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Geologic Model of The Miravalles Geothermal Field, Costa Rica

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ABSTRACT

The Miravalles geothermal field is located on the southwestern flank of the Miravalles volcano, within a 14 km diameter semi-circular structure known as the Guayabo Caldera.

Based on the information obtained from drilling fifty-two deep wells, a geologic model, which encompasses lithostratigraphic, structural and hydrothermal mineral alteration data has been generated.

Ten stratigraphic units related to the formation and filling of the caldera, including pyroclastic materials, lavas, debris avalanches and lacustrine deposits, have been defined.

The permeability of the field is mainly secondary in nature, controlled by structural systems striking NW-SE, N-S, NE-SW and E-W, due to a distensive tectonic setting that has formed a series of horsts and grabens in the deep units.

The use of illite and epidote as high temperature indicating minerals, along with the 220°C isotherm, has contributed to the understanding of the thermal conditions of the field, observing a good correlation in the central sector and varying towards the field boundaries, where the data indicate a marked cooling.

1. INTRODUCTION

Costa Rica is located at the southern extreme of Central America, in the zone of interaction between the Cocos and Caribbean plates that has generated an internal magmatic arc, in which, the Guanacaste Volcanic Cordillera comprises the northwestern segment (Figure 1). Miravalles volcano, with an elevation of 2028 m a.s.l. is the highest peak of this cordillera and was formed in the northeastern part of a 14 km diameter semicircular structure, known as the Guayabo Caldera.

Within this caldera, over the past three decades, different geoscientific studies have culminated in the development of the Miravalles Geothermal Field, with an installed capacity of 163 MWe.

Based on the information acquired from 52 deep wells and field geology, a geologic model, which includes lithostratigraphic, structural, mineralogical and direct temperature measurements, is presented. A series of geologic profiles that integrate the information obtained has been created to facilitate the interpretation of this model.

Lithostratigraphically, ten units, composed mainly of pyroclastic, lava, debris flow and lacustrine deposits, dating from the Miocene to the Holocene, are described.

The location of structures has been defined based on geophysical, photogeologic and field studies, whereas relative fault movements are modelled from the stratigraphic correlations between the wells.

To illustrate the thermal conditions of the field, the 220°C isotherm (as a parameter representing commercial temperature) and the first appearances of epidote and illite have been used, given their ample spatial field distribution, and the temperatures at which they are observed in the field. Epidote is used as a high temperature indicator; illite, given its rapid response to thermal changes, is used as an indicator of current temperature conditions.

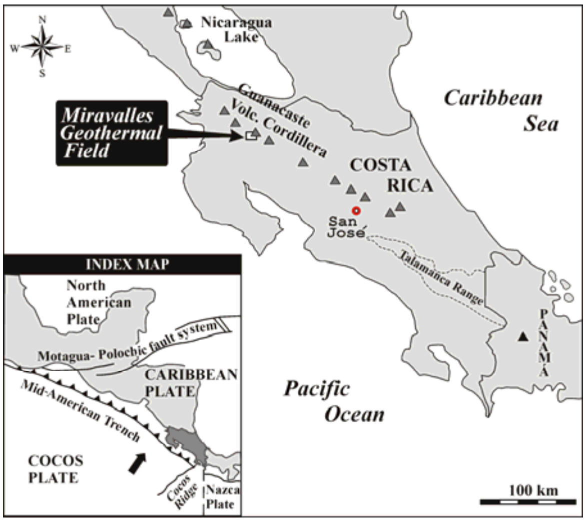

Figure 1: Location map showing Costa Rica and the Miravalles Geothermal Field.

2. STRATIGRAPHIC SEQUENCE

The rock sequence within and around the Guayabo Caldera, as well as that described in the deep wells includes a series of stratigraphic units related to processes that occurred before, during and after the formation of the aforementioned structure (Figure 2). In the wells drilled, the majority of these rocks show strong hydrothermal alteration, which makes it difficult, in some cases, to recognize the original textures.

2.1 Deep Lava Unit (DLU)

It is composed of a lava flow sequence originated from emission centres possibly related to a paleo-volcanic arc. These rocks are predominantly andesitic and are observed only in the bottom section of well PGM-15, between 2500 and 3022 meters depth.

In the study area there are no outcrops correlated with this unit, however, due to its stratigraphic position, it is interpreted as the local basement rock, and could be associated with Tertiary rocks (Aguacate Group).

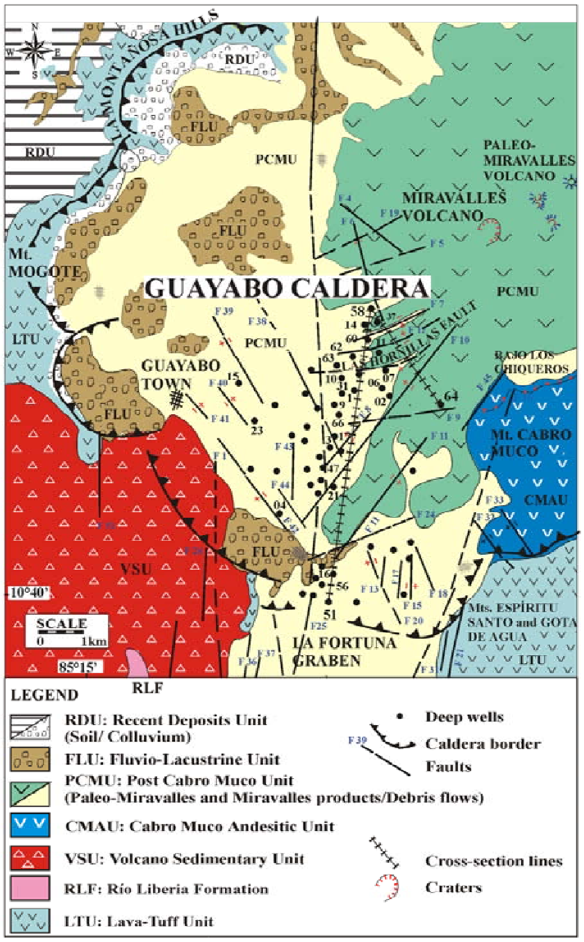

Figure 2. Geologic map of the Guayabo Caldera.

2.2 Ignimbrite Unit (IU)

It is composed of pyroclastic deposits and sporadic lava flows associated with paleo-volcanic calderas.

The pyroclasts consist of tuff and ignimbrite sequences, with scarce andesitic lava intercalations.

This Formation has been drilled in the wells of the northern and central sectors, reaching a maximum thickness of 1087 m, in well PGM-15.

These materials could be correlated with pyroclastic sequences of the Bagaces Formation, which crop out various km south of the caldera border.

It has been dated from 8 to 1.6 Ma (Gillot et al, 1994), indicating a wide period of deposition.

2.3 Lava -Tuff Unit (LTU)

This unit is composed of lavas and sporadic pyroclastic deposits. It is inferred that these materials correspond with the activity of a paleo-volcanic complex, known as Guayabo Volcano (ICE-Elc, 1983), which was emplaced over the products of the Ignimbrite Unit.

The lavas are predominantly andesitic, with occasional intercalations of tuff, ignimbrite and epiclastic levels.

In the wells, a thickening of this unit is observed towards the southern and western sectors of the field, reaching thicknesses between 260 and 1190 m.

These rocks are associated with outcrops in the La Montañosa Hills and Mogote Mountain (to the northwest), and the Espiritu Santo and Gota de Agua Mountains (to the southeast), corresponding with the present-day caldera border.

The lavas of these mountains are mainly basaltic and andesitic, with remote dacitic outcrops, as well as sporadic pyroclastic flows.

This sequence has been dated at 2.3± 0.1 Ma (ICE, 1976), represented by single hand sample from the La Montañosa Hills. Based on this age, it is associated with the Bagaces Formation.

2.4 Río Liberia Formation (RLF)

It is composed of a pumitic pyroclastic sequence that includes at least four flows, which are differentiated by variations in lithic content, crystals, and the level of consolidation. All of these flows are characterized by the presence of biotite, in varying amounts.

These pyroclastic flows form a regional ignimbrite mesa, with thicknesses of up to 60 m.

It is considered that at the time of deposition there was a topographic high at the present-day Guayabo Caldera (possibly the Guayabo Volcano), which is why these rocks have not been found within the caldera. This Formation ranges from 1.29 ± 0.03 and 1.83 ± 0.03 Ma (Gillot et al., 1994).

2.5 Volcano Sedimentary Unit (VSU)

This unit includes pumitic pyroclastic flows, tuffs, epiclastic deposits and lacustrine deposits, as well as occasional andesite and basaltic andesite levels. It is widely distributed in the drilled wells, with thicknesses ranging from 255 to 1050 m. This unit represents the products emitted during the formation process and filling of the Guayabo Caldera.

In this document, the Volcano Sedimentary Unit is correlated with the Guayabo Pyroclastic Formation (defined by Chiesa et al., 1992), which has been dated from 1.456 ± 0.036 Ma to 0.6 ± 0.011 Ma (Alvarado et al., 1992) and consists of a series of pyroclastic flows that crop out southwest of the caldera, partially covering and extending beyond its border for various kilometres.

2.6 Dome-Flow Unit (DFU)

It is series of rocks that were emplaced in the form of a dome-flow, whose distribution is limited to the northern part of the field. This unit developed during the final phases of the Volcano Sedimentary Unit, taking advantage of the distensive E-W structural system. Texturally, it is characterized by its low porphyritic index, where sparse plagioclase phenocrysts and mafic minerals, replaced by chlorite, are observed embedded in an intensely silicified matrix. Due to these characteristics, a dacitic composition is inferred for these rocks.

2.7 Cabro Muco Andesitic Unit (CMAU)

It includes mainly andesites and basaltic-andesites, as well as sporadic lithic tuff levels. These rocks are the product of activity from the Cabro Muco-La Giganta volcanic complex. This volcanic edifice rose in the southeastern sector of the caldera, after the emplacement of the Dome-Flow Unit. It has been affected by collapses associated with volcanic explosions, erosion and tectonism.

It has been reported in the majority of the wells with thicknesses between 50 and 1000 m.

Radiometric dating indicates ages from 0.4±0.1 Ma (Alvarado et al., 1992).

2.8 Post Cabro Muco Unit (PCMU)

This unit is composed of lavas and pyroclasts, from the Paleo-Miravalles and Miravalles volcanoes, as well as debris flows from these and other volcanic centres. A thickness of 25 to 156 m has been observed for this unit.

2.8.1 Lavas and Pyroclasts from the Paleo-Miravalles and Miravalles volcanoes

These consist mainly of andesites and basaltic-andesites with sporadic pyroclastic deposits. They are volcanic products posterior to the formation of the Cabro Muco-La Giganta volcanic edifice. This complex is located in the eastern sector of the field.

Paleo-Miravalles is considered as the second-most oldest post-caldera edifice, estimated at less than 200,000 ybp (ICE-Elc, 1983); followed by the current Miravalles volcano whose activity could have initiated around 50,000 ybp (ICE, 1976). The youngest rocks are pumitic pyroclastic flows with limited extension.

2.8.2 Debris Flow

This consists mainly of debris avalanches, lahars, and lacustrine deposits. They correspond in part with the activity of the Miravalles volcano as well as volcanic collapse events in the Bajo Los Chiqueros area and probably extending towards the Espiritu Santo Mountain. The avalanches cover a large part of the caldera interior, resulting in a relatively flat topography, where isolated hills characteristic of hummocky topography stand out.

These rocks were deposited in different stages, where dates from the lower sections indicate ages greater than 40,000 ybp (ICE, 1976) and the upper levels show ages near 9000 ybp (Alvarado et al., in press).

2.9 Fluvio-Lacustrine Unit (FLU)

This unit consists of clay, silt and fine sand intercalations that grade to andesitic alluvial deposits, which are found distributed in various localities within the caldera. These materials evidence a period of quiescence, where laminar flows and low volcanic activity dominated. The total thickness of these deposits is not known, however in outcrop they are up to 3 m.

2.10 Recent Deposits Unit (RDU)

This unit includes thick soil levels and colluvium formed by lava fragments from the border of the caldera, cropping out towards the northwest sector.

3. VOLCANO-TECTONIC STRUCTURES

The Guayabo Caldera and the Miravalles and Paleo-Miravalles volcanic edifices comprise the most noticeable volcano-tectonic structures in the region. This caldera consists in a marked semi-circular crescent-shaped 14 km diameter depression built up in various stages of volcanism and caldera collapse. Its NE and E extremities are masked by post-calderic materials from the aforementioned volcanoes, whose craters are aligned along a NE-SW strike, associated with deep fractures. The northern and southern borders of the caldera are truncated by the N-S distensive structural system that provoked downthrowing of the caldera border in the area of the La Fortuna graben. There is not a clear panorama with respect to the tectonic forces that have affected the region, however, taking into consideration the stresses caused by interaction between the Cocos and Caribbean Plates, as well as field evidence, it is inferred that the N-S and NE-SW structural systems, identified in the Miravalles area, present recent activity.

During the prospecting and drilling processes, four structural systems were defined, in which morphological, field geology and geophysical evidence, as well as the stratigraphic correlation between wells, have been considered. Chronologically, these systems (from oldest to youngest) correspond with the directions: NW-SE, N-S, NE-SW and E-W, all contributing significantly to the permeability of the geothermal system.

The N-S fault system, to which the La Fortuna graben is associated, existed prior to the caldera formation and was later reactivated (Chiesa et al., 1992), thus offsetting it and hence favouring the lateral discharge of reservoir fluids.

In the northern part of the field a series of horsts and grabens, associated to the E-W structural system, which is considered to be the most recent, has been defined. It has surficial expressions such as thermal anomaly and hydrothermal alteration lineations, which is why some of these faults are considered to be active.

4. ALTERATION MINERALOGY

The Miravalles Geothermal Field is comprised of a high enthalpy reservoir where the water-rock interaction has developed a pattern of hydrothermal alteration, which has been separated into the smectite (Sm), transition (I/Sm), and Illite (I) zones (Figure 3).

The smectite zone (< 165°C) corresponds to the most surficial part of the field (upper level of the cap rock) and is characterized by the presence of clays from the smectite group along with iron oxides/hydroxides and the appearance of subordinate pyrite, calcite, chlorite, zeolites, and some forms of silica (tridimite, cristobalite and quartz). Alunite and kaolinite can be present locally, particularly in areas affected by acidic fluids.

The transition zone is defined by the appearance of the mixed layered clay illite/smectite, in which the percentage of illite increases with depth. It corresponds with a range of temperatures between 140 and 220°C (Vega, 2000; Sánchez & Vallejos, 2000) and its base is localized near the top of the reservoir. In this level, there is a clear increase in the amount of calcite, quartz and chlorite minerals; as well as the first appearances of other mineral species such as adularia, leucoxene/titanite, epidote (particularly incipient type I, based on the classification given in Reyes 1990, 2000), anhydrite, pennine, zeolites, wairakite and the mixing of chlorite and smectite layers.

The illite zone is associated particularly to reservoir levels with temperatures of at least 220° C. It is characterized by the presence of illite, higher percentages of epidote (types I, II and III according to the classification given in Reyes 1990, 2000) and well-crystallized chlorite minerals. Also, quartz, wairakite, adularia, pyrite, and the mixing of chlorite and smectite layers can be observed. In some cases, prehnite, garnet, and some sulfides have been identified (Milodowski et al., 1989), in association to the highest temperatures registered at the Miravalles Geothermal Field.

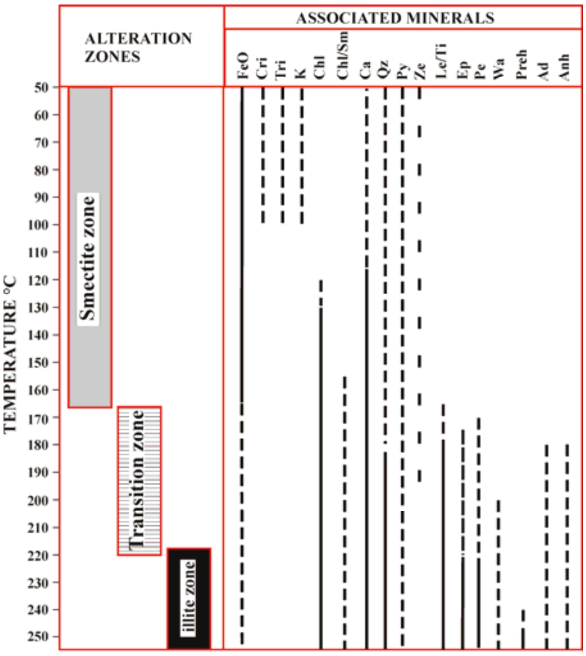

Figure 3: Clay alteration zones and associated minaralogy. FeO: Iron oxides/hydroxides, Cri: Cristobalite, Tri: Tridimite, K: Kaolinite, Chl: Chlorite, Chl/Sm: Mixed layered clay Chlorite Smectite, Ca: Calcite, Qz: Quartz, Py: Pyrite, Ze: Zeolites, Le/Ti: Leucoxene/Titanite, Ep: Epidote, Pe: Pennine, Wa: Wairakite, Preh: Prehnite, Ad: Adularia, Anh: Anhydrite.

5. DISTRIBUTION OF ILLITE, EPIDOTE AND THE 220° C ISOTHERM

To illustrate the thermal conditions of the field, the 220° C isotherm was correlated with the first appearances of epidote and illite, given their spatial distribution. Epidote is used as a high temperature indicator; illite on the other hand, due to its rapid response to temperature changes, represents current thermal conditions.

In general, the first stable appearance of these minerals corresponds well with the 220°C isotherm although this behaviour is affected by local thermal anomalies generated by fluid circulation along permeable structures (NE-SW and E-W), that disturb this condition. In the northern sector of the field there are increased temperatures, whereas to the east, south and west of the borehole field there is marked cooling. (Figures 4 and 5).

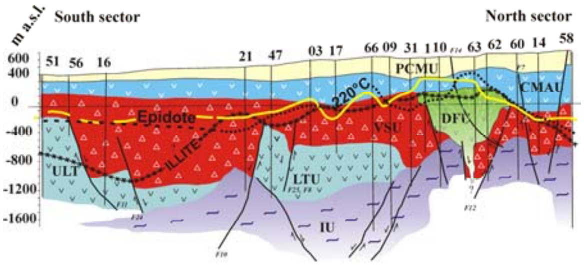

Figure 4. S-N geologic cross-section showing stratigraphy, faults and the distribution of the first appearances of illite and epidote as well as the 220 °C isotherm between wells 58 y 51. Unit abbreviations correspond to those described in the text.

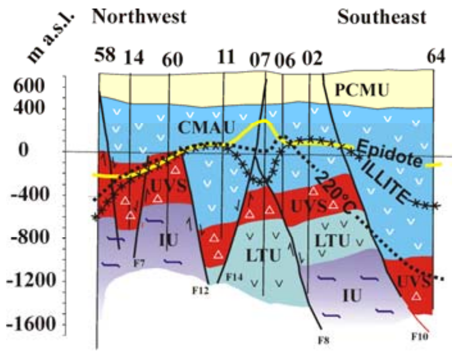

Figure 5. NW-SE geologic cross-section showing stratigraphy, faults and the distribution of the first appearances of illite and epidote as well as the 220 °C isotherm between wells 58 y 64. Unit abbreviations correspond to those described in the text.

6. FINAL REMARKS

The Guanacaste Volcanic Cordillera is located at the southern extreme of the Central American volcanic arc, related to the convergence of the Cocos and Caribbean plates. As a result of this interaction, magma chambers have been emplaced, giving rise to volcanic activity in different stages, with the formation of great structures such as the Guayabo Caldera.

Volcanic activity developed since the Miocene has produced a superposition of materials from effusive and explosive events, which along with the different structural systems affecting these rocks, has contributed in the formation of the Miravalles Geothermal Field (Figure 6).

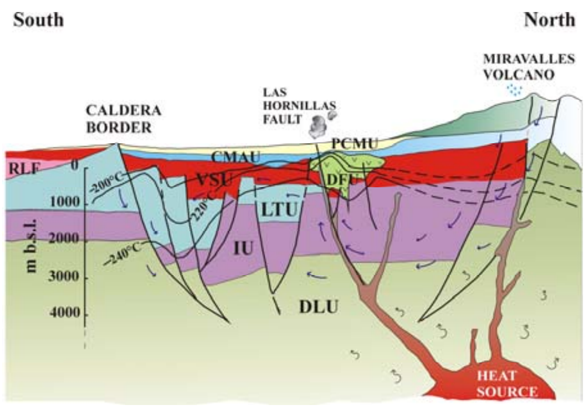

Figure 6. Geologic Model of the Miravalles Geothermal Field. Unit abbreviations correspond to those described in the text.

This field is composed of a high enthalpy reservoir that is divided into three hydrothermal alteration zones, based upon mineralogy. Each one of these is related with different temperature ranges indicating the cap rock and the top of the geothermal reservoir.

The most recent volcanic products are associated to the Miravalles Volcano, which along with the presence of intrusions, the decrease in depth of the 220°C isotherm and the alteration mineralogy observed in the northern sector of the field, suggest that the heat source is related to the magmatism of the Miravalles Volcano and that the movement of fluids has a north to south tendency. This direction is parallel to the structural system associated with the La Fortuna graben.

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