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La Primavera Caldera (Mexico): Structure inferred from gravity and hydrogeological considerations

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RESUMEN

El campo geotérmico de La Primavera, Jalisco, México, está asociado a una caldera riolítica Pleistocena. Este estudio gravimétrico fue conducido para apoyar su desarrollo y explotación. Procesamiento digital de los datos gravimétricos (continuaciones ascendentes y descendentes, derivadas verticales) permitieron delinear las principales características de la estructura subsuperficial de la caldera. Un modelo estructural 3-D fue establecido, el cual fue apoyado por modelado gravimétrico (modelado directo 2-D y 3-D). La caldera está caracterizada por una estructura subsuperficial asimétrica: una depresión mayor en su mitad norte, y un alto estructural en forma de boomerang hacia el sur. Se observan lineamientos reflejando la fábrica estructural NW-SE y NE-SW. Las unidades volcánicas basamentales están afectadas por lineamientos del sistema NW-SE, mientras que el sistema NE-SW afecta a las unidades someras. El alto estructural tiene una orientación NW-SE en su porción occidental y sur-occidental. De su parte media y hacia el este, presenta una dirección NE-SW. La actual zona de producción geotérmica se localiza sobre este alto estructural. Correlación con datos hidrogeológicos y geoquímicos permitieron interpretar las diferentes estructuras geológicas en el contexto del sistema hidrotermal: a profundidad las estructuras NW-SE parecen controlar la migración lateral de fluidos y conecta áreas de permeabilidad realzada (por ejemplo, la zona central de producción y las manifestaciones hidrotermales localizadas en el extremo occidental de la caldera). Se delinean zonas con fracturamiento realzado favorables para actuar como trampas de fluidos hidrotermales y accidentes que pueden actuar como conductos (respectivamente como barreras) de fluidos. En particular, una nueva área, hacia donde la producción de fluidos geotérmicos se podría extender ha sido identificada al sur de la zona de producción. La imagen estructural aquí elaborada constituye un marco geológico para el modelo geohidrológico conceptual prevaleciente. Esta información estructural es también útil para las tareas de selección de sitios para la reinyección de la salmuera geotérmica.

PALABRAS CLAVE: Estructura sub-superficial, caldera riolítica, La Primavera, Jal. (México), estudio gravimétrico, consideraciones geohidrológicas.

ABSTRACT

La Primavera geothermal field (Mexico) is associated with a Pleistocene rhyolitic caldera. A gravity study was conducted to assist in its development and exploitation. Digital processing of the gravity data (upward and downward continuations, vertical derivatives) enabled delineation of the main features of the caldera's subsurficial structure. A 3-D structural model was established, which could be supported by gravity modeling (2-D and 3-D forward modeling). The caldera features an asymmetric subsurface structure: a major depression in its northern half, and a boomerang-shaped structural high to the south. Lineaments reflecting the regional northwest-southeast and northeast-southwest structural fabric were observed. The basal volcanics units are affected by lineaments of the northwest-southeast system, whereas the northeast-southwest system affects only the shallower units. The structural high has a northwest-southeast trend at the western and southwestern portion of the caldera. From its middle part eastward, it has a northeast-southwest direction. The actual geothermal production zone is located above this structural high, on the portion where it changes orientation. Correlation with hydrogeological and geochemical data enabled interpreting the different geologic structures in the context of the hydrothermal system: at depth the northwest-southeast structures seem to control lateral fluid migration, and connect areas of enhanced permeability (i.e., the central production zone and the hydrothermal manifestations located at the caldera's western rim). Enhanced zones of fracturing favorable for entrapping hydrothermal fluids and structural accidents that may act as conduits (respectively as barriers) for fluids are delineated. In particular, a new target zone, where the production of geothermal fluids may extend, has been identified to the south of the production zone. The structural image elaborated here constitutes a geologic frame for the prevailing hydrogeological conceptual model. This structural information is also useful for the tasks of selecting sites for the reinjection of geothermal brines.

KEY WORDS: Subsurficial structure, rhyolitic caldera, La Primavera, Jal. (Mexico), gravity study, hidrogeological considerations.

INTRODUCTION

Mexico possesses, in different geologic environments, a large geothermal potential. The installed capacity for generating electrical power from high enthalpy hydrothermal systems amounts at present to 645 MW. It is expected that increasing the generation of electricity in the short term is possible by bringing into production geothermal fields located in the Trans-Mexican Volcanic Belt (TMVB). The TMVB (Figure 1) hosts most of the developed or

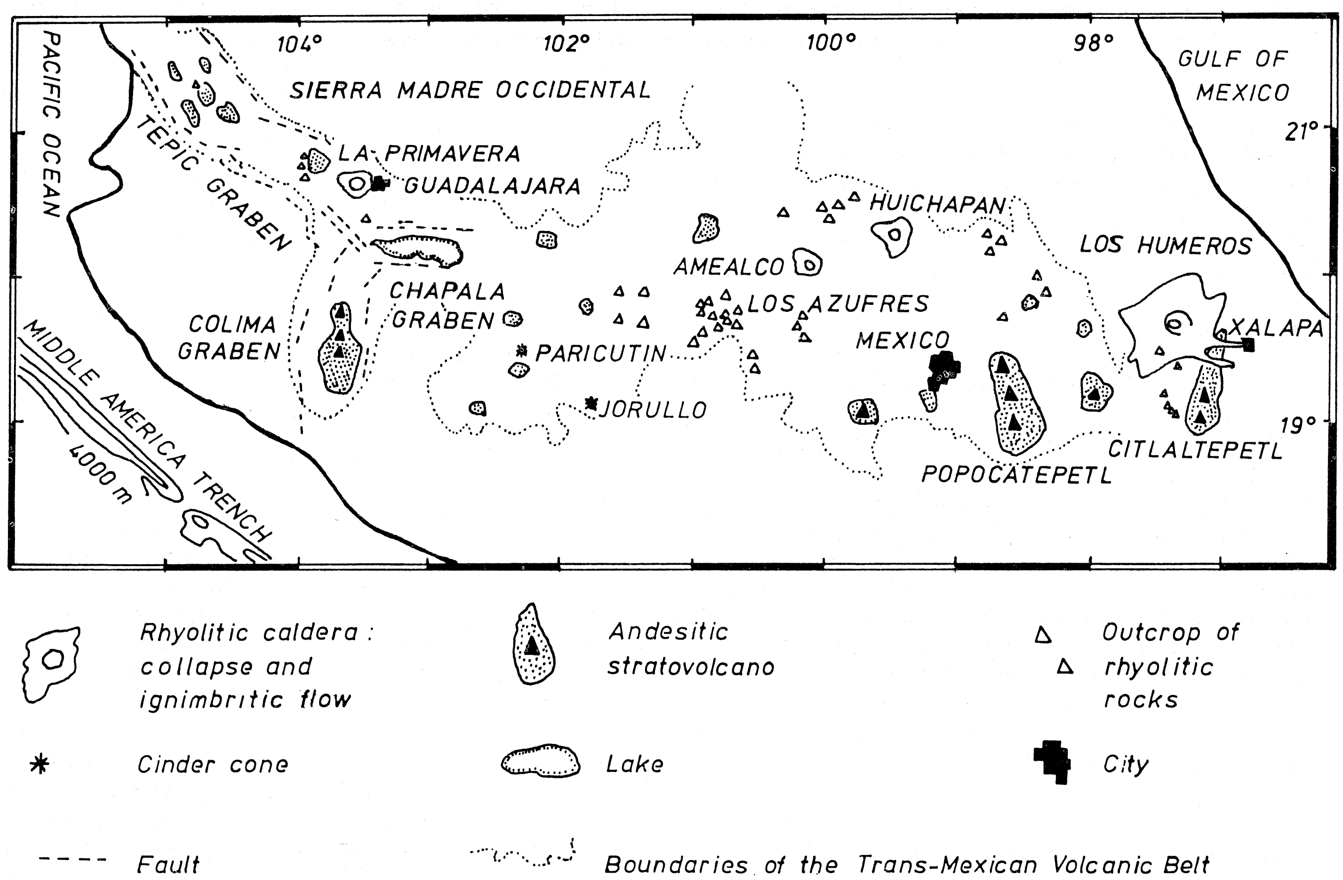

Fig. 1. Location of study area in the Trans-Mexican Volcanic Belt. The main andesitic and silicic volcanic centers are indicated.

promising geothermal areas (Alonso-Espinosa *et al.*, 1985). This geothermal potential is directly related to the historic and presented-day volcanic activity of this geologic province. In the western sector of the TMVB, 5 km west of Guadalajara City, the geothermal field of La Primavera is located. This field is associated with a rhyolitic caldera complex of Pleistocene age. González-Salazar and Razo-Montiel (1966) initiated a series of studies to assess the potential of this area. Since then the feasibility for generating electric power from geothermal fluids has been well established through different geologic, geochemical, and geophysical studies, as well as by the first exploratory wells (for example, Romero *et al.*, 1979; Romero, 1981; Reyes-Vermot, 1982). Plans exist to start production with two 5-MW electricity generating units at wellhead by 1990 (Alonso-Espinosa, 1987). Current exploratory studies are aimed to develop this field. The main concern here is to characterize the geothermal system, and to define its extension. In this context a knowledge of structures affecting the geologic units of this area plays a key role. This information, when correlated with geochemical and hydrogeological data, can also help to gain understanding of the hydrogeological system. This information is useful also for the task of locating sites for the reinjection of geothermal brines. In the final phase of the above mentioned exploratory campaign, with the purpose of characterizing the actual production zone, Comision Federal de Electricidad (CFE) and the Japan International Cooperation Agency (JICA), in the framework of a cooperation agreement, conducted geologic, structural, geochemical, magnetotelluric, and gravity surveys (JICA, 1986). These studies also confirmed the existence of an hydrothermal system. Regional aeromagnetic and paleomagnetic studies were also conducted (Campos-Enríquez, 1986; Campos-Enríquez *et al.*, 1987; Urrutia-Fucugauchi *et al.*, 1988).

The gravity study allowed delineation of the major structural features underlying the geothermal field (JICA, 1986). In particular, it was possible to delineate the presence of an elongated structural high underneath the production zone. The origin of this structure has been explained as due to resurgence (Mahood, 1981; JICA, 1986). The north and south rims of the caldera were established through 2-D modeling, constrained by well data and density information.

The structural model so obtained was accurate enough according to the semidetail purposes of the integrated study (JICA, 1986). Subsequently, as new well data were gathered, it was realized that detailed facts were not accounted for by this preliminary structural model. Even if the well data are of a local nature, they indicate that the production zone may extend toward the south (i.e., the isotherms trend in this direction). Resistivity studies had already defined a low resistivity anomaly with this same trend (Romero *et al.*, 1979; Bigurra-Pimentel, 1987).

We decided to pursue further interpretation of the gravity data to add detail to the preliminary structural model. We expected that a new refined geologic picture could help us to understand the hydrogeological system better by defining the continuity of the different units; to help us to identify places to which the production zone may extend, as well as to contribute useful information to the question of the reinjection of geothermal brines.

LOCATION AND GEOLOGIC SETTING

The TMVB crosses Mexico between 19° and 21° north latitude (Figure 1). It comprises most of the historic and present-day volcanic activity in Mexico: strato-volcanoes, cinder-cone fields, isolated occurrences of rhyolitic volcanism, and major silicic centers. A large geothermal potential is closely related to this volcanic activity. La Primavera geothermal field is associated with a major silicic center located in the western sector of the TMVB, just west of Guadalajara City (Figure 1). Because the rhyolitic domes associated with this late Pleistocene caldera constitute local mountain ranges outstanding in the study area, it is also known as Sierra La Primavera (SLP).

This area is interesting from at least two points of view. First of all, the TMVB intersects the Sierra Madre Occidental (SMO) here. The TMVB and the SMO are two of the major volcanic provinces of Mexico, and are related to present and past tectonic plate subduction processes occurring in this part of the Pacific Ocean (Molnar and Sykes, 1969; Atwater, 1970; Urrutia-Fucugauchi and Del Castillo-García, 1979; Urrutia-Fucugauchi, 1984). Secondly, this westernmost sector of the TMVB includes three regional grabens (Figure 1): the Colima graben, with an approximate length of 80 km and a north-south trend; the Chapala graben running about the same distance in an east-west direction; and the Tepic graben, with a northwest-southeast trend and a 180 km length. The intersection of these structures seems to constitute an incipient triple junction related to the plate tectonic phenomena acting in the Pacific Ocean at present (Luhr and Carmichael, 1981). La Primavera caldera is located approximately 50 km north of the intersection point. The regional structural fabric is dominated by the northwest-southeast system associated with the Tepic graben. In the southeast portion of the study area, the east-west system associated with the Chapala graben is also present (see, for example, Venegas *et al.*, 1979; Nieto *et al.*, 1985; Campos-Enríquez, 1986). Locally, in the caldera there exists a northeast-southwest system of normal faulting (JICA, 1986).

The regional basement is represented by a granitic substratum that has affinity with the Cretaceous-Miocene granitoids exposed along the western margin of Mexico. Overlaying this basement the following sequence occurs: (1) metamorphosed volcano-sedimentary group of Triassic to late Cretaceous age (limestones, sandstones, shales, schists and tuffs), in some places lower Tertiary units are present also; (2) the SMO group of dominantly volcanic products (ignimbrites, rhyolitic tuffs, flows, smaller amounts of andesites and basalts, all of Tertiary age) although mid-Tertiary lacustrine deposits are found locally; (3) the TMVB group, "sensu stricto," represented by calc-alkaline units of Plio-Quaternary age (mainly andesites and dacites); (4) recent sediment group (lacustrine, alluvial, and residual sediments).

This is the geological setting of the SLP, which formed during the Pleistocene (Figure 2). Activity apparently initiated with emplacement of rhyolitic lavas between 140 000 and 95 000 years. The eruption of the Tala tuff (ignimbrite and air-fall tuffs) followed. The products of this emission amounted to about 32-40 km^3 (Wright, 1981; Mahood, 1981), and gave rise to an 11 km-diameter caldera. Several flow units can be observed in the Tala tuff (JICA, 1986; Venegas, 1987), implying that the formation of the caldera was an intermittent phenomena. The middle part of the Tala tuff but not its upper and lower portions is well welded. Formation of a lake in the caldera permitted accumulation of sediments. A group of rhyolitic domes was then emplaced in the central portion and along a ring-like fracture zone (95 000 to 85 000 years). These events were followed by a period of relatively reduced volcanic activity during which some 30 m of lake sediments were deposited. A new group of domes was emplaced at about 75000 years ago, along the southern portion of the ring fracture system, and their emplacement was followed by uplift. According to Mahood (1980) this uplift was due to a rise of magma, and ended with the emplacement of domes and rhyolitic lavas to the south of the caldera (between 60 000 and 30 000 years ago).

The geothermal production zone is located 1000 to 1900 m below the surface, in andesites, and between 2000 and 2800 m below the surface, in basalts and andesites similar to those of the SMO (for example, Venegas, 1987). This correlation has been proposed mainly because of petrographic similarities (Clough *et al.*, 1982; JICA, 1986; Venegas, 1987), and because of the existence, in the northern neighborhood of the SLP, of volcanic units that correlate with the upper part of the SMO sequence (Gilbert *et al.*, 1985). Recently, preliminary results of a magneto-stratigraphic study seem to corroborate the existence of cordilleran (i.e., SMO) volcanic units under La Primavera caldera (Campos-Enríquez *et al.*, 1988).

Nieto *et al* (1985) reported geochronologic, petrologic, as well as structural data related to the area north of La Primavera caldera, where the TMVB intersects the SMO. They observed, based on statistical analysis of more than one thousand fractures, that the fractures clearly define two systems, striking N55°W and N35°E respectively. The first one is constituted by transcurrent faults with a left-handed "en échelon" arrangement and presenting a right-lateral sense of motion. Adjacent to the main fault trace,

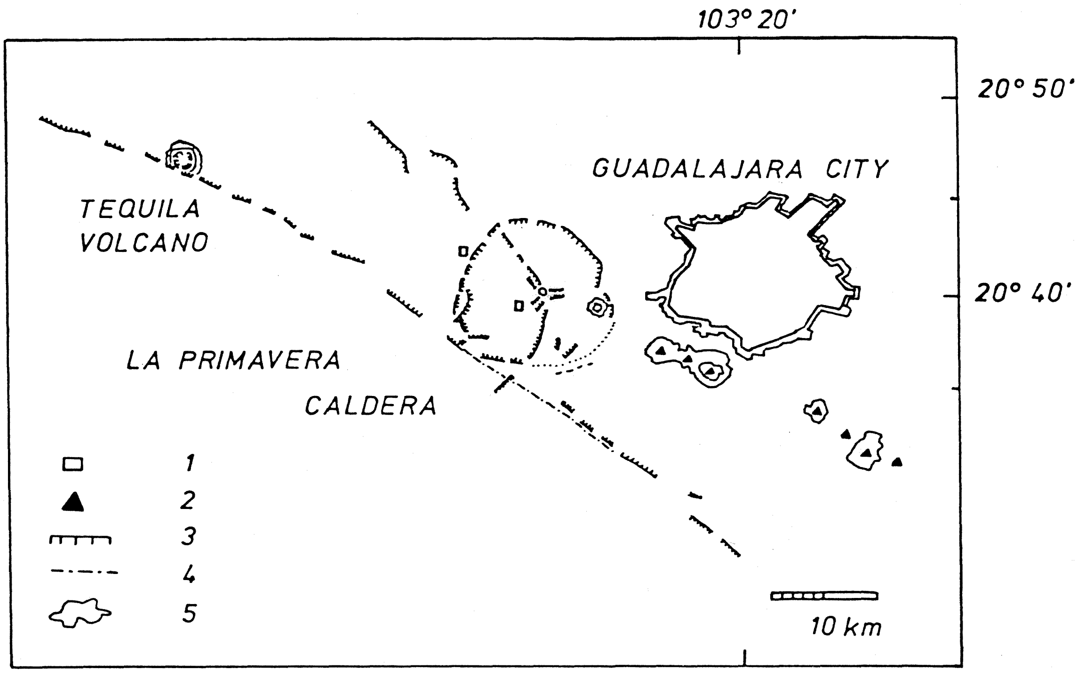

Fig. 2a. Regional geologic structures affecting the study area. 1: geothermal manifestations and actual production zone; 2: chain of Plio-Pleistocenic lava and cinder cones (Luhr and Lazaar, 1985); 3: mapped geologic faults; 4: inferred geologic structure after Campos-Enríquez (1986); 5: topographic high.

large sets of parallel fractures can be observed. Left-lateral strike-slip faults, with a minimum displacement, comprise the second system, and often connect the transcurrent faults at their ends. According to Nieto *et al.* (1985) these two systems constitute "ridels" or synthetic faults, and conjugate antithetic faults respectively (see Wilcox *et al.*, 1973). This right-lateral fault system seems to act as a conjugate fault system of a larger regional system of left-lateral strike-slip faults. The tectonic and geologic implications of such fault systems, as well as the mechanism that produced them, are beyond the scope of this paper and can be found in Nieto *et al.* (1985).

The faults present inside the caldera have orientations north-south, northwest-southeast, northeast-southwest, and east-west. These faults do not extend outside the caldera's rim, i.e., they do not affect older units (Venegas, 1987). A regional fault was inferred to run, in a northwest-southeast direction, from the Tequila volcano through the caldera. This fault was inferred because of the alignment of several volcanic cones (Venegas *et al.*, 1979). To the southeast of the study area, eight small lava and cinder cones, all of Plio-Pleistocene age, are also aligned in a northwest-southeast orientation (Luhr and Lazaar, 1985). This alignment, when prolonged towards the northwest cuts the caldera through its middle part. Even if no evidence at the surface of structures belonging to this system can be observed in the study area, it is reasonable to think that the northwest-southeast system affects the cordilleran units, i.e., the caldera's basement. Campos-Enríquez (1986), based on an aeromagnetic study, interpreted the presence of a northwest-southeast structure affecting the basement, and coinciding with the fault inferred by Venegas *et al.* (1979). This fault is tangent to the caldera's rim at its southwest portion. It is supposed that the northeast-southwest system affects the shallower units, while the northwest-southeast system affects the lower part of the cordilleran sequence (JICA, 1986; Venegas, 1987).

GRAVITY DATA BASE

In 1984, within the framework of the previously mentioned cooperation agreement between JICA and CFE, a gravity survey of the study area was conducted. This gravity study was done at two scales: (1) a regional survey of a broader area, including the SLP in its middle part (156 observations in 14 000 km^2 approximately), and (2) a detailed gravity coverage limited to the area of La Primavera caldera itself (306 measurements in a 238 km^2 area). The purpose of the regional coverage was to establish relationships between (1) the basement in La Primavera area (widely covered by Quaternary rocks) and its outcroppings outside the study area, and (2) between the caldera's structure itself and the above-described regional structural fabric.

A Lacoste and Romberg gravity-meter (type G) was used. Tidal, latitude, free-air, Bouguer, and terrain corrections were applied. Details of the gravity survey and corresponding data processing are reported in JICA (1986). Density was measured on samples from outcrops, and from selected drilling cores. Table 1, modified after JICA

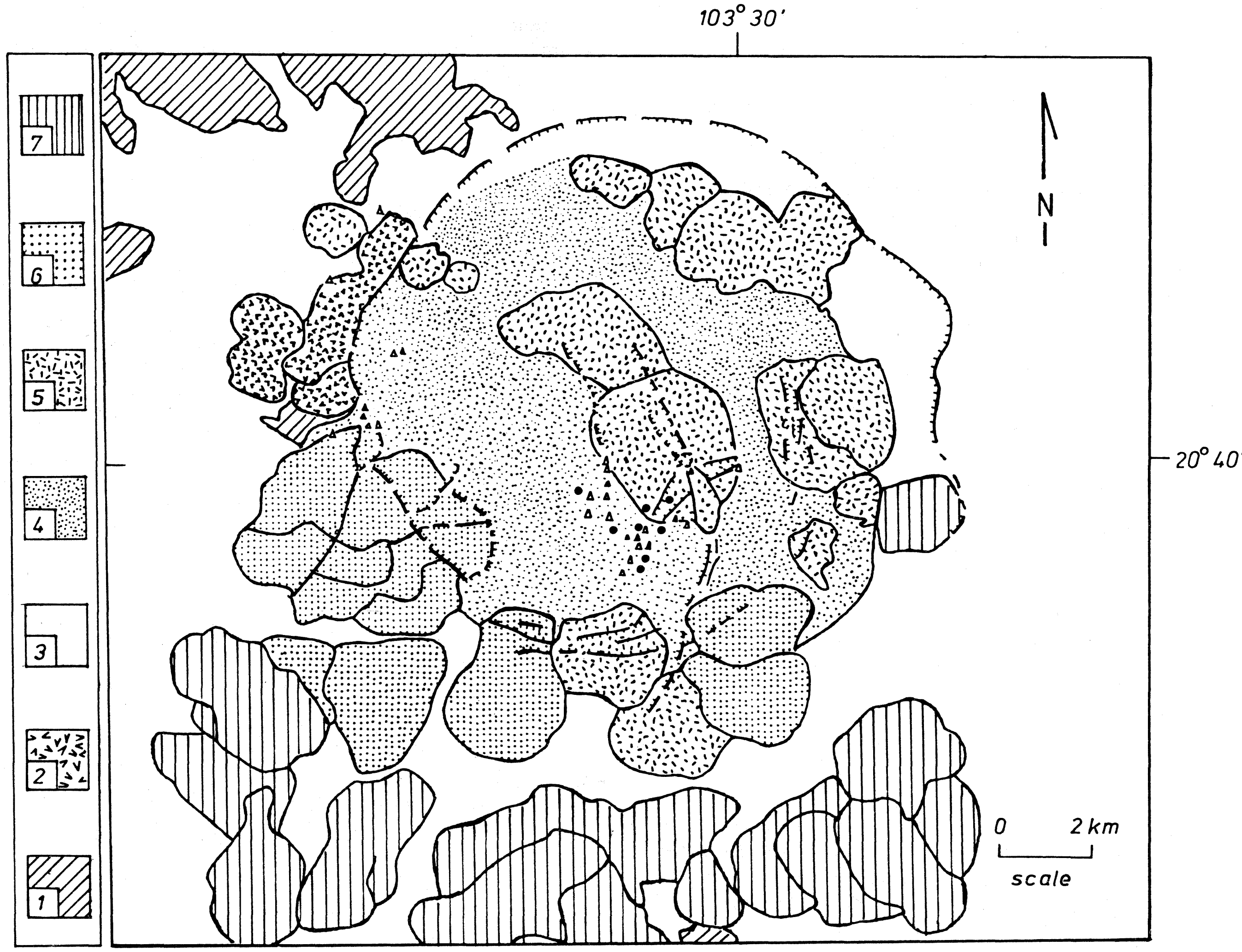

Fig. 2b. Simplified geology of La Primavera caldera. 1: local basement (ignimbrites and andesitic lavas); 2: precaldera rhyolitic lavas (0.14-0.095 My); 3: Tala tuff; 4: recent lake sediments; 5:older rhyolitic domes (0.095 to 0.085 My); 6: younger rhyolitic domes (0.075 My); 7: southern domes and rhyolitic lavas (0.06-0.03 My). Triangles represent locations of geothermal manifestations. Circles represent locations of geothermal wells.

Table 1

Densities of rocks of La Primavera caldera and of its basal sequence modified after JICA (1986).

Age	Rock type	Density range (kg/m^3)	Mean density (kg/m^3)	Number of samples	Source	Gravity model unit
Quaternary caldera	Rhyolite	2090–2360	2200 ± 100	6	1)	Top
La Primavera	Tala tuff	1670–2350	2050 ± 200	9	2)	
Tertiary	Rhyolite	1900–2550	2330 ± 180	10	1)	Middle
"SMO"	Tuff	1750–2450	2210 ± 210	7	2)	
(Cordilleran group)	Andesite	2200–2700	2370 ± 190	6	2)	
Subbasement	Basalt	2150–2850	2620 ± 190	6	1)	Bottom
tertiary and quaternary	Sedimentary rocks	2500–2600	2575	2	1)	

1) Surface samples
2) Surface and core samples

(1986), summarizes the densities of the main geologic units constituting La Primavera caldera and its basal sequence. The average density of the Quaternary, constituting the topography of the area, is 2.12 g/cm^3 (2120 kg/m^3). Because of the lower density of the lake deposits, a density of 2.00 g/cm^3 (2000 kg/m^3) was selected for the Bouguer correction (Figure 3). In Table 1 it can be observed that the rocks become denser with age, and a remarkable density contrast is observed between the basal sequence and the units of La Primavera. In particular, the rhyolite of the central dome presents a mean density of 2.21 g/cm^3 (2210 kg/m^3), and the Tala tuff (welded) has a mean density of 2.06 g/cm^3 (2060 kg/m^3), whereas the rhyolites and tuff of the upper part of the cordilleran sequence present densities of 2.33 and 2.22 g/cm^3 (2330 and 2220 kg/m^3), respectively.

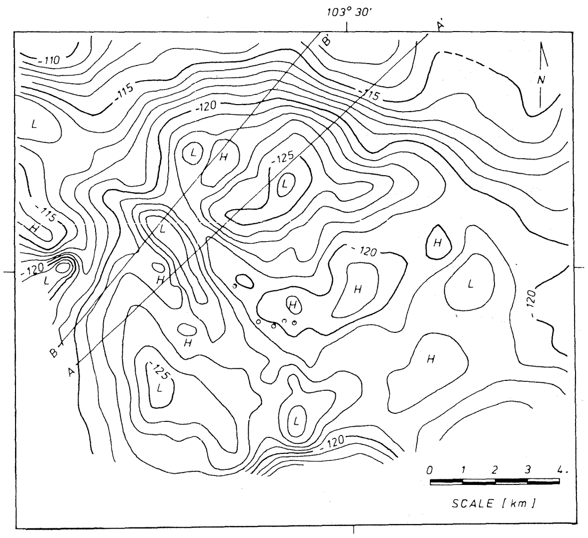

Fig. 3a. Bouguer anomaly map of the study area. Locations of profiles A-A' and B-B' are indicated. The geothermal manifestations and exploratory wells are represented by open circles. Density of Bouguer correction is 2.00 g/cm3 (2000 kg/m3). Contour interval is 1 mGal.

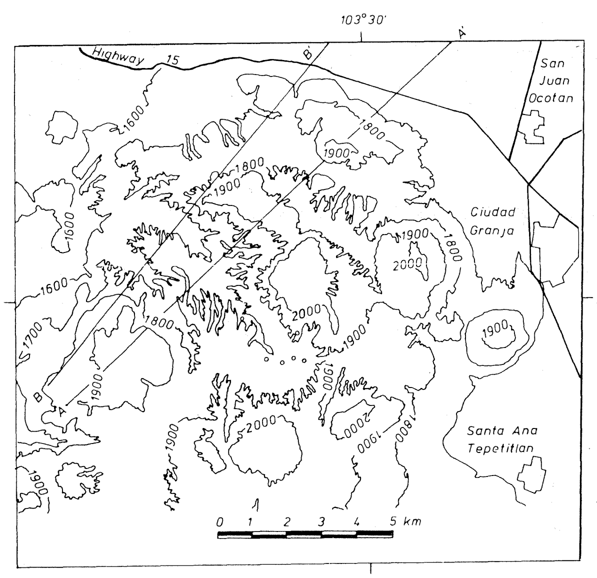

Fig. 3b. Topography of the study area. Location of profiles A-A' and B-B' is indicated. The geothermal manifestations and exploratory wells are represented by open circles. Contour interval is 1000 m.

PROCESSING AND INTERPRETATION

As a first step, several regional-residual separations were carried out. This was accomplished by least-squares fitting of polynomial surfaces of first and second degree to the data. The residual obtained by considering only the local detailed gravity survey is similar to that obtained when constraining the regional-residual separation process with the additional regional coverage. Thus, it was decided to work on the first order local residual anomaly map (Figure 4). This residual anomaly map correlates fairly well with the Bouguer anomaly map (Figure 3) reported by JICA

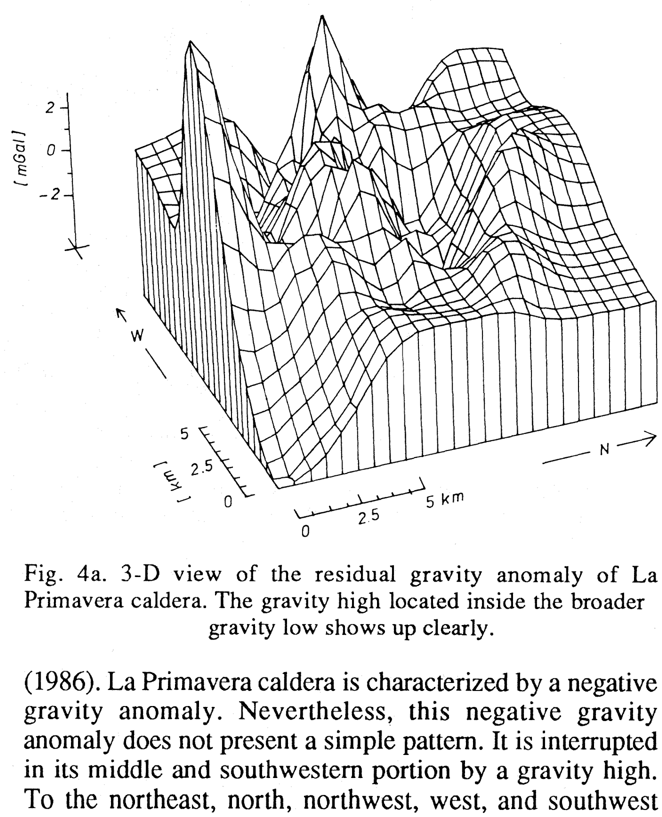

Fig. 4a. 3-D view of the residual gravity anomaly of La Primavera caldera. The gravity high located inside the broader gravity low shows up clearly.

(1986). La Primavera caldera is characterized by a negative gravity anomaly. Nevertheless, this negative gravity anomaly does not present a simple pattern. It is interrupted in its middle and southwestern portion by a gravity high. To the northeast, north, northwest, west, and southwest the anomalies have elongated shapes with a northwest-southeast trend. To the east and southeast, the anomalies have a northeast-southwest orientation. The gravity low that occupies the northern half of the collapse is also characterized, at its northeastern and southwestern limits by northwest-southeast lineaments, but it also presents lineaments with a northeast-southwest orientation. The northeast-southwest lineaments become more evident in the downward continuation and vertical derivative maps (Figures 5 and 6). The gravity high inside the caldera has a boomerang shape. At its western branch, it is cut in two by a gravity low oriented northwest-southeast. These features

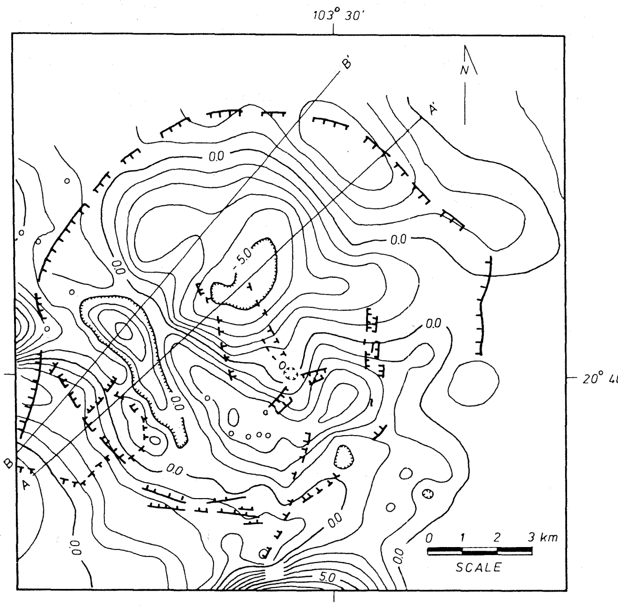

Fig. 4b. Residual gravity anomaly of La Primavera caldera. Main faults affecting and delimiting the caldera are indicated. The geothermal manifestations and exploratory wells are represented by open circles. Contour interval is 1 mGal.

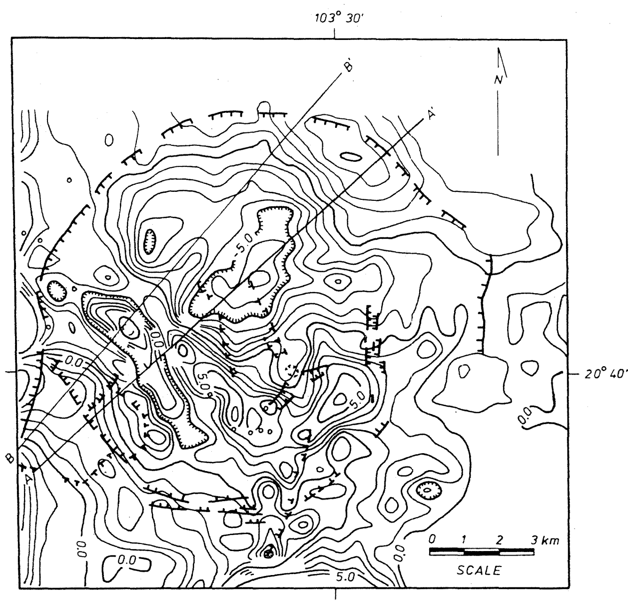

Fig. 5. First vertical derivative of the residual gravity anomaly of La Primavera caldera. Straight lines indicate locations of profiles A-A' and B-B'. Main faults affecting and delimiting the caldera are indicated. The geothermal manifestations and exploratory wells are represented by open circles. Contour interval is 1 mGal/km.

can also be observed in an upward continuation map (height of continuation 500 m, not shown here).

The vertical derivatives (Evjen, 1936; Elkins, 1951) and the downward and upward continuations (Peters, 1949)

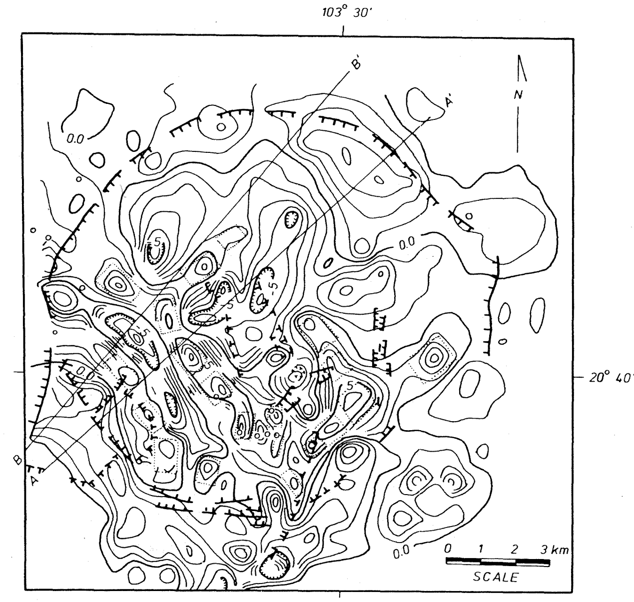

Fig. 6. Downward continuation to a depth of 200 m of the residual gravity anomaly of La Primavera caldera. Main faults affecting and delimiting the caldera are indicated. Horizontal boundaries of structural highs are approximately indicated by discontinuous lines. The geothermal manifestations and exploratory wells are represented by open circles. Contour interval is 1 mGal.

were done in the wavenumber domain, where the convolutions implied in these operations reduce to multiplying the FFT- transformed data by the respective wavenumber expressions of the respective operators (for example, Fuller, 1974; Campos-Enríquez, 1980).

A straightforward qualitative interpretation of this gravity pattern is the following: gravity lows (highs) are associated to structural depressions (highs), whereas the gravity gradients indicate faulting zones. As will be seen below, gravity modeling confirms this qualitative interpretation. In particular, the downward continuation and the first vertical derivative enabled us to decompose each anomaly into its major components, i.e., delimiting of the horizontal boundaries of the corresponding geologic bodies (Figure 6). This information led us to establish a global schematic picture, which shows the presence of a boomerang-shaped structural high in the southwestern and middle parts of the caldera. In its southwestern portion, an elongated depression with a northwest-southeast direction cuts this high in two. On the downward-continued map, the northern half of the caldera is characterized by a gravity low showing the presence of minor structural highs and lows with northeast-southwest directions. All this pattern is featured by northwest-southeast and northeast-southwest lineaments. The former ones are more marked in the south, southwest, and north, while the last ones are more evident in the north, northeast, and east. In particular, the structural high has a northwest-southeast direction in the west and southwest. From its middle part toward the east, it has a northeast-southwest direction. The actual geothermal production zone way, the production zone with the westernmost geothermal manifestations. In this last zone, the intersection of the collapse fault and this deep northwest-southeast fault would give rise to a zone of vertical permeability that enables the geothermal fluids to rise to the surface after having interacted with the shallower aquifer. In the production area, the zone of up-flow of geothermal fluids is also governed by fracturing associated to the intersection of the deep and shallow structural systems.

The indication of lateral flow along the deep faults limiting the structural high seems to be supported by other geophysical data. Resistivity studies have enabled mapping of the resistivity anomalies around the production zone. The pattern of the low resistivity zones also present lineaments of northwest-southeast, and northeast-southwest trend, and a boomerang shape (Romero *et al.*, 1979; Romero, 1981; Reyes-Vermot, 1982; Bigurra-Pimentel, 1987).

Since it seems that the permeability is indeed controlled by the northwest-southeast and northeast-southwest structural systems, the lineaments here are very interesting when selecting key targets for further exploratory drilling. In particular, south of the actual production zone where the northwest-southeast and northeast-southwest systems intersect each other, it is worth noting the presence of two structural lows in the middle part of the structural high and cutting through it. They represent zones of enhanced fracturing directly connected to the actual production zone. The existence, at approximately 1.5 km south of the production zone, of a low resistivity zone, reported by the MT study (JICA, 1986) could be associated with a vertical zone of enhanced permeability located along the limits of one of the structural lows. The fact that this zone is also affected by a high micro-seismic activity also seems to indicate the existence of geothermal activity (Reyes-Zamora, 1980).

CONCLUSIONS

This gravity study has delineated the major structural features of La Primavera caldera. It is characterized by an asymmetric subsurface structure: a major depression is located in its northern half. To the south, the basement presents a structural high, which constitutes a major feature of the geologic units underneath La Primavera. Lineaments of the northwest-southeast and northeast-southwest systems were observed to affect these two major features. The northwest-southeast lineaments represent a deep and regional system affecting the basal units, whereas the northeast-southwest, is a local one affecting only the shallower units. The limits of the caldera are clear in the northeast, north, northwest, southwest, and south, and are constituted by faults of subvertical to intermediate dip. To the west and east they are not clear. The faults delimiting the structural high are rather steep. The northwest-southeast system is likely to have played a key role in the evolution of the caldera. The production zone is located in the central part of the structural high. In this place the intersection of these two systems has given rise to localized enhanced zones of vertical permeability, that allow the vertical flow of geothermal fluids. At depth, the northwest-southeast structures seem to control the lateral migration of fluids, and connect areas of enhanced permeability, i.e., the central production zone and the hydrothermal manifestations located at the western rim of the caldera. This study has corroborated the presence of structures belonging to the northwest-southeast system. The correlation of this structural information with hydrogeological, and geochemical data enabled interpretation of the different subsurface geologic features in the context of the hydrothermal system, e.g., structural highs and other zones of enhanced fracturing, capable of entrapping, or acting as conduits for geothermal fluids. In this way it was possible to define a new target zone where the production of geothermal fluids may be possible. This structural information is also very interesting for the task of selecting sites for the reinjection of geothermal brines. The structural picture elaborated here constitutes the geologic frame of the prevailing hydrogeological conceptual model. Digital processing (vertical derivatives and downward continuations) proved useful in establishing the conceptual model, which was supported by numerical modeling (2-D and 3-D forward modeling).

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