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Some Considerations on Resource Evaluation of The Geysers

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Abstract

Although large amounts of data have been collected at The Geysers, some reservoir parameters, such as initial liquid saturation, matrix permeability and the fracture network characteristics, are still poorly known These parameters greatly affect results of resource evaluation and predictions of reservoir behavior. Several two-dimensional fractured porous medium models have been developed for The Geysers; these models differ in assumptions regarding the initial liquid saturation and matrix permeabilities. These models indicate that the permeability-thickness product (kH) of the fracture network ranges from 10 to 75 Dm (30,000 to 225,000 md·ft) and matrix permeability ranges from 1 to 3 μDarcies (μD). All three models yielded surprisingly similar predictions regarding the future generating capacities of different areas.

Introduction

The Earth Sciences Division of Lawrence Berkeley Laboratory (LBL) is conducting research studies on The Geysers geothermal field for the California State Lands Commission (SLC). SLC receives royalties for steam produced from State-owned leases at The Geysers, and the funds are used for the California Teachers Retirement Fund.

The LBL project on The Geysers started in 1985 with the development of a comprehensive computerized data base; the following year various geological and reservoir engineering studies were conducted using the data base. During the last two years numerical modeling studies were carried out with the purpose of understanding the reservoir response to production and injection.

In this paper various aspects of resource assessment of The Geysers are discussed. The available data are briefly described and some results of data analysis are presented. Then the limitations of the data base for numerical modeling are discussed and poorly known reservoir parameters are identified. Different modeling approaches are evaluated in terms of The Geysers data and information regarding appropriate initial and boundary conditions are summarized. Finally, two-dimensional fractured/porous medium models of The Geysers and some simulation results are described.

Available data

Over five hundred wells have been drilled at The Geysers providing large amounts of data for this resource. These data include lithologic logs, directional surveys, steam entry locations, static and flowing temperature and pressure surveys, production and injection histories, pressure decline, pressure transient tests and geochemical data. In terms of the overall resource evaluation the most important data are the production and injection histories and the pressure decline data. Figures 1 and 2 show pressure contours based on open file data for 1984 and 1988, respectively. Most of the current proprietary data are for wells located in recently drilled areas such as Northwest and Southeast Geysers, hence, the pressure drawdown in these areas is not well defined by the open file data. Also, the open file pressure decline data for 1988 are very limited, so that the contours drawn in Figure 2 are approximate. The original pressure at The Geysers was close to 35 bars (500 psi), so that by 1984 the pressure had declined to 17 bars (250 psi) or below in some of the older producing areas (Sulphur Banks, Happy Jack and PRC 4596). By 1988 the pressure had declined below 14 bars (200 psi) over a large portion of The Geysers. In the last few years the pressure decline has accelerated considerably due to recent development in The Southeast Geysers. It should be emphasized that the pressure contour maps shown in Figures 1 and 2 cannot be extrapolated because of the heterogeneous fault/fracture dominated nature of the resource.

The reservoir pressure decline has caused large decreases in flow rates of producing wells. Figure 3 illustrates a typical production history for a Geysers well. The figure shows that initially the well produced about 25 kg/s (200,000 lbs/hr), and that it currently produces only about 5 kg/s (40,000 lbs/hr). Because of flow rate decline of the wells, the field is currently producing about 1400-1500 MW_e, which is significantly below the total installed capacity of about 2000 MW_e.

From well lithologic logs, the graywacke has been identified as the main producing reservoir rock, with typically 2 to 8 major steam entries per productive well. Most of the wells are directionally drilled because of the rugged topography in the area, but overall the deviated wells do not have more steam entries, nor higher production rates, than the near-vertical wells. This suggests that the permeability at The Geysers is not limited to major near-vertical faults, and that lateral permeability is significant; this is also indicated by the pressure decline data. We have found that many of the major steam entries are associated with intervals containing a significant fraction of shale or micrograywacke, suggesting high contact permeability between the shale layers and the main graywacke (Halfman et al., 1989).

Pressure transient data (primarily pressure buildup data)

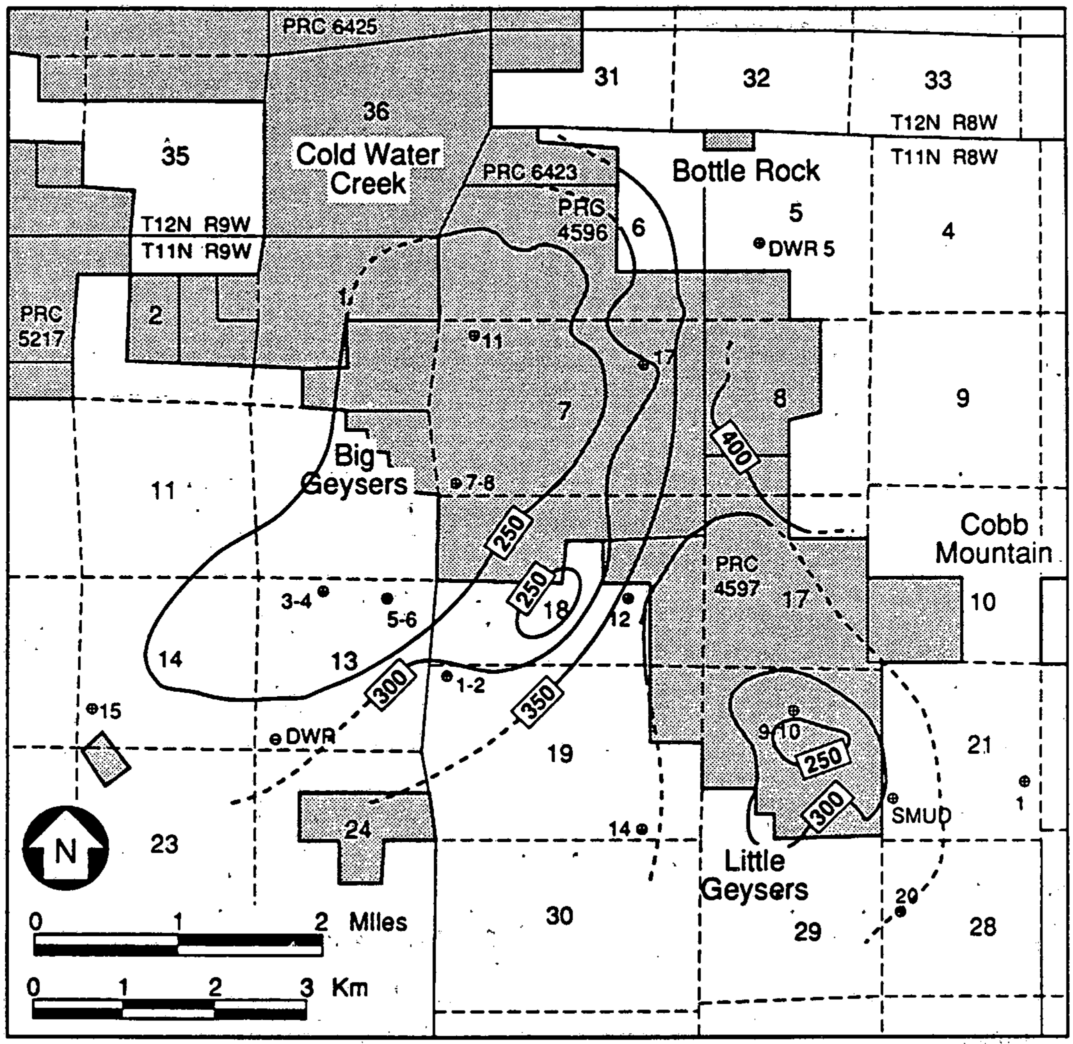

Figure 1. Pressure contours based upon open file data for 1984. The shaded areas represent SLC leases.

indicate that there is high fracture kH product at The Geysers in the range of 10 to 100 Dm (30,000 to 300,000 md·ft). Few open file data are available on matrix porosities or permeabilities, but the average matrix porosity is believed to be within the range of 3 to 7% (Lipman et al., 1977). Analysis of flow rate decline data, assuming that most of the reserves are located in the matrix blocks, yielded values for the so called recharge factor between 1 and 10 (Ripperda et al., 1989). The recharge factor R is defined as (Bodvarsson and Witherspoon, 1985):

$$R = C \frac{k_m}{D^2}$$

where k_m is the matrix permeability, D is the average fracture spacing, and C is a constant with a value of 1×10^{22}. Steam entry data suggest average fracture spacing on the order of 100 m (300 ft), yielding matrix permeabilities in the range of 1 to 10 μD. This range of values for the matrix permeability is consistent with the measurements from other geothermal fields such as Los Azufres, Mexico (Contreras et al., 1986; Iglesias et al, 1987) and Nesjavellir, Iceland (Sigurdsson et al., 1988). Note, however, that both of these fields reside in volcanic rocks, whereas the main reservoir rock at The Geysers is meta-sedimentary.

Poorly known parameters

There are several parameters that are poorly known at The Geysers and greatly affect the results of resource evaluations using analytical or numerical models. These parameters include the initial distribution and amount of liquid water, reservoir thickness, matrix permeability, and data on the characteristics of the fracture network. These are briefly discussed below.

Initial liquid saturation

It is well known that most of the fluid reserves at The Geysers must be in liquid form, because of the large volume of

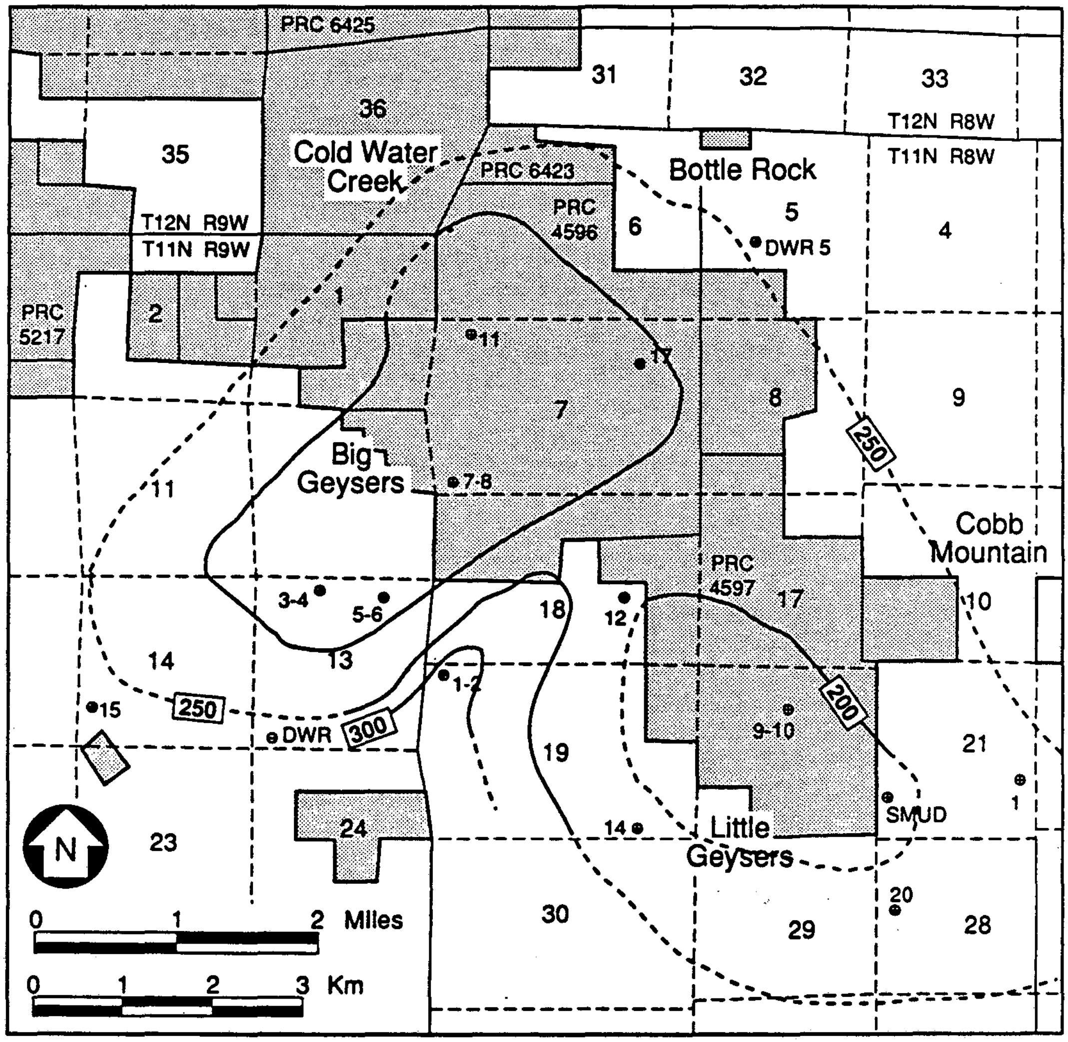

Figure 2. Pressure contours based upon open file data for 1988. The shaded areas represent SLC leases.

steam that has already been produced (James, 1968; Nathenson, 1975; Weres et al., 1977). The amount of liquid and its spatial distribution is not known at present. It is commonly believed that the liquid is primarily stored in the "tight" matrix blocks, and not concentrated in a deep "water table". Pruess and Narasimhan (1982) showed that the matrix would have to possess low permeability (μD) for the matrix water to boil to steam on its way to the fractures. Analysis of non-condensible gases indicate that most of the steam originated as liquid water in the reservoir (D'Amore et al., 1982).

The primary heat transfer mechanism in vapor-dominated systems and other two-phase systems is boiling/condensation associated with the heat pipe phenomena (White et al., 1971). In the case of liquid-dominated systems the fractures are nearly saturated with water so that the matrix blocks with small pores must also be close to saturation (capillary pressure effects), hence, the determination of reserves is straight forward. For vapor-dominated systems the liquid saturation in the fractures must be small (vaporstatic pressure gradient), but the liquid saturation in the matrix could be anywhere between zero and unity. This makes the determination of reservoir fluid reserves difficult, but it is likely that at The Geysers the initial liquid saturation in the matrix exceeded 25% because of the large volume of steam that has been produced.

Reservoir thickness

The reservoir thickness is generally not well known for most geothermal reservoirs, and The Geysers is no exception. Estimates for the average reservoir thickness at The Geysers vary from 2 to about 6 km (1.2 to 4 mi); in some areas the reservoir may be considerably thinner. The depth to the top of the reservoir ranges from less than 330 m (1000 ft) in the Thermal and Sulphur Bank areas to over 1500 m (5000 ft) in the Northwest Geysers. Wells have been drilled to depths exceeding 3500 m (12,000 ft) without encountering the reservoir bottom.

Matrix permeability and fracture network characteristics

Open file data on matrix permeability is scarce, but this parameter is very important as it, along with average fracture

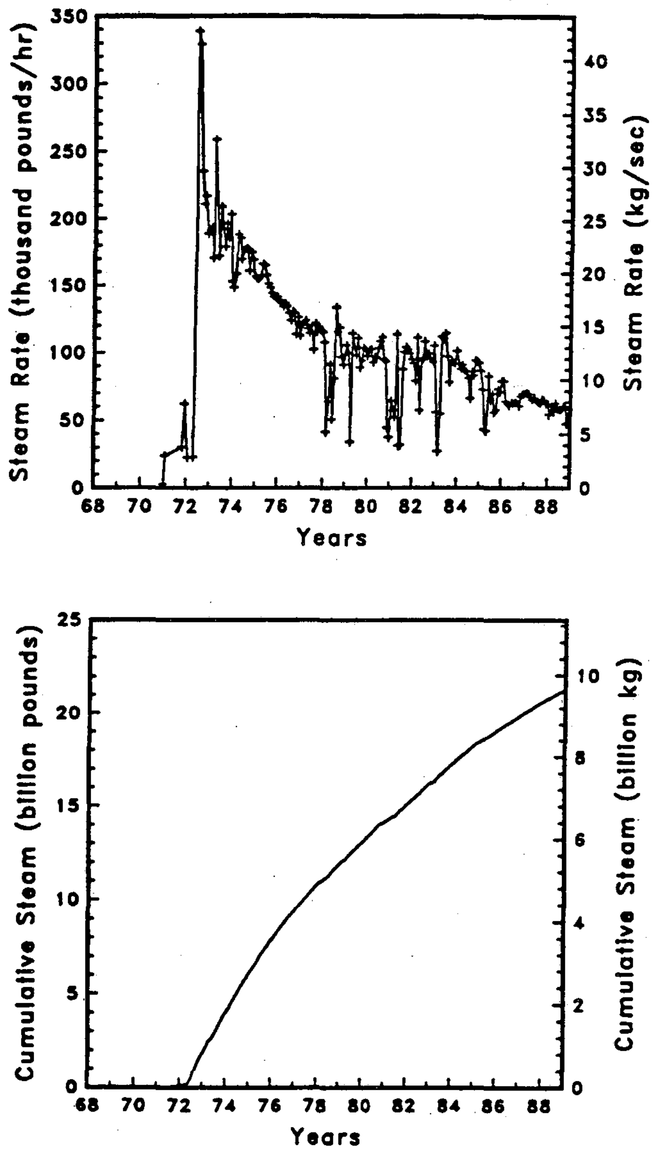

Figure 3. Production history for a typical well at The Geysers.

spacing, controls the amount of steam flow recharging the fractures (Bodvarsson and Witherspoon, 1985). The characteristics of the fracture system especially the surface area per unit volume of are not well known. The connectivity of the fracture system, however, seems to be good based upon the pressure decline data, although there are several fault blocks that appear to be in poor hydrologic communication with the rest of the reservoir. Other important unknown parameters include the relative permeability functions for the fracture networks and the matrix blocks.

Considerations for Modeling The Geysers

Porous medium versus fractured/porous medium models

The Geysers reservoir is characterized by high fracture permeabilities providing pathways for steam flow, and low permeability matrix blocks providing the liquid reserves. The relatively high steam mobility can be represented by a porous medium model by preserving the estimated reservoir kH product in different reservoir regions. However, the time and pressure dependent steam recharge from the matrix blocks and the associated in-situ boiling cannot adequately be represented by a porous medium model. We have tried to modify the relative permeability curves to "mimic" the matrix block response, using high residual (immobile) liquid saturations, but the results were not very satisfactory.

Now the question arises how one can apply fractured/porous medium models for The Geysers when so little is known about the characteristics of the fracture network. What little is known includes surface traces of major faults and the locations and perhaps relative importance of the steam entries. Because of this lack of data and because of the large volume of The Geysers reservoir, one can never hope to develop a discrete fracture model for the entire resource. The best approach appears to be discrete (and approximate) modeling of the major faults known to be predominant steam conduits or barriers to steam flow, and represent the less predominant fractures (or faults) using double porosity concepts. One can probably limit the number of faults that need discreet representation to below ten and then use concepts of average fracture spacings and porosities to represent the bulk of the resource. Fracture spacing and porosity may be spatially variable as indicated by drilling results, geological features and other data.

Model dimensionability

Most geothermal systems are very heterogeneous with strong spatial variations in important reservoir parameters such as the degree of fracturing, hydrothermal alteration and permeabilities. Also, there are often large spatial differences in thermodynamic conditions (pressure, temperature and in-place saturation) both areally and with depth. Therefore, in most cases one must use a three-dimensional model to adequately simulate the natural state of the reservoir and its behavior under exploitation. However, we believe that it is often beneficial to start with a two-dimensional areal fractured/porous medium model and investigate its applicability. In the case of The Geysers a two-dimensional model can reasonably well assess lateral steam migration and yield good first estimates for spatial variations in fracture and matrix permeabilities. This is because vertical permeabilities at The Geysers are high and therefore vertical pressure gradients are small and near-vaporstatic. A two-dimensional model is less useful for investigating effects of water injection because of the strong vertical pressure and temperature gradients that develop with the associated vertical mass and heat flows.

Initial conditions

All reservoir models need the appropriate initial (natural state) conditions before exploitation. Over most of The Geysers the initial pressure was about 35 bars (500 psi) and varied little with depth because of the low density of vapor. The corresponding temperature is about 240 °C (460 °F). In some areas of The Geysers much hotter reservoir conditions have been found with temperatures exceeding 300 °C (600 °F); an example is the deep reservoir in Northwest Geysers (Drenick, 1986). It is often beneficial to perform natural state model studies to obtain the proper initial conditions, as well as to obtain coarse estimates of the permeability distribution. This involves balancing the natural mass and heat inflow into the system with mass and heat losses through surface manifestations and through conduction. As there are little spatial variations in pressures and temperatures at The Geysers (except for the deeper hotter zones), natural state modeling should consider the large observed gradients in non-condensible gases and isotopes. These data may yield estimates for the initial in-place liquid saturations (reserves), which is much needed information.

Two-dimensional double porosity models of The Geysers

As a part of our work for SLC, LBL has developed several double porosity models of The Geysers, using the Multiple Interacting Continuum method (MINC; Pruess, 1983) and the numerical simulator MULKOM (Pruess, 1983). Here we will briefly describe the approach used and the assumptions employed in developing these models.

Reservoir boundaries

The boundaries of the reservoir were inferred from the locations of dry wells (DW) as shown in Figure 4, and from the available heat flow data. These wells appear to define the reservoir limits fairly well except in The Northwest Geysers. All boundaries were assumed to be no flow boundaries both in terms of mass and heat flow.

Reservoir thickness

Over most of The Geysers, the reservoir was assumed to be 3 km (~ 2 miles) thick. A thinner reservoir was assumed in some areas based upon geological information. The depth to the reservoir varied according to first reported steam entries. For example, in The Northwest Geysers the depth to the reservoir was assumed to be much greater than that near the center of the resource.

Initial conditions

Near-uniform initial conditions of about 35 bars (500 psi) and 240°C (460°F) were used. As the gridblocks were located at different elevations because of the different depths to the reservoir, a gravity equilibration was done initially to ensure stable initial conditions. The "abnormal" thermodynamic conditions of the hot deep zones, for example in The Northwest Geysers, were neglected. Different initial liquid saturations were assumed for the matrix blocks as will be described later; the initial liquid saturation in the fractures was assumed to be 2%.

Fracture network parameters

It is assumed that three orthogonal fracture sets are present in the reservoir with an average fracture spacing of 100 m (330 ft) based on steam entry data. As mentioned earlier, the fracture spacing and matrix permeability jointly affect the flow of steam from the matrix blocks to the fractures, so that if the proper fracture spacing is not used in some parts of the reservoir the matrix permeability, adjusted to match the pressure decline data should offset this error. A fracture porosity of 1% was assumed, based upon the work of Weber and Bakker (1981); this parameter does not affect the results significantly. A matrix porosity of 5% was assumed (Lipman et al., 1977) and the initial estimate for the matrix permeability was 3 μD based on our estimates for the recharge factor from flow rate decline data. The initial estimate of the fracture kH product distribution was based upon Fetkovich analysis of flow rate declines. Linear relative permeability fractions were used for both the fractures and the matrix blocks, with residual liquid saturation of 80% for the matrix blocks and zero for the fractures.

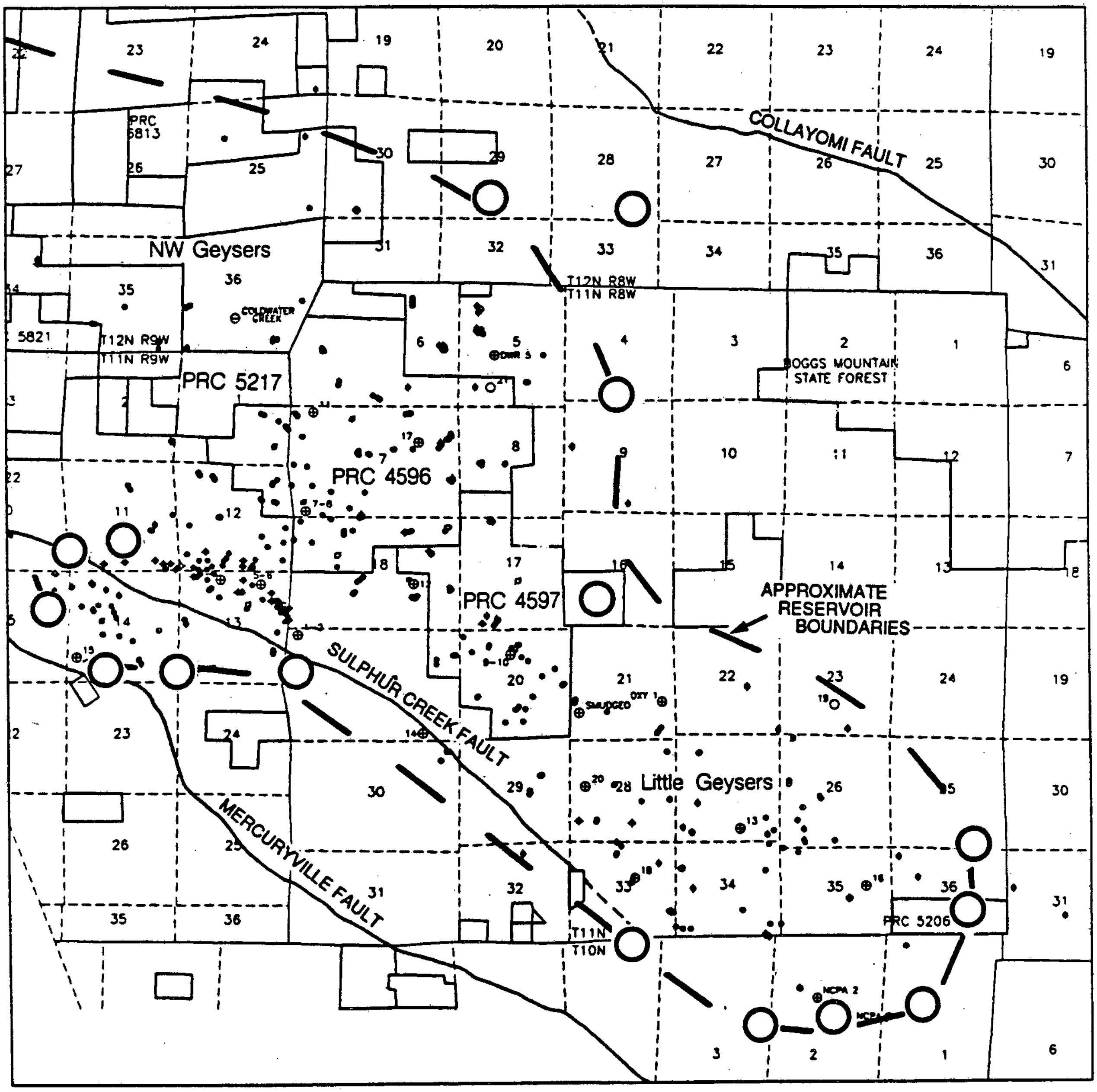

Figure 4. Open circles indicate the locations of dry (non-productive) wells close to assumed reservoir boundaries.

Approach

The main unknown reservoir parameters at The Geysers are the initial liquid saturation, the matrix permeability and the relative permeability curves. It was decided not to vary the relative permeability curves, but only the other two parameters. Three different models were developed, the first two with initial liquid saturations of 50% and 25%, respectively, and the third one with a constant average matrix permeability and variable initial liquid saturation. Thus, for the first two models the matrix permeability and the fracture kH product were the adjustable parameters and for the third model the initial liquid saturation and the fracture kH product. All three models used 250 gridblocks. It was hoped that although the three models were based upon drastically different parameter assumptions that their predictions after the history matching would be similar. The three models were developed and calibrated against the pressure decline data by different technical personnel in order to reduce human bias on the results.

History matching and results

All three models could be calibrated to match the pressure decline data and their respective matches were similar in quality. Figures 5 and 6 show the observed and calculated pressure decline data for two areas at The Geysers for Model 1

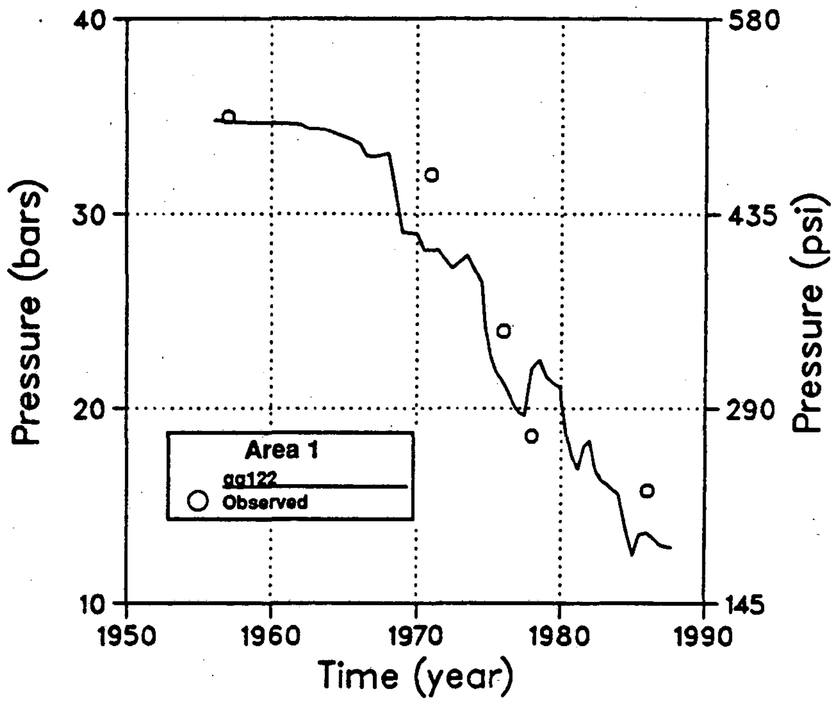

Figure 5. Observed and calculated pressures for Area 1 for Model 1.

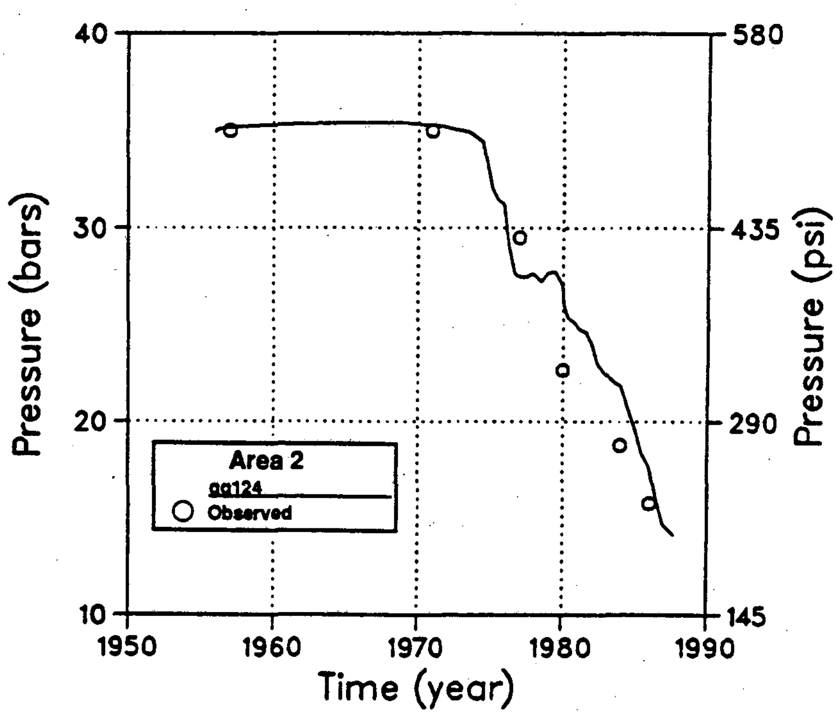

Figure 6. Observed and calculated pressures for Area 2 for Model 1.

(50% initial liquid saturation). Both matches are reasonably good and representative of the history matches for all of the other areas. However, for some areas it was difficult to match the start of the pressure decline because of the coarseness of the model. The results of the history matching yielded fracture permeability thickness products in the range of 10 to 75 Dm (30,000 to 225,000 md·ft) over most of The Geysers. Matrix permeabilities for Models 1 and 2 were generally in the range of 1 to 3 μD. For Model 3, an average matrix permeability of 1.8 μD was used, and the initial liquid saturation was used as an adjustable parameter along with the fracture transmissivities. This yielded initial liquid saturation values ranging from about 5% to over 60% for the different areas of The Geysers.

The three models were used to predict the future behavior of the different areas of The Geysers. Detailed results of these predictions will not be given here, as they may be inaccurate because of the incomplete data base and the various assumptions and approximations used. However, one important finding was that the performance predictions for the three models were surprisingly similar, given the drastically different assumptions made. Also, the model results indicate that injection has significantly helped in halting the pressure decline, suggesting that increased injection would greatly enhance the long term generating capacity of the resource.

Conclusions

1. Large amounts of open-file data are available for The Geysers resource, but an assessment of the future generating capability of the field is difficult because crucial parameters, such as the initial liquid saturation, matrix permeability and the characteristics of the fracture system, are poorly known.
2. A fracture/porous medium model must be employed to evaluate The Geysers, because of the strong fracture matrix interaction and low matrix permeabilities. Two-dimensional models are appropriate for initial studies, but three-dimensional models are required for reliable evaluations, such as investigating the long term effects of injection on reservoir performance.
3. Several two-dimensional fractured porous medium models have been developed for the entire Geysers field. These models are based upon different assumptions regarding initial liquid saturation (reserves), and matrix permeabilities. All three models match the observed pressure decline equally well, and the predicted reservoir performance is remarkably similar for all models. The results of the history matching yielded fracture transmissivities in the range of 10 to 75 Dm (30,000 to 225,000 md·ft) and matrix permeabilities in the range of 1 to 3 μD, for most of The Geysers.

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