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LBL RESEARCH ON THE GEYSERS: CONCEPTUAL MODELS, SIMULATION AND MONITORING STUDIES

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ABSTRACT

As part of The Geysers research activities of DOE's Geothermal Reservoir Technology Program, LBL, in close co-operation with industry, is performing fundamental and applied studies of vapor-dominated geothermal systems. These studies include the development of new methods for evaluating cold water injection, monitoring of the seismic activity in The Geysers associated with injection and production, interpretation of pressure and geochemical changes measured during well tests and long-term production and injection operations, and improvement of existing models of the geothermal system. A review is given of the latest results of DOE-sponsored LBL reservoir engineering and seismic studies relevant to The Geysers.

INTRODUCTION

In Fiscal Year 1990, shortly after it became known that there was an accelerated decline in production and a deterioration in the quality of the steam produced at The Geysers, DOE's Geothermal Division, working with industry, initiated a reservoir technology program to study issues and problems related to that field. Since then a significant part of LBL's geothermal program has been directed to understanding the geochemical and thermodynamic characteristics of vapor-dominated systems, especially those of The Geysers field, and to defining the reservoir processes brought about by the intense exploitation of the resource and by the reinjection of liquid water. The ultimate goal of this work is to provide a technical basis for reservoir management practices that could increase heat extraction from the reservoir, reduce the pressure decline, decrease the corrosive nature of some of the steam, reduce the amount of produced noncondensible gases, and lengthen the commercial life of the field.

RESERVOIR ENGINEERING STUDIES

Conceptual Studies of the High-Temperature Zone and the Vapor-Dominated Reservoir at The Geysers Geothermal Field

In the late 1970s and early 1980s several studies of conceptual models for vapor-dominated systems were conducted. LBL published a major report on The Geysers reviewing the resource and the production technology (Weres et al., 1979). The report discussed the fracture/matrix characteristics of the resource and concluded that large amounts of the reserves must be contained as liquid water in the matrix. Later LBL studies addressed the question of how can there be water in the matrix blocks and only steam be produced from the wells. These studies identified a complex process of boiling due to conductive heat transfer, as the liquid migrates towards the fractures within the matrix blocks (Pruess and Narasimhan, 1982). For matrix blocks with very low permeability, such as The Geysers graywacke, all of the water will boil and only steam will flow into the fractures. The evolution and development of vapor-dominated systems has also been studied using numerical models (e.g., Pruess and Truesdell, 1980). The results indicated that a relatively small discharge event could cause a liquid-dominated, two-phase system to evolve into a vapor-dominated heat pipe in the fractures with high liquid saturation in the matrix blocks (Pruess, 1985).

On-going work includes conceptual and model studies of the high temperature reservoir (HTR) at The Geysers, and modeling of Rayleigh-type condensation patterns.

Conceptual models: The "typical" reservoir at The Geysers is a vapor-dominated, two-phase reservoir with mostly steam in the fractures and significant liquid water reserves in the matrix blocks. The heat is transmitted through the reservoir by a vapor-static heat pipe. In the NW Geysers, a deeper, higher-temperature (exceeding 600°F) reservoir has been found. One of the main objectives of the LBL research was to investigate the development of the two reservoirs, as well as their degree of connectivity. A two-dimensional model of the typical reservoir and the HTR was developed assuming a low permeability zone separating the reservoirs. The model matched well the observed pressure and temperatures in the two reservoirs, but not the large temperature gradient in the zone between them.

Another numerical model was developed based upon the hypothesis that the typical reservoir evolved from a hot dry (steam saturated) rock through infiltration at the top of the reservoir (Truesdell, 1991). The model studies show that under these conditions a vapor-dominated heat pipe will develop that gradually migrates downward (Figure 1). The temperature gradient between the typical reservoir and the HTR is very large as is observed in the field. The boiling of the water "rainfall" also dilutes the steam in the shallow parts of the reservoir, resulting in higher concentrations of non-condensible gases deep in the system, in agreement with the field data.

The two-dimensional simulations of the typical reservoir and the HTR indicate that the sharp temperature gradient between the reservoirs cannot be explained by low permeability rocks. The conceptual model that was developed, suggests that the typical reservoir evolved from a hot dry rock (steam-saturated) reservoir. Numerical modeling studies show that this new conceptual model is feasible and creates both reservoirs with a sharp temperature gradient in between.

Rayleigh condensation processes: Model studies have started in an effort to understand heat transfer and steam composition in vapor-dominated reservoirs such as The Geysers. A two-dimensional cross-sectional model has been developed with non-uniform heat flux at the bottom. The model, when run to steady state, shows many of the features that have been observed at The Geysers, including high gas concentrations near the edges, a water-dominated zone at the bottom of the model close to the edges, and a vapor-dominated heat-pipe in the central part. The circulation patterns that evolve are interesting, with a lateral heat pipe close to the bottom of the reservoir due to capillary pressure effects and the increasing steam density with temperature. Everywhere else, a vertical vapor-dominated heat pipe dominates with near-uniform liquid saturations (reserves).

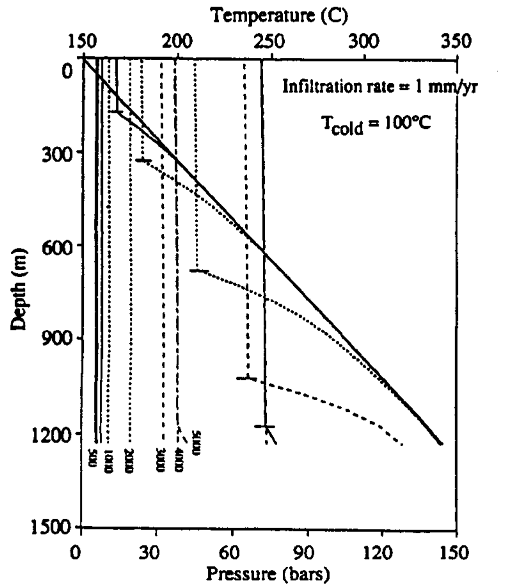

Figure 1. Changes in temperature and pressure profiles with time for an initial "hot dry" rock being infiltrated on top by a small waterflux.

Two-phase flow in rough-walled rock fractures

Understanding and quantifying multi-phase flow in fractures is important for simulating the behavior of geothermal reservoirs. An important part of the description of multi-phase flow in any porous or fractured system is the relative permeability relationships which describe how the flow of each phase is impeded when part of the pore or fracture space is unavailable for flow because it is occupied by the other phase(s).

While the cubic law for single-phase flow in parallel-plate fractures has been well established theoretically and experimentally (Witherspoon et al., 1980), no reliable measurements of multi-phase flow and relative permeability in rough-walled fractures have been reported. In the absence of experimental data, it is usually assumed that the relative permeability of each phase is equal to its saturation, and this assumption is supported by limited experimental and field data (Romm, 1966; Pruess et al., 1984; Bodvarsson et al., 1987). This implies that the phases do not interfere with each other's flow, and the sum of relative permeabilities is 1. However, results of numerical simulations, using a locally-parallel-plate model of a single fracture with stochastically generated local apertures, by Pruess and Tsang (1990) showed strong phase interference, with the sum of relative permeabilities for two phases being much less than one at intermediate saturations. The goals of this work are to resolve the apparent discrepancy between these results, and to provide experimental data to support the approach advanced by Pruess and Tsang (1990).

We designed and fabricated an apparatus for visualizing two-phase flow and measuring gas-liquid relative permeability in realistic rough-walled rock fractures, and used it to make preliminary relative permeability measurements for gas-liquid flow in a transparent replica which reproduces the geometry of a natural fracture (Persoff et al., 1991).

The results of the flow visualization studies have provided evidence that even for very slow flows, there may be no true steady states. Instead, there is a continual succession of transient changes in phase occupancy at critical pore throats. At large values of liquid saturation, sufficient liquid is available to intermittently block some of the gas flow paths (or, in extreme cases, the only gas flow path). This results in continual episodes of throat blocking and clearing.

The limited experiments carried out so far have confirmed the viability of the Hassler (1944) design for achieving two-phase flow conditions in a small fracture under well-defined capillary conditions, without end effects. A series of quasi-steady two-phase flow conditions has been achieved. The relative permeability data plotted in Figure 2 show that strong phase interference occurs between the gas and liquid phases, with the sum of gas and liquid relative permeabilities much less than one at intermediate saturations.

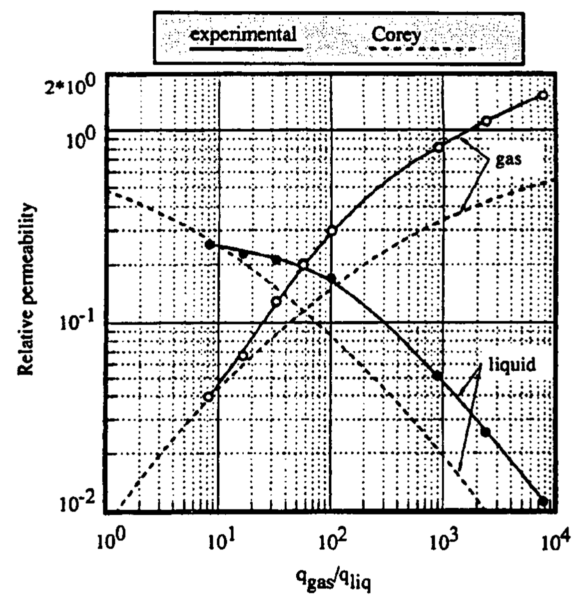

Figure 2. Preliminary experimental results of relative permeability as a function of the flow rate ratio. The broken lines show for comparison the Corey relative permeability curves (from Persoff et al., 1991).

Water Injection into Vapor-Dominated Zones

Recent strong declines in reservoir pressures and production rates at The Geysers have renewed interest in water injection as a means of replenishing dwindling fluid reserves. There is a considerable body of field experience with injection into the vapor-dominated reservoirs at The Geysers and Larderello; the results have been mixed. In some cases injection has increased flow rates of nearby wells, and the return of injected fluid as steam from production wells has been observed directly through chemical and isotopic changes in the produced fluids. In other cases injection has degraded the temperature and pressure of production wells.

Water injection into depleted vapor zones gives rise to complex two-phase fluid flow and heat transfer processes with phase change. These are further complicated by the fractured-porous nature of the reservoir rocks. An optimization of injection design and operating practice is desirable; this requires realistic and robust mathematical modeling capabilities.

Water injection into a medium containing superheated vapor can be classified as a process of immiscible displacement, though it is made considerably more complicated by the fact that some of the displacing water may vaporize, while some of the vapor undergoing displacement may condense. These phase change processes are accompanied by strong latent heat effects. The large contrast in thermophysical properties between liquid and vapor and associated relative permeability effects give rise to highly non-linear flow behavior. The goal of numerically simulating injection is to provide a robust and realistic prediction of injection effects.

Ideally, numerical simulation predictions should be independent of the orientation of the computational grid used. However, our studies showed a potential for strong grid orientation errors (Pruess, 1991). These were explained through a quantitative analysis of finite difference approximations and remedies were suggested to avoid such errors. Specific results are as follows:

When neglecting capillary pressures, as has been traditional practice in geothermal reservoir simulation, exceedingly strong grid orientation effects arise in the vertical direction. For the most commonly used five-point differencing in rectangular grids aligned with the vertical direction, injection plumes slump downward, with very little horizontal spreading. Diagonal grids, higher-order differencing or inclusion of capillary pressure effects all yield substantial horizontal spreading of injection plumes (Figure 3). The grid orientation effects are not diminished by finer space discretization.

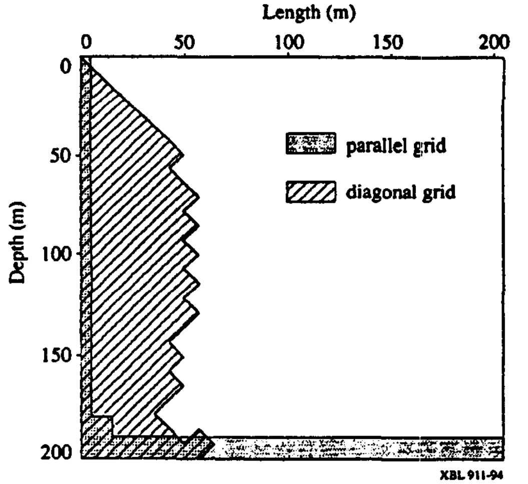

Figure 3. Simulated plumes after 717 days of injection for parallel and diagonal five-point grids (from Pruess, 1991).

Capillary pressures and hydrodynamic dispersion provide mechanisms for horizontal spreading of injection plumes. Neglecting these effects may be justifiable under special circumstances (e.g., in the presence of "wide open" sub-vertical fractures), but will in general produce unrealistic results.

Effects of Capillarity and Vapor Adsorption in the Depletion of Vapor-Dominated Geothermal Reservoirs

Vapor-dominated geothermal reservoirs in natural (undisturbed) conditions contain water as both vapor and liquid phases. The most compelling evidence for the presence of distributed liquid water is the observation that vapor pressures in these systems are close to saturated vapor pressure for measured reservoir temperatures (White et al., 1971; Truesdell and White, 1973). Analysis of natural heat flow conditions provides additional, indirect evidence for the ubiquitous presence of liquid. From an analysis of the heat pipe process (vapor-liquid counterflow), Pruess (1985) inferred that effective vertical permeability to liquid phase in vapor-dominated reservoirs is approximately 10^{-17} m^2, for a heat flux of 1 W/m^2. This value appears to be at the high end of matrix permeabilities of unfractured Geysers rocks, suggesting that at least the smaller fractures contribute to liquid permeability. For liquid to be mobile in fractures, the rock matrix must be nearly completely liquid-saturated. Otherwise the liquid phase would be sucked from the fractures into the matrix by capillary force. Large water saturation in the matrix, well above the irreducible saturation of perhaps 30%, has been shown to be compatible with production of superheated steam (Pruess and Narasimhan, 1982).

In response to fluid production the liquid phase will boil, with heat of vaporization supplied by the reservoir rocks. As reservoir temperatures decline, reservoir pressures will decline also. For depletion of "bulk" liquid, the pressure would decline along the saturated vapor pressure curve, while for liquid held by capillary and adsorptive forces inside porous media, an additional decline will arise from "vapor pressure lowering."

Capillary pressure and vapor adsorption effects, and associated vapor pressure lowering phenomena, have received considerable attention in the geothermal literature, and also in studies related to geologic disposal of heat-generating nuclear wastes, and in the drying of porous materials.

Our work is primarily concerned with evaluating the impact of vapor pressure lowering (VPL) effects on the depletion behavior of vapor-dominated reservoirs. We have examined experimental data on vapor adsorption and capillary pressures in an effort to identify constitutive relationships that would be applicable to the tight matrix rocks of vapor-dominated systems such as The Geysers and Larderello. Numerical simulations have been performed to evaluate the impact of these effects on the depletion of vapor-dominated reservoirs (Pruess and O'Sullivan, 1992).

Capillarity, vapor adsorption on rock surfaces, and vapor pressure lowering are interrelated and strongly coupled effects. Different geologic media show a tremendous variety of capillary and adsorptive behavior. Although existing data are insufficient for a detailed quantitative description of vapor pressure lowering effects in vapor-dominated reservoirs, a survey of literature data indicates that VPL effects will become significant (reducing vapor pressure by 10% or more) only at low liquid saturations of 20% or less. Initial liquid saturations in vapor-dominated systems are believed to be high, probably exceeding

50% (Pruess and Narasimhan, 1982; Pruess, 1985), so that VPL effects on production rates and pressures appear to be small over most of the productive life of such systems.

MICROSEISMIC MONITORING AT THE GEYSERS

Microearthquake (MEQ) data are being obtained from the northwest and southeast Geysers areas using existing and newly installed arrays of digital high-frequency, three-component instrumentation. The aims of this study are to demonstrate the utility of high-resolution MEQ data to develop a three-dimensional velocity structure of the geothermal reservoir, to obtain accurate hypocenters which can be used to track fluid flow, to identify high-permeability paths, and to link the MEQ parameters to the production activities.

A number of studies have concluded that the high seismicity in The Geysers is induced by geothermal development. Eberhart-Phillips and Oppenheimer (1984) suggested that seismicity in the area is related to production, while Stark (1990) documented the clear correlation between seismicity and injection.

The main data set analyzed to date consists of hand-picked P- and S-wave arrival times recorded by the Coldwater Creek Operating Company's (CCOC) 16-element borehole array located in the northwest Geysers. Data are digitized at the remote sites at 400 samples per second and telemetered by radio to a central recording site. The system detection threshold is M = -0.9. From 2600 events recorded during the first six months of operation (January-June 1988), 300 high-quality events were selected for the simultaneous velocity inversion. The resulting 3-D velocity structure was then used to relocate the 2600 events. Processing is continuing on subsequent events.

Initial results indicate that seismicity seems to be related to both production and injection activities (Romero et al., 1992). MEQs are concentrated within the CCOC area extending south and east into the older sections of the producing field. Present seismicity is low to the north and west of the CCOC area in the direction where the field is undeveloped. Seismicity occurs at two zones: a broad, shallow zone between 1 and 2.5 km depth, presumably related to the production zone, and a tight cluster between 3.5 and 4.5 km depth just beyond the southeast edge of the field. Majer and McEvilly (1979) suggested that seismicity in the production zone may be caused by volumetric change due to steam withdrawal.

A cluster of MEQs with focal depths between 2 and 3 km is located beneath the injector well PRATI-8, as shown in Figure 4. The MEQ distribution seems to define a vertical planar structure striking roughly north-south. In addition, PRATI-8's injection history exhibits a general correlation with the rate of earthquake occurrence nearby (Figure 5). Seismicity increased markedly with the start of sustained injection, and peaks in seismic activity occur during periods of maximum injection. Focal depths suggest a deepening of MEQs with time, although the trend is tentative. Spatial and temporal correlation between injection and seismic activity provide compelling evidence for induced seismicity around well PRATI-8. High resolution MEQ locations hold promise for inferring fluid flow paths.

The three-dimensional Vp/Vs model from the joint inversion is shown in Figure 6. The production zone is marked by anomalously low Vp/Vs ratio between depths of 1 and 3 km, an observation previously reported by Majer and McEvilly (1979), Majer et al. (1988) and O'Connell and Johnson (1991), and interpreted in terms of increasing dry steam fraction in the pore spaces of the reservoir rocks. Although less well resolved, a region of high Vp/Vs ratio located north of the field at 2 to 4 km depth suggests the possibility of increased fluid saturation, the presence of more fractures or an area of higher permeability (Romero et al., 1992).

The resolution of this method is sufficiently good to allow the monitoring of reservoir processes. It is hoped that such monitoring could be useful in optimizing reservoir exploitation.

Seismicity around PRATI-8

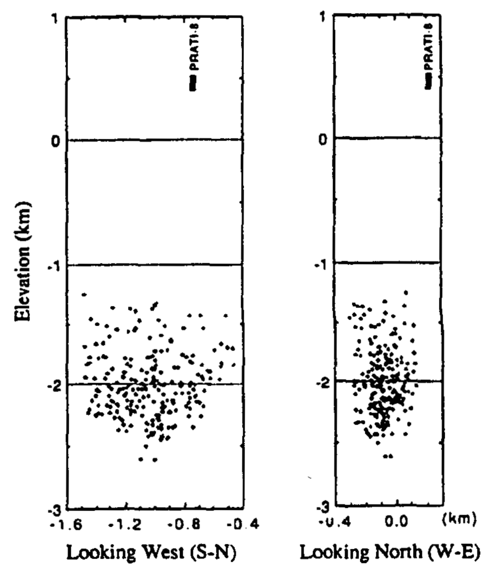

Figure 4. N-S and W-E cross sections showing the locations of MEQs around CCOC's injector PRATI-8. The MEQ distribution seems to define a vertical planar structure oriented roughly north-south (from Romero et al., 1992).

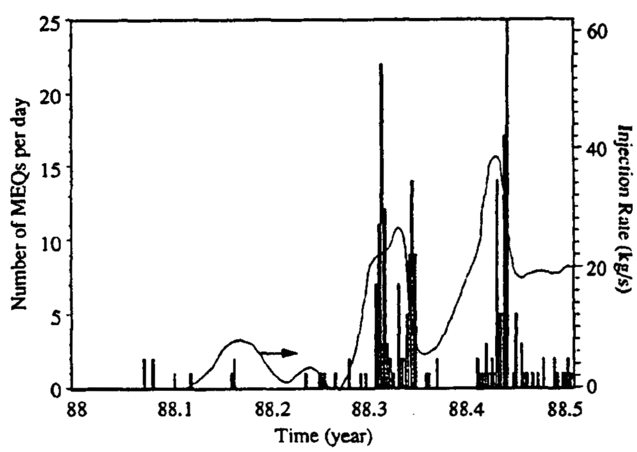

Figure 5. Comparison between injection history of PRATI-8 and seismicity rate nearby. Note the good correlation between peaks in seismic activity and injection rate (from Romero et al., 1992).

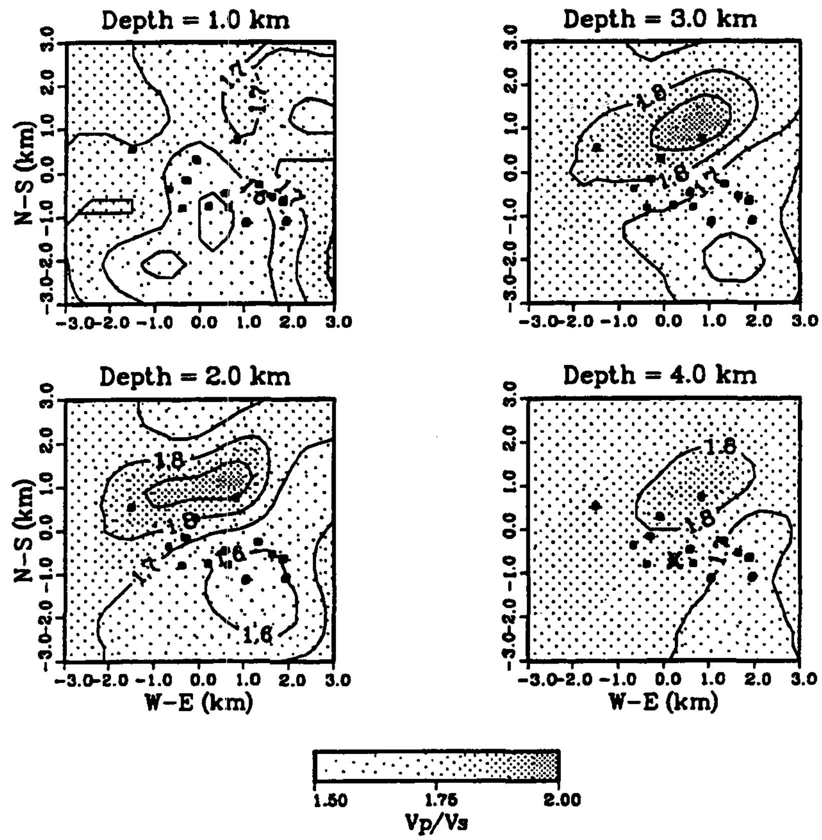

Figure 6. NW Geysers, 3-D Vp/Vs structure at several depths; datum: 700 masl. Solid circles correspond to wellhead locations. Well PRATI-8 is indicated by the X in the lower right figure. Note the anomalously low Vp/Vs within the producing horizon and the high Vp/Vs anomaly north of the CCOC area (from Romero et al., 1992).

FINAL REMARKS

The results of LBL research on The Geysers and vapor-dominated geothermal systems are becoming available through review meetings like this and by way of publications. The interaction between the group and industry has been increasing. During the first year of devoting about half of our DOE geothermal funding to study The Geysers (FY 1991), a significant part of LBL involvement was spent in obtaining data from the operators and installing MEQ instrumentation in the field. Presently, most of the effort is spent in analyzing the information. By summarizing our results we hope not only to inform industry representatives but also to get their comments and inputs.

ACKNOWLEDGMENTS

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