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Hydrographic Characterization of the La Primavera, Mexico, Geothermal Field

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Keywords

La Primavera geothermal field, hydrographic characterization, hydrographic basin, drainage system, streams, Digital Elevation Model (DEM)

ABSTRACT

The La Primavera, Jalisco, Mexico, geothermal field is located within a hydrographic micro-basin of 39 square kilometers, named El Caracol. Six of the 13 wells drilled in the field are classified as producers, with a probable combined production of 221 tons per hour of steam at 8 bar of separation pressure, after their cleaning and possible repairing. Since 1989 Comisión Federal de Electricidad had to suspend its development operations in the field, and to carry on an environmental restoration program to get the environmental licenses, which has not progressed very far. Recent hydrographic characterization of El Caracol indicates this is a 4th order micro-basin, located at 1,591-2092 meters above sea level, with an average slope of 11.5%, a radial to semi-parallel dendritic drainage of intermittent type (July-September as the main rainy season), a hydrographic density of 2.62 run-offs per square kilometer and an average of 4.35 tributaries per stream. El Caracol presents a middle-high topographic relief, an efficient rainfall removal and a medium to high erosive potential.

Introduction

La Primavera is one of the five well-identified geothermal fields in Mexico. It is presently the only field with no geothermal-electric power plants, whereas in Cerro Prieto there are 13 power units with 720 MW, in Los Azufres 11 (93 MW), seven in Los Humeros (42 MW) and two in Las Tres Vírgenes (10 MW) (Figure 1).

The La Primavera field is located near Guadalajara City, capitol of the State of Jalisco, within a pine-oak

forest of the same name. Comisión Federal de Electricidad (CFE), which remains as the public utility in charge of generation, distribution and commercialization of electricity in Mexico, started the first reconnaissance studies in that field in the late 1960s. Since then, several geological, geochemical and geophysical surveys have been carried out. Geological studies included regional and detailed surveys, hydrothermal alteration mapping, volcanologic and micro-structural studies. Geophysical prospecting involved superficial thermometry, passive seismic, vertical electric sounding, magneto-telluric surveying, magnetometry and gravimetry (Palma-Pérez, 2001).

CFE drilled the first exploration well in 1980 (well PR-1), and then drilled another 11 wells between 1980 and 1988: wells RC-1, PR-2, PR-4, PR-5, PR-8, PR-9, PR-10, PR-11, PR-12, PR-13 and PI-1. One more well, PR-7, had to be abandoned at 1,386 meters depth. RC-1 was an exploration well located outside the reservoir, while the wells PR-4 and PR-5 were com-

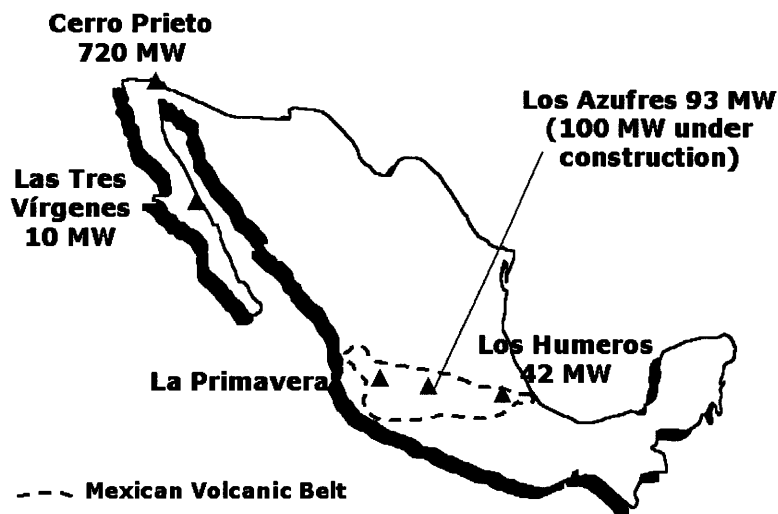


Figure 1. Location of geothermal fields in Mexico.

Table 1. General Conditions of La Primavera Wells.

Well	Depth (m)	Completion date	Max. Temp (°C)	Wellhead Press. (bar)	Production (t/h)		Status
					Steam	Brine	
PR-1	1,822	Sep. 84	299	11	40	55	Producer
RC-1	1,900	Jul. 80	98	0	0	0	Exploratory
PR-2	2,000	Apr. 81	334	0	0	0	Injection
PR-4	668	Aug. 81	80	0	0	0	Failed
PR-5	1,215	Aug. 82	262	0	0	0	Failed
PR-7	1,386	Aug. 87	0	Not yet measured			Adjourned
PR-8	1,861	Jun. 85	258	9	19	69	Producer
PR-9	2,986	Nov. 85	356	9	61	118	Producer
PR-10	2,271	Ago. 86	290	0	0	0	Failed
PR-11	2,157	Jul. 87	274	11*	58*	88*	Producer
PR-12	2,303	Jan. 87	340	14	24	34	Producer
PR-13	2,006	Feb. 88	288	18	19	70	Producer
PI-1	442	Dec. 88	100	0	0	0	Injection
Average	1,771		229	Total	221	434	

* Estimated. Table prepared with some data from Sánchez-Upton (2001).

pleted too shallow to reach the reservoir. Wells PR-2 and PI-1 are considered to be injection wells and well PR-10 failed due to some problems during its drilling and completion. The remaining six wells are producers, with a combined mass flow rate measured (and one estimated) at 221 tons per hour (t/h) of steam and 434 t/h of brine at 8 bars as separation pressure (Table 1).

These wells have not been under production for a period of 17 years. Thus, they need to be cleaned and probably repaired before they can be operated for production (and injection). A recent estimation on the combined production of these wells after their probable repairing, by applying a wellbore simulation model, results between 193 and 213 t/h of steam and 390-422 t/h of brine at the same separation pressure of 8 bars (Sánchez-Upton, 2001).

By March 1989 CFE was asked by the Jalisco state government to suspend all of its activities at the La Primavera field, as well as at an adjacent field, known as Las Planillas, where CFE was going to drill the first exploration well, until environmental impacts due to those activities were restored. Through 1989-1994 CFE developed a very complete program of environmental restoration over the 0.6 km² area affected by its former activities, under the unofficial supervision of state environmental authorities. More than 0.4 km² were covered with compost material and then local grass to stabilize slopes, 170,000 pine-trees were transplanted over 1 km², all the access roads were covered with asphalt, 196 filtering-dams were installed intercepting the run-offs to retain sediments, and many civil works were constructed (CFE, 1994). Since then, CFE has made the necessary maintenance of these works, but up to now has not got the official licenses to continue working in field. CFE has plans to install three 25-MW each condensing units in La Primavera, since assessment modeling has resulted in a potential electric output of 75 MW or more for the known reservoir (JICA, 1989; Suárez, 1995).

Recently the main physical characteristics of the hydrographic micro-basin where the field lies were defined with more detail, as a part of a new and comprehensive study on the present situation and results of the restoration works in La Primavera.

These characteristics are presented in this paper, with the main objective of update the hydrographic framework of the geothermal field.

Geological Setting

The La Primavera field is located at the western portion of the Mexican Volcanic Belt, adjacent to the jointing of three major continental structural elements: the N-S Colima Graben, the E-W Chapala Graben, and the NW-SE Tepic Graben, where there has been some active volcanism (Volcán de Fuego and Ceboruco volcanoes). Those regional structures have been considered as an extension zones, along which the western portion of continental Mexico would be moving towards northwest, thus becoming the Tepic Graben, a transform fault, and the Colima Graben, an extension basin (Nelson and Sánchez, 1986).

Tectonics could probably explain the peralkaline chemical type of rhyolitic lavas and domes (comenditic rhyolites) that constitute the Sierra La Primavera (Mahood, 1980). This sierra is a rhyolitic complex whose rocks exhibit excess of silica, which is a typical chemical feature of volcanism in zones under tensional stresses.

The La Primavera complex is a caldera whose formation process began at least 120,000 years ago, when an ascending magma chamber extruded the first rhyolitic domes and lavas. Then, 95,000 years ago, a series of explosive eruptions produced huge pyroclastics flows, flooding the surrounding valleys and forming the Toba Tala ignimbrites that presently cover an area estimated at 700 km². The aftermath of these quick eruptions, representing an evacuated magma volume of 20 km³ (Mahood, 1980), was a collapse of a roughly circular area of 11-13 km in diameter, forming the La Primavera caldera, inside of which a lake was formed. Over some 25,000 years lacustrine sediments covered the lake floor, and then, 70,000 years ago, a differential resurgence took place in the magma chamber, so forming the present sierra and extruding further domes and lavas. The youngest domes (El Colli dome among them) are dated at 20,000-25,000 years old.

The magma chamber has been since then in its hydrothermal stage of evolution, giving rise to a geothermal system at subsurface. Superficial evidences of this include fumaroles at the central-south part of caldera and perennial hot springs, with a combined mass flow of 400 liters per second, at the western caldera ring. Water from these springs is 65°C at the surface and of sodium bicarbonate geochemical type.

Subsurface lithology of the field, as indicated by wells, can be grouped into five units. From the top, the first one is composed of lacustrine sediments and pumice post-caldera deposits, with an average thickness of 33 meters and Quaternary age (<70,000 years). The second unit is composed of ignimbrites from the Toba Tala formation, presenting an average thickness of 366 meters and a radiometric age of 95,000 years. The third unit, underlying the ignimbrites, is composed of rhyolites, which present an average thickness of 64 meters and an age of 120,000

years. More than a single, continuous lava flow, this unit seems to be formed by several lava flows and domes close to each other. The fourth unit has been divided into three parts: a sequence of andesites and tuffs with an average thickness of 1,476 meters, a thin layer of rhyolites (69 meters) and another sequence of andesites with minor basalts with a thickness of 772 meters. Thus, this fourth unit presents a combined thickness of 2,317 meters, and an age from Late Miocene to Early Pliocene, which can be related to the early basement of the Mexican Volcanic Belt or the late volcanic activities of the Western Sierra Madre. Finally, the fifth unit is a granodiorite basement, cut only by the deepest well, PR-9, with a radiometric age of at least 7.3 Ma (Late Miocene) (Superintendencia General Guadalajara, 1989).

From a structural viewpoint, there has been identified a deep fault system of a NW-SE trend that affects the rocks of the fourth unit but does not seem to present a superficial expression. Some shallower systems, mainly due to the collapse and resurgent processes, are represented by some ring caldera fractures and some high angle fractures and normal faults of a NW-SE and NE-SW trends (Superintendencia General Guadalajara, 1989).

High temperature geothermal fluids are contained in the andesites, tuffs and rhyolites belonging to the fourth lithological unit, whose permeability seems to be mainly secondary, due to local and regional faults and fractures. Under this unit, granodiorite basement presents a much lower permeability, as do the overlying rhyolites constituting the third unit and so acting as a cap-rock.

The natural thermodynamic state of the system corresponds to a compressed liquid reservoir. The vertical pressure profile is almost hydrostatic at shallow depths and higher than hydrostatic below 1,750 meters depth. At shallow depths, fluids flash in the formation adjacent to wells, and then flow in as two phases inside the holes. At deeper depths, fluids come into holes in liquid phase and flash inside it. The average porosity has been estimated at 10% in the first 1,500 meters depth. Below this depth, the average falls to around 6%, but the fracture permeability is as high as hundreds to thousands of milidarcys (Suárez, 1995).

Up-flow of the geothermal system seems to be located adjacent to wells PR-1, PR-8 and PR-9, from where geothermal fluids tend to move towards west. Interaction between these fluids and the host rocks has left a hydrothermal mineral assemblages of medium temperatures, including calcite, quartz, clay minerals, chlorites and pyrite. Some relatively scarce epidote was found mainly in the well PR-1. In cuttings and core samples from several wells, the original rocks have been intensely altered (Gutiérrez-Negrin, 1988).

El Caracol Hydrographic Micro-Basin

The La Primavera field is located within a hydrographic micro-basin known as El Caracol, which is the name of its main stream. The El Caracol micro-basin occupies the eastern portion of the hydrographic sub-basin of the Etzatlán-Ahualuco-Río Salado Valley, which in turn is a part of the hydrographic basin of Río Ameca (Figure 2).

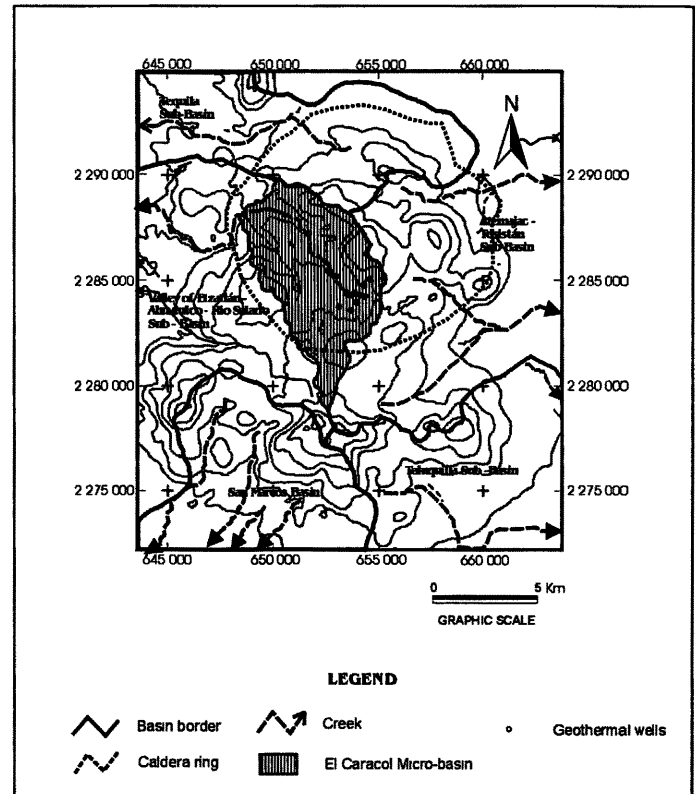


Figure 2. Location of the El Caracol hydrographic micro-basin in the La Primavera caldera.

Shape and Dimensions

The El Caracol micro-basin was delimited by using vector files from the official topographic chart, which were transformed to *shp* format of the Geographical Information System (GIS) ArcView 3.2. The main stream and drainage net were defined by means of the SWAT (Soil and Water Assessment Tool) hydrologic model applied on the Digital Elevation Model of the area, which in turn was obtained from the Geomodelos de Altimetría del Territorio Nacional (GEMA) edited by INEGI (Mexican statistical and geographical institution) with pixels of 100 x 100 meters.

The main stream is El Caracol, with a total length of 13.21 km, and an average slope of 3.4%.

The El Caracol micro-basin is kidney-shaped, enlarged in a N-S and NW-SE orientations. Its area is 38.97 km², and its perimeter 30.68 km, both determined through the GIS ArcView. The perimeter is defined as the length of the imaginary line contacting maximum-height points of the micro-basin.

The axial length of the El Caracol micro-basin, defined as the straight distance between ends of the main stream, is 6.59 km, while the middle length is 11.89 km. Shape index, which is defined as the ratio of the micro-basin area to the square of length of its main stream, resulted in 0.2233. The closer this index is to 1, the more circular is the shape of a basin and vice versa.

The so-called compactness coefficient of a basin, is the ratio of the basin perimeter to perimeter of a circle with the same area of that basin. For the El Caracol micro-basin this coefficient is 1.376, and, again, the closer this number is to 1, the more circular-shaped is the basin.

Shape coefficient is defined as the relation between the middle width of the basin and axial length. At El Caracol the middle width is 5.49 km and axial length is, as already mentioned, 6.59 km, thus the shape coefficient results 0.83.

Elongation ratio is defined as the ratio of a circle diameter with same area of the basin to the middle length of the basin (D/L). The area of a circle is πr^2 , and since $r = D/2$, then $A_c = \pi (D/2)^2 = \pi D^2/4$. So, $D = 2\sqrt{A_c/\pi}$. Replacing D and considering that micro-basin area is 38.97 km² and its length is 11.89 km, the elongation ratio for El Caracol results in 0.59. Plain basins have a elongation ratios around 1, and thus the El Caracol is a high to middle relief basin.

All of these shape and size features are shown in Table 2.

Table 2. Main Shape and Size Characteristics of the El Caracol Micro-basin.

Area	38.97 km ²
Perimeter	30.68 km
Axial length	6.59 km
Middle length	11.89 km
Length of main stream	13.21 km
Average slope of main stream	3.4%
Shape index	0.2233
Compactness coefficient	1.376
Shape coefficient	0.83
Elongation ratio	0.59

Drainage

The drainage system of the micro-basin is exogenous, since its main stream discharges outside. The type of drainage is intermittent, because there are water flows only during the rainy season: 80% of rainfall falls from July through September. Drainage is radial where streams begin, and then becomes semi-parallel dendritic, with segmented and incipiently mini-meander run-offs.

The hydrographic net of a basin is composed of one main stream and several tributaries which branches-off to the highest portions of the basin. A stream is defined as a transversal section of the basin through which water flows after rain. There are different criteria to classify streams, but one of them is based on number and type of branches the stream presents. A first order stream is a short tributary without branches. A second order stream has only first order tributaries. A third order stream only presents tributaries of first and second order, and so on.

The vector hydrographic net contained in the topographic chart of the zone was used to classify streams of the El Caracol micro-basin, and also GIS ArcView and the Spatial Analyst utility were utilized to measure each one. The main stream, El Caracol, is a 4th order class, and gathers water from the other four 3rd order streams, which are: Arroyo El Caballo, Arroyo Hondo, Arroyo El Gallo and Arroyo Arena Grande, with a combined length of 21.82 km. A complete classification of streams is presented in Table 3, and the whole micro-basin can be considered as 4th order.

Table 3. Classification and Features of Streams in the El Caracol Micro-basin.

Stream Order	Number	Total Length (km)	Bifurcation Ratio	Average Length (km)	Length Relation
1 st	81	74.60	5.06	0.92	—
2 nd	16	28.78	4.00	1.80	1.97
3 rd	4	21.82	4.00	5.46	3.03
4 th	1	13.21	—	13.21	2.42
Total or Average	102	138.41	4.35	5.35	2.47

Bifurcation ratio is defined as relation between the number of streams of a certain order and the number of streams of immediately higher order. The same Table 3 presents the bifurcation ratio for each stream order, and average for the whole micro-basin. This means there are 4.35 tributaries per stream on average, which indicates a good efficiency for draining the rainfall.

The average length for every stream order is presented also in Table 3. From these averages it is possible to obtain the length relation for micro-basin, which is defined as the ratio of average length of streams of order X to average length of streams of order $X-1$. Typical values for a basin are between 1.5 and 3.5, and the higher the number the more efficient drainage. The average length relation for El Caracol is 2.47 (Table 3).

The drainage density of a basin is the relation between total length of streams and its area, while the so-called hydrographic density is defined as the relation between number of streams and area. Both are an important parameters to evaluate possible floods at the topographically low portions of the basin. The El Caracol drainage density is 3.55 km/km², which results from dividing 138.41 km (total length of streams in the micro-basin, Table 3) by 38.97 km² (micro-basin area), and means there are 3.55 kilometers of run-offs per square kilometer. The hydrographic density is 2.62, resulting from 102 (total number of streams, Table 3) divided by 38.97, which means there are 2.62 run-offs per square kilometer.

Slopes

The average slope of a basin is defined as the ratio between difference of heights of the highest point and outlet of the main stream to half of the basin perimeter. There are several methods to calculate slopes, but now it is possible to use the Digital Elevation Model and the GIS ArcView to do that. Applying these tools to the El Caracol micro-basin, the average slope is 11.53% (with a standard deviation of 7.77%), minimum slope is 0.06% and maximum is 51.86%. Classification of the slopes is shown in Table 4. As one can see, a half of the micro-basin presents gentle slopes between 0 and 10%, and a third presents slopes between 10 and 20%.

Regarding elevations, the El Caracol micro-basin presents elevations between 1,590.64 and 2,091.75 meters above sea level (masl), with an average of 1,851.98 masl and a standard deviation of 108.35. These data were obtained by using ArcView and the Digital Elevation Model, which also gave the classification of micro-basin by elevations presented in Table 5. It is possible

Table 4. Classification of the El Caracol Micro-basin by slopes.

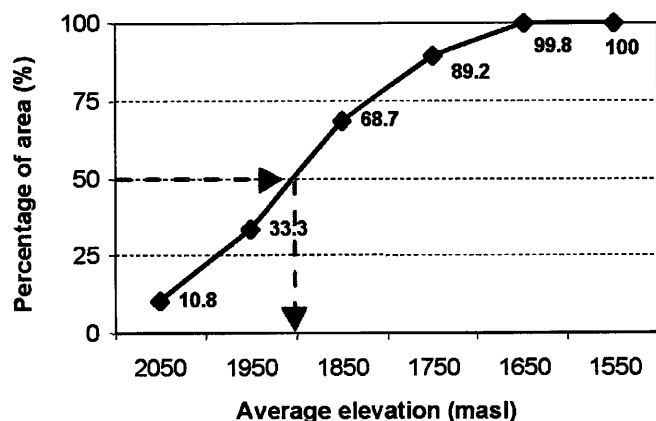
Slope Rank (%)	Area in	
	km ²	%
0 - 10	19.78	50.76
10 - 20	13.55	34.77
20 - 30	4.46	11.44
30 - 40	0.80	2.05
40 - 50	0.37	0.95
50 - 60	0.01	0.03
Total	38.97	100.00

to see that a third of the micro-basin lies between 1,800 and 1,900 masl, almost a quarter between 1,900 and 2,000 masl, and a fifth at 1,700-1,800 masl.

In addition, hypsometric curves were obtained in the El Caracol micro-basin. These curves express the relation between relative areas and their relative heights inside basin, and offer a general idea on the erosion potential. The typical behavior of these curves reflects three possible cases: basins with a high erosion potential, basins in balance and basins already highly eroded. The hypsometric curve for El Caracol is shown in the Figure 3, expressed in percentage of area. This curve implies the micro-basin presents an erosive potential from medium to high, considering the steep slope of its first half.

Table 5. Classification of the El Caracol Micro-basin by Elevations.

Elevation Rank (masl)	Area in	
	Km ²	%
1500 - 1600	0.09	0.2
1600 - 1700	4.13	10.6
1700 - 1800	7.97	20.5
1800 - 1900	13.80	35.4
1900 - 2000	8.78	22.5
2000 - 2100	4.20	10.8
Total	38.97	100.0

**Figure 3.** Hypsometric curves for El Caracol.

Some Conclusions

The La Primavera geothermal field lies within a hydrographic micro-basin, named El Caracol, which is a part of the Etzatlán-Ahululco-Río Salado Valley hydrographic sub-basin. The hydrographic characterization of the El Caracol micro-basin is as follows.

The main stream is El Caracol, with a total length of 13.21 km, an average slope of 3.4% and an intermittent type. The micro-basin is kidney-shaped, and it is located at elevations between 1,591 and 2,092 masl. Its area is 38.97 km², its middle length 11.89 km, and its elongation ratio results in 0.59, which means that El Caracol presents a high to middle relief.

The average slope of that micro-basin is 11.53%, the minimum slope is 0.06% and maximum is 51.86%. A half of its area presents a slope between 0 and 10%, and 35% a 10-20% slope rank.

El Caracol is a micro-basin of the 4th order, after the order of its main stream. Drainage is radial and semi-parallel dendritic, with a drainage density of 3.55 km of run-off per square kilometer, and a hydrographic density of 2.62 run-off per square kilometer. On average, there are 4.35 tributaries discharging in each stream, implying an efficient rainfall removal.

According to results of the hypsometric curve obtained for El Caracol, this micro-basin presents a high to medium erosive potential.

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