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Geology of the Platanares geothermal area, Departamento de Copán, Honduras

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ABSTRACT

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The Platanares geothermal area, Departamento de Copán, Honduras, is located within a graben that is complexly faulted. The graben is bounded on the north by a highland composed of Paleozoic (?) metamorphic rocks in contact with Cretaceous – Tertiary redbeds of unknown thickness. These are unconformably overlain by Tertiary andesitic lavas, rhyolitic ignimbrites, and associated sedimentary rocks. The volcanic rocks are mostly older than 14 Ma, and thus are too old to represent the surface expression of an active crustal magma body. Thermal fluids that discharge in the area are heated during deep circulation of meteoric water along faults in a region of somewhat elevated heat flow. Geothermometry based upon the chemical composition of thermal fluids from hot springs and from geothermal gradient coreholes suggests that the reservoir equilibrated at temperatures as high as 225 to 240°C, within the Cretaceous redbed sequence. Three continuously cored geothermal gradient holes have been drilled; fluids of about 165°C have been produced from two drilled along a NW-trending fault zone, from depths of 250 to 680 m. A conductive thermal gradient of 139°C/km, at a depth of 400 m, was determined from the third well, drilled 0.6 km west of that fault zone. These data indicate that the Platanares geothermal area holds considerable promise for electrical generation by moderate- to high-temperature geothermal fluids.

Introduction

Most hydrothermal systems in Central America, such as those at Momotombo, Nicaragua; Miravalles, Costa Rica; and Ahuachapán, El Salvador, are associated with Recent volcanic fields with intermediate to silicic lavas and pyroclastic rocks. The numerous geothermal manifestations scattered throughout central and western Honduras are not, however, associated with similar young volcanoes. The youngest rocks of these compositions in Honduras are mid- to late Tertiary. Central Honduras is crossed by a discontinuous line of Quaternary basaltic cinder cones and lava flows, but none of these young volcanic areas offer the promise of hydrothermal systems of commercial quality.

Surface manifestations of the hydrothermal systems of Honduras are associated with late Cenozoic faults and crustal extension, much like those of the Basin-and-Range Province of

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the western United States. Meteoric waters, which circulate deeply along fault systems, fill isolated geothermal reservoirs that feed hot springs and boiling springs, where silica sinter and carbonate travertine are deposited (Flores, 1980; Goff et al., 1987b).

Ten geothermal sites were investigated in Honduras as part of a reconnaissance study by Los Alamos, Empresa Nacional de Energia Electrica de Honduras, and the U.S. Geological Survey; this study included investigations of the geology of Azacualpa (Eppler et al., 1987b), Pavana (Eppler et al., 1987a), Platanares (Heiken et al., 1986, 1987), and San Ignacio (Aldrich et al., 1987), and of the hydrogeochemistry of all ten sites (Goff et al., 1987b) (Fig. 1). Platanares was chosen for detailed investigation on the basis of preliminary geologic mapping and hydrogeochemical studies, which indicated reservoir temperatures of 225° to 240°C, the highest in Honduras. Since 1986, additional geologic and geochemical studies and gravity, self-potential, and resistivity surveys (Hoover and Pierce, 1988; Ander et al., 1991-this volume; Aiken et al., 1991-this volume) have been completed.

The Platanares geothermal area is located in west-central Honduras in the Departamento de Copán, 30 km east of the border with Guatemala and 16 km west of Santa Rosa de Copán, which is the provincial capital. The village of Platanares is located on a gravel terrace, a few tens of meters above the Quebrada del Agua Caliente, a canyon whose name reflects the presence of numerous hot springs, boiling springs, and fumaroles that issue from the banks and bed of the quebrada over a distance of about 3 km. The local terrain is rugged and ranges in elevation from 700 to 1300 m. The quebrada follows a fault zone, along which the faulted and brecciated rocks are easily eroded.

This work, funded by the U.S. Agency for International Development, followed earlier countrywide reconnaissance studies by the United Nations Development Program (Gislason, 1980) and GeothermEx, Inc. (1980).

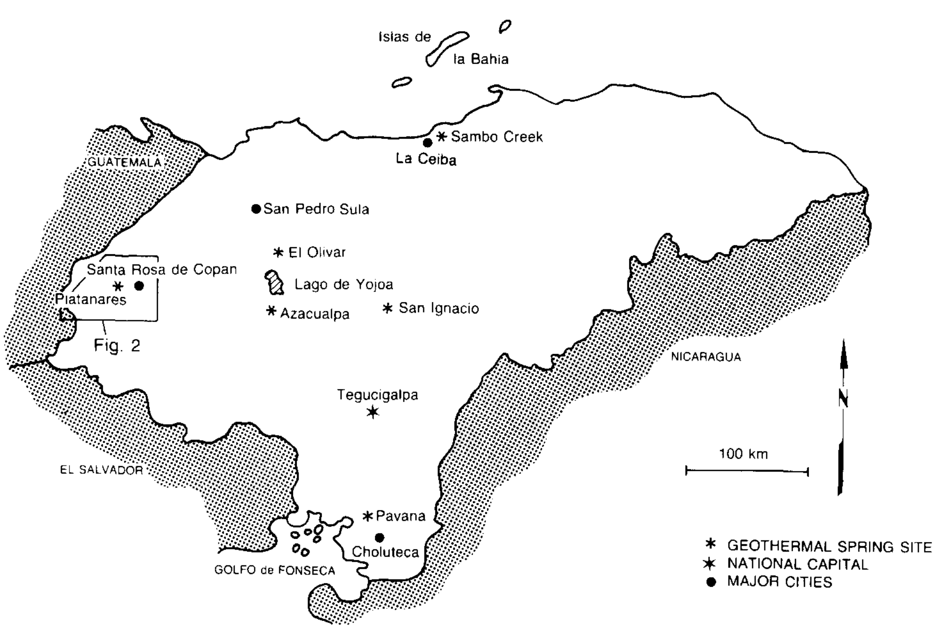

Fig. 1. Map showing geothermal areas investigated during the countrywide survey by Los Alamos, the U.S. Geological Survey, and Empresa Nacional de Energía Eléctrica.

Regional geologic setting

Western Honduras is a highland bounded by major left-lateral, strike-slip faults on the north, including the Motagua fault zone of Guatemala and Honduras, and the Jocotan-Chamelecón fault zone and the convergent plate margin of the Central American volcanic front on the southwest. These faults define the northwest corner of the Caribbean plate and form the northern boundary of the Chortis Block, a block of Paleozoic and younger continental crust (Horne and Finch, 1990). To the south, the Chortis block is in contact with younger crust associated with subduction of the Cocos plate along the Middle America trench (Burkart and Self, 1985). Extension and crustal thinning within the Chortis block are manifested as NW-trending grabens and rhomb grabens (cf. Mills et al., 1967; Williams and McBirney, 1969). This extension may be related to:

(1) eastward movement of the Caribbean plate while the NW corner (western Honduras) is pinned between the Cocos and America plates (Plafker, 1976);

(2) rotation of the trailing edge of the Caribbean plate around a bend in the Motagua and Jocotan-Chamelecón faults (rotation of the Chortis block) (Burkart and Self, 1985); or

(3) extension of lithosphere, forming N–S grabens and ENE-trending fractures with left-lateral strike-slip motion that formed "pull-apart" basins (Manton, 1987).

The Platanares geothermal area is in the middle of this tectonically complex block that

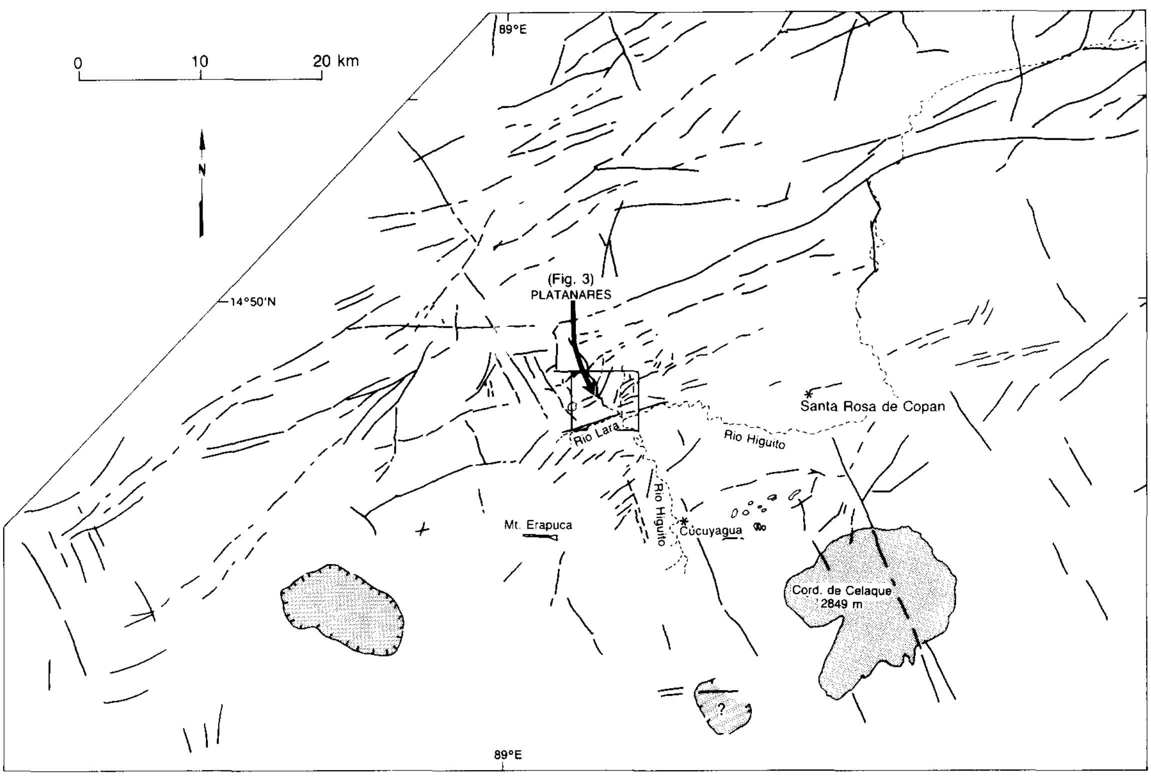

Fig. 2. Structure and lineament map of northwestern Honduras and eastern Guatemala, based upon interpretation of Seasat synthetic aperture radar and Landsat imagery, the geologic map of Honduras, and 1:50,000-scale topographic maps. Patterned areas are depressions that may be calderas, including the Cordillera de Celaque. The location of Platanares geothermal area is marked.

forms the NW corner of the Caribbean plate, 15 km south of the Chamelecón fault zone and near the northern boundary of a zone of extension with NNW-trending normal faults (Fig. 2). Immediately south of Platanares, the NNW-trending Río Higuito makes a 90° turn toward the east. As will be discussed later, we believe that this turn may be related to a major E – W fault. Alternatively, Manton (1987) interprets this bend as a reversal of a drainage that originally flowed to the northwest by uplift of the mountains behind Platanares. Twenty km SE of Platanares is the ~15-km-diameter highlands of the Cordillera de Celaque, which may be a late Tertiary resurgent caldera complex; vents at this caldera may have erupted large volumes of silicic tuff that crop out at Platanares. Mostly nonwelded pyroclastic flow deposits cover a large region around the Cordillera and bank up against what appears to have been a mid-Tertiary highland area near the present-day geothermal area.

Stratigraphy

Paleozoic (?) metamorphic rocks

The oldest rocks in the Platanares area are Paleozoic (?) metamorphic rocks exposed in

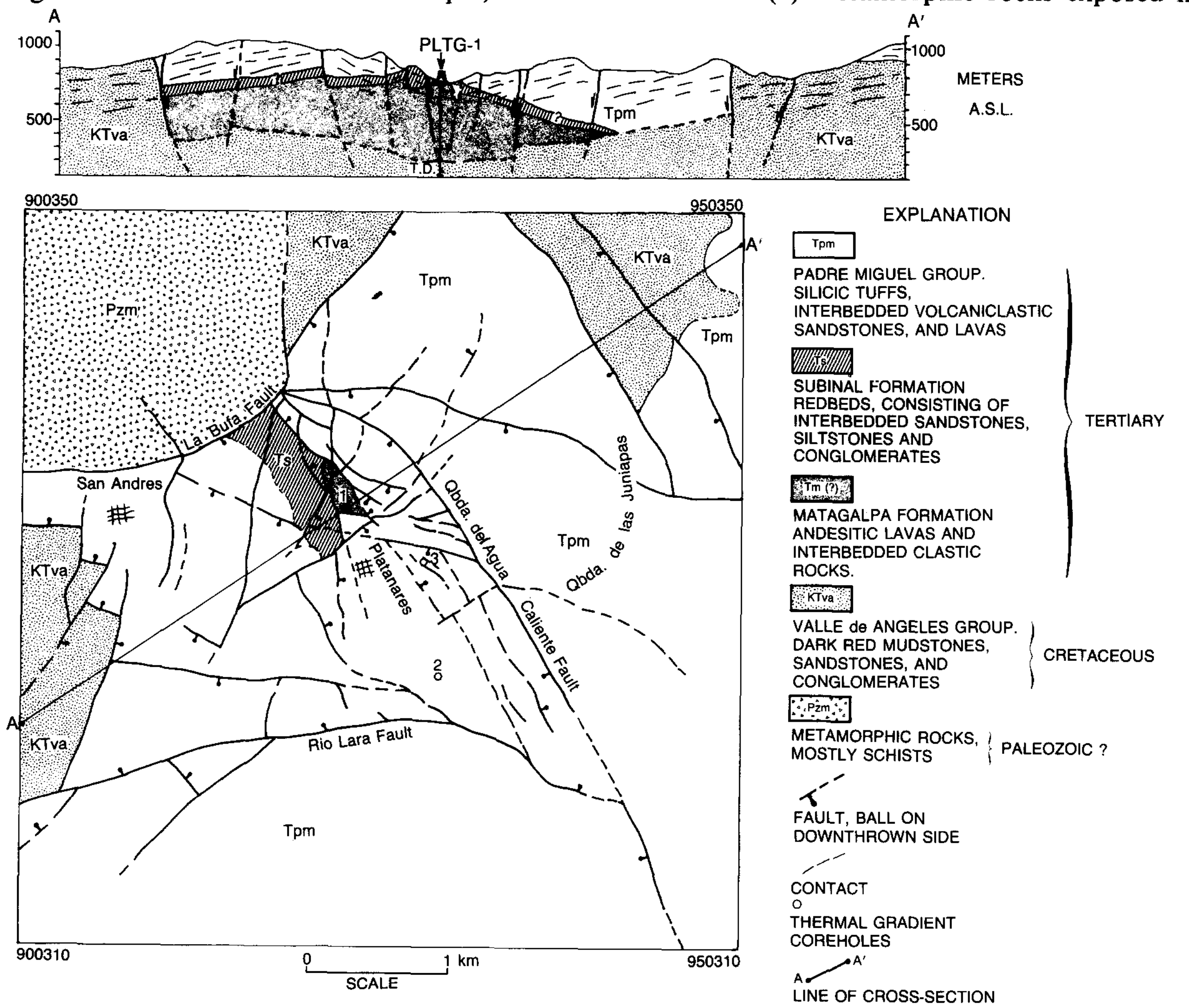

Fig. 3. Generalized geologic map and cross-section of the Platanares geothermal area. Larger-scale maps and cross-sections are available upon request from the authors.

the highland north of the hot springs. All contacts between the metamorphic sequence and younger rocks are along faults (Figs. 3 and 4). Elsewhere in Honduras, similar rock units have been termed Cacaguapa Schist (Fakundiny and Everett, 1976), Petén Schist, or "basement" (Finch, 1972; Horne et al., 1976; UNDP, 1972). The most common rock types are graphitic and muscovitic schists, metaquartzites, and phyllites. The metamorphic sequence has apparently been a highland at least since mid-Cretaceous time, because clasts of metaquartzite and schist are major components of adjacent Cretaceous and Tertiary redbeds. Conglomerates and sandstones interbedded with the Tertiary volcanic rocks also are composed mostly of metaquartzite and schist clasts from this highland.

Valle de Angeles Group redbeds

The Valle de Angeles Group redbeds (Mills et al., 1967; Finch, 1981) are exposed east, north, and west of Platanares and were penetrated at depths of 500 to 600 m during drilling near the center of the geothermal area (S. Goff et al., 1987). In this area, the redbeds consist of moderately- to poorly-bedded siltstone, pebbly coarse sandstone, coarse immature sandstone, and conglomerate. Most of the rocks are red, but locally the color is pale green or tan where hydrothermally altered. Total observed thickness in this area is at least 200 m. Based upon the chemical composition of hot spring waters at the site, it is inferred that a geothermal reservoir has equilibrated at 225°C, in fractured Valle de Angeles redbeds at an approximate depth of 1.2 to 1.5 km (Goff et al., 1987a). This inference implies that the minimum thickness of the Valle de Angeles Group at Platanares is 1000 m. Maximum observed thickness of the Group at the type locality may exceed 3000 m. The closest previously studied stratigraphic sections of the Valle de Angeles Group are in the Zacapa area, 80 km east of Platanares, where the sequence consists of upper and lower redbeds, separated in places by limestone and gypsum (Finch, 1972). These Valle de Angeles rocks are believed to be Late Cretaceous and Early Tertiary in age. Within the Zacapa Quadrangle the Valle de Angeles Group overlies the

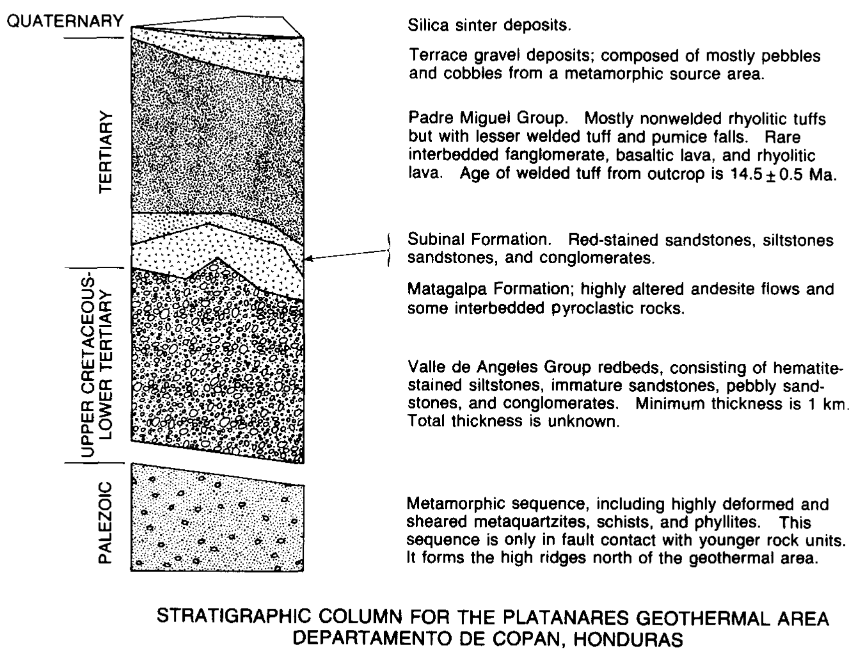

Fig. 4. Composite stratigraphic section of lithologic units in the Platanares geothermal area.

mid-Cretaceous Yojoa Group (limestones, shales, and redbeds), Jurassic to Early Cretaceous Honduras Group (sandstones and conglomerates), and Jurassic El Plan Formation (black shale and thin-bedded sandstone) (Finch, 1981; Horne and Finch, 1990). None of these older Mesozoic units crops out in the area of Platanares.

Valle de Angeles redbeds are difficult to distinguish from the younger redbeds of the Subinal Formation (described below). Both units contain immature sandstone: litharenite as well as pebbly immature sandstones, conglomerates, and siltstones. Some of the coarser clastic beds in both contain calcite cement. Thus, in drillcores and in the field, it is nearly impossible to identify a redbed sequence as either Valle de Angeles or Subinal without independent stratigraphic control. However, modal abundances of lithic clasts that make up most of these clastic rocks provide a means of discrimination. The Valle de Angeles sandstones and conglomerates contain 20% to 92% basalt clasts (Fig. 5). The Subinal Formation contains sandstones consisting of 65% to 93% metaquartzite and schist clasts, with only traces of basalt (Fig. 5).

Matagalpa Formation

With the exception of a few interbedded, thin tuff beds and sandstones, the Matagalpa Formation at Platanares consists of massive, silicified andesitic lavas. These lavas crop out along the bottom of the upper Quebrada del Agua Caliente (Fig. 3), where they are cut by quartz- and calcite-filled and partly open fractures. The andesites were penetrated by geothermal gradient wells PLTG-1 and -3, where they are 556 m and 263 m thick, respectively. PLTG-3 is only 680 m south of PLTG-1. The lavas were not encountered in well PLTG-2, which is about 1,360 m south of PLTG-1. This abrupt southward thinning of the lavas is reflected in a small positive gravity anomaly

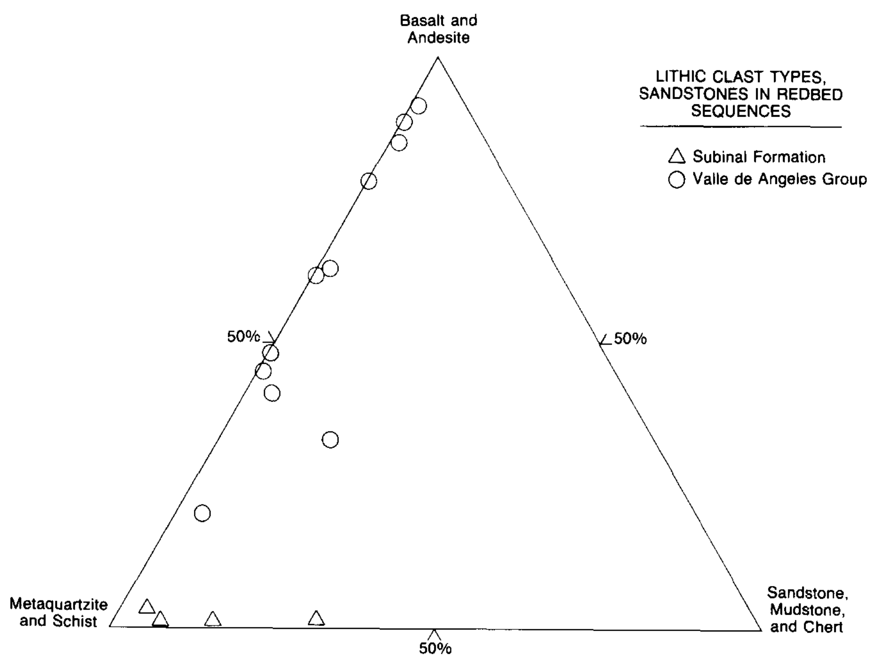

Fig. 5. Triangular diagram of lithic clast compositions from sandstone and conglomerate redbeds within the Cretaceous – Tertiary Valle de Angeles Group and Tertiary Subinal Formation. Based on 300-point modal analyses (with a spacing of 0.4 mm) of polished thin sections.

(Aiken et al., 1991-this volume), which is interpreted as a small stack of lava flows (see interpretive cross-section in Fig. 3).

The lavas are porphyritic, with 15% to 25%, 0.2- to 3-mm-long phenocrysts and glomerocrysts of plagioclase and mafic minerals in a coarse trachytic groundmass. All of the lavas seen in outcrop and sampled from drillcore are moderately to intensely hydrothermally altered and therefore descriptions of igneous textures are interpretative, based upon relict textures. Feldspars have been replaced by smectite, authigenic quartz, chlorite, and traces of calcite; mafic minerals have been altered to chlorite and magnetite. Veins are filled with authigenic quartz and biotite, chlorite, pyrite, stibnite, calcite, and other minerals (Bargar, 1991-this volume).

Our interpretation that these andesitic lavas are part of the mid-Tertiary Matagalpa Formation is based on similarity to a description of the formation in nearby Guatemala by Williams et al. (1964), where it consists of highly altered pyroxene-andesite flows and laharic breccias, and lesser flows of platy dacite. Such a sequence has been mapped in northwestern Honduras, where it overlies the Valle de Angeles Group and is, in turn, overlain by the tuffs of the Padre Miguel Group (Williams and McBirney, 1969). In Honduras, local relief on these rocks ranges from 100 m to 300 m, forming knobby ridges. Near Zacapa, 80 km east of Platanares, the Matagalpa Formation is up to 500 m thick (Finch, 1972).

Subinal Formation

An 80- to 120-m-thick redbed sequence, which is nearly identical in appearance to the older redbeds of the Valle de Angeles Group, unconformably overlies andesitic lavas of the Matagalpa Formation. The redbeds consist of red and green sandstones, siltstones, and conglomerates. As discussed earlier, the sandstones and conglomerates mostly consist of metaquartzite and schist clasts (Fig. 5). Most of the coarser clastic rocks are immature, with poorly sorted clasts in a matrix of grayish-purple silt. This clastic rock sequence, underlying the tuffs of the Padre Miguel Group, crops out along the west wall of the upper Quebrada de Agua Caliente and is penetrated by wells PLTG-2 and -3.

The Subinal Formation was defined first by Hirschmann (1963) in the Motagua Valley of Guatemala as red clastic strata between Paleozoic rocks and Tertiary volcanic rocks. Williams and McBirney (1969) applied the name to redbeds underlying the Padre Miguel Group in Honduras; these rocks are contemporaneous with the type Subinal section, and were deposited after the eruptions of Matagalpa andesitic lavas. Use of the name "Subinal" is based on stratigraphic position between Matagalpa andesitic lavas and the Padre Miguel Group tuffs. At Platanares, rocks assigned to the Subinal Formation are interpreted as alluvial fans derived from a metamorphic highland, which partly buried downfaulted piles of Matagalpa andesites and older rocks. Correlation of these redbeds with others described in Honduras and Guatemala, on the basis of clast types, is difficult because each of these fanglomerates or small basin-filling deposits has a unique source.

Padre Miguel Group

The Padre Miguel Group consists of mostly tuffs and tuffaceous sedimentary rocks that crop out over much of western Honduras and southwestern Guatemala; Williams and McBirney (1969) estimated the thickness of the group to be between 300 and 1000 m. Most of the tuffs are rhyolitic. The group designation refers to ignimbrite sequences visible over much of western Honduras, which may come from several caldera sources and whose depositional history spans a considerable length of time; K-Ar ages for the Padre Miguel Group range from 5 Ma to 30 Ma (F. McDowell, University of Texas, pers. commun., 1988; Williams and McBirney, 1969; Eppler et al., 1987a). Tuffs and associated minor lavas and sedimentary rocks of the Padre Miguel Group crop out over most of the Platanares geothermal area. At Platanares the thickness of this group varies, reaching a maximum of 310 m.

Although most of the tuffs at Platanares are nonwelded ignimbrites, one consists of 15% welded, flattened pumice clasts, 5% quartz, biotite, and hornblende phenocrysts, and 5% lithic clasts (andesitic lava) in a matrix of devitrified shards. Similar welded tuffs, possibly correlative, were sampled for K-Ar age determinations from outcrops along the Quebrada de las Juniapas and at a depth of 286 m in well PLTG-2. The dates, determined by E. McKee, of the U.S. Geological Survey are, respectively, 14.2 ± 0.5 Ma and 14.7 ± 0.5 Ma (Table 1).

Above the welded tuff sampled in PLTG-2 are at least eight tuff units, most of which are massive, nonwelded, white, cream-colored, or grey, fine-grained ignimbrites; these units range, in thickness, from about 5 m to 70 m. Most are vitric or vitric-lithic tuffs, with 5% to 20% phenocrysts of quartz, sanidine and lesser plagioclase, biotite, hornblende, and ilmenite; pumice lapilli up to 1 cm long are in a matrix of shards (20 μm to 500 μm long). These tuffs also contain a trace to 20% lithic clasts (mostly basalt and andesite lava and clasts of older tuffs). Accretionary lapilli, up to 1 cm in diameter, are common in some of the finer-grained ignimbrites.

Beds of nonwelded tuffs, with thicknesses of 0.5 to 10 m, are exposed along the Río Lara (top of the section south of the Río Lara, middle of the section to the north of the Río; Fig. 3) and near the top of the section penetrated by well PLTG-2. Most are normally graded, with lava lithic clasts and coarser pumice clasts near the base, grading up into fine ash. Interbedded with these tuffs are concentrations of lithic clasts and matrix-supported breccias, which may be volcanic mudflow deposits; some of the breccias are concentrated in 1- to 3-m-deep channels. Within the tuffs penetrated during drilling, there are interbedded "muddy sandstones" associated with sheared rock. In outcrops along the Quebrada de Agua Caliente, such "sandstones" are seen to be clastic dikes that formed along normal faults in the tuffs.

Pumice fall deposits are rare and are interbedded with nonwelded, fine-grained ignimbrites along the Quebrada de Agua Caliente. Also included in the Padre Miguel Group are poorly bedded, reddish fanglomerates a few meters thick; these are found only near fault contacts with the metamorphic sequence and not south of the Río Lara.

TABLE 1

Potassium-argon ages of welded tuffs from the Platanares geothermal area, Departamento de Copán, Honduras

Sample number	Rock type	Material dated	K_2O (wt.%)	$^{40}Ar^{rad}$ (mol/g)	$^{40}Ar^{rad}$ (%)	Age (Ma)
PTLG-2	Rhyolitic welded tuff	Biotite	8.19	1.7369×10^{-10}	65.0	14.7 ± 0.5
JUNIAPA	Rhyolitic welded tuff	Biotite	7.31	1.50179×10^{-10}	40.5	14.2 ± 0.5

Note: all sample preparation and analytical work was done at the U.S. Geological Survey laboratories in Flagstaff, Arizona and Menlo Park, using the techniques described in Dalrymple and Lanphere (1969). We analyzed potassium after lithium metaborate fusion, using a flame photometer, with the lithium serving as the internal standard (Ingamells, 1970). Error, shown as the ± value, is the estimate of the standard deviation of analytical precision. K-Ar age was calculated using the constants for the radioactive decay and abundance of ^{40}Ar recommended by the International Union of Geological Sciences Subcommision on Geochronology (Steiger and Jäger, 1977). These constants are: $Y_t = 0.581 \times 10^{-10} yr^{-1}$, $Y_t = 4.962 \times 10^{-10} yr^{-1}$, and $^{40}K/K_{total} = 1.167 \times 10^{-4}$ mol/mol. Age determination provided by E.H. McKee, U.S. Geological Survey.

Many of the tuffs are silicified along major faults. These rocks are brittle and crossed by abundant open and calcite-filled fractures. Silicified tuffs locally form erosion-resistant ridges. Many of the tuffs penetrated during drilling of wells PLTG-2 and PLTG-3 are silicified, and only relict textures remain.

A few lava flows have been identified at Platanares within the Padre Miguel Group; rhyolitic lava flow breccia crops out along and near the Quebrada de las Juniapas and basaltic lava crops out along the Río Lara. No vent areas have been identified for these lavas.

Sources for the tuffs of the Padre Miguel Group at Platanares are not known. However, the massive, nonwelded ignimbrites extend southward to the Cordillera de Celaque, a propable caldera complex 20 km south of Platanares. The tuffs at Celaque are lithologically similar to those at Platanares, suggesting that this caldera complex may be the source for the ignimbrites at Platanares. If this interpretation is correct, then pyroclastic flows from the Celaque area flowed north, burying a complex terrain at Platanares that consisted of a highland of Paleozoic metamorphic rocks and Mesozoic redbeds overlain by mid-Tertiary andesite flows and alluvial fans. As mentioned above, the Padre Miguel Group in western Honduras and eastern Guatemala ranges in age from 5 to 30 Ma; the range of ages at Platanares is unknown, but tuffs we dated near the base of the section have ages of about 14.5 Ma. There may be multiple sources for the Padre Miguel tuffs, such as a nearby silicic lava field of unknown location, but field work is needed to identify all possible sources, including calderas other than that inferred at the Cordillera de Celaque. Important to geothermal models of Platanares, however, is the fact that these volcanic rocks are relatively old and thus their source magma bodies have solidified and presumably cooled to background crustal temperatures, whether they are located beneath Platanares or some distance away (Smith and Shaw, 1975).

Terrace gravels

The village of Platanares is located on a 1.0- by 1.25 km stream terrace, which forms the upper part of the southwestern slopes of the Quebrada del Agua Caliente. The terrace slopes about 3.5° to the southeast from an elevation of 800 m to 740 m. Terrace gravels form an irregular deposit, up to 60 m thick, which overlies a surface of moderate relief eroded into tuffs of the Padre Miguel Group. The gravels are poorly bedded and consist of angular to subangular cobbles and pebbles, mostly quartzite, schist, andesite and tuff. The upper third of the deposit is stained red by hematite.

A lower-elevation terrace is present in the southeast part of the mapped area, near the confluence of the Quebrada del Agua Caliente with the Río Higuito. This terrace slopes gently to the southeast at an average elevation of about 700 m.

Silica sinter deposits

Deposits of siliceous sinter and conglomerates cemented by silica sinter unconformably overlie tuffs and lavas along the Quebrada del Agua Caliente. The conglomerates are lithogically similar to modern stream gravels and consist of cobbles and pebbles from metamorphic, volcanic (lava), and redbed clastic sources. The sinter deposits form overhanging ledges and locally form impermeable caprocks over hot springs. Modern stream gravels in the main hot spring area are now being cemented by silica from hot springs. One of the sinter deposits is cut by a fault in the upper Quebrada del Agua Caliente.

Hot springs and fumaroles

Most hot springs and all of the boiling springs at Platanares lie within a 0.5-1.0-km-wide, NW-trending fault and fracture zone whose principal physiographic expression is Quebrada de Agua Caliente. A few warm springs discharge from silicified, fractured tuffs along the Río Lara. Most springs vent at the bottom of the quebrada but some discharge occurs from fractured tuffs as high as 35 m above stream level. At a waterfall, which flows over a fault scarp, hot springs flow along bedding planes in silicified tuff. For maps and detailed descriptions of the springs, see Heiken et al. (1986) and Goff et al. (1987b); (Janik et al., 1991-this volume).

Structural framework

Most stratification in the tuffs of the Padre Miguel Group dips 15° to 30° to the south; attitudes diverge from this regional dip near faults and landslides. Bedding within the Valle de Angeles redbeds dips generally to the south or southwest, at 15° to nearly vertical.

An area of about 5 km^2, bounded by La Bufa fault on the northwest, a possible fault parallel to the Río Lara on the south, unnamed faults on the west, and the Quebrada del Agua Caliente fault on the east is highly disrupted by normal faults (Fig. 3); slickenside orientations indicate that a number of high-angle faults have predominantly strike-slip motion. The Tertiary volcanic rocks, including the andesitic lavas of the Matagalpa Formation and the tuffs of the Padre Miguel Group, are downfaulted against Cretaceous-Tertiary redbeds of the Valle de Angeles Group, defining a NW-trending graben. The graben is terminated on the north by the E – W to NE-trending La Bufa fault. All hot springs of the Platanares area lie south of this fault. A detailed structural map of the center of this area has been prepared by Aldrich et al. (1991-this volume).

Although poorly exposed in outcrop, a major E-trending fault may parallel the Río Lara ("Rio Lara Fault" on Fig. 3). North of the Río Lara, there are numerous faults and hot springs, whereas to the south there is little deformation other than the gentle regional dip and no hot springs are visible. Eastward from the mouth of the Río Lara, the Río Higuito takes a 90° bend and follows the extension of the apparent Río Lara fault (Fig. 2). Well PLTG-2, drilled 0.5 km north of the Río Lara, penetrates a sequence of heavily fractured and faulted rocks and clastic dikes.

The main trace of the Quebrada del Agua Caliente fault is parallel to the quebrada of the same name and has a strong physiographic expression, including escarpments along alluvial terraces at the mouth of the quebrada. Twenty-eight groups of hot and boiling springs rise along NW-trending faults and fractures of this fault zone.

Nearly all of the rock units sampled by drilling are fractured and faulted. The characteristics of all fracture sets within rock units sampled by drilling are controlled by lithology. Steeply dipping fractures (dip = 60° to 90°) are found within hydrothermally altered lavas and welded tuff only, whereas those with low dips are found in all rock types, and are most abundant in siltstones. Fractures filled with authigenic minerals are most common in such competent rock units as the andesitic lavas.

Hydrothermal alteration

Three exploration coreholes (PLTG-1, PLTG-2, and PLTG-3) were drilled to depths of 650 m, 428 m, and 679 m, respectively at Platanares to provide data on lithologies, temperature gradients, physical properties, and chemical composition of fluids (Figs. 3 and 6) (S. Goff et al., 1987, 1988; Goff et al., 1991-this volume).

PLTG-1 and PLTG-3 are located within the main NW-trending fault zone close to the Quebrada de Agua Caliente (Fig. 3). PLTG-1 encountered hot water at 252 m and from 625 m to 644 m. PLTG-3, located 650 m SE of PLTG-1, encountered hot water at depths of 459 m and 622 m to 635 m (Fig. 7). Rock units sampled by coring in both wells 1 and 3 are hydrothermally altered.

PLTG-2, located 1 km south of PLTG-1 and away from the main hot spring area, shows a conductive geothermal gradient of 139°C/km

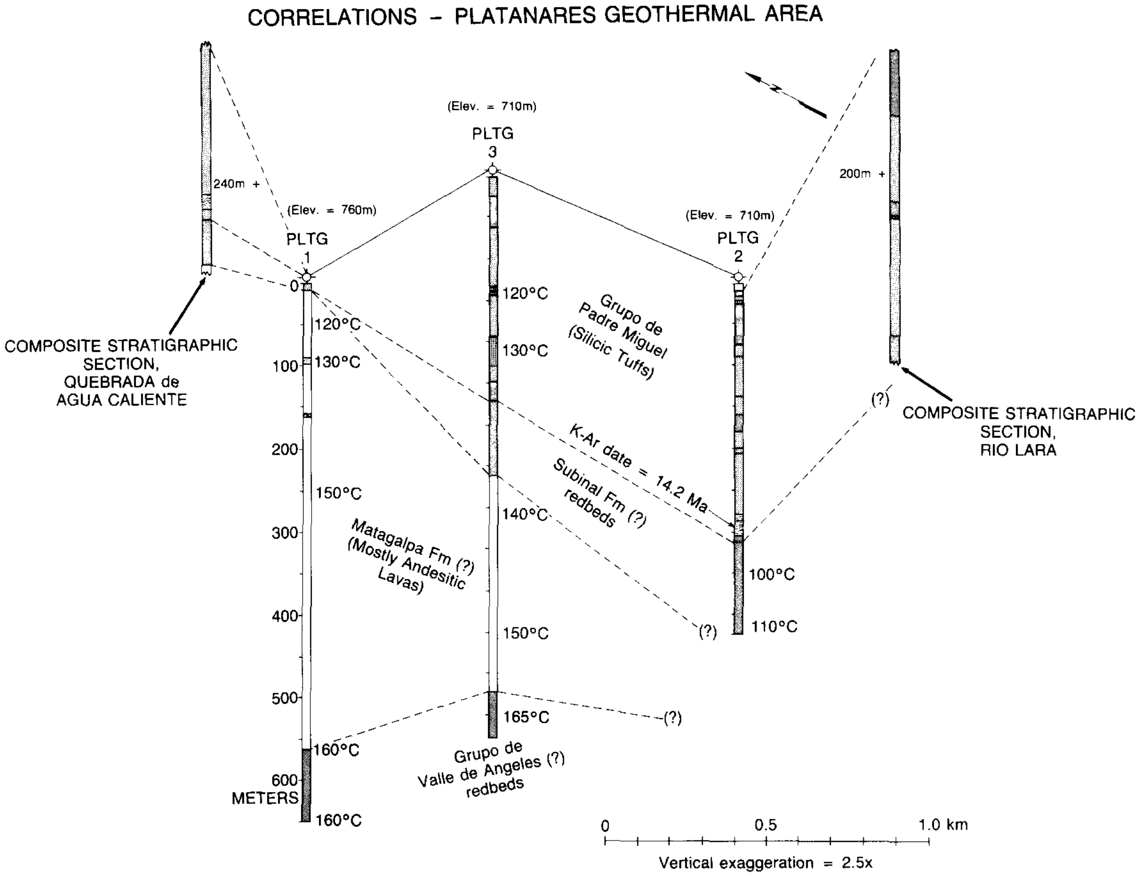

Fig. 6. Fence diagram of stratigraphy of the Platanares geothermal area, based upon composite stratigraphic sections (outcrops) and three geothermal gradient coreholes. Patterns within the Matagalpa Formation: white = lavas and stippled = interbedded tuffs. Patterns within the Padre Miguel Group; wavy pattern = welded tuff, light stipple = massive, nonwelded tuffs, and coarse stipple = bedded tuffs.

at a depth of 400 m (linear gradients of 239°C/km from 0 to 150 m and 139°C from 170 to 400 m; Meert and Smith, 1991-this volume) (Fig. 7). The rock units penetrated by this well show little hydrothermal alteration.

Methods and procedure

Cores from PLTG-1 were sampled every 10 m and those from PLTG-2 and PLTG-3 were sampled every 20 m (most were representative of the whole rock and some samples are of veins). Thin sections were cut from each sample and ion-etched before petrographic, EDS analyses on a scanning electron microscope and electron microprobe analyses. Bulk rock samples from each interval were crushed and the powders ground to 5 μm before analysis on a Siemens D500 automated X-ray diffractometer at a step of 0.02, a rate of 1.0 s/step, scanned from 2 to 37° 2-theta, under Cu Ka radiation. Instrument settings were 50 kV accelerating voltage and 40 mA tube current. Mineral phases were identified by optical methods, XRD, and energy-dispersive X-ray spectrometry during examination with a scanning electron microscope. The weight percentages of mineral phases in Figure 7 are semi-quantitative and were calculated using a program (Quant V) that uses peak intensities of the sample, compared with those of standards.

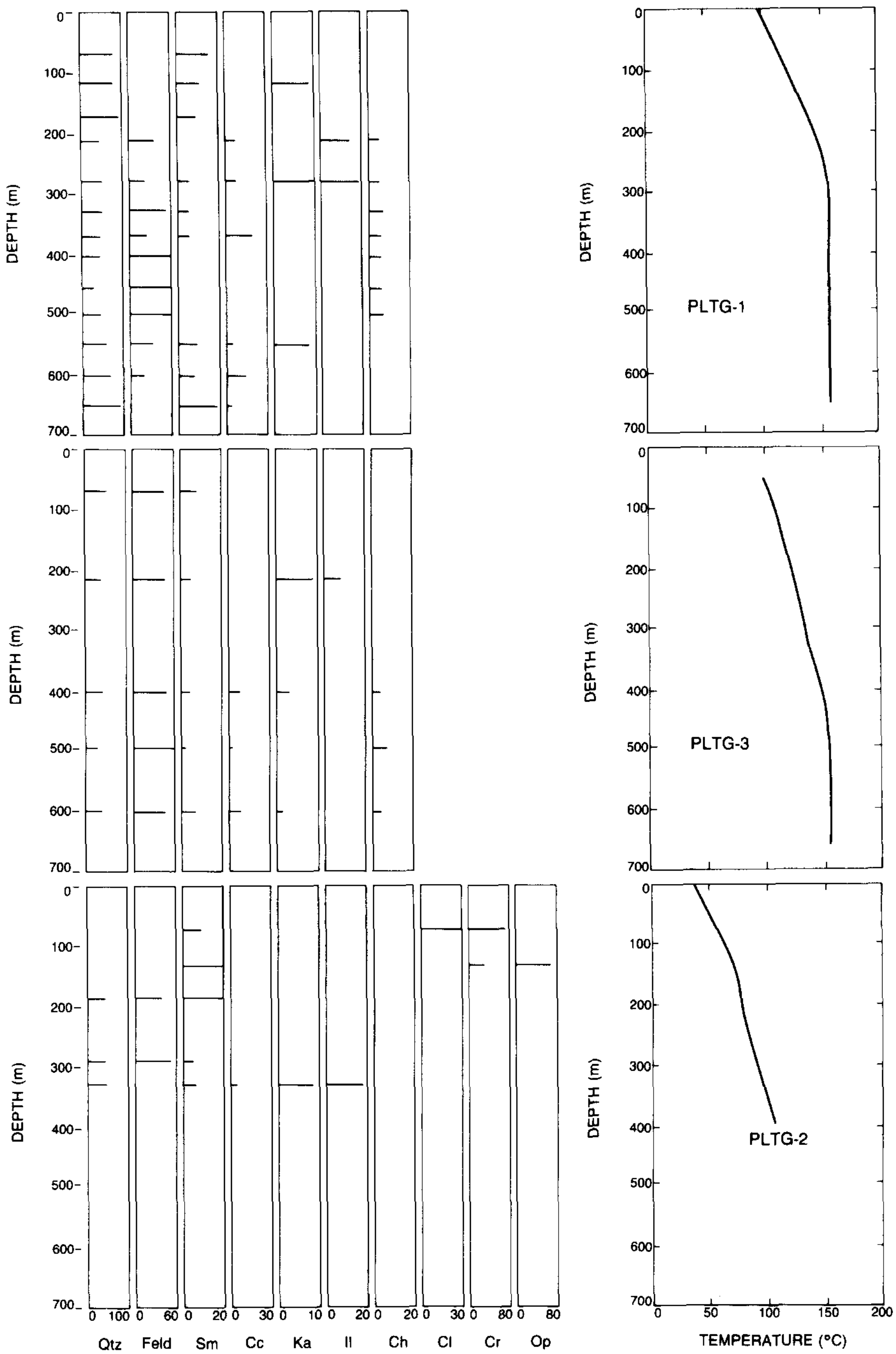

Fig. 7. Variation of minerals from bulk rock samples with depth in three geothermal gradient coreholes ("host rock" samples). Qtz = quartz, Feld = feldspar, Sm = smectite, Cc = calcite, Ka = kaolinite, Il = illite, Ch = chlorite, Cl = clinoptilolite, Cr = cristobalite, and Op = opal C-T. Values are in weight per cent. Temperature measurements (from D. Smith, University of Florida and onsite drilling teams, unpublished reports) were made at 30-m intervals, both during descent and ascent of the probe. Samples representative of the major lithologic units were collected for thermal conductivity values.

Selected, homogenized rock powders (177 to 40 μm) of volcanic rocks were analyzed by X-ray fluorescence, following the procedures of Valentine (1983); the data appear in Table 2.

Hydrothermal mineralogy – PLTG-1

Principal hydrothermal minerals include quartz, smectite, mixed-layer illite-smectite, illite, kaolinite, pyrite, marcasite, calcite, fluorite, and minor to trace amounts of laumontite, rutile, stibnite, and sphalerite. Phenocrysts within andesitic lavas are partly to completely altered to smectite, mixed-layer illite-smectite, illite, and trace amounts of kaolinite. The groundmass minerals of lava samples are altered to quartz, smectite, illite, and kaolinite (also identified by Bargar, this volume). Smectite is more or less evenly distributed throughout the groundmass, whereas kaolinite and illite occur as small clumps. Chlorite and barite are present as discontinuous veinlets, and replaces mafic minerals; it is most abundant from depths of 390 m to 540 m (Fig. 7). There is a weak vertical zonation of alteration minerals, with decreasing smectite and increasing chlorite with depth. Allophane is present at all depths and makes up as much as 5 volume per cent. Near a major thermal-water entry at a depth of 252 m, there is an increase in the volume of kaolinite and illite (15 and 20 wt. %). Insufficient time for work on alteration ages precludes any discussion on which of the alteration products are related to an older or present-day hydrothermal system. The kaolinite-illite in the 200 – 300-m interval suggests that at least some of the alteration was caused by the present hydrothermal system. The severity of alteration is evident in the chemical analyses presented in Table 2. Although the entire volcanic sequence in PLTG-1 is andesitic, contents of divalent and monovalent metals are variable and the totals are < 94 wt. %, reflecting alteration with hydrous minerals.

Pyrite occurs throughout the entire 650-m-thick section, principally as veinlets up to 1 mm wide. Typically it forms loose, irregular aggregates of fine-grained, euhedral crystals; in the uppermost 100 m of the section, pyrite is intergrown with marcasite. Open fractures at a depth of 70 m are lined with smectite, quartz, pyrite, marcasite, and stibnite. The marcasite occurs as clusters of cockscomb crystals and the stibnite forms sprays of acicular crystals up to 18 mm long.

Veins of quartz, calcite, and fluorite are present at all depths up to 3 cm wide. A 2-cm-thick quartz vein at a depth of 150 m contains vugs

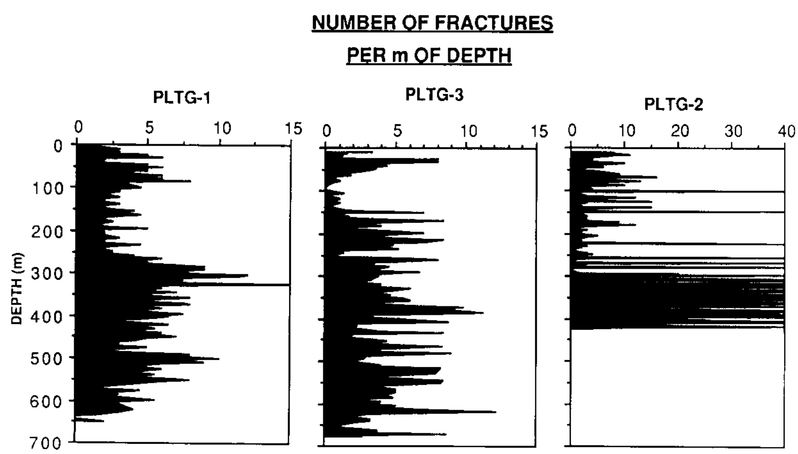

Fig. 8. Variation of open fracture density, with depth, in three geothermal gradient coreholes, Platanares Geothermal Site. Fractures were measured along all of the cores collected (continuous coring) and averaged at 2-m intervals.

TABLE 2

Whole rock chemical analyses of selected core samples of volcanic rocks, Platanares, Honduras; major elements in wt.% and trace elements in ppm[a]

Sample No.[b]:	PLTG-1 100.0	PLTG-1 200.0	PLTG-1 500.0	PLTG-2 70.5	PLTG-2 150.0	PLTG-2 271.0	PLTG-3 210.0	PLTG-3 400.5	PLTG-3 480.95	PLTG-3 588.15
Formation :	Matagalpa	Matagalpa	Matagalpa	Padre Miguel	Padre Miguel	Padre Miguel	Padre Miguel	Matagalpa	Matagalpa	Matagalpa
Rock type[c] :	Andesite	Andesite	Andesite	Ignimbrite	Ignimbrite	Ignimbrite	Ignimbrite	Andesite	Andesite	Andesite
SiO_2	66.01	64.74	62.29	80.45	68.84	73.03	72.10	63.15	64.63	62.37
TiO_2	0.46	0.64	0.64	0.33	0.27	0.38	0.37	0.63	0.63	0.61
Al_2O_3	11.06	14.52	14.75	9.39	15.42	12.85	15.09	15.04	15.59	14.85
Fe_2O_3	1.24	3.36	3.66	1.91	2.54	1.33	1.47	3.77	3.93	3.63
MnO	0.05	0.04	0.06	0.03	0.05	0.03	0.02	0.06	0.06	0.05
MgO	0.33	0.85	1.20	0.13	0.16	0.19	0.19	1.08	1.25	0.78
CaO	9.29	4.72	2.23	0.92	1.40	0.21	1.42	4.30	2.30	5.01
K_2O	2.56	2.94	2.50	1.83	5.14	8.27	3.67	3.13	2.52	2.49
Na_2O	0.21	1.04	4.96	1.36	2.08	0.73	3.28	3.11	5.04	4.03
P_2O_5	0.21	0.24	0.24	0.02	0.02	0.06	0.11	0.25	0.23	0.23
Totals	91.43	93.09	90.03	96.34	95.88	97.34	97.71	94.50	96.18	94.04
Ba	244	813	842	897	643	749	819	859	766	1111
Rb	82	74	68	65	142	205	87	102	65	55
Sr	448	296	455	127	151	56	189	389	355	487
V	36	46	46	9	15	12	37	53	39	62
Cr	9	9	10	2	19		1	15	8	5
Ni	10	4	9	5	16	10	20	10	7	
Zn	47	63	72	49	97	42	38	66	71	64
Y	14	16	14	22	56	37	17	17	16	5
Zr	168	228	236	169	255	262	192	233	238	237
Nb	20	21	23	19	21	19	20	21	21	21

[a] Analyst: G. Luedemann, LANL; XRF spectroscopy.
[b] Sample number shows depth.
[c] All samples exhibit varying degrees of alteration.

lined with fluorite crystals. Other veins containing calcite and fluorite are typically narrower, less than 5 mm wide.

A sample of andesitic wall rock adjacent to open fractures partly filled with stibnite, pyrite, and marcasite (depth = 75 m) contains < 6 ppb Au, 18.3 ppm Sb, 91 ppm Zn, 42 ppm As and < 3 ppm Ag. Vein quartz from a depth of 252 m (a major water entry) contains 3.1 ppm Au, 374 ppm Sb, 26 ppm Zn, 2900 ppm As, 8.5 ppm Ag, 1.8% Ba, 3000 ppm Mo, and 17 ppm Se (instrumental neutron activation analyses by S. Garcia, Los Alamos). A limonitic jasperoid from a fault SE of the Quebrada de las Juniapas contains < 6 ppb Au but 47 ppm As and 11 ppm Sb.

Hydrothermal mineralogy – PLTG-2

Hydrothermal minerals identified in the rocks of PLTG-2 contain smectite, mixed-layer illite-smectite, quartz, cristobalite, opal-CT, clinoptilolite, and minor calcite, kaolinite, illite, and chlorite. The uppermost 150 m of the section contains opal C-T and varying amounts of cristobalite and clinoptilolite. From depths of 150 m to 310 m, there is an argillic assemblage consisting of smectite, quartz, and sparse kaolinite. The argillic assemblage is better-developed with depth and predominates below 180 m. At a depth of 271 m there is minor chlorite, and below 320 m illite is more abundant, suggesting a transition to a more phyllic assemblage. Chemically, the tuffs of PLTG-2 show weak to moderate alteration. The least altered sample (depth = 150 m) might be classed as a rhyodacite (67% SiO_2). The other samples show silicification and potassic alteration (Table 2).

Hydrothermal mineralogy – PLTG-3

Within the third and deepest corehole the principal hydrothermal alteration minerals are quartz, smectite, mixed-layer illite-smectite, and minor to trace amounts of kaolinite, calcite, illite, and chlorite. The uppermost 210 m is silicified and weakly altered to an argillic assemblage. A tuff sample from the bottom of the Padre Miguel section shows little alteration and has a rhyolitic composition (Table 2). Below this depth, quartz, smectite, illite, and rare kaolinite are the dominant phases; however, this assemblage continues only to 250 m where smectite and minor kaolinite are once again dominant to the bottom of the hole at 679 m. There is a trace of chlorite at a depth of 400 m. The andesites of PLTG-3 show less alteration than those in PLTG-1.

Pyrite is lacking in the tuffs (surface to a depth of 271 m) but is present in andesitic lavas (depth = 362 m to 622 m), where it occurs as disseminated crystals and discontinuous veinlets. At a depth of 380.5 m, a quartz vein contained acicular crystals of berthierite ($FeSb_2S_4$). The wall rock adjacent to this vein contains 490 ppb Au, 550 ppm As, 17 ppm Sb, 800 ppm Ba, 130 ppm Zn, and 2 ppm Ag (INAA analysis).

Veinlets of anhydrite are present in the upper 30 m of PLTG-3, but the remainder of the tuff section (30 – 271 m) lacks anhydrite veins. The andesitic lavas (364 – 622 m) contain numerous veins, up to 5 mm wide, of quartz, calcite, and clay. Calcite veins, up to 2 cm wide, occur at depths of 565 and 645 m.

Surface hydrothermal alteration

Areas of surface alteration are similar to the alteration encountered in the coreholes; mostly silicification and argillic in character. There are two mines near the Platanares geothermal area; the San Andrés gold mine and the El Quetzal antimony mine (Roberts and Irving, 1957). The San Andrés mine is producing from ore hosted in quartz veins that are found in lavas and tuffs of the Padre Miguel Group and Matagalpa Formation. A sample from the ore horizon contained quartz, cinnabar, and pyrite (XRD analysis) as well as visible gold flakes.

The El Quetzal mine is located about 3.2 km NNW of the village of San Andrés. The ore is hosted in calcite and quartz veins, which appear to be associated with Tertiary (?) diorite sills and dikes that intrude the Paleozoic schists (Goff et al., 1991-this volume). The hydrothermal system responsible for these deposits appears to have been volcanogenic and related to the Matagalpa andesitic composite cones; it does not appear to be related in any way to the present-day hydrothermal system, which is related to extensional and strike-slip faults.

Discussion

The Platanares geothermal area is located near the intersection of major structural elements of western Honduras, a group of ENE-trending, sinistral strike-slip faults that form the northern boundary of the Chortis block and NW-trending normal faults formed during the extension that has thinned this block during the past 10 m.y. (Mills et al., 1967). Cretaceous and Tertiary redbeds of unknown thickness overlie metamorphic basement and appear to serve as the major geothermal reservoir rock. They, in turn, are overlain by a sequence of Oligocene to Miocene volcanic and sedimentary rocks, including andesitic lavas, a thin fanglomerate, and a group of nonwelded and welded ignimbrites. Normal faults offset all of the Tertiary rocks and appear to offset terrace gravels of probable Quaternary age. Boiling springs are located along fractures of the NW-trending fault system. Most hot springs, surface patches of intense hydrothermal alteration, and siliceous sinter deposits occur within an area of about 5 km^2. Beneath this area, a geothermal reservoir is inferred to be located in redbeds of the Valle de Angeles Group, at a depth of 1.2 to 1.5 km, and at a temperature of 225°C (Goff et al., 1987a, 1991-this issue). Two of the three coreholes encountered a 165°C reservoir at shallower depths.

None of the volcanic rocks within this area appear to be Quaternary; two welded tuffs from the lower part of the Padre Miguel Group were dated at 14.2 and 14.7 Ma and the andesitic lavas are older. There is no evidence for a magmatic heat source for this geothermal system. The volcanic rocks, including the rhyolitic ignimbrites, are all over 14 m.y. old, precluding a magmatic heat source (interpretation based on thermal models by Smith and Shaw, 1975). All thermal springs are located along normal faults in a region of extensional tectonics, suggesting that the system is similar to those of the Basin-and-Range province of the United States. The geothermal gradient hole drilling at Platanares indicates that there is a considerable geothermal resource there and that it should be developed by production drilling.

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