lara, has the most depleted δD -value (-46.9‰) of any spring sampled at Platanares; thus, its average recharge elevation is even higher than that of the thermal springs along the quebrada.

Springs PL-10 and PL-12 are isotopically dominated by meteoric water and appear to be mixtures of geothermal fluid and shallow groundwater such as from the quebrada. Spring PL-10 in fact issues from stream gravel adjacent to the quebrada. The other mixed springs, however, do not have so simple an origin. They must be mixtures of geothermal fluid and various other meteoric groundwaters because the scatter in their isotopic compositions does not permit only one cool end member. An extreme case is sample PL-15, from the hot spring on the Río Lara. It is so isotopically depleted compared with other thermal waters that it appears to be derived from a different subsystem of the reservoir.

A plot of δD versus C_l (Fig. 32) defines two mixing lines. We interpret one line to reflect mixing of thermal water with shallow groundwater like that

Figure 31. Plot of δD versus $\delta^{18}O$ for thermal and nonthermal waters at Platanares, Honduras.

Figure 32. Plot of δD versus C_l for thermal and nonthermal waters at Platanares, Honduras.

in the quebrada and the other line to reflect mixing with a deeper cold groundwater. Extrapolation of the deeper trend to a reasonable background Cl value of about 2.5 mg/l yields an average δD -value for this deeper groundwater of -49.1‰ . Using the equation for the world meteoric water line, $\delta D = 8\delta^{18}O + 10$, the average $\delta^{18}O$ -value of this deeper groundwater is roughly -7.4‰ . Assuming the oxygen-18 gradient of -0.26‰ per 100 m, the average recharge elevation for this deeper groundwater is about 150 m higher than for the Quebrada Agua Caliente and the main geothermal reservoir. Assuming that the $\delta^{18}O$ -values of springs PL-11 and PL-4 are too positive (possibly as a result of bad analyses or exchange with calcite), the same shallow and deep mixing trends could be shown on Fig. 31.

Even more complicated mixing relations are possible, as shown by the dashed three-component mixing line in Fig. 32. For example, mixed springs PL-10 and PL-12 could also be generated by mixing surface water PL-13 with thermal water along the "deeper" mixing line. The important points, however, are that at least two types of mixing occur and that the "deeper" trend is evident.

E. Tritium

Tritium (3H) contents of thermal and nonthermal waters at Platanares range from 0.09 to 7.24 T.U. (Table X). As mentioned previously (Section IV-B), tritium values in the Río Lara and the Quebrada Agua Caliente are higher than present background tritium values for Honduras (2 to 5 T.U.), implying that part of their flow is contributed from very shallow groundwater a few years old. In contrast, geothermal fluids contain 0.09 to 0.41 T.U., implying that the reservoir fluid may be as old as 500 to 2500 yr (Fig. 10).

Mixed geothermal waters (Fig. 33) show the same pattern reflected in Fig. 31: a shallow-mixing trend in which thermal water mixes with near-surface groundwater and a deeper-mixing trend in which thermal water mixes with a deeper groundwater system. If we extrapolate the deeper-mixing trend to a reasonable background Cl value of 2.5 mg/l, the average tritium value of the deeper groundwater system is now about 3.1 T.U. According to Fig. 10, this would imply that this deeper groundwater system is composed of water between 5 and 50 yr old. It is most likely that this deeper groundwater

TABLE X. Major Chemistry^a and Isotope Data^b for the Platanares Geothermal System

Sample No.	Temp (°C)	Field pH	Flow (l/s)	SiO ₂	Na	K	Li	Cs	Ca	Mg	Cl	F	HCO ₃	CO ₃	SO ₄	B	As	NH ₄	δD	δ ¹⁸ O	³ H	δ ¹³ C
PL-1	99.5	8.75	5	288	310	38	4.04	0.54	2.5	0.06	36.7	12.4	78.1	206	225	16.7	1.26	10.4	-41.6	-6.14	--	-8.72
PL-2	99.3	8.75	20	290	291	33	3.50	0.55	3.2	0.07	35.4	12.9	215	132	215	16.4	1.00	11.7	-42.8	-6.03	--	--
PL-3	100.1	8.75	30	277	305	36	3.85	0.48	3.0	0.04	33.4	12.7	171	168	238	15.5	0.89	13.0	-42.4	-6.17	0.09	-7.69
PL-4	88.3	6.80	seep	183	231	26	2.94	0.42	20.9	1.54	25.9	9.6	473	0	193	12.2	0.71	17.3	-44.0	-6.33	0.96	--
PL-5	96.0	8.30	4	305	289	18	3.56	0.29	1.2	0.06	36.0	12.3	154	142	239	16.0	0.88	11.9	-41.6	-6.03	0.12	--
PL-6	92.0	7.20	2	183	260	21	3.29	0.52	5.4	0.08	26.0	9.5	530	0	199	12.5	0.58	11.0	-44.6	-6.02	--	--
PL-7	98.5	8.75	5	236	311	26	3.53	0.43	3.8	0.08	34.4	12.6	171	154	245	16.0	0.79	9.5	-42.1	-6.12	--	-7.23
PL-8	98.6	8.75	10	233	299	37	3.72	0.48	1.0	0.04	34.0	12.9	68.3	202	246	16.4	0.68	7.95	-42.7	-6.00	0.41	-7.11
PL-9	26.7	6.90	>400	22	10	1.6	<0.01	<0.002	72.0	15.5	2.6	0.21	45.7	0	110	0.03	<0.05	0.12	-42.8	-7.01	5.50	-8.48
PL-10	38.4	6.30	seep	35	45	10.3	0.28	0.035	42.2	8.73	6.2	0.84	137	0	128	2.27	<0.05	0.09	-42.1	-6.51	--	--
PL-11	70.8	7.40	4	191	230	25	2.86	0.30	16.3	1.19	31.2	12.4	355	0	232	15.0	0.21	17.1	-43.6	-6.09	--	-6.78
PL-12	35.1	6.60	8	39	52	20	0.45	0.053	42.7	11.7	7.2	0.85	187	0	135	2.76	0.39	0.15	-41.2	-6.53	5.14	--
PL-13	25.3	6.80	2	17	5	2.5	0.04	<0.002	20.8	4.56	2.7	0.48	32.9	0	50	<0.02	<0.05	0.12	-39.5	-5.92	--	--
PL-14	37.1	7.00	--	84	91	11.0	0.99	0.12	43.3	10.2	11.4	3.49	229	0	160	5.35	<0.05	0.09	-42.8	-6.36	--	--
PL-15	54.0	6.00	2	107	113	23	1.60	0.33	70.2	1.34	10.2	5.00	456	0	94	5.12	<0.05	9.7	-46.9	-6.94	2.37	--
PL-16	28.0	7.00	1000	31	17	3.3	0.06	0.007	49.9	10.2	3.3	0.27	183	0	48.4	0.11	<0.05	0.13	-37.7	-5.95	7.24	--

^aChemical analyses reported in mg/l.^bδD and δ¹⁸O reported in ‰ relative to Standard Mean Ocean Water (SMOW); δ¹³C reported in ‰ relative to Pee Dee Belemnite (PDB); tritium (³H) reported in tritium units (T.U.).

Gas Analyses (in vol% dry gas) of Selected Springs at the Platanares Site

Sample No.	Temp (°C)	CO ₂	H ₂ S	H ₂	CH ₄	N ₂	NH ₃	O ₂	Ar	He	Total %	CO ₂ δ ¹³ C
PL-1	99.0	81.62	2.597	0.031	0.318	0.93	14.46	0.0096	0.024	0.00005	99.98	-10.84
PL-1	99.0	82.02	3.006	0.034	0.216	1.17	13.54	0.004	0.028	0	100.02	-10.76
PL-3	99.0	88.6	1.557	0.017	0.341	3.55	5.82	0	0.090	0	100.04	-10.05

system resides in the more permeable and fractured rocks of the Padre Miguel Group.

F. Chemical Geothermometry

Section VI presented a general discussion of chemical geothermometers. Table XI shows the estimated reservoir temperatures according to various chemical geothermometers.

The least-altered, highest-temperature (>70°C), and highest-Cl (>25 mg/l)

thermal waters yield indications of subsurface temperatures from 180 to 193°C (average for quartz saturation) to 238°C (gas geothermometer, average

224 ± 14°C). The SiO₂-Cl relations described above indicate that silica deposition affects most or all samples, so silica temperatures are too low.

The geothermometer temperatures least affected by reequilibration are probably from SO₄ isotope fractionation (assuming continuous steam loss) and average 224 ± 4°C (maximum 237°C). These temperatures are similar to those found for gas reactions (quoted above), Na-K-Ca (maximum 235°C, average 214 ± 16°C), and Na/K (maximum 236°C, average 219 ± 21°C). The warm spring (silica-enthalpy) mixing model cannot be used directly because most waters are boiling and the silica model, which assumes boiling after mixing, indicates temperatures only slightly higher than quartz adiabatic temperatures. The boiling spring mixing (chloride-enthalpy) model, using subsurface temperatures based on Na-K-Ca (Fig. 34), suggests maximum temperatures of 222 to 241°C.

The SiO₂-enthalpy relations and the considerably lower temperatures indicated by silica compared with those indicated by cation geothermometers suggest that quartz is being deposited in upflow channels (Fig. 35). This quartz mantling is apparently preventing the reequilibration of cations that would otherwise be expected to occur in these dilute waters. The mixing model based on chloride-enthalpy requires reequilibration after mixing. This reequilibration may occur at greater depths than does the silica deposition

Figure 33. Plot of tritium versus Cl for the thermal and nonthermal waters at Platanares, Honduras.

TABLE XI. Calculated Geothermometers for the Platanares Geothermal System^a

Sample No.	Measured Temperature (°C)	Qtz ^b	Qtz ^c	Chalcedony	Na-K-Ca				Na-Li	¹⁸ O-SO ₄			Gas	
					Na-K	$\beta = 4/3$	$\beta = 1/3$	Mg Corr		T ₁ ^b	T ₂ ^c	T ₃ ^d	T _{D-P} ^e	T _{CO₂-CH₄} ^f
PL-1	99.5	207	190	190	235	(263)	225	(225)	300	248	220	227	230	181
PL1(2) ^g	99.5	---	---	---	---	---	---	---	---	---	---	---	238	195
PL-2	99.3	202	186	185	228	(239)	216	(211)	289	---	---	---	---	---
PL-3	100.1	203	187	186	232	(250)	221	(221)	295	253	224	231	205	182
PL-4	88.3	174	163	152	227	(150)	192	161	297	---	---	---	---	---
PL-5	96.0	211	193	195	180	(242)	190	(189)	292	---	---	---	---	---
PL-6	92.0	174	163	152	199	(187)	189	(188)	295	---	---	---	---	---
PL-7	98.5	192	178	172	202	(217)	197	(195)	281	254	224	231	---	---
PL-8	98.6	191	177	171	236	(310)	235	(235)	293	261	229	237	---	---
PL-10	38.4	86	89	55	(285)	70	(195)	70	211	---	---	---	---	---
PL-11	70.8	177	166	155	224	(156)	193	(166)	293	245	209	219	---	---
PL-12	35.1	91	93	60	(368)	99	(230)	70	247	---	---	---	---	---
PL-15	54.0	141	136	115	271	(101)	201	(201)	312	---	---	---	---	---
Average ^h	---	201±7	185±6	183±9	219±21		214±16		292±6	254±5	224±4	232±4	224±14	186±6

^aParentheses indicate values that are calculated but that violate rules of application.

^bNo steam loss.

^cMaximum steam loss.

^dContinuous steam loss.

^eD'Amore and Panichi (1980).

^fNorman and Bernhardt (1981).

^gCollected for gas only.

^hAverage of least-altered thermal waters (PL-1, PL-2, PL-3, PL-7, and PL-8).

and thus not be hindered. The Na-Li geothermometer yields results of 290 to 300°C, which we consider too high. Because boiling in the reservoir is suggested by other geochemical data, the SO₄-H₂O geothermometer with continuous steam loss is used for our estimates. The most likely reservoir temperature, based on the average and maximum indications of all these geothermometers, is between 225 and 240°C. We consider this estimate to be conservative because all geothermometer reactions must reequilibrate to some extent. The consistency of the indicated temperatures (except silica, which precipitates during upflow) is very impressive.

G. System Model

Figure 36 shows our model of the Platanares geothermal system schematically superimposed on the A-A' cross section of Heiken et al. (1986).

Figure 34. Plot of enthalpy versus Cl for the thermal and nonthermal waters at Platanares, Honduras.

Figure 35. Plot of silica versus enthalpy for the thermal and nonthermal waters at Platanares, Honduras.

Figure 36. Schematic model of the Platanares geothermal system, Honduras.

From the high contents of NH_4 , B, and SO_4 in the thermal fluids and the high concentrations of NH_3 and depleted $\delta^{13}\text{C}$ -values of CO_2 in the gases, we strongly believe that the geothermal reservoir equilibrates in fractured red beds of the Valle de Angeles Group. This group is known to contain gypsum, petroleum, and organic deposits and marine clay shales in the upper half of the sequence (Finch, 1981), which could supply SO_4 , NH_3 , CO_2 , H_2S , and B during thermal metamorphism.

Our work and the geologic work of Heiken et al. (1986) show that the major hot springs discharge along a northwest-trending fracture system across

the entire width of a structural graben (springs PL-8 to PL-5). Because hot end-member fluids also encompass this entire zone, it appears to us that the reservoir underlies the entire graben and not just one fault block. The northwestern limit of the reservoir is bounded by the major northeast-trending fault that juxtaposes Paleozoic schist (north) against Tertiary volcanics (south). Other limits of the reservoir are not well defined at this time, although mixed fluids discharge as far south as the Rfo Lara.

From constraints supplied by stable isotope data, recharge to the Platanares system probably comes from the higher elevations to the north and northwest. Tritium data suggest that the percolation rate is relatively slow and that the mean residence time of fluid in the reservoir may be several thousand years. After heating and equilibration, geothermal fluid exemplified by end-member waters PL-1, PL-5, and PL-8 rises convectively along the many faults cutting the reservoir rocks. Reservoir fluid entering the fractured ignimbrite sequence of the Padre Miguel Group mixes with a deep, cool groundwater to produce mixed thermal waters such as PL-4, PL-6, and PL-11. We feel that this deep groundwater must flow slowly through the Padre Miguel Group because geologic evidence indicates that these rocks extend to depths as great as 400 m and that the groundwater contains relatively high tritium (indicating a probable age of not less than 5 yr). We are uncertain as to the source of this cool groundwater because stable isotopes indicate that its average recharge elevation is roughly 150 m higher than the geothermal fluid in the reservoir, perhaps at the volcanic highlands to the northeast and south.

After thermal waters reach the surface, localized mixing occurs with shallow groundwater in alluvium along the Quebrada Agua Caliente (PL-10) and in colluvium along the canyon walls (PL-12). The isotopes of this near-surface end member resemble those of the quebrada as do their high tritium contents, which are above present background levels (indicating an age of only a few years).

Based on cation geothermometry (Table XI), the average temperature of the geothermal reservoir appears to be at least 225°C. Temperatures based on quartz solubility are low because of precipitation of quartz or chalcedony during upflow. Temperatures based on D'Amore-Panichi gas geothermometry are

in good agreement with the 225°C value. Temperatures based on $\text{SO}_4\text{-H}_2\text{O}$ geothermometry agree if we assume continuous steam loss.

According to the boiling-point vs depth relation between pure water and steam, the minimum depth of a reservoir whose temperature is 225°C is about 300 m, and boiling in unmixed geothermal water may occur above 300 m. If some cooling is conductive, then the top of the 225°C reservoir may be deeper than 300 m. However, because of the unusually high CO_2 , NH_3 , and B contents of the gases and liquids, it is possible that the Platanares reservoir is a "gas-dominated" or gas-rich system, like those documented for the Ohaaki-Broadlands and Ngawha geothermal fields of New Zealand (Grant, 1977; Donaldson and Grant, 1981) and described for the Sulphur Springs field in St. Lucia (Williamson, 1979). In such fields, unusually high partial pressures of CO_2 and other noncondensable gases in the reservoir fluid cause the fluid to boil at greater depths (i.e., hydrostatic pressures) for a given temperature than pure water. If Platanares is a gas-dominated system, then boiling and separation of volatile components (two-phase zone) may be occurring at much greater depths than 300 m.

H. Power Output of the Hot Spring System

The energy output (E) of the hot springs discharging into the Quebrada Agua Caliente can be calculated as follows:

$$E = Vf[H_r - H_a] \quad , \quad (10)$$

where V is the volume of water in the quebrada below the hot springs, f is the fraction of geothermal water in the quebrada below the hot springs, H_r is the enthalpy of reservoir fluid, and H_a is the enthalpy of water at ambient temperature. From samples taken from the quebrada upstream (PL-9) and downstream (PL-14) of the hot springs, we can calculate the fraction of geothermal fluid in the quebrada. By averaging nine components that are likely to behave conservatively in creek water, we obtain a value of about 26% geothermal water down-stream of the hot springs (Table XII). We visually estimated the flow in the quebrada to be roughly 12,000 l/min (3000 gal./min) downstream of the hot springs. This measurement has a probable error of $\pm 25\%$. Assuming the reservoir has an equilibration temperature of 225°C, using the ambient temperature

TABLE XII. Calculated Geothermal Fluid in Quebrada Agua Caliente Downstream from all Hot Springs

Component	Upstream PL-9 (mg/l)	Downstream PL-14 (mg/l)	Difference in River (mg/l)	End-member ^a Geothermal Fluid (mg/l)	Geothermal Fluid (%)
As	<0.05	0.21	0.21	0.93	22.6
B	0.03	5.35	5.32	16.2	32.8
Cl	2.6	11.4	8.8	35.0	25.1
Cs	<0.02	0.12	0.12	0.45	26.7
F	0.21	3.49	3.28	12.6	26.0
K	1.6	11.0	9.4	32.0	29.4
Li	<0.01	0.99	0.99	3.79	26.1
Na	10.0	91.0	81.0	301.0	26.9
SO ₄	110.0	160.0	50.0	237.0	21.1
Average ^b					26.3±1.1

^a Average of PL-1, PL-3, PL-5, and PL-8.

^b Error reported is standard deviation.

of 26.7°C in the quebrada above the springs (PL-9), and converting temperatures to enthalpies using steam tables (Keenan et al., 1969), we find that the energy output of the geothermal fluids discharging at the surface is approximately 45 MW (thermal). Assuming an efficiency of 12.5 to 18.5% in the conversion of thermal energy to electrical energy (Tester and Grigsby, 1980; Fig. 12), the geothermal reservoir at Platanares would, therefore, be capable of generating 5.6 to 8.3 MW (electrical) based only on the volume of water discharging at the surface.

We believe, however, that the reservoir is probably capable of greater electrical output because the areal extent of the reservoir, based on the distribution of thermal springs and the width of the structural graben, is sizable—at least 2 to 3 km². Because of indicated reservoir temperature, volume of discharge, and size, we feel Platanares is clearly the best geothermal target that we have investigated in Honduras.

IX. SAN IGNACIO SITE

The San Ignacio (La Tembladera) geothermal site (Figs. 5 and 37) is located in the Departamento de Francisco Morazán, 3 km northwest of the village of Barrosa and 8 km northwest of the town of San Ignacio. The study area encompasses roughly 10 km² (El Porvenir sheet, UTM coordinates 910/245). The hot springs issue from the northern side of the broad Valle de Siria at the southern edge of a ridge of the Montañas de la Flor. Elevation of the springs is roughly 750 m, whereas the ridge immediately behind the springs crests at about 1000 m. Although access to the site is convenient by automobile and the topography is not particularly rugged, uncultivated areas are covered with scrub forest, thorn thickets, and cactus. The site has been previously investigated by Geonomics (1977) and GeothermEx (1980a).

Figure 37. Map of the San Ignacio geothermal area, Honduras, showing locations of various springs and faults.

A. Geology

Simonson (1977) mapped the general geology of the region, and Aldrich et al. (to be published) recently completed a detailed map of the geothermal site. Although the main fault scarp separating the range and the valley generally trends northwest, the fault zone abruptly bends east to west in the vicinity of the springs. This east-west fault segment is named the Arenal fault (Simonson, 1977) and cuts Paleozoic augen and garnet schists (see description of the Cacaguapa Schist in Fakundiny, 1970), which are exposed in the hills of the range and in arroyos of the Quebrada el Arenal. The schist is locally intruded by Cenozoic plutonic rocks, and Tertiary volcanic rocks locally cap some of the hills, primarily on the south side of the Arenal fault. Much of the geology south of the Arenal fault is obscured by Quaternary alluvium and silica sinter deposits from the springs. North- and northwest-trending cross faults cut the Arenal fault (Aldrich et al., to be published) and mark the west and east limits of hot spring discharge, respectively. Various branches of the Quebrada el Arenal follow these cross faults. Old sinter deposits with no active springs occur along the trace of the Arenal fault for a distance of at least 1 km west of the present springs. No Quaternary volcanic rocks are known in the area.

B. Surface Features

Aldrich et al. (to be published) divided the hot springs into four areas and prepared detailed maps.

Area 1 (Main Area). At least 60 hot springs and seeps, ranging in temperature from cool (30°C) to slightly superheated, issue from a rather impressive silica sinter terrace in the main area (Figs. 38 and 39). The terrace measures roughly 100 m by 150 m and covers colluvium/alluvium of metamorphic fragments. The hill immediately north of the terrace has a scalloped face, suggesting that the main area overlies the buried trace of the Arenal fault.

Springs with the highest temperatures and discharges, such as SI-1 (Fig. 40), SI-7, and SI-9, generally issue from the margins of the terrace, although a few hot springs also flow from north-trending fractures that cut the terrace. All springs from the main area collect into a stream composed

Figure 38. Map of the main spring area (Area 1), San Ignacio, Honduras.

solely of geothermal water whose estimated flow is 1000 l/min. The gases smell strongly of H_2S .

Area 2. This area consists of a small silica sinter terrace with two springs located roughly 200 m northwest of the main area, adjacent to a dirt road. The hotter spring (SI-13, 59°C) flows 1 l/min.

Area 3. Area 3 consists of two groups of hot springs that issue from a north-trending fault cutting Paleozoic schist in the western tributary of the Quebrada el Arenal. The northern group of perhaps five to ten springs (i.e.,

Figure 39. Photograph looking due east of silica terrace at main spring area, San Ignacio, Honduras. Break in slope between hill on left and terrace on right marks the approximate trace of the buried Arenal fault.

Figure 40. Photograph of hot springs at San Ignacio, Honduras.

SI-12, 72°C, 0.5 l/min) flow from hydrothermally altered schist (jarosite, gypsum, and silica) in the stream channel. About 150 to 200 m downstream, several intermediate-temperature springs (<65°C) emerge from stream gravels.

The southern group of springs issue from behind a waterfall located 50 m farther south where the stream drops over a 10-m-high cliff of faulted schist. Approximately 20 springs and seeps at temperatures of 40 to 95°C discharge from the cliff face and associated fault leaving small deposits of silica sinter. The total flow of geothermal water from area 3 is estimated at roughly 100 l/min.

Area 4. Hot springs at area 4 issue from schist, colluvium, and stream gravel along the northeastern tributary of the Quebrada el Arenal about 600 m east of the main area. The largest group of five to ten springs and seeps discharge from the west side of the quebrada in an open slope where the trees are blackened and large boulders are chaotically scattered along the stream channel. The hottest spring (SI-15, 97.8°C, 16 l/min) discharges into a small pool between large boulders. Total flow of this group is roughly 75 l/min. Gases smell of H₂S. This is the only area where bladed crystals of calcite in a form called thiolite (Radbruch, 1957) form along with the silica sinter (Table VIII).

Other warm springs discharge farther upstream for a distance of 200 to 300 m but their flow is not significant and their temperatures do not exceed 65°C. Still other warm and hot seeps discharge in the scrub forest between Areas 1 and 4.

C. Chemistry and Stable Isotopes

Table XIII gives the chemical compositions of San Ignacio thermal and nonthermal waters; these compositions are compared in Fig. 13. Table XIII also gives compositions of gases from boiling hot springs. Thermal fluids are near neutral to alkaline Na-K-Ca-HCO₃-SO₄-Cl waters with Cl <80 mg/l and total dissolved solids ranging from 900 to 1000 mg/l. The nonthermal waters are about one-third as concentrated as the thermal waters and may be described as Ca-Na-Mg-HCO₃-SO₄-Cl waters with Cl <10 mg/l. Concentrations of Ca and Mg are high in the nonthermal waters and low to very low in the highest-Cl thermal waters. Concentrations of SiO₂, B, K, Cs, F, and NH₄ (except for two samples) are high in the thermal waters but notably low in the nonthermal

TABLE XIII. Major Chemistry^a and Isotope Data^b for the San Ignacio Geothermal System

Sample No.	Temp (°C)	Field pH	Flow (L/s)	SiO ₂	Na	K	Li	Cs	Ca	Mg	Cl	F	HCO ₃	CO ₃	SO ₄	B	As	NH ₄	δD	δ ¹⁸ O	³ H	δ ¹³ C
SI-1	99.0	9.78	--	214	330	26	1.44	0.21	0.8	0.06	75.1	12.2	112	194	140	3.81	<0.05	2.78	-49.00	-6.95	0.00	--
SI-2	99.0	9.78	--	214	336	26	1.46	0.16	3.2	0.06	75.5	13.0	117	190	141	3.63	<0.05	3.40	--	--	--	--
SI-3	98.9	9.59	--	215	332	25	1.44	0.17	1.3	0.05	75.5	13.0	120	192	139	3.65	<0.05	3.34	-48.30	-6.78	0.43	-7.11
SI-4	99.6	9.51	--	215	324	27	1.42	0.16	4.4	0.08	75.8	12.6	181	158	142	3.70	<0.05	3.78	-49.85	-6.80	--	--
SI-5	99.6	9.13	--	211	322	26	1.38	0.15	5.6	0.10	73.0	12.2	312	86.4	147	2.89	<0.05	5.79	-49.90	-6.88	--	--
SI-6	98.6	7.27	--	170	288	24	1.30	0.15	7.5	0.23	69.9	11.3	410	19.2	140	3.40	<0.05	5.35	-51.00	-7.05	0.22	--
SI-7	98.0	7.41	16	170	302	25	1.08	0.15	3.0	0.15	72.7	12.2	342	50.4	148	3.76	<0.05	4.82	-50.10	-6.75	0.18	-7.10
SI-8	96.7	6.75	4	169	296	26	1.28	0.14	7.1	0.30	69.9	11.4	412	16.9	145	3.30	<0.05	5.50	-51.00	-7.08	--	--
SI-9	99.0	8.50	--	185	314	26	1.40	0.13	4.1	0.09	73.4	12.0	368	55.2	149	3.56	<0.05	5.07	-50.00	-7.05	--	-7.37
SI-10	30.9	6.85	--	140	260	25	1.20	0.11	14.1	1.47	67.5	10.6	376	0	171	3.47	<0.05	0.37	-48.00	-6.42	0.81	-6.82
SI-11	28.0	7.00	2	25	22	2.0	0.14	<0.002	51.4	19.9	8.6	0.34	261	0	21.2	0.07	<0.05	0.16	-43.00	-6.58	0.00	--
SI-12	72.0	7.00	1/2	189	266	22	1.12	0.16	11.2	1.86	62.7	9.6	427	0	130	3.12	<0.05	5.40	-51.10	-7.06	0.61	-8.15
SI-13	59.0	7.30	1	179	294	24	1.02	0.17	4.5	0.45	68.3	11.3	432	0	149	3.52	<0.05	5.99	-50.50	-7.26	--	--
SI-14	28.0	--	20	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	-45.40	-6.47	--	--
SI-15	97.8	7.80	16	161	288	23	1.32	0.17	1.8	0.11	70.5	10.3	322	52.8	137	3.47	<0.05	0.12	-48.50	-6.81	--	-8.10

^aChemical analyses reported in mg/L.^bδD and δ¹⁸O reported in ‰ relative to Standard Mean Ocean Water (SMOW), δ¹³C reported in ‰ relative to Pee Dee Belemnite (PDB); tritium (³H) reported in tritium units (T.U.).

Gas Analyses (in vol% dry gas) of Selected Springs at the San Ignacio Site

Sample No.	Temp (°C)	CO ₂	H ₂ S	H ₂	CH ₄	N ₂	NH ₃	O ₂	Ar	He	Total %	CO ₂ δ ¹³ C
SI-2	98.6	88.3	0.608	0.230	0.350	5.550	4.846	0.017	0.147	0.001	100.049	-11.75
SI-3	99.8	91.3	1.768	0.134	0.073	4.987	1.681	0	0.131	0	100.074	-11.01
SI-7	99.0	90.58	5.163	0.073	0.061	2.492	1.591	0	0.067	0	100.027	-12.80
SI-9	99.0	74.02	5.842	0.211	0.127	14.66	5.068	0	0.360	0.0005	100.289	-15.75

waters, and As is low in both. The predominant gas is CO_2 (>70%) with moderately high concentrations of N_2 , H_2S , and NH_3 and low concentrations of He and Ar.

The small compositional variations observed in boiling and near-boiling San Ignacio thermal waters can result from either mixing with dilute water or boiling and loss of steam. The evidence for boiling lies in the numerous boiling springs, in the correlation of δD with Cl (Fig. 41), and in the high pH and CO_3 content of many of the waters. The evidence for mixing lies in the apparent correlation of Cl with other elements such as Li, F, B, and total HCO_3 (Fig. 42) along lines that do not trend to the composition of steam but have concentrations equal to zero at about 25 mg/l of Cl. Because low-pressure steam cannot carry Cl, the apparent correlations cannot result from steam addition or loss.

Evidence for Boiling. Most springs sampled at San Ignacio are boiling (9 of 14). If springs boil at the surface, it is reasonable to assume they

Figure 41. Plot of δD versus Cl for thermal and nonthermal waters of San Ignacio, Honduras.

Figure 42. Plots of B, F, Li, and total HCO_3 ($\text{CO}_3 + \text{HCO}_3$) versus Cl for thermal and nonthermal waters at San Ignacio, Honduras.

Figure 42. (continued)

boil in the shallow subsurface as well. The variation in Cl concentration of the boiling springs is only 8.5%. This could result from conductive cooling (from the reservoir temperature to nearly 100°C) of the lowest-Cl water, with other waters showing increasing fractions of boiling and increasing concentrations of Cl. The highest-Cl water could result from cooling by conduction to 150°C and then by boiling and steam loss from 150 to 100°C, which would produce the observed Cl increase.

If this process occurred with single-stage steam separation, the change in δD and Cl could be calculated from the combined isotope and chloride balance equations (Henley et al., 1984). Thus,

$$\delta D_f = \delta D_i + y \cdot 10^3 \ln \alpha(T_f) \quad (11)$$

and

$$Cl_i = Cl_f (1-y) \quad (12)$$

as

$$\Delta D / \Delta Cl = 10^3 \ln \alpha(T_f) / Cl_f, \quad (13)$$

where y is the steam fraction, subscripts i and f are initial and final states, and Δ is the difference between initial and final states.

With 100°C as the final temperature and 76 mg/l Cl as the final Cl content, the calculated slope for San Ignacio waters is $27.8/76 = 0.37$. The observed slope (Fig. 41) is 0.45, excluding samples SI-10, -12, -13, and -15, which appear to be mixed with meteoric water. The observed range in δD corresponds with boiling from 150 to 100°C, with maximum boiling for SI-3 and minimum boiling for SI-6 and SI-8. The δD - $\delta^{18}O$ plot (Fig. 43) shows the expected general trend but does not agree in detail. The correlations are probably asking too much of deuterium and oxygen-18 analyses, which are usually considered accurate to ± 1 and $\pm 0.1\text{‰}$, respectively.

Because geothermometers indicate reservoir temperatures of 180 to 230°C at San Ignacio (as will be discussed later), the waters must be conductively cooled to 150°C before some of them boil. This conductive cooling would not change nonreactive constituents (e.g., Cl, B, and D). Reactive constituents,

however, might be altered during the slow upward flow implied by conductive cooling.

If boiling and fluid-mineral reaction are the major processes at San Ignacio, then the negative correlation between Ca and Cl (Fig. 44) must result from CO₂ loss and precipitation of calcite by the reaction

with Mg decrease caused by coprecipitation of magnesian calcite. A problem with the boiling hypothesis is that total HCO₃ increases with increasing Cl rather than decreasing (like Ca) from calcite precipitation caused by boiling. If this reaction explains the low Ca in the boiling springs, then their Na-K-Ca temperatures would be significantly too high. Of the high-Cl springs, only spring SI-1 has significantly low Ca and indicates a high Na-K-Ca temperature (Table XIV); most temperatures from the Na-K-Ca geothermometer are

Figure 43. Plot of δD versus $\delta^{18}\text{O}$ for thermal and nonthermal waters at San Ignacio, Honduras.

Figure 44. Plot of Ca versus Cl for thermal and nonthermal waters at San Ignacio, Honduras.

TABLE XIV. Calculated Geothermometers for the San Ignacio Geothermal System^a

Sample No.	Measured Temperature (°C)	Qtz ^b	Qtz ^c	Chalcedony	Na-K	Na-K-Ca			Mg Corr	Na-Li	¹⁸ O-SO ₄			Gas	
						$\beta = 4/3$	$\beta = 1/3$				T ₁ ^b	T ₂ ^c	T ₃ ^d	T _{D-P} ^e	T _{CO₂-CH₄} ^f
SI-1	99.0	185	172	164	197	295	211	208	177	---	---	---	---	---	---
SI-2	99.0	185	172	164	196	227	196	191	177	---	---	---	---	192	181
SI-3	98.9	184	172	165	194	266	203	197	177	240	214	220	203	238	---
SI-4	99.6	185	172	165	201	215	197	195	178	---	---	---	---	---	---
SI-5	99.6	184	171	163	199	202	192	192	176	---	---	---	---	---	---
SI-6	98.6	169	159	146	201	184	189	189	180	---	---	---	---	---	---
SI-7	98.0	169	159	146	201	224	199	199	160	229	206	212	203	245	---
SI-8	96.7	169	159	146	206	191	193	191	177	---	---	---	---	---	---
SI-9	99.0	175	164	153	201	214	196	196	179	238	213	219	169	210	---
SI-10	30.9	157	149	133	207	158	185	147	182	---	---	---	---	---	---
SI-12	72.0	176	165	154	205	167	186	129	174	239	205	214	---	---	---
SI-13	59.0	173	162	150	200	204	193	179	158	---	---	---	---	---	---
SI-15	97.8	166	156	142	198	241	201	201	180	250	221	228	---	---	---
Average ^g	---	169	159	146	204	188	191	190	179	---	---	---	---	---	---

^aParentheses indicate values that are calculated but that violate rules of application.

^bNo steam loss.

^cMaximum steam loss.

^dContinuous steam loss.

^eD'Amore and Panichi (1980).

^fNorman and Bernhardt (1981).

^gAverage of unmixed and unboiled hot end-member fluid (SI-6 and SI-8).

similar to those from other geothermometers. In addition, no travertine deposits have been found in the area, which does not rule out deposition of calcite in the subsurface because of boiling during ascent.

Evidence of mixing. Chloride correlates well with Li, F, and total HCO₃, with intercepts on the Cl axis at about 25 mg/l Cl (Fig. 42). These correlations could result from mixing of thermal water with a cold water containing relatively high Cl and low Li, F, and total HCO₃. However, we found no cold waters in the San Ignacio area with this composition, and we found no waters anywhere in Honduras that have high Cl and low HCO₃. Moreover, Li, F, and total HCO₃ are probably reactive constituents. If we consider the correlation between two conservative constituents, Cl and B, we may extrapolate the line through the origin (Fig. 42). This line could represent steam loss from boiling or mixing with a dilute water.

Boiling, Mixing, and Conductive Cooling. Thus, there is persuasive evidence for both boiling and mixing processes at San Ignacio. The answer possibly lies in a combination of processes. All spring waters have probably cooled by conduction to about 150°C. Spring waters that fall along the calculated δD versus Cl line (Fig. 41) have probably been cooled from 150 to 100°C by boiling alone (sample SI-3), by conduction alone (samples SI-6 and SI-8), or by a combination of these processes (samples SI-1, -5, -7, and -9). Variable amounts of boiling and steam loss are consistent with the correlation of B with Cl (Fig. 42). Lower-chloride samples that fall off the line (SI-10, -12, -13, and -15) may be mixtures of high-Cl thermal water with meteoric water like SI-11, or with other meteoric water having lower δD . In this interpretation greater weight is given to Cl and D because these constituents are little affected by water-rock reactions. The suggested mixing agrees with the high Ca and Mg in samples SI-10 and SI-12 and with the elevated Mg in sample SI-13.

D. Tritium

Tritium values of deep fluids range from 0 to 0.43 T.U., with an average of 0.21 ± 0.18 . Assuming a well-mixed reservoir, we determine that the average age of the water in the San Ignacio system is about 1200 yr (Fig. 10). Values of two of the most Cl-rich fluids (SI-1 and SI-3 with values of 0 and 0.43 T.U. respectively) average 0.215 T.U. The considerable difference in tritium values between these two samples suggests that sample SI-3 is contaminated with a small amount of surface meteoric water.

Mixed waters SI-10 and SI-12 show a slight enrichment in tritium, as expected. Extrapolation of the data in Fig. 45 to a reasonable value of background Cl (5 mg/l) yields a tritium value of about 3.5 T.U. for cold end-member water. This would imply an age as young as about 8 yr or an age as old as about 45 yr for this cold end member (Fig. 10). Unfortunately, the tritium content of sample SI-11 (cold water) is 0 T.U. No reasonable tritium value of present-day cold meteoric water from the study area is available for comparison.

E. Chemical Geothermometry

Table XIV shows subsurface reservoir temperatures for the San Ignacio system calculated from various chemical geothermometers. For the highest-Cl

waters (SI-1 through SI-9), there is reasonably good agreement among the average temperatures of the gas (192°C), Na-K-Ca (197°C), and Na-K (200°C) geothermometers. Magnesium corrections to the Na-K-Ca temperatures are small and are significant only in mixed waters that have altered composition after leaving the thermal reservoir. The quartz geothermometer (which averages 157 to 178°C) indicates lower values than do most cation geothermometers because of precipitation of silica, as evidenced by the presence of the large silica sinter terrace in the main area. Figure 46 is a plot of silica versus chloride. If SI-12 is a mixed spring, then a line extrapolated from the point representing cold end-member water, such as SI-11, through SI-12 to the Cl value of deep geothermal water (70 to 80 mg/l Cl) locates a point represented by the starred point. The silica value at this point (212 mg/l) indicates a reservoir temperature of 184 to 190°C, which is more in line with other estimates. Based on this interpretation, all the hottest springs, whether boiled at depth or not, are precipitating silica. The Na-Li geothermometer (which averages 176°C) indicates temperatures similar to those of the quartz conductive geothermometer.

Figure 45. Plot of tritium versus Cl for thermal and nonthermal waters at San Ignacio, Honduras.

Figure 46. Plot of silica versus Cl for thermal and nonthermal waters at San Ignacio, Honduras.

Sulfate isotope geothermometry of San Ignacio waters must be reconciled with the boiling model described above. If samples SI-6 and SI-8 represent the deep water in unboiled form, then the correct sulfate-temperature calculation should not allow for boiling. Using the average ^{18}O composition of $+0.15 \pm 0.36$ for sulfate dissolved in San Ignacio hot water (based on SI-3, SI-7, and SI-9), the calculated temperature for conductive cooling of springs SI-6 and SI-8 ($\delta^{18}\text{O}, \text{H}_2\text{O} = -7.06 \pm 0.02$) is $230 \pm 12^\circ\text{C}$. Only if single-stage steam loss is assumed is the calculated temperature as low as 208°C .

It is probable that temperatures higher than 200°C and possibly as high as 230°C exist deep in the system. Such a probability is supported by calculated temperatures of 223 to 230°C for sample SI-3, cooled by conduction to 150°C and then by boiling, and temperatures of 220 to 229°C for samples SI-7 and SI-9, cooled mostly by conduction, with temperature interpolated between temperatures calculated for the end-member processes.

F. System Model

We believe the San Ignacio geothermal system is a surface manifestation of deep, fault-controlled circulation and convective upflow of meteoric water. Figure 47 depicts our model for the San Ignacio system using the cross section of the site from Aldrich et al. (to be published). The geothermal system is recharged by precipitation and relatively slow percolation of groundwater through metamorphic basement rocks, possibly from the ridge north of the site. The geothermal fluid equilibrates in the reservoir rocks and rises convectively through fractured rocks of the Arenal fault zone and associated cross faults while losing heat by boiling and conduction. Near the surface (at a depth of about 30 m) slower-moving waters may cool from 140°C to 100°C by conduction, and other waters may continue to boil to the surface. Alternatively, there is minor mixing with cold water, and after mixing, all waters boil to the surface.

Because of the relatively high CO_2 , NH_3 , H_2S , and B contents of the liquids and gases, we suggest that a thin layer of unmetamorphosed Cretaceous rocks (possibly from the Valle de Angeles Group) may overlie the downfaulted Paleozoic rocks south of the Arenal fault zone. Such a layer has been identified in the Valle de Siria region west of San Ignacio. Another source

Figure 47. Schematic model of the San Ignacio geothermal system, Honduras.

of the volatile-organic components could be organic material and clays in the Tertiary and Quaternary basin fill deposits.

Because the hot springs are so linearly arranged along the Arenal fault zone, we cannot easily estimate the size of the geothermal system. However, the most conservative assessment is that it is roughly 1 km long and restricted almost entirely to the fault zone. A more liberal assessment, based on the presence of warm springs northeast of the main area and old sinter deposits 1 km west of the main area, suggests a reservoir several times larger. We feel that electrical resistivity surveys are required in this area to help establish the dimensions of the thermal aquifer.

G. Power Output of Surface Features

The energy output of hot springs at San Ignacio is relatively easy to estimate. The total discharge of the springs (Areas 1, 3, and 4) is about 1200 l/min, whereas the temperature of the reservoir is about 190°C and ambient temperature is 28°C. Using Eq. (10) from Section VIII and assuming the fraction of hot water to be 100%, the energy output of springs at San

Ignacio is 13.8 MW (thermal), equivalent to roughly 2.1 MW (electrical) at 15% conversion efficiency. Without independent data to predict the size of the reservoir or its permeability, we find it difficult to speculate whether the system might produce more power.

X. AZACUALPA SITE

The Azacualpa geothermal area (Figs. 5 and 48) lies adjacent to the Río Jaitique along the east side of the north-trending Santa Barbara graben in the San Pedro Zacapa quadrangle (UTM coordinates 843/262). The geothermal area is located in rugged mountains 35 km southwest of Lago de Yojoa. Access to the hot springs is by rough dirt roads from Zacapa to the village of Azacualpa and then by a 2-km trail heading due east along the Río Jaitique.

A. Geology

Structural geology at the Azacualpa site is characterized by a series of west-stepping fault blocks of Atima limestone and overlying red beds of the Valle de Angeles Group (Finch, 1972; Eppler et al. to be published). Microdiorite stocks and sills correlated with the early Tertiary Matagalpa Formation have locally intruded the sedimentary rocks. Sills of microdiorite in limestone are exposed in the gorge of the Río Jaitique downstream from spring AZ-8 (Fig. 48). The major group of hot springs discharge along the Zacapa fault, which juxtaposes Atima limestone on the east against the Valle de Angeles Group. Displacement along this fault may exceed 1000 m (Eppler et al. to be published), and the fault forms a major topographic lineament that stretches for several kilometers north of the springs. Displacement along an unnamed fault to the east, where limestone is juxtaposed against limestone, is not as large. However, this fault zone also forms a prominent topographic scarp associated with hot spring activity along the river. During geologic mapping, Eppler et al. (to be published) found no cross-cutting structures that could explain the precise location of the hot springs. Rather, these springs seem to be controlled by a combination of normal faults and the hydrology of the river. In addition, no Quaternary volcanic rocks are known to exist in the immediate region surrounding the hot springs although some Quaternary basalts have erupted north of Lago de Yojoa.

Figure 48. Map of the Azacualpa geothermal area, Honduras, showing locations of hot springs and faults.

B. Surface Features

Hot springs at the Azacualpa site can be conveniently subdivided into three groups: those associated with the Zacapa fault, those associated with the unnamed fault to the east, and those issuing from the limestone block between the two faults.

Zacapa Fault Group. The main group of hot springs (Fig. 48) issue along the Zacapa fault at its intersection with the mouth of the gorge of the Río Jaitique. This area is named La Cueva because many of the hot springs flow into a creek that runs through a tunnel of older travertine straddling the fault on the south margin of the river. South of the hot springs and west of the fault (spring AZ-3, 28°C), the creek intermittently flows through red beds. Hot spring AZ-1 (98°C, 1 l/min) emanates from a small mound of travertine about 100 m south of La Cueva, roughly 20 m above the creek on the fault scarp. Spring AZ-2 (90°C, 1 l/min) issues from faulted red beds along the creek bottom beneath spring AZ-1. A boiling spring (AZ-4, 40 l/min) is one of several seeps and springs along the east side of the creek at the southern entrance to La Cueva. Spring AZ-5 (98°C), a large pool (fed by many seeps) opposite spring AZ-4, bubbles violently and produces large clouds of steam (Fig. 49). Eppler et al. (to be published) estimate the total flow of hot water through La Cueva into the Río Jaitique at 900 l/min. Although these springs produce much vapor, the odor of H₂S is barely evident.

Several fumaroles, pools, and springs, some of which are superheated during the dry season (e.g., spring AZ-6, 101°C), discharge from boulders along the north margin of the Río Jaitique and from faulted limestone opposite La Cueva. The combined flow of these springs is at least 150 l/min. About 200 m north of the river, a trail passes another hot spring (AZ-11, 78°C) that issues from the fault scarp.

Limestone Block Group. From the La Cueva area to a point about 1 km upstream along the Río Jaitique, hot springs and seeps flow from the limestone rubble along the river and from eastward-dipping fractured limestone exposed in the cliffs of the gorge. Spring AZ-7 (99°C, <1 l/min), just upstream of La Cueva, is typical of this group. Perhaps 50 springs and seeps discharge in the gorge, and more probably issue below river level. The estimated flow of this group is roughly 150 l/min. No odor of H₂S was noted, and most springs had no gas discharges.

Figure 49. Photograph looking north toward La Cueva and hot spring AZ-5, Azacualpa, Honduras. The cave is cut in older travertine deposits.

Unnamed Fault Group. About 1 km upstream from La Cueva at a major bend in the river, a hot creek flows into the Río Jaitique from the north. The principal source of this creek can be traced 250 m north of the river to a very large spring (AZ-9, 50°C) that issues from a small cliff of limestone near the scarp of another normal fault. Total flow of this spring is roughly 1200 l/min, suggesting that the spring issues from a highly permeable karstic limestone.

Roughly 500 m upstream from the intersection of the river with the hot creek, a very impressive spring (AZ-8, 115°C) sprays superheated water horizontally over the river (Fig. 50). The jet of spray from this spring is approximately 5 m long and emerges from a 5-m-wide zone of brecciated limestone exposed in the cliff north of the river. Although the spring was roughly 0.3 m above the river when we sampled it, it is clearly submerged during the rainy season. Several small seeps and pools discharge upstream and downstream of spring AZ-8. We detected no odor of H_2S in the vapors from these springs.

C. Chemistry and Stable Isotopes

Azacualpa hot springs issue from fractures and bedding planes in limestone of the Yojoa Group and from faulted red beds of the Valle de Angeles

Figure 50. Photograph looking north of hot spring AZ-8, which issues from faulted limestone in the gorge of the Rio Jaitique.

Group. The chemistry of the waters is strongly dominated by reaction with Na aluminosilicates and solution of calcite and gypsum in the presence of high CO_2 pressure, as discussed earlier. The waters have $\text{Na} > \text{K} \approx \text{Ca} \gg \text{Mg}$ and $\text{SO}_4 > \text{total HCO}_3 > \text{Cl}$ (Table XV). The waters show small ranges in Na, K, Cl, and SO_4 and much larger ranges in Mg and Ca, which could result from small amounts of mixing with Ca, Mg, and HCO_3 from cold water, or from mineral reactions. Compared with thermal waters, cold waters of the locality are much lower in Li, Na, K, Cl, F, B, and NH_4 , similar in HCO_3 and SO_4 , and higher in Mg and Ca.

Because the concentration range of conservative constituents (Cl, Li, B, and apparently Na, K, and SO_4) is small and the correlations of these elements pass close to the origin, these correlations (Fig. 51) do not clearly distinguish between boiling and mixing processes for the high-Cl boiling waters. The presence of some mixed waters with intermediate compositions is clear, but the variation of conservative constituents in the more concentrated boiling or near-boiling thermal waters could result either from mixing with small amounts of dilute cold water or from boiling and steam loss. The variation of reactive constituents suggests that both mixing and boiling are important.

TABLE XV. Major Chemistry^a and Isotope Data^b for the Azacualpa Geothermal System

Sample No.	Temp (°C)	Field pH	Flow (l/s)	SiO ₂	Na	K	Li	Cs	Ca	Mg	Cl	F	HCO ₃	CO ₃	SO ₄	B	As	NH ₄	δD	δ ¹⁸ O	³ H	δ ¹³ C
AZ-1	98.0	7.20	1	210	266	21	0.80	0.13	33.2	1.94	25.2	8.8	195	0	455	1.35	<0.05	1.05	-34.3	-5.92	0.10	-6.38
AZ-2	95.0	8.90	1	185	294	22	0.89	0.13	6.9	0.12	26.7	11.6	107	48	480	1.49	<0.05	0.73	-34.1	-5.78	--	-5.26
AZ-3	28.0	6.80	12	34	31	2.0	0.02	0.12	316	15.2	3.5	0.48	173	0	730	0.10	<0.05	0.11	-28.9	-4.83	7.62	--
AZ-4	100.3	8.50	40	226	302	26	0.93	0.15	8.4	0.07	27.8	12.8	63.4	48	479	1.62	<0.05	0.59	-33.4	-5.73	0.08	-5.05
AZ-5	98.0	7.50	--	222	312	25	0.95	0.17	10.0	0.12	28.4	12.7	124	15.6	495	1.65	<0.05	0.75	-32.9	-4.90	--	--
AZ-6	101.4	7.60	120	203	302	25	0.90	0.13	18.9	0.42	27.6	11.6	115	27.6	499	1.57	0.06	0.47	-32.1	-5.03	0.04	-4.29
AZ-7	98.7	8.00	<1	180	268	21	0.70	0.15	16.3	0.56	26.8	12.3	43.9	28.8	472	1.53	<0.05	0.67	-30.3	-5.76	--	-3.16
AZ-8	115.4	8.00	--	211	291	25	0.94	0.14	23.0	0.51	28.2	11.7	166	24.0	451	1.59	0.07	1.09	-31.2	-5.67	0.00	-7.01
AZ-9	50.2	7.10	1200	36	33	2.8	0.06	0.15	47.0	10.2	3.4	1.09	212	0	51.1	0.12	<0.05	0.11	-29.7	-5.49	--	-7.25
AZ-10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	-32.8	-5.03	4.83	--
AZ-11	77.7	0.0	1	132	207	15	0.57	0.12	39.9	3.52	19.4	6.7	264	0	338	1.01	<0.05	0.56	-30.6	-5.52	--	--

^aChemical analyses reported in mg/l.

^bδD and δ¹⁸O reported in ‰ relative to Standard Mean Ocean Water (SMOW); δ¹³C reported in ‰ relative to Pee Dee Belemnite (PDB); tritium (³H) reported in tritium units (T.U.).

Gas Analyses (in vol% dry gas) of Selected Springs at the Azacualpa Site

Sample No.	Temp (°C)	CO ₂	H ₂ S	H ₂	CH ₄	N ₂	NH ₃	O ₂	Ar	He	Total %	CO ₂ δ ¹³ C
AZ-4	100.3	76.66	5.453	0.039	0.317	15.59	1.084	0.415	0.369	0.002	99.929	-12.63
AZ-6	101.4	79.87	0.224	0.073	0.867	18.04	0.021	0.742	0.519	0.008	100.364	-7.04

Figure 51. Plots of B, F, and Li versus Cl for thermal and nonthermal waters, Azacualpa, Honduras.

Concentrations of Ca, NH_4 , and probably total HCO_3 , F, and SiO_2 increase with Cl for waters below boiling along mixing lines, but waters at the boiling point show wide concentration ranges, suggesting precipitation of CaCO_3 , CaF_2 , and SiO_2 and NH_3 separation into steam (Fig. 52). The change of δD with Cl (Fig. 53) is similar to the predicted slope for boiling [$\Delta\text{D}/\Delta\text{Cl} = 10^3 \ln \alpha(100^\circ\text{C})/\text{Cl}_f \approx 1.0$], as derived in the discussion of San Ignacio. The ranges of δD can be explained by boiling from 190°C (a reasonable temperature based on geothermometers) to 100°C , with some high- $\delta^{18}\text{O}$ waters resulting from surface evaporation (Fig. 54).

Thus, the compositions of reactive constituents in boiling springs are controlled by reactions related to boiling and steam loss causing an increase in pH, increase in CO_3 and F, and isotope fractionation, but lower-temperature waters appear to result from mixing. Nonreactive (conservative) constituents are probably controlled by both mixing and steam loss from boiling, with mixing dominant in lower-temperature, more dilute waters and steam loss dominant for boiling waters.

Although both mixing and boiling processes are active at Azacualpa, we do not know whether or not the thermal water that mixes has already boiled. The Cl-F, Cl- SiO_2 , and δD -Cl relations suggest that boiling occurs before mixing because the mixing lines trend toward the lower SiO_2 , lower F, higher δD , and higher Cl end of the boiling lines. However, the relations of Cl with Ca, and less clearly with NH_4 , suggest that the water that mixes has not boiled, since the hot end member is high in those constituents that decrease with boiling. It is possible that Ca and NH_4 loss occurs mainly very near the surface, where steam separates from boiling water and CO_2 pressure decreases sharply by several orders of magnitude, whereas the other processes occur at depth.

We conclude that boiling has produced most of the variation in composition of thermal waters at Azacualpa and that the boiled fluid has mixed to a limited extent with local cold water. During boiling the waters lose steam (and NH_4) and cool from about 190°C to 100°C , increase in δD and $\delta^{18}\text{O}$, and precipitate SiO_2 , CaF_2 , and (mainly near the surface) CaCO_3 containing some Mg. The changes in δD are consistent with some waters (springs AZ-1 and AZ-2) being conductively cooled from 190°C and others showing increasing amounts of

Figure 52. Plots of Ca, SiO₂, and NH₄ versus Cl for thermal and nonthermal waters, Azacualpa, Honduras.

Figure 53. Plot of δD versus Cl for thermal and nonthermal waters, Azacualpa, Honduras.

Figure 54. Plot of δD versus $\delta^{18}O$ for thermal and nonthermal waters, Azacualpa, Honduras.

boiling and increasing δD , with spring AZ-7 entirely cooled by boiling. The change in Cl is somewhat smaller than expected, possibly because of slight dilution of the more boiled waters. Mixing with cold water occurs near the surface. Thermal waters involved in mixing have boiled during ascent. Loss of Ca and NH_4 occurs very near the surface, subsequent to mixing, and does not appreciably alter the compositions of the mixed waters.

D. Tritium

Four samples of Azacualpa thermal waters showing minimal to no mixing (AZ-1, -4, -6, and -8) have a narrow range of tritium values between 0 and 0.10 T.U., with an average of 0.06 T.U. Based on our curves for well-mixed and piston-flow reservoirs in Central America (Fig. 10), end-member geothermal fluid at Azacualpa has a maximum average residence time in the reservoir of about 4000 yr.

We analyzed two samples of cold water (AZ-3 and AZ-10); their tritium values are 7.62 and 4.83 T.U. respectively. Tritium in water from spring AZ-3 is so high that this water must be controlled primarily by piston flow and is estimated to be roughly 16 yr old. Tritium in the Rio Jaitique indicates that it is composed primarily of water 12 to 20 yr old. Because we did not sample any mixed thermal springs for tritium, we cannot see any mixing relationships between cold waters and end-member thermal waters (Fig. 55).

E. Chemical Geothermometry

Chemical geothermometers of thermal spring waters (Table XVI) that are relatively unmixed but perhaps partially boiled (springs AZ-1, AZ-2, AZ-4, AZ-5, AZ-6, and AZ-8) yield fairly consistent subsurface reservoir temperatures of 183°C (quartz geothermometer, no steam loss), 199°C (Na/K geothermometer), and 182°C (Na-K-Ca geothermometer). The Na-Li geothermometer gives calculated temperatures that we believe are too low (148°C). The effect of boiling and mixing on Ca and SiO_2 suggests that geothermometers involving these constituents ideally should be applied to the least-mixed, least-boiled waters, such as AZ-1 or AZ-2. The Na-K-Ca and quartz (conductively cooled) geothermometers applied to these waters indicate temperatures of about 170 to 180°C, as will be discussed later.

The SO_4 isotope temperatures calculated for either boiling or conductive cooling increase with amount of boiling. Estimating fractions of boiling from

δD -values and interpolating between SO_4 isotope temperatures calculated for conductive cooling and for boiling, we calculated temperatures of 198, 201, 195, 202, 199, and 188°C (with an average of 197°C) for the least-boiled to most-boiled samples (AZ-1, -2, -4, -6, and -8). Gas geothermometer temperatures for only two samples range from 162 to 231°C. Our conservative estimate is that the temperature of the reservoir is at least 185°C and possibly as high as 200°C.

F. System Model

The system model we propose for the Azacualpa area is shown in the cross section of Fig. 56, modified from Eppler et al. (to be published).

Although we analyzed only two meteoric waters (AZ-3, which may be evaporated, and AZ-9) for their isotopes, their values fall within the range reported for the deep fluids. It is probable, therefore, that recharge to the system is from the mountains surrounding the Azacualpa area. However recharge occurs, the percolation rate is slow and mean residence time in the reservoir is relatively long, about 4000 yr, according to tritium data.

Our chemical data suggest that the reservoir at Azacualpa may straddle the Zacapa fault zone because the waters are very high in Ca and SO_4 , which may originate from gypsum in the Valle de Angeles Group; yet many of them (all those to the east) issue from Atima limestone of the Yojoa Group. If this is the case, the depth to the reservoir is a minimum of 150 m or so along the Zacapa fault but possibly a maximum of 1000 m or so if the reservoir is localized at the Valle de Angeles/Atima limestone contact east of the Zacapa fault. It is not known how well electrical surveys could resolve this point because shales of the Valle de Angeles Group will undoubtedly be conductive,

Figure 55. Tritium versus Cl for thermal and nonthermal waters, Azacualpa, Honduras.

TABLE XVI. Calculated Geothermometers for the Azacualpa Geothermal System^a

Sample No.	Measured Temperature (°C)	Qtz ^b	Qtz ^c	Chalcedony	Na-K-Ca				¹⁸ O-SO ₄			Gas		
					Na-K			Mg Corr	Na-Li	T ₁ ^b	T ₂ ^c	T ₃ ^d	T _{D-P} ^e	T _{CO₂-CH₄} ^f
						β = 4/3	β = 1/3							
AZ-1	98.0	183	170	163	198	(129)	171	150	147	198	183	186	---	---
AZ-2	95.0	175	164	153	190	(180)	182	(182)	147	203	186	189	---	---
AZ-4	100.3	188	175	169	204	(185)	191	182	149	198	184	186	248	179
AZ-5	98.0	187	174	167	199	(178)	186	(186)	148	---	---	---	---	---
AZ-6	101.4	181	169	160	201	(155)	181	(181)	146	209	192	196	213	144
AZ-7	98.7	173	162	151	197	(150)	177	173	136	201	185	188	---	---
AZ-8	115.4	184	171	163	204	(149)	181	(181)	152	206	193	195	---	---
AZ-9	50.2	87	90	56	203	33	(139)	33	111	138	126	129	---	---
AZ-11	77.7	153	146	128	191	(107)	161	125	140	---	---	---	---	---
Average ^g	---	183±5	171±4	163±6	199±5	---	182±7	---	148±2	202±5	188±5	190±5	231±17	162±17

^aParentheses indicate values that are calculated but that violate rules of application.

^bNo steam loss.

^cMaximum steam loss.

^dContinuous steam loss.

^eD'Amore and Panichi (1980).

^fNorman and Bernhardt (1981).

^gAverage of least-altered thermal waters (AZ-1, AZ-4, AZ-5, AZ-6, and AZ-8).

whereas the relatively dilute nature of the thermal waters may make them relatively nonconductive. Thermal fluids from the reservoir rise along the north-trending faults and fractures in the limestone and locally boil and mix with cold fluids in the near-surface environment.

G. Power Output of Surface Discharges

Using Eq. (10) from Section VIII and assuming the maximum reservoir temperature to be roughly 185°C, the ambient temperature to be 28°C, and the estimated volume of discharge to be 1200 l/min, we calculate that the power output of the surface springs is about 13.4 MW (thermal) or about 2.0 MW (electrical) at 15% efficiency. The discharge volume does not include the value for spring AZ-9, the hot karstic spring. Because it is dilute water, it cannot be accounted for as end-member thermal water. However, if we calculate its energy output using just its discharge temperature, we can add another 1.8 MW (thermal) to the system for a grand total of 15.2 MW (thermal). We feel this value may still be low because of our inability to estimate thermal flow beneath the water level of the river. Because the hot spring system at

Figure 56. Schematic model of the Azacualpa geothermal system, Honduras.

Azacualpa stretches across a structural block between two fault zones, the Azacualpa reservoir may be relatively large, extending beneath an area of 2 to 3 km². Because of its remoteness and because its equilibration temperature appears to be slightly lower than that of the San Ignacio reservoir, we feel that Azacualpa is the third best target area for geothermal development of electricity in Honduras.

XI. CHOLUTECA REGION

During our investigations we sampled several thermal sites throughout the Choluteca region of southern Honduras (Figs. 5 and 57). Of these, the Pavana site is the most interesting. It is located approximately 3 km southeast of the village of Pavana adjacent to the Pan-American Highway (San Lorenzo sheet, UTM coordinates 656/812). Three other isolated spring areas were visited: one adjacent to a paved road at Agua Caliente, El Rosario (Ciudad de Nacaome sheet, UTM coordinates 527/956), a second south of Namasigue (Santa Marfa sheet, UTM coordinates 848/486 and 905/441), and a third near El Triunfo (Somotillo sheet, UTM coordinates 025/485). The latter two areas are reached by dirt roads. Although other areas of thermal springs occur in the region, we did not visit them. This region was previously investigated by Einarsson (1976), Geonomics (1977), and GeothermEx (1980a). The Geonomics investigation included an electrical resistivity survey of the Pavana site. Savannah, marsh, scrub forest, and low volcanic hills characterize this region where it is not cultivated.

A. Geology

The Choluteca region of southern Honduras is located about 35 km east of the axis of the Central American volcanic arc and, therefore, overlies an eastward-dipping subduction zone (Fig. 3). The main structure of the region is the northwest-trending Pavana Fault (Geonomics, 1977), which is apparently an extension of the major fault zone bordering the northeast edge of the Nicaragua Depression. Northwest-trending faults dipping southwest define a series of asymmetrical grabens (Duffield et al., to be published). The Golfo de Fonseca west of the Pavana area is a point at which the Nicaragua

Figure 57. Map of the Choluteca region, southern Honduras, showing the approximate locations of the four areas that were sampled.

Depression intersects the Medial Trough of El Salvador, also a northwest-trending graben system. Geonomics (1977) recognized at least two northeast-trending fault zones that appear to cross the Pavana fault and that are on trend with and parallel to the Guayape fault zone in eastern Honduras.

The Pavana region is characterized by a sequence of intermediate to mafic lahars and lavas overlain by silicic tuffs and lavas, which are capped with intermediate to mafic breccias, lavas, and tuffs. These volcanic rocks are all presumably Tertiary in age. The closest Quaternary volcanics are located 40 km southwest and, hence, are not related to the geothermal system

at Pavana (Duffield et al., to be published). Williams and McBirney (1969) identified ignimbrites and domes as well as marls and pumiceous sediments in the region. They dated a dacite dike in a roadcut near Nacaome at approximately 7 Ma. However, Duffield et al. (to be published) report a K-Ar age of a sample of rhyolite at Pavana at 5.2 ± 0.2 Ma.

The Pavana site, mapped by Geonomics (1977), is located southwest of the Pavana fault in a graben filled with soil and alluvium on a floor of basalt. Possibly, a cross fault trending N45°E controls the locations of springs and the course of the Río Agua Caliente. Tertiary rhyolite tuffs, andesites, and basalts form the hills north of the site. Duffield et al. (to be published) present a more detailed geologic description of this site. A report by Geonomics (1977) contains descriptions of the other sites, which have similar geology.

B. Surface Features

Nacaome. We sampled one hot spring (PV-1, 91°C) at Agua Caliente, El Rosario near Nacaome. It is one of a group of springs that issues from marshy alluvium bordered by scrub forest. Several volcanic hills rim the area to the southeast. Although no single spring has large flow, the combined discharge of this area is roughly 1200 l/min. There was no visible gas discharge.

Pavana. The Pavana site (Fig. 58) is rather impressive as well as extensive. Possibly 20 to 30 springs and seeps issue from the main site about 200 m southwest of the intersection of the Río Agua Caliente and the Pan-American Highway in a clearing in cultivated savannah. A large, hot pond lies just west of the main area across a barbed-wire fence. The appearance of the springs is initially foreboding because they boil and flow from a maze of pits that resemble hydrothermal explosion craters. We were told, however, that local residents dynamited the spring site to mine away the coarse calcite crystals in the 1-m-thick alluvium for cement manufacture. Although deposits around active springs consist mostly of calcite, some quartz is also precipitated (Table VIII). Gases from the boiling springs smell of H₂S (Fig. 59). Total flow from the area is estimated at roughly 1000 l/min at 60°C.

Thermal seeps issue along the quebrada near the bridge of the Pan-American Highway and farther upstream for about 500 m (e.g., spring PV-5, 65°C). Still other thermal springs flow from the marshy savannah 1 to 2 km

Figure 58. Map of the Pavana geothermal area, Honduras, showing locations of hot springs and a cold well.

Figure 59. Photograph looking east of hot spring PV-3 during gas sampling operations.

west of the main site (e.g., spring PV-7, 73°C), but their combined flow is not large.

Namasigue. We sampled two hot springs in the rolling volcanic hills south of Namasigue. Spring PV-8 (82°C) is one of two or three springs that flow from tuffaceous sandstone in a cleared area. Spring PV-9 (68°C), shown in Fig. 60, flows from a marshy area at the edge of a patch of scrub forest next to a newly cleared pasture. A large, hot pool about 7 m in diameter lies only 20 m north of this spring. No gases were noted at these two sites.

El Triunfo. We sampled one hot spring at Agua Caliente el Estribo near El Triunfo close to the Nicaraguan border. Spring PV-10 (81°C) is one of several hot springs that discharge from mixed scrub forest and savannah. Total flow of this group is estimated at roughly 800 l/min. No gases were noted at any of these springs.

C. Chemistry

Hot spring waters in the Choluteca region are Na-SO₄-HCO₃-Cl waters (Table XVII). Two springs (PV-8 and PV-9) near Namasigue contain the highest Cl and Br concentrations measured in Honduras. The Br/Cl ratio (mg/l) of PV-8

Figure 60. Photograph looking northwest of hot spring PV-9.

(0.0037) and PV-9 (0.0035) is similar to that of sea water (0.0034), suggesting that these springs are partially derived from sea water. Strictly on a chloride basis, they consist of about 2.5% sea water. No apparent chemical relations exist among the various hot spring systems in this region (Fig. 61). All systems appear to be isolated, and all systems except Pavana have relatively low SiO_2 and trace element concentrations, suggesting low-temperature reservoirs.

We sampled several hot springs at the Pavana site, two higher-temperature springs in the main area (PV-3 and PV-4) and two lower-temperature springs, one to the north (PV-5, 65°C) and the other to the west (PV-7, 73°C). All four springs show remarkably similar chemistry and little, if any, evidence of mixing (Fig. 61). Concentrations of As, Cs, B, F, Br, Li, and NH_4 are slightly anomalous, whereas contents of Ca and Mg are relatively high for high-temperature thermal waters. In contrast, silica concentrations (<128 mg/l) are not particularly high for high-temperature waters. As noted above, the springs precipitate calcite and only minor silica, suggesting that the temperature of the underlying reservoir does not exceed 150°C.

Concentrations of HCO_3 (<80 mg/l) in the Pavana springs are lower than at other thermal sites in Honduras. An inverse relation exists between pH and

TABLE XVII. Major Chemistry^a and Isotope Data^b for the Choluteca Geothermal Region

Sample No.	Temp (°C)	Field pH	Flow (L/s)	SiO ₂	Na	K	Li	Cs	Ca	Mg	Cl	F	HCO ₃	CO ₃	SO ₄	B	As	NH ₄	δD	δ ¹⁸ O	³ H	δ ¹³ C
PV-1	90.6	7.30	1200	109	190	6.2	0.03	0.017	26.2	0.10	45.5	7.3	146	0	316	1.01	0.07	0.31	-47.9	-7.46	0.37	-5.92
PV-2	34.0	6.70	--	76	25	1.8	0.02	<0.002	78.2	11.6	6.2	0.15	339	0	4	0.05	<0.05	0.09	-44.9	-6.30	--	--
PV-3	101.8	8.00	1/2	128	237	9.9	0.27	0.036	21.1	0.05	67.4	3.92	34.2	24	438	1.43	0.11	0.17	-43.8	-7.16	0.00	-5.86
PV-4	92.6	7.00	100	127	243	9.6	0.27	0.022	27.3	0.18	67.9	3.81	51.2	13.2	446	1.46	0.14	0.09	-47.0	-6.97	--	-5.46
PV-5	65.0	6.70	1/8	125	230	9.9	0.26	0.020	28.2	0.46	65.0	3.57	78.1	0	437	1.54	0.08	0.12	-48.1	-7.09	2.55	--
PV-6	29.3	6.25	--	79	28	4.2	<0.01	<0.002	43.4	6.44	5.7	0.12	231	0	3.4	0.07	<0.05	0.17	-38.9	-6.26	0.08	--
PV-7	73.3	6.80	--	103	235	9.6	0.32	0.021	30.1	0.19	69.7	3.81	78.1	0	444	1.46	<0.05	0.23	-43.8	-6.94	0.24	-6.42
PV-8	82.0	6.90	200	69	329	8.6	0.29	0.044	55.1	0.16	408	1.12	40.3	0	294	0.74	<0.05	0.22	-45.2	-6.69	--	-8.71
PV-9	67.8	6.70	20	67	392	8.9	0.40	0.047	73.4	0.14	519	1.08	47.6	0	297	0.71	0.07	0.13	-38.8	-6.36	0.05	--
PV-10	81.1	6.90	--	73	200	5.9	0.17	<0.002	38.7	0.04	44.7	1.67	19.5	12.0	416	1.06	<0.05	0.20	-45.7	-6.27	--	-11.92
PV-11	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	-40.9	-6.29	--	--
PV-12	32.6	6.00	--	56	24	3.6	0.03	<0.002	40.3	12.2	27.3	0.08	173	0	18.7	0.11	<0.05	0.23	-45.1	-6.09	--	--

^aChemical analyses reported in mg/L.^bδD and δ¹⁸O reported in ‰ relative to Standard Mean Ocean Water (SMOW); δ¹³C reported in ‰ relative to Pee Dee Belemnite (PDB); tritium (³H) reported in tritium units (T.U.).

Gas Analysis (in vol% dry gas) of a Selected Spring at the Pavana Site

Sample No.	Temp (°C)	CO ₂	H ₂ S	H ₂	CH ₄	N ₂	NH ₃	O ₂	Ar	He	Total %	CO ₂ δ ¹³ C
PV-3	101.8	71.81	3.542	0.003	0.141	18.35	0.399	4.987	0.507	0	99.739	-9.74

total HCO_3 , suggesting that springs PV-3 and PV-4 are losing HCO_3 during boiling by precipitation of CaCO_3 , whereas the springs on the margin of the reservoir (PV-5 and PV-7) are cooling conductively. This idea is supported by the much lower silica concentration of spring PV-7 (103 mg/l).

D. Stable Isotopes

Figure 62 shows stable isotope compositions for waters of the Choluteca region. All thermal waters have compositions that plot close to the meteoric water line, and we observe no large isotopic shifts that can be attributed to isotopic exchange between hot water and rock.

Meteoric waters at Nacaome and Pavana are more enriched in heavy isotopes than are nearby thermal waters, indicating that average recharge elevations of the hot-water systems are higher than their discharge elevations. At the Pavana site, we sampled one cold well (PV-6, 29°C) east of Cerro Saracuco at an elevation of 128 m. The isotope values for this well water are considerably heavier than the average values for the hot springs. Based on the oxygen gradient of -0.26‰ per 100 m for Nicaragua (Payne and Yurtsever, 1974), the average recharge

Figure 61. Plots of B, F, and Li versus Cl for thermal and nonthermal waters in the Choluteca region, Honduras.

Figure 62. Plot of δD versus $\delta^{18}O$ for thermal and nonthermal waters in the Choluteca region, Honduras.

elevation of the Pavana system is about 285 m higher than well PV-6, or at least 430 m. This means that recharge to the system could come only from the volcanic hills to the northeast.

E. Tritium

As mentioned above, no mixing of thermal and nonthermal waters is shown by the chemistry of the hot springs at the Pavana site. Although we analyzed only two hot springs at Pavana for tritium (PV-3 with 0 T.U. and PV-7 with 0.08 T.U.), both springs contain such small amounts of tritium that any component of cool, shallow water must be very small. Assuming that the Pavana reservoir is representative of the well-mixed case (Fig. 10) and that its tritium content averages 0.04 T.U., the thermal waters have a mean residence time in the reservoir of at least 5000 yr.

Because we collected only single samples for tritium at the other sites, we cannot say much about the age of their thermal fluids. Their relatively low values (0.37 to 0.05 T.U.) suggest that their reservoir fluids are relatively old, between 600 and 4500 yr.

F. Chemical Geothermometry

At the Pavana site, relatively good agreement exists among the quartz-conductive (150°C), Na-K (152°C), and Na-K-Ca (140°C) geothermometers (Table XVIII). Magnesium concentrations are too low to require a correction to the Na-K-Ca geothermometer. We believe the Na-Li geothermometer yields temperatures that are too low. The low temperature predicted by the quartz geothermometer at spring PV-7 (140°C) probably results from precipitation of SiO_2 at the margin of the reservoir as mentioned above.

Based on chemical geothermometry, temperatures for the other hot spring systems in the Choluteca region appear to be relatively low. Most important in this deduction are temperatures indicated by the Na-K-Ca ($\beta = 4/3$) geothermometer. Because the $\beta = 4/3$ values are below 100°C for hot springs PV-1,

TABLE XVIII. Calculated Geothermometers for the Choluteca Geothermal Region^a

Sample No.	Measured Temperature (°C)				Na-K-Ca				¹⁸ O-SO ₄				Gas	
		Qtz ^b	Qtz ^c	Chalcedony	Na-K	$\beta = 4/3$	$\beta = 1/3$	Mg Corr	Na-Li	T ₁ ^b	T ₂ ^c	T ₃ ^d	T _{D-P} ^e	T _{CO₂-CH₄} ^f
PV-1	90.6	142	137	116	137	84	(127)	(83)	103	203	186	189	---	---
PV-3	101.8	151	145	126	152	(109)	142	(142)	84	206	190	193	93	144
PV-4	92.6	151	144	126	149	(101)	138	(137)	82	214	194	198	---	---
PV-5	65.0	150	143	125	154	(101)	141	(141)	83	---	---	---	---	---
PV-7	73.3	139	134	112	151	(99)	138	(136)	94	208	184	190	---	---
Average ^g	---	151±1	144±1	126±1	152±2	---	140±2	---	83±1	210	192	196	---	---
PV-8	82.0	117	116	89	124	85	(120)	(85)	70	171	159	161	---	---
PV-9	67.8	116	115	87	116	81	(115)	(81)	78	167	153	155	---	---
PV-10	81.1	120	118	92	131	75	(120)	(75)	68	175	161	164	---	---

^aParentheses indicate values that are calculated but that violate rules of application.

^bNo steam loss.

^cMaximum steam loss.

^dContinuous steam loss.

^eD'Amore and Panichi (1980).

^fNorman and Bernhardt (1981).

^gAverage of hot end-member fluid at Pavana site (PV-3, PV-4, and PV-5).

PV-8, PV-9, and PV-10, these springs all appear to be at or near equilibrium at their surface discharge temperatures (Fournier and Truesdell, 1973).

G. System Model

The system model we propose for the Pavana site (Fig. 63) is based in part on the resistivity survey performed by Geonimics (1977). According to that report the alluvial plain around the Pavana site is underlain at a depth of 600 to 700 m by a low resistivity zone having an areal extent of roughly 30 km². This being the case, the thermal fluid must circulate in layered lahar(?) units downfaulted southwest of the Pavana fault zone. Recharge to the system is by slow percolation of meteoric fluid from the volcanic highlands to the northeast. Once the fluids are heated to about 150°C, they rise

Figure 63. Schematic model of the Pavana geothermal system, Honduras, based on geology of Duffield et al. (to be published), resistivity of Geonimics (1977), and geochemistry of this report.

primarily along the Pavana fault zone and cross faults that feed hot water into permeable lahar(?) strata. The heart of the system occurs at the main site (springs PV-3 and PV-4). Because of loss of SiO_2 at spring PV-7, we predict the reservoir may be colder to the west. We have given no models for the other systems because they have low estimated reservoir temperatures and are considered to be very unlikely targets for geothermal development.

H. Power Output of System

Using Eq. (10) in Section VIII, we calculate that the power output of the surface features at the Pavana site is about 8.4 MW (thermal), assuming a reservoir temperature of 150°C , an ambient temperature of 30°C , and an estimated discharge of 1000 l/min. Although the maximum reservoir temperature of the Pavana system is too low to be of economic importance without a binary-cycle power plant, the resistivity survey by Geonomics (1977) indicates the reservoir may be sizable, in relatively permeable strata, and at reasonably shallow depths. Thus, if relatively complex and expensive binary systems are to be used, we feel the Pavana site might be very attractive as a geothermal target. The attractiveness of the site is also enhanced by its easy access to the Pan-American Highway and its proximity to an existing power line and substation. Of the six sites, the Pavana site would probably be the easiest in which to drill a shallow gradient well because of access, relatively soft rock formations, and shallow depth to reservoir.

XII. LA CEIBA REGION

During our investigations in Honduras, we visited three geothermal areas in the La Ceiba region. They are, from west to east, La Masica, Sambo Creek, and La Labor (Figs. 5 and 64). La Masica is located 36 km west of La Ceiba (La Masica sheet, UTM coordinates 805/248), Sambo Creek is located approximately 1.5 km south of the village of Sambo Creek (Jutiapa sheet, UTM coordinates 405/445), and La Labor is located about 8 km east of Sambo Creek (Jutiapa sheet, UTM coordinates 494/414). GeothermEx (1980a) and Geonomics (1977) have previously given descriptions of these areas.

A. Geology

According to Horne et al. (1976), the most prominent structural feature of the La Ceiba region is the northeast-trending Cordillera Nombre de Dios,

Figure 64. Map of the La Ceiba region, northern Honduras, showing the locations of the three areas that were sampled.

bounded on the north by an extension of the Chamelecón fault zone and on the south by the Aguán fault zone (Fig. 65). This mountain range has a maximum elevation of 2400 m and is composed of Paleozoic metamorphic basement intruded by granitic stocks and small plutons 93 to 57 Ma old (Horne et al., 1976; Case and Holcombe, 1980). Reconnaissance geology by Fakundiny* suggests that the Sambo Creek block is located north of the axis of the main part of the range and is bounded on the north by a high-angle reverse fault. During our sampling, we located sheared and faulted rocks adjacent to both the Sambo Creek and La Labor thermal springs. Outcrops are rare at Sambo Creek, but a fault can be seen trending east-west and dipping 75°N in foliated mica schist

*R. H. Fakundiny, personal communication, 1985.

Figure 65. Simplified structural map of northern Honduras showing the major strike-slip faults of the region; striped patterns are metamorphic rocks, and solid black is ultramafic rocks (from Horne et al., 1976).

just north of spring SC-4 (Fig. 66). A more obvious fault zone at La Labor forms a 1.3-m-high scarp in sheared granite in the drainage immediately south of spring SC-5. This zone trends N50°W and dips 70°N. The dips on the fault planes measured at these locations suggest that they might be high-angle normal faults, contrary to the suggestion of Fakundiny. We observed no obvious faults at La Masica although both metavolcanic and xenolith-bearing granitic rocks are highly fractured. These fractures generally trend northeast, parallel to the nearby Chamelecón fault zone.

B. Surface Features

Thermal springs at Río La Masica issue for a distance of about 300 m south (upstream) of the bridge on the main highway. Most springs discharge from fractured greenstone (meta-dacite or meta-andesite) or from heavily forested colluvium on the west side of the river. We observed roughly 15 springs and seeps; temperatures of flowing springs varied from 48 to 80°C, and total discharge was about 400 l/min. The main spring (HN-6, 78°C) flows from colluvium about 2 m above river level within 15 m of the bridge. Another spring (80°C) is noteworthy because it is the most southerly of the group and

Figure 66. Map of the Sambo Creek geothermal area showing locations of hot springs and the major east-west fault zone.

issues from a gravel bar in the center of the river between outcrops of granite. We observed intermittent gas discharges only at the main spring; the amount was insufficient for sampling.

The Sambo Creek group of springs (Figs. 66 and 67) flow from faulted metamorphic rocks in an otherwise inconspicuous drainage about 1 km east of Sambo Creek proper. The springs emerge from heavily forested, steep terrain about 30 to 50 m above the relatively flat coastal plain to the north. Perhaps 25 to 35 springs and seeps, most of which are boiling or near boiling, form the main group. Total flow is estimated at 2000 l/min. The rocks surrounding the springs and exposed in the stream channel are coated and cemented with white silica sinter. The odor of H_2S is obvious in the vicinity of the hot springs.

The setting at La Labor is somewhat similar to that of Sambo Creek. One main spring (SC-5, 88°C, ~1200 l/min) discharges from faulted granitic rocks at the mountain front in dense vegetation, and its stream channel is cemented with silica sinter. Two springs of much smaller flow (e.g., SC-6, 87°C, 20 l/min) issue from alluvium in a pasture about 750 m north of the main spring and 300 m northwest of Ranchería La Labor (Fig. 68). Rocks surrounding these springs are also coated with silica sinter. Gas discharges at all springs of La Labor were extremely small and could not be sampled. Local residents claim that other springs emerge in the jungle along the mountain front 1 to 2 km northwest of the main spring, but we did not visit those springs.

C. Fluid Chemistry

Thermal springs at each of the three areas in the La Ceiba region are quite similar in fluid chemistry although the thermal spring at La Masica is roughly half as concentrated as the others. The geothermal waters encountered in the region are neutral to slightly alkaline, dilute $Na-SO_4-HCO_3-Cl$ waters (Table XIX). Total dissolved solids at each site are less than 420 ppm. Concentrations of Na plus K are consistently greater than the combined concentrations of Ca, Mg, and Sr. Silica concentrations are relatively high. Concentrations of trace elements (As, B, Br, Cs, Li, NH_4 , and Rb) are low compared with those in the Platanares area and in most high-temperature geothermal systems around the world. The chemistry of the springs at Sambo

Figure 67. Photograph looking north of the hot creek formed by the thermal waters of the Sambo Creek geothermal area. Spring SC-3 is located just behind the photographer. Note thick jungle surrounding the site.

Figure 68. Photograph looking west of hot spring SC-6 at La Labor thermal area, Honduras.

Creek and La Labor does not show much, if any, mixing. Different B/Cl and Li/Cl ratios at each hot spring area (Fig. 69) indicate that the geothermal fluids originate in distinct fault-controlled reservoirs along the Cordillera Nombre de Dios.

D. Stable Isotopes

Figure 70, a plot of δD versus $\delta^{18}O$, shows that all sampled waters in the La Ceiba region plot close to the meteoric water line (Craig, 1961). No samples exhibit oxygen enrichment suggestive of high-temperature isotopic

TABLE XIX. Major Chemistry^a and Isotope Data^b for the La Ceiba Geothermal Region

Sample No.	Temp (°C)	Field pH	Flow (L/s)	SiO ₂	Na	K	Li	Cs	Ca	Mg	Cl	F	HCO ₃	CO ₃	SO ₄	B	As	NH ₄	δD	δ ¹⁸ O	³ H	δ ¹³ C
SC-1	99.9	8.10	50	134	132	6.3	0.19	0.009	3.6	0.06	35.3	4.28	19.5	55.2	162	0.09	<0.05	0.12	-25.60	-5.05	0.00	-7.00
SC-2	100.3	6.90	40	135	134	6.1	0.19	0.009	3.7	0.05	35.1	4.09	48.8	31.2	149	0.09	<0.05	0.12	-28.00	-5.04	0.12	-6.59
SC-3	99.5	8.00	1000	133	135	6.4	0.17	0.020	7.1	0.09	34.9	4.05	31.7	39.6	149	0.09	<0.05	0.12	-27.70	-4.97	--	--
SC-4	31.0	6.50	1	33	15	0.3	<0.01	<0.002	11.9	2.09	9.9	0.17	69.5	0	4.6	<0.02	<0.05	0.05	-19.20	-3.66	4.23	--
SC-5	87.7	7.30	1200	88	125	4.9	0.10	0.013	4.0	0.03	32.3	4.06	52.5	26.4	141	0.04	<0.05	0.10	-21.70	-4.09	0.13	-10.53
SC-6	87.0	8.10	20	91	129	5.1	0.10	0.002	3.8	0.02	33.6	4.19	68.3	24.0	147	<0.02	<0.05	0.09	-22.10	-4.06	--	-9.73
SC-7	27.2	6.30	--	21	6	0.9	<0.01	<0.002	2.6	0.47	3.4	0.07	39.0	0	1.7	<0.02	<0.05	0.07	-12.70	-3.80	3.45	--
HN-6	78.8	8.10	400	89	84	2.7	0.15	0.009	1.9	0.04	14.5	3.18	48.8	31.2	72	<0.02	<0.05	0.12	-19.00	-4.18	0.32	-12.30
HN-7	28.7	6.75	4000	34	10	1.1	<0.01	0.003	8.1	2.40	5.8	0.10	15.3	0	2.7	<0.02	<0.05	0.13	-14.77	-3.78	4.15	--

^aChemical analyses reported in mg/L.

^bδD and δ¹⁸O reported in ‰ relative to Standard Mean Ocean Water (SMOW); δ¹³C reported in ‰ relative to Pee Dee Belemnite (PDB); tritium (³H) reported in tritium units (T.U.).

Gas Analysis (in vol% dry gas) of a Selected Spring at the Sambo Creek Site

Sample No.	Temp (°C)	CO ₂	H ₂ S	H ₂	CH ₄	N ₂	NH ₃	O ₂	Ar	He	Total %	CO ₂ δ ¹³ C
SC-3	100.0	12.58	4.809	0.024	0.806	76.97	0.399	1.428	2.439	0.037	99.492	-14.73

Figure 69. Plots of B, F, and Li versus Cl for thermal and nonthermal waters in the La Ceiba region, Honduras.

Figure 70. Plot of δD versus $\delta^{18}O$ for thermal and nonthermal waters in the La Ceiba region, Honduras.

exchange between water and rock. The lack of oxygen enrichment throughout the La Ceiba region may imply that the geothermal systems are relatively cool ($<200^{\circ}C$) and/or have short residence time in the ground and/or have a large ratio of water to rock in the reservoir. Another possibility, which we do not favor, is that the geothermal systems are old and the fluids have depleted the surrounding rocks of ^{18}O . The different position of each spring system along the meteoric water line is further evidence that the systems are small and isolated.

Cold spring SC-4 is enriched in both δD and $\delta^{18}O$ in comparison with the adjacent hot springs at Sambo Creek (Fig. 70). If we assume that SC-4 is

isotopically representative of meteoric water at its discharge elevation, then we can apply the $\delta^{18}\text{O}$ -gradient of -0.26‰ per 100 m for Nicaragua to determine that the average recharge elevation of the hot springs ($\delta^{18}\text{O} \approx -5.00\text{‰}$) is roughly 470 m higher than the recharge elevation of cold spring SC-4 ($\delta^{18}\text{O} \approx 3.7\text{‰}$) at 70 m.

E. Tritium

Measured tritium values of geothermal waters throughout the La Ceiba region are 0.32 T.U. for La Masica and <0.13 T.U. for Sambo Creek and La Labor (Table XIX). These low tritium values indicate maximum mean residence times of 700 yr for the La Masica system and 1800 yr for the Sambo Creek and La Labor systems. These ages imply relatively deep and/or low-velocity circulation of meteoric fluids through basement rocks before convective upflow along faults. The tritium values of cold-water samples in the region range from 3.45 to 4.23 T.U., within the estimated current background level for Honduras of 2 to 5 T.U.

F. Chemical Geothermometry

Calculated reservoir temperatures in the La Ceiba region are in excellent agreement and indicate that the reservoir temperatures of the three systems are $\leq 155^\circ\text{C}$ (Table XX). Sambo Creek is 150 to 155°C , La Labor is 130 to 135°C , and La Masica is about 130 to 135°C . The good agreement between silica and cation temperatures suggests that near-surface mixing with cold water does not occur. Reequilibration effects on the fluid chemistry and calculated geothermometers are not presently known for this area. One must assume that the values calculated in Table XX are realistic and that the reservoir temperatures in the La Ceiba region are too low to effectively generate electrical power without binary-cycle technology.

G. System Model

Although the three sites studied in the La Ceiba region exhibit similar dilute fluid compositions, they are surface manifestations of separate geothermal systems emerging at three locations along the same structural zone. The thermal fluids are at least 700 to 1800 yr old, indicating moderately deep circulation. Of the three thermal systems in the La Ceiba region, the one at Sambo Creek exhibits the highest surface flow rate and subsurface reservoir temperatures and appears to be the best target for further exploration.

TABLE XX. Calculated Geothermometers for Geothermal Systems in the La Ceiba Region^a

Sample No.	Measured Temperature (°C)	Qtz ^b	Qtz ^c	Chalcedony	Na-K-Ca				Na-Li	¹⁸ O-SO ₄			Gas	
					Na-K	$\beta = 4/3$	$\beta = 1/3$	Mg Corr		T ₁ ^b	T ₂ ^c	T ₃ ^d	T _{D-P} ^e	T _{CO₂-CH₄} ^f
SC-1	99.9	154	147	130	161	(130)	153	(153)	97	172	163	164	---	---
SC-2	100.3	155	147	130	158	(128)	151	(151)	96	167	159	160	---	---
SC-3	99.5	154	147	129	160	(113)	148	(148)	89	---	---	---	152	80
Average ^g	---	154±1	147±0	130±1	160±1	---	151±2	---	94±4	170	161	162	---	---
SC-5	87.7	130	127	103	148	(116)	142	138	65	149	142	142	---	---
SC-6	87.0	132	128	105	148	(120)	144	130	64	158	149	150	---	---
HN-6	78.8	131	127	103	136	(107)	133	(133)	110	182	167	170	---	---

^aParentheses indicate values that are calculated but that violate rules of application.

^bNo steam loss.

^cMaximum steam loss.

^dContinuous steam loss.

^eD'Amore and Panichi (1980).

^fNorman and Bernhardt (1981)

^gAverage of hot end-member fluid at Sambo Creek site (SC-1, SC-2, and SC-3).

We postulate two system models for the Sambo Creek area (Fig. 71). In one model, the springs at Sambo Creek issue from normal faults. According to the isotopic evidence presented, water is recharged from the mountains to the south. Meteoric water percolates downward through the metamorphic and intrusive rocks forming the range and is heated at depth. Thermal water then flows convectively upward along the normal fault planes and emerges along the fault scarp observed at the surface.

The second model combines the findings of Horne et al. (1976) and Fakundiny.* The block located between the left-lateral faults of Horne et al. could conceivably be moving north to northeastward as a thrust block. The thrusting motion would be accompanied by east-west extension forming north-trending tensional faults. Hence, meteoric water percolates through the basement complex of the Cordillera, is heated, and rises convectively up the tension faults to the surface. Two models are presented because each implies a different drilling strategy should exploration at Sambo Creek continue.

*R. H. Fakundiny, personal communication, 1985.

Figure 71. Schematic models of the Sambo Creek geothermal system, Honduras. Model A assumes normal faulting, and model B assumes high-angle reverse faulting.

H. Power Output

The power output of surface discharges at the Sambo Creek site is 17.6 MW (thermal), assuming a reservoir temperature of 155°C, an ambient temperature of 30°C, and an estimated discharge rate of 2000 l/min. The temperature of this reservoir is too low to be economically useful unless a binary-cycle power plant is constructed. Although the Sambo Creek and Pavana sites are estimated to be at about equivalent temperatures (155°C and 150°C, respectively), no geophysical studies of Sambo Creek are available to help

assess the reservoir. Thus, it is our belief that the Sambo Creek site would cost more to develop than would the Pavana site at this time.

Because the La Labor and La Masica sites are estimated to contain only 130°C geothermal fluid, we do not consider them to be viable targets for electrical geothermal development.

XIII. EL OLIVAR SITE

The El Olivar thermal area (Figs. 5 and 72) is located approximately 20 km north of Lago de Yojoa and about 50 km south of San Pedro Sula.

Figure 72. Map of the El Olivar geothermal region in the southern Sula graben of Honduras showing locations of thermal sites at El Olivar proper and Laguna Agua Caliente.

We investigated two areas: El Olivar proper (Río Lindo Sheet, UTM coordinates 058/729) and Laguna Agua Caliente (Río Lindo Sheet, UTM coordinates 977/705). GeothermEx (1980a) previously investigated both areas. The thermal springs, easily reached by paved and dirt roads, are located in the Sula Valley, which is one of the most productive agricultural areas in Honduras.

A. Geology

The El Olivar area lies at the southern end of the Sula graben, part of the greater Honduras Depression (Fig. 3). The hot springs emerge from major northeast-trending range faults bordering both sides of the graben. Farther north, east-west-trending cross faults cause the graben to become wider. Uplifted rock units exposed in the fault blocks flanking the valley consist of the Cretaceous Atima Formation, predominantly limestone. Oligocene(?) volcanic rocks of the Matagalpa Formation cap the limestone on the east side of the valley. A field of Quaternary trachy-basalt, trachy-andesite, and trachyte cones and flows fills the southern Sula graben and has dammed the drainage between the Sula Valley and Lago de Yojoa to the south (Williams and McBirney, 1969; Gislason, 1980). Lavas and scattered scoria cones form a very young topographic surface stretching across the valley between the two groups of hot springs. The volcanics are interbedded with Quaternary alluvium that fills the rest of the valley.

The subsurface geology of the Sula graben can be inferred from the geophysical investigations of Zuniga (1975) and from surface geology. Modeling of the southernmost east-west gravity profile, which was laid out just north of Santa Rita (approximately 10 km north of the El Olivar thermal area), reveals that the graben is about 400 m deep with maximum displacement toward the axis of the valley. Using a density contrast of 0.374, the model predicts the graben floor is composed of Cretaceous limestone. Near-surface magnetic anomalies are assumed to result from Quaternary lavas interbedded with alluvium. In contrast, the graben becomes broader and deeper to the north (up to 2000 m) with maximum displacements along the east margin. The floor of the graben in the north is composed of Paleozoic metamorphic rocks intruded by granitic plutons.

B. Surface Features

Thermal springs at El Olivar discharge along 750 m of the prominent northeast-trending fault scarp bounding the east side of the Sula graben (Fig. 73). Spring E0-1 (66°C, 2 l/min) is the hottest of several small springs and seeps that feed a marshy area east of the ranch house at Los Leones. About 100 m northeast of spring E0-1, two 50°C seeps issue from faulted limestone. Another 185 m northeast of the seeps, spring E0-2 (73°C, <1 l/min) flows out of a 4-m-high mound of travertine stained with hydrous iron oxides (Fig. 74). Two larger springs located south of Los Leones discharge from small mounds of travertine along the fault (e.g., E0-3, 76°C, 12 l/min). Brecciated limestone can be found all along the fault scarp as can blocks of lava from flows capping the ridge.

Gas discharge from the springs in this area is minimal, and the springs are not particularly impressive in terms of temperature, flow, or type of deposits. However, the rancher at Los Leones claims that the spring activity increased dramatically for about two weeks after a major Central American earthquake that occurred a few years ago, indicating that the reservoir feeding these springs is very sensitive to tectonic disturbances.

The springs at Laguna Agua Caliente (El Aguacate) issue primarily from the eastern and southern margins of a marshy lagoon that lies west of a prominent northeast-trending fault scarp of Cretaceous limestone. Two small hills of folded and faulted argillaceous limestone stand north and south of the marsh. Flows of olivine basalt overlies contorted limestone beds on the southern hill. These hills appear to be small fault blocks east of the main fault scarp.

As many as 50 small springs and seeps discharge in the reeds of the marsh (Fig. 75). The larger ones deposit travertine and hydrous iron oxides (e.g., spring E0-6, 77°C), but their flow rates are barely measurable. The temperature, flow rate, and gas-discharge characteristics of hot springs at Laguna Agua Caliente resemble those of the El Olivar springs on the opposite side of the graben.

C. Chemistry

Thermal waters found in the El Olivar and Laguna Agua Caliente areas are very similar chemically, as noted by Gislason (1980). They are also the most

Figure 73. Map of the El Olivar area showing spring locations and a major normal fault.

Figure 74. Photograph looking northeast of hot spring E0-2 and its travertine deposit at El Olivar.

Figure 75. Photograph looking east of hot spring E0-6 at Laguna Agua Caliente, Honduras.

concentrated fluids analyzed in our survey of Honduras (2000 to 2400 mg/l TDS). The springs consist of Na-HCO₃ water with secondary amounts of SO₄ and Cl, although Cl values are among the highest we observed (Table XXI). Contents of Ca, Mg, Sr, and Ba are also higher than in any of the other thermal areas investigated and reflect equilibration in or passage through limestone reservoir rocks at only moderate temperatures. Contents of B, Br, Cs, Li, and NH₄ are relatively high, but the amount of As is low (<0.05 mg/l).

Although the waters are similar, subtle differences in chemistry suggest the two systems are not derived from a single, large reservoir beneath the Sula graben. The thermal fluids of the two areas have slightly different B/Cl, Li/Cl, and F/Cl ratios (Fig. 76). In addition, they have very different ratios of SO₄/Cl, averaging 0.86 for El Olivar and 1.83 for Laguna Agua Caliente.

Some of the data, particularly F and Li versus Cl (Fig. 76) and the inverse relation between Ca plus Mg and Cl contents, suggest that mixing may be occurring between hot and cold end-member waters. However, the data are few, and the range in compositions of thermal waters is small. If we extrapolate the F versus Cl trend to 0 mg/l F (assuming all F comes from the hot end member), the cold end member would contain roughly 50 mg/l Cl. Cool groundwaters having this much Cl are not likely to occur in the region. A more typical Cl value for cool groundwater in limestone is 6 mg/l, as measured in a sample from a large spring just south of Lago de Yojoa (spring HN-3, 24°C).

Another point worth noting is the lack of any correlation between temperature and Cl content. This suggests that the springs do not cool by mixing and, considering the low flow rates of the springs, that significant conductive cooling occurs before discharge.

D. Stable Isotopes

Figure 77 shows hydrogen and oxygen isotope compositions of the waters at El Olivar and Laguna Agua Caliente. The thermal waters exhibit an apparent oxygen-18 enrichment of 2.0 to 2.7‰ from the meteoric water line. This enrichment might be interpreted to result from high-temperature isotopic exchange between water and rock. However, considering that the reservoir rock is most likely limestone, a more probable explanation is an isotopic exchange

TABLE XXI. Major Chemistry^a and Isotope Data^b for the El Olivar Region

Sample No.	Temp (°C)	Field pH	Flow (l/s)	SiO ₂	Na	K	Li	Cs	Ca	Mg	Cl	F	HCO ₃	CO ₃	SO ₄	B	As	NH ₄	δD	δ ¹⁸ O	³ H	δ ¹³ C
EO-1	66.4	6.80	2	113	526	41	1.56	0.11	36.3	8.48	105	6.3	1357	0	75.2	8.15	<0.05	8.9	-32.2	-3.14	0.31	0.47
EO-2	73.2	6.40	seep	103	452	39	1.28	0.11	46.6	14.4	99.3	5.9	1176	0	113	6.93	<0.05	8.7	-35.5	-3.59	--	0.07
EO-3	75.9	7.00	12	120	480	40	1.38	0.13	38.0	7.43	102	6.3	1215	0	100	8.02	<0.05	10.0	-30.2	-3.20	0.17	0.07
EO-4	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	-23.8	-3.88	--	--
EO-5	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	-38.6	-5.38	--	--
EO-6	77.4	6.40	--	105	550	39	1.34	0.11	32.1	3.72	115	7.8	1210	0	216	7.66	<0.05	7.08	-35.6	-3.17	0.23	-0.11
EO-7	67.8	6.90	--	101	600	44	1.48	0.11	38.2	5.25	122	7.9	1293	0	217	7.80	<0.05	6.83	-36.8	-2.79	0.05	-0.75

^aChemical analyses reported in mg/l.^bδD and δ¹⁸O reported in ‰ relative to Standard Mean Ocean Water (SMOW); δ¹³C reported in ‰ relative to Pee Dee Belemnite (PDB); tritium (³H) reported in tritium units (T.U.).

Gas Analyses (in vol% dry gas) of Selected Springs for the El Olivar Region

Sample No.	Temp (°C)	CO ₂	H ₂ S	H ₂	CH ₄	N ₂	NH ₃	O ₂	Ar	He	Total %	CO ₂ δ ¹³ C
EO-1	66.44	97.33	0.006	0	0.312	1.695	0.016	0.590	0.026	0.00007	99.975	-2.69
EO-7	67.8	99.39	0.031	0.0006	0.113	0.392	0.008	0.050	0.010	0.0003	99.995	-3.56

between water and carbonate rocks that occurs at moderate temperatures. For example, a sample of limestone taken from the El Olivar region has a $\delta^{18}\text{O}$ -value of $+21.6\text{‰}$. Assuming that this value is representative of the oxygen isotope composition of the reservoir rock and that water from spring E0-7 ($\delta^{18}\text{O} = -2.8\text{‰}$) is typical of the reservoir fluid in the Laguna Agua Caliente area, we can determine an equilibrium temperature for the rock-water reaction. Using the oxygen isotope fractionation curve for the $\text{CaCO}_3\text{-H}_2\text{O}$ system (O'Neil et al., 1969), the indicated temperature is $\sim 50^\circ\text{C}$.

Carbon isotope data on water, gas, and limestone samples from the El Olivar region also indicate equilibrium fractionation temperatures similar to spring discharge temperatures. The El Olivar limestone sample has a $\delta^{13}\text{C}$ -value of $+3.0\text{‰}$ (Table V). According to data from Friedman and O'Neil (1977) carbon-isotope equilibrium between a limestone of this composition and CO_2 gas from spring E0-1 or E0-7 indicates temperatures of 75°C and 65°C . Using the carbon isotope fractionation curve of Mook et al. (1974), the difference between $\delta^{13}\text{C}$ -values for

Figure 76. Plots of B, F, and Li versus Cl for thermal and nonthermal waters in the El Olivar area, Honduras.

Figure 77. Plot of δD versus $\delta^{18}O$ for thermal and nonthermal waters in the El Olivar area, Honduras.

total dissolved CO_2 (as HCO_3) and CO_2 gas (Table XXI) indicates temperatures of $75^\circ C$ and $80^\circ C$.

Although we see no obvious mixing trends in the isotope compositions of the thermal fluids, there is a general trend toward oxygen-18 enrichment with increasing Cl. However, just the opposite occurs with D and Cl, indicating that the thermal waters are not connate waters (White et al., 1973; Taylor, 1974).

In our brief study of this area, we were not able to find samples of cool flowing springs to get background isotope values, but we did collect samples of the Río Potrero (EO-4) and tap water from a cistern (EO-5) that supplies a store in the village of El Olivar. Both samples could be slightly evaporated (Fig. 77), but their δD -values bracket those of thermal fluids at both sites in the graben. Local recharge of the thermal waters from precipitation on the highlands bordering the graben is possible.

Gislason (1980) has suggested a very interesting model in which groundwater from Lago de Yojoa recharges the southern Sula graben and, possibly, the hot spring system through the dam of Quaternary lavas. Results of our only isotope analysis of the surface lake water are typical of an evaporated water

and reflect a deuterium content that is significantly heavier than that of the thermal waters of this region. On the basis of this one analysis, we would say the lake cannot be recharging the springs. We realize, however, that this sample may not be representative of the entire lake and feel that more samples should be collected, preferably from different depths, to test Gislason's model.

Interestingly, cool groundwater and water from the Rio Jaitique at Azacualpa have δD -values similar to those of the El Olivar fluids, as does water from the cold spring in limestone south of Lago de Yojoa (HN-3). Possibly, the limestone rocks in this part of Honduras act as a huge karstic reservoir that recharges many other groundwater systems. However, we emphasize that the isotopes do not rule out local recharge as a source for the El Olivar and Laguna Aguacaliente hot springs.

E. Tritium

Measured tritium values of thermal waters in this area range from 0.05 to 0.31 T.U., implying maximum ages of 700 to 4500 yr for the fluids (Fig. 10).

F. Chemical Geothermometry

Geothermometer temperatures for El Olivar (Table XXII) are in substantial disagreement and suggest that two reservoirs may exist in the system. Geothermometer reactions that equilibrate rapidly indicate lower temperatures (103°C, Na-K-Ca geothermometer with Mg correction; 115°C, chalcedony saturation; 65 to 80°C, carbon isotopes), whereas geothermometers that equilibrate slowly indicate higher temperatures (185°C, SO_4 - H_2O isotopes; 139°C, Na-Li geothermometer). Such high Ca and Mg in the waters suggest equilibration at low temperatures, and the addition of these elements by rock reactions in a shallow 110°C reservoir may have made use of Na-K-Ca and Na-K geothermometers less reliable. Without correction, these geothermometers indicate temperatures of 182°C and 197°C, respectively. It is also possible that silica contents result from quartz saturation at temperatures above 142°C (with some reequilibration) and do not represent lower-temperature chalcedony equilibration. Thus, although the surface appearance of the springs is not promising, their chemistry suggests the possibility that some of their flow comes from a 140-180°C reservoir.

TABLE XXII. Calculated Geothermometers for Geothermal Systems in the El Olivar Region^a

Sample No.	Measured Temperature (°C)	Qtz ^b	Qtz ^c	Chalcedony	Na-K-Ca				¹⁸ O-SO ₄			Gas		
					Na-K	$\beta = 4/3$		Mg Corr	Na-Li	T ₁ ^b	T ₂ ^c	T ₃ ^d	T _{D-P} ^e	T _{CO₂-CH₄} ^f
						$\beta = 1/3$								
EO-1	66.4	144	139	118	197	(168)	182	90	146	159	146	148	---	188
EO-2	73.2	139	134	112	205	(154)	183	67	142	164	151	154	---	---
EO-3	75.9	148	141	122	202	(163)	184	101	143	170	157	159	---	---
EO-6	77.4	140	135	114	189	(170)	179	134	191	215	191	196	---	---
EO-7	67.8	138	133	111	192	(172)	181	124	132	215	188	195	108	226
Average ^g	---	142±4	136±3	115±4	197±6	---	182±1	103±24	139±6	185±28	167±21	170±23	---	207

^aParentheses indicate values that are calculated but that violate rules of application.

^bNo steam loss.

^cMaximum steam loss.

^dContinuous steam loss.

^eD'Amore and Panichi (1980).

^fNorman and Bernhardt (1981).

^gAverage of hot end-member fluid (EO-1, EO-2, EO-3, EO-6, and EO-7).

The SO₄-H₂O isotope temperatures may be fortuitous because the $\delta^{18}\text{O}$ (SO₄) values (averaging +7.7‰ at El Olivar) are similar to but somewhat lower than those of sedimentary gypsum (+10 to +12‰) and may not represent equilibrium fractionation. On the other hand, the difference between the observed $\delta^{18}\text{O}$ (SO₄) of the waters and that expected for gypsum may be significant and the indicated temperatures may be real. This difference could not result from low-temperature (110°C) fractionation, which would increase the $\delta^{18}\text{O}$ -value of dissolved sulfate rather than lowering it. Thus, the sulfate isotope chemistry remains ambiguous.

G. System Model

Figure 78 shows our model of the El Olivar and Laguna Agua Caliente geothermal systems schematically. We are speculating that recharge to this geothermal system comes from precipitation on the upfaulted ridges adjacent to the graben although we recognize that recharge could also come from aquifers in the alluvium of the graben fill as suggested previously by Gislason (1980) or from karstic aquifers in the Atima Formation. Because of the slight differences in chemistry between the two groups, we see them as related but isolated systems. Because we see little evidence of mixing, we feel the waters are

Figure 78. Schematic model for the geothermal systems of the El Olivar region, Honduras, based on the geophysical studies of Zuniga (1975) and this report.

equilibrating in limestone reservoir rocks, picking up their trace element contents from interbedded sand, shale, and organic-rich zones, and flowing slowly to the surface along graben faults. Slow flow results in conductive cooling and the poor correlation between temperature and chloride content. Because the reservoir is moderately hot, isotopic exchange between water and rock easily occurs in the limestone. Tritium data suggest the circulation time is relatively long, possibly 4500 yr. There is the possibility, suggested by some geothermometers, that a deeper, higher-temperature reservoir exists in the system. The indications are so ambiguous that we did not show this reservoir in Fig. 78.

Although Quaternary(?) mafic rocks occur in the area, they usually have their origin in the mantle and are not considered to be effective heat sources for geothermal aquifers by themselves. It is our opinion that the El Olivar system is heated by a combination of extensional tectonics, thin earth crust, and mafic volcanism.

H. Power Output

The energy output of both hot spring systems is not impressive. If we apply Eq. (10) from Section VIII, using an estimated reservoir temperature of 120°C, an ambient temperature of 30°C, and a liberal estimate of flow (200 l/min), the total power output for the two systems is only 1.3 MW (thermal). Compared with other sites we have investigated, the El Olivar area appears to be the least promising for geothermal development in Honduras.

XIV. CONCLUSIONS

Honduras is located on the western edge of the Caribbean Plate, north-east of the active Central American volcanic arc. The present tectonic regime of Honduras is dominated by east-west extension that has caused formation of a major north-trending graben system (Honduras Depression). Only in the Choluteca region of southern Honduras is the tectonic picture dominated by northwest-trending fault systems associated with the Nicaragua Depression. No Quaternary silicic volcanic rocks are known in Honduras, other than a few small-volume trachyte lavas in the southern Sula graben. Quaternary volcanism in Honduras consists primarily of basalt and basaltic-andesite eruptions

associated with grabens and fault zones in the central and extreme southern parts of the country. As a result, geothermal systems in Honduras reflect percolation, conductive heating, and convective upflow in a back-arc environment of thin earth crust and active extension rather than in an environment of shallow silicic magmatism. Although no heat-flow measurements have been made in Honduras, application of an empirical relationship between silica content of near-surface groundwaters and heat flow for parts of the United States suggests the average heat flow of western Honduras may be as high as 3 HFU (approximately 120 mW/m^2). The tectonic setting, volcanic style, geothermal features, and heat flux of Honduras greatly resemble those characteristics of the Basin and Range tectonic province of the western United States.

The six geothermal areas of Honduras that we studied do not discharge acid-sulfate waters nor do they possess the high-pressure, superheated fumaroles characteristic of vapor-dominated systems. Instead, geothermal fluids are neutral to alkaline in pH and are best classified as $\text{Na-HCO}_3\text{-SO}_4\text{-Cl}$ waters. The higher-temperature systems generally deposit silica sinter. These characteristics resemble many hot-water hydrothermal systems of the Basin and Range province of the United States, particularly the 240°C system at Beowawe, Nevada.

Stable isotope contents of Honduran groundwaters show that pronounced regional isotopic variations are caused by the north-to-south weather pattern and elevation changes, as expected. Isotopic analyses of thermal waters show the same regional patterns. Isotopic analyses of cool groundwaters adjacent to or within the geothermal areas indicate that recharge to the systems is local and generally from zones of higher elevation adjacent to the systems.

The present background tritium of Honduras groundwaters is 2 to 5 T.U. whereas hot, unmixed geothermal fluids generally contain 0 to 0.25 T.U. Using the well-mixed reservoir model as the most representative end-member case, the geothermal waters of Honduras are roughly between 1000 and 5000 yr old.

Table XXIII summarizes estimated reservoir temperatures of the six geothermal areas of Honduras. When various chemical and geologic considerations are applied to the geothermometers, the most reliable estimates (those underlined in the table) indicate the Platanares system is clearly the hottest

TABLE XXIII. Summary of Averaged Geothermal Calculations (°C) for Geothermal Sites in Honduras (underlined values represent estimated reservoir temperatures)

Site	Silica			Na-K	Na-K-Ca		Na-Li	$^{18}\text{O-SO}_4^{\text{d}}$	Gas	
	Quartz ^a	Quartz ^b	Chal.	(Fournier)	$\beta=1/3$	Mg-corr. ^c			D-P ^e	$\text{CO}_2\text{-CH}_4^{\text{f}}$
Platanares	<u>201</u>	185	183	<u>219</u>	<u>214</u>	---	292	<u>232</u>	<u>224</u>	186
San Ignacio	<u>178</u>	167	158	<u>200</u>	<u>197</u>	---	<u>176</u>	218	192	219
Azacualpa	<u>183</u>	171	163	199	<u>182</u>	---	148	<u>190</u>	231	162
Pavana	<u>151</u>	144	126	<u>152</u>	<u>140</u>	---	83	196	93	<u>144</u>
Sambo Creek	<u>154</u>	147	130	<u>160</u>	<u>151</u>	---	94	<u>162</u>	<u>152</u>	80
El Olivar	142	136	<u>115</u>	197	182	<u>103</u>	139	170	<u>108</u>	207

^aNo steam loss.

^bMaximum steam loss.

^cMagnesium correction applies only at El Olivar site.

^dContinuous steam loss.

^eD'Amore and Panichi (1980).

^fNorman and Bernhardt (1981).

(225°C) with the San Ignacio and Azacualpa sites next (190°C and 185°C, respectively). The Pavana and Sambo Creek sites (150°C and 155°C, respectively) can generate electricity only by using binary-cycle power plants. The reservoir fluid at El Olivar is too cool (120°C) to generate electricity by any practical method. These estimates are considered to be slightly on the conservative side.

Table XXIV shows the estimated volume and power output of surface discharges for the six sites. Although we estimated discharge volumes only by eye or by bucket and stopwatch, the Platanares site apparently discharges the largest volume of fluid whereas the El Olivar site discharges the smallest. When discharge volume is combined with temperature data, the Platanares system produces the most thermal power [45 MW (thermal), equivalent to roughly 6.7 MW (electrical)]. On this basis, the San Ignacio and Azacualpa sites [each producing <14 MW (thermal), equivalent to <2.1 MW (electrical)] do not look nearly so attractive. We conclude that Platanares is the best geothermal site known in Honduras.

TABLE XXIV. Power Output of Surface Discharges at Six Geothermal Sites, Honduras

Area	Estimated Surface Discharge (l/min)	Estimated Reservoir Temperature (°C)	Ambient Temperature (°C)	Thermal Energy (MW)	Electrical Energy Equivalent ^a (MW)
Platanares	3150	225	27	44.9	6.7
San Ignacio	1200	190	28	13.8	2.1
Azacualpa	1200 ^b	185	28	13.4	2.0
Pavana ^c	1000	150	30	8.4	---
La Ceiba Region					
Sambo Creek	2000	155	30	17.6	---
La Labor	1250	130	30	8.8	---
La Masica	500	130	30	3.5	---
El Olivar ^d	200	120	30	1.3	---

^aConversion of thermal energy to electrical energy is assumed to be roughly 15% efficient but practical only if reservoir exceeds 180°C.

^bDischarge rate may be underestimated.

^cOther sites in Choluteca region not calculated because of low-temperature reservoir (<100°C).

^dIncludes both El Olivar and Laguna Aguacaliente sites.

XV. RECOMMENDATIONS

A. Site-Specific Geochemistry

We recommend limiting additional detailed hydrogeochemical investigations to the three most promising sites: Platanares, San Ignacio, and Azacualpa. We propose a trip to these sites in early 1986 to collect samples to analyze for seasonal variations, additional mixing relationships, and additional isotope data. We also propose that ENEE personnel collect stream samples during wet and dry seasons to acquire flow rate, temperature, and basic chemistry data. These data will be used to accurately calculate discharge volumes.

B. Regional Geochemistry

We propose to leave field equipment in Honduras so that ENEE personnel can collect hydrogeochemical samples from other geothermal sites in Honduras. Los Alamos or USGS personnel will analyze these samples as necessary. These data will be used to locate other prospective geothermal targets in Honduras as well as to add to the regional data base.

C. Location of Thermal Gradient Hole at Platanares

Because Platanares is the best geothermal target that we have identified in Honduras, we feel it is appropriate to suggest a location there for a thermal gradient well (shown by X in Fig. 25). This well will allow us to measure the bottom-hole temperature and thus verify that a high-temperature resource exists. The well will also enable us to obtain continuous-core, borehole geophysical and hydrogeochemical data.

The site we have chosen is on a major bend in the Quebrada del Agua Caliente. It can be reached on a bulldozed track and trail from Platanares Village. It is on trend with the major northwest-trending fracture zone and lies between the boiling springs at La Bufa and the boiling springs in the lower quebrada. Because it is in the canyon, this site requires the least drilling to penetrate tuffs of the Padre Miguel Group (whose estimated thickness is roughly 400 m). This is good because hydrogeochemical data indicate the reservoir is in the red beds of the Valle de Angeles Group. A core hole 500 to 700 m deep might yield the temperature and permeability information needed to verify a resource.

A proposed site for a second core hole is on the ancient river terrace southeast of the Village of Platanares but south of the main group of boiling springs in the lower quebrada. This second hole would enable us to assess the southern limits of the reservoir and its hydrology. The site is located between the boiling springs and mixed thermal springs on the Río Lara. It is possible the core hole would intersect a lateral plume of mixed thermal water moving toward the south in the subsurface.

D. Location of Thermal Gradient Hole at San Ignacio

We propose that a core hole be drilled in the vicinity of the Arenal fault either just east or just west of the main hot spring area (Area 1) at San Ignacio. The object of this hole would be to penetrate the fractured zone

up which thermal waters apparently flow. We hope the core hole would be deep enough to obtain stratigraphic information that would confirm or refute the occurrence of the Valle de Angeles Group in the down-dropped block south of the fault.

E. Location of Thermal Gradient Hole at Azacualpa

At Azacualpa, we propose that a core hole 500 to 700 m deep be drilled on the flat river terrace, south of the Río Jaitique but just west of the La Cueva group of hot springs. This would place the site just west of the Zacapa fault. The object of the core hole would be to intersect this fault zone at depths greater than 100 m and to intersect thermal waters that rise along the fault. Water for coring could come from the Río Jaitique. Access to this site would require substantial road building from the village of Azacualpa and road repair between Azacualpa and Zacapa.

ACKNOWLEDGMENTS

We are very grateful for the help and cooperation provided by ENEE, which has made this effort possible. Special thanks to M. Waimin, W. Flores, and N. Ramos, who helped with various aspects of planning, logistics, and field work. Stable isotope analyses were performed by J. Borthwick, Institute for the Study of Earth and Man, Southern Methodist University, Dallas, Texas. Tritium analyses were obtained from H. Gote Ostlund, Tritium Laboratory, University of Miami, Miami, Florida. Carbon-13 analyses of rocks were done by H. Kruger, Geochron Laboratories, Cambridge, Massachusetts. S. Chipera of Los Alamos provided the x-ray diffraction analyses. We gratefully acknowledge K. Wohletz of Los Alamos and W. A. Duffield and R. Mariner of USGS for reviewing the manuscript.

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APPENDIX A
HYDROGEOCHEMICAL DATA

TABLE A-I. Location, Field Data, and Comments for Thermal and Nonthermal Waters of Honduras

Field No.	Date	Location UTM Grid Coordinates	Temp. (°C)	Field pH	Lab. Eh (mV)	Lab. Conduc. (μmhos/cm)	Flow Rate ^a (l/min)	Comments
<u>Platanares Site, Santa Rosa de Copán Sheet</u>								
PL-1	5/17/85	929327	99.5	8.75	-55	1451	5	1 x 0.5 m vigorously boiling spring in cemented boulders ~4 m above river; field H ₂ S ⁺ = 2.5 ppm; HS ⁻ >5 ppm; Miocene tuff host rock
PL-2	5/17/85	928327	99.3	8.75	-66	1428	20	vigorously boiling; flows from small cave; depositing silica; field H ₂ S ⁺ = 16 ppm; HS ⁻ >5 ppm
PL-3	5/17/85	928327	100.1	8.75	-67	1393	30	1 x 0.6 m vigorously boiling spring; spouts intermittently; field HS ⁻ = 12.5 ppm
PL-4	5/17/85	927329	88.3	6.8	145	1255	seep	issues from side drainage; field HS ⁻ = 1.5 ppm; Miocene tuff host rock
PL-5	5/17/85	934323	96.0	8.3	79	1337	4	issues from side stream on north side of the creek
PL-6	5/17/85	933323	92.0	7.2	81	1356	2	issues from fracture in Miocene tuff along south side of river
PL-7	5/17/85	929325	98.5	8.75	81	1430	5	forms vigorously bubbling pool; field HS ⁻ = 4 ppm; Miocene tuff
PL-8	5/18/85	917338	98.6	8.75	-2	1433	10	vigorously boiling pool (named La Bufo) issuing from Paleozoic schist; can hear the hiss of steam; field HS ⁻ = 7.5 ppm
PL-9	5/18/85	917341	26.7	6.9	205	485	>400	stream sample of Quebrada del Agua Caliente; upstream from PL-8
PL-10	5/18/85	925330	38.4	6.3	292	509	seep	warm spring 100-200 m upstream from waterfall; field HS ⁻ = 0; in Miocene tuff
PL-11	5/18/85	925330	70.8	7.4	265	1268	4	hot spring 130 m upstream from waterfall; field HS ⁻ = 0; Miocene tuff host rock

^aFlow rates estimated visually or by bucket and stopwatch.

TABLE A-I. (continued)

Field No.	Date	Location UTM Grid Coordinates	Temp. (°C)	Field pH	Lab. Eh (mV)	Lab. Conduc. (µmhos/cm)	Flow Rate ^a (L/min)	Comments
PL-12	5/18/85	926331	35.1	6.6	280	590	8	seep; 30 m above waterfall; in Miocene tuff
PL-13	5/18/85	922328	25.3	6.8	303	154	2	cold seep; from tiny creek crossing the road about 100 m above gate; in Miocene tuff
PL-14	5/18/85	938313	37.1	7.0	289	730	---	stream sample just upstream of junction with Río Lara
PL-15	5/18/85	925316	54.0	6.0	239	926	2	warm spring on bank of Río Lara; issues from silicified tuff; green algae and white filamentous bacteria
PL-16	5/18/85	925316	28.0	7.0	241	361	1000	Río Lara above warm spring (PL-15)
<u>San Ignacio Site, El Porvenir Sheet</u>								
SI-1	5/15/85	913249	99.0	9.78	-165 ^b	1995 ^b	---	Vigorously boiling spring; issues gas
SI-2	5/15/85	913249	99.0	9.78	-423 ^b	1750 ^b	---	field H ₂ S ⁺ = 7 ppm; HS ⁻ = 25 ppm
SI-3	5/15/85	913249	99.5	9.59	-455 ^b	2100 ^b	---	Vigorously boiling; 0.75-m-diameter pool with concrete lining
SI-4	5/15/85	914248	99.6	9.51	-455 ^b	1720 ^b	---	issues gas
SI-5	5/15/85	915249	99.6	9.13	-433 ^b	1925 ^b	---	issues gas
SI-6	5/15/85	915249	98.6	7.27	-409 ^b	1560 ^b	---	small spring issues gas; Paleozoic schist host rock
SI-7	5/15/85	917245	99.0	7.41	-427 ^b	1560 ^b	16	1.2 x 1.5 m spring with largest flow in area; deposits siliceous sinter; vigorously boiling; issues gas from 1-m-long vent
SI-8	5/15/85	916245	96.7	6.75	-400 ^b	1620 ^b	4	issues little gas; to west of sinter terrace; field H ₂ S ⁺ = 28 ppm; HS ⁻ = 10 ppm
SI-9	5/15/85	917245	99.0	8.50	-430 ^b	1800 ^b	---	issues gas
SI-10	5/15/85	915251	30.9	6.85	-70 ^b	1220 ^b	---	cold seep in alluvium; Paleozoic schist host rock

^aFlow rates estimated visually or by bucket and stopwatch.^bField measurements.

TABLE A-I. (continued)

Field No.	Date	Location UTM Grid Coordinates	Temp. (°C)	Field pH	Lab. Eh (mV)	Lab. Conduc. (μmhos/cm)	Flow Rate ^a (l/min)	Comments
SI-11	5/27/85	905252	28.0	7.0	397	449	2	cold spring west of main site, in N-S drainage; Paleozoic schist host rock
SI-12	5/27/85	905251	72.0	7.0	105	1213	1/2	hot spring 20 m south of SI-11; issues from Paleozoic mica schist
SI-13	5/27/85	909251	59.0	7.3	128	1293	1	warm spring on SiO ₂ mound
SI-14	5/27/85	913245	28	---	---	---	20	cold spring SW of main group; issues from alluvium
SI-15	5/27/85	920249	97.8	7.8	57	1278	16	1/2 km E of main group; issues from alluvium in bottom of small crater; possible steam explosion a few years ago; Paleozoic schist surrounds area
SI-16	5/27/85	917245	98.0	7.41	-427 ^b	1560	16	Duplicate of SI-7
Azacualpa Site, San Pedro Zacapa Sheet								
AZ-1	5/24/85	843261	98.0	7.2	120	1404	2	travertine depositing hot spring; Atima Fm in surrounding area
AZ-2	5/24/85	843261	95.0	8.9	118	1441	1	spring issues from fault scarp in Valle de Angeles SS and shale
AZ-3	5/24/85	842260	28.0	6.8	195	1475	12	cold spring issues from Valle de Angeles SS; 300 m upstream (south) of hot springs
AZ-4	5/24/85	843262	100.0	8.5	6	1495	40	boiling spring at edge of creek, south of cave; issues gas; field HS ⁻ = 1 ppm; in Valle de Angeles
AZ-5	5/24/85	843262	98.0	7.5	110	1521	---	forms large, deep bubbling pool; main vent in arch in Valle de Angeles; field HS ⁻ = 0.3 ppm
AZ-6	5/24/85	843263	101.4	7.6	106	1499	120	3 high-temperature fumaroles and springs in the area on north side of river (101°C); field HS ⁻ = 0.4 ppm; in Atima Fm

^aFlow rates estimated visually or by bucket and stopwatch.^bField measurements.

TABLE A-I. (continued)

Field No.	Date	Location UTM Grid Coordinates	Temp. (°C)	Field pH	Lab. Eh (mV)	Lab. Conduc. (umhos/cm)	Flow Rate ^a (l/min)	Comments
AZ-7	5/24/85	844262	98.7	8.0	108	1350	<1	issues gas; field HS ⁻ = 0.25 ppm; in Atima Fm
AZ-8	5/25/85	851262	115.4	8.0	78	1439	---	high-pressure water discharges horizontally from fracture in Atima Fm on canyon wall
AZ-9	5/25/85	846265	50.2	7.1	202	429	1200	largest spring in area; issues from limestone of Atima Fm
AZ-10	5/25/85	848263	---	---	---	---	---	Río Jaitique, upstream of AZ-9
AZ-11	5/25/85	843265	77.7	7.98	289	1140	1	issues from Valle de Angeles Fm along NW-SE trending fault north of river and NW of main area; Fe-oxides
<u>Choluteca Region, Southern Honduras</u>								
PV-1	5/29/85	527956	90.6	7.3	285	1043	1200	Agua Caliente, El Rosario; issues from alluvium in marsh; calcite deposition; Ciudad de Nacaome sheet
PV-2	5/29/85	532956	34.0	6.7	358	535	---	14-m-deep well; well #E-172-S; at El Rosario; Ciudad de Nacaome sheet
PV-3	5/29/85	656812	101.8	8.0	280	1266	1/2	Pavana main area; super- heated spring in depression surrounded by steaming ground; deposits carbonate; field H ₂ S ⁺ = 80 ppm, HS ⁻ = 0.1 ppm; in volcanic alluvium; San Lorenzo sheet
PV-4	5/29/85	656812	92.6	7.0	268	1290	100	flowing hot spring near PV-3; in volcanic alluvium; San Lorenzo sheet
PV-5	5/29/85	659819	65.0	6.7	289	1280	1/8	hot seep north of main high- way and along Río Agua Caliente; in volcanic alluvium; San Lorenzo sheet
PV-6	5/29/85	667850	29.3	6.25	336	359	---	issues from 12-m-deep well out of hornblende andesite (Atillos de la Castaña); San Lorenzo sheet

^aFlow rates estimated visually or by bucket and stopwatch.

TABLE A-I. (continued)

Field No.	Date	Location UTM Grid Coordinates	Temp. (°C)	Field pH	Lab. Eh (mV)	Lab. Conduc. (umhos/cm)	Flow Rate ^a (l/min)	Comments
PV-7	5/29/85	638811	73.3	6.8	311	1282	---	(Belisa de Pavana) several springs in marshy area; orange, red, and green algal mat surrounds deep vent; San Lorenzo sheet
PV-8	5/30/85	848486	82.0	6.9	298	1937	200	issues from tuffaceous SS; south of Namasigue; intermittent gas; field HS ⁻ = 0 ppm; deposits CaCO ₃ ; issues gas; Santa Maria sheet
PV-9	5/30/85	905441	67.8	6.7	306	2120	20	issues from alluvium in marsh; brush and dead trees in and around spring; Santa Maria sheet
PV-10	5/30/85	025485	81.0	6.9	292	1180	---	Agua Caliente el Estribo at El Triunfo; field HS ⁻ = 0 ppm; in volcanic alluvium; Somotillo sheet
PV-11	5/30/85	023465	---	---	---	---	---	well-water sample near El Triunfo; Somotillo sheet
PV-12	5/30/85	858541	32.6	6.0	324	396	---	18-m-deep well at El Obraje; Santa Maria sheet
PV-14	5/30/85	848486	82.0	6.9	298	1937	200	Duplicate of PV-8; Santa Maria sheet
<u>La Ceiba Region, La Masica, and Jutiapa Sheets</u>								
SC-1	5/21/85	406445	99.9	8.1	90	649	50	~2 m diameter; vigorously boiling; issues gas; field HS ⁻ = 1.0 ppm; in faulted Paleozoic schist
SC-2	5/21/85	404444	100.3	6.9	120	649	40	small boiling spring; in faulted Paleozoic schist
SC-3	5/21/85	405445	99.5	8.0	80	646	1000 ^b	boiling spring in main spring area; issues gas; field HS ⁻ = 1.0 ppm; in faulted Paleozoic schist
SC-4	5/21/85	404444	31.0	6.5	212	131	1	cold spring; issues from foliated mica schist; in faulted Paleozoic schist

^aFlow rates estimated visually or by bucket and stopwatch.^bCumulative flow of area.

TABLE A-I. (continued)

Field No.	Date	Location UTM Grid Coordinates	Temp. (°C)	Field pH	Lab. Eh (mV)	Lab. Conduc. (µmhos/cm)	Flow Rate ^a (l/min)	Comments
SC-5	5/22/85	494413	87.7	7.3	77	601	1200	La Labor near Jutiapa; issues from base of fault scarp in SiO ₂ cemented, sheared Paleozoic granite; field HS ⁻ = 1.0 ppm
SC-6	5/22/85	494416	87.0	8.1	103	632	20	2 small springs in pasture, issue from alluvium; intermittent, weak gas discharge; field HS ⁻ = 1.0 ppm
SC-7	5/22/85	398454	27.2	6.3	222	35	---	Sambo Creek at bridge
HN-6	5/21/85	805248	78.8	8.1	230	380	400 ^b	Agua Caliente, La Masica; 30 km west of La Ceiba; issues from Paleozoic metadacite (or andesite) north of main fault zone; intermittent gas
HN-7	5/21/85	805248	28.7	6.75	352	88	4000	Río Agua Caliente de la Masica; upstream of last hot spring
El Olivar Site, Río Lindo Sheet								
E0-1	5/23/85	059732	66.4	6.8	220	2290	2	large spring in marshy area; issues steady flow of gas
E0-2	5/23/85	062733	73.2	6.4	171	2120	seep	deposits CaCO ₃ ; occasional gas bubbles; Cretaceous limestone host rock
E0-3	5/23/85	058729	75.9	7.0	177	2190	12	southwestern-most spring in El Olivar group; field HS ⁻ = 5 ppm; deposits CaCO ₃ ; filamentous bacteria; Fe-oxide staining in Cretaceous limestone
E0-4	5/23/85	058732	---	---	---	---	---	Río El Potrero
E0-5	5/23/85	065756	---	---	---	---	---	tapwater
E0-6	5/23/85	977704	77.4	6.4	206	2410	---	Laguna Agua Caliente, SW of El Olivar; folded Cretaceous limestone and Quaternary basalt; CaCO ₃ ; field HS ⁻ = 0 ppm

^aFlow rates estimated visually or by bucket and stopwatch.^bCumulative flow of area.

TABLE A-I. (continued)

Field No.	Date	Location UTM Grid Coordinates	Temp. (°C)	Field pH	Lab. Eh (mV)	Lab. Conduc. (μmhos/cm)	Flow Rate ^a (l/min)	Comments
E0-7	5/23/85	977705	67.8	6.9	225	2560	---	Laguna Agua Caliente; 50 m from E0-6; issues gas; Fe staining; deposits CaCO ₃ ; total flow of area <90 l/min
<u>Miscellaneous</u>								
SF-1	5/16/85	626729	35.0	6.0	425	225	20	issues from concrete well in alluvium; Zambrano sheet
HN-1	5/16/85	561793	24.0	6.35	428	30	10	cold spring; along highway 10-15 km north of Zambrano; in Miocene tuff; Zambrano sheet
HN-2	5/16/85	207021	23.0	7.2	420	69	---	cold spring in nonwelded Miocene tuff; 20 km south of Siguatepeque; Comayagua sheet
HN-3	5/16/85	966306	24.0	6.5	333	384	1200	spring is blocked by a dam and forms a pool at Ojo Lajas; issues from Cretaceous limestone; Siguatepeque sheet
HN-4	5/19/85	972202	26.7	6.8	319	468	0-2	well water near Colonia San Antonio; issues from Miocene tuff; Corquín sheet
HN-5	5/19/85	038442	25.0	6.7	318	501	60	spring issues from concrete crib through a hose; (Agua Zarca); in Cretaceous limestone; Dulce Nombre sheet
HN-8	5/27/85	958483	---	---	---	---	---	Lago de Yojoa; Santa Cruz de Yojoa sheet
HN-9	5/27/85	921022	---	---	---	---	---	small stream in Miocene volcanics; Cedros sheet
HN-10	5/29/85	753725	26.0	---	---	---	---	well water at Río Abajo; in Miocene volcanics; San Juan de Flores sheet
HN-11	5/29/85	655209	25.0	6.2	380	21	2	issues through steel pipe; in Padre Miguel Miocene volcanics; Sabana Grande sheet

^aFlow rates estimated visually or by bucket and stopwatch.

TABLE A-II. Major Element Analyses in mg/l for Thermal and Nonthermal Waters of Honduras

Field No.	Temp. (°C)	SiO ₂	Ca	Mg	Sr	Na	K	Li	CO ₃	HCO ₃	SO ₄	Cl	F	Br	B	TDS	Σcat	Σan	bal
<u>Plantanares Site</u>																			
PL-1	99.5	288	2.5	0.06	0.35	310	38	4.04	206	78.1	225	36.7	12.4	<0.1	16.7	1044	15.20	14.78	0.03
PL-2	99.3	290	3.2	0.07	0.39	291	33	3.50	132	215	215	35.4	12.9	<0.1	16.4	972	14.86	14.36	0.03
PL-3	100.1	277	3.0	0.04	0.33	305	36	3.85	168	171	238	33.4	12.7	<0.1	15.5	988	14.93	15.20	-0.02
PL-4	88.3	183	20.9	1.54	0.66	231	26	2.94	0	473	193	25.9	9.6	<0.1	12.2	999	12.36	13.20	-0.07
PL-5	96.0	305	1.2	0.06	0.05	289	18	3.56	142	154	239	36.0	12.3	<0.1	16.0	912	13.63	14.13	-0.04
PL-6	92.0	183	5.4	0.08	0.14	260	21	3.29	0	530	199	26.0	9.5	<0.1	12.5	1067	12.63	14.25	-0.12
PL-7	98.5	236	3.8	0.08	0.32	311	26	3.53	154	171	245	34.4	12.6	<0.1	16.0	979	14.93	14.91	0.002
PL-8	98.6	233	1.0	0.04	0.45	299	37	3.72	202	68.3	246	34.0	12.9	<0.1	16.4	922	14.58	14.86	-0.02
PL-9	26.7	22	72.0	15.5	0.54	10	1.6	<0.01	0	45.7	110	2.6	0.21	<0.1	0.03	259	5.39	3.13	0.53
PL-10	38.4	35	42.2	8.73	0.43	45	10.3	0.28	0	137	128	6.2	0.84	<0.1	2.27	388	5.12	5.27	0.03
PL-11	70.8	191	16.3	1.19	0.16	230	25	2.86	0	355	232	31.2	12.4	<0.1	15.0	922	12.00	12.40	-0.03
PL-12	35.1	39	42.7	11.7	0.70	52	20	0.45	0	187	135	7.2	0.85	<0.1	2.76	462	5.98	6.17	0.03
PL-13	25.3	17	20.8	4.56	0.08	5	2.5	0.04	0	32.9	50.0	2.7	0.48	<0.1	<0.02	121	1.77	1.69	0.05
PL-14	37.1	84	43.3	10.2	0.42	91	11.0	0.99	0	229	160	11.4	3.49	<0.1	5.35	579	7.42	7.87	0.06
PL-15	54.0	107	70.2	1.34	1.15	113	23	1.60	0	456	94	10.2	5.00	<0.1	5.12	792	9.98	10.08	0.009
PL-16	28.0	31	49.9	10.2	0.36	17	3.3	0.06	0	183	48.4	3.3	0.27	<0.1	0.11	317	4.19	4.13	0.02
<u>San Ignacio Site</u>																			
SI-1	99.0	214	0.8	0.06	0.11	330	26	1.44	194	112	140	75.1	12.2	0.5	3.81	900	15.30	14.11	0.08
SI-2	99.0	214	3.2	0.06	0.14	336	26	1.46	190	117	141	75.5	13.0	0.5	3.63	910	15.69	14.10	0.11
SI-3	98.9	215	1.3	0.05	0.12	332	25	1.44	192	120	139	75.5	13.0	0.5	3.65	906	15.39	14.18	0.08
SI-4	99.6	215	4.4	0.08	0.14	324	27	1.42	158	181	142	75.8	12.6	0.5	3.70	933	15.24	14.10	0.08
SI-5	99.6	211	5.6	0.10	0.13	322	26	1.38	86.4	312	147	73.0	12.2	0.5	2.89	990	15.19	13.83	0.09
SI-6	98.6	170	7.5	0.23	0.21	288	24	1.30	19.2	410	140	69.9	11.3	0.5	3.40	976	13.75	12.91	0.06
SI-7	98.0	170	3.0	0.15	0.12	302	25	1.08	50.4	342	148	72.7	12.2	0.5	3.76	962	14.12	13.14	0.07
SI-8	96.7	169	7.1	0.30	0.13	296	26	1.28	16.8	412	145	69.9	11.4	0.5	3.30	990	14.14	12.97	0.09
SI-9	99.0	185	4.1	0.09	0.12	314	26	1.40	55.2	368	149	73.4	12.0	0.5	3.56	1008	14.77	13.76	0.07
SI-10	30.9	140	14.1	1.47	0.26	260	23	1.20	0	376	171	67.5	10.5	0.4	3.47	934	12.94	12.32	0.05

TABLE A-II. (continued)

Field No.	Temp. (°C)	SiO ₂	Ca	Mg	Sr	Na	K	Li	CO ₃	HCO ₃	SO ₄	Cl	F	Br	B	TDS	Σcat	Σan	bal
SI-11	28.0	25	51.4	19.9	0.18	22	2.0	0.14	0	261	21.2	8.6	0.34	<0.1	0.07	387	5.26	4.99	0.05
SI-12	72.0	189	11.2	1.86	0.12	266	23	1.12	0	427	130	62.7	9.6	0.5	3.12	937	13.07	12.04	0.08
SI-13	59.0	179	4.5	0.45	0.15	294	24	1.02	0	432	149	68.3	11.3	0.5	3.52	989	13.84	12.78	0.08
SI-15	97.8	161	1.8	0.11	0.14	288	23	1.30	52.8	322	137	70.5	10.3	0.5	3.47	911	13.43	12.50	0.07
<u>Azacualpa Site</u>																			
AZ-1	98.0	210	33.2	1.94	0.93	266	21	0.80	0	195	455	25.2	8.8	<0.1	1.35	1010	14.09	13.88	0.01
AZ-2	95.0	185	6.9	0.12	0.44	294	22	0.89	48	107	480	26.7	11.6	<0.1	1.49	999	13.84	14.75	-0.06
AZ-3	28.0	34	316	15.2	2.30	31	2.0	0.02	0	170	730	3.5	0.48	<0.1	0.10	1274	18.52	18.19	0.02
AZ-4	100.3	226	8.4	0.07	0.81	302	26	0.93	48	63.4	479	27.8	12.8	<0.1	1.62	971	14.41	14.11	0.02
AZ-5	98.0	222	10.0	0.12	0.80	312	25	0.95	15.6	124	495	28.4	12.7	<0.1	1.65	1027	14.90	14.37	0.04
AZ-6	101.4	203	18.9	0.42	0.74	302	25	0.90	27.6	115	499	27.6	11.6	<0.1	1.57	1031	14.93	14.63	0.02
AZ-7	98.7	180	16.3	0.56	0.53	268	21	0.70	28.8	43.9	472	26.8	12.3	<0.1	1.53	893	13.19	12.95	0.02
AZ-8	115.4	211	23.0	0.51	1.04	291	25	0.94	24.0	166	451	28.2	11.7	<0.1	1.59	1025	14.67	14.37	0.02
AZ-9	50.2	36	47.0	10.2	0.61	33	2.8	0.06	0	212	51.1	3.4	1.09	<0.1	0.12	362	4.74	4.71	0.006
AZ-11	77.7	132	39.9	3.52	0.75	207	15	0.57	0	264	338	19.4	6.7	<0.1	1.01	896	11.79	12.30	-0.04
<u>Choluteca Region</u>																			
PV-1	90.6	109	26.2	0.10	0.53	190	6.2	0.30	0	146	316	45.5	7.3	<0.1	1.01	741	9.83	10.68	0.08
PV-2	34.0	76	78.2	11.6	0.63	25	1.8	0.02	0	339	4.0	6.2	0.15	<0.1	0.05	480	6.04	6.04	0.0007
PV-3	101.8	128	21.1	0.05	0.65	237	9.9	0.27	24	34.2	438	67.4	3.92	<0.1	1.43	839	11.71	12.63	0.08
PV-4	92.6	127	27.3	0.18	0.64	243	9.6	0.27	13.2	51.2	446	67.9	3.81	<0.1	1.46	864	12.25	12.72	-0.04
PV-5	65.0	125	28.2	0.46	0.34	230	9.9	0.26	0	78.1	437	65.0	3.57	<0.1	1.54	856	11.78	12.45	0.06
PV-6	29.3	79	43.4	6.44	0.68	28	4.2	<0.01	0	231	3.4	5.7	0.12	<0.1	0.07	324	4.06	4.03	0.007
PV-7	73.3	103	30.1	0.19	0.35	235	9.6	0.32	0	78.1	444	69.7	3.81	0.4	1.46	874	12.08	12.73	0.05
PV-8	82.0	69	55.1	0.16	0.85	329	8.6	0.29	0	40.3	294	408	1.12	1.5	0.74	1140	17.40	18.41	0.06
PV-9	67.8	67	73.4	0.14	1.00	392	8.9	0.40	0	47.6	297	519	1.08	1.8	0.71	1344	21.08	21.74	0.03
PV-10	81.1	73	38.7	0.04	0.60	200	5.9	0.17	12.0	19.5	416	44.7	1.67	<0.1	1.06	741	10.86	10.76	0.009
PV-12	32.6	56	40.3	12.2	0.28	24	3.6	0.03	0	173	18.7	27.3	0.08	<0.1	0.11	315	4.58	4.13	0.10

TABLE A-II. (continued)

Field No.	Temp. (°C)	SiO ₂	Ca	Mg	Sr	Na	K	Li	CO ₃	HCO ₃	SO ₄	Cl	F	Br	B	TDS	Σcat	Σan	bal
<u>La Cieba Region</u>																			
SC-1	99.9	134	3.6	0.06	0.22	132	6.3	0.19	55.2	19.5	162	35.3	4.28	<0.1	0.09	419	6.14	6.77	0.10
SC-2	100.3	135	3.7	0.05	0.23	134	6.1	0.19	31.2	48.8	149	35.1	4.09	<0.1	0.09	413	6.23	6.16	0.01
SC-3	99.5	133	7.1	0.09	0.23	135	6.4	0.17	39.6	31.7	149	34.9	4.05	<0.1	0.09	409	6.45	6.15	0.05
SC-4	31.0	33	11.9	2.09	0.07	15	0.3	<0.01	0	69.5	4.6	9.9	0.17	<0.1	<0.02	114	1.44	1.53	0.06
SC-5	87.7	88	4.0	0.03	0.28	125	4.9	0.10	26.4	52.5	141	32.3	4.06	<0.1	0.04	391	5.81	5.81	0.001
SC-6	87.0	91	3.8	0.02	0.29	129	5.1	0.10	24.0	68.3	147	33.6	4.19	<0.1	<0.02	416	5.97	6.16	0.03
SC-7	27.2	21	2.6	0.47	0.03	6	0.9	<0.01	0	39.0	1.7	3.4	0.07	<0.1	<0.02	55	0.47	0.78	0.50
HN-6	78.8	89	1.9	0.04	0.05	84	2.7	0.15	0	48.8	72.0	14.5	3.18	<0.1	<0.02	259	3.86	3.92	0.02
HN-7	28.7	34	8.1	2.40	0.08	10	4.7	<0.01	0	15.3	2.7	5.8	0.10	<0.1	<0.02	50	1.18	0.48	0.84
<u>El Olivar Site</u>																			
EO-1	66.4	113	36.3	8.48	2.22	526	41	1.56	0	1357	75.2	105	6.3	0.3	8.15	2168	26.80	27.28	-0.02
EO-2	73.2	103	46.6	14.4	2.20	452	39	1.28	0	1176	113	99.3	5.9	0.3	6.93	1957	24.47	24.89	-0.02
EO-3	75.9	120	38.0	7.43	1.75	480	40	1.38	0	1215	100	102	6.3	0.3	8.02	2117	24.72	27.79	-0.12
EO-6	77.4	105	32.1	3.72	1.67	550	39	1.34	0	1210	216	115	7.8	0.3	7.66	2185	27.13	28.16	-0.04
EO-7	67.8	101	38.2	5.25	1.81	600	44	1.48	0	1293	217	122	7.9	0.3	7.80	2339	29.90	29.75	-0.005
<u>Miscellaneous Areas</u>																			
SF-1	35.0	74	6.6	2.20	0.07	45	7.3	0.03	0	142	4.1	6.0	0.24	<0.1	<0.02	215	2.68	2.62	0.02
HN-1	24.0	67	1.8	0.32	0.03	10	2.6	<0.01	0	25.6	2.6	5.5	0.07	<0.1	<0.02	53	1.08	0.64	0.52
HN-2	23.0	101	1.9	0.42	0.03	12	8.9	<0.01	0	51.2	2.3	6.2	0.22	<0.1	<0.02	85	0.97	1.10	0.12
HN-3	24.0	10	76.9	2.77	0.18	4	0.8	<0.01	0	220	27.3	5.7	0.07	<0.1	<0.02	338	4.29	4.35	0.02
HN-4	26.7	103	3.4	0.59	0.04	103	10.4	<0.01	0	195	42.8	22.7	0.55	<0.1	<0.02	384	5.02	4.88	0.03
HN-5	25.0	57	66.9	16.8	0.58	18	1.7	0.01	0	288	35.5	5.6	0.16	<0.1	<0.02	436	5.58	5.67	0.02
HN-11	25.0	51	1.2	0.18	0.03	5	2.2	<0.01	0	20.7	2.7	4.8	0.05	<0.1	<0.02	38	0.40	0.54	0.30

TABLE A-III. Trace Element Analyses in mg/l for Thermal and Nonthermal Waters of Honduras

Field No.	Ag	Al ^a	As	Ba	Cd	Co	Cr	Cs	Cu	Fe	Hg	Mn	Mo	NH ₄	Ni	NO ₃	Pb	PO ₄	Rb	S	Sb	Se	Zn
<u>Platanares Site</u>																							
PL-1	<0.001	0.1	1.26	0.03	<0.001	<0.001	<0.001	0.54	<0.001	0.01	<0.1	<0.01	<0.1	10.4	<0.001	1.5	<0.002	<0.1	0.010	0.01	<0.1	<0.1	0.14
PL-2	<0.001	0.1	1.00	0.02	<0.001	<0.001	<0.001	0.55	<0.001	<0.01	<0.1	<0.01	<0.1	11.7	<0.001	0.8	<0.002	<0.1	0.026	0.02	<0.1	<0.1	0.61
PL-3	<0.001	0.1	0.89	0.03	<0.001	<0.001	<0.001	0.48	<0.001	0.01	<0.1	<0.01	<0.1	13.0	<0.001	1.0	<0.002	<0.1	<0.001	0.02	<0.1	<0.1	0.34
PL-4	<0.001	<0.1	0.71	0.07	<0.001	<0.001	<0.001	0.42	<0.001	0.03	<0.1	0.15	<0.1	17.3	<0.001	1.3	<0.002	<0.1	0.005	<0.01	<0.1	<0.1	<0.01
PL-5	<0.001	<0.1	0.88	<0.01	<0.001	<0.001	<0.001	0.29	<0.001	0.01	<0.1	<0.01	<0.1	11.9	<0.001	0.5	<0.002	<0.1	0.004	<0.01	0.1	<0.1	<0.01
PL-6	<0.001	<0.1	0.58	0.01	<0.001	<0.001	<0.001	0.52	<0.001	0.01	<0.1	0.03	<0.1	11.0	<0.001	<0.1	<0.002	<0.1	0.007	<0.01	<0.1	<0.1	0.04
PL-7	<0.001	0.1	0.79	0.02	<0.001	<0.001	<0.001	0.43	<0.001	0.03	<0.1	0.01	<0.1	9.5	<0.001	0.8	<0.002	<0.1	0.004	<0.01	<0.1	<0.1	2.10?
PL-8	<0.001	<0.1	0.68	0.05	<0.001	<0.001	0.002	0.48	<0.001	0.04	<0.1	<0.01	<0.1	7.95	<0.001	0.8	<0.002	<0.1	<0.001	<0.01	<0.1	<0.1	<0.01
PL-9	<0.001	<0.1	<0.05	0.19	<0.001	<0.001	<0.001	<0.02	<0.001	0.10	<0.1	0.04	<0.1	0.12	<0.001	<0.1	<0.002	<0.1	0.001	<0.01	<0.1	<0.1	<0.01
PL-10	<0.001	<0.1	<0.05	0.27	<0.001	<0.001	<0.001	0.035	<0.001	0.01	<0.1	<0.01	<0.1	0.09	0.009	6.4	<0.002	<0.1	0.014	<0.01	<0.1	<0.1	<0.01
PL-11	<0.001	<0.1	0.75	0.08	<0.001	<0.001	<0.001	0.30	<0.001	0.08	<0.1	0.09	<0.1	17.1	<0.001	0.7	<0.002	<0.1	0.030	<0.01	<0.1	<0.1	<0.01
PL-12	<0.001	<0.1	<0.05	0.58	<0.001	<0.001	<0.001	0.053	<0.001	0.05	<0.1	0.03	<0.1	0.15	<0.001	0.4	<0.002	<0.1	0.014	<0.01	<0.1	<0.1	<0.01
PL-13	<0.001	<0.1	<0.05	0.23	<0.001	0.001	0.003	<0.002	0.003	0.84	<0.1	0.07	<0.1	0.12	<0.001	<0.1	<0.002	<0.1	0.008	<0.01	<0.1	<0.1	<0.01
PL-14	<0.001	<0.1	0.21	0.14	<0.001	<0.001	<0.001	0.12	<0.001	0.01	<0.1	0.01	<0.1	0.09	<0.001	11.9	<0.002	<0.1	0.008	<0.01	<0.1	<0.1	<0.01
PL-15	<0.001	<0.1	0.39	0.10	<0.001	<0.001	<0.001	0.33	<0.001	<0.01	<0.1	0.78	<0.1	9.7	<0.001	<0.1	<0.002	<0.1	0.030	<0.01	<0.1	<0.1	<0.01
PL-16	<0.001	<0.1	<0.05	0.19	<0.001	<0.001	<0.001	0.007	<0.001	0.01	<0.1	0.03	<0.1	0.13	<0.001	<0.1	<0.002	<0.1	0.002	<0.01	<0.1	<0.1	<0.01
<u>San Ignacio Site</u>																							
SI-1	<0.001	<0.1	<0.05	0.02	<0.001	<0.001	<0.001	0.21	<0.001	<0.01	<0.1	<0.01	<0.1	2.78	0.050	3.7	<0.002	<0.1	<0.001	<0.01	<0.1	<0.1	0.01
SI-2	<0.001	<0.1	<0.05	0.03	<0.001	<0.001	<0.001	0.16	<0.001	<0.01	<0.1	0.01	<0.1	3.40	<0.001	1.8	<0.002	<0.1	<0.001	<0.01	<0.1	<0.1	0.94
SI-3	<0.001	<0.1	<0.05	0.03	<0.001	<0.001	<0.001	0.17	<0.001	<0.01	<0.1	0.02	<0.1	3.34	<0.001	2.3	<0.002	<0.1	<0.001	<0.01	<0.1	<0.1	<0.01
SI-4	<0.001	<0.1	<0.05	0.03	<0.001	<0.001	<0.001	0.16	<0.001	<0.01	<0.1	0.03	<0.1	3.78	0.009	1.9	<0.002	<0.1	<0.001	0.08	<0.1	<0.1	4.32?
SI-5	<0.001	<0.1	<0.05	0.03	<0.001	<0.001	<0.001	0.15	<0.001	<0.01	<0.1	0.04	<0.1	5.79	<0.001	1.0	<0.002	<0.1	<0.001	<0.01	<0.1	<0.1	4.80?
SI-6	<0.001	<0.1	<0.05	0.05	<0.001	<0.001	0.002	0.15	<0.001	<0.01	<0.1	0.05	<0.1	5.35	<0.001	0.4	<0.002	<0.1	<0.001	<0.01	<0.1	<0.1	0.28
SI-7	<0.001	<0.1	<0.05	0.03	<0.001	<0.001	<0.001	0.15	<0.001	<0.01	<0.1	0.04	<0.1	4.82	<0.001	0.5	<0.002	<0.1	<0.001	<0.01	<0.1	<0.1	<0.01
SI-8	<0.001	<0.1	<0.05	0.04	<0.001	<0.001	<0.001	0.14	<0.001	<0.01	<0.1	0.06	<0.1	5.50	<0.001	<0.1	<0.002	<0.1	<0.001	<0.01	<0.1	<0.1	0.04
SI-9	<0.001	<0.1	<0.05	0.05	<0.001	<0.001	<0.001	0.13	<0.001	<0.01	<0.1	0.06	<0.1	5.07	<0.001	0.8	<0.002	<0.1	<0.001	<0.01	<0.1	0.1	0.13

^aTotal aluminum.

TABLE A-III. (continued)

Field No.	Ag	Al ^a	As	Ba	Cd	Co	Cr	Cs	Cu	Fe	Hg	Mn	Mo	NH ₄	Ni	NO ₃	Pb	PO ₄	Rb	S	Sb	Se	Zn	
SI-10	<0.001	0.2	<0.05	<0.01	<0.001	<0.001	0.002	0.11	0.003	0.13	<0.1	0.02	<0.1	0.37	<0.001	4.5	<0.002	<0.1	<0.001	<0.01	<0.1	<0.1	0.02	
SI-11	<0.001	<0.1	<0.05	<0.01	<0.001	<0.001	<0.001	<0.002	<0.001	<0.01	<0.1	<0.01	<0.1	0.16	<0.001	<0.1	<0.002	<0.1	<0.001	<0.01	<0.1	<0.1	<0.01	
SI-12	<0.001	<0.1	<0.05	<0.01	<0.001	<0.001	<0.001	0.16	<0.001	<0.01	<0.1	0.17	<0.1	5.40	<0.001	<0.1	<0.002	<0.1	<0.001	<0.01	<0.1	<0.1	<0.01	
SI-13	<0.001	<0.1	<0.05	<0.01	<0.001	<0.001	<0.001	0.17	<0.001	<0.01	<0.1	0.05	<0.1	5.99	<0.001	<0.1	<0.002	<0.1	0.005	<0.01	<0.1	<0.1	<0.01	
SI-15	<0.001	<0.1	<0.05	<0.01	<0.001	<0.001	<0.001	0.17	<0.001	<0.01	<0.1	0.01	<0.1	0.12	<0.001	0.6	<0.002	<0.1	0.12	<0.01	<0.1	<0.1	<0.01	
Azacualpa Site																								
AZ-1	<0.001	<0.1	<0.05	0.05	<0.001	<0.001	<0.001	0.13	<0.001	<0.01	<0.1	<0.01	<0.1	1.05	<0.001	<0.1	<0.002	<0.1	0.056	<0.01	<0.1	<0.1	<0.01	
AZ-2	<0.001	0.1	<0.05	0.02	<0.001	<0.001	<0.001	0.13	<0.001	0.01	<0.1	<0.01	<0.1	0.73	<0.001	<0.1	<0.002	<0.1	0.034	<0.01	<0.1	<0.1	0.02	
AZ-3	<0.001	<0.1	<0.05	0.23	<0.001	<0.001	<0.001	0.012	<0.001	<0.01	<0.1	<0.01	<0.1	0.11	<0.001	<0.1	<0.002	<0.1	0.001	<0.01	<0.1	<0.1	<0.01	
AZ-4	<0.001	0.1	<0.05	0.05	<0.001	<0.001	<0.001	0.15	<0.001	0.01	<0.1	<0.01	<0.1	0.59	<0.001	<0.1	<0.002	<0.1	0.040	<0.01	<0.1	<0.1	0.03	
AZ-5	<0.001	<0.1	<0.05	0.07	<0.001	<0.001	<0.001	0.17	<0.001	0.02	<0.1	<0.01	<0.1	0.75	<0.001	<0.1	<0.002	<0.1	0.044	<0.01	<0.1	<0.1	0.02	
AZ-6	<0.001	<0.1	0.06	0.06	<0.001	<0.001	<0.001	0.13	<0.001	<0.01	<0.1	<0.01	<0.1	0.47	<0.001	0.3	<0.002	<0.1	0.048	<0.01	<0.1	<0.1	0.01	
AZ-7	<0.001	<0.1	<0.05	0.04	<0.001	<0.001	<0.001	0.15	<0.001	<0.01	<0.1	<0.01	<0.1	0.67	<0.001	<0.1	<0.002	<0.1	0.020	<0.01	<0.1	<0.1	<0.01	
AZ-8	<0.001	<0.1	0.07	0.06	<0.001	<0.001	<0.001	0.14	<0.001	0.01	<0.1	<0.01	<0.1	1.09	<0.001	0.7	<0.002	<0.1	0.020	<0.01	<0.1	<0.1	<0.01	
AZ-9	<0.001	<0.1	<0.05	0.11	<0.001	<0.001	<0.001	0.015	<0.001	<0.01	<0.1	0.01	<0.1	0.11	<0.001	0.4	<0.002	<0.1	0.006	<0.01	<0.1	<0.1	<0.1	
AZ-11	<0.001	<0.1	<0.05	0.06	<0.001	<0.001	<0.001	0.12	<0.001	<0.01	<0.1	0.03	<0.1	0.56	<0.001	<0.1	<0.002	<0.1	0.010	<0.01	<0.1	0.1	<0.1	
Choluteca Region																								
PV-1	<0.001	<0.1	0.07	0.04	<0.001	<0.001	<0.001	0.017	<0.001	<0.01	<0.1	0.03	<0.1	0.31	<0.001	0.7	<0.002	<0.1	0.001	<0.01	<0.1	<0.1	0.03	
PV-2	<0.001	<0.1	<0.05	<0.01	<0.001	<0.001	<0.001	<0.002	0.030	0.25	<0.1	<0.01	<0.1	0.09	<0.001	12.6	<0.002	<0.1	<0.001	<0.01	<0.1	<0.1	0.87	
PV-3	<0.001	<0.1	0.11	0.03	<0.001	<0.001	<0.001	0.036	<0.001	<0.01	<0.1	<0.01	<0.1	0.17	<0.001	<0.1	<0.002	<0.1	0.009	<0.01	<0.1	<0.1	0.02	
PV-4	<0.001	<0.1	0.14	0.03	<0.001	<0.001	<0.001	0.022	<0.001	<0.01	<0.1	0.01	<0.1	0.09	<0.001	<0.1	<0.002	<0.1	0.013	<0.01	<0.1	<0.1	0.01	
PV-5	<0.001	<0.1	0.08	0.05	<0.001	<0.001	<0.001	0.020	<0.001	0.01	<0.1	0.01	<0.1	0.12	<0.001	0.8	<0.002	<0.1	0.012	<0.01	<0.1	<0.1	0.02	
PV-6	<0.001	<0.1	<0.05	0.05	<0.001	<0.001	<0.001	<0.002	<0.001	<0.01	<0.1	0.01	<0.1	0.17	<0.001	<0.1	<0.002	<0.1	0.003	<0.01	<0.1	<0.1	0.05	
PV-7	<0.001	<0.1	<0.05	0.05	<0.001	<0.001	<0.001	0.021	<0.001	0.02	<0.1	0.03	<0.1	0.23	<0.001	<0.1	<0.002	<0.1	0.009	<0.01	<0.1	<0.1	0.01	
PV-8	<0.001	<0.1	<0.05	0.02	<0.001	<0.001	<0.001	0.044	0.004	<0.01	<0.1	0.02	<0.1	0.22	<0.001	<0.1	<0.002	<0.1	0.001	<0.01	<0.1	<0.1	<0.01	
PV-9	<0.001	<0.1	0.07	0.05	<0.001	<0.001	<0.001	0.047	<0.001	<0.01	<0.1	0.02	<0.1	0.13	<0.001	<0.1	<0.002	<0.1	0.001	<0.01	<0.1	<0.1	0.49	

^aTotal aluminum.

TABLE A-III. (continued)

Field No.	Ag	Al ^a	As	Ba	Cd	Co	Cr	Cs	Cu	Fe	Hg	Mn	Mo	NH ₄	Ni	NO ₃	Pb	PO ₄	Rb	S	Sb	Se	Zn
PV-10	<0.001	<0.1	<0.05	0.01	<0.001	<0.001	<0.001	<0.002	<0.001	0.01	<0.1	0.02	<0.1	0.20	<0.001	<0.1	<0.002	<0.1	0.005	<0.01	<0.1	<0.1	<0.1
PV-12	<0.001	<0.1	<0.05	0.08	<0.001	<0.001	0.038	<0.002	<0.001	7.26	<0.1	0.05	<0.1	0.23	<0.001	7.6	<0.002	<0.1	<0.001	<0.01	<0.1	<0.1	0.03
<u>La Ceiba Region</u>																							
SC-1	<0.001	<0.1	<0.05	0.02	<0.001	<0.001	<0.001	0.009	<0.001	<0.01	<0.1	<0.01	<0.1	0.12	<0.001	<0.1	<0.002	<0.1	<0.001	<0.01	<0.1	<0.1	<0.01
SC-2	<0.001	0.1	<0.05	0.01	<0.001	<0.001	<0.001	0.009	<0.001	0.02	<0.1	<0.01	<0.1	0.12	<0.001	<0.1	<0.002	<0.1	0.012	<0.01	<0.1	<0.1	0.02
SC-3	<0.001	<0.1	<0.05	0.02	<0.001	<0.001	<0.001	0.020	<0.001	<0.01	<0.1	0.02	<0.1	0.12	<0.001	<0.1	<0.002	<0.1	0.005	<0.01	<0.1	<0.1	6.707
SC-4	<0.001	<0.1	<0.05	0.02	<0.001	<0.001	<0.001	<0.002	<0.001	<0.01	<0.1	<0.01	<0.1	0.05	<0.001	<0.1	<0.002	<0.1	<0.001	<0.01	<0.1	<0.1	0.01
SC-5	<0.001	<0.1	<0.05	<0.01	<0.001	<0.001	<0.001	0.013	<0.001	<0.01	<0.1	<0.01	<0.1	0.10	<0.001	<0.1	<0.002	<0.1	0.005	<0.01	<0.1	<0.1	<0.01
SC-6	<0.001	<0.1	<0.05	<0.01	<0.001	<0.001	<0.001	0.002	<0.001	<0.01	<0.1	<0.01	<0.1	0.09	<0.001	<0.1	<0.002	<0.1	0.004	<0.01	<0.1	<0.1	<0.01
SC-7	<0.001	<0.1	<0.05	<0.01	<0.001	<0.001	<0.001	<0.002	<0.001	0.01	<0.1	<0.01	<0.1	0.07	<0.001	<0.1	<0.002	<0.1	<0.001	<0.01	<0.1	<0.1	<0.01
HN-6	<0.001	<0.1	<0.05	<0.01	<0.001	<0.001	<0.001	0.009	<0.001	<0.01	<0.1	<0.01	<0.1	0.12	<0.001	<0.1	<0.002	<0.1	0.010	<0.01	<0.1	<0.1	0.01
HN-7	<0.001	<0.1	<0.05	0.01	<0.001	<0.001	<0.001	0.003	<0.001	<0.01	<0.1	<0.01	<0.1	0.13	<0.001	<0.1	<0.002	<0.1	0.001	<0.01	<0.1	<0.1	<0.01
<u>El Olivar Site</u>																							
EO-1	<0.001	<0.1	<0.05	0.31	<0.001	<0.001	<0.001	0.11	<0.001	0.12	<0.1	0.08	<0.1	8.9	<0.001	<0.1	<0.002	<0.1	0.001	<0.01	<0.1	<0.1	0.02
EO-2	<0.001	<0.1	<0.05	0.21	<0.001	<0.001	<0.001	0.11	<0.001	<0.01	<0.1	<0.01	<0.1	8.7	<0.001	<0.1	<0.002	<0.1	0.003	<0.01	<0.1	<0.1	0.01
EO-3	<0.001	<0.1	<0.05	0.20	<0.001	<0.001	<0.001	0.13	<0.001	<0.01	<0.1	0.05	<0.1	10.0	<0.001	<0.1	<0.002	<0.1	0.002	<0.01	<0.1	<0.1	0.01
EO-6	<0.001	<0.1	<0.05	0.11	<0.001	<0.001	<0.001	0.11	<0.001	<0.01	<0.1	0.01	<0.1	7.08	<0.001	0.2	<0.002	<0.1	0.003	<0.01	<0.1	<0.1	<0.01
EO-7	<0.001	<0.1	<0.05	0.11	<0.001	<0.001	<0.001	0.11	0.001	0.01	<0.1	0.02	<0.1	6.83	<0.001	0.3	<0.002	<0.1	0.003	<0.01	<0.1	<0.1	<0.01
<u>Miscellaneous</u>																							
SF-1	<0.001	<0.1	<0.05	0.03	<0.001	<0.001	<0.001	<0.002	<0.001	<0.01	<0.1	<0.01	<0.1	0.15	<0.001	<0.1	0.003	0.6	0.010	<0.01	<0.1	<0.1	0.01
HN-1	<0.001	3.8	<0.05	0.06	<0.001	<0.001	0.002	<0.002	0.006	0.27	<0.1	<0.01	<0.1	0.39	0.011	<0.1	<0.002	<0.1	0.005	<0.01	<0.1	<0.1	0.05
HN-2	<0.001	0.7	<0.05	0.02	<0.001	<0.001	<0.001	0.005	<0.001	0.05	<0.1	<0.01	<0.1	0.17	<0.001	<0.1	<0.002	0.6	0.019	<0.01	<0.1	<0.1	0.01
HN-3	<0.001	<0.1	<0.05	0.06	<0.001	<0.001	<0.001	<0.002	0.002	<0.01	<0.1	<0.01	<0.1	0.10	<0.001	<0.1	<0.002	<0.1	<0.001	<0.01	<0.1	<0.1	0.03
HN-4	<0.001	0.3	<0.05	0.12	<0.001	<0.001	<0.001	0.006	0.005	0.13	<0.1	0.02	<0.1	0.11	<0.001	1.9	<0.002	2.8	0.002	<0.01	<0.1	<0.1	0.52
HN-5	<0.001	<0.1	<0.05	0.11	<0.001	<0.001	<0.001	<0.002	0.001	<0.01	<0.1	<0.01	<0.1	0.10	0.002	2.4	<0.002	<0.1	0.001	<0.01	<0.1	<0.1	0.02
HN-11	<0.001	0.3	<0.05	0.01	<0.001	<0.001	<0.001	<0.002	0.003	0.03	<0.1	<0.01	<0.1	0.25	<0.001	<0.1	<0.002	<0.1	0.007	<0.01	<0.1	<0.1	0.02

^aTotal aluminum.

TABLE A-IV. Isotope Analyses for Thermal and Nonthermal Waters of Honduras

Field No.	Date	Elev. (m)	Temp. (°C)	δD (‰)	$\delta^{18}O$ (‰)	3H (T.U.)
<u>Platanares Site</u>						
PL-1	5/17/85	700	99.5	-41.6	-6.14	---
PL-2	5/17/85	700	99.3	-42.8	-6.03	---
PL-3	5/17/85	700	100.1	-42.4	-6.17	0.09
PL-4	5/17/85	700	88.3	-44.0	-6.33	0.96
PL-5	5/17/85	700	96.0	-41.6	-6.03	0.12
PL-6	5/17/85	700	92.0	-44.6	-6.02	---
PL-7	5/17/85	720	98.5	-42.1	-6.12	---
PL-8	5/18/85	800	98.6	-42.7	-6.00	0.41
PL-9	5/18/85	800	26.7	-42.8	-7.01	5.50
PL-10	5/18/85	740	38.4	-42.1	-6.51	---
PL-11	5/18/85	740	70.8	-43.6	-6.09	---
PL-12	5/18/85	735	35.1	-41.2	-6.53	5.14
PL-13	5/18/85	800	25.3	-39.5	-5.92	---
PL-14	5/18/85	770	37.1	-42.8	-6.36	---
PL-15	5/18/85	700	54.0	-46.9	-6.94	2.37
PL-16	5/18/85	700	28.0	-37.7	-5.95	7.24
<u>San Ignacio Site</u>						
SI-1	5/15/85	750	99.0	-49.0	-6.95	0
SI-2	5/15/85	750	99.0	---	---	---
SI-3	5/15/85	750	98.9	-48.3	-6.78	0.43
SI-4	5/15/85	755	99.6	-49.8	-6.80	---
SI-5	5/15/85	770	99.6	-49.9	-6.88	---
SI-6	5/15/85	790	98.6	-51.0	-7.05	0.22
SI-7	5/15/85	710	98.0	-50.1	-6.75	0.18
SI-8	5/15/85	710	96.7	-51.0	-7.08	---
SI-9	5/15/85	705	99.0	-50.0	-7.05	---
SI-10	5/15/85	820	30.9	-48.0	-6.42	0.81
SI-11	5/27/85	780	28.0	-43.0	-6.58	0
SI-12	5/27/85	780	72.0	-51.1	-7.06	0.61
SI-13	5/27/85	780	59.0	-50.5	-7.26	---
SI-14	5/27/85	700	28.0	-45.4	-6.47	---

TABLE A-IV. (continued)

Field No.	Date	Elev. (m)	Temp. (°C)	δD (‰)	$\delta^{18}O$ (‰)	3H (T.U.)
SI-15	5/27/85	730	97.8	-48.5	-6.81	---
SI-16 ^a	5/27/85	710	98.0	-50.0	-6.93	0.14
<u>Azacualpa Site</u>						
AZ-1	5/24/85	360	98.0	-34.3	-5.92	0.10
AZ-2	5/24/85	345	95.0	-34.1	-5.78	---
AZ-3	5/24/85	350	28.0	-28.9	-4.83	7.62
AZ-4	5/24/85	340	100.3	-33.4	-5.73	0.08
AZ-5	5/24/85	340	98.0	-32.9	-4.90	---
AZ-6	5/24/85	360	101.4	-32.1	-5.03	0.04
AZ-7	5/24/85	340	98.7	-30.3	-5.76	---
AZ-8	5/25/85	380	115.4	-31.2	-5.67	0
AZ-9	5/25/85	370	50.2	-29.7	-5.49	---
AZ-10	5/25/85	380	---	-32.8	-5.03	4.83
AZ-11	5/25/85	360	77.7	-30.6	-5.52	---
<u>Choluteca Region</u>						
PV-1	5/29/85	50	90.6	-47.9	-7.46	0.37
PV-2	5/29/85	50	34.0	-44.9	-6.30	---
PV-3	5/29/85	20	101.8	-43.8	-7.16	0
PV-4	5/29/85	20	92.6	-47.0	-6.97	---
PV-5	5/29/85	25	65.0	-48.1	-7.09	---
PV-6	5/29/85	140	29.3	-38.9	-6.26	2.55
PV-7	5/29/85	15	73.3	-43.8	-6.94	0.08
PV-8	5/30/85	10	82.0	-45.2	-6.69	0.24
PV-9	5/30/85	25	67.8	-38.8	-6.36	---
PV-10	5/30/85	10	81.1	-45.7	-7.23	0.05
PV-11	5/30/85	60	---	-40.9	-6.29	---
PV-12	5/30/85	50	32.6	-45.1	-6.09	---
PV-14 ^b	5/30/85	10	82.0	-45.5	-6.78	---

^aDuplicate of SI-7.^bDuplicate of PV-8.

TABLE A-IV. (continued)

Field No.	Date	Elev. (m)	Temp. (°C)	δD (‰)	$\delta^{18}O$ (‰)	3H (T.U.)
<u>La Ceiba Region</u>						
SC-1	5/21/85	50	99.9	-25.6	-5.05	0
SC-2	5/21/85	60	100.3	-28.0	-5.04	0.12
SC-3	5/21/85	40	99.5	-27.7	-4.97	---
SC-4	5/21/85	70	31.0	-19.2	-3.66	4.23
SC-5	5/22/85	60	87.7	-21.7	-4.09	0.13
SC-6	5/22/85	50	87.0	-22.1	-4.06	---
SC-7	5/22/85	20	27.2	-12.7	-3.80	3.45
HN-6	5/21/85	45	78.8	-19.0	-4.18	0.32
HN-7	5/21/85	45	28.7	-14.7	-3.78	4.15
<u>El Olivar Site</u>						
E0-1	5/23/85	50	66.4	-32.2	-3.14	0.31
E0-2	5/23/85	80	73.2	-35.5	-3.59	---
E0-3	5/23/85	50	75.9	-30.2	-3.20	0.17
E0-4	5/23/85	55	---	-23.8	-3.88	---
E0-5	5/23/85	65	---	-38.6	-5.38	---
E0-6	5/23/85	50	77.4	-35.6	-3.17	0.23
E0-7	5/23/85	50	67.8	-36.8	-2.79	0.05
<u>Miscellaneous</u>						
SF-1	5/16/85	1000	35.0	-48.0	-6.92	1.54
HN-1	5/16/85	1470	24.0	-53.4	-7.65	4.92
HN-2	5/16/85	940	23.0	-46.1	-6.94	1.01
HN-3	5/16/85	610	24.0	-32.2	-5.11	7.01
HN-4	5/19/85	700	26.7	-37.4	-5.60	0.89
HN-5	5/19/85	1100	25.0	-41.2	-7.01	6.34
HN-8	5/26/85	640	---	-12.7	-2.44	---
HN-9	5/29/85	780	---	-10.4	-1.94	---
HN-10	5/29/85	1000	26.0	-43.5	-6.04	---
HN-11	5/29/85	730	25.0	-57.1	-8.44	---

TABLE A-V. Calculated Geothermometer Temperatures ($^{\circ}\text{C}$) for Thermal Waters of Honduras

Field No.	Measured Temp. (°C)	Qtz ^a	Qtz ^b	Chalcedony	Na-K-Ca				¹⁸ O-SO ₄			Gas		
					Na-K	β = 4/3	β = 1/3	Mg Corr	Na-Li	T ₁ ^a	T ₂ ^b	T ₃ ^c	T _{D-P} ^d	T _{CO₂-CH₄} ^e
Platanares Site														
PL-1	99.5	207	190	190	235	263	225	225	300	248	220	227	230	181
PL-1(2) ^f	99.5	---	---	---	---	---	---	---	---	---	---	---	238	195
PL-2	99.3	202	186	185	228	239	216	211	289	---	---	---	---	---
PL-3	100.1	203	187	186	232	250	221	221	295	253	224	231	205	182
PL-4	88.3	174	163	152	227	150	192	161	297	---	---	---	---	---
PL-5	96.0	211	193	195	180	242	190	189	292	---	---	---	---	---
PL-6	92.0	174	163	152	199	187	189	188	295	---	---	---	---	---
PL-7	98.5	192	178	172	202	217	197	195	281	254	224	231	---	---
PL-8	98.6	191	177	171	236	310	235	235	293	261	229	237	---	---
PL-10	38.4	86	89	55	285	70	187	187	211	---	---	---	---	---
PL-11	70.8	177	166	155	224	156	193	166	293	245	209	219	---	---
PL-12	35.1	91	93	60	368	99	230	70	247	---	---	---	---	---
PL-15	54.0	141	136	115	271	96	193	96	312	---	---	---	---	---
Average ^g	---	201±7	185±6	183±9	219±21	249±29	214±16	213±16	292±6	254±5	224±4	232±4	224±14	186±6
San Ignacio Site														
SI-1	99.0	185	172	164	197	295	211	208	177	---	---	---	---	---
SI-2	99.0	185	172	164	196	227	196	191	177	---	---	---	192	181
SI-3	98.9	184	172	165	194	266	203	197	177	240	214	220	203	238
SI-4	99.6	185	172	165	201	215	197	195	178	---	---	---	---	---
SI-5	99.6	184	171	163	199	202	192	192	176	---	---	---	---	---
SI-6	98.6	169	159	146	201	184	189	189	180	---	---	---	---	---
SI-7	98.0	169	159	146	201	224	199	199	160	229	206	212	203	245
SI-8	96.7	169	159	146	206	191	193	191	177	---	---	---	---	---
SI-9	99.0	175	164	153	201	214	196	196	179	238	213	219	169	210
SI-10	30.9	157	149	133	207	158	185	147	182	---	---	---	---	---
SI-12	72.0	176	165	154	205	167	186	129	174	239	205	214	---	---
SI-13	59.0	173	162	150	200	204	193	179	158	250	221	228	---	---
SI-15	97.8	166	156	142	198	241	201	201	180	---	---	---	---	---
Average ^h	---	169	159	146	204	188	191	190	179	---	---	---	---	---

^aNo steam loss.

^bMaximum steam loss.

^cContinuous steam loss.

^dD'Amore and Panichi (1980).

^eNorman and Bernhardt (1981).

^fCollected for gas only.

^gAverage of unmixed and unboiled hot end-member fluid (PL-1, PL-2, PL-3, PL-7, and PL-8).

^hAverage of unmixed and unboiled hot end-member fluid (SI-6 and SI-8).

TABLE A-V. (continued)

Field No.	Measured Temp. (°C)	Qtz ^a	Qtz ^b	Chalcedony	Na-K	Na-K-Ca			Na-Li	¹⁸ O-SO ₄			Gas	
						β = 4/3	β = 1/3	Mg Corr		T ₁ ^a	T ₂ ^b	T ₃ ^c	T _{D-P} ^d	T _{CO₂-CH₄} ^e
Azacualpa Site														
AZ-1	98.0	183	170	163	198	129	171	150	147	198	183	186	---	---
AZ-2	95.0	175	164	153	190	180	182	182	147	203	186	189	---	---
AZ-4	100.3	188	175	169	204	185	191	182	149	198	184	186	248	179
AZ-5	98.0	187	174	167	199	178	186	186	148	---	---	---	---	---
AZ-6	101.4	181	169	160	201	155	181	181	146	209	192	196	213	144
AZ-7	98.7	173	162	151	197	150	177	173	136	201	185	188	---	---
AZ-8	115.4	184	171	163	204	149	181	181	152	206	193	195	---	---
AZ-9	50.2	87	90	56	203	33	139	33	111	138	126	129	---	---
AZ-11	77.7	153	146	128	191	107	161	125	140	---	---	---	---	---
Average ^f	---	184±5	171±4	163±6	199±6	173±14	185±4	183±2	149±2	202±4	188±5	190±5	231	162
Choluteca Region														
PV-1	90.6	142	137	116	137	84	127	83	103	203	186	189	---	---
PV-3	101.8	151	145	126	152	109	142	142	84	206	190	193	93	144
PV-4	92.6	151	144	126	149	101	138	137	82	214	194	198	---	---
PV-5	65.0	150	143	125	154	101	141	141	83	---	---	---	---	---
PV-7	73.3	139	134	112	151	99	138	136	94	208	184	190	---	---
Average ^g	---	151±1	144±1	126±1	152±2	104±4	140±2	140±2	83±1	210	192	196	---	---
PV-8	82.0	117	116	89	124	85	120	85	70	171	159	161	---	---
PV-9	67.8	116	115	87	116	81	115	81	78	167	153	155	---	---
PV-10	81.1	120	118	92	131	75	120	75	68	175	161	164	---	---

^aNo steam loss.^bMaximum steam loss.^cContinuous steam loss.^dD'Amore and Panichi (1980).^eNorman and Bernhardt (1981).^fAverage of unmixed and unboiled hot end-member fluid (AZ-2, AZ-4, AZ-5, and AZ-8).^gAverage of unmixed and unboiled hot end-member fluid at Pavana site (PV-3, PV-4, and PV-5).

TABLE A-V. (continued)

Field No.	Measured Temp. (°C)	Qtz ^a	Qtz ^b	Chalcedony	Na-K-Ca				¹⁸ O-SO ₄			Gas		
					Na-K	$\beta = 4/3$	$\beta = 1/3$	Mg Corr	Na-Li	T ₁ ^a	T ₂ ^b	T ₃ ^c	T _{D-P} ^d	T _{CO₂-CH₄} ^e
La Ceiba Region														
SC-1	99.9	154	147	130	161	130	153	153	97	172	163	164	---	---
SC-2	100.3	155	147	130	158	128	151	151	96	167	159	160	---	---
SC-3	99.5	154	147	129	160	113	148	148	89	---	---	---	152	80
Average ^f	---	154±1	147±0	130±1	160±1	124±8	151±2	151±2	94±4	170	161	162	---	---
SC-5	87.7	130	127	103	148	116	142	138	65	149	142	142	---	---
SC-6	87.0	132	128	105	148	120	144	130	64	158	149	150	---	---
HN-6	78.8	131	127	103	136	107	133	133	110	182	167	170	---	---
El Olivar Site														
EO-1	66.4	144	139	118	197	168	182	90	146	159	146	148	---	188
EO-2	73.2	139	134	112	205	154	183	67	142	164	151	154	---	---
EO-3	75.9	148	141	122	202	163	184	101	143	170	157	159	---	---
EO-6	77.4	140	135	114	189	170	179	134	131	215	191	196	---	---
EO-7	67.8	138	133	111	192	172	181	124	132	215	188	195	108	226
Average ^g	---	142±4	136±3	115±4	197±6	165±6	182±1	103±24	139±6	185±28	167±21	170±23	---	207

^aNo steam loss.^bMaximum steam loss.^cContinuous steam loss.^dD'Amore and Panichi (1980).^eNorman and Bernhardt (1981).^fAverage of unmixed and unboiled hot end-member fluid at Sambo Creek site (SC-1, SC-2, and SC-3).^gAverage of unmixed and unboiled hot end-member fluid (EO-1, EO-2, EO-3, EO-6, and EO-7).

TABLE A-VI. Residence Times for Tritium Concentrations under Well-Mixed and Piston-Flow Conditions in Central America (Base Year is 1985)

Residence Time, τ (yr)	Tritium Concentration (T.U.)	
	Well-Mixed Conditions	Piston-Flow Conditions
1	1.7	1.69
2	1.91	1.86
3	2.19	2.05
4	2.58	2.27
5	3.02	2.50
7.5	4.01	3.19
10	4.63	4.07
12.5	4.91	5.20
15	5.00	6.64
17.5	4.96	10.16
20	4.86	32.11
22.5	4.72	101.51
25	4.57	---
27.5	4.40	---
30	4.24	---
40	3.66	---
50	3.18	---
75	2.38	---
100	1.89	---
150	1.33	---
200	1.03	---
300	0.71	---
400	0.54	---
500	0.43	---
750	0.29	---
1000	0.22	---
1500	0.15	---
2000	0.11	---
3000	0.07	---
4000	0.06	---
5000	0.04	---
7500	0.03	---
10000	0.02	---
15000	0.01	---

APPENDIX B

TRITIUM CODES

Well-Mixed Model

We wish to solve

$$C(t) = \frac{e^{-(1/\tau+\lambda)t}}{\tau} \left[\frac{a_1}{(1/\tau+\lambda-b_1)} \left(e^{(1/\tau+\lambda-b_1)t_1} - 1 \right) + \frac{a_2}{(1/\tau+\lambda-b_2)} \left(e^{(1/\tau+\lambda-b_2)t} - e^{(1/\tau+\lambda-b_2)t_1} \right) \right]$$

for various values of τ . Values of the various constants are

$$\begin{array}{lll} a_1 = 275 & b_1 = 0.5161 & t_1 = 5 \text{ years} \\ a_2 = 44.87 & b_2 = 0.1535 & \end{array}$$

The value for t is given by the current year (year in which the sample was collected) minus 1963:

$$\text{i.e., } 1985-1963 = 22 \text{ years.}$$

These constants are entered as described under the description of storage registers in the program listing.

Piston-Flow Model

We wish to solve

$$C_{\text{out}}(t) = C_{\text{in}}(t-\tau) e^{-\lambda\tau}$$

for various values of τ . The input concentrations are given by

$$C_{in}(t-\tau) = a_1 e^{-b_1(t-\tau)} \quad \text{for } 0 \leq t-\tau < t_1-\tau$$

and

$$C_{in}(t-\tau) = a_2 e^{-b_2(t-\tau)} \quad \text{for } t_1-\tau \leq t-\tau$$

where $t_1 = 5$ and $t = (\text{current year} - 1963)$.

The following HP-41C computer program solves both the well-mixed and the piston-flow models. To run the program, first enter the program, and then store the variables λ , a_1 , a_2 , b_1 , b_2 , t_1 , and t in the appropriate storage registers. Execute the program. Pressing the key "A" will prompt you for a value for τ . Enter this value and press R/S. The calculator will display the result of the well-mixed calculation. To solve the piston-flow case, press "E". To recover the well-mixed case, press "C". To enter a new value for τ , press "A". You will be prompted for the value of τ . Enter the new value and press R/S.

Program Listing for Tritium Calculations

		<u>Comments</u>
01	LBL TRITIUM	
02	LBL A	
03	TAU?	Prompt for τ
04	PROMPT	
05	STO 00	Store τ in 00
06	1/X	
07	STO 01	
08	RCL 02	
09	+	Calculate $1/\tau + \lambda$
10	STO 03	Store in 03
11	RCL 09	
12	-	Calculate $1/\tau + \lambda - b_2$
13	STO 05	Store in 05
14	RCL 03	
15	RCL 08	
16	-	CALCULATE $1/\tau + \lambda - b_1$
17	STO 04	Store in 04
18	RCL 00	
19	RCL 02	
20	*	
21	CHS	
22	e^x	calculate $e^{-\lambda\tau}$
23	STO 12	Store in 12
24	LBL C	Start of well-mixed calculation
25	RCL 04	
26	RCL 11	
27	*	
28	e^x	
29	1	

30	-	
31	RCL 06	
32	*	
33	RCL 04	
34	/	
35	RCL 05	
36	RCL 10	
37	*	
38	e^x	
39	RCL 05	
40	RCL 11	
41	*	
42	e^x	
43	-	
44	RCL 07	
45	*	
46	RCL 05	
47	/	
48	+	
49	RCL 01	
50	*	
51	RCL 03	
52	CHS	
53	RCL 10	
54	*	
55	e^x	
56	*	
57	MIXED=	Display result of well-mixed calculation
58	ARCI x	
59	AVIEW	
60	STOP	
61	LBL E	Start of piston-flow calculation
62	rc1 11	
63	rc1 10	

64	rc1 00	calculate $t-\tau$
65	-	
66	$x \leq y?$	if $t-\tau \leq 5$
67	gto 01	go to 01
68	rc1 09	
69	*	
70	CHS	Calculate piston-flow concentration for $t-\tau > 5$
71	e^x	
72	RCL 07	
73	*	
74	RCL 12	
75	*	
76	GTO 02	
77	LBL 01	
78	RCL 08	
79	*	
80	CHS	
81	e^x	Calculate piston-flow concentration for $t-\tau \leq 5$
82	RCL 06	
83	*	
84	RCL 12	
85	*	
86	LBL 02	
87	PLUG=	
88	ARCL x	Display result of piston-flow calculation
89	AVIEW	
90	STOP	
91	END	

<u>Storage Registers</u>			<u>Initial Values</u>
00	τ	mean residence time	
01	$1/\tau$		
02	λ	tritium decay constant	0.055764
03	$1/\tau+\lambda$		
04	$1/\tau+\lambda-b_1$		
05	$1/\tau+\lambda-b_2$		
06	a_1	coefficient for first exponential in 1963	275
07	a_2	coefficient for second exponential in 1963	44.87
08	b_1	time constant for first exponential	0.5161
09	b_2	time constant for second exponential	0.1535
10	t	number of years since 1963	22
11	t_1	number of years to start of second exponential	5
12	$e^{-\lambda\tau}$	decay factor for piston-flow calculation	