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ABSTRACT

During the last decade the use of numerical modeling for geothermal resource evaluation has grown significantly, and new modeling approaches have been developed. In this paper we present a summary of the present status in numerical modeling of geothermal systems, emphasizing recent developments. Different modeling approaches are described and their applicability discussed. The various modeling tasks, including natural-state, exploitation, injection, multi-component and subsidence modeling, are illustrated with geothermal field examples.

INTRODUCTION

A number of different methods for modeling the behavior of geothermal reservoirs are currently available to reservoir engineers. These methods vary widely in complexity and cost of application. In selecting the proper method for a particular study, one must consider the amount and quality of field data available and the objectives of the study.

Geothermal systems are generally very complex, exhibiting such features as fracture-dominated flow, phase change, chemical reactions and thermal effects. In order to accurately analyze data from geothermal wells and estimate the generating potential of a system, modeling studies must be carried out. When a model of a geothermal system is developed, the existing field data must be carefully evaluated, and the important physical processes that occur in the system identified. After a plausible conceptual model of the field is developed, one must choose a mathematical (numerical) model that can realistically evaluate the performance of the geothermal reservoir, and reliably predict its future behavior.

We have found that modeling the natural state of a field prior to modeling the field under exploitation can give very valuable reservoir information. It not only tests qualitatively the conceptual model, but also gives estimates of mass and heat flow in the system. Futhermore, it provides consistent initial conditions for the exploitation models.

The primary objectives for geothermal reservoir modeling are to provide answers to important reservoir management questions, relating to well decline, well spacing, the generating capacity (power potential) of the reservoir, injection effects, and potential subsidence and scaling problems. These questions must be addressed by a proper exploitation model that has evolved from the conceptual model and the natural state modeling studies.

In this paper, we present a brief review of geothermal reservoir modeling, emphasizing recent developments. The different modeling approaches are described and their benefits and limitations are discussed. We briefly describe the governing equations for mass and heat flow and discuss phase transitions and solution techniques. Examples are given to illustrate the different methodologies for modeling of natural state, exploitation, injection, multicomponent flow and subsidence. Finally, we identify problems of current interest in geothermal reservoir modeling.

PHYSICAL PROCESSES AND CONCEPTUAL MODELS

In comparison with oil and gas reservoirs, geothermal systems are very dynamic in their natural state.[1] There is continuous transport of fluid, heat and chemical species. Important physical processes in geothermal systems include mass transport, convective and conductive heat transfer, phase change (boiling and condensation), dissolution and precipitation of minerals, and stress change due to pore pressure changes. Most of these processes are strongly coupled; for example, phase change disturbs chemical equilibria, often resulting in precipitation/dissolution of minerals that in time can alter porosities and permeabilities of the subsurface rocks. This in turn can affect the mass transport in the system.

In modeling geothermal reservoirs one must carefully evaluate which physical processes need to be considered in a specific modeling study.[2] This will depend upon the objectives of the study and the complexity of the geothermal system. Most presently available geothermal simulators only consider single-component mass and heat transport. In recent years several simulators capable of modeling the trans-

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References and Illustrations at end of paper.

port of a second component, either a non-condensible gas or a dissolved solid, have been developed.

Conceptual models of geothermal systems vary greatly in complexity. Perhaps the "simplest" geothermal systems are those created by hot water upflow through a single fault or at the intersection of two or more faults (e.g., Susanville, California;[3] East Mesa, California.[4,5]) A rather complex porous medium type geothermal reservoir is the Cerro Prieto field, Mexico[6] (Fig. 1). The lithology consists of interlayered shale and sandstone beds. The detailed lithology shown in Figure 1 has been determined mainly on the basis of wireline well logs.[6] Very high temperatures (up to 360°C), and a small two phase zone have been identified.[7] Hot fluids rise from the northeast into the so called β-reservoir (reservoir below a depth of 1500 m) and recharge the shallower α-reservoir (about 1000-1400 m depth). In the natural state some of the hot fluids ascend to shallower depths and eventually feed surface springs.[7]

Two-phase reservoirs in fractured rocks are generally the most complex of all. As an example, the conceptual model of the Krafla field consists of a single-phase upper reservoir (~200°C) overlying a two-phase reservoir[8,9] (Fig. 2). A low permeability confining layer separates the reservoirs. Fluid flow in the lower reservoir is from west to east, and a two-phase mixture rich in non-condensible gases rises through a fracture zone (Hveragil gully). A separate upflow zone is located to the east, and fluids from it flow laterally to the west at shallower depth and mix with fluids from the lower reservoir. After mixing, steam and non-condensible gases escape to surface springs in the Hveragil gully; the remaining fluids recharge the upper reservoir. Temperatures in the upper reservoir gradually decline towards the west due to conductive heat losses through the caprock.

In summary, a good conceptual model is one which considers all of the important physical processes that affect the system and represents the current knowledge of the geothermal system and its dynamics. It serves as a starting point for resource assessment.

MODELING METHODS

There are presently three methods available for modeling the behavior of geothermal reservoirs. They are decline curve analysis, lumped-parameter methods and distributed parameter methods.[10] Each method is described briefly below.

Decline curve analysis

Decline curve analysis is used to predict future well decline by fitting algebraic equations to flow rate decline data from wells.[11] The predicted flow decline can then be used to estimate the number of make-up (additional) wells that will be needed in the future. Various functional forms have been suggested in the literature, including exponential, hyperbolic and harmonic expressions.

Decline curves have been used with some success for vapor dominated systems;[12,13] much less experience is available for hot water reservoirs. Major problems with decline curve analysis are the lack of a sound theoretical basis and the fact that they cannot take into account changes in field operation (e.g., infill drilling, injection).[14]

Lumped-parameter models

For the sake of tradition, we will discuss lumped- and distributed-parameter models separately, although basically lumped-parameter models are simply distributed-parameter models with a coarse spatial discretization. Lumped-parameter models have been developed for many geothermal reservoirs, including Wairakei[15-17] and Broadlands[18] in New Zealand; Cerro Prieto, Mexico;[19] East Mesa, California;[20] Italian vapor-dominated reservoirs;[21-23] The Geysers, California;[24] and Svartsengi, Iceland.[25]

Most lumped-parameter models use two blocks to represent the entire system. One of the blocks represents the main reservoir (or the wellfield) and the other acts as a recharge block. The governing equations for these models can often be reduced to ordinary differential equations that can be solved semi-analytically. Lumped-parameter models are generally calibrated against a pressure history and the average enthalpy of the produced fluids. Atkinson et al.[23] and Grant[18] also included CO_2 in their models. After obtaining a history match, the model is used to predict future average reservoir pressure and fluid enthalpy.

The main advantages of the lumped-parameter models are their simplicity and the fact that they do not require the use of large computers. Some of the disadvantages are:

(i) They do not consider fluid flow within the reservoir and neglect spatial variations in thermodynamic conditions and reservoir properties.

(ii) They cannot match well the average enthalpy and non-condensible gas content of the produced fluids because of the large grid block sizes.

(iii) They cannot simulate fronts such as phase or thermal fronts due to the coarse space discretization.

(iv) They cannot consider questions of well spacing or injection well locations.

Distributed-parameter models

Distributed-parameter models are very general models that can be used to simulate reservoirs with few (equivalent to lumped-parameter models) or many (>100-1000) grid blocks. They can be used to simulate the entire geothermal system, including reservoir, caprock, bedrock, shallow cold aquifers, recharge zones, etc. They allow for spatial variations in rock properties and thermodynamic conditions. The principal advantage of the distributed-parameter models is that they have all the mathematics built into a computer code and allow the user to decide on how detailed (e.g., number of grid blocks), the simulation should be and what physical processes should be considered. Disadvantages of the distributed-parameter models are the need for a computer and an experienced modeler. Distributed parameter models will be discussed in more detail in a following section.

Choice of method

Reservoir assessment is a continuous process from the time a geothermal field is discovered to the time its development is completed. This process may extend over thirty years, so one would expect that all of the different reservoir assessment methods would be tested. However, the various methods are most applicable at different stages of the project.

In the exploration stage, geological and geophysical surveys and geochemical sampling of surface springs can give indications of the areal extent and possible downhole temperature of the resource. At this stage no wells have been drilled, permeability values are not yet available and the only possible assessment method is the volumetric (stored heat) method. This method involves estimating the total stored heat in the reservoir and applying a recovery factor for an estimate of the recoverable energy. Although at this stage the available data is scarce, the approximate resource evaluation using the volumetric method is quite useful as it will determine if further investment, e.g., drilling, is warranted at the site.

When several wells have been drilled, pressure transient data should be available and analysis of the data should give estimates of the reservoir transmissivity (permeability-thickness product). At this stage, the volumetric approach should be abandoned since it does not consider permeability values, and a simple lumped-parameter model should be constructed. This model should not necessarily be developed in the same manner as earlier lumped-parameter models. We believe that if computing facilities are available, it will be much less time consuming and less costly to use an existing distributed-parameter code to perform the calculations, rather than to develop a new semi-analytic model. Our experience is that lumped-parameter models can be developed using an existing numerical simulator in a week or less, whereas a conventional semi-analytical lumped-parameter model tailored to the particular characteristics of a given field may require 6 months to a year.[14] The difference is simply that the available numerical simulators have all of the mathematics already in place; such a modeling effort only requires the proper approach by an experienced modeler.

Finally, when some production history is available, the only assessment tool that can incorporate the entire set of available field data is the distributed-parameter model. It is the only model that can make a realistic evaluation of all important reservoir management questions that need to be considered.

GOVERNING EQUATIONS AND SOLUTION METHODS

In the last decade rapid advances in the development of numerical simulators for modeling the behavior of geothermal systems have been made. The development of various simulators began in the early 1970s and by the time of the 2nd U.N. Symposium in San Francisco in 1975, several single and two-phase models had been developed.[26-31] Since then development has continued on many of these simulators, and additional ones have become available. Although simulators currently in use apply different numerical schemes for solving the governing equations, a code comparison study showed good agreement among different simulators for a set of test problems.[32,33]

Several authors have presented governing equations for the physical processes occurring in geothermal reservoirs in their natural state and during exploitation (see the references given by Pinder[34]). Only a limited number of these processes have been found significant in practical applications, including viscous flow of liquid and vapor phases, boiling and condensation, heat transport by conduction and convection, and changes in pore volume and fluid density in response to pressure and temperature variations. The governing equations representing these processes can be written down as mass or heat balances for reservoir domains V_n in the following general form,[35]

$$\frac{d}{dt} \int_{V_n} M^{(\kappa)} \, dv = \int_{\Gamma_n} \underset{\sim}{F}^{(\kappa)} \cdot \underset{\sim}{n} \, d\Gamma + \int_{V_n} q^{(\kappa)} dv \quad (1)$$

Here κ (= 1, 2, 3 ...) labels the various components of the system, which may include heat, water, non-condensible gases and others. The accumulation term $M^{(\kappa)}$ represents the amount of component κ present in a unit volume of the domain, V_n. Changes in M occur in response to flow across the boundary Γ_n of domain V_n (expressed by the flux term F), and in response to sinks or sources with volumetric rate q. For mass components, F is usually written as a sum of the Darcy flow terms for liquid and gaseous phases. The heat flux $F^{(\kappa = \text{heat})}$ is a sum of conductive and convective contributions. The source term q can represent production or injection wells, and recharge or discharge zones.

Various approximations can be invoked when writing down the individual terms of Eqs. (1) as functions of a set of basic thermodynamic variables, such as temperature, pressure, vapor saturation, CO_2 partial pressure, etc. Virtually all work in geothermal reservoir modeling has made the following approximations: (1) rock and fluids are in local thermodynamic equilibrium; and (2) capillary pressure and phase adsorption effects are negligible (however, such effects were taken into account by Herkelrath et al.[36] in modeling laboratory experiments).

In earlier work on geothermal reservoir analysis the pore fluid was usually idealized as pure water, reducing Eqs. (1) to just one mass balance, and one heat balance. More recently, additional mass balance equations have been considered by several investigators to account for noncondensible gases, dissolved solids, and rock-fluid interactions.[23,37-43]

Eqs. (1) can describe a "lumped-parameter" model when the entire reservoir is represented by one or a very few domains, V_n. The same equations describe a "distributed-parameter" model when the reservoir is partitioned into many "small" domains (or volume elements), V_n. In the latter case the continuum Eqs. (1) have to be approximated by a discrete set of algebraic equations for solution on a digital computer. This can be accomplished in several different ways, which, although essentially equivalent, mathematically lead to quite different descriptions of reservoir geometry.

Most authors have employed a finite difference discretization, implementation of which requires that Eqs. (1) first be re-written as a set of differential equations.[44-46] The development of Lawrence Berkeley Laboratory's geothermal reservoir simulation codes[47-50] is based on an "integral finite difference" method (IFD)[51,52] in which the integrals in Eqs. (1) are discretized directly, without going through differential equations. The chief advantage of the IFD method is geometric flexibility. IFD avoids any reference to a global system of coordinates, which permits representation of one-, two-, and three-dimensional regular or irregular flow systems with the same ease, and is especially useful for modeling fractured reservoirs, using double- or multiple-porosity methods.[35]

The time variable in Eqs. (1) has usually been discretized as a first order finite difference with all flux terms evaluated fully implicitly to obtain good numerical stability and time step tolerance.

After performing space and time discretizations on Eqs. (1) one obtains a set of nonlinear algebraic equations. These are strongly coupled and have to be solved simultaneously. In the two-phase codes SHAFT79[48] and MULKOM[50] this is done by means of Newton-Raphson iteration. The linear equations occurring at each iteration step can be solved by direct or iterative methods.

In the literature there has been some controversy about the proper treatment of phase transitions, which represent extreme non-linearities in the governing equations. We have found that problems in computing phase transitions reported by Voss and Pinder[53] can be avoided by ensuring that all functions of thermodynamic variables appearing in the governing equations are in fact numerically continuous across the phase boundary, even as derivatives of these functions may undergo changes by several orders of magnitude.

There has also been considerable argument and confusion in earlier work on geothermal reservoir simulation about the "proper" choice of dependent variables in Eqs. (1).[34] For single-phase problems involving pure water, the natural choice of dependent variables is pressure and temperature. However, these variables are unsuitable for problems involving two-phase conditions where they become dependent on each other through the vapor pressure curve $p = p_{sat}(T)$. There are two ways to deal with general multi-phase problems:

(i) "switch" variables when phase transitions are encountered, e.g., use (p, T) for single-phase states and (p, S) for two-phase states;

(ii) select a ("persistent") set of dependent variables which remain independent of each other even as phases appear or disappear, such as (p, h) in the case of pure water.

Here p, T, S, h denote pressure, temperature, phase saturation and enthalpy, respectively.

Some authors have expressed the erroneous view that use of "persistent" variables offers distinct advantages. Our experience indicates that satisfactory results can be obtained regardless of choice of primary variables. We prefer the "switching" approach (i), because it facilitates an accurate representation of the thermophysical properties of water[54] and is easily implemented on a computer.

NATURAL-STATE MODELING

Geothermal reservoirs evolve over geologic time. The rates at which thermodynamic conditions change in the natural state are generally small in comparison to the changes induced by exploitation. Therefore, for most practical purposes undeveloped geothermal reservoirs can be considered to be in a quasi-steady state. Efforts at quantitatively modeling this natural state can provide very useful information for evaluating a geothermal resource and for planning its development.

Quantitative modeling of the natural state must be based on a (perhaps preliminary) conceptual model, which in turn is developed from diverse pieces of information (i.e., geological, geophysical, geochemical, and reservoir engineering data). By quantifying its various aspects a conceptual model can be tested and refined. A successful natural state model will match quantitatively or qualitatively a wide range of observations, and in doing so will provide insight into important reservoir parameters, such as formation permeability, boundary conditions for fluid and heat flow at depth, and thermodynamic state of fluids throughout the system. Even if an unambiguous quantification of these parameters cannot be achieved, it may be possible to obtain constraints which are useful for modeling reservoir response to exploitation.

For some of the less complex geothermal systems, successful applications of analytical or semi-analytical methods have been made.[55,56] As an example, Figure 3 shows matches of theoretical temperature distributions with data from the fault-charged low-temperature system at Susanville, California.[3] From the match it is possible to estimate natural recharge and the age of the system.

A detailed description of the natural state will usually require a numerical model, and a trial-and-error process of calibration. Such models have been developed for Wairakei, New Zealand;[57] Cerro Prieto, Mexico;[7] Krafla, Iceland;[9] Heber[58] and Lassen,[59] California; and Baca, New Mexico.[60] They have provided quantitative information on rates of natural recharge and discharge, fluid and heat flow patterns, extent of boiling zones, formation permeabilities (horizontal and vertical), temperature and pressure distribution, and location and spatial extent of upflow zones. Figure 4 shows temperature distributions and fluid flow patterns calculated for a two-dimensional vertical section of the Krafla reservoir. The pronounced temperature drop to the west in the upper reservoir is caused by steam discharge to the surface in the area of the Hveragil gully. The simulation indicates large permeability values in the upflow zone beneath Hveragil. Subsequent efforts to intercept this zone by directional drilling have shown promising results.

The few examples available to date suggest that natural state modeling is an important component of a comprehensive reservoir assessment. It appears to be the only way in which a consistent set of initial and boundary conditions for exploitation models can be developed.

EXPLOITATION MODELING

Tasks of a reservoir engineer include estimation of the generating capacity of a field and of well decline rates and evaluation of alternative development plans. These tasks can best be accomplished by developing a model that makes comprehensive use of all available field data. The field data of most importance are the reservoir properties (permeabilities and porosities), the thermodynamic state of the system (pressure, temperature, phase saturation and chemical concentration distributions) and the exploitation history (transient flow rate, enthalpy, chemical characteristics and reservoir pressure data). If all of these data are available, it is possible to construct a model that should be able to reliably predict the future behavior of the system. However, in most cases the data set is incomplete and sensitivity studies must be conducted on the most important parameters.

When an exploitation model is to be developed, the modeling approach taken should be based upon the objectives of the study. Typically, one needs to obtain answers to one or more of the following questions:

(1) What is the generating potential of the system?

(2) What is the appropriate well spacing?

(3) How fast will the production wells decline?

(4) How will the average enthalpy and chemistry of the produced fluids change with time?

(5) How will injection affect well performance?

(6) What is the effect of injection on long term reservoir behavior?

(7) Where should injection wells be located and how should they be completed?

The various types of exploitation models have different capabilities for answering these questions. Figure 5 shows schematically the different modeling approaches.

The lumped-parameter model consists of a single reservoir block with an adjacent recharge block. It can only be expected to give a rough estimate of the generating capacity (Question 1), although several investigators have attempted to use it to match enthalpy and chemical data. The lumped-parameter model is not capable of predicting long-term changes in enthalpies and chemical concentrations because the long-term enthalpies and chemical concentrations will be those flowing from the recharge block into the reservoir block. The lumped-wellfield model may give better estimates of the generating capacity (Question 1). In addition it has the capability of predicting the long-term characteristics (enthalpy and chemical composition) of the produced fluids (Question 4). The well-by-well model has the capability of addressing all the questions listed above, but for most complex geothermal systems, it will have to be fully three-dimensional. The development of such models requires initially substantial manpower and computation expense, when the model is calibrated against all available well data.

Lumped-wellfield models

Lumped-wellfield models can be used to estimate the generating capacity of a system. Such models have been developed for various geothermal fields including Wairakei,[57,61-62] Cerro Prieto, Mexico;[7,63] Baca, New Mexico;[60,64] Heber, California;[58,65] Krafla, Iceland;[66] Kirishina, Japan;[67] Ahuachapán, El Salvador;[68] and Olkaria, Kenya.[69,70] Most of them are two-dimensional areal models, but some are vertical cross sections or two-dimensional r-z models.

If a lumped-wellfield model of a geothermal field is to be developed, one must carefully determine which type of model is most appropriate (i.e., areal, vertical cross section, or r-z model). The data that will most influence this decision are the hydrogeologic model of the field, the temperature-pressure and chemical concentration distributions in the natural state, and inferred patterns of natural flow. If the geothermal anomaly has an approximate circular geometry, the r-z model is much preferred over the others. It allows rather good vertical definition of the resource at a modest computing cost (a good example is the modeling of the Heber field).[58,65] If field data indicate that recharge may be preferentially from some direction, a two-dimensional areal model is usually the most appropriate. It has the disadvantage of poor vertical resolution (one layer; gravity neglected) that can lead to some errors.[46] However, it has the capability of modeling lateral permeability barriers and multiple upflow zones.

In general, the least attractive of the two-dimensional lumped-wellfield models is the vertical slice model because of its limited recharge capability. Such a model may be appropriate for natural state studies, especially where pressure gradients are fairly uniform in one direction and the cross flow is therefore negligible. This is the case with many geothermal fields. However, during exploitation, a three-dimensional pressure anomaly is created and recharge into the wellfield occurs from all directions. The two-sided recharge assumption built into the vertical slice model is inappropriate for most geothermal systems. An exception is a system with very strong vertical recharge (e.g. from depth).

Three-dimensional lumped-wellfield models will of course give the most detailed results of all lumped-wellfield models. As an example, let us consider the lumped-wellfield model of the Baca geothermal field, New Mexico, developed by Faust et al.[60] Their model is three-dimensional; Figure 6 shows an areal view of the grid used. The primary purpose of the modeling study was to assess the impact of geothermal power production within the Valles Caldera on a shallow groundwater system outside the caldera. The main geothermal reservoir and the ring fracture zone are represented rather coarsely, in order to be able to follow the fluid flow patterns at large distances from the geothermal field. The model was initially calibrated against the natural conditions observed in the field (natural state model) and then used to assess the generating capacity of the reservoir and the effects of exploitation on the shallow groundwater system.

Well-by-Well Models

Well-by-well models have been developed for the single-phase East Mesa reservoir[71] and the two-phase reservoirs at Serrazzano, Italy,[72] Krafla, Iceland[73] and Olkaria, Kenya.[74-75] In developing such models one must first obtain a history match with all relevant data. For each individual well the model is calibrated against the flow rates and enthalpies and, if possible, variations in chemical composition (dissolved solids or non-condensible gases) of the discharge. The model should also be calibrated against the observed reservoir pressure decline. Subsequently performance predictions for individual wells and for the entire field can be made.

As an example, an areal view of the grid used in the Olkaria model[75] is shown in Figure 7. Note that the nodal points of grid blocks 2 through 26 correspond to actual surface locations of Olkaria wells 2 through 26. When short-term (on the order of months) flow rate and enthalpy behavior of wells is to be matched, a grid such as the one shown in Figure 7 is too coarse. However, a satisfactory match with the early time data can be obtained by embedding a radial mesh into the grid blocks containing the wells.[73,75]

The vertical dimensions of the grid are primarily determined by the locations of feed zones. Figure 8 shows major feed zones encountered in Olkaria wells and their relative contributions. Note that at Olkaria there is a steam zone at a depth of approximately 650-750 m as indicated by the 35 bar pressure contour. Based upon the feed zone data shown in Figure 8 it was decided that the feed zones could be grouped into three layers, a steam zone layer (100 m) and two underlying liquid zone layers (250 and 500 m thick).

In most geothermal simulations it is necessary to maintain a certain rate of steam flow to the turbines. In well-by-well models the flow rates and enthalpies from individual wells are not prescribed, but calculated based upon a productivity index (PI), fluid mobilities and the reservoir pressure adjacent to the feed zone[73] (deliverability model). At present, however, no satisfactory methods have been published for modeling geothermal wells with multiple feed zones in two phase conditions.

The history matching process involves numerous iterations and parameter adjustments until a reasonable match is obtained with the time-dependent production history. Ideally, a match with flow rates and enthalpies of all production wells, downhole pressures in observation wells, and the concentration of dissolved solids and non-condensible gases in the discharge of each well should yield a rather unique solution. In practice, however, history match models may retain a certain amount of ambiguity because available data tend to be incomplete, and because the scope of a modeling effort will be limited by cost consideration (each additional component adds one equation per grid block).

In the simulations of the Olkaria and Krafla fields three sets of adjustable parameters were used: productivity indices, permeabilities and porosities. These parameters were adjusted until the calculated data matched observed data on flow rates and enthalpies of all wells, and the reservoir pressure decline. The productivity index primarily affects the early time flow rate, the permeability the flow rate decline, and the porosity the enthalpy rise. The fact that the adjustable parameters influence the simulated behavior of individual wells quite differently gives hope that a rather unambiguous determination is possible.

In general, one attempts to match enthalpy to within 100-200 kJ/kg (which is basically the data accuracy), and flow rate to within 1 kg/s. An example of the results of the history match for Olkaria well 11 is shown in Figure 9. This well was flow tested for a short period in 1980, and was connected to the first 15 MW_e unit in 1981. The history match for all wells will give estimates of the permeability and porosity distribution in the system. Figure 10 shows such results for the well-by-well model of the two-phase reservoir at Krafla, Iceland.[73] In order to match the discharge history, 23 materials with different hydrological properties (permeabilities and porosities) were needed. However, the variation is not large, with transmissivity varying from 0.8 to 4.0 Dm and porosity from 0.7 to 5%. The history match yields the pressure, temperature, and vapor saturation conditions throughout the system at all times.

When the history matching is completed, the model can be applied to predict future field performance for various exploitation scenarios. A rule of thumb is that reliable predictions can only be made for as many years as the history match period. However, in most cases predictions for longer periods are desired in order to obtain estimates of long-term behavior. Whereas most models can only assess the overall field capacity, the well-by-well models can actually predict future performance of all existing wells, the number of additional wells needed and proper spacing of make-up wells.

For example, the Olkaria simulations show that the present well density used, 20 wells/km^2 (225 m spacing), is too high and that a well density of less than 11 well/km^2 (300 m spacing) should be used in future drilling.[75] Figure 11 shows predictions for the number of make-up wells needed at Olkaria for 45 MW_e power production over the next 30 years for the two different well densities. It is probable that when the long term flow rate declines are considered, well densities are too high in most geothermal fields. However, other factors such as cost of fluid transmission lines must also be considered when well spacing is determined.

The performance predictions allow evaluation of the overall reservoir depletion as shown in Figure 12 for the Krafla field in Iceland.[73] The figure shows that large pressure lows develop around producing wells, with a rather small decline occurring in the reservoir as a whole. The vapor saturation contour shows that a large vapor zone may develop at Krafla within the next 10 years.

INJECTION MODELING

For most geothermal fields, reinjection of effluents must be considered in predictions of future field behavior, because reinjection is the preferred disposal method. In modeling injection many complications arise, especially with regard to the movement of cold water fronts, and possible chemical reactions altering porosities and permeabilities of the subsurface rocks. Figure 13 illustrates a typical production-injection system for a doublet in a fractured reservoir. The fractures may short-circuit flow between injection and production wells. Another potential problem is that the separated waste water may become super-saturated with minerals.

The possible benefits of injection in maintaining reservoir pressure in single-phase reservoirs has been well documented in the literature. Recently, it has been predicted that injection in two-phase reservoirs can also help to maintain pressures and reduce the number of make-up wells needed.[76,77] This is illustrated in Figure 11 for 45MWe power production of the Olkaria field. Full (100%) injection reduced by more than half the number of make-up wells needed for the thirty year period.[75]

The modeling of injection effects on pressure transients in geothermal reservoirs is rather straightforward in comparison to modeling the advance of the cold water front away from injection wells. For long term pressure transient or exploitation calculations porous medium models may often give good approximations for fractured systems; however, the modeling of cold water fronts necessitates the use of fracture models. One potential problem with cold water injection is premature breakthrough at the producing wells, which would reduce the enthalpy and temperature of the produced fluids. In order to predict the cold water advance it is necessary to know the fracture patterns in the system.[78] Such information is not available for most geothermal systems. However, it may be possible to predict the cold water advance using tracer tests[78,79] or geophysical methods.[80]

MULTI-COMPONENT MODELING

Most geothermal fields contain fluids with moderate amounts of dissolved solids (<20,000 ppm) and non-condensible gases (<1% by mass). There are, however, often spatial variations in the concentration of these components and transient changes are observed in the produced fluids. The modeling of these changes can give additional constraints on the modeling results, hence, make them less ambiguous. For example, the spatial variations in the fluid chemistry can yield information about flow patterns in the reservoir and locations of upflow zones; this type of information is very valuable when natural state models are being developed. Transient changes in concentrations of dissolved solids and non-condensible gases can indicate mixing of fluids from different production zones or recharge areas. A classic example is Cerro Prieto, Mexico, where changes in chloride and silica concentrations have helped identify cold water inflow from above.[81]

In many geochemical applications mixing cell calculations are performed in order to study the origin of the fluids and determine fluid flow patterns.[82,83] A simple example of the use of multi-component modeling is given by Lai et al.[43] They consider data from the Ellidaar geothermal field in Iceland that show pressure, temperature, and silica decline in the reservoir due to exploitation. Using a simple lumped-wellfield model they were able to obtain estimates of the reservoir volume and effective porosity in addition to permeability values for the reservoir and the caprock. Another example is the modeling of radon transport through vapor-dominated systems, discussed by Semprini and Kruger.[84] They analyzed the transient changes in the radon content in the discharge during drawdown tests and found a reasonable agreement with data observed at The Geysers geothermal field.

As mentioned earlier there are fields where multi-component modeling is essential because of high concentrations of dissolved solids (e.g., Salton Sea, California) or non-condensible gases (e.g., Broadlands and Naughwa, New Zealand). These constituents can not only alter the fluid properties (e.g., densities, enthalpies and viscosities) but also the thermodynamic relationships of two-phase mixtures. Non-condensible gases have been modeled, among others, by Zyvolosky and O'Sullivan,[37] Pritchett et al.,[38] Atkinson et al., [22,23] and O'Sullivan et al.[39]

SUBSIDENCE MODELING

As mentioned earlier, pore pressure decline in a reservoir due to fluid extraction will alter the state of stress in the system and may result in vertical and horizontal ground surface movements (i.e., subsidence). At Wairakei, New Zealand, vertical displacements exceeding 9 m and horizontal movements greater than 0.5 m have been measured[85-86]. Considerably less, but still significant, ground surface movements have been detected at the Broadlands and Kawerau fields, New Zealand;[86] The Geysers, California;[87] and Cerro Prieto, Mexico.[88-89] At other fields, such as Lardarello, Italy, ground surface displacements have not been observed in spite of extensive exploitation.[90]

Field observations indicate that in geothermal systems there exists a time-lag between fluid production and subsidence, that non-linear stress-strain relationships control deformations, and that in some instances the subsidence bowl is offset from the main area of fluid production. Following Narasimhan and Goyal,[90] the fundamental sequence of events leading to ground surface movements is: (1) mass withdrawal causes reduction in fluid pressure; (2) fluid pressure reduction causes an increase in stresses on the rock matrix, accompanied by a reduction in the reservoir bulk volume; (3) the reduction of reservoir volume leads to the generation of a three-dimensional displacement field within the reservoir and some deformation may also be induced by contractions associated with temperature declines; and (4) the reservoir displacements propagate to the land surface to cause horizontal and vertical ground movements.

A comprehensive modeling of subsidence due to geothermal fluid withdrawal should couple the conventional mass and energy conservation equations to an equation for the maintenance of force balance. These equations will have to be supplemented by appropriate relations between pore pressure and rock skeleton stresses, and data on compressibility and thermal expansivity of the bulk medium and of the solids.[47,90,91] This would require highly sophisticated computer codes. Actually, only simple models have been used to predict the magnitude and pattern of subsidence.

A number of distributed-parameter models[92-93] and analytical studies[94] of subsidence in geothermal systems have incorporated Terzaghi's one-dimensional consolidation theory.[95] In this approach thermal contraction is neglected. It is most applicable when the system is compressed vertically over a wide area, so that lateral strains can be disregarded.

Pure deformation modeling of subsidence in geothermal systems, without considering fluid and/or heat flow and usually using analytical methods, has been carried out for the Wairakei[57,86,96] and Broadlands[86] fields of New Zealand and The Geysers[96] and Heber[97] fields of California.Figure 14 summarizes the results of Allis's[86] studies in Wairakei using analytical solutions for consolidating circular disks. It shows the relationship between subsidence, the geology and temperature variations within the field, and the pressure and gravity changes resulting from fluid withdrawal. The modeling of the area of intense subsidence suggests that the top of the consolidating zone is at about 150 m depth, and that about 15 m of consolidation had caused about 8.5 m of surface vertical displacement as of December 1980. Miller et al. [96] also concluded that at Wairakei subsidence is dominated by spatial variations in pressure drawdown, bed thickness and rock deformation properties.

Miller et al.[96] used various models of different complexity to study ground deformation at The Geysers. It was found that in this field subsidence resulting from thermal contraction may be more important than consolidation due to pore pressure changes. A good match could be obtained with field data using models of different sophistication--even the back-of-the-envelope calculation--if proper assumptions are made.

CURRENT PROBLEMS

We believe that at the present time satisfactory techniques are available for simulating the flow of liquid water, vapor, and heat in porous media in one-, two-, and three-dimensions. What is lacking is a "track record" of applications of these techniques to a broad range of field problems. Each geothermal field has its own set of special features, which pose special challenges to the modeler. The art and science of geothermal reservoir modeling will mature only as more detailed field case studies become available in the literature, which can serve as reference cases for future modeling efforts.

There are a number of topics that require special attention; either because adequate modeling techniques are not yet available, or because field application of available techniques poses particular problems. A case in point is the fracture-dominated nature of most high-temperature geothermal fields. This makes the application of porous medium-type models questionable, and special double- and multi-porosity techniques have in fact been developed for modeling fluid and heat flow in fractured porous media.[35] So far these techniques have only been applied to idealized generic problems and laboratory experiments. Applications to field problems are difficult because the required rather detailed data on fracture distributions are not usually available.[98] A more fundamental problem in modeling fractured reservoirs is the description of "preferential flowpaths," which can cause rapid interference between wells.[78] These features operate on a scale which can not be described with the volume averaging techniques used in present geothermal reservoir simulators.

A somewhat related issue is propagation of sharp fronts (hydrodynamic, chemical, thermal), which is of particular significance for injection operations. Such fronts can not be adequately resolved on the spatial scale normally employed in discretizing flow domains (10-100 m or more) and special techniques are needed to minimize numerical dispersion. The actual physical (hydrodynamic) dispersion to which fronts are subjected in the field is a controversial topic, as there is growing evidence that the mechanisms involved can not be adequately represented by means of the traditional diffusion-convection equation.[99]

The fluids encountered in geothermal systems are usually multi-component mixtures containing a number of dissolved solids and non-condensible gases. Relatively few efforts have been reported at modeling the transport of species other than water, and rock-fluid interations with associated porosity and permeability change have usually been neglected. It is well established that such effects can be very significant,[81] and should be included in numerical models. In many cases it may be possible to obtain more detailed insight into reservoir processes from multi-component modeling than is available from only fluid-and-heat transport modeling.

Little information is available in the literature about coupling of reservoir and wellbore flow. Especially needed are methods for accurate and efficient computation of flow in wells with multiple feed points. There is also a need for reliable data on relative permeabilities for water-steam systems, as these have often large effects on the modeling results.

SUMMARY

Geothermal reservoirs are complex and dynamic systems with many hydrological, thermal, chemical and mechanical processes occurring. They possess individual characteristics so that no universal modeling strategy is applicable to all of them. Modeling studies of geothermal reservoirs however, are essential in order to optimize the development of a resource.

When a geothermal system is to be evaluated, all relevant field data must be integrated into a conceptual model of the field. The model should be verified by natural state modeling and the natural mass and heat transfer in the system quantified. In determining the proper approach for exploitation studies, e.g., lumped-parameter, lumped-wellfield or well-by-well model, one must carefully determine what questions are to be addressed. The complexity of the modeling approach chosen should also be consistent with the quantity and quality of the available data. It is generally advisable to start with the simplest possible model that can explain the data, and if data allows, attempt to include spatial or temporal variations in selected chemical components. The addition of even one component can give added insight into the behavior of the system, and make the modeling results less ambiguous.

At present it appears that there are sophisticated methods available for modeling geothermal systems; however, high quality field data are needed. Long term production histories are being developed at various geothermal fields worldwide. Geothermal simulators should be applied to these data in order to validate them and to document their usefulness in geothermal reservoir evaluation.

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References

1. Donaldson, I. G., Grant, M. A., and Bixley, P. F., 1983, Nonstatic reservoirs: The natural state of the geothermal reservoir, Jour. Pet. Tech., v. 35, p. 189-194.
2. Witherspoon, P. A., Neuman, S. P., Sorey, M. L., and Lippmann, M. J., 1977, Modeling geothermal systems, Accademia Nazionale dei Lincei,Atti dei Convegni Lincei, v. 30, p. 173-221.
3. Bodvarsson, G. S., Benson, S. M., and Witherspoon, P. A., 1982, Theory of the development of geothermal systems charged by vertical faults, Jour. Geophys. Res., v. 87, p. 9317-9328.
4. Goyal, K. P., and Kassoy, D. R., 1981, A plausible two-dimensional vertical model of the East Mesa geothermal field, California, Jour. Geophys. Res., v. 86, p. 10719-10733.
5. Riney, T. D., Pritchett, J. W., Rice, L. F., and Garg, S. F., 1979, A preliminary model of the East Mesa hydrothermal system, Proceedings,. 5th Workshop on Geothermal Reservoir Engineering, Stanford University, report SGP-TR-40, p. 211-214.
6. Halfman, S. E., Lippmann, M. J., Zelwer, R., and Howard, M. H., 1984, Geological interpretation of geothermal fluid movement in Cerro Prieto field, Baja California, Mexico, Bull. Amer. Assoc. Petr. Geol., v. 68, p. 18-30.
7. Lippmann, M. J., and Bodvarsson, G. S., 1983, Numerical studies of the heat and mass transport in the Cerro Prieto geothermal field, Mexico, Water Resour. Res., v. 19, p. 753-767.
8. Stefansson, V., 1981, The Krafla geothermal field, northeast Iceland, in Geothermal Systems, Principles and Case Histories, Ryback and L. J. P. Muffler, eds., John Wiley, N. Y., p. 273-294.
9. Bodvarsson, G. S., Pruess, K., Stefansson, V., and Eliasson, E. T., 1984, The Krafla geothermal field, 2: The natural state of the reservoir, Water Resour. Res., v. 20, p. 1531-1544.
10. Grant, M. A., 1983, Geothermal reservoir modeling, Geothermics, v. 12, p. 251-263.
11. Zais, E. J., and Bodvarsson, G., 1980, Analysis of production decline in geothermal reservoirs, Lawrence Berkeley Laboratory report LBL-11215, Berkeley, California, 75 pp., September.
12. Budd, C. F., Jr., 1972, Producing geothermal steam at The Geysers field, SPE-4178, presented at the 39th California Regional Meeting of SPE-AIME Bakersfield, California.
13. Stockton, A. D., Thomas, R. P., Chapman, R. H., and Dykstra, H., 1984, A reservoir assessment of The Geysers geothermal field, Jour. Pet. Tech., v. 36, p. 2137-2159.
14. Grant, M. A., Donaldson, I. G., and Bixley, P. F., 1982, Geothermal Reservoir Engineering, Academic Press, N.Y., 369 p.
15. Whiting, R. L., and Ramey, H. J., Jr., 1969, Application of material and energy balances to geothermal steam production, Jour. Pet. Tech., v. 21, p. 893-900.
16. Sorey, M. L., and Fradkin, L., Jr., 1979, Validation and comparison of different models of the Wairakei geothermal reservoir, Proceedings, 5th Workshop on Geothermal Reservoir Engineering, Stanford University report SGP-TR-40, p. 215-220.
17. Fradkin, L. J. Jr., Sorey, M. J., and McNabb, A., 1981, On identification and validation of some geothermal models, Water Resour. Res., vol. 17, p. 929-936.
18. Grant, M. A., 1977, Broadlands - A gas dominated geothermal field, Geothermics, v. 6, p. 9-29.
19. Westwood, J. D., and Castanier, L. M., 1981, Application of a lumped-parameter model to the Cerro Prieto geothermal field, Trans. Geothermal Resources Council, v. 5, p. 381-384.
20. Castanier, L. M., Sanyal, S. K. and Brigham, W. E., 1980, A practical analytical model for geothermal reservoir simulation, SPE-8887, presented at 50th Annual California Regional Meeting of SPE-AIME, Huntington Beach,California.
21. Brigham, W. E., and Neri, G., 1979, Preliminary results on a depletion model for the Gabbro Zone, Proc. 5th Workshop on Geothermal Reservoir Engineering, Stanford University report SGP-TR-40, p. 229-240.
22. Atkinson, P., Miller, F. G., Marconcini, R., Neri, G., and Celati, R., 1978, Analysis of reservoir pressure and decline curves in Serrazzano zone, Larderello geothermal field, Geothermics, v. 7, p. 133-144.
23. Atkinson, P., Celati, R., Corsi, R., Kucuk, F., and Ramey, H. J., Jr., 1978, Thermodynamic behavior of the Bagnore geothermal field, Geothermics, v. 7, p. 185-208.
24. Brigham, W. E. and Dee, J., 1985, Reservoir engineering analysis of a vapor-dominated geothermal field, paper presented at the 10th Workshop on Geothermal Reservoir Engineering, Stanford University, January.

25. Kjaran, S. P., Halldorsson, G. K., Thorhallson, S. and Eliasson, J., 1979, Reservoir engineering aspects of Svartsengi geothermal area, Trans. Geothermal Resources Council, v. 3, p. 337-339.

26. Sorey, M. L., 1975, Numerical modeling of liquid geothermal systems, U.S. Geological Survey Open-file report 75-613, 66p.

27. Mercer, Jr., J. W., Faust, C. R., and Pinder, G. F., 1974, Geothermal reservoir simulation, Proceedings NSF/RANN Conference on Research for the Development of Geothermal Resources, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, p. 256.

28. Toronyi, R. M., and Forouq Ali, S. M., 1975, Two-phase, two-dimensional simulation of a geothermal reservoir and the wellbore system, SPE-5521, presented at the SPE 50th Annual Fall Meeting, Dallas, Texas.

29. Faust, C. R., and Mercer, J. W., 1976, Mathematical modeling and Geothermal systems, Proceedings, 2nd United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, v. 3, p. 1635-1641.

30. Garg, S. K., Pritchett, J. W., and Brownell, D. H., 1976, Transport of mass and energy in porous media, Proceedings, 2nd United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, v. 3, p. 1651-1656.

31. Lasseter, T. J., Witherspoon, P. A., and Lippmann, M. J., 1976, Multiphase multidimensional simulation of geothermal reservoirs, Proceedings, 2nd United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, v. 3, p. 1715-1723.

32. Stanford Geothermal Program, 1980, Proceedings Special Panel on Geothermal Model Intercomparison Study, SGP-TR-42, Stanford University, report SGP-TR-42, 120 p., December.

33. Molloy, M. W., and Sorey, M. L., 1981, Code comparison project - A contribution to confidence in geothermal reservoir simulation, Trans. Geothermal Resources Council, v. 5, 189-192.

34. Pinder, G. F., 1979, State-of-the-Art Review of Geothermal Reservoir Modeling, Lawrence Berkeley Laboratory report LBL-9093, 144 p., March.

35. Pruess, K. and Narasimhan, T. N., 1985, A practical method for modeling fluid and heat flow in fractured porous media, Soc. Pet. Eng. Jour., v. 25, 14-26.

36. Herkelrath, W. N., Moench, A. F., and O'Neal, C. F. II, 1983, Laboratory investigations of steam flow in a porous medium, Water Resour. Res., v. 19, p. 931-937.

37. Zyvoloski, G. A., and O'Sullivan, M. J., 1980, Simulation of a gas-dominated two-phase geothermal reservoir, Soc. Pet. Eng. Jour., v. 20, p. 52-58.

38. Pritchett, J. W., Rice, M. H., and Riney, T. D., 1981, Equation-of-state for water-carbon dioxide mixtures: Implications for Baca reservoir, report DOE/ET/27163-8, Systems, Science and Software, La Jolla, California, February.

39. O'Sullivan, M. J., Bodvarsson, G. S., Pruess, K., and Blakeley, M. R., 1985, Fluid and heat flow in gas-rich geothermal reservoirs, paper SPE-12102, Soc. Pet. Eng. Jour., in press.

40. Li, T.M.C., Mercer, J.W., Faust, C.R., and Greenfield, R.J., 1978, Simulation of geothermal reservoirs including changes in porosity and permeability due to silica-water reactions. Proceedings, 4th Workshop on Geothermal Reservoir Engineering, Stanford University report SGP-TR-30, p. 275-279.

41. Keith, L.A., Delaney, P.T., and Moore, D.E., 1983, Permeability reduction due to precipitation of quartz under nonisothermal conditions. Proceedings, 9th Workshop on Geothermal Reservoir Engineering, Stanford University report SGP-TR-74, p. 239-245.

42. Pruess, K., Celati, R., Calore, C., and D'Amore F., 1985, CO_2 Trends in the depletion of the Larderello vapor-dominated reservoir, presented at 10th Workshop Geothermal Reservoir Engineering, Stanford University, January.

43. Lai, C.H., Bodvarsson, G.S., and Witherspoon, P.A., 1985, Numerical studies of silica precipitation/dissolution, presented at 10th Workshop on Geothermal Reservoir Engineering, Stanford University, January.

44. Coats, K. H., 1977, Geothermal reservoir modeling, SPE-6892, presented at 52nd Annual Fall Technical Conference and Exhibition of SPE-AIME, Denver, Colorado.

45. Brownell, D. H., Jr., Garg, S. K., and Pritchett, J. W., 1977, Governing equations for geothermal reservoirs, Water Resour. Res., v. 13, p. 929-939.

46. Faust, C. R., and Mercer, J. W., 1979, Geothermal reservoir simulation. 2. Numerical solution techniques for liquid and vapor-dominated hydrothermal systems, Water Resour. Res., v. 15, p. 31-46.

47. Lippmann, M.J., Tsang, C.F., and Witherspoon, P.A., 1977, Analysis of the response of geothermal reservoirs under injection and production procedures, SPE-6537, presented at the 47th Annual California Regional Meeting of SPE-AIME, Bakersfield, California.

48. Pruess, K., and Schroeder, R. C., 1980, SHAFT79 User's Manual, Lawrence Berkeley Laboratory report LBL-10861, 47 p., March.

49. Bodvarsson, G.S., 1982, Mathematical modeling of the behavior of geothermal systems under exploitation, Lawrence Berkeley Laboratory report LBL-13937, 348 p., January.

50. Pruess, K., 1983, Development of the general purpose simulator MULKOM, in Annual Report 1982, Earth Sciences Division, Lawrence Berkeley Laboratory report LBL-15500., p. 133-134.

51. Edwards, A. L., 1972, TRUMP: A computer program for transient and steady state temperature distributions in multidimensional systems, National Technical Information Sevice, National Bureau of Standards, Springfield, Virginia.

52. Narasimhan, T. N. and Witherspoon, P. A., 1976, An integrated finite difference Method for Analyzing Fluid Flow in Porous Media, Water Resour. Res., v. 12, p. 57-64.

53. Voss, C. I., and Pinder, G. F., 1978, The Achilles' heel of geothermal reservoir simulators, Proceedings, 4th Workshop on Geothermal Reservoir Engineering, Stanford University report SGP-TR-30, p. 286-293.

54. International Formulation Committee, 1967, A formulation of the thermodynamic properties of ordinary water substance, IFC Secretariat, Duesseldorf, Germany.

55. Cheng, P., 1978, Heat transfer in geothermal systems, in Advances in Heat Transfer, v. 14, T.F. Irvine., and J.P. Hartnett, eds., Academic Press, N.Y., p. 1-105.

56. Nathenson, M., Urban, T.C., and Diment, W.H., 1979, Approximate solution for the temperature distribution caused by flow up a fault and its application to temperatures measured in a drill hole at Raft River geothermal area, Cassia County, Idaho, Trans. Geothermal Resources Council, v. 3, p. 477-480.

57. Pritchett, J.W., Rice, L.F., and Garg, S.K., 1980, Reservoir simulation studies: Wairakei geothermal field, New Zealand, Lawrence Berkeley Laboratory report LBL-11497, 103 p., January.

58. Lippmann, M.J., and Bodvarsson, G.S., 1985, The Heber geothermal field, California: natural state and exploitation modeling studies, Jour. Geophys. Res., v. 90, p. 745-758.

59. Sorey, M.L., and Ingebritsen, S.E., 1984, Quantitative analysis of the hydrothermal system in Lassen volcanic national park and Lassen known geothermal resource area, U.S. Geological Survey open-file report 84-4278, 80 p.

60. Faust, C.R., Mercer, J.W., Thomas, S.D., and Balleau, W.P., 1984, Quantitative analysis of existing conditions and production strategies for the Baca geothermal system, New Mexico, Water Resour. Res., v. 20, p. 601-618.

61. Mercer, J.W., and Faust, C.R., 1979, Geothermal reservoir simulation 3: Application of liquid and vapor-dominated modelling techniques to Wairakei, New Zealand, Water Resour. Res., v. 15, p. 653-671.

62. Blakeley, M.R., and O'Sullivan, M.J., 1982, Modeling of production and recharge at Wairakei, Proceedings, 4th New Zealand Geothermal Workshop, Univ. Auckland, p. 23-32.

63. Ayuso, M.A., Márquez, R., Esquer, C.A., and Negrin, G., 1984, Modeling studies in the Cerro Prieto geothermal field, Trans. Geothermal Resources Council, v. 8, p. 175-182.

64. Bodvarsson, G.S., Vonder Haar, S., Wilt, M.F., and Tsang, C.F., 1982, Preliminary estimation of the reservoir capacity and the generating potential of the Baca geothermal field, New Mexico, Water Resour. Res., v. 18, p. 1713-1724.

65. Tansev, E., and Wasserman, M.L., 1977, Modeling the Heber geothermal field, Proceedings, 3rd Workshop Geothermal Reservoir Engineering, Stanford University report SGP-TR-25, p. 107-115.

66. Bodvarson, G.S., Pruess, K., Stefansson, V., and Eliasson, E. T., 1984, The Krafla geothermal field, Iceland: 3. The generating capacity of the field, Water Resour. Res., v. 20, p. 1534-1559.

67. Tachimori, M., 1982, Description of geothermal reservoir simulator "HSCGREATS" and a preliminary simulation of the Kirishina field, Proceedings 8th Workshop on Geothermal Reservoir Engineering, Stanford University report SGP-TR-60, p. 149-151.

68. Liguori, P., Jarach, F., Choussy, M., Campos, T., and Escobar, D., 1982, Reservoir engineering of the Ahuachapan geothermal field, Trans. Geothermal Resources Council, v. 6, p. 289-292.

69. Pruess, K., Weres, O., and Schroeder, R., 1983, Distributed parameter modeling of a producing vapor-dominated geothermal reservoir, Serrazzano, Italy, Water Resour. Res., v. 19, p. 1219-1230.

70. Bodvarsson, G.S., Pruess, K., 1981, Olkaria geothermal field - numerical studies of the generating capacity of the reservoir, report prepared for the Virkir Consulting Company, Iceland, and Kenya Power Company, Kenya, 80 p.

71. Bodvarsson, G.S., Pruess, K., Lippmann, M.J., and Björnsson, S., 1982, Improved energy recovery from geothermal reservoirs, Jour. Pet. Tech. v. 34, p. 1920-1928.

72. Morris, C.W., and Campbell, D.A., 1981, Geothermal reservoir energy recovery: A three-dimensional simulation study of the East Mesa field, Jour. Pet. Tech., v. 33, p. 735-742.

73. Pruess, K., Bodvarsson, G.S., Stefansson, V., and Eliasson, E.T., 1984, The Krafla geothermal field: 4. History match and individual well performance, Water Resour. Res., v. 20, p. 1561-1984.

74. Bodvarsson, G.S., Pruess, K., Stefansson, V., Björnsson, S., and Ojiambo, S.B., 1985 The East Olkaria geothermal field, Kenya, 1: History match of well performance, submitted to Jour. Geophys. Res.

75. Bodvarsson, G.S., and Pruess, K., Stefansson, V., Björnsson, S., and Ojiambo, S.B., 1985, The East Olkaria geothermal field, Kenya, 2: Performance predictions, submitted to Jour. Geophys. Res.

76. Schroeder, R.C., O'Sullivan, M.J., Pruess, K., Celati, R., and Ruffilli, C.,1982, Reinjection studies of vapor-dominated systems, Geothermics, v. 11, p. 93-120.

77. Bodvarsson, G.S., Pruess, K., and O'Sullivan, M.J., 1985, Injection and energy recovery in fractured geothermal reservoirs, Soc. Pet. Eng. Jour., in press.

78. Pruess, K., and Bodvarsson, G.S., 1984, Thermal effects of reinjection in geothermal reservoirs with major vertical fractures, Jour. Pet. Tech. v. 36, p. 1567-1578.

79. Walkup, S.W. and Horne, R., 1985, Tracer returns and thermal breakthrough, paper to be presented at the Geothermal Resources Council International Symposium, Hawaii, August.

80. Pruess, K., Wilt, M., Bodvarsson, G.S., and Goldstein, N.E., 1983, Simulation and resistivity modeling of a geothermal reservoir with waters of different salinities, Geothermics, v. 12, p. 291-306.

81. Truesdell, A.H., D'Amore, F., and Nieva, D., 1984, The effects of localized aquifer boiling on fluid production at Cerro Prieto, Trans. Geothermal Resources Council, v. 8, p. 223-230.

82. Henley, R.W., Truesdell, A.H., Barton, P.B., Jr., and Whitney, J.A., 1984, Fluid-mineral equilibrium in hydrothermal systems, reviews in Economic Geology, v. 1, 267 p.

83. Arnorsson, S., 1985, The use of mixing models and chemical geothermometers for estimating underground temperatures in geothermal systems, Jour. Volc. Geotherm. Res., v. 23, p. 299-335.

84. Semprini, L. and Kruger, P., 1983, Simulation of radon transport in geothermal reservoirs, Proceedings, 9th Workshop on Geothermal Reservoir Engineering, Stanford University report SGP-TR-40, p. 261-268.

85. Stilwell, W.B., Hall, W.K., and Tawhai, J., 1976, Ground movement in New Zealand geothermal fields, Proceedings, 2nd United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, v. 2, p. 1427-1434.

86. Allis, R.G., 1982, Comparison of subsidence at Wairakei, Broadlands and Kawerau fields, New Zealand, Proceedings, 8th Workshop on Geothermal Reservoir Engineering, Stanford University report SGP-TR-60, p. 183-188.

87. Lofgren, B.E., 1981, Monitoring crustal deformation in The Geysers - Clear Lake region, in, Research in The Geysers - Clear Lake geothermal area, northern California, eds., McLaughlin, R.J. and Donnelly-Nolan, J.M., U.S.G.S. Prof. Paper 1141, p. 139-148.

88. de la Peña, A., 1981, Results of the first order leveling surveys in the Mexicali Valley at the Cerro Prieto field, Proceedings, 3rd Symposium on the Cerro Prieto Geothermal Field, Lawrence Berkeley Laboratory report LBL-11967, p. 281-291.

89. Massey, B.L., 1981, Measured ground-surface movements, Cerro Prieto geothermal field, Proceedings, 3rd Symposium on the Cerro Prieto Geothermal Field, Lawrence Berkeley Laboratory report LBL-11967, p. 299-305.

90. Narasimhan, T.N. and Goyal, K.P., 1984, Subsidence due to geothermal fluid withdrawal, Geol. Soc. Amer. Review Engr. Geol., v. VI, p. 35-66.

91. Helm, D.C., 1982, Conceptual aspects of subsidence due to fluid withdrawal, in Narasimhan, T.N., ed., Recent trends in hydrogeology, Geol. Soc. Amer. Special Paper 189, p. 103-142.

92. Lippmann, M.J., Narasimhan, T.N., and Witherspoon, P.A., 1977, Numerical simulation of reservoir compaction in liquid-dominated geothermal systems: Proceedings Land Subsidence Symposium, Anaheim, California: Intern. Assoc. Hydrol. Sci. Publ. 121, p. 179-189.

93. Narasimhan, T.N., and Goyal, K.P., 1979, A preliminary simulation of land subsidence at the Wairakei geothermal field in New Zealand: Lawrence Berkeley Laboratory report LBL-10299, 7 p., December.

94. Robertson, A., 1984, Analysis of subsidence compaction and subsidence at Wairakei geothermal field, Proceedings, 6th New Zealand Geothermal Workshop, University of Auckland, p. 217-224.

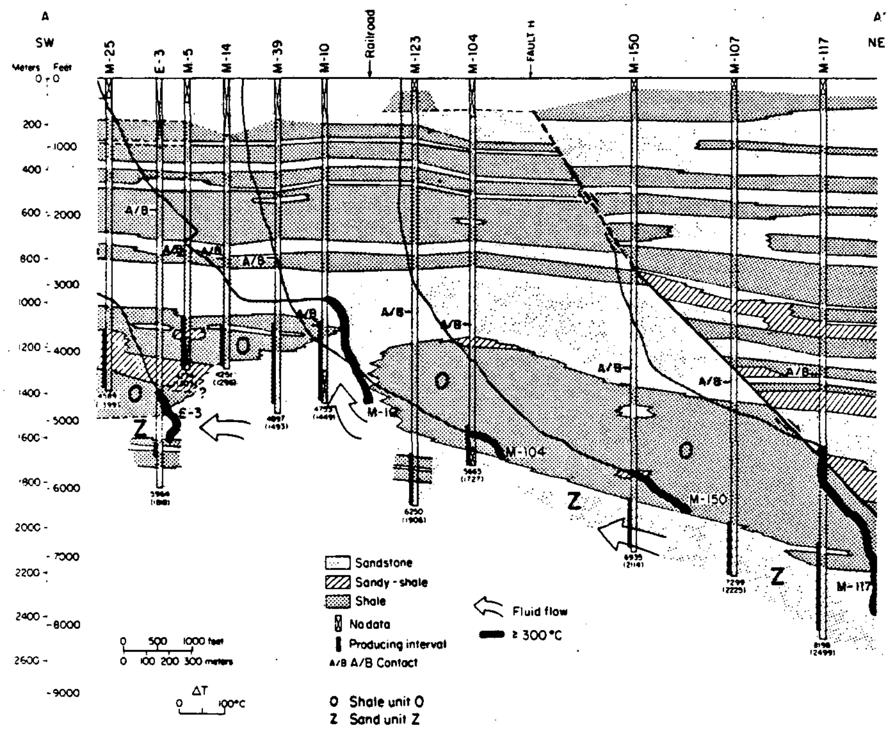
95. Terzaghi, K., 1925, Principles of soil mechanics: IV, Settlement and consolidation of clay, Engineering News-Record, p. 874-878.

96. Miller, I., Dershowitz, W., Jones, K., Myer, L., Roman, K., and Schauer, M., 1980, Simulation of geothermal subsidence, Lawrence Berkeley Laboratory report LBL-10794, 160 p., March.

97. Geonomics Inc., 1976, Geotechnical environmental aspects of geothermal power generation at Heber, Imperial Valley, California, Electrical Power Research Institute report EPRI ER-290, 70 p., October.

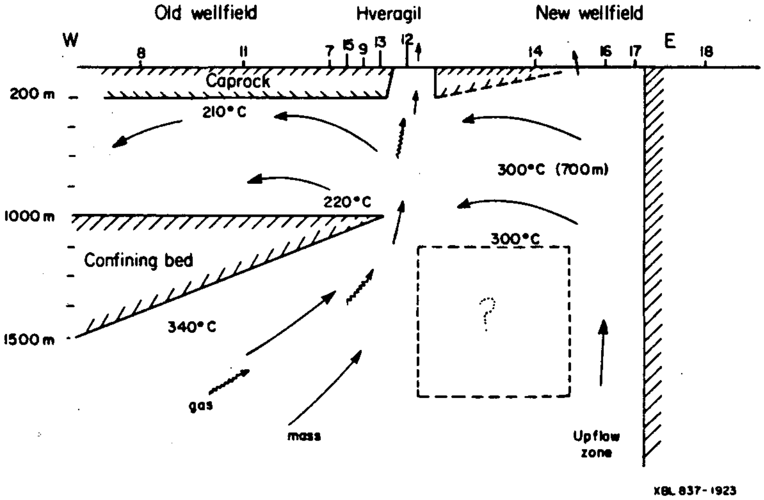
98. Goldstein, N.E., 1984, Fracture detection and mapping for geothermal reservoir definition: An assessment of current technology, research and research needs, Lawrence Berkeley Laboratory report LBL-18146, 41 p. November.

99. Sauty, J-P., 1980, An analysis of hydrodispersive transfer in aquifers, Water Resour. Res., v. 16, p. 145-158.



XBL 8211-3227

Figure 1. Conceptual model of the Cerro Prieto field, Mexico, showing the lithology and the fluid flow patterns (after Ref. 6).



XBL 837-1923

Figure 2. Conceptual model of the Krafla field, Iceland (after Ref. 9).

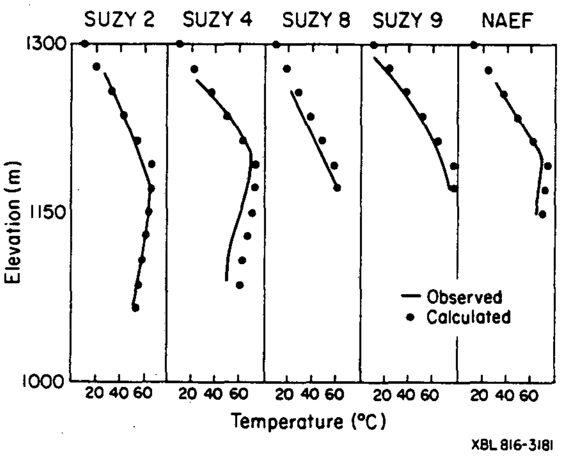


Figure 3. Comparison between the observed and calculated temperature profiles for wells at the Susanville field, California (after Ref. 3).

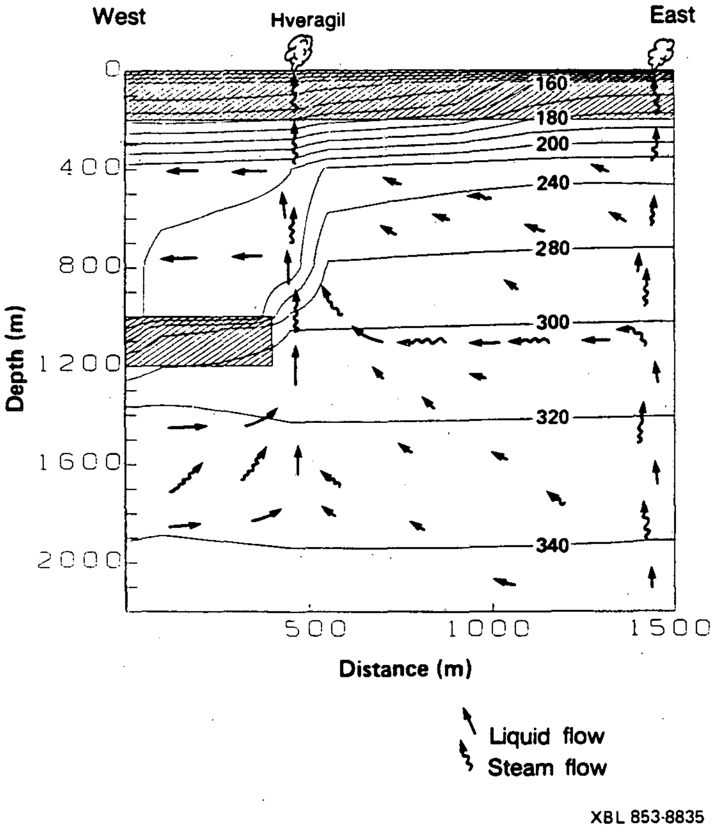


Figure 4. The natural state temperature distribution and the fluid flow patterns computed for the Krafla field, Iceland (modified from Ref. 9).

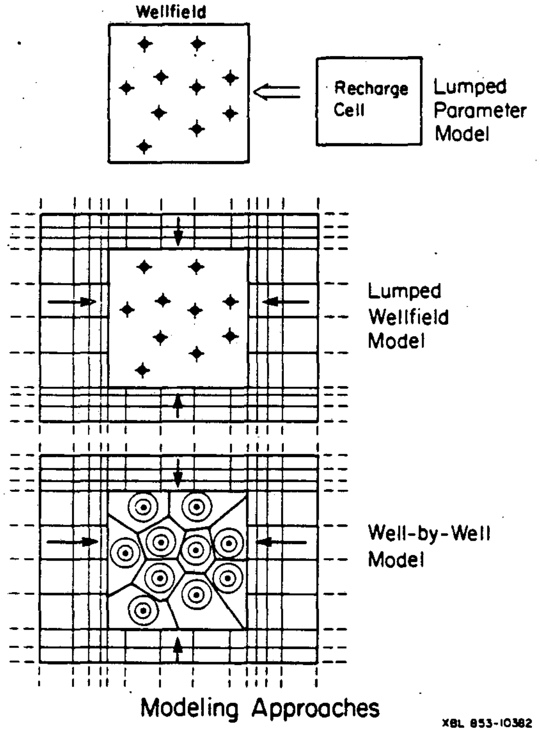
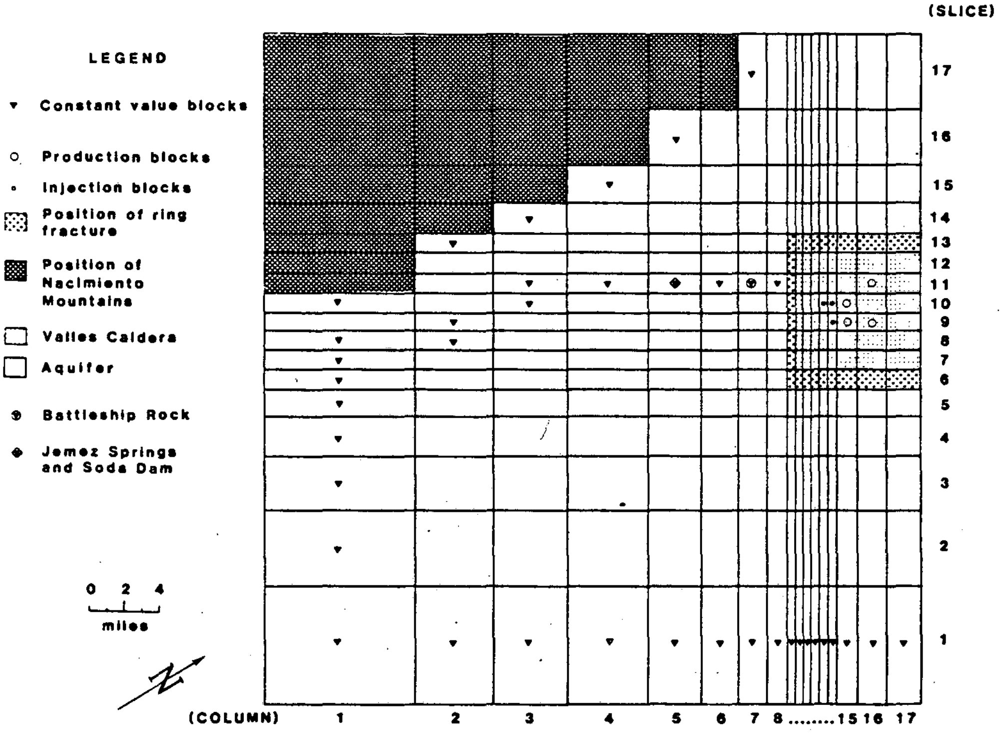


Figure 5. Schematic representation of the different modeling approaches.



-- XBL 853-1812 --

Figure 6. Areal view of the finite difference grid used in the lumped-wellfield model of the Baca field, New Mexico (after Ref. 60).

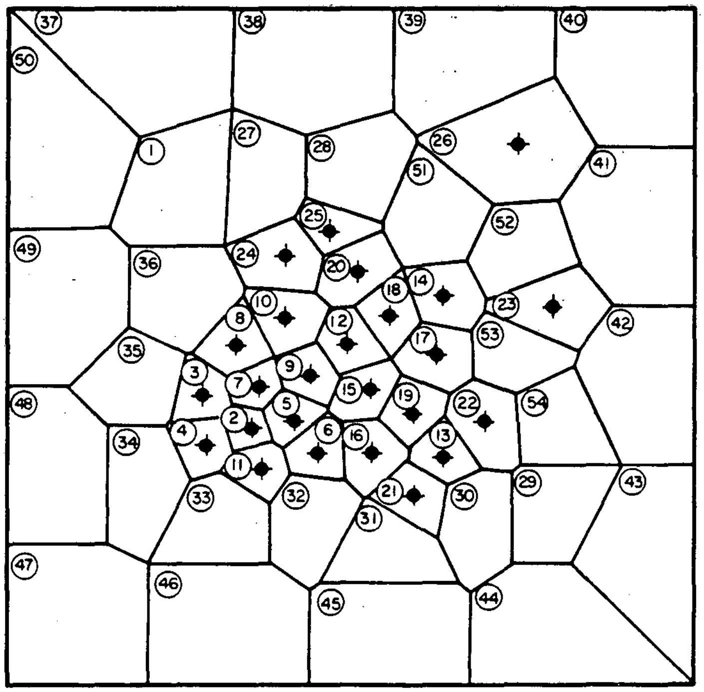
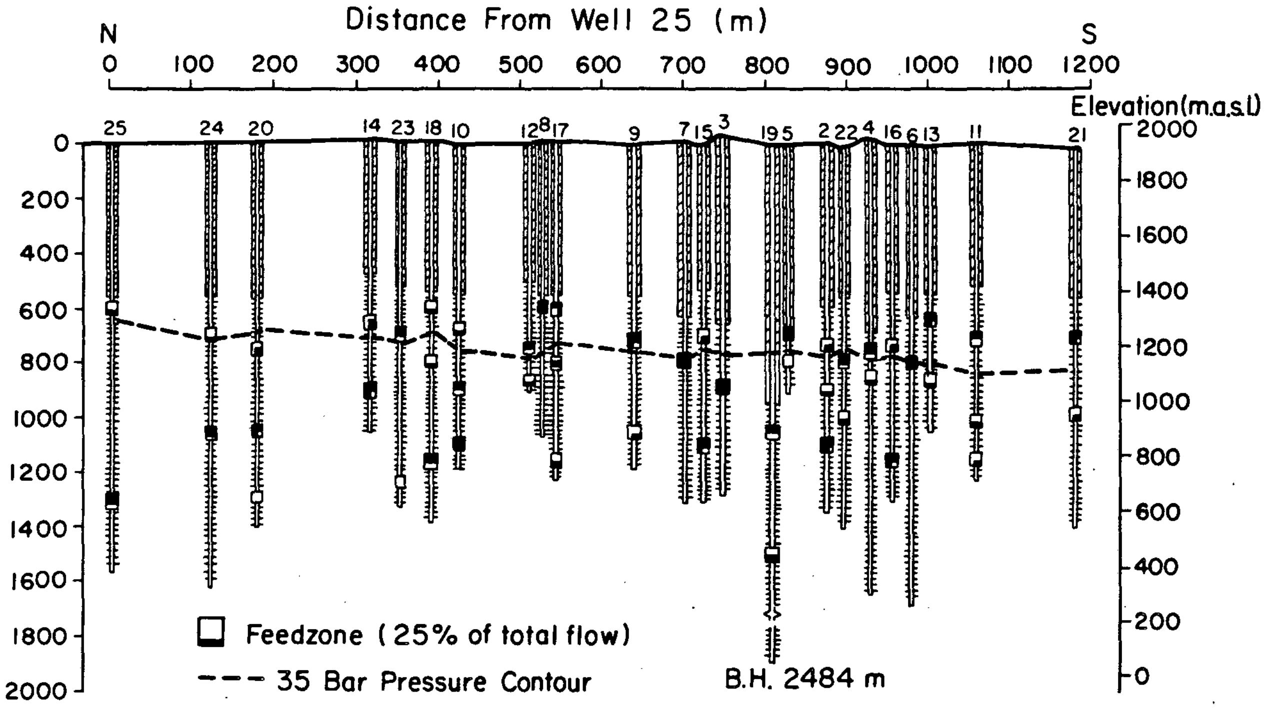
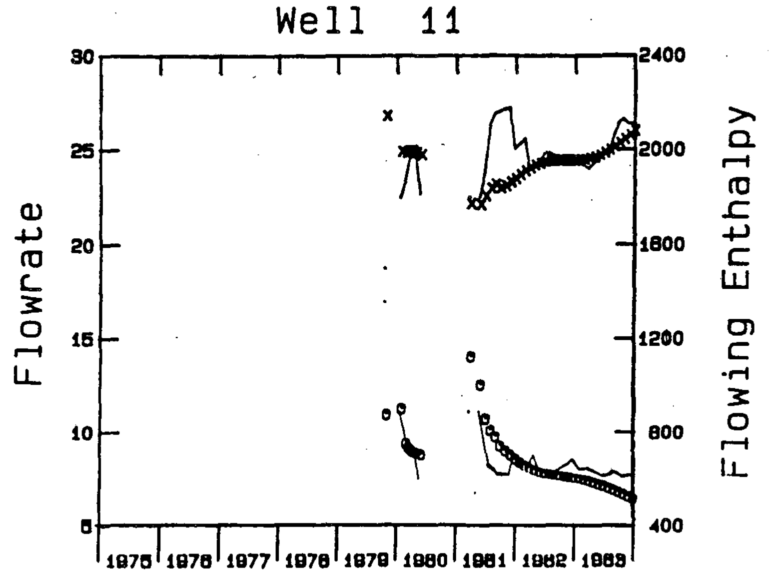


Figure 7. The numerical grid used for the well-by-well model of the Olkaria field, Kenya (after Ref. 74).



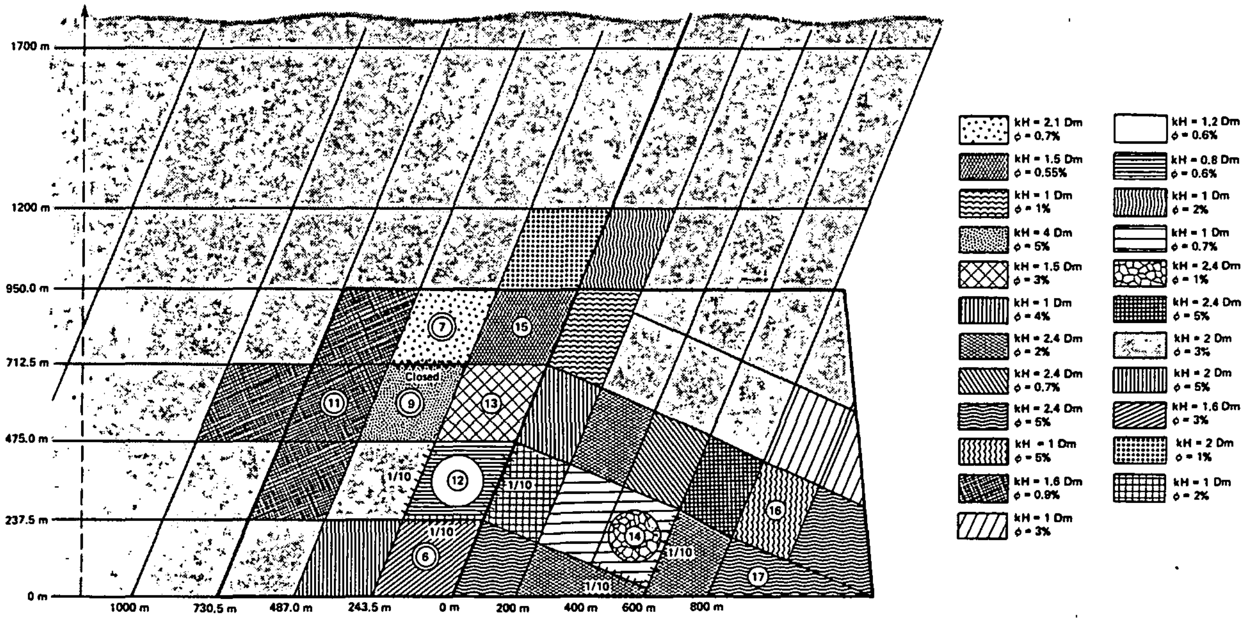
XBL 853-10378

Figure 8. Major feed zones of wells at the Olkaria field, Kenya (after Ref. 74).



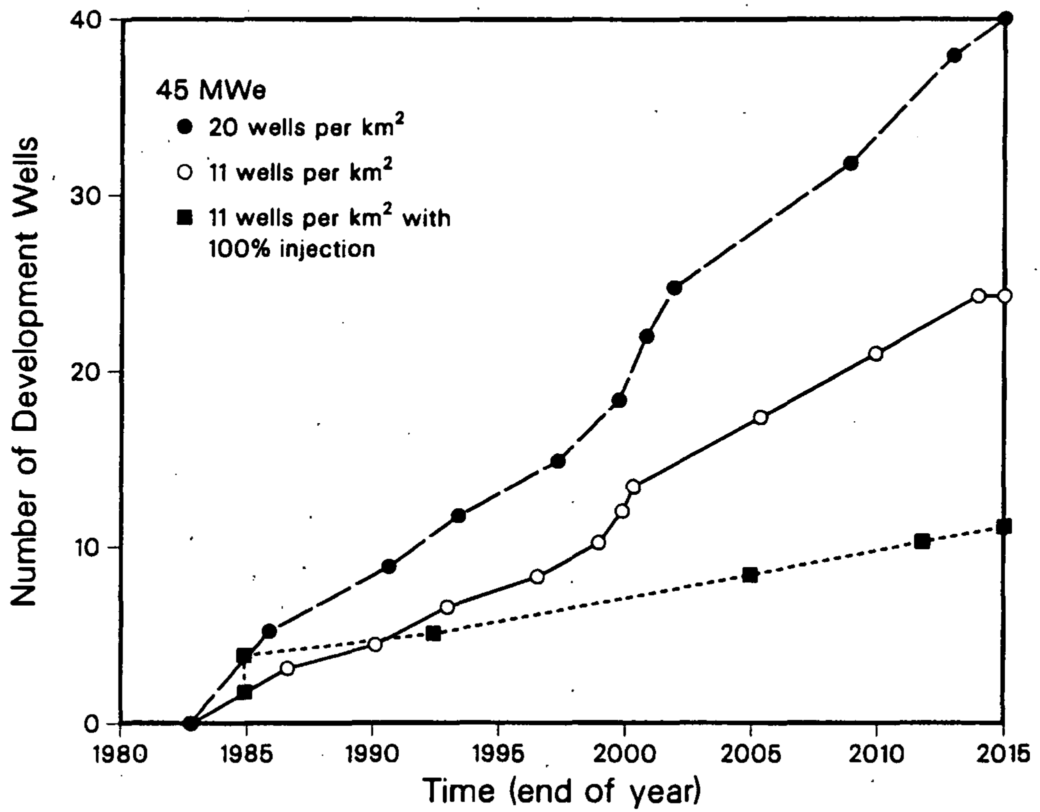
-- XBL 853-1811 -

Figure 9. History match for well 11 at the Olkaria field, Kenya (after Ref. 74).



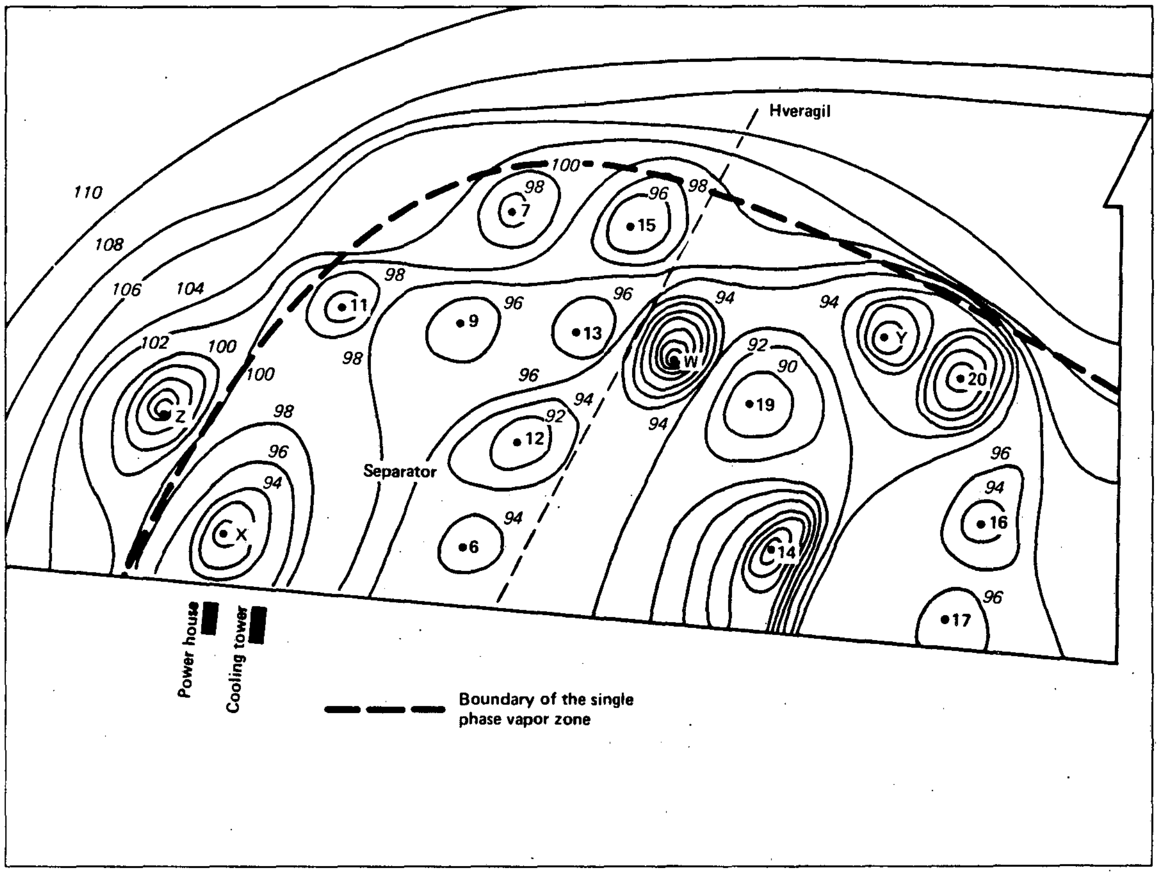
XBL 8210-4770

Figure 10. Properties of different zones and flow restrictions in the lower reservoir at the Krafla field, Iceland (after Ref. 73).



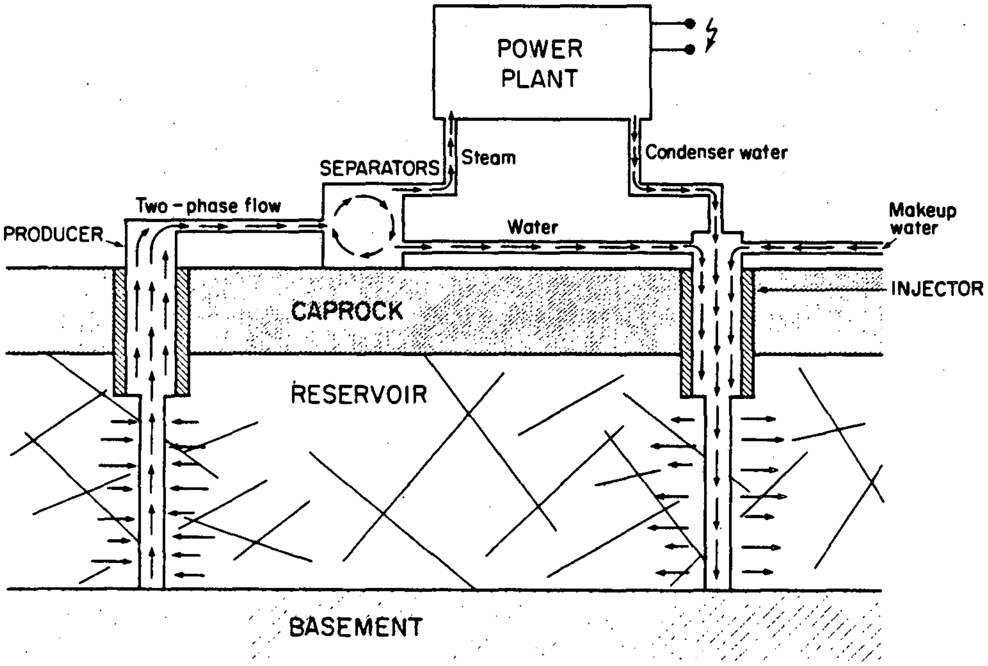
XCG 8410-13344 A

Figure 11. Number of development wells needed to maintain $45 MW_e$ at the Olkaria field for different well densities and with 100% injection (after Ref. 75).



XBL 8210-4683

Figure 12. Predicted pressure contours at the end of 1992 for the Krafla field, Iceland (modified from Ref. 73).



XBL 832-1704

Figure 13. Schematic figure of an injection-production doublet-well system.

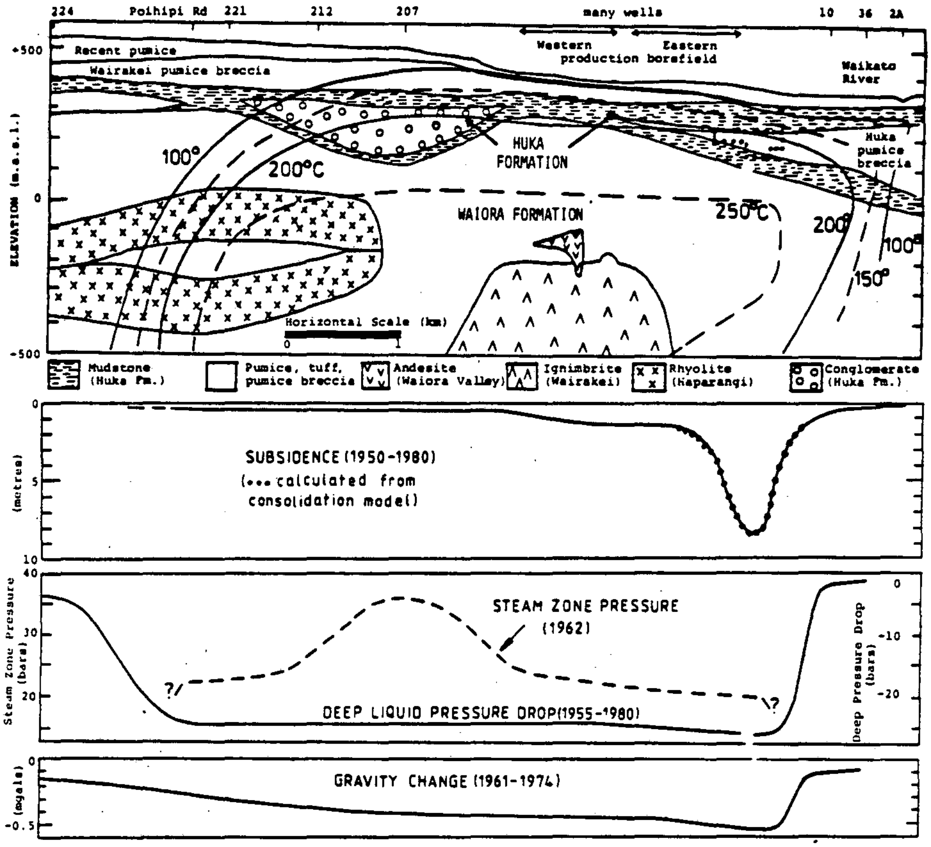


Figure 14. Cross-section of Wairakei field showing relationship between geology and temperature, and the subsidence, pressure changes and gravity change caused by exploitation (after Ref. 86).

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