

Rigorous Analysis of Available Data from Cerro Prieto and Las Tres Virgenes Geothermal Fields with Calculations for Expanded Electricity Generation

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Changes in legislation have opened the Mexican geothermal resources for exploitation to private companies; therefore the evaluation of the known geothermal areas has a high priority to plan further exploitation and possibly the expansion of the well fields. The calculation of the remaining productivity of geothermal fields currently in exploitation can be achieved with less uncertainty using the parameters obtained from production and injection wells, as well as the production efficiency of the installed plants. No information about previous volumetric evaluation is available for the fields presently being exploited, and there is the possibility that they may support an increase in their energy output or extend further their production life. The most widely used calculation technique is the USGS volumetric method that requires the knowledge of parameters that can be measured only after exploitation started. Heat in place-volumetric evaluation was undertaken for two fields in Mexico: Cerro Prieto and the Las Tres Vírgenes geothermal fields, using all information obtained by exploration surveys and exploitation drilling. The obtained values allow planning a possible expansion of the fields based on their estimated mean potential output that is 1397 MWe for Cerro Prieto and 48 MWe for Las Tres Vírgenes compared to the presently installed capacity of 580 MWe.

KEY WORDS: Volumetric heat in place method, Cerro Prieto, Las Tres Vírgenes, Mexico, Baja California, Geothermal resources evaluation.

INTRODUCTION

Geothermal energy exploitation in México started in the 1950s with the commissioning of the 3 MWe Pathé geothermal plant, and the Cerro Prieto geothermal field started producing electricity in 1973. Since then, México has been one of the leading producers of geothermal energy with four fields that rep-

resent almost 3% of the total electricity production in the country: Cerro Prieto, Las Tres Vírgenes, Los Azufres, and Los Humeros (Fig. 1). All the geothermal energy of Mexico used to be produced by the state-owned company Federal Commission of Electricity (CFE—Comisión Federal de Electricidad), but recent changes in legislation allow private companies to produce and sell electricity, and it has been announced that more of 90% of the probable geothermal resources in Mexico are now open for private investment. These new regulations are expected to promote investment in geothermal energy exploitation and utilization, and a key factor for this to happen is a reliable evaluation of Mexico's geothermal resources.

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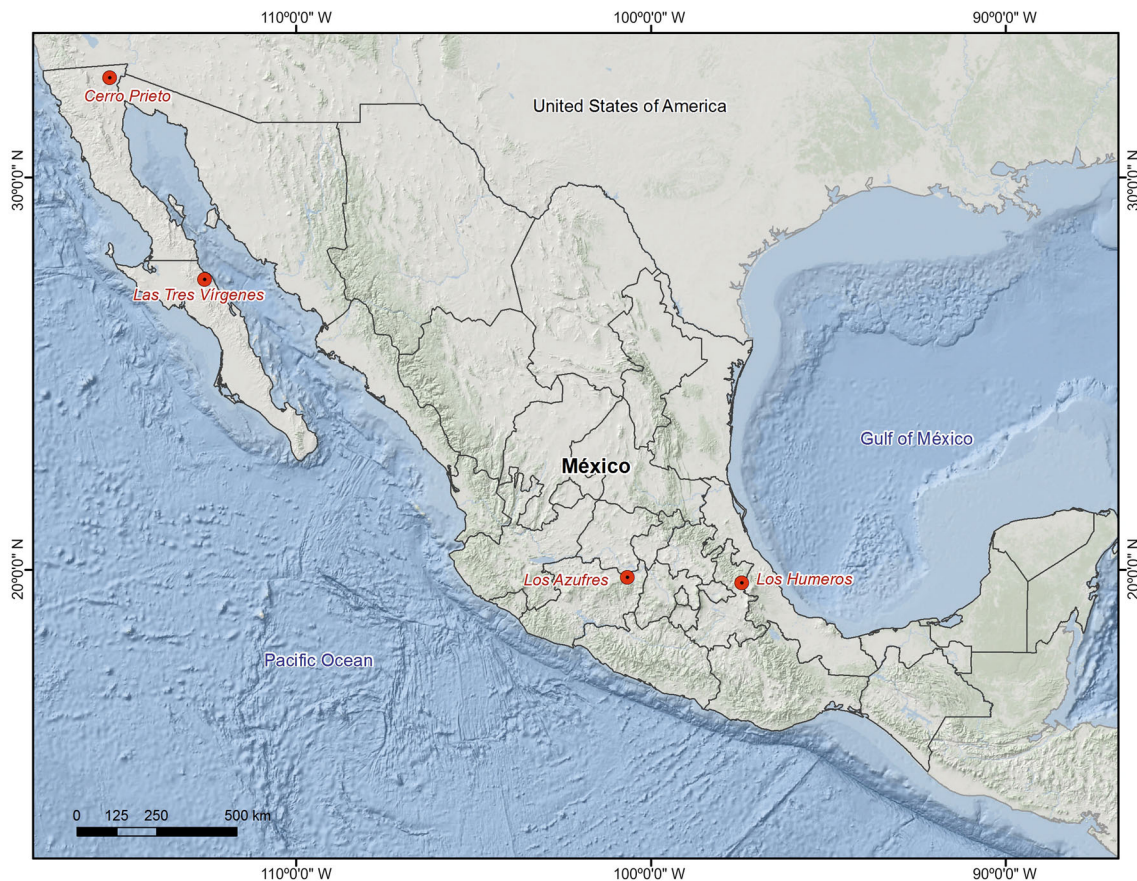


Figure 1. Location of the four geothermal fields currently in exploitation in Mexico.

Numerous evaluations of Mexico's electrical potential have been conducted since the early years of geothermal exploration; the results vary in several orders of magnitude (Table 1). The most recent national evaluation produced by CFE (Ordaz-Méndez et al. 2011) defines total geothermal reserves of almost 10,000 MWe for 1380 geothermal areas; more than 90% of which lack geophysical studies that would allow calculation of the reservoir volume. The most recent evaluation was published by Gutiérrez-Negrín (2012) based on data from Ordaz-Méndez et al. (2011) and Hiriart et al. (2011) with a total of 1940 MWe.

Traditionally, estimation of the energy potential of a hydrothermal system has been performed using the "heat in place" methodology proposed by Muffler and Cataldi (1978). However, recently more strict requirements have been established and geothermal resources must be assessed using the presently accepted methodology (AGEA-AGEG 2010; van Wees et al. 2013). Most published evalu-

ations of the geothermal resources in México do not abide by any of the presently accepted codes, as most of them lack geophysical surveys and exploration drilling that provide information on the reservoir parameters. Therefore, the planning of future development of Mexican geothermal fields requires intense work to gather required information. For instance, numerous geothermal systems have been studied in the Baja California Peninsula and preliminary evaluations indicate possible resources of more than 400 MWe (Arango-Galván et al. 2015) in addition to the 580 MWe installed in the Cerro Prieto and Las Tres Vírgenes geothermal fields (Flores-Armenta et al. 2014).

Knowledge of the estimated capacity of a geothermal field is vital in planning for further development. The geothermal potential of Mexico offers immense possibilities for investment in geothermal energy exploitation in new geothermal fields or developing joint ventures in fields already in exploitation that could be suitable for further

Table 1. Evaluation of the Geothermal Resources in México, Published by Different Institutions/Authors Since the Start of Geothermal Exploitation in the Country (Alonso 1975, 1985; Mercado et al. 1982, 1985; Iglesias and Torres 2003, 2009; Ordaz-Méndez et al. 2011; Hiriart et al. 2011; Gutiérrez-Negrín 2012; Arango-Galván et al. 2015)

Author (year)	Proved Reserves	Probable Reserves	Possible Reserves	MWe (Total)	Remarks
Alonso (1975)				4000	
Mercado (1976)				13,110	
Alonso (1985)	1340	4600	6000	11,940	
Mercado et al. (1985)				45,815	Hydrothermal manifestations with temperature in the range 125–135°C
Iglesias and Torres (2003)				2.26 10 ¹⁰ MWth	(276 geothermal areas with T between 60 and 180°C)
Iglesias and Torres (2009)				33.8 10 ¹⁰ MWth	918 zones with $T \leq 200^\circ\text{C}$ (1631 manifestations)
Ordaz-Méndez et al. (2011)	186	2077	7423	9686	1380 geothermal manifestations and geothermal fields
Hiriart et al. (2011)				751	Volumetric evaluation of 20 geothermal areas (with and without geophysical data)
Gutiérrez-Negrín (2012)	75	655	1210	2310	Based on Ordaz et al. Ordaz-Méndez et al. (2011) and Hiriart et al. (2011)
Arango-Galván et al. (2015)				>400 MWe	Only for Baja California Peninsula

development to increase production. Consequently, it is important to refine the estimation for future production in producing fields like Cerro Prieto and Las Tres Virgenes based on information gathered during their exploitation history. A similar approach was applied to compare previous evaluations by Turner (1969) and Bodvarsson and Bolton (1971) with the actual production of the Ahuachapán Geothermal Field by McNitt (1978), as well as in some geothermal fields in the Great Basin (Williams 2014) and in the Sumikawa geothermal field (Garg and Combs 2015).

In this paper we present most available data from the Cerro Prieto and Las Tres Virgenes geothermal fields, which have been producing electricity for many years, as in the case of Cerro Prieto more than 30 years. Production in both fields has remained stagnant or even decreased in the last few years, and the possibility of increasing energy production would be appealing for CFE and private investors. The analysis of the electricity generation capacity may be useful in planning for further development of both fields, and to compare previous resource evaluation with present production and future possibilities. In the analysis of the potential of both geothermal fields, we included data of surface manifestations, pre- and post-exploitation geophysical surveys, as well as well data to improve the results of the calculated resource potential.

GEOTHERMAL RESOURCE ASSESSMENT

There are several methods to estimate the amount of energy that can be extracted from a geothermal reservoir but the most widely used is the volumetric-probabilistic method utilized by the USGS, which evaluates the heat content in the rocks in the reservoir and the geothermal fluid (Muffler and Cataldi 1978; Muffler 1979; Williams et al. 2008; Garg and Combs 2010, 2015; Williams 2014). This method requires knowledge of the main reservoir parameters: temperature, rock specific heat, depth, effective porosity, permeability, as well as the fluid circulation model including recharge, predominant phase in the geothermal fluid, and the production methodology including extraction technique, drilling cost, efficiency of electricity production, investment cost, energy cost, investment risk, and environmental restrictions. The volumetric method includes several parameters, such as the reference temperature that are critical for the energy output. In a recent paper, Garg and Combs (2015) demonstrated that the reference temperature traditionally used in the volumetric method (i.e., ambient or condenser temperature), yields estimates that are too optimistic, as the reference temperature should be taken as the abandonment temperature, which would be the saturation temperature corresponding to the separation pressure. This value may reduce the

estimated energy output of the system by more than 50% (Garg and Combs 2015).

Generally, the application of the volumetric method in early exploration stages relies upon the estimated values of some parameters based on the results of geochemical and geophysical studies. However, continuous upgrade of these calculations should be conducted using the data acquired during each phase of the reservoir exploitation. This would provide fine tuning of the estimation of the reservoir electrical capacity by assigning more realistic values to the recoverable heat and the production efficiency and load factor. Williams (2014) demonstrated that comparison of results of the volumetric method with actual production in some fields in the Great Basin validates this method, provided it is properly calibrated with field measurements.

The common strategy for evaluation of geothermal areas includes estimation of reservoir temperature from geothermometer calculations, assessment of volume reservoir based on geophysical surveys, and average values calculated for known areas are assigned to the rest of the parameters. In the case of geothermal fields that are already in exploitation, data from exploitation wells are included in order to obtain better estimates, especially for the thermal recovery factor that is the critical parameter in the volumetric method. The thermal recovery factor can be known only after drilling data define parameters like permeability and porosity. This factor is generally assumed to be in the range from 0 to 0.20 (Garg and Combs 2010, 2015). Williams (2014) suggests that the range of the thermal recovery factor for sediment-hosted reservoirs, with higher permeability than those in volcanic rocks, is slightly higher from 0.10 to 0.25 and for fractured reservoirs the range should be from 0.05 to 0.20.

CERRO PRIETO GEOTHERMAL FIELD (CPGF)

The CPGF is located on the Colorado River delta plain where the Cerro Prieto volcano stands out with a height of 225 masl (Fig. 1). The reservoir is contained within the thick sediment cover deposited from Pliocene to Pleistocene (Halfman et al. 1984). The regional tectonics of Baja California is strongly related to the geodynamic setting of the Gulf of California. The opening of the Gulf of California and subsequent oceanic extension are the result of a local reorganization of the plate movement. In the northern part of

the peninsula, active faults associated with geothermal areas (Cerro Prieto and Ensenada) have an orientation N40°W and N70°W (Cruz-Castillo 2002). The fault systems in the Cerro Prieto area have NE–SW (Morelia, Hidalgo, Pátzcuaro and Delta faults) and NW–SE (Cerro Prieto, Imperial and Michoacán faults) directions; the latter system presents high volcanic and seismic activity and a close relation with hydrothermal manifestations (Puente and De-La-Peña 1979).

The Cerro Prieto volcano is located approximately 35 km south of Mexicali. The dacitic Cerro Prieto lavas are the only surface manifestation of volcanic activity in the surroundings of the CPGF. The volcanic activity has been dated by paleomagnetic evidence between 100,000 and 10,000 years (De Boer 1980). The volcanic rocks in Cerro Prieto are grouped in four types (Quintanilla-Montoya and Suárez-Vidal 1996): (a) basalt, (b) basaltic andesite, (c) andesite, and (d) dacite.

Thermal manifestations are mud pools, hot springs, and hot wells; additionally, most irrigation wells have temperatures ranging from 23 to 47°C (Portugal et al. 2005a). Geothermal water from hot springs and exploration/observation wells is sodium chloride type. Water samples from hot springs show partial equilibrium yield geothermometer temperatures in the range from 206 to 253°C, and the reservoir temperature calculated with geothermometers for well samples that are in full equilibrium is above 300°C (Portugal et al. 2005a). Measured temperatures in the exploration and production wells are between 280 and 350°C (Gutiérrez-Puente and Rodríguez 2000). All production strata are contained in sedimentary rocks.

The first geophysical surveys (Razo and Fonseca 1978), focused on the geothermal potential evaluation of the Cerro Prieto and Imperial faults, defined a typical pull-apart basin structure for the valley (Lira 2005). Further resistivity surveys (Razo and Arellano 1978; Díaz and Arellano 1979) detected three different geo-electrical units: the first one from 400 to 900 m depth with a resistivity value of 30 Ω m, a second more conductive horizon from 1300 to 3000 m with a resistivity value of 6 Ω m, and the deepest one (depth >3000 m) with resistivity values varying between 30 and 150 Ω m. Structures revealed by the geophysical studies in the CPGF are presented in Figure 2. These results were used in the early stages of development to determine the location of the reservoir and for delineation of the production area. A subsequent survey by Castillo et al.

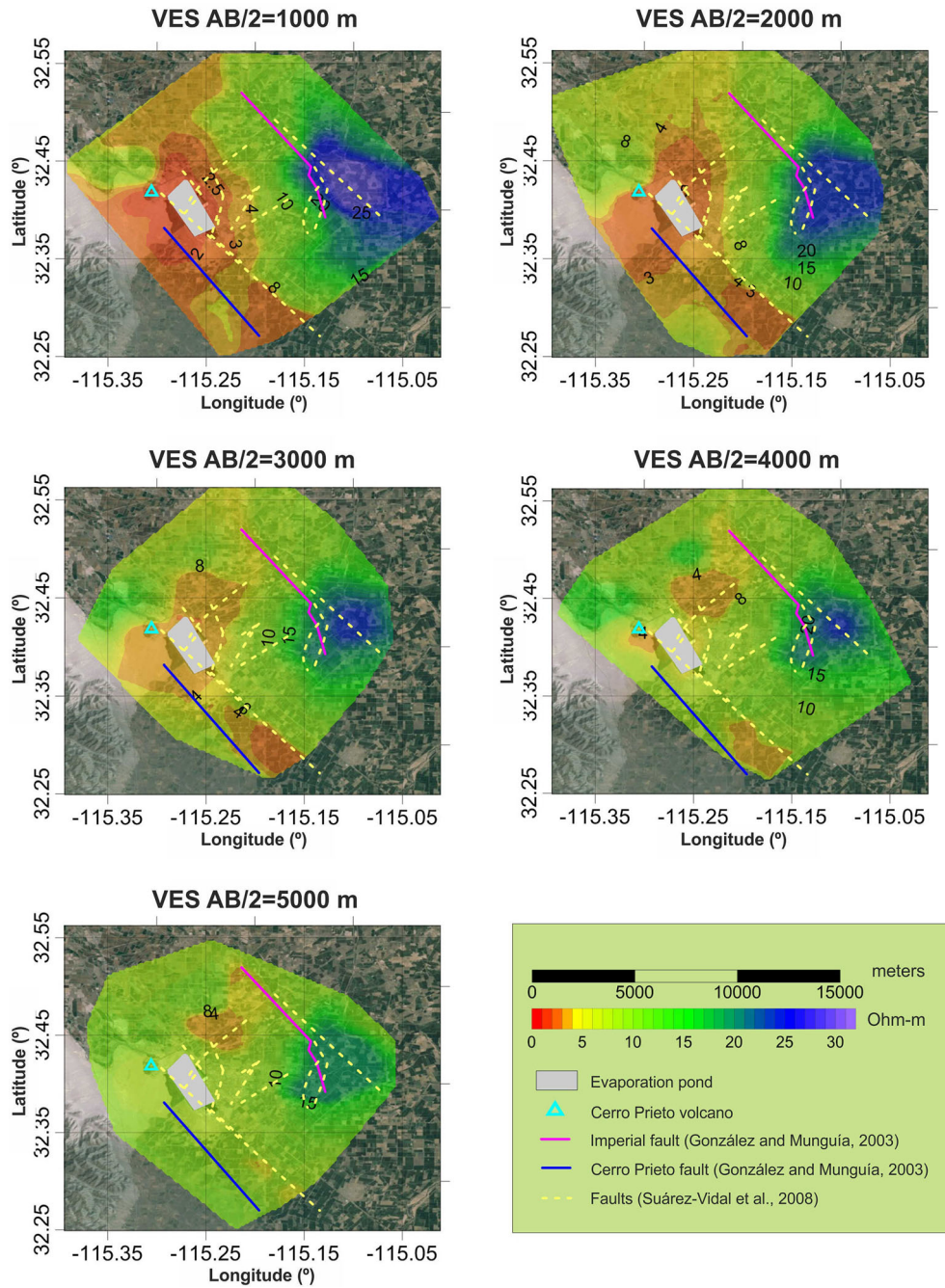


Figure 2. Structures defined by geophysical studies in the CPGF (after González and Munguía 2003; Suárez-Vidal et al. 2008; CFE 1984).

(1981) estimated that the reservoir maximum thickness was about 2 km and its area was in the interval between 18 and 30 km² based on high conductivity anomalies. These estimations agree with

the results of a 1979–1980 dipole–dipole survey (Wilt et al. 1984). A conceptual model of the field based on well data and hydrogeological parameters is shown in Figure 3.

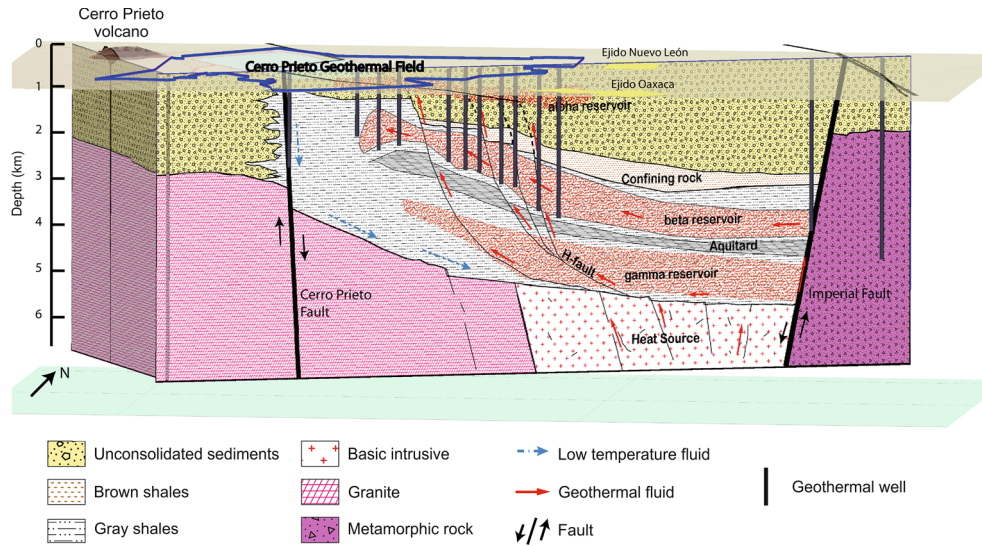


Figure 3. Conceptual model of the CPGF (after Lippmann et al. 1991; Lira 2005).

CPGF Production History

The CPGF is the largest producer of geothermal energy in México. In 2005 it produced 50% of the electricity (720 MWe) required in the NW part of the country (Portugal et al. 2005a). The long exploitation history of Cerro Prieto has been summarized by Gutiérrez-Puente and Rodríguez (2000), Lippmann et al. (2004), and DiPippo (2012).

Presently, the field is divided into four areas: CP-I (Cerro Prieto I), CP-II (Cerro Prieto II), CP-III (Cerro Prieto III), and CP-IV (Cerro Prieto IV). CP-1 was the first part of the field to be exploited in 1973. The CPGF reservoir has been divided into three sections: alpha, beta, and gamma. The alpha reservoir is restricted to the western part of the field; it is the shallowest one (depths are between 1000 and 1500 m; Gutiérrez-Puente and Rodríguez 2000). The beta reservoir is deeper (depths ranging from 1500 to 2700 m) with a minimum area of 15 km² (Portugal et al. 2005b); its temperature is much higher than that of the alpha reservoir and its top is defined by the upper limit of the silica-epidote continuous occurrence (Cobo 1979). There are no reports of exploitation of the gamma reservoir (Izquierdo et al. 2001), which is the deepest and hottest portion of the reservoir contained in the sand unit found below 3300 m depth with temperatures probably above 350°C (Lippmann et al. 1991). It has been hypothesized that temperatures above 350°C predominate at least over an area of approximately 5 km² in the Nuevo Leon section of the field (Cas-

tillo et al. 1981) that would be the minimum value of the gamma reservoir extent. The parameters of the deepest reservoir were estimated using completion and reservoir data for the deep well M-201 (depth = 3820 m) to simulate pseudo-transient flowing conditions (García et al. 1999): pressure—321 bar; temperature—350°C; porosity—0.15; transmissivity—8 Darcy-m; reservoir thickness—300 m; rock thermal conductivity—1.7 W/m K; rock density—2500 kg/m³.

Currently, the CPGF production is generated by 9 units (Flores-Armenta et al. 2014)—four 110 MW double-flash, four single-flash of 25 MW each, and one 30 MW single-flash, low pressure—amounting a total of 570 MWe, as the four 37.5 MW units in CP-I were decommissioned in 2012. The power units produced 3996 GWh in 2013 at an annual capacity factor of 78% with an annual average consumption of 8.5 tons of steam per MWh (Flores-Armenta et al. 2014), while in 2011 the capacity factor was 72% (Flores-Armenta 2012).

Based on early simulations of the first three exploitation stages for a period of 20 years, the pressure could at the end of this period be maintained close to 100 bars and the reservoir enthalpy would decrease to 1030 kJ/Kg, corresponding to a liquid water temperature value of 237°C (Castañeda et al. 1983). However, more recent numerical models (Antunez et al. 1991; Butler et al. 2000) agree that the most reliable source for long-term production, in order to ensure a 30-year long generation of at least 600–700 MW, would be the beta reservoir

(deeper than 1600 m). This statement has proved to be realistic as most wells in the alpha reservoir have now been shut. Some authors (e.g., Lippmann et al. 2004) stress the fact that large deep parts of the reservoir still remain unexploited and they could support future expansion of the field given the high temperatures expected.

Parameters for Volumetric Evaluation of the CPGF

Available data from the CPGF that can be used as input to volumetric evaluation are presented in Table 2. The only reservoir section that currently has enough information to be considered for a consistent volumetric evaluation is the beta reservoir. It extends over most of the well field at depths below 1600 m for at least 15 km² (Portugal et al. 2005b) and has an estimated minimum thickness of 1600 m (Butler et al. 2000). The area that bounds the producing area of the CPGF as reported by DOE-CFE (1982; in Castañeda et al. 1983) is 19.5 km², liquid water was the dominant phase in the reservoir but exploitation induced local boiling and the presence of small two phase areas (Grant et al. 1981). However, the reservoir remained liquid dominated. Castillo et al. (1981) reported that the maximum thickness of the reservoir is about 2 km and the maximum value for the area is 30 km² (Castillo et al. 1981) on the basis of the observed high electrical conductivity anomalies.

The maximum temperature measured in the eastern part of the field is 350°C (Lippmann et al. 1997). Exploitation data from Cerro Prieto for 28 years indicate minimum and maximum temperatures of 280 and 350°C, respectively (Gutiérrez-Puente and Rodríguez 2000). Production data indicate a mean temperature of 320°C (DiPippo 2012).

Feeding hot fluids ($T > 350^\circ\text{C}$) from the deepest reservoir (below 3300 m; Lippmann et al. 1991) have helped to keep the high temperatures of the beta reservoir. Therefore, even after more than 30 years of continuous exploitation, the beta reservoir was still keeping a maximum temperature close to 350°C (Gutiérrez-Puente and Rodríguez 2000). This hot recharge with the high porosity and transmissivity detected for the beta reservoir (Butler et al. 2000) validate the use of a recovery factor in the range of 0.10–0.25 for the CPGF beta reservoir (Garg and Combs 2010; 2015; Williams 2014).

The inlet saturation temperature of the low pressure turbine in CP-II and CP-III is approxi-

mately 135°C and the utilization efficiency is 49.3% (DiPippo 2012). This temperature can be assumed as the abandonment temperature for the volumetric evaluation (Table 2).

In addition to the evaluation of the beta reservoir, we attempted to estimate the minimum potential of the gamma reservoir using the minimum values for the reservoir parameters suggested by different authors and production parameters of CP-IV (Table 2). The future exploitation of this section of the reservoir would be an important contribution to the energy output of the CPGF.

LAS TRES VÍRGENES GEOTHERMAL FIELD (LTVGF)

The LTVGF is located in the central part of the Baja California Peninsula in a volcanic complex that includes three volcanic systems (Fig. 4): La Reforma Caldera to the east, Aguajito complex to the north, and the Las Tres Virgenes volcanoes to the southwest. These structures were emplaced along a NW–SE fault system between 3.5 and 0.8 Ma (López-Hernández et al. 1989) for La Reforma Caldera; between 0.7 and 0.45 Ma for the Aguajito complex (López-Hernández et al. 1993), and from 0.4 Ma to the present for Las Tres Virgenes volcanoes (López-Hernández et al. 1995).

Three volcanoes form the Las Tres Virgenes complex. The oldest is called El Viejo (0.44 Ma) and the youngest is located to the south (La Virgen), which is still active (Fig. 4). The composition of these volcanoes is mostly dacitic to the north but shifts to basaltic to the south (López-Hernández et al. 1995). The volcanic complex is located in a Plio-Quaternary depression that is the western border of a NW–SE regional transform fault related to the opening of the Gulf of California (López-Hernández et al. 1995). The NW–SE Las Víboras fault system is the one related with the hydrothermal activity.

Exploration studies were conducted in a 250 km² area and defined an extension of the geothermal field of 57 km² (García-Cruz and Ramírez 2000). Numerous hydrothermal manifestations occur in the field and chemical compositions include: sodium chloride, sulfate, and bicarbonate water (Portugal et al. 2000; Tello et al. 2005; Viggiano-Guerra et al. 2009; Birkle et al. 2010). Geothermal water from the production wells is sodium chloride type and presents full equilibrium

Table 2. Parameters for Calculation of Production Potential of Cerro Prieto and Las Tres Vírgenes Geothermal Fields, Obtained from Available Information

	Cerro Prieto (Beta Reservoir)	Cerro Prieto (Gamma Reservoir)	Tres Vírgenes
Area (m ²)			
Min.	15,000,000 ^a	5,000,000 ^c	6,000,000 ^k
Mean	19,500,000 ^b		
Max.	30,000,000 ^c		30,000,000 ^l
Thickness (m)			
Min.	1600 ^d	300 ⁱ	300 ^k
Max.	2000 ^c		1300 ^m
Temperature (°C)			
Min.	280 ^e	350 ^j	225 ^m
Mean	320 ^f		275 ^m
Max.	350 ^e		300 ⁿ
Abandonment temperature (at Psep)	135 ^f	135 ^f	150 ^k
Recovery factor ^g			
Min.	0.10		0.05
Max.	0.25		0.20
Utilization efficiency (%)	49.3 ^f	49.3 ^f	13 ^o
Average plant capacity factor (%)	78 ^h	78 ^h	56 ^h

Data from: ^aPortugal et al. (2005b); ^bCastañeda et al. (1983); ^cCastillo et al. (1981); ^dButler et al. (2000); ^eGutiérrez-Puente and Rodríguez (2000); ^f(DiPippo 2012); ^gWilliams (2014); ^hFlores-Armenta et al. (2014); ⁱGarcía et al. (1999); ^jLippmann et al. (1991); ^kTello-López and Torres-Rodríguez (2015); ^lbased on the extension of the conductivity anomalies reported by Flores and Velasco (1998) and Romo et al. (2000); ^mGarcía-Cruz and Ramírez (2000); ⁿPortugal et al. (2000); ^obased on calculations from Zarrouk and Moon (2014).

with a calculated reservoir temperature around 300°C and the isotopic composition indicates a magmatic contribution of at least 30% (Portugal et al. 2000).

Permeability in the field is secondary and associated with the NW–SE and N–S faults. It varies from 0.3 to 3.0 mD, with an effective porosity from 0.4 to 5% (Contreras and García 1998). The national water authority (CONAGUA) has evaluated 4.7 hm³/year as the mean annual recharge of the local aquifer (CONAGUA 2011) and the average annual rainfall amounts to 62 mm with maximum values of 150 mm at the summit of La Virgen and El Azufre volcanoes (Portugal et al. 2000). Climate, hydrogeological conditions, and age data of the geothermal water suggest that modern water recharge might be practically absent (Birkle et al. 2010). However, hydrogeological studies have not yet provided enough evidence to establish the nature and volume of the field recharge (Birkle et al. 2010).

Geophysical information for the Las Tres Vírgenes geothermal field is abundant. A review of the reported surveys is shown in Figure 5. The earliest results obtained by Razo Montiel (1984) indicate the presence of a conductive body (between 3 and 8 Ωm) at a depth of 1900 m. Gravity

and magnetic data show that the main structures have a direction NE–SW in Volcán El Azufre, Volcán Partido, and Sierra El Aguajito, and NW–SE in El Azufre Canyon. Minimum magnetic values are associated with hydrothermal alteration in the area of El Azufre, La Biznaga, and Las Víboras. The most recent geoelectric studies (Flores and Velasco 1998; Romo et al. 2000) showed that the most interesting area for geothermal exploration is located along El Azufre Canyon that represents the border between the volcanic complex Las Tres Vírgenes and El Aguajito Caldera (Fig. 5). Both reports provide results that indicate the presence of conductive bodies at approximate depths of 1500 and 12,000 m. The thickness of the shallow conductive layer observed in those studies varies from 0.5 to 3 km and has an area of at least 30 km². However, very low resistivity values could be partly related to the presence of a clay layer. This would cause overestimation of the reservoir volume. Therefore, the area of resistivity anomalies (30 km²) should be considered as a maximum value for the reservoir extension. A conceptual model of the Las Tres Vírgenes field based on compiled geological and geophysical data is presented in Figure 6.

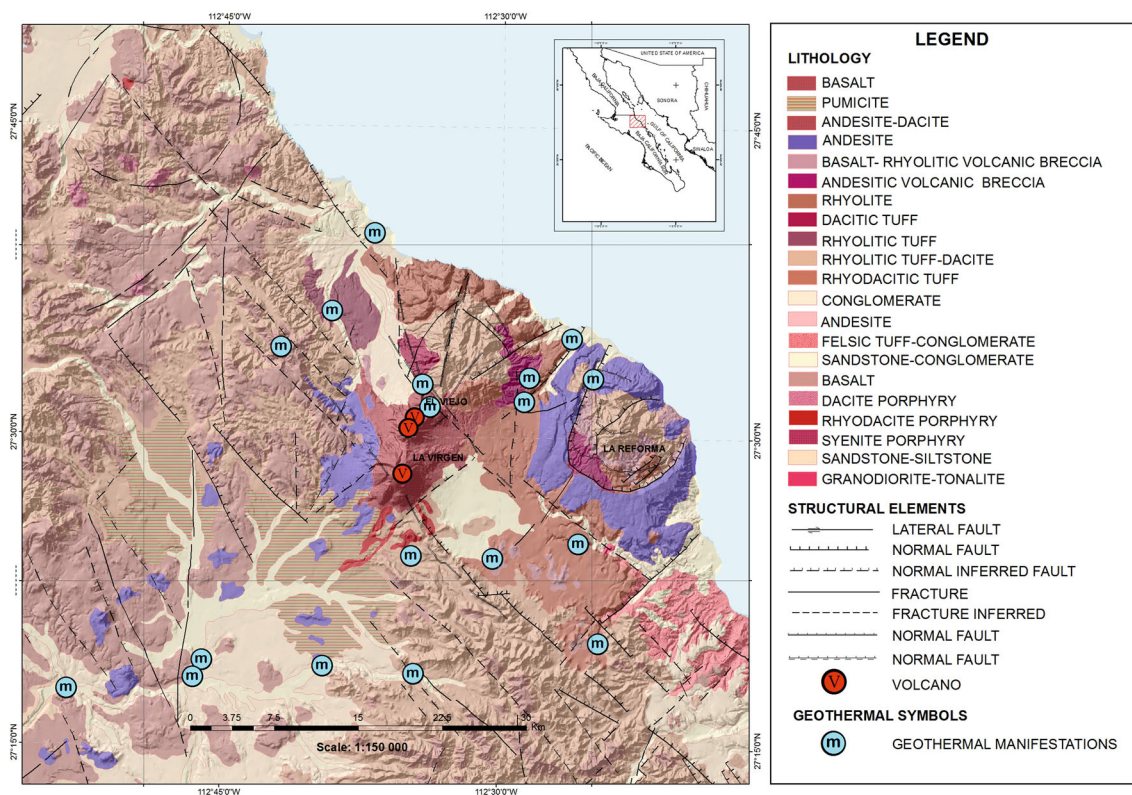


Figure 4. Surface geology and main structures in the LTVGF (after Wong et al. 2001).

Production History and Parameters for Volumetric Evaluation

Exploration in the LTVGF started in 1986 and production started in 2001. Currently, it has an installed capacity of 10 MWe with two back-pressure 5 MW generation units at an annual mean capacity factor of 56% in 2013 (Flores-Armenta et al. 2014).

The initial evaluation of the field for exploitation assessed an area of 90 km² and 1500 m thickness for the reservoir that is contained in the granodiorite horizon at a depth of more than 1000 m (Flores-Armenta and Jaimes-Maldonado 2001). However, a recent evaluation of the reservoir reports an area of 6 km² by considering only the producing wells location (Tello-López and Torres-Rodríguez 2015); these authors estimate a reservoir thickness of 300 m based on the main permeable zone. García-Cruz and Ramírez (2000) proposed 1300 m as the thickness of the reservoir using observations during drilling (circulation loss, alteration intensity, and temperature profiles). Feeding

zones have been identified at different depths in the wells (Barragán et al. 2010).

After almost 15 years of exploitation, the uncertainty in the reservoir parameters is large: 6–90 km² for the area and from 0.3 to 1.5 km for the thickness. Therefore, we use the values that are supported by drilling or geophysical evidence and designate the minimum and maximum values for the area and the thickness as 6 and 30 km², and 0.3 and 1.3 km, respectively.

The lowest temperature reported is 225°C in the northern part of the field, which is not presently in exploitation (Torres-Rodríguez and Sánchez-Velasco 1995). The most recent report for temperature and pressure is 275°C and 144 bars, respectively, in producing wells in the southern part of the field (Tello-López and Torres-Rodríguez 2015). However, the highest temperature calculated for the reservoir is 300°C (Portugal et al. 2000). Abandonment temperature is considered to be the saturation temperature at the installed plants—150°C (Tello-López and Torres-Rodríguez 2015).

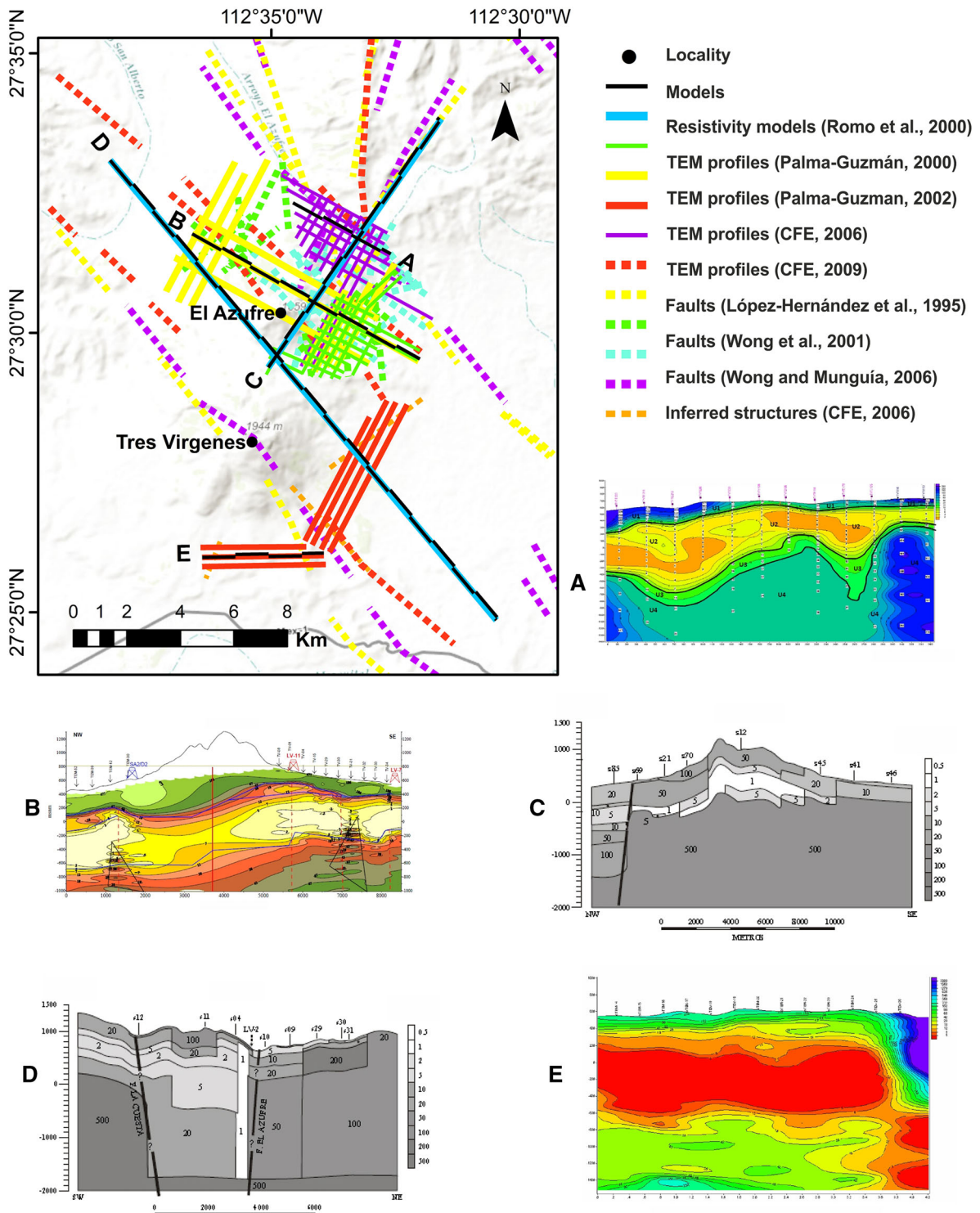


Figure 5. Geophysical surveys in the LTVGF. Information from Palma-Guzmán (2000, 2002); CFE (2006, 2009); López-Hernández et al. (1995); Romo et al. (2000); Wong et al. (2001); Wong and Munguía (2006).

The recovery factor for a fractured reservoir, as the LTVGF, is estimated to be in the range from 0.05 to 0.20 (Williams 2014).

Based on the analysis by Zarrouk and Moon (2014), the utilization efficiency of the plants installed in the Las Tres Virgenes geothermal field can be estimated as 13% from the mass output of 265 (t/h) with an enthalpy of 1188 kJ/kg. The average capacity factor for the year 2011 was 50% according to Flores-Armenta (2012) and 56% in 2013 (Flores-Armenta et al. 2014).

APPLICATION OF THE VOLUMETRIC METHOD TO THE CPGF AND THE LTVGF

The long exploitation history of the CPGF allows assignment of more realistic values for parameters like: thermal recovery factor, conversion efficiency, and load factor that will allow a reliable estimation of the energy potential for the next 30 years.

The LTVGF presents additional challenges for exploitation as low permeability, lack of recharge, and intense scaling. However, evaluation of the potential is important to assess the expected relation investment risk versus revenue.

Calculations for the reservoir potential are performed using the method described in “Geothermal Resource Assessment” section for a plant life of 30 years assuming the present temperature and the estimated range for the reservoir area and thickness based on geophysics and well data to determine the volume of the reservoir but considering the present efficiency and load factor of the installed plants (Table 3). The input data for the calculation are those presented in Table 2, which were produced based on our rigorous analysis of the compiled information (“Cerro Prieto Geothermal Field (CPGF)” and “Las Tres Virgenes Geothermal Field (LTVGF)” sections). Temperature ranges are obtained from well measurements and reservoir volumes are constrained by geophysical and well data, especially permeability to define the production zone. Calculations of the volumetric heat contained in the reservoir were performed for the parameter value ranges indicated in Table 2 using the Monte Carlo method. The results are presented in Table 3 for three probability values: 10, 50, and 90%.

The results indicate that more than 1000 MWe could be produced in CPGF at 50% probability for the present load factor of 78%. However, if the load factor could be increased to 90%, then production could increase to more than 100 MWe. The volu-

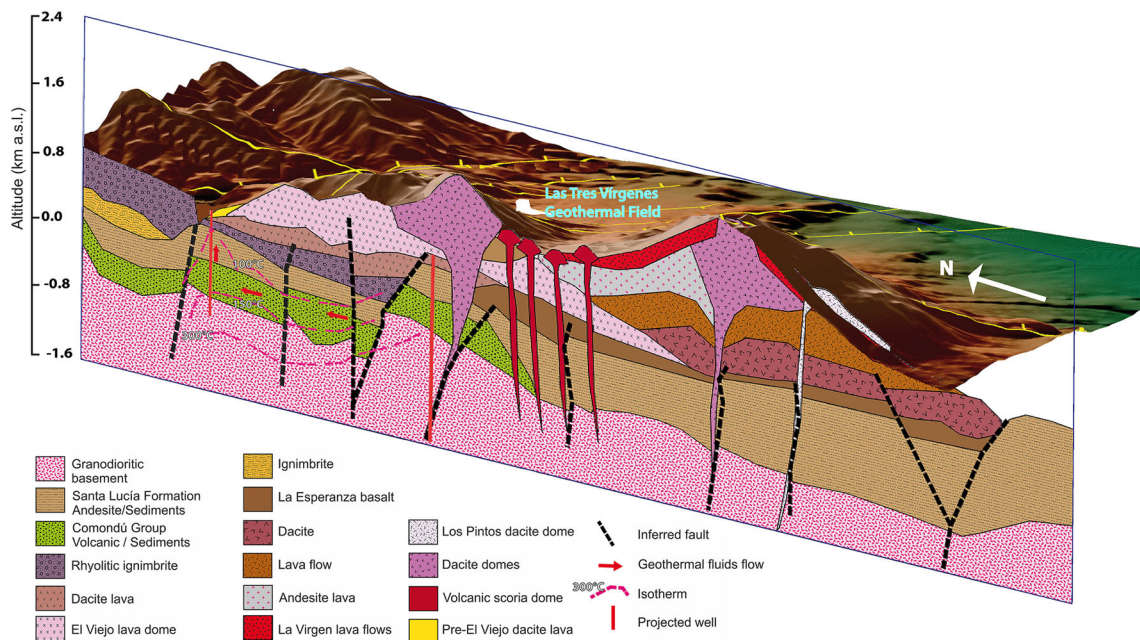


Figure 6. Conceptual model of the LTVGF (after López-Hernández et al. 1995; Macías-Vázquez and Jiménez-Salgado 2013).

Table 3. Results of the Monte Carlo Simulations to Evaluate the Energy Potential of the Cerro Prieto and the Las Tres Vírgenes Geothermal Fields

		Cerro Prieto (Beta Reservoir)	Cerro Prieto (Gamma Reservoir-Minimum)	Tres Virgenes
MWe capacity	90%	411	88	2
	50%	1397		48
	10%	3341		239

Calculations were performed assuming the present utilization efficiency and load factor: 49.3 and 78% for Cerro Prieto, and 13 and 56% for the Las Tres Virgenes.

metric calculation for the LTVGF field shows that it is possible to increase production up to 48 MWe at 50% probability, even with the load factor of 56% of the present exploitation scheme.

The results demonstrate that the potential of both fields is promising since the calculated available energy is >1000 MWe for both fields with the present exploitation schemes, and further increase in efficiency and plant factor would allow a larger expansion of electricity production.

SUMMARY

The reported data from the Cerro Prieto and Las Tres Virgenes geothermal fields, and our analysis of these data, provide enough information to estimate more accurately the reservoir parameters required to calculate the probable maximum energy potential. In both cases, the results support expectations of possible expansion of the fields, which might reach more than double the present production. In addition, further expansion of the electricity production can also be achieved by installing a more efficient plant setting with a higher plant factor.

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