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LAS PAILAS GEOTHERMAL AREA
RINCON DE LA VIEJA VOLCANO, COSTA RICA

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ABSTRACT

The Rincón de la Vieja is a composite strato-volcano in the northwestern part of Costa Rica, 240 km from the capital (San José). The volcano is a part of the Guanacaste volcanic mountain belt. The most significant hydrothermal manifestations in the country occur on the southwestern flank of the volcano. The Pacific side of Rincón de la Vieja has been studied from aerial photos. The apparent geological features on these photos have been correlated with rock formations, making use of previous work. Age-dating and rock composition show a magmatic evolution from basaltic-andesitic through andesite to more acidic rocks with decreasing age. This evolution extends from west to east and then to the northeast.

The present study focuses on an area 30 km^2 in size, here referred to as the Las Pailas geothermal area. Las Pailas hydrothermal manifestations are on the northeastern side of this area, and the Hornillas hydrothermal manifestations are close to its northern margin. The study includes the lithology, clay mineralogy and thermal distribution in thermal gradient wells. A magmatic evolutionary model is presented as well as two competing hydrothermal models, A and B. Model A assumes a geothermal reservoir within an assumed San Vicente caldera, younger than 1 m.y. old. Model B assumes the hydrothermal reservoir is linked to the presently active Rincón de la Vieja volcanoic complex, younger than 500,000 m.y. Model A is favoured for exploitation outside the Rincón de la Vieja national park and needs to be tested accordingly.

1. INTRODUCTION

Costa Rica is located in Central America. Its volcanic mountain range belongs to the "Circum Pacific Ring of Fire", characterized by seismic and volcanic activity. Accordingly, the geological environment is favourable for potential geothermal energy at several locations within the country.

The first geothermal studies were carried out in 1963 oriented to develop the geothermal energy in the

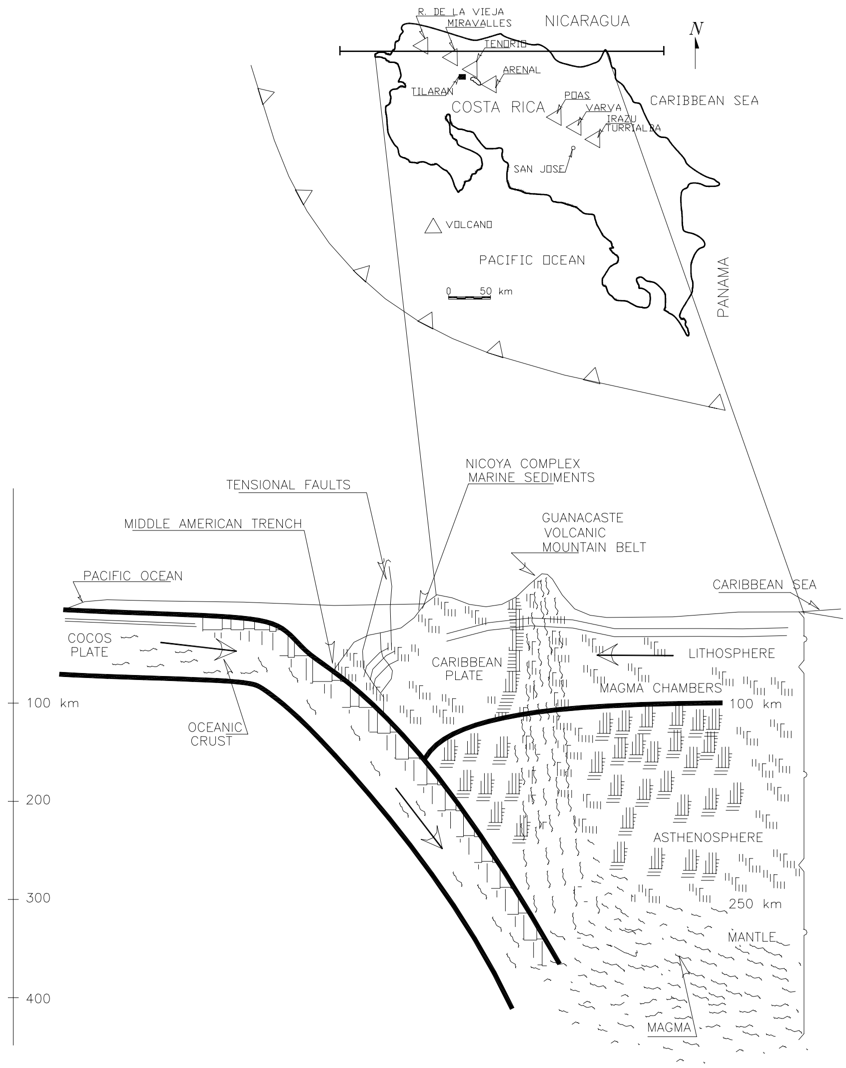

FIGURE 1: Location map of Costa Rica and a cross-section from the Pacific coast to the Atlantic coast, showing the Cocos Plate and the Caribbean Plate

Guanacaste region (northwestern part of the country). The first condensing power plant of 55 MWe (Miravalles I) was commissioned in 1994; its nominal installed capacity is now 142.5 MWe. Once the Miravalles geothermal field had been successfully developed, and exploratory drilling proved unsuccessful in Tenorio geothermal area, the next objective was a feasibility study of the Rincón de la Vieja geothermal area.

The Rincón de la Vieja is a composite stratovolcano in the northwestern part of Costa Rica, 240 km from the capital (San José). The volcano is a part of the Guanacaste volcanic mountain belt (Figure 1). On the Pacific side there are four promising thermal manifestations: Borinquen, Hornillas, Las Pailas and San Jorge - Santa María. They are aligned in a NW-SE direction, roughly parallel to the axis of the Rincón de la Vieja volcano and the regional volcanic axis (Figure 2). Due to the geothermal potential in this volcanic complex regional geological, geochemical and geophysical surveys were carried out intermittently over the last two decades. While the four geothermal manifestations may be connected at depth, the present report focuses on an area of 30 km^2, called the Las Pailas geothermal area (Figure 2). The purpose of this research is to combine information from different sources in order to make a geothermal model that can be tested by exploration drillings and other studies.

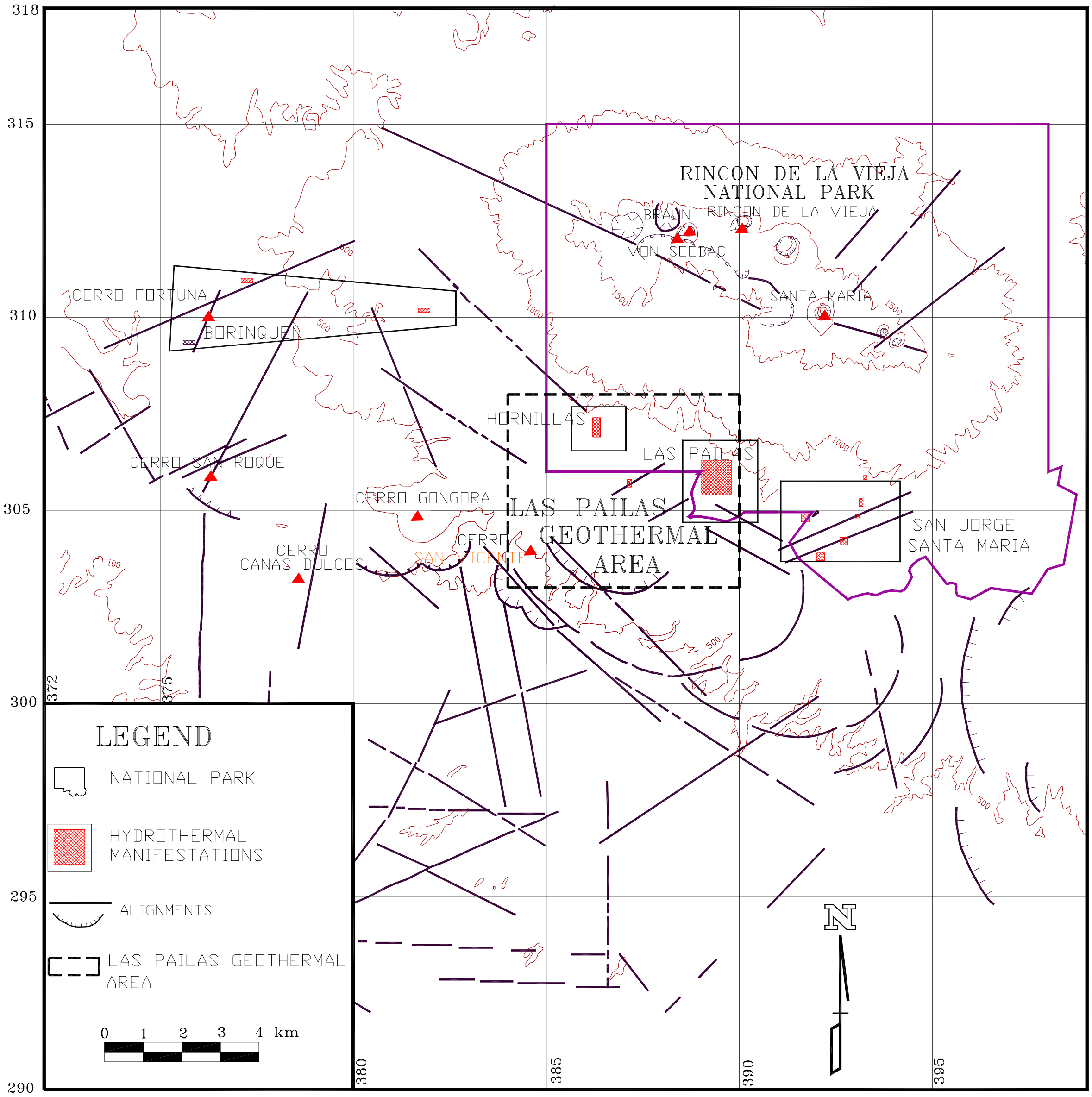

FIGURE 2: Regional map of Rincón de la Vieja volcano, showing different aerial photo alignments, hydrothermal manifestations and the Las Pailas geothermal area, map coordinates for this and following maps are abbreviated Lambert

2. GEOLOGICAL REVIEW

2.1 Regional geology

The most important tectonic feature that influences the geological evolution of the region is the collision of the Cocos plate that sinks under the Caribbean Plate, generating a magmatic arc which strikes NW-SE (Figure 1). The Guanacaste volcanic mountain belt constitutes the northwest segment of the volcanic arc of Costa Rica. It extends approximately over a distance of 100 km, located between the Nicaraguan border and the city of Tilaran. It is mainly composed of four recent stratovolcanoes and an ignimbrite plateau on the Pacific side. The Guanacaste volcanic belt is mainly composed of volcanic rocks of Pliocene-Quaternary age, overlaying an older basement of volcanic and marine sediments. The stratigraphic sequence of the mountain range can be described in the following way:

- The basement is composed of peridotites and basaltic rocks of the Nicoya complex (Upper Cretaceous).
- The basement is covered by a marine series: sandstone, shales, limestone reef of Paleogene age, attributable to the Barra Honda and Brito formations. On the Atlantic side there are sandstones, shales, clays of Cenozoic age and limestone, shales and sandstone of late Miocene age belonging to the Venado formation.
- Increased volcanic activity gave then rise to lavas from basaltic to dacitic composition, tuff and volcanoclastic sediments formed during Neogene, belonging to the Aguacate group and Ignimbrites with intercalation of fluvial and fluvio-lacustrine deposits that range in age from middle Paleocene to Miocene. Volcanic relics, consisting of tuffs and lava flows of andesitic composition (of Plio-Pleistocene age), compose the Monte Verde formation.
- Finally, the stratovolcanoes, all of which are younger than 0.5 m.y., comprise sequences and intercalations of basaltic-andesite and andesite lavas, tuffs, pyroclastic flows and lahars.

2.2 Volcanic activity

The area occupied by the Rincón de la Vieja complex is approximately 250 km^2, with an elliptical form aligned with nine craters in a NW-SE direction (Figure 2). Among the craters are Rincón de la Vieja (1806 m a.s.l.), Santa María (1916 m a.s.l.) and Von Seebach (1895 m a.s.l.). The only crater presently active is the Rincón de la Vieja. Its main activity is fumarolic, with sporadic phreatic eruptions and ash rain, that from time to time generate lahars or mud flows. The known historical volcanic activity is presented in Table 1 below.

TABLE 1: Historical volcanic activity

Year	Date	Observation
1765		First eruption reported
1966-1967	From October 1966 to January 1967	Moderate explosive activity
1967	From January to April	More violent explosions
1967-1970		Eruptions of tephra with development of lahars
1983	February 6 and 21	Eruptions of tephra with development of lahars
1984	March	Eruptions of tephra with development of lahars
1986	December 31	Phreatic eruptions
1987	April 1	Phreatic eruptions with development of lahars
1991	May 8	Phreatic eruptions with development of lahars
1995	November	Phreatic eruptions with development of lahars
1998	February 15	Phreatic eruptions with development of lahars

The volcanic history of other craters is not known. The fact remains that the ridge-shaped stratovolcano is aligned in a NW-SE direction. The distribution of geothermal manifestations at the base of the volcano on the western side, are roughly parallel to this NW-SE axis.

2.3 Hydrothermal manifestations

The most significant hydrothermal manifestations in Costa Rica are located at the base of Rincón de la Vieja volcano. The thermal manifestations are of different types, some of which are described below.

The Borinquen thermal manifestations are in the Salitral river area, mostly at altitudes between 300 and 600 m a.s.l. The manifestations which are close to 600 m a.s.l. include near-boiling *acid sulphate* hot springs. Furthermore, there are fumaroles that give rise to clouds of steam and sulphurous gas. The rock in the area is partly altered to clays. One of the most important hot springs in the area is located at 300 m a.s.l. close to Fortuna hill. It discharges 70°C hot *sodium chloride* water, with pH ~ 6. There are travertine deposits in the surroundings. It is considered to be representative of the reservoir water.

Hornillas (little ovens) are located inside the Rincón de la Vieja national park (Figure 2), near 800 m a.s.l. The area is characterised by fumarolic activity and hot springs, and severe clay alteration on the surface (smectite and kaolinite). The water is *bicarbonate* rich and to a lesser proportion acid, *sulphate* water.

Las Pailas (low pans for cooking or boiling things) has a surface alteration area of approximately 0.4 km^2 located inside the Rincón de la Vieja national park. It is located at an altitude of 700-800 m a.s.l. and shows the greatest hydrothermal activity. The manifestations include fumaroles, hot springs, boiling mud pools, sulphuric ponds, a number of little mud cones with vapour, and jets of steam. The rock is altered, mainly to clays (smectite and kaolinite) and in some places sulphur deposits and iron oxides occur. The hydrothermal fluid is *acid sulphate*, generated by mixing steam with meteoric water.

San Jorge - Santa Maria thermal manifestations are located in the east, between 700 and 800 m a.s.l., along two tributaries of the Negro river (Figure 2). They are characterised by *acid sulphate* hot springs, generated by mixing steam with meteoric water, giving rise to sulphur deposits. The environment shows intense alteration to clays (smectite and kaolinite) and iron oxides.

2.4 Photogeology and previous works

Different versions of aerial photo-geological maps are available of the Rincón de la Vieja volcano. These were reviewed and an additional effort was made to interpret geological and structural features on aerial photos from November 26, 1987 (strips 302 and 308). This is presented in the air photo-geological map in Figure 3. The results are discussed below with reference to older work.

2.4.1 Bagaces formation

Found in the middle part of the Rincón de la Vieja volcano and on the southern flank, Dondoli (1950) called it Grey Tuff, and Dengo (1962) defined it and called it the Bagaces formation. According to Mainieri (1976), the greatest thickness of the Bagaces formation is 500 m, dipping slightly towards the southwest. It has been divided into three units based on potassium-argon (K-Ar) dating, the lowest unit is grey and contains clays and gravels (7.5 m.y.). The middle part has a dark-brown colour, consolidated hard tuff and black ignimbrite, rich in glass, and vesicular andesite or basaltic andesite (3.8 m.y.). The youngest unit contains a light-brown well cemented tuff, with colourful lithic fragments. It also contains pumiceous lapilli tuff and glass (0.637 m.y.). Interbedded lacustrine and fluvial deposits compose a strata of sand and oxidised pumiceous ash of red colour, with badly conserved fossils. Deposits of alluvial origin also occur with gravel horizons, and in the area to the northeast of Cañas Dulces, deposits of diatomite exist.

2.4.2 Domes (volcanic relics)

In the southeast margin of the Rincón de la Vieja edifice, a contrasting landscape with eroded hills of volcanic origin is observed. These hills interfinger with the deposits described above. Previously, these were called volcanic relics. In the present study, however, they are simply referred to as the Domes.

Mainieri (1976) describes the hills, Fortuna, San Roque, Góngora and San Vicente as four domes of crystalline vitric tuff, formed by rocks of andesitic composition, 4.3 m.y. old (dating done by K-Ar method on rocks originating from the Góngora hill). Bergoeing et al. (1983) mention the San Vicente hill as a dacite dome of Pleistocene age. However, the San Vincent dome is here considered to be younger than 1 m.y., but this will be proved by age dating. Structurally the Cañas Dulces hills are two domes formed by lava classified as hypersthene hornblende andesite that extends in a northwest direction. The K-Ar dating gave an age of 1.55 m.y.

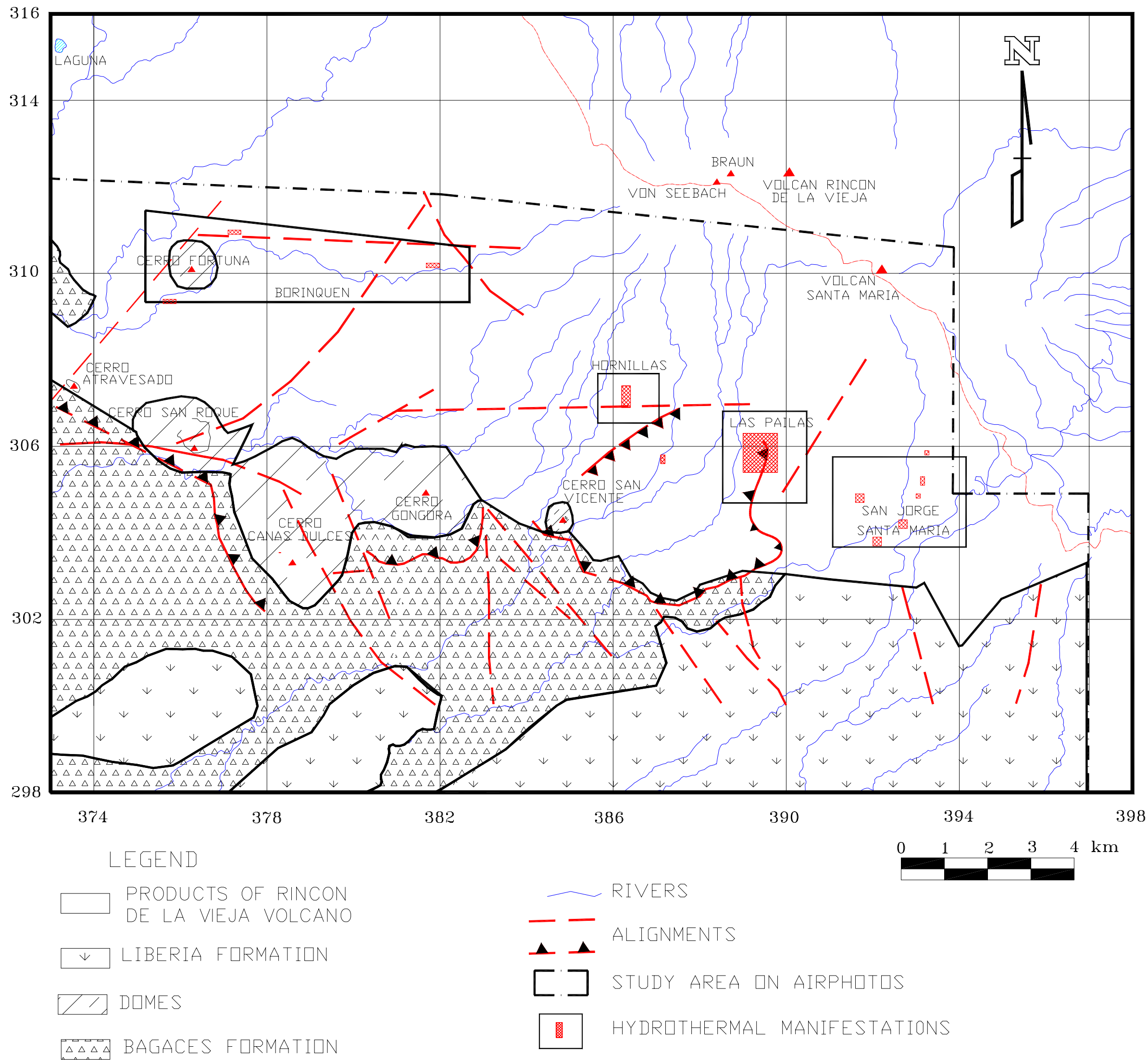

FIGURE 3: Photo-geological map based on air photos from November 26, 1987 (strips 302 and 308)

2.4.3 Liberia formation

The Liberia formation is characterized by flat topography and deep and narrow valleys, it was described as the white tuff by Dondoli (1950) and defined later as the Liberia formation by Dengo (1962). Good exposures occur on the south and southwest sides of the Rincón de la Vieja complex. There they overlie the Bagaces formation. Chiesa (1991) has estimated the original extent of this deposit to be 3500 to 4000 km^2, with an erupted volume of 25 km^3. According to Mainieri (1976), it is composed of pseudo-stratified volcanic ash, of homogeneous mineralogy, dipping at a low angle to the southwest away from the Rincón de la Vieja volcano. The tuff is mainly composed of quartz, biotite and lithic fragments in white and grey cement of rhyolite composition. Its deposition seems to have initiated 600,000 years ago. Funaioli and Rossi (1991) interpreted the Liberia tuff as having been erupted from the Guayabo-Miravalles volcanic complex. Other researchers have interpreted it as a product of the Rincón de la Vieja complex.

2.4.4 Products of Rincón de la Vieja volcanic complex

The recent products of the Rincón de la Vieja complex are in the northern part. These rocks are lava flows, tuffs, tephra deposits, air fall deposits and recent lahars. The lava composition is andesitic and two types of pyroxenes are detected (Sprechmann, 1984). The present volcanic edifice of the Rincón de la Vieja is younger than 500,000 years, and it is likely that most of the deposits that make up the edifice are younger than 200,000 years. The total thickness of the volcanic sequence may be in excess of 1,000 meters.

Based on geological studies, Mainieri (1976) subdivided the products of the volcano into three units, according to different grades of erosion as recognized on aerial photographs. The oldest unit is strongly dissected and forms the major part of the Rincón de la Vieja volcano. The second unit forms a tongue covered on the surface by pyroclastics that erupted from the Braun cone, and extends to the south from there. The youngest unit, little dissected, extends northeastwards from the cones of Rincón de la Vieja and Santa María. The Hornillas thermal area is located in rocks of intermediate age, whereas the Las Pailas and Borinquen thermal areas are located within the oldest rock unit of the Rincón de la Vieja complex.

2.5 Alignments on aerial photos

Different morphological characteristics could be related to the regional tectonics. In this study, the recognized alignments have been separated into two groups (Figure 3):

2.5.1 Volcano-tectonic origin

In the surroundings of the Góngora, Cañas Dulces and San Roque hills, a border of a caldera has been interpreted. It is the oldest alignment and affects the products of the Bagaces formation. It is intersected mainly by alignments striking northwest and north-northwest. Other authors have called it the Cañas Dulces caldera.

Another structure of semi-circular form is evident near the Las Pailas area. It is elongated in a northeasterly direction and is 5 km long. The eastern boundary is poorly exposed, being mostly buried by the younger volcanic products of the Rincón de la Vieja volcano. Nevertheless, escarpments in the volcanic products may outline a caldera margin. Escarpments in the Bagaces formation may outline its southern margin. This semicircular alignment is called the San Vicente caldera.

2.5.2 Straight alignments

i. Alignments with *northwesterly and north-northwesterly* direction. These are the most abundant alignments and are observed affecting all the litological units except the products of the Rincón de la Vieja (with one exception). This suggests that the northwesterly alignments are older than 500,000 years.
ii. A system with a *northeasterly* direction. These alignments are younger than i), cut the Domes, the Bagaces, and the Liberia formations, and are present in the northwestern part of the Rincón de la Vieja volcanic products. It does not appear to cut the Cañas Dulces caldera.
iii. A system with an *E-W* direction is the youngest system. Only two alignments are observed and both cut the products of the Rincón de la Vieja volcano. The Borinquen hydrothermal manifestations may be related to this E-W alignment.

The different thermal manifestations. Borinquen, Las Hornillas, Las Pailas and San Jorge-Santa María are arranged in a northwesterly direction, but a morphological evidence might suggest a structural trap that has not been identified. However, Lescinsky et al. (1987) mention that there is a trend in the soil Hg concentration that coincides with the distribution of surface thermal manifestation within the Las Pailas and interpreted it to be associated with a buried fault. That fault is co-linear to a lineament defined by the location of Miravalles, Las Pailas and the Hornillas thermal manifestation.

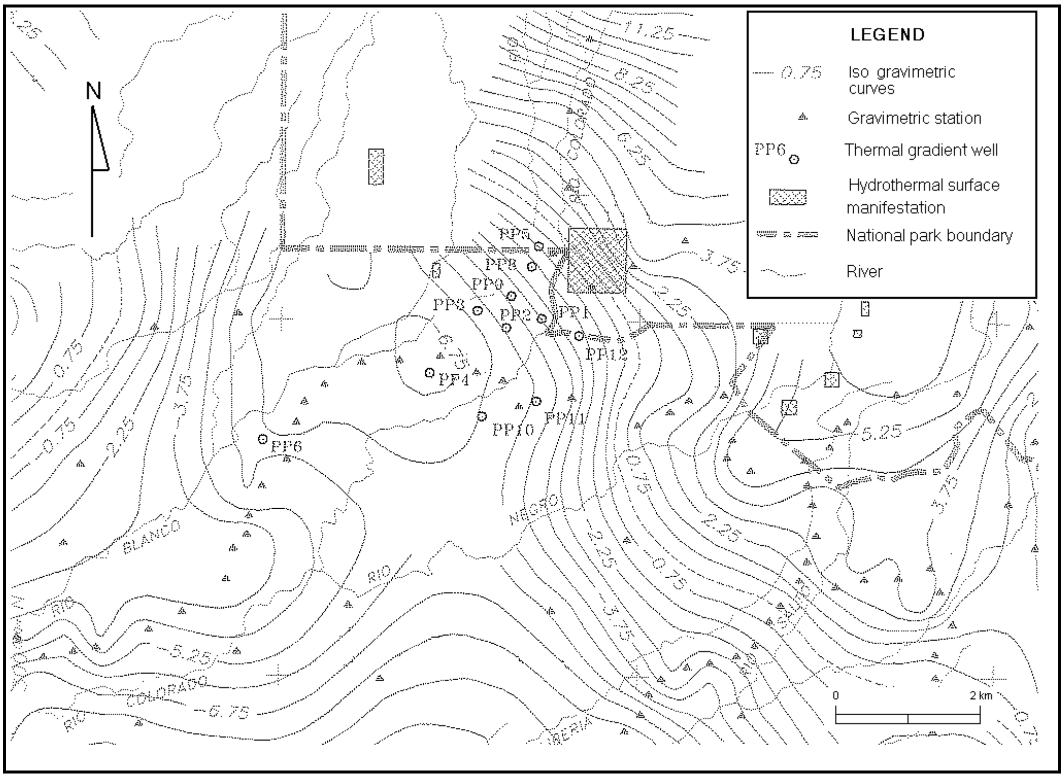

FIGURE 4: Bouguer anomaly map of the Las Pailas geothermal area, reduction density 2.2 - 2.3 gr/cm3 (modified from GeothermEx 1999)

2.6 Geophysical data

Different types of geophysical investigations have been carried out on the Pacific flank of the Rincón de la Vieja volcano. GeothermEx Inc. (1999) summarised the geophysical investigation in the region. Data from the Las Pailas geothermal area is presented in this section. Two anomalies have been detected by different methods in the same area (Figures 4 and 5, modified from GeothermEx inc. 1999). In the surroundings of the San Vicente caldera, an important gravity low is noticed as shown in Figure 4 (Bouguer gravity anomaly map). It has a semicircular shape, with a negative gravity anomaly centre close to drillhole PP4.

The magnetic map shows an anomaly inside the Las Pailas geothermal area, elongated in a W-E direction and with a magnetic low close to drillhole PP11 (Figure 5). A good correlation exists between the magnetic anomaly and the Bouguer gravity anomaly. Furthermore, a resistivity anomaly appears inside the San Vicente caldera, evidenced by top of the highly conductive layer, below 400 m. The hypothesis of the inferred caldera structure (San Vicente caldera) in the Las Pailas geothermal area is supported by the geophysical anomalies.

3. GEOLOGIC MAPPING

3.1 Geology of the Las Pailas geothermal area

Field work was done in January and February 2000, covering about 30 km^2 in a region called Las Pailas geothermal area (Figures 2 and 6A). In addition, drill cores from available gradient wells were studied to map the surface geology in more detail. The result of the study is shown below, beginning with the oldest unit (Figures 6B and 7).

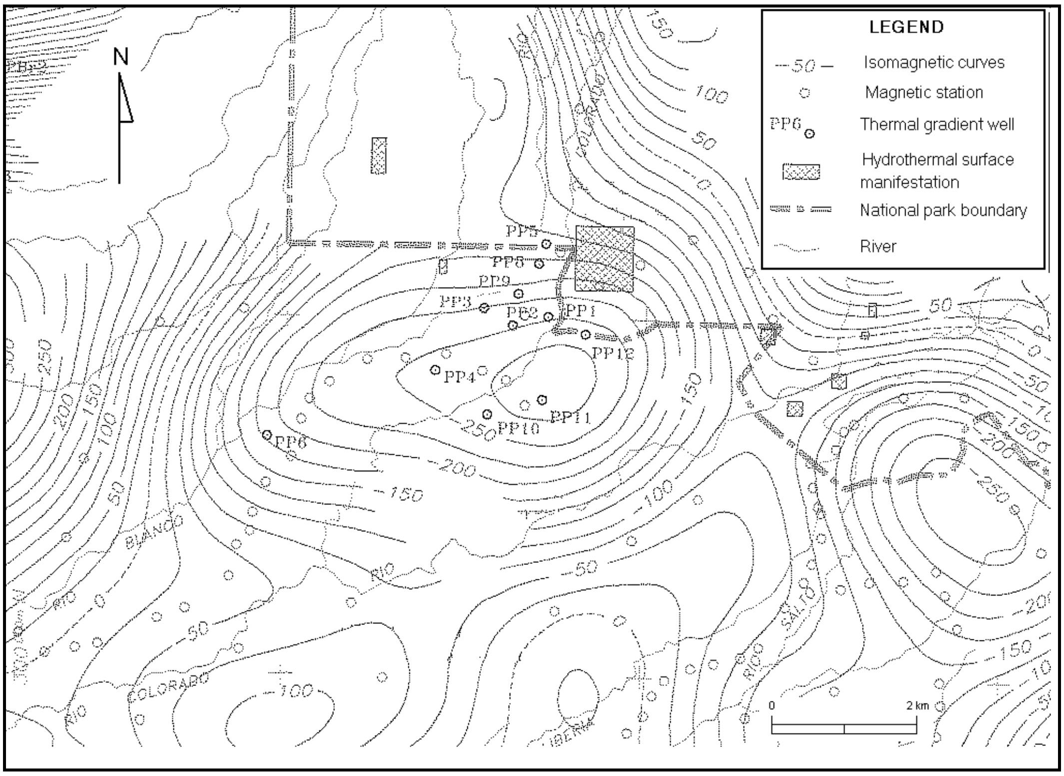

FIGURE 5: Magnetic map of the Las Pailas geothermal area; the magnetic field is low-pass filtered with a cut-off wavelength of 4 km (modified from GeothermEx Inc. 1999)

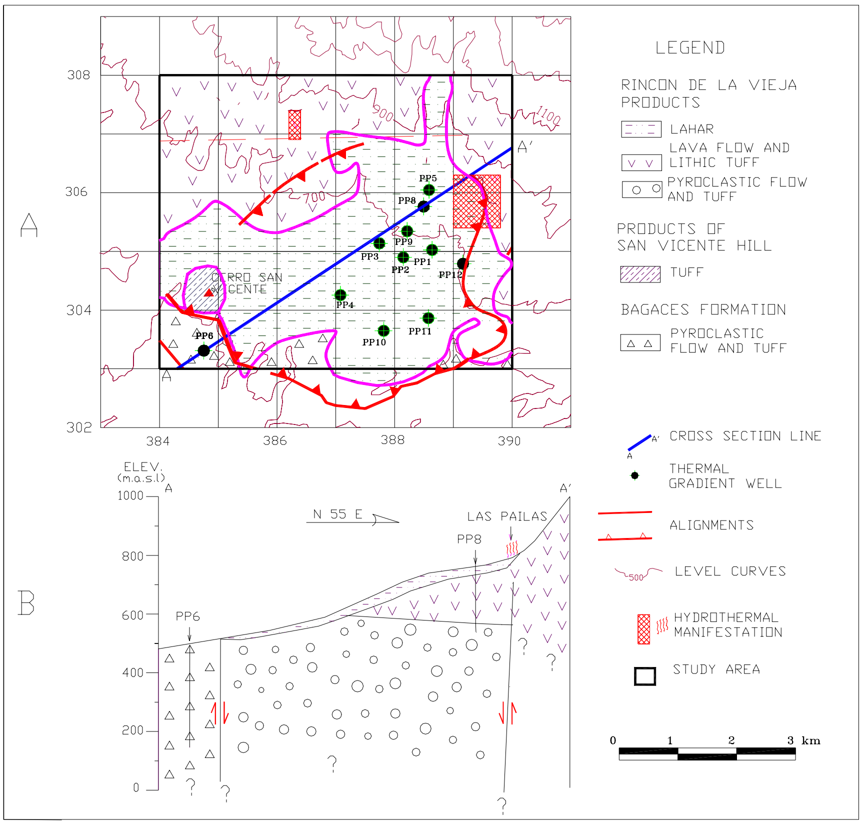

FIGURE 6: A) Geological map of the Las Pailas geothermal area; and B) Geological profile across the Las Pailas geothermal area

3.1.1 Bagaces formation

In the zone of interest, the Bagaces formation is characterized by low hills with steep slopes and sharp crests, caused by the water erosion. The river valleys are deep and narrow. In the study area at least 350 m of the Bagaces formation are found in drillhole PP-6. The outcrops of this formation are found in the south and southwest (in the Blanco river), overlain by the lahars from Rincón de la Vieja in some places, and in other parts limited by the San Vicente caldera margin. Bergoeing et al. (1983), mention that this formation composes the base of the western pedestal of the Guanacaste volcanic mountain range. It is composed of pyroclastic flows interbedded with tuffs.

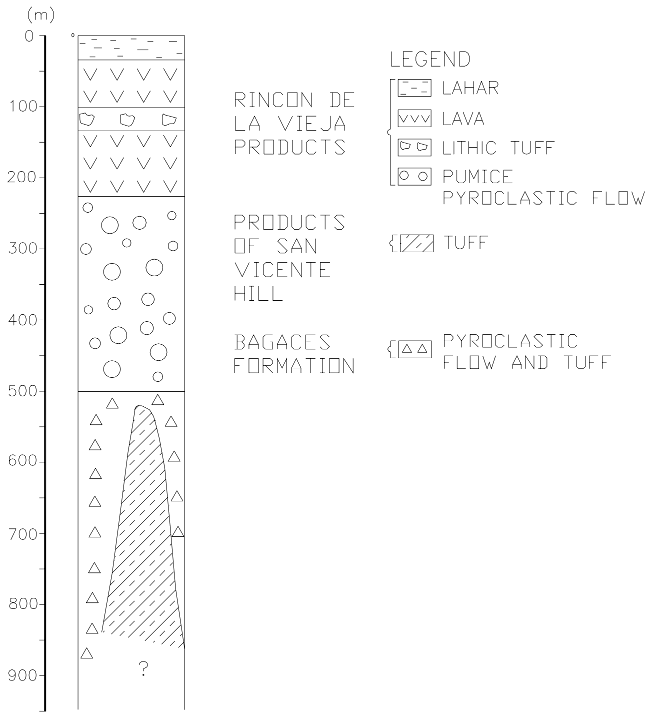

FIGURE 7: Stratigraphic column of the Las Pailas geothermal area

The pyroclastic flows, depending on the degree of alteration and composition, range in colour from grey to brown and orange. The rock is porous and of low density. Generally, it is composed of a matrix that consists of pumice, ash, plagioclase and hornblende crystals (80-95%), else it is of welded pumice and lithic fragments (5-20%).

The tuffs range in colours from grey to yellow to violet. The tuff is laminated with a grain size that oscillates from millimetres to centimetres. It is of low density, of variable hardness (some are very soft while others are enriched in amorphous silica). The tuff is 95% ash, ranging in grain size from clay to fine sand, with phenocrystals of plagioclase, hornblende and quartz.

3.1.2 Products of San Vicente hill

The San Vicente hill belongs to a series of tuff domes located on the southwest flank of Rincón de la Vieja volcano. The rock is classified as a tuff of dacite composition (63% SiO_2, Chemical analysis was done by the Geochemistry laboratory of the Miravalles geothermal field), and is more evolved than the earlier magmatic products. The dome has steep slopes, with a height of 600 m a.s.l., rising about 100 m above its surroundings. In the south it is bound by the caldera margin and to the north it is overlain by lahars.

The tuff colour varies from pink to grey. It is massive with fine-grained texture, crystalline, of moderated density, compact and not very porous. About 98% of the material is glassy matrix containing microlites of plagioclases (semi-oriented) and opaque minerals, conforming a vitrophyric texture. The remaining 2% are composed of phenocrysts of plagioclase and brown hornblende.

3.1.3 Products of Rincón de la Vieja volcanic complex

This unit is younger than the Bagaces formation and the San Vicente hill products and occurs in the central and northern part of the study area (Figure 6A). It is mainly composed of pyroclastic flows, tuffs, lavas, lithic tuffs and lahars that filled the San Vicente caldera. A minimum thickness of 505 m is estimated (Figures 6B and 7), but greater thickness is also known.

Pyroclastic flows are not exposed on the surface, but are found in the drillholes. They are less than 276 m thick. They appear to thicken to the south and probably towards the centre of the caldera as well. This rock type is more abundant inside the caldera. In drillhole PP11, the pyroclastic flows are found to overlay fluvial-lacustrine deposits (interbeddings of limestone, sandstone and diatomite), but so far there is not enough evidence to correlate these deposits with the Bagaces formation lacustrine deposits. The pyroclastic flows vary in colour from white, yellowish, orange and violet to red. It is of low density, rich in rounded fragments of pumice, 8 cm of diameter. The fragments are welded in a matrix of white and yellowish colours, composed mainly of pumice and, in smaller proportions ash, quartz crystals, plagioclase, hornblende and magnetite. Interbedded with the pyroclastic flows are packages of tuffs which include well sorted fine-grained ash, including pumice fragments. It appears that these packages of tuff represent airfallen tuffs.

Lava flows interbedded with lithic tuffs. Lava flows are observed in the northern part of the study area. A thickness of 195 m was measured in drillhole PP8. The lava flows are characterized by pronounced downhill dips in excess of 45° in some areas. The lavas in fresh outcrops show either massive or laminar structure, and range in colour from grey to dark, fine grained texture, crystalline, of moderated density and low porosity. In altered exposures, the colours are different (brown, dark brown, brown reddish, grey and greenish grey). The lavas contain phenocrysts of plagioclase and pyroxene that commonly are found in agglomerates that reach 5 mm, characterized by hypocrystalline - porphyritic texture. The porphyritic index varies from 25 to 40%. The phenocrysts are found immersed in a matrix composed of the same minerals with opaque minerals and glass, forming a texture that varies from hyalopilitic to intersertial. The rocks are of andesitic composition but show two varieties, the most abundant with two pyroxenes (hypersthene and augite), and the other variety with hypersthene alone.

In drill holes PP8 and PP9, lithic tuff is sometimes found in between the lavas. It varies in colour from brown to grey. The grain size of the matrix is highly variable from fine sand to coarse sand and shows indications of a turbulent environment. In this matrix are welded subrounded blocks of lava up to 40 cm across and fragments of pumice and other pyroclastics.

The lahars generate relatively flat morphology. Their greatest thickness of 34 cm is measured in PP9. It is a heterogeneous and massive material, polygenetic, composed of lithic andesitic fragments with a grain size ranging from millimetres to 3 m; colours vary from grey, dark grey to brown, with similar characteristics and composition to the lavas described above. Scoria fragments occur, too. These fragments are immersed in a matrix, of grain size from clays to fine sand.

3.2 Volcanic history

The rocks included in the Bagaces formation formed over a long period (about 7 m.y.). However, this formation mainly constitutes products of explosive volcanism that extruded domes of crystalline-vitric tuff such as Fortuna, San Roque and Góngora, around 4.3 m.y. ago (middle unit). They are all located close to and within an inferred Cañas Dulces caldera structure that is observed by a fault escarpment close to Góngora hill and onwards along the Cañas Dulces, San Roque and Atravesado hills (Table 2).

TABLE 2: Magmatic evolution and volcanic products

Rincón de la Vieja products	0.5 m.y.	Lava, lithic tuff, lahar, etc., andesite composition
Liberia formation domes (San Vicente hill)	0.6 m.y.	Tuff, rhyolite composition Tuff dome, dacite composition
Domes (Cañas Dulces and Torre hills)	1.55 m.y.	Lava domes, andesite hyperstene hornblende composition
Bagaces formation middle unit	3.8 m.y.	Tuff, basaltic-andesite and andesite composition
Domes (Fortuna, San Roque and Góngora hills)	4.3 m.y.	Tuff domes, andesite hornblende composition
Bagaces formation lower unit	7.5 m.y.	Clays and gravel

Later, 1.55 m.y. ago, the volcanism changed to a more effusive nature, while the composition remained the same (hypherstene - hornblende andesite), producing the Cañas Dulces and Torre hills. The similar chemical composition of the rocks suggests that the magmatic ascent generated from the same magmatic source, but took advantage of the caldera margin.

Later still, in the east and northeastern parts, dacitic to acid volcanism developed the San Vicente hill. Probably the summons of the dome was contemporary with the caldera development. This seems to be a continuity of earlier activity that generated the Cañas Dulces caldera and the oldest domes. About 600,000 years ago the Liberia formation was deposited. Although some authors have interpreted the Liberia tuff as having erupted from the Guayabo-Miravalles volcanic complex, other researchers have interpreted it as a product of the Rincón de la Vieja complex. So far, these rocks have not been found within the San Vicente Caldera, possibly due to erosion. Some natural barrier might have impeded its deposition, assuming the caldera developed later than the Liberia formation. The third possibility is that the Liberia formation occurs at greater depth within the caldera.

A little later, 500,000 years ago, the volcanic activity migrated to the north to the Rincón de la Vieja volcano that filled the San Vicente caldera with younger rocks (pyroclastic flows, rich in pumice and in decreasing quantity, tuffs, lavas and lahars, Figure 6B). This volcano is still active. The volcanic history and the region's rock composition show that the volcanic activity was strongly explosive. Furthermore, in the eastern and northeastern parts of the Pacific flank, acidic products were generated. It is deduced that part of the volcanism was generated by magma ascending to shallow levels into a magmatic chamber, where a magmatic evolutionery process took place. Later, explosive volcanism erupted acidic products and resulted in a caldera collapse.

In summary, it appears that the volcanism of the area evolved along an axis oriented W-E, first eastwards until 0.5 m.y. ago, then migrating northwards, building up the present complex of Rincón de la Vieja volcano (Figure 8).

4. THERMAL GRADIENT WELLS IN THE LAS PAILAS GEOTHERMAL AREA

Thermal gradient determination, using shallow drillholes, is a valuable tool in investigating the geothermal distribution of an area. Drillholes also provide stratigraphic information. The first drilling of gradient wells in the Las Pailas geothermal area was done in 1975. Seven wells were drilled, ranging in depth from 52 to 349 m. From 1995 to 1996, a second drilling phase was undertaken with five new drillholes, ranging in depth from 186 to 341 m (Table 3).

TABLE 3: Exploratory wells drilled in the Las Pailas geothermal area

Well no.	Location	Coordinates		Elevation	Depth	T_{max}	Gradient	Drilling time	
		North	East	(m a.s.l.)	(m)	(°C)	(ºC/km)	Start	End
PP1	Las Pailas	305025.81	388638.26	692	57.00	94.0		21/08/75	28/08/75
PP2	Las Pailas	304898.57	388147.87	682	101.60	33.0		20/09/75	27/11/75
PP3	Las Pailas	305135.19	387741.01	683	52.80	26.0		30/11/75	14/12/75
PP4	Las Pailas	304255.88	387077.54	610	52.80	28.0		17/12/75	19/12/75
PP5	Las Pailas	306047.19	388587.43	786	108.55	51.0		22/01/76	02/03/76
PP6	Las Pailas	303308.90	384754.54	492	349.50	46.0	106.5	11/03/76	
PP8	Las Pailas	305762.86	388494.49	755	220.55	<110.0	528.0	20/02/95	03/03/95
PP9	Las Pailas	305343.43	388214.85	712	286.25	<110.0	522.0	21/03/95	04/08/95
PP10	Las Pailas	303647.63	387815.52	614	302.50	54.0	156.0	27/09/95	04/01/96
PP11	Las Pailas	303862.60	388575.57	625	340.70	74.7	153.2	08/02/96	09/05/96
PP12	Las Pailas	304788.95	389164.03	626	186.00	101.0	496.1	06/06/96	20/07/96

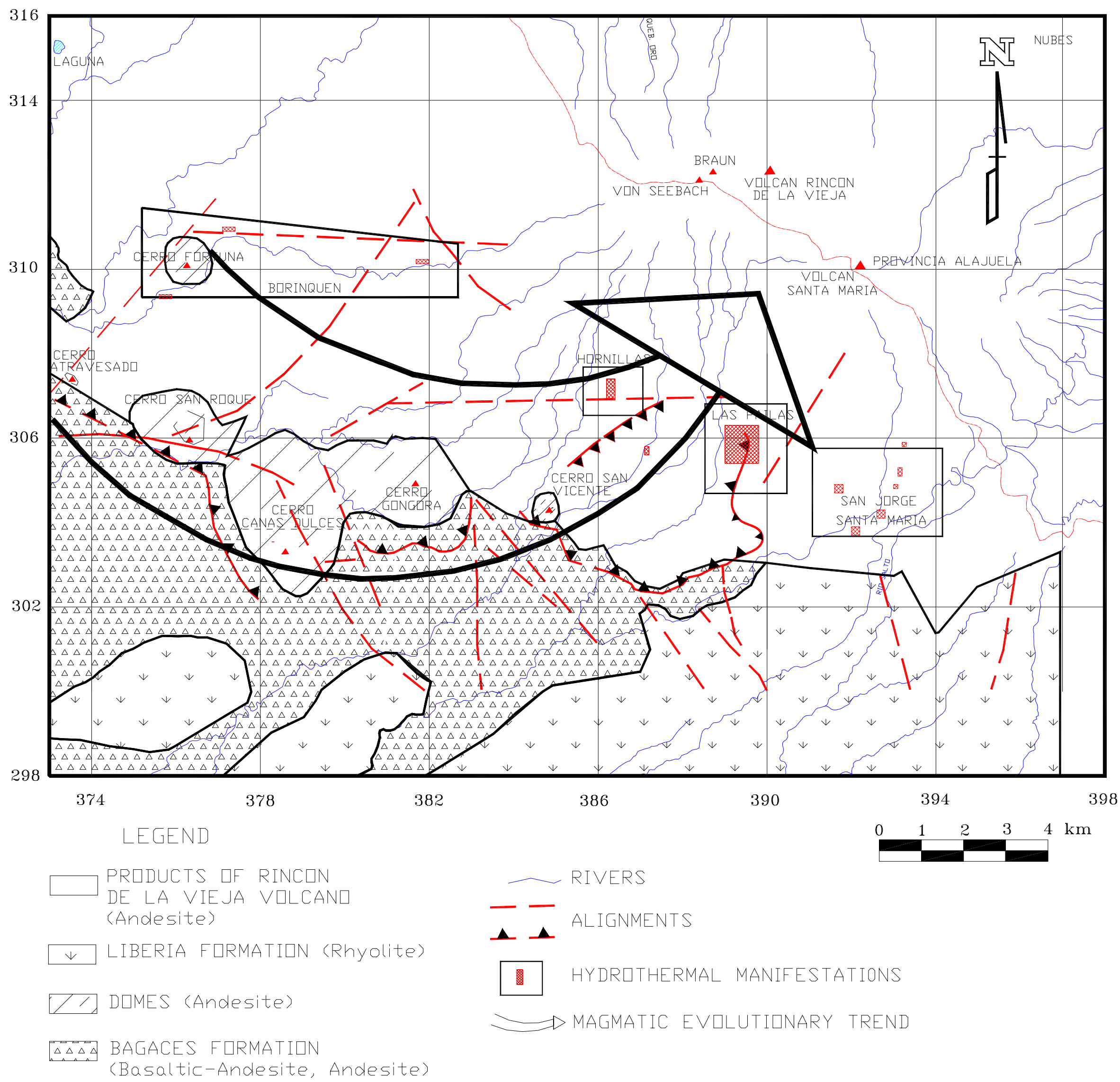

FIGURE 8: Magmatic evolution trend of Rincón del la Vieja volcano on the Pacific side

Altogether, 12 drillholes have been drilled and five of them are shallower than 150 m. They are good for stratigraphic correlation but not good for geothermal gradient studies due to a negative thermal gradient that exists above the water table. Only reliable temperature data is used in this study and the first part of the temperature profiles is ruled out (Figure 9).

The drillholes are distributed in a 10 km^2 area (Figure 6A). All of them cut the Rincón de la Vieja products, except PP6, which is outside the caldera and just cuts the Bagaces formation. The only well within the caldera, which may reach down into the Bagaces formation is well PP11 (340 m deep). Close to the bottom of PP11, fluvial-lacustrine deposits are observed, and they may possibly belong to the Bagaces formation, but could be much younger, emplaced in a caldera lake.

Pyroclastic flows are the predominant rock type in the area, ideal for thermal gradient measurement. This has been attributed to the low rock permeability. Influence from a lateral aquifer can only be seen in PP9, in permeable lava between 120 and 190 m depth. The thermal gradient has a similar slope above and below this aquifer, with similar values as in nearby drillholes (Figure 9).

4.1 Clays in the drillhole cores

Samples for clays analysis were selected from the drillcores. The material was picked out from mineralised fractures (veins) and altered wall rocks. The clays were analysed by using the X-ray diffractometric method and have been identified as kaolinite and smectite (Table 4).

Kaolinite is a common mineral of secondary origin, formed by weathering or hydrothermal alteration of aluminium silicates, particularly feldspar (Klein & Hurlbut, 1993). The hydrothermal alteration process indicates a pH between 3 and 4. Furthermore, it can be formed near surface environments. In the Las Pailas area, the kaolinite is a product of hydrothermal alteration. This clay is easily identified by its white or yellowish white colour and its plastic behaviour which relates to high water content. The rocks in the drill cores show evidence of incipient kaolinization. The kaolinite can indicate a fossil soil in some cases, but mostly old fumaroles.

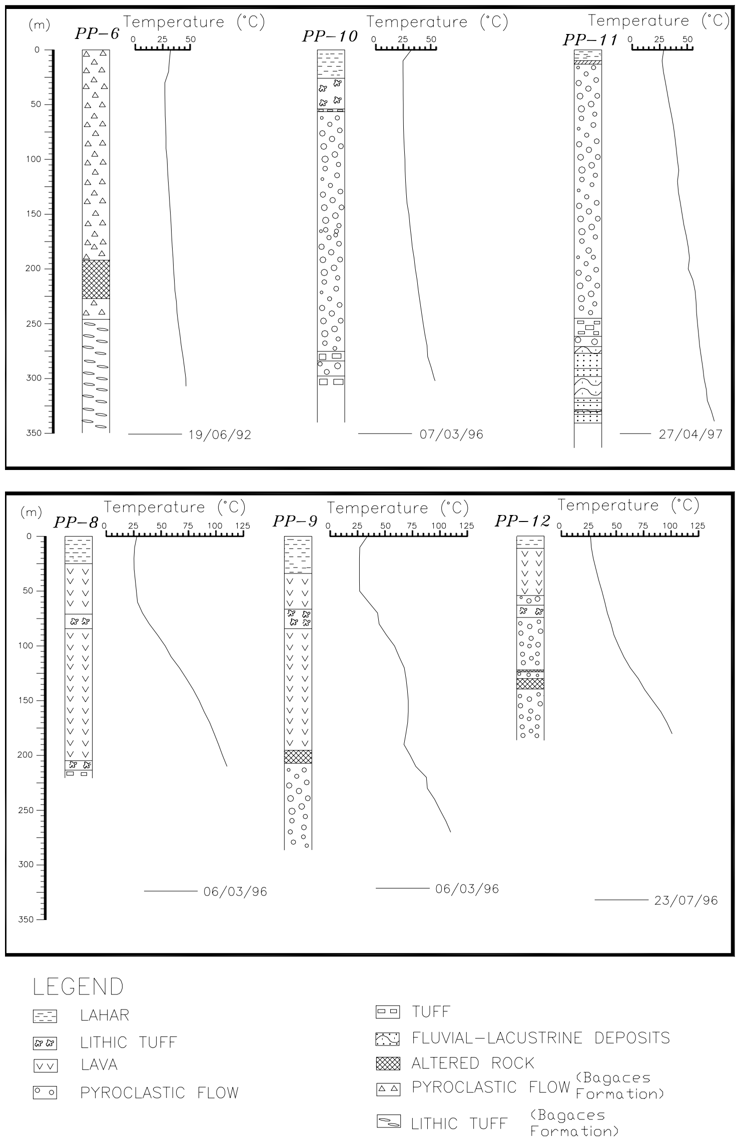

FIGURE 9: Lithological columns and temperature profiles of thermal gradient wells, Las Pailas

Smectite is a general term used for a clay mineral group, in which montmorillonite is the most common. The smectite colours in the Las Pailas vary from red, orange, yellow, and grey to light green. It is characterized by its high compressibility. The crystallinity improves with increasing temperature and depth, as is seen in the PP8 drillhole (Table 4). The Geology Laboratory of Miravalles geothermal field did the X-ray analysis.

From the limited study of clay mineral distribution, as seen in wells PP8 and PP9 that are close to the surface manifestations, the smectite is well crystallized below 200 m deep. Comparison with well PP10 shows that away from the surface manifestation, much poorer clay crystalinity is observed. The former group shows better developed clay minerals apparently related to higher temperatures.

4.2 Thermal distribution

With the available information, isothermals and gradient maps were constructed. The program "Surfer version 6.02" was used to process the data. In the Las Pailas drillholes, thermal gradients vary from 106.5 to 528°C/km. The lowest gradient was measured in PP6. Inside the inferred caldera, the lowest gradient was measured in PP11 (153°C/km) and the highest in well PP8 (528°C/km). This high thermal gradient simply means one can expect high fluid temperature at relatively shallow depth. Once within the

TABLE 4: Results on X-ray diffractometry on Las Pailas well samples

Well no.	Depth (m)	Mineral identified
PP8	55.80	Cristobalite
	66.00	Cristobalite
	71.15	Kaolinite
	190.05	Smectite (almost well crystallized)
	200.70	Smectite (well crystallized)
	220.00	Smectite (well crystallized) and kaolinite (badly crystallized)
	220.55	Smectite (well crystallized) and kaolinite (badly crystallized)
PP9	57.00	Cristobalite
	84.60	Smectite (badly crystallized) and kaolinite (badly crystallized)
	93.30	Smectite (badly crystallized) and kaolinite (improve crystallization)
	109.00	Smectite (improved crystallization)
	113.00	Smectite (improved crystallization)
	203.00	Smectite (well crystallized)
	286.26	Smectite (badly crystallized) and Cristobalite
PP10	158.50	Smectite (badly crystallized) and kaolinite (badly crystallized)
	281.30	Smectite (improved crystallization)
	285.00	Smectite (improved crystallization)
PP12	122.60	Smectite (badly crystallized) and kaolinite (well crystallized)
	130.00	Smectite (badly crystallized) and kaolinite (well crystallized)

reservoir, the maximum temperatures are controlled by the boiling point curve. Figure 10 shows the thermal gradient distribution, with the gradient clearly increasing in a north-northeast direction.

In order to obtain a clear idea of the isothermal distribution with depth, three isothermal maps are

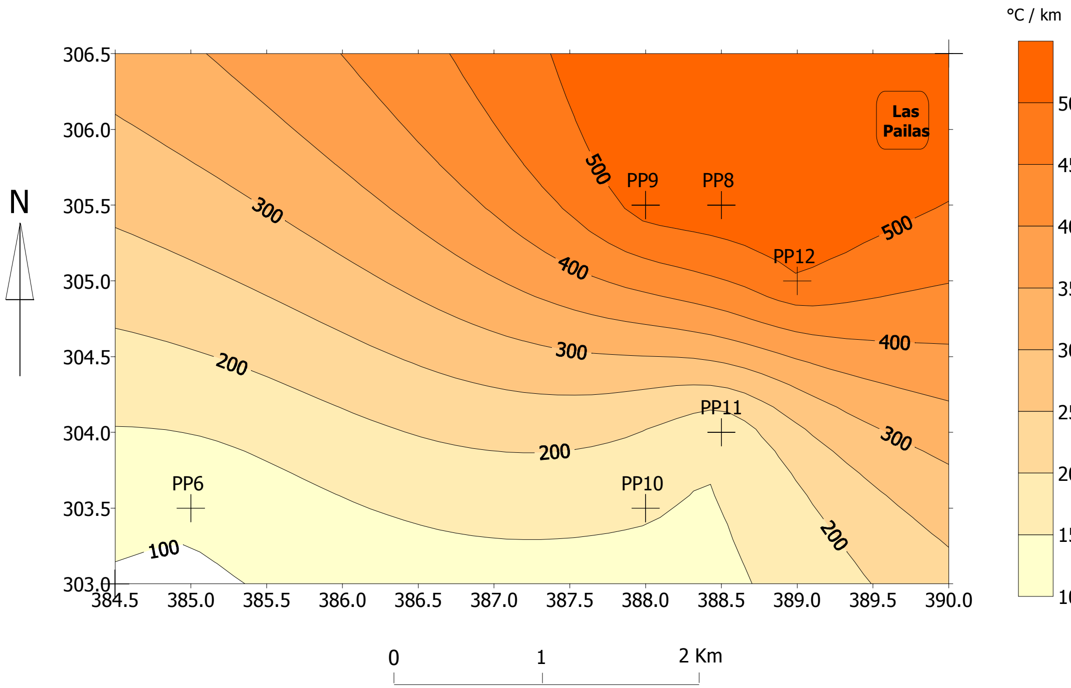

FIGURE 10: Thermal gradient map of the eastern and southern part of the Las Pailas geothermal area

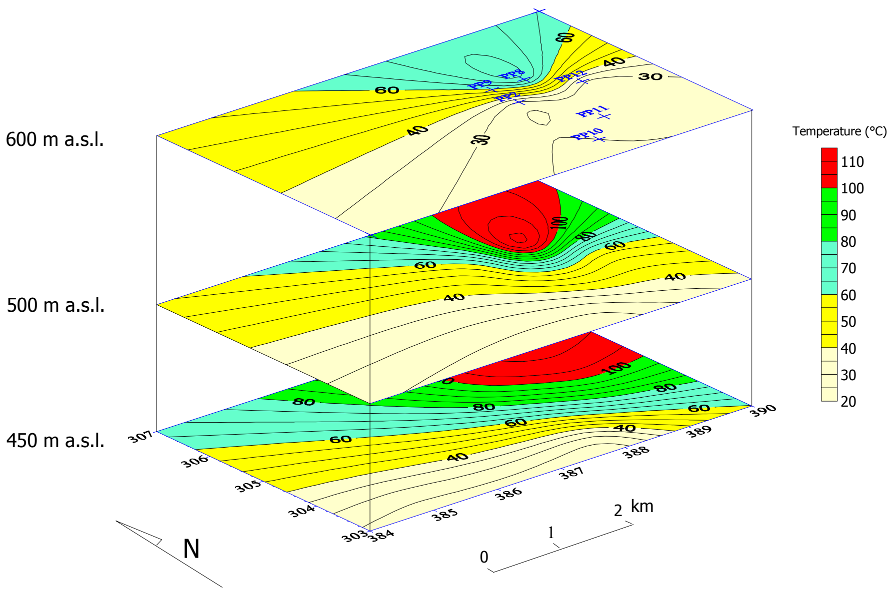

FIGURE 11: Isothermal distribution maps of the eastern and southern parts of the Las Pailas geothermal area, at 600, 500 and 450 m a.s.l.

presented in Figure 11, at 600, 500 and 450 m a. s. l. A plume-shaped anomaly appears in the northeastern corner of the maps, closest to the Las Pailas geothermal manifestation. It seems to be that the high heat flow ascends and takes advantage of existing structures (the northeast caldera margin, E-W alignment, or another buried structure). This, together with the topography, slope change (around the 800 m a.s.l.), generates the Las Pailas hydrothermal manifestations. Accordingly, further geothermal development of the Las Pailas geothermal area, such as drilling a deep exploration well, should focus on the north-northeast part of the field.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Geological frame for a hydrothermal model

The volcanism on the Pacific side of the Rincón de la Vieja complex evolved along an axis oriented W-E, progressing first eastwards, and then northeastwards toward the active Rincón de la Vieja volcano (Figure 8). The magmatic evolution began about 4.5 m.y. ago, first by an explosive activity producing the Cañas Dulces Caldera and the Fortuna, San Roque and Góngora andesite domes. Later, 1.5 m.y. ago, the same magma source gave rise to the Cañas Dulces and Torre domes of similar composition.

The migration of volcanic activity continued to the east and northeast parts of the area. This activity involved magma ascent to shallow depths, where magmatic evolutionary processes occurred in a magma chamber. Explosive activity and the formation of the San Vicente caldera and the San Vicente dacite dome followed (Figure 12). The acid Liberia formation was probably formed at the same time, although the volcanic crater and its location remain unknown. Inside the caldera, fluvial and lacustrine deposits were emplaced.

Later, 500,000 years ago, the volcanism migrated to the north, building up the present Rincón de la Vieja volcano. The volcano has produced pyroclastic flows, tuffs, lavas flows and lahars that filled the caldera.

5.2 Hydrothermal models A and B

The geothermal anomaly inside the San Vicente caldera shows an increasing thermal gradient to the north-

northeast, with the highest value of 528°C/km. The hot fluid appears to ascend along existing structures like a caldera margin at the foot of the Rincón de la Vieja complex. Two competing models to explain the thermal anomaly are presented below and in Figure 12.

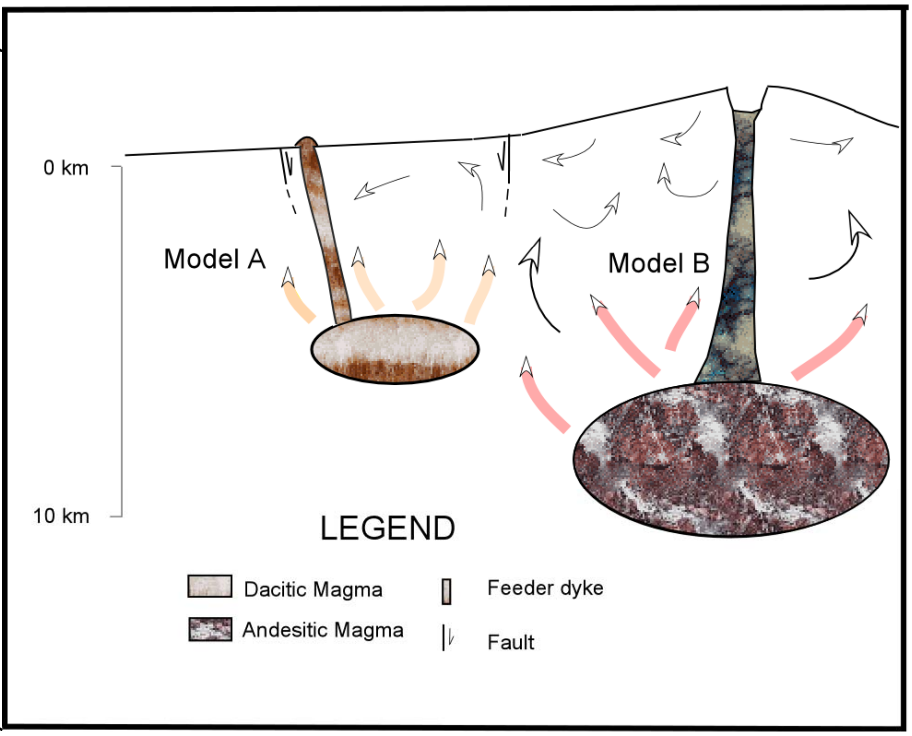

FIGURE 12: Geothermal models A and B for the Las Pailas geothermal area

- Model A assumes that a cooling magma chamber rests under the San Vicente caldera. This case is more favourable to future exploitation as a considerable part of the geothermal reservoir would be outside the Rincón de la Vieja national park.

- Model B assumes the present day hydrothermal activity is only related to a heat source under the Rincón de la Vieja volcano. This case is the more likely one in view of the younger volcanism. According to model B, most of the geothermal resource would be inside the national park. Directional drilling may be necessary in future exploitation.

- A combination of both may also be the case.

Either model could explain the existing thermal anomaly. The potential exploitation of the Las Pailas geothermal field rests on models of this kind. Accordingly, the models should be tested by further exploration and exploration drilling.

5.3 Recommendations

- The four thermal manifestation areas on the Pacific side of the volcano (Borinquen, Hornillas, Las Pailas and San Jorge-Santa María) are arranged in a northwesterly direction. A morphological support that might indicate a structural trap in this direction has not been noticed. A buried fault, like a caldera fault, might be present at depth. Further exploration is needed to assess the potential geothermal energy of the region.

- In order to obtain a model that might clear up the sequence of geological events in the Las Pailas geothermal area, it is essential to expand the area of study, to the east and north-northeast as well as the northwest. Furthermore, it is necessary to carry out age dating on the San Vicente dome, and in the fluvial lacustrine deposits in PP 11.

- The proposed hydrothermal models should be tested in future investigations. Exploration inside the national park is just as necessary as exploration outside it for that purpose.

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REFERENCES

Bergoeing, J., Brenes L., and Malavassi, E., 1983: *Geomorphology of the north Pacific side of Costa Rica (in Spanish). Explanation of a geomorphological map in 1:100,000*. U.C.R.-I.G.N., Costa Rica, 97 pp.

Chiesa, S., 1991: Biotite bearing flow in the Liberia river (Guanacaste), Costa Rica, Central America (in Spanish). *Geol. Amer. Central, 13*, 73-84.

Dengo, G., 1962: *Geological study of the Guanacaste region, Costa Rica* (in Spanish). I.G.N (National Geographic Institute), Costa Rica, 112 pp.

Dóndoli, C., 1950: *Liberia and its surrounding area* (in Spanish). Bol. Técn. Ministerio Agric. e Industria, Costa Rica, 8 pp.

Funaioli, G., and Rossi, L., 1991: *Geologic map of the Rincón de la Vieja volcanic complex in 1:50,000* (in Italic). Università Degli Studi Di Pisa, Italy.

GeothermEx Inc., 1999: *Pre-feasibility assessment of the Rincon de la Vieja geothermal field, Costa Rica*. Instituto Costarricense de Electricidad, San José, draft report.

Klein, C., and Hurlbut, C., S., 1993: *Manual of mineralogy* (by James D. Dana). John Wiley & Sons, Inc., NY, 704 pp.

Lescinsky, D., Connor, C., and Stoiber, R., 1987: Soil mercury study of thermal areas, Rincón de la Vieja volcano, Costa Rica. *Geothermics, 16-2*, 159-168.

Mainieri, A., 1976: *Guanacaste geothermal project, technical pre-feasibility geology report* (in Spanish). Instituto Costarricense de Electricidad, San José, internal report revised for GeothermEx Inc.

Sprechmann, P. (editor), 1984: *Manual of Costa Rica geology. Vol 1: Stratigraphy* (in Spanish). University of Costa Rica, San José, 320 pp.