Cerro Prieto Geothermal Field

Subsurface Evaluation and Model Update—Nonproprietary Version

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Technical Update, June 2022

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ABSTRACT

Cerro Prieto is the world's largest developed liquid-dominated geothermal resource with an installed generating capacity of 720 megawatts (MW). Continual exploitation and extensive drilling over more than five decades resulted in peak field-wide steam production in the early-2000s followed by continuous production declines. The current running capacity of the field, owned and operated by Mexico's state utility CFE, is 570 MW. CFE's existing reservoir model was updated and revalidated to examine six different field management scenarios ranging from no operational changes to new drilling and workovers and binary production with cascaded use of produced fluids. Modeling forecasts indicate the results of different actions and operational strategies that can be applied by CFE in the future and can or cannot improve field performance. Future work should include reconsideration of individual field region performance and further cascaded use of produced brines. This report presents a nonproprietary overview of the modeling work.

Keywords

Conceptual model
Enthalpy
Geothermal
Injection
Production
Numerical simulation

EXECUTIVE SUMMARY

Cerro Prieto is the world's largest developed liquid-dominated geothermal resource and has produced geothermal electricity since 1973. Continual step-out drilling eventually expanded the installed generating capacity to 720 megawatts (MW) from a developed area of approximately 18 square kilometers (km^2). Years of exploitation led to a peak in production in the early-2000s, followed by continuous declines in reservoir pressures, enthalpy, and temperatures, so after 2010, the capacity was 570 MW. The current running capacity is 300 MW. Mitigating production declines has become a primary goal for future field management. Potential changes include decommissioning the oldest and least-efficient generating units, shifting production to different field sectors, working over viable wells and drilling additional production wells, including those in the deep hotter eastern portion of the field, to augment steam production.

This study initially evaluated the performance of the Cerro Prieto field by reviewing the existing numerical reservoir model and integrating new production data collected since the last update in 2015. The updated model was validated by matching historical field production data with simulated results.

Across the field, changes in reservoir pressure and enthalpy are connected. Within individual reservoir regions, initial and expanded production causes pressure to decline, resulting in the development of steam in the reservoir with corresponding increases in enthalpy and flow. Reservoir pressure generally stabilizes after 5–10 years, but flow rate and enthalpy both continue to decline over time, tending toward stabilization 10–15 years after peak production.

A validated reservoir model provides the basis for evaluating several proposed field management options including:

1. Status Quo plus workovers and new wells
2. Status Quo, no well integration
3. Deliberate production curtailment
4. Eastern deep injection wells.
5. Deep in-field injection
6. Supplemental binary production

Reservoir modeling suggests that Cerro Prieto production is sustainable but cannot attain the capacity of decades past. The heat associated with the core resource persists and still represents a viable resource. Reasonable utilization should include determining which wells are most productive or can be reworked to become viable, how surface facilities should be configured to sustain production, and how cascaded use might add generation capacity.

LIST OF TERMS

barg	pressure above or below atmospheric pressure
CFE	Comisión Federal de Electricidad, state-owned electric utility of Mexico
°C	degrees Celsius
EPRI	Electric Power Research Institute
km	kilometer
km^2	square kilometer
kPa	kilopascal (unit of absolute pressure)
LBNL	Lawrence Berkeley National Laboratory
m	meter
mD	millidarcy
mRSL	meters relative sea level
MW	megawatt
tph	tons per hour
TVD	true vertical depth
USGS	United States Geological Survey

CONTENTS

LIST OF FIGURES

1
INTRODUCTION

Cerro Prieto in the Mexican state of Baja California is the world's largest developed, liquid-dominated geothermal field. It has been exploited continuously for commercial electrical generation since 1973. The developed reservoir includes more than 450 wells and covers approximately 18 square kilometers (km^2). The installed capacity of the field was 720 megawatts (MW); after 2010, the capacity was 570 MW. The current running capacity is 300 MW because pressure, temperature, and enthalpy have declined over five decades of production—as shown in 2020 slides from the Comisión Federal de Electricidad (CFE) (CFE, personal communication; Gutierrez-Negrin, 2015). Many of the surface production facilities have exceeded their useful lifetimes.

The purpose of the present review is to update reservoir conditions and evaluate how the available geothermal resource might sustain reasonable levels of production for current and future electrical generation. The most recent formal review of numerical reservoir simulations was completed by GeothermEx in 2015 (GeothermEx, 2015). The present review uses reservoir performance data from the past seven years to evaluate specific scenarios for mitigating production declines in the shallower western parts of the field developed in the 1970s and 80s and the deeper, hotter eastern core of the geothermal resource. The challenge—common to that in all mature, developed geothermal resources—is to plan and implement rational production schemes to sustain a reasonable level of production while maintaining the viability of the resource that remains.

2
GEOLOGIC BACKGROUND

The Cerro Prieto geothermal field is in northwestern Mexico in the northern part of the Baja Peninsula, 30 kilometers (km) south of the international border with the United States (Figure 2-1). The field lies on the alluvial plain of the Mexicali Valley and is part of the Salton Trough pull-apart basin between the right lateral strike-slip Cucapah-Cerro Prieto and Imperial Faults that are part of the southern extension of the San Andreas Fault system. The heat sources for the field are deeper mafic intrusions emplaced in thinned continental crust related to the northern propagation of the East Pacific Rise (Elders et al., 1984).

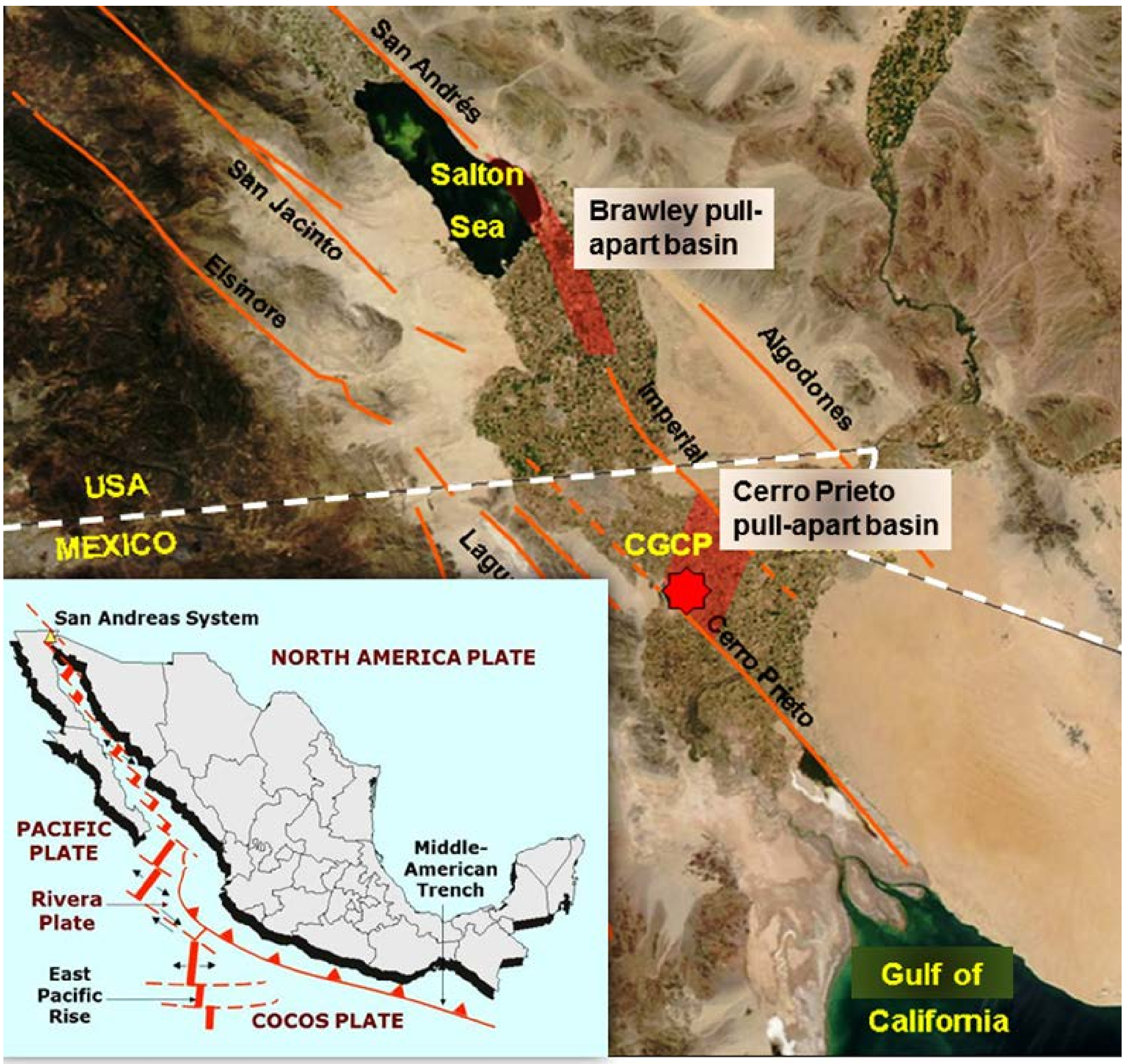

Figure 2-1
Cerro Prieto field location (after Gutiérrez-Negrin, 2015)

The conceptual geologic model of the Cerro Prieto field is based on extensive drilling and geochemical and geophysical studies conducted over more than four decades of exploration and development. The 18-km^2 developed field includes more than 450 wells (Figure 2-2). Numerous step-out wells have been drilled to identify potential outlying prospect areas, to evaluate the lateral limits of the geothermal system, or to investigate deeper source regions of the central geothermal system. Cooperative studies with Lawrence Berkeley National Laboratory (LBNL) (Lippmann, 1987; Lippmann et al., 1991, 1997, 2000, 2003) and the United States Geological Survey (USGS) (Truesdell and Lippman, 1990; Truesdell et al., 1989, 1997, 1998) resulted in well-constrained models of the stratigraphy, structure, hydrogeology, and geochemistry of the Cerro Prieto reservoir. Since then, additional drilling and production monitoring from ongoing CFE studies have continually updated and altered the conceptual model of field production (Puente and Rodriguez, 2000; Aguilar-Dumas, 2010; Lira, 2005; Aellan-Gomez et al., 2010; Aragon et al., 2011; Gallardo-Federico et al., 2012).

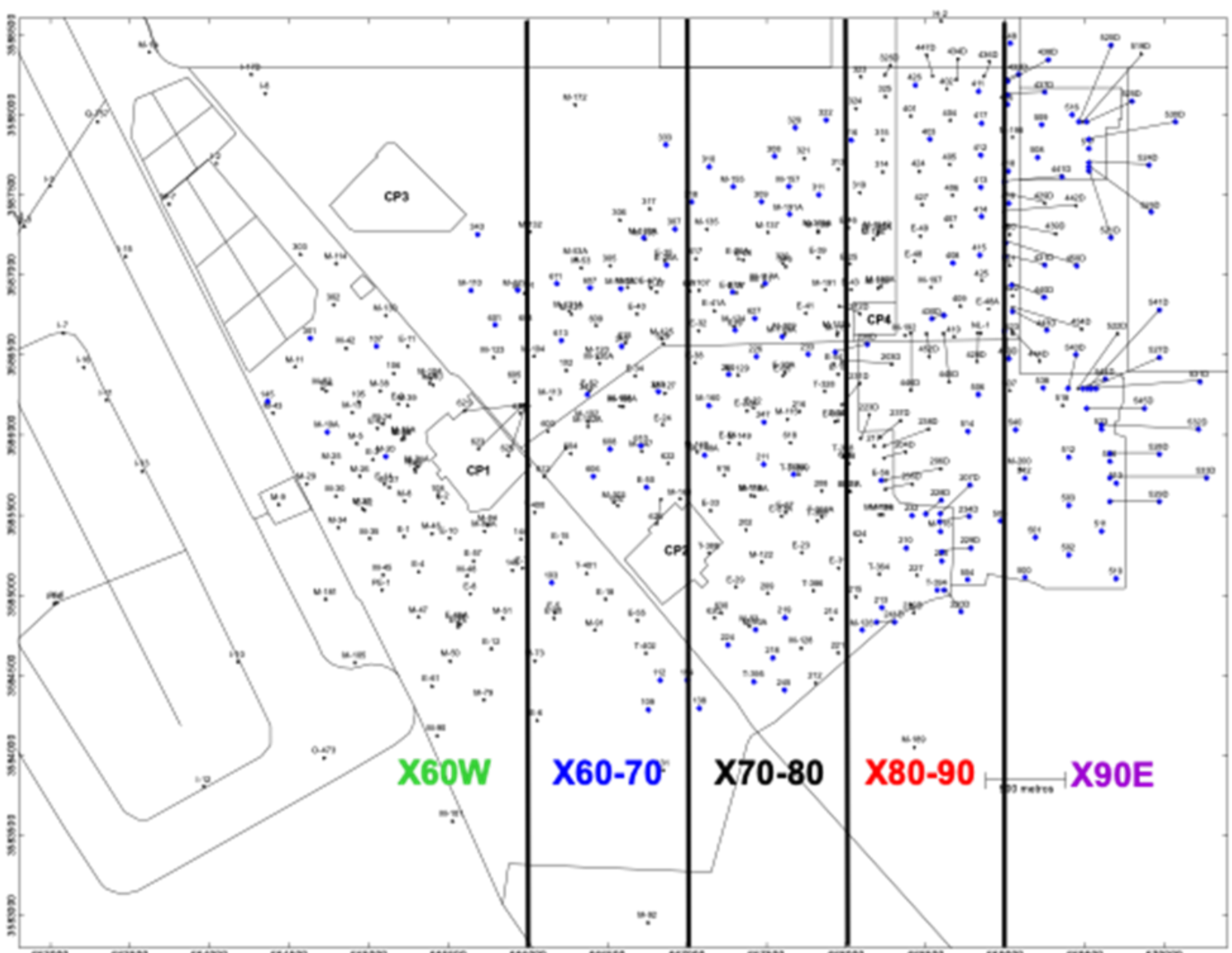

Figure 2-2
Cerro Prieto field with notations for modeled field regions referenced in text (from CFE, 2020)

The Cerro Prieto geothermal reservoir rests in variably faulted Mid-Late Tertiary interbedded argillaceous sandstones and shales that overlie older regional Mesozoic crystalline basement rocks (Figure 2-3) (Lira, 2005). The Tertiary reservoir section occurs at a depth of 400 meters (m) in the western part of the field and extends more than 2900 m to the east. The reservoir section is overlain by unconsolidated gravel, sands, and clays of Quaternary age deposited within the evolving Colorado River delta or alluvial fans from the Cucapah Range (Lira, 2005; Aguilar-Dumas, 2010). Based on hydrothermal alteration mineralogy (Cobo, 1979; Elders et al., 1981; Lippmann et al., 2003), the top of the production reservoir is characterized by silica and epidote (~300 degrees Celsius [°C]) mineralization predominantly in the deep part of the Tertiary sedimentary section (Figure 2-3).

Lippman et al. (1991) and Truesdell et al. (1997) divided the reservoir into sections and distinct blocks based on production depths and subsurface faults. Initial development of 310 °C fluids occurred in the shallowest alpha reservoir that extends to depths of 1500 m and occurs only in the western part of the field. The deeper beta reservoir, with temperatures up to 350 °C at depths of 1600–2900 m is the predominant producing zone of the Cerro Prieto resource across the field. Recent exploration has revealed a deeper gamma reservoir in the western section of the field with temperatures of 360 °C in the deeper parts of the Tertiary stratigraphic units (Gutiérrez-Negrin, 2015).

Fluid flow within the Cerro Prieto is controlled by a series of subsurface faults that divide the reservoir into distinct fault blocks and offset interior portions of the reservoir as much as 500 m (Truesdell and Lippmann, 1998; Lippmann et al., 2003). Reservoir recharge is from alluvial aquifers and the Colorado River east of the field and is controlled horizontally by permeable layers and vertically by permeable fault zones. Regional recharge accounts for significant natural mass replacement within the reservoir (Lippmann et al., 1997; CFE, personal communication, 2020). Long-term reservoir monitoring and regular geochemical sampling has shown that the natural-state eastern upflow and western outflow within the reservoir have been reversed by shallow injection and long-term pressure declines. Numerical simulation grids for the reservoir are directly related to this very well-constrained conceptual model.

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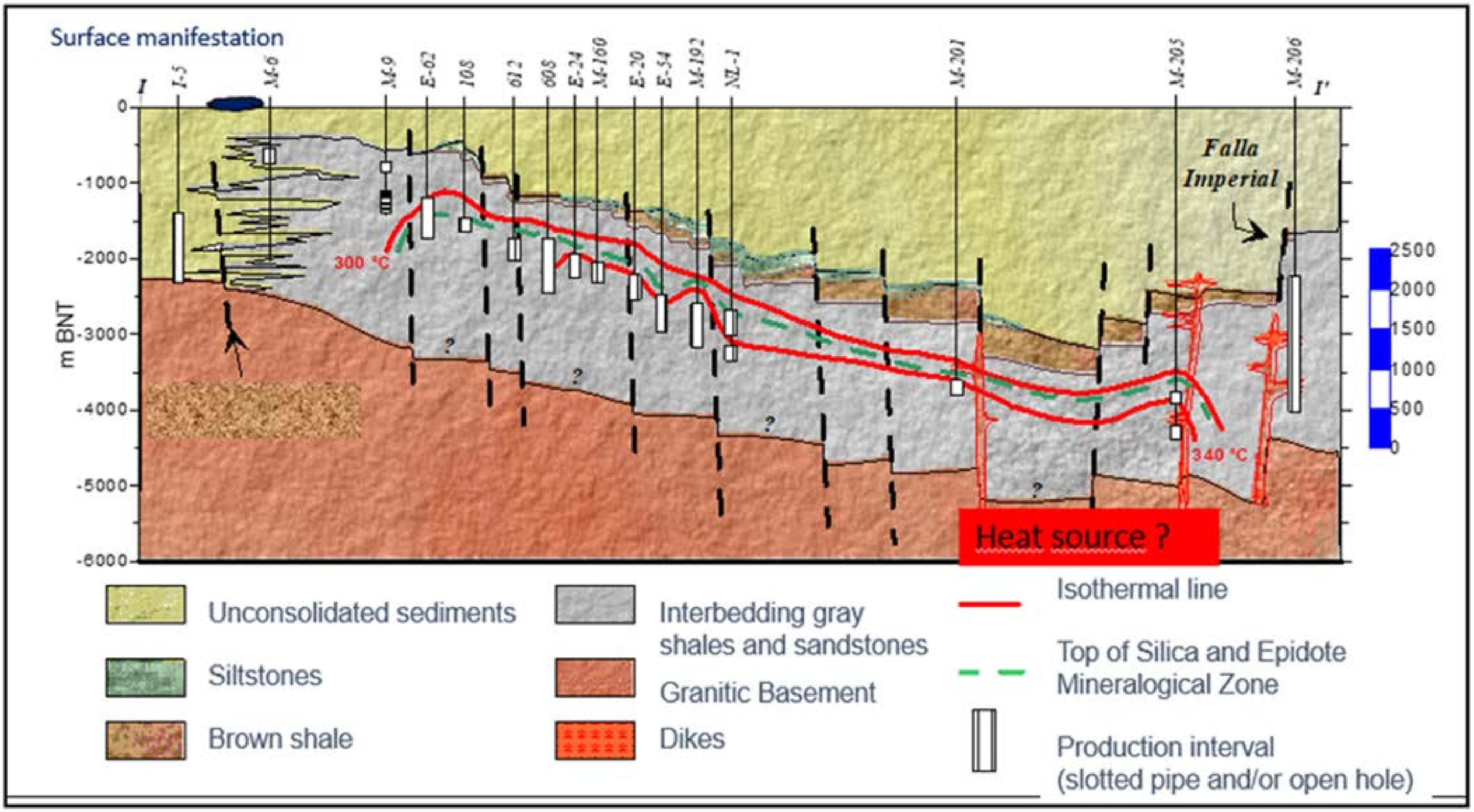

Figure 2-3
Conceptual schematic of Cerro Prieto subsurface stratigraphy (adapted from Lira, 2005; Aguilar-Dumas, 2010; Gutiérrez-Negrin, 2015)

3
RESERVOIR MODELING

Subsurface Temperature Distribution

Knowledge of the natural state subsurface temperature distribution is a fundamental part of developing a geothermal reservoir numerical model. Conditions that make it particularly difficult to accurately interpretation the natural state temperature distribution at Cerro Prieto include the size of the reservoir, the number of wells drilled (approximately 450), the time fame during which the wells were drilled (approximately 50 years), and reservoir thermodynamics. For this modeling effort, CFE provided their layer-by-layer, interpreted natural state temperature distributions derived from a detailed and comprehensive analysis and interpretation of all available data. Figures A-1 to A-18 show the interpreted temperature contours on model layers 1 through 18, respectively.

Applicability of Reservoir Simulation at Cerro Prieto

The primary objective of a reservoir study is to develop a way to make quantitative predictions of future reservoir conditions and production characteristics to support various development and optimization options. As discussed in the conceptual model section below, the reservoir properties and thermodynamic conditions at Cerro Prieto are known to vary both within and around the reservoir in a fully three-dimensional and heterogeneous manner. Quantifying effects in this situation is beyond the capability of classic techniques in reservoir engineering. These simplified approaches average heterogeneities together to simplify complexities and allow direct analytical solutions of reservoir equations. However, in a geothermal production field such as Cerro Prieto, spatial characterization of heterogeneities and quantification of their effects is the best way to optimize field development and management. For this purpose, reservoir simulation is a technique that allows a reservoir's complexities to be represented in a more rigorous way than can be attained using other analytical techniques (Aziz and Settari, 1979).

The geothermal industry has fully accepted reservoir simulation as the best practice in analyzing geothermal reservoirs. Its application at Cerro Prieto is the best method for generating forecasts of future reservoir behavior. Numerical modeling of Cerro Prieto employed the commercially available reservoir simulation software, TETRAD (ADA International, 2000). TETRAD is a three-dimensional, single or dual porosity, multi-phase, multi-component, thermal, finite-difference simulator (Vinsome and Shook, 1993). In the geothermal industry, TETRAD is widely used by operating companies, consulting firms, and research organization. A published research study by a U.S.-based national laboratory concluded that TETRAD provides valid solutions to the complex equations in geothermal applications (Shook and Faulder, 1991).

Description of the Numerical Model

The current project's workflow involved receiving CFE's TETRAD model, previously developed and most recently calibrated through 2015. This model and its associated files were supplied to EPRI. While the project did not require EPRI to build the model, EPRI reviewed all the components of the model that would have been constructed had a new model been built. This thorough review allows a better understanding of the physical processes in the model and provides context to better interpret the forecast results.

Numerical Simulation Grid

In the Cerro Prieto numerical model, the conceptual model is represented in the digital format required by the reservoir simulator, TETRAD. The grid of the numerical model covers a 14 × 14-km area centered on the Cerro Prieto project. The model contains 18 layers extending from ground surface to -5800 meters relative to sea level (mRSL). The ground surface is modeled as level at an elevation of 0 mRSL, for a total thickness of 5,800 meters. The model grid was rotated 45° west with respect to true north to allow the x and y axes of the model to be approximately in parallel with the direction of fractures and the flow direction in the field area in its natural state. The model contains 57 grid divisions in its X-direction and 49 grid divisions in its Y-direction. There are 50,274 main gridblocks in the model; including dual porosity, there are twice as many or 100,548 total gridblocks. Figure 3-1 shows an aerial view and a three-dimensional view of the numerical model.

As described above in Section 2, Geologic Background, the conceptual model of the reservoir and its surrounding volume contains several distinct rock types. In simplified terms, the rock types in the model include:

- crystalline basement rocks below the reservoir zone,
- tertiary interbedded sandstones and shales forming the reservoir zone,
- a silica and epidote zone indicating the top of the reservoir,
- unconsolidated gravel sands and shales overlying the reservoir, and
- background country rock outside the productive reservoir area.

The following qualitative description characterizes these rock types. Rocks below the silica and epidote zone and within the reservoir areal boundary have high permeability. These reservoir rocks are surrounded by (adjacent horizontally to) high-permeability shallow gravel sands at shallow depths and low-permeability background country rock or basement at deeper levels. Low-permeability basement rocks lie below the reservoir. Discreet faults with high permeability extend as planar units from the bottom of the deep part of the reservoir in the east to the bottom of the model (the ultimate source of very hot brine).

Permeability and Porosity Distribution

Deep, hot upflow upwells along discreet faults deep in the eastern area and flows into a distributed fracture network within the reservoir. To model discreet faults that contain upflow, the model employs discreet planes of high permeability (with high vertical and horizontal permeability). To model the distributed fracture network within the reservoir rocks (interbedded sandstones and shale), the model includes high fracture permeability in broad regions (with horizontal permeability higher than vertical permeability to account for shale beds). For areal extent in the model, gridblocks located in the area of highest natural state temperatures tend to have the highest permeability on each layer within the path of natural flow. For vertical extent in the model, depths below the silica and epidote zone are higher permeability reservoir rocks. In particular, note that the top of the reservoir is clearly defined in the model by a contrast in permeability that is shallow in the west (~400 mRSL) and dips to more than 2900 mRSL in the east. Within the reservoir zone, particular permeabilities are assigned based on best-fitting values from history matching.

Permeability in the model was assigned first, on the basis of rock type (for example: reservoir, basement, and shallow zones) and second, on the basis of iterations to find the best-fitting value and whether or not it is an upflow block (in a discreet fault). The fracture permeability and porosity are shown as follows:

The matrix permeability and porosity are shown as follows:

Boundary Conditions on the Numerical Model

The boundary conditions on the numerical model are as follows:

Top of Model: There is a no-flow boundary across the top of the model and a fixed-temperature boundary set to a constant temperature of 20 ºC.

Bottom of Model: The entire bottom of the model (at 5800 mRSL) is attached to a fixed-temperature boundary “hot plate” consistent with deep temperature contours ranging from 90 to 374 ºC. This boundary represents an estimate of the deep temperatures below and adjacent to the field, based on projecting measured static temperatures to greater depths.

Source Inflow: In the interpreted source area of the model (eastern model edge), 180 tph of water at 374 ºC is flowed into the bottom of the model under constant mass flux conditions in the natural state. Also attached in the source area is a pressure-dependent source that flows a large amount of hot recharge into the model as the field pressure declines, thus forming a significant pressure support to the reservoir.

Sides of Model: All sides of the model are attached to pressure-dependent recharge aquifers. During the natural state modeling, the pressures in these aquifers are adjusted so that the source inflow flows equally out of the model as shallow subsurface discharge. Also attached to all sides of the model are pressure-dependent recharge aquifers that flow into the model a large amount of cold recharge as the field pressure declines, providing pressure support to the reservoir.

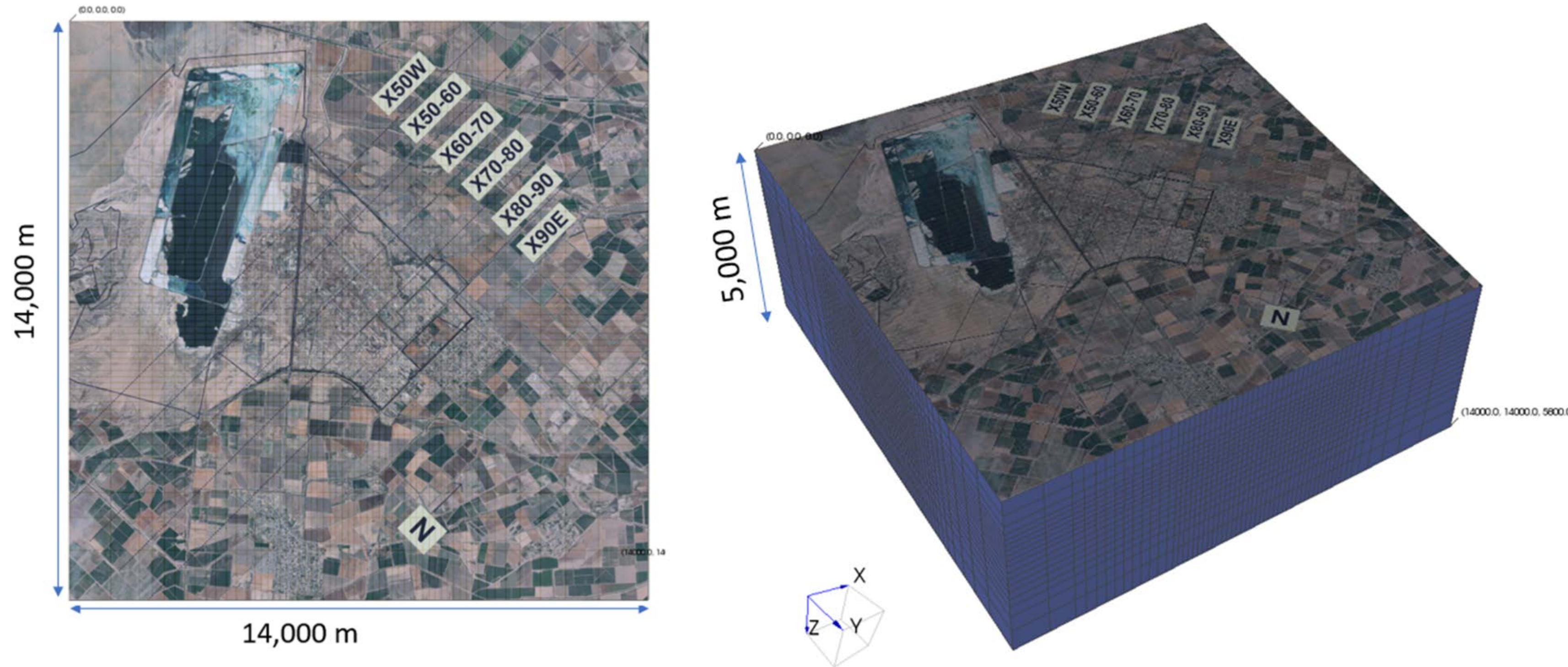

Figure 3-1
Modeling stratigraphy and structure

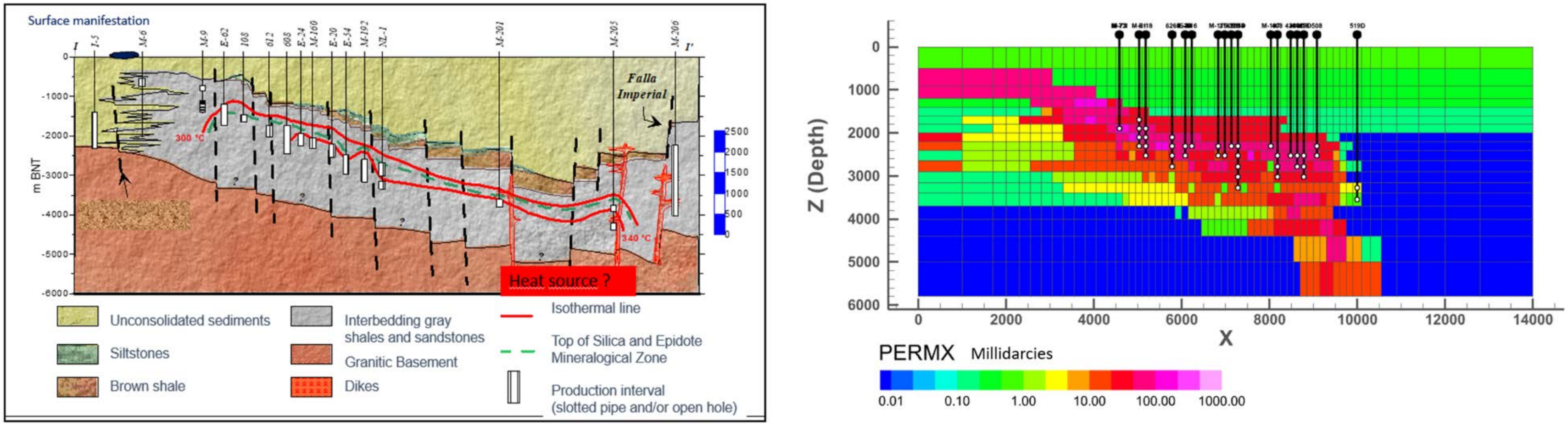

Figure 3-2
Conceptual geologic model and numerical model defining porosity and permeability distribution for simulating the Cerro Prieto geothermal reservoir

Simulation of the Natural State Conditions

The first step in running a geothermal reservoir simulation is to run the model with reservoir properties and boundary conditions in place. The goal is to obtain model results that match the data from the natural state of the pre-production reservoir. Typically, this involves a considerable number of iterations on permeability distribution, source inflow properties and location, and subsurface discharge location of the source inflow. After the model is run for a representative "geologic time" to reach steady state, the simulated subsurface distributions of temperature and pressure are compared to measured, and in part interpreted, subsurface distributions of temperature and pressure.

CFE provided both their interpreted subsurface temperatures and the TETRAD files for their natural state model of the Cerro Prieto reservoir (Figure 3-3). EPRI ran the natural state model using TETRAD (version 2019-3) for a representative time span and generated simulated natural state temperature distributions. For confirmation of the initial state model, the simulated natural state temperatures were compared to CFE's interpreted natural state temperatures (see Figures A-55 to A-72. Good matches were obtained, providing a suitable validation of the natural state model.

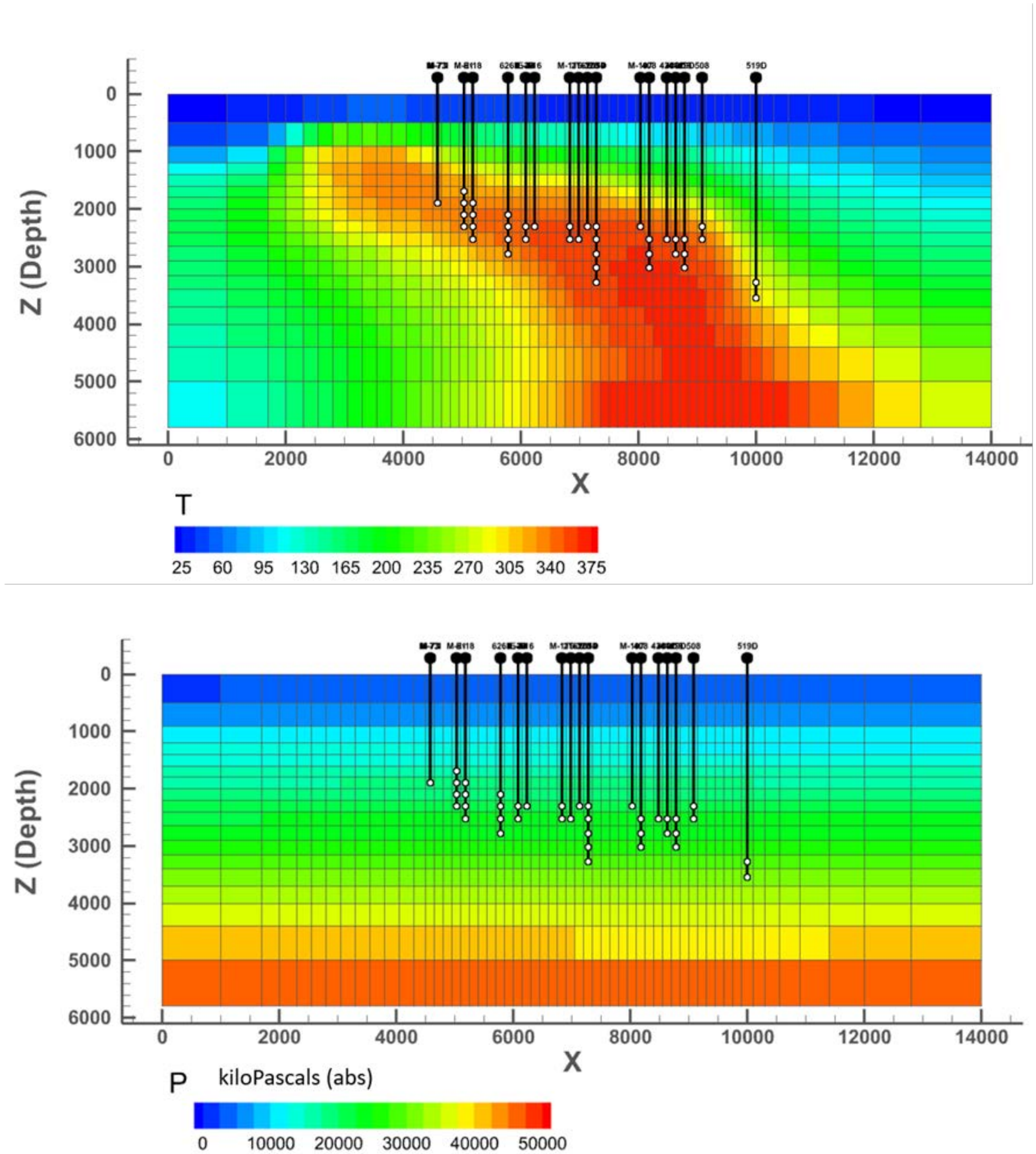

Figure 3-3
Cerro Prieto simulated reservoir natural state subsurface temperature distributions (reservoir model from CFE)

Production History Match

Production history matching, the next phase in model development, begins with the natural state model described above and subjects the numerical model to the production/injection history of the field. In the case of the Cerro Prieto reservoir, this history match covers a time span of 50 years (1973 to the present) and approximately 450 drilled wells. CFE provided their TETRAD production history match model that spanned 1973–2015 and demonstrated a good match to measured data. For the present review, that model was updated with production and injection data from 2015–2022 and history matching was extended from 2015 to 2021.

History matches were analyzed on a well-by-well basis, a method that provided reasonable matches. For concise presentation and the ability to compare performance and behavior on a regional basis, individual wells were grouped into six regions (see Figure 3-1 above). Because the individual well matches were reasonable, mismatches in individual wells tended to cancel out when wells were grouped into regions, resulting in high-quality regional matches for flowing enthalpy and reservoir pressure.

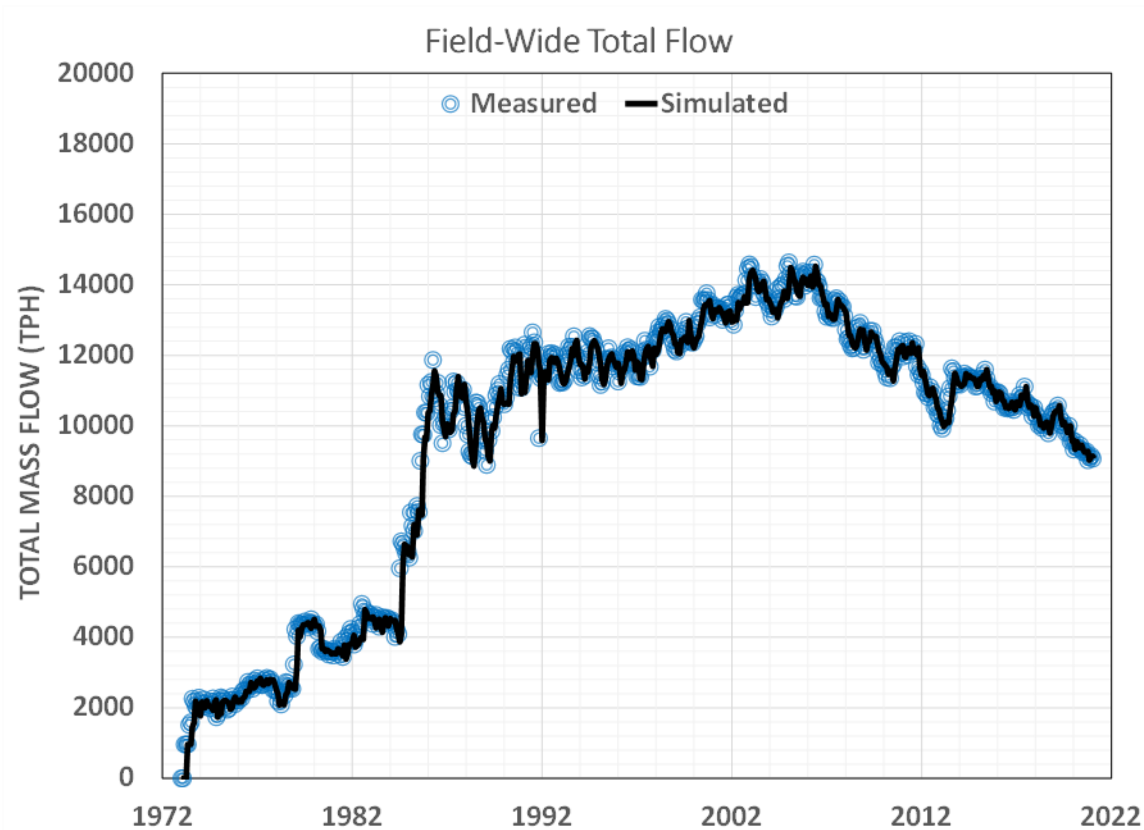

Figure 3-4
Field-wide history match for Cerro Prieto total flow

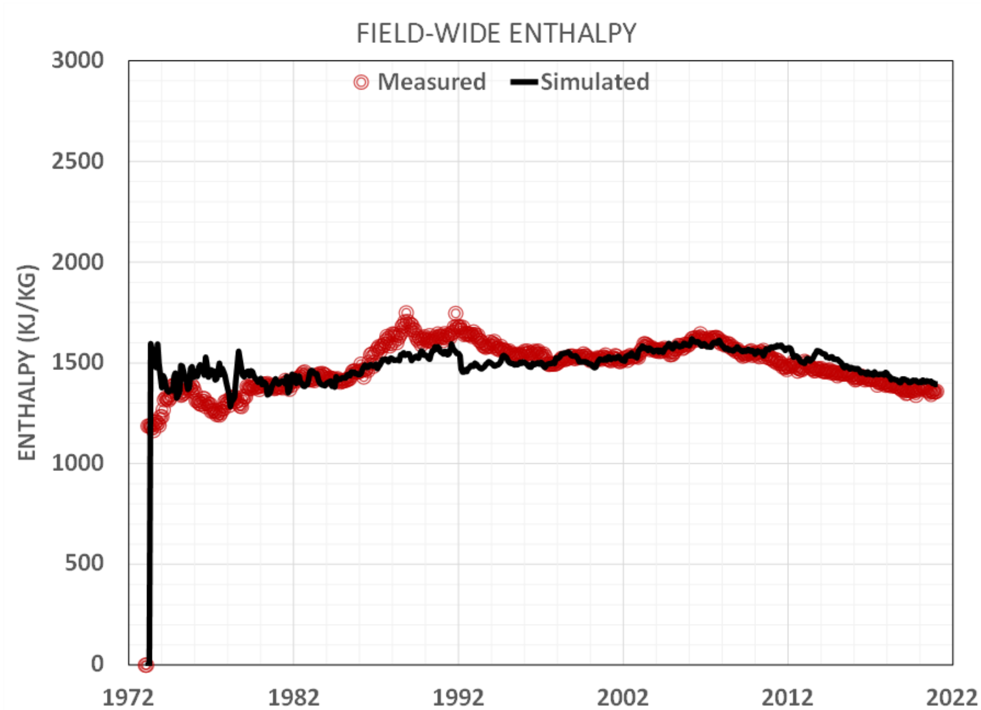

Figure 3-5
Field-wide history match for enthalpy of produced fluids at Cerro Prieto

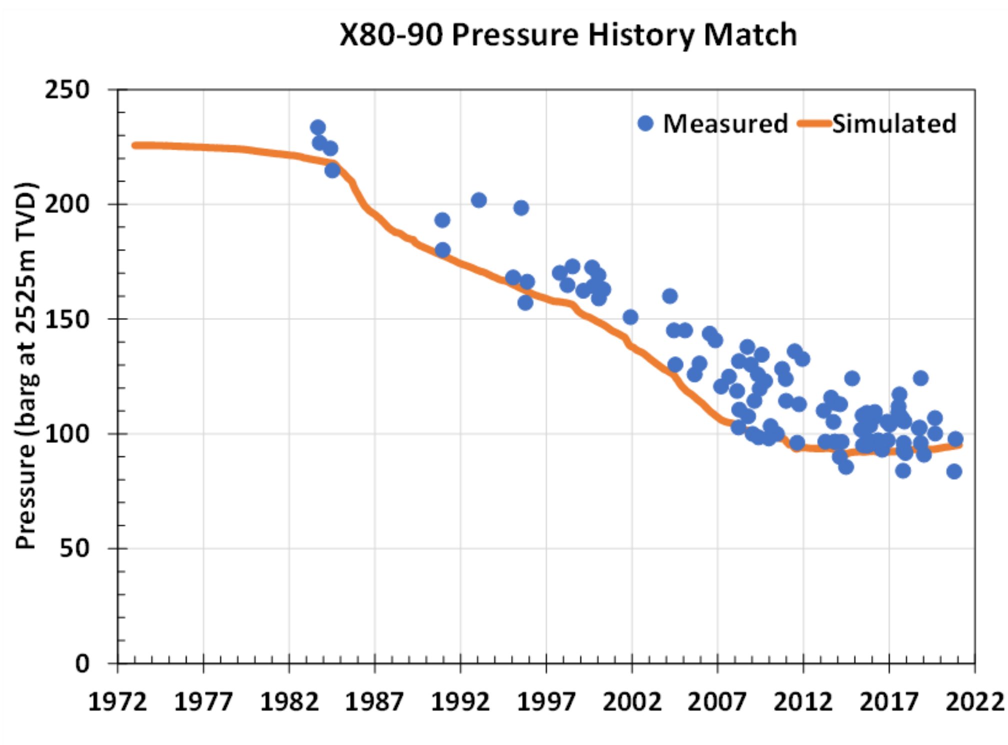

Figure 3-6
Pressure history match for region X80-90 in the eastern part of the Cerro Prieto field (barg @ 2525-m TVD)

Observations:

- The simulation provides a good match to measured data through 2021.
- Production rate, reservoir pressure, and enthalpy are connected.
- As production starts in a region, localized reservoir pressure decline causes steam to develop in the reservoir within that region. Steam increases enthalpy, which results in enough extra flow potential to more than offset the tendency for the reservoir pressure decline to reduce flow. The combined result is an initial increase in enthalpy and flow when a new region is first produced.

Design of Simulation Forecast Scenarios

The updated 2021 version of the Cerro Prieto numerical model was used to make a series of forecast runs specified by CFE in the document "Escenarios de interes," CFE translated, September 2021 (updated January 2022). The scenarios span a wide range of possible future developments or operations.

Scenario 1: Drill 5 new production wells and perform 14 workovers.

1A—Done over 3 years from 2022 to 2025. This is currently the planned scenario.
1B—Done over 9 years from 2022 to 2031. This is currently the planned scenario.

Scenario 2: Do nothing.

2A—Continue as is without drilling well work.

Scenario 3: Deliberate shut-in of select wells to reduce total field steam production from a late-2020 level

Scenario 4: Drill and inject into six deep (5000 m) injection wells

Scenario 5: Drill and inject into six deep (5000 m) injection wells

Scenario 6: Use hot brine from eastern part of field to supply a binary power plant

4
SUMMARY

This study considered the performance of the Cerro Prieto geothermal field in the Mexican state of Baja California. It began by reviewing the existing numerical reservoir model, integrating new production data since the last update in 2015, and establishing good matches between natural state and reservoir temperatures, steam flow, and reservoir pressure. The field-wide steam flow at Cerro Prieto was 3100 tph at the end of the history match period in December 2020.

Existing data describe characteristics of the field. Changes in reservoir pressure and enthalpy are connected across the field. Within individual reservoir regions, initial (or expanded) production causes regional reservoir pressure to decline, resulting in the development of steam in the reservoir that continues to exist while reservoir pressure is declining. The pressure decline, on its own, should cause production to *decrease*. However, the pressure decline also causes steam saturation and flowing enthalpy in the wells to increase—which, on its own, should cause production to *increase*. In this initial phase of a region's production, the increased enthalpy causes more of an increase in production than the decrease in production that would otherwise occur from the reservoir pressure drop. The net result is that production increases as more production wells are added.

When reservoir pressure stops declining or the rate of decline slows down, steam saturation in the reservoir begins to decrease, causing enthalpy of the production wells to decline even as reservoir pressure has stabilized. After steam production peaks in a region, it initially declines at a rate that lessens over time and the region's steam production becomes more stable.

A validated reservoir model provides a means of evaluating different field management options. At CFE's request these included:

1. Status Quo plus workovers and new wells
2. Status Quo, no well integration
3. Deliberate production curtailment
4. Eastern deep injection wells
5. Deep in-field injection
6. Supplemental binary production

Reservoir modeling suggests that Cerro Prieto steam production could attain stability, but at a rate lower. The heat associated with the core resource persists. How the resource is utilized will dictate how long, and at what levels, the field can sustain electrical generation. The next steps should involve establishing which wells remain usable, which can be reworked to add to production, how cascaded use might add generation capacity, and how surface facilities should be configured for future sustainable production levels.

5
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