## Title
RECENT GEOTHERMAL RESERVOIR ENGINEERING ACTIVITIES AT LAWRENCE BERKELEY LABORATORY



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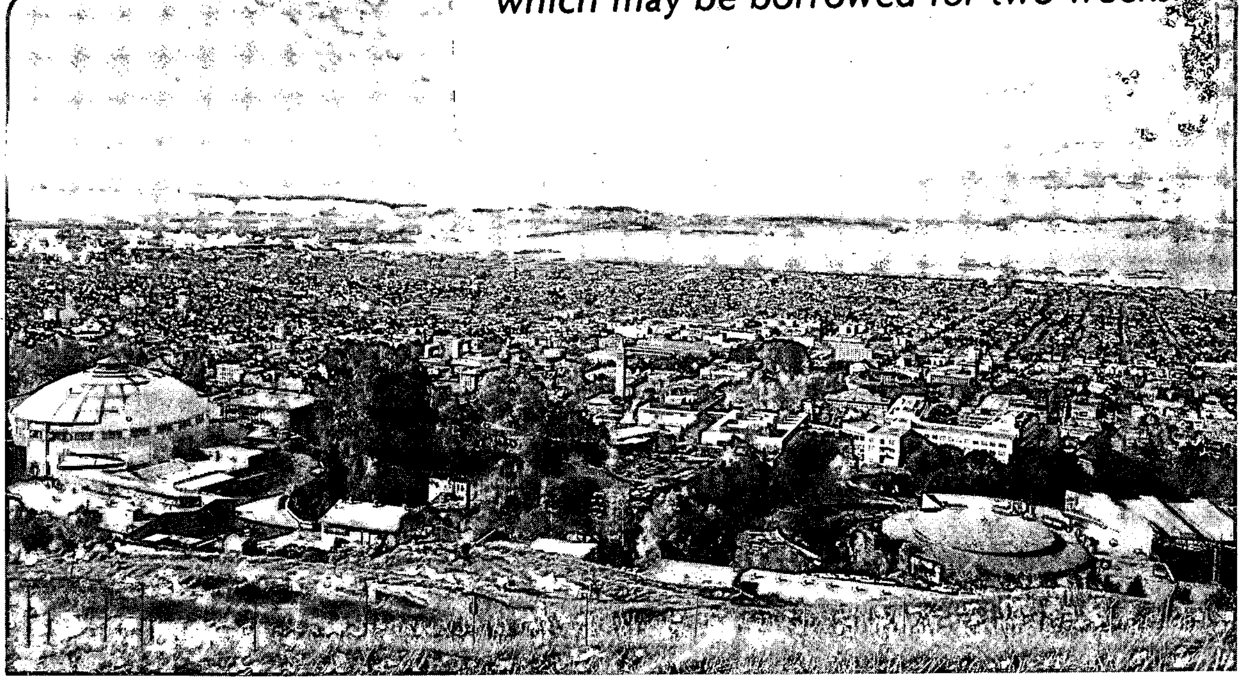



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# Recent Geothermal Reservoir Engineering Activities at Lawrence Berkeley Laboratory

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## RESUMEN

En el presente trabajo se describen brevemente las más recientes actividades en ingeniería de yacimientos realizadas por el grupo geotérmico del Lawrence Berkeley Laboratory (LBL).

Actualmente gran parte del programa geotérmico del LBL está dedicado a la ingeniería de yacimientos, incluyendo investigaciones teóricas, trabajos de desarrollo y aplicación de modelos matemáticos, y estudios de campo. El propósito de dichas actividades es desarrollar, mejorar y validar métodos e instrumental que se utiliza en la determinación de propiedades de sistemas geotérmicos, y en la identificación y evaluación de la importancia de los distintos procesos que ocurren en el yacimiento. El objectivo final del programa es mejorar la tecnología que se emplea para caracterizar yacimientos geotérmicos, y evaluar su capacidad y vida productiva.

## INTRODUCTION

Lawrence Berkeley Laboratory (LBL) is a national, multiprogram laboratory managed by the University of California for the U.S. Department of Energy (DOE). The Earth Sciences Division manages LBL's geothermal program, which began in the mid-seventies in response to the energy crisis. The emphasis of the multidisciplinary geothermal program has changed over the years. Originally it was mainly oriented toward the exploration of geothermal resources, that is geology, geophysics and geochemistry. As U.S. industry moved from exploration to exploitation of known geothermal fields, LBL's research shifted towards the development and validation of new techniques for characterizing and evaluating hydrothermal systems. At the present time, reservoir engineering activities constitute about 75% of LBL's geothermal program, with geophysics and geology constituting the remaining 25%.

Geothermal research at LBL is funded primarily by the Geothermal Technology Division of DOE. Recently, additional support was obtained from the California State Lands Commission (CSLC) for the evaluation of The Geysers field in California, and from the U.S. Agency of International Development (USAID) through the Los Alamos National Laboratory (LANL), for the modeling of the Ahuachapán reservoir in El Salvador.

The objectives of LBL's geothermal reservoir engineering activities are to develop, improve and validate methods and instrumentation to (1) determine geothermal reservoir parameters, and (2) identify and evaluate the importance of reservoir processes. The ultimate goal of the program, which includes theoretical, modeling and field activities, is to advance the state-of-the-art for characterizing geothermal systems and evaluating their productive capacity and longevity under commercial exploitation.

## THEORETICAL AND MODELING STUDIES

In order to (1) determine the characteristics of geothermal reservoirs, (2) effectively analyze the measurements made at the surface and downhole, and (3) predict the changes resulting from the exploitation of geothermal systems, it is necessary to have a good understanding of the complex processes occurring in the reservoir. Theoretical and modeling studies are performed to evaluate the importance of different phenomena in geothermal systems. LBL's numerical modeling and field capabilities are continuously being expanded and updated in order to be able to address complex multi-component problems.

The mass and energy recovery from tight rock matrix blocks of fractured geothermal reservoirs is of considerable interest to industry. By way of modeling studies it was found that noncondensible gases can greatly affect mass recovery, with less mass being recovered if these gases are present in the reservoir (Bodvarsson and Gaulke, 1987). Analytical expressions quantifying the effects of noncondensible gases on mass and energy recovery have been developed. Gaulke and Bodvarsson (1987) incorporated in their numerical studies both double porosity and noncondensible gas effects to determine the reservoir characteristics near well BR21 at Ohaaki (Broadlands), New Zealand; the inferred distribution of reservoir properties (i.e., permeability, porosity and initial $CO_2$ concentration) is shown in Figure 1.

Geochemistry of noncondensible gases is a topic of great current interest in the study of two-phase geothermal reservoirs. Recent work in this area has defined possibilities for estimating in-place phase compositions of reservoir fluids from gas analysis data. The effects of transport processes and rock-fluid interactions on produced gas compositions have been studied for the Lar-

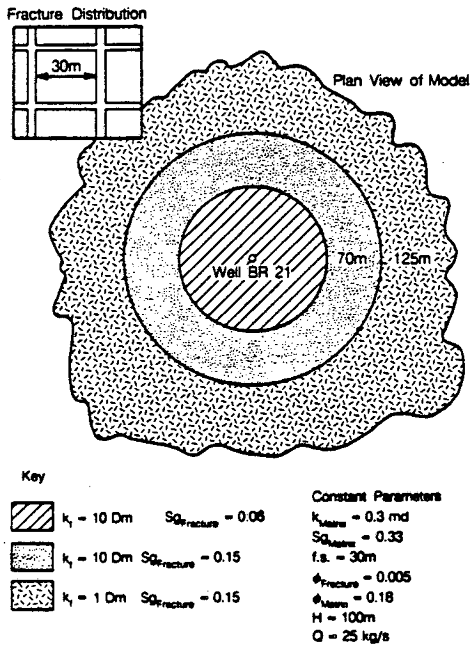


Fig. 1. Diagram of best fit model for the reservoir region near well BR-21, Ohaaki, New Zealand (from Gaulke and Bodvarsson, 1987). XBL 8612-12791

derello geothermal field (D'Amore and Pruess, 1986). This analysis revealed that $CO_2$ released from minerals during reservoir exploitation does not attain chemical equilibrium with other noncondensible gases such as $H_2$ and $CH_4$.

The temperature range of LBL's reservoir simulator MULKOM (Pruess, 1983) is being extended to near-critical and supercritical conditions of pure water (374 °C and beyond), in order to attain a capability for modeling heat transfer in deep zones of geothermal systems. Initial results are encouraging, indicating strong enhancements in convective and dispersive heat transfer near the critical point.

Numerical simulation methods have been used to investigate gravity effects on reservoir pressure transients and depletion patterns in two-phase reservoirs (Bodvarsson and Cox, 1986). These studies showed that production from a deep feed zone gives rise to an efficient gravity drainage mechanism that causes only gradual long-term pressure changes at the well (Fig. 2). On the other hand, because of gravity effects, production from shallow feeds results in considerably higher pressure drawdowns.

A wellbore simulator has recently been developed to model one- or two-phase flow in a vertical geothermal well fed by two or more production zones (Bjornsson and Bodvarsson, 1987). The governing equations are solved numerically by finite difference methods, assuming steady state flow in the well. Either wellhead or wellbottom flowrates, enthalpies and pressures are given as boundary conditions; well geometry and feedzone properties have to be specified. The simulator can handle variable diameter wells, injection and production, and internal flow. Figure 3 shows the calculated and observed flowing temperature and pressure data for well NJ-7 at Nesjavellir, Iceland. The model estimates that 63% of the fluids enter the well through the feedzone at 1000 m depth. This zone produces a two-phase mixture with an estimated enthalpy of 1500 kJ/kg. Most of the remaining fluid flowing in the well (37%) is a subcooled liquid coming from an aquifer at 1550 m depth. A third, minor feedzone is found at 2000 m.

The highly heterogeneous and faulted nature of geothermal systems makes the application of conventional well testing analysis methods for parameter assessment unreliable. New techniques, tailored to the of heterogeneity typical of geothermal systems, are needed. LBL has developed a method for locating and assessing the size and permeability of high-permeability regions within reservoirs (Benson and Lai, 1986). The approach consisting of a combination of composite and naturally fractured reservoir models was successfully applied to the Klamath Falls, Oregon, geothermal system.

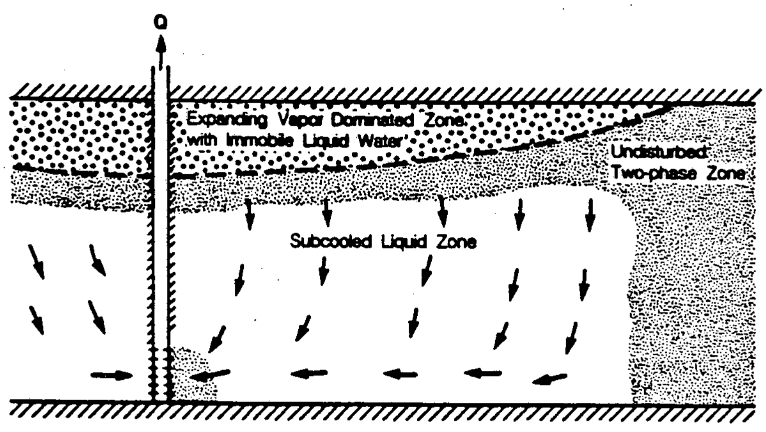


Figure 2. Schematic model of flow patterns and depletion mechanisms for a well with a deep feed zone (from Bodvarsson and Cox, 1986). XBL 866-10863

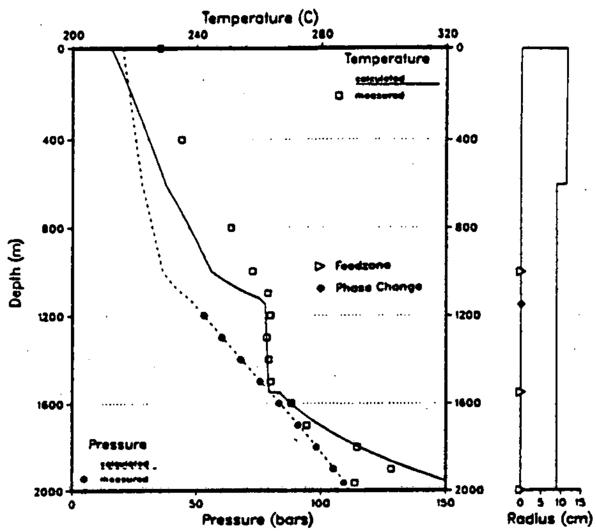


Fig. 3. Calculated and measured downhole profiles in well NJ-7 at Nesjavellir, Iceland (from Bjornsson and Bodvarsson, 1987).

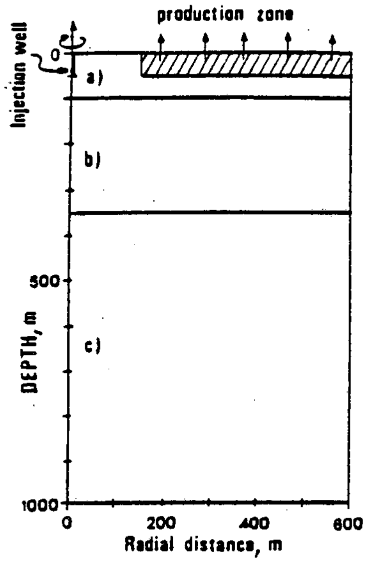


Fig. 4. Two-dimensional radial porous model used to simulate cold water injection into fluid-depleted vapor-dominated reservoirs (from Calore et al., 1986).

Italian and LBL researchers cooperated in the study of cold water injection into depleted vapor-dominated reservoirs (Calore et al., 1986). The idealized flow geometry used in these studies is shown in Figure 4. It was determined that injection plumes migrate primarily downward rather than outward (see Fig. 5). An efficient heat extraction mechanism is provided by heat pipe effects on the boiling surface of the plume. The results of this study indicate that the prospects for enhanced energy recovery by means of injection into depleted vapor-dominated zones are excellent.

Heat extraction experiments using a large-scale laboratory model at Stanford University have been successfully modeled with the computer code MULKOM (Pruess, 1983) using the "Multiple Interacting Continua" (MINC) method (Pruess and Narasimhan, 1985). This work, carried out in collaboration with Stanford researchers, validated the methodology used for modeling the behavior of two-phase systems with complex geometry and boundary conditions (Lam et al., 1987).

Cold water injection into two-phase or vapor zones can give rise to sharp (hydrodynamic, chemical, thermal) fronts. Numerical simulation of processes involving these fronts is difficult, and the accuracy of the most commonly used methods (finite difference, finite element) is questionable. Pruess et al. (1987a) obtained an analytical solution to an injection problem involving a moving boiling front which can be used to verify numerical simulators and to obtain approximate estimates of field response. Figure 6 shows predictions for pressures and temperatures at the moving boiling front for different reservoir porosities and transmissivities, assuming initial conditions of 240 °C and 6 bars, and an injection temperature of 29 °C. The agreement between the analytical solution and results of MULKOM simulations is excellent.

Major problems in modeling sharp fronts are numerical diffusion errors and grid orientation effects. Both of these cause an artificial smearing of the fronts, yielding unreliable results for analysis of field data. Lai et al. (1986) developed a finite difference method for modeling sharp fronts that consists of an explicit second-order Godunov method and the operator splitting technique. It was found that this method practically eliminates numerical diffusion errors and grid orientation effects, thus providing a tool for reliable analysis of thermal interference and tracer well test data.

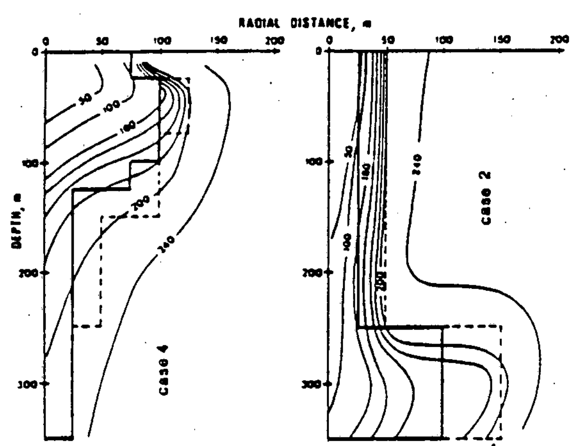


Fig. 5. Shape of the liquid plume and isotherms for the anisotropic (left) and isotropic (right) cases after about one year of injection, when liquid volume (including that in the two-phase elements) is about 356,000 $m^3$. Solid line: limit of liquid-saturated region. Dashed line: limit of two-phase region (from Calore et al., 1986).

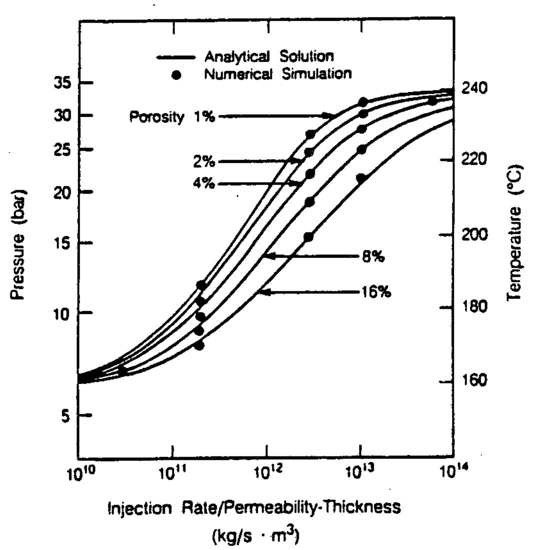


Fig. 6. Comparison of results from analytical and numerical calculations of boiling front pressures (from Pruess et al., 1987).

## FIELD-RELATED STUDIES

Data from geothermal fields throughout the world are continuously been gathered and analyzed by LBL. The main purpose of this effort is (1) to continue the field validation of the reservoir engineering technology developed by LBL and other organizations; (2) to add to the understanding of the phenomena occurring in geothermal systems in their natural and exploited state; and (3) to make available to the geothermal community information on the characteristics of different geothermal systems and their response to exploitation. Short descriptions of these field-related studies follow below; in many instances the data analysis was done with the help of computer modeling techniques reviewed by Bodvarsson et al. (1986b).

## FIELDS IN THE U.S.

*Klamath Falls, Oregon.* A reevaluation of the significant amount of information available on the Klamath Falls geothermal system was completed. Supported by borehole, geochemical, geophysical and hydrological data, a conceptual model of the area was developed (Prucha et al., 1987). Two main aquifers are present in the field, interconnected by a number of normal faults. At depth the system may be recharged by hot waters from the east and west; at shallow depths the thermal waters spread laterally through permeable layers and mix with colder regional groundwaters. A three-dimensional numerical simulation of the field has provided estimates of the quantity of hot water recharging the system.

*Crater Lake, Oregon.* The geothermal/hydrogeologic system of Crater Lake was modeled to establish the impact of drilling exploration wells to evaluate the geothermal resources in the area outside this national park. The numerical simulations indicated that (1) the significant recharge derived from the caldera lake plays a dominant role in the hydrology of the surrounding region, and (2) the injection of drilling mud that might result from the proposed drilling activities will not pose a threat to the lake or affect the hydrologic system in the immediate vicinity of the Crater Lake caldera (Sammel and Benson, 1987).

*East Mesa, California.* In August 1987 LBL began a joint Industry/DOE injection test at the GEO Operator Corporation East Mesa site. This field project will help validate nonisothermal well testing techniques developed under DOE sponsorship. LBL is providing downhole instrumentation and will analyze the test data to determine the parameters of the injected formation and track the fronts of injected fluids.

*The Geysers, California.* In 1985 LBL began a research project on the vapor-dominated Geysers field for CSLC. The long-term objectives of the project are to evaluate the productive characteristics of developed and undeveloped geothermal State leases. During 1985-86 a computerized data base on the field was created and the data were analyzed using conventional reservoir engineering methods (Bodvarsson et al., 1986a). Recently, a geological model of the field was developed and the steam production correlated with major faults, the global fracture system and contact permeability. The pressure decline of the field was analyzed in terms of cumulative production of various areas. Computerized type-curve modeling techniques were developed, and the flow rate decline of selected wells was analyzed using numerical techniques. Finally, studies of pressure transient tests for steam wells were carried out and the effects of injection on nearby producers quantified. The results of all of these studies are given in Bodvarsson et al. (1987a).

## FIELDS OUTSIDE THE U.S.

*Cerro Prieto, Mexico.* The updating of the hydrogeologic model of Cerro Prieto continues. As information becomes available, lithological, thermal and completion data from new exploration and development wells are incorporated into the model. Recent data allowed delineation of the $\beta$ reservoir in the eastern part of the field (Fig. 7), and confirmed the important role of normal fault H in controlling the flow of geothermal fluids in that region (Halfman et al., 1986). A recently completed review paper summarizes the geological, geochemical and reservoir engineering characteristics, and the exploitation history of Cerro Prieto (Lippmann and Mañón, 1987).

A careful study showed that contrary to earlier suggestions, the geochemical and reservoir engineering data from the shallow Cerro Prieto $\alpha$ reservoir cannot confirm the hypothesis of a massive influx of hot water into the system related to two large local 1979-80 earthquakes (Truesdell and Lippmann, 1986). The analysis of the information showed that the cold water recharge to the $\alpha$ reservoir in response to production-induced drawdown continues, unaffected by these earthquakes (Fig. 8).

*Los Azufres, Mexico.* Test data from geothermal wells at Los Azufres suggest that the permeability of the

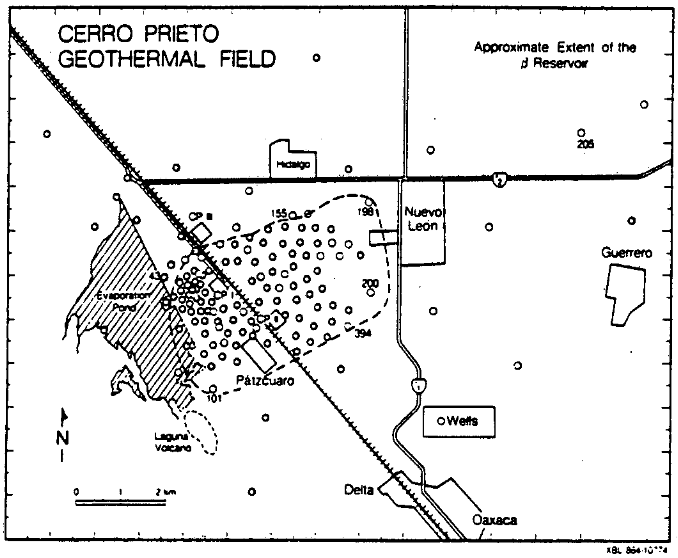


Fig. 7. Approximate extent of the Cerro Prieto $\beta$ reservoir as inferred from well data (from Halfman et al., 1986).

near-bore region is enhanced during cold water injection (Fig. 9). A newly developed analysis method (Benson et al., 1987) indicates that during a 2- to 3-hour long injection period the permeability of the region cooled by the injected fluids increases by a factor of about five. A good correlation between the permeability increase and the sandface injection temperature (Fig. 10) suggests that this increase is related to the cooling of the formation. Thermal contraction and thermal stress cracking are the most probable causes of the near-bore permeability enhancement. Research on this topic continues.

*Ellidaar and Seltjarnarnes, Iceland.* The Ellidaar and Seltjarnarnes fields are supplying geothermal fluids for space heating in the capital city of Reykjavik. The transport of heat, mass and chemical species in these low-temperature systems was simulated using computer programs developed at LBL (Bodvarsson, 1982; Lai et al., 1986; Spencer, 1986; Tulinius et al., 1987). The models were calibrated against observed temperature, pressure and chemical data. In the case of Seltjarnarnes the results of the simulations revealed regions of different permeabilities and porosities, and suggested the possible encroachment of colder seawater into the reservoir.

*Svartsengi, Iceland.* A new conceptual model of the Svartsengi field was developed (Bodvarsson, 1987). In contrast to earlier models, this model includes the effects of a two-phase zone overlying the main geothermal reservoir. A simple radial model was used to obtain a history match with the pressure decline observed in the reservoir during the 1976-83 period.

*Larderello, Italy.* In cooperation with Italian researchers, a preliminary analysis of the permeability structure and fluid and heat flow conditions in the deeper horizons of the Larderello system was completed (Pruess et al., 1987b). From an analysis of heat transfer mechanisms it was inferred that under natural state conditions a transition from vapor-dominated to liquid-dominated conditions must have occurred; the transition could have occurred at a depth of 2000 m or more. It was also found that in deep high-temperature zones (T>300 °C) vapor-liquid counterflow provides efficient heat transport at temperatures of up to 350 °C. This work indicated that the estimation of vertical permeability from temperature-depth data might be possible in two-phase reservoirs.

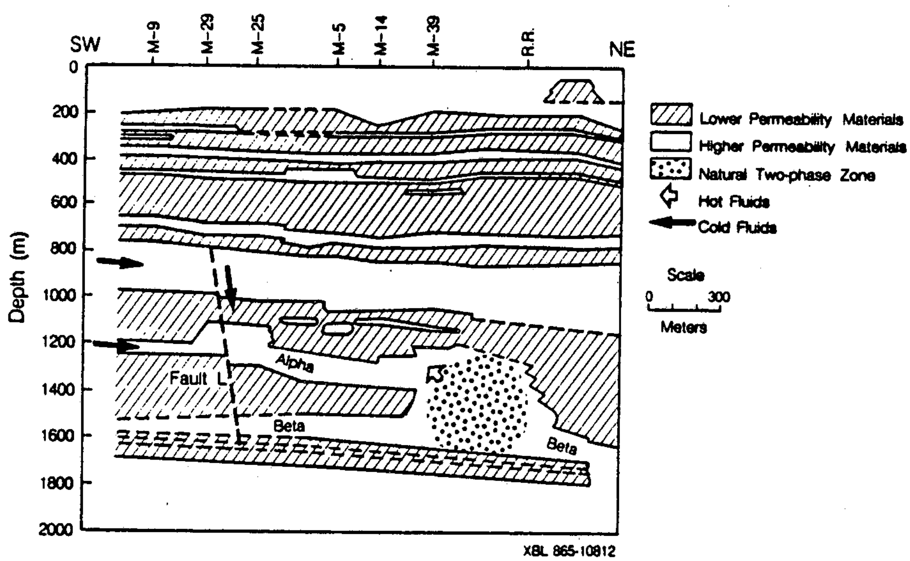


Figure 8. Postulated fluid recharge in the Cerro Prieto $\alpha$ reservoir resulting from its exploitation (from Truesdell and Lippmann, 1986).

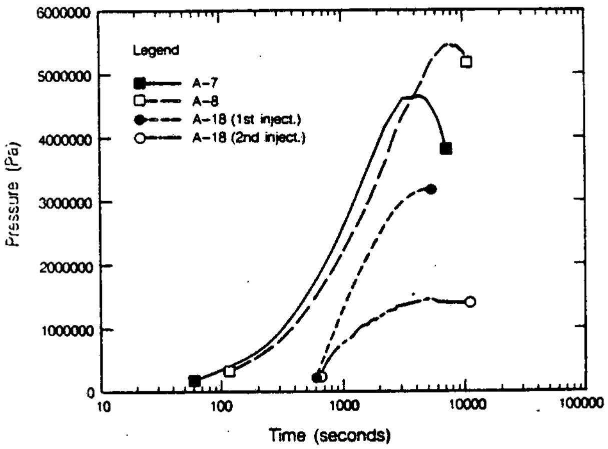


Fig. 9. Pressure transient data from four injection tests at the Los Azufres, Mexico, geothermal field (from Benson et al., 1987).

*Olkaria, Kenya.* A detailed three-dimensional model of the East Olkaria well field was developed (Fig. 11; Bodvarsson et al., 1987b). A reasonable match was obtained of flow rate and enthalpy data from all existing wells. This modeling study suggests that the reservoir system is of rather uniform permeability with the possible exception of a high permeability north-south anomaly below 1000 m depth. The model was then used to investigate various reservoir development schemes (Bodvarsson et al., 1987c). The analysis focused on evaluating the effects of different well spacings on well deliverabilities and total electrical power production, and the effects of injection on well performance and reservoir depletion.

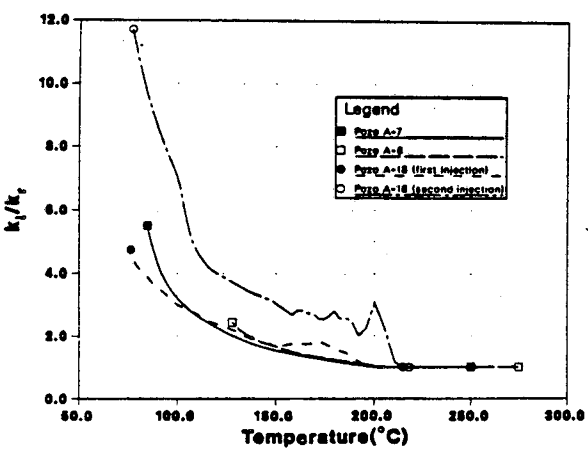


Fig. 10. Permeability enhancement plotted as a function of the sandface injection temperature for the four Los Azufres injection tests (from Benson et al., 1987).

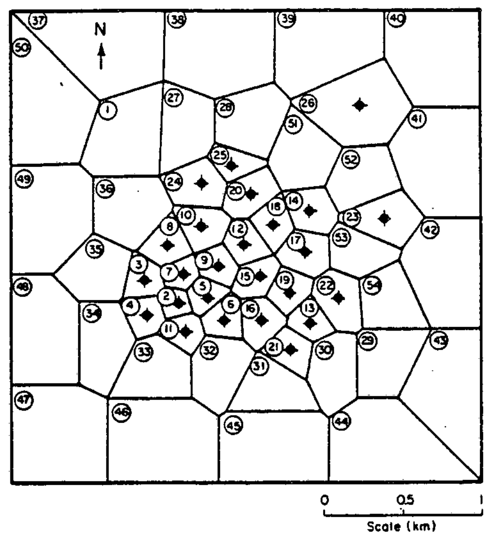


Fig. 11. Areal view of the mesh used in the Olkaria, Kenya, modeling studies (from Bodvarsson, et al., 1987b).

*Ahuachapán, El Salvador.* Sponsored by USAID through LANL, LBL is initiating a reservoir engineering analysis of the Ahuachapán field. This system has been under exploitation since 1975 and provides a critically needed source of electricity to the city of San Salvador. Although the installed capacity of the power plant is 95 MWe, only about 45 MWe are being produced due to a significant decline in reservoir pressure. LBL will develop a model of the field with the ultimate purpose of designing an optimal reservoir management plan that includes an effective brine injection program.

## DEVELOPMENT OF INSTRUMENTATION

Pressure transient tests provide the most useful data for determining the hydrologic properties of a geothermal formation. Present-day methods of analyzing these tests require extremely accurate pressure data measured at short time intervals. The high temperature of geothermal systems precludes the use of conventional instruments for making these measurements. LBL has developed and tested a high-resolution, high-speed, computer-controlled system for collecting interference and injection test data. The system is far superior to its commercially available counterparts and opens new doors for collecting the types of data needed to fully understand geothermal systems. The characteristics of this system are described by Benson (1986).

LBL's downhole fluid sampler (Solbau et al., 1986) was successfully used in the Salton Sea Scientific Drilling Project well. On the first and only downhole run into the well, a sample was collected at a depth of about 3000 m, where the temperature was approximately 350°C. An improved version of this sampler with a 2-liter capacity has been built and is ready to be tested in the field.

## ACKNOWLEDGMENTS

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