doi: 10.22564/brjg.v5i2.2248

Revista Brasileira de Geofísica; 1987, Vol. 5, 301-310

CONVECTIVE HEAT TRANSPORT IN GEOTHERMAL SYSTEMS

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Most geothermal systems under exploitation for direct use or electrical power production are of the hydrothermal type, where heat is transferred essentially by convection in the reservoir, conduction being secondary. In geothermal systems, buoyancy effects are generally important, but often the fluid and heat flow patterns are largely controlled by geologic features (e.g., faults, continuity of layers) and location of recharge and discharge zones. During exploitation, these flow patterns can drastically change in response to pressure and temperature declines, and changes in recharge/discharge patterns.

Conective circulation models of several geothermal systems, before and after start of fluid production, are described, with emphasis on different characteristics of the systems and the effects of exploitation on their evolution. Convective heat transport in geothermal fields is discussed, taking into consideration (1) major geologic features; (2) temperature-dependent rock and fluid properties; (3) fracture-versus porous-medium characteristics; (4) single-versus two-phase reservoir systems; and (5) the presence of noncondensible gases.

A maioria dos sistemas geotermais que estão sendo explorados para uso direto ou para geração de energia elétrica são do tipo hidrotermal, onde o calor é transferido essencialmente por convecção dentro do reservatório térmico, sendo que a condução de calor tem participação secundária. Em sistemas geotermais diferenças de densidade no fluido são, em geral, importantes, mas frequentemente os fluxos de fluido e de calor são em grande parte controlados por feições geológicas (por exemplo, falhas, fraturas, e pela localização das zonas de recarga e descarga. Durante a exploração, o padrão de ambos os fluxos pode mudar drasticamente como consequência da diminuição da pressão e da temperatura, e de variações no padrão de descarga e recarga. Transporte convectivo de calor em campos geotermais é afetado por: (1) feições geológicas principais, (2) propriedades da rocha e do fluido que dependem da temperatura, (3) características de meio fraturado em contraste com características de meio poroso, (4) contraste entre sistemas com reservatório monofásico e bifásico, (5) presença de gases não condensáveis. Modelos de vários sistemas geotérmicos com circulação convectiva, tanto antes quanto durante a sua exploração, são descritos com ênfase nas diferentes características dos sistemas, e nos efeitos da exploração em sua evolução.

(Traduzido pela Revista)

INTRODUCTION

To date, only hydrothermal convection systems have been commercially developed. For geopressured, hot dry rock, and magma type of geothermal resources, the economics are still uncertain, and the technology has only started to be developed.

In most hydrothermal systems liquid water, contained in the pores and fractures of the rocks, is the predominant fluid that controls the vertical pressure gradient. These are the so-called liquid-dominated systems. In a few fields this pressure gradient is controlled by the vapor phase (e.g., The Geysers, USA; Larderello, Italy; Kamojang, Indonesia; Matsukawa, Japan); these systems are referred to as vapor-dominated.

In hydrothermal systems convection is the main mode of heat transport in the reservoir. However, in the less permeable caprock and bedrock, conduction is the dominant heat transfer mechanism. Elder (1966) and Cheng (1978), amgong others, give detailed discussion of heat transfer in geothermal systems.

Under natural (pre-exploitation) conditions, hydrothermal reservoirs are not static like oil and gas reservoirs but are dynamic in nature (Donaldson et al., 1983). The distribution of temperatures, pressures, and fluids is controlled by natural convection, which can be dominantly free or forced. That is, the fluid flow patterns are determined primarily by either the buoyant effect of the heated fluid or by external forces (i.e., location of heat/mass sources and sinks). The overall movement of geothermal fluids in the reservoir is driven by natural pressure gradients. However, circulation patterns may be controlled by geologic features such as faults, zones or layers of differing permeability, and multiphase zones. The reader is referred to Donaldson (this volume) for a literature review of thermal convection in geothermal reservoirs.

When exploitation begins a number of changes occur in the reservoir. Changes in fluid temperatures, pressures, and composition occur and stresses in the rock mass increase or decrease. Also high pressure and high temperature gradients are formed around the production and injection wells (in single-phase reservoirs the temperature gradient near production wells is generally small). Changes in the pattern of heat and mass (convective) transport tend to reflect the production and injection scheme used in the field. In other words, forced convection is predominant in the reservoir.

Grant et al. (1982) and Donaldson (*this volume*) have discussed the changes in geothermal systems under exploitation. In this paper we will review the various processes occurring in geothermal reservoirs and give examples of their evolution in response to production, emphasizing the changes in convective patterns within the reservoirs.

MAIN PROCESSES OCCURRING IN THE RESERVOIR

Since a geothermal reservoir is a dynamic system there is a continuous movement of fluids (liquid, steam, gases) controlled by the pressure gradient, the effective permeability of the rocks, and the viscosity and density of the fluids, as described by Darcy's law. Simultaneously there is heat transfer, mainly by convection. While conduction occurs in response to thermal gradients, convection is directly related to fluid movement.

Boiling and condensation in the geothermal reservoir have very important effects because of the significant difference in steam and liquid water enthalpies (at 250°C the latent heat of vaporization is about 1,700 kJ/kg). During these processes the rock mass acts as a buffer, transfering heat to the fluid during boiling and absorbing heat during condesation.

In many two-phase geothermal systems a counterflow of steam and liquid resulting from density differences is observed (Fig. 1). This convective process is a very effective heat transfer mechanism that is strongly controlled by the vertical permeability of the reservoir formation. When fluids are produced from the bottom of the reservoir the pressures at the top could increase as a result of steam upflow from depth and condensation in the shallow regions. The condensation causes a temperature rise and consequently a pressure increase.

Under this lower-zone production scheme, if the vertical permeability is high enough, the pressure at the bottom of the reservoir could stabilize in response to a constant pressure region existing at the top of the system. Bodvarsson & Cox (1986) show that the fluid depletion occurs primarily at the top of the reservoir, where a steam-dominated zone develops that is recharged by lateral steam flow. During production from the bottom layer, the pressure declines until it induces significant vertical recharge, and gravity drainage becomes the dominating flow mechanism. This causes with an expanding steam zone at the top of the reservoir. Little localized boiling occurs in this upper zone, so that temperatures (and pressures) are maintained (Fig. 2).

Boiling and condensation also affect the general transport of fluids in the reservoir and of dissolved solids and gases. Changes in steam saturation cause the effective permeability of the reservoir rocks to change (relative permeability effects). Phase changes also alter chemical equilibria, resulting in the dissolution or precipitation of minerals in the reservoir pores and fractures, thus increasing or decreasing the rock permeability. The amount of noncondensible gases in the liquid and gaseous phase is also controlled by boiling and condensation.

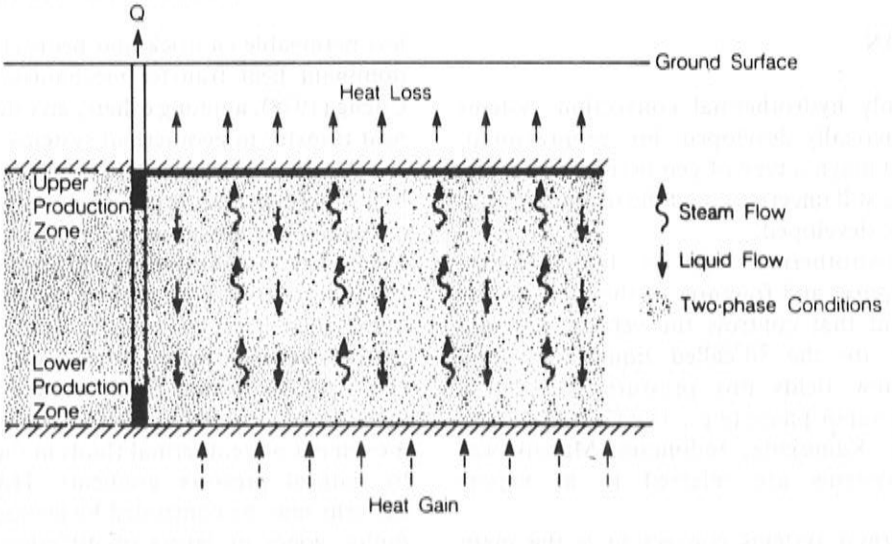

Figure 1 — Schematic model of liquid-steam counterflow in a two-phase geothermal reservoir (from Bodvarsson and Cox, 1986).

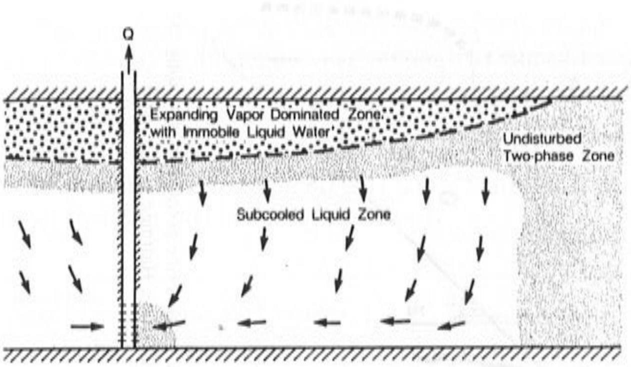

Figure 2 — Schematic model of flow patterns and depletion mechanisms for a well producing from a deep zone in a two-phase geothermal reservoir (from Bodvarsson and Cox, 1986).

Another process often observed in geothermal systems is the mixing of different fluids as a result of natural recharge and/or injection/production operations. Changes in temperature, saturation, and chemical composition of the reservoir fluids can be the result of mixing; such changes can in turn cause chemical reactions between the fluids and the reservoir rocks.

Production reduces pore pressure in the reservoir rocks and increases the effective stress on the rock grains. Thus, it may eventually result in the consolidation of the reservoir formation at depth and cause ground deformation at the surface.

The thermal contraction of reservoir rocks in response to the influx of colder waters or to the lowering of pressures in two-phase boiling systems can produce microfracturing of the rock and thus increase its permeability. There are other processes acting in the system, such as capillary pressure effects, osmosis and adsorption, but their effects on reservoir behavior are generally not believed to be significant.

Another phenomenon that can occur during exploitation is a change in well production characteristics. This could be related to changes in the reservoir such as boiling, steam segregation, or shifts in recharge patterns. However, the changes observed at the wellhead could be only a function of well behavior. For example, by lowering the wellhead pressure, thus increasing production and decreasing the pressure in the borehole, nonproducing zones might begin feeding the well, resulting in fluid mixing in the borehole and possible temperature and chemistry changes in produced fluids. In some instances scaling could occur, reducing the effective diameter of the well and increasing pressure losses.

Variations in parameters measured at the wellhead can be the result of complex reservoir processes or of well operation methods. Thus, to predict the future behavior of a geothermal field under a given development plan, it is difficult to extrapolate values measured during the early evaluation phase of the resource. Initially, only limited changes may occur in the system. With large-scale development quite different processes may be active in the reservoir and the wells. All of these processes and the associated geologic complexities can be taken into account only by using numerical simulation techniques, as discussed by Bodvarsson et al. (*this volume*).

FIELD CASE EXAMPLES

To illustrate the processes and changes discussed above we will describe the evolution of three liquiddominated geothermal systems in response to exploitation. These are: Cerro Prieto, Mexico; Wairakei, New Zealand and Svartsengi, Iceland. Vapor dominated systems are not discussed because their behavior under production have not been extensively documented, and there are still many unanswered questions about their genesis and dynamics. Published data are limited to changes in the chemistry of the produced steam and to partial information on pressure and temperature distribution before and during field exploitation.

CERRO PRIETO, MEXICO

The Cerro Prieto geothermal system is located in the heterogeneous sedimentary fill of the Mexicali Valley. A number of reservoirs interconnected through faults and permeable layers have been identified by wells up to and over 4,000m in depth (Fig. 3).

The temperatures of the producing zones vary, but temperatures above 350°C have been measured. The distribution of isotherms reflects the natural movement of geothermal fluids in the subsurface (Figs. 3 and 4). Before large-scale fluid production began, hot fluids from a source deep in the eastern regions of the system tended to ascend toward shallower zones as they flowed west. At the western edge of the field some of the geothermal fluids reached the surface, as evidenced by abundant surface manifestations. Under natural conditions, compressed liquid was present in most parts of the field. Only in the western part of the system could a twophase zone have existed (Lippmann & Bodvarsson, 1983).

The permeabilities of the reservoirs generally vary between 20 and 50 md, and the transmissivities between 2 and 40 darcy-meters (Dm). The permeability of the producting zones is predominantly controlled by primary and secondary pores. Fracture permeability appears to be more significant in the deeper, hotter eastern reservoirs.

The exploitation of Cerro Prieto began in 1973. Initially, fluid production was restricted to wells drilled in the western part of the field, completed between 1,000 and 1,500 m depth. After 1980, deeper wells drilled in the central and eastern areas started to supply significant amounts of fluids to the power plant (Lippmann & Mañón, 1987). To date, large quantities of fluids have been extracted from the field, changing the conditions and processes in the reservoirs.

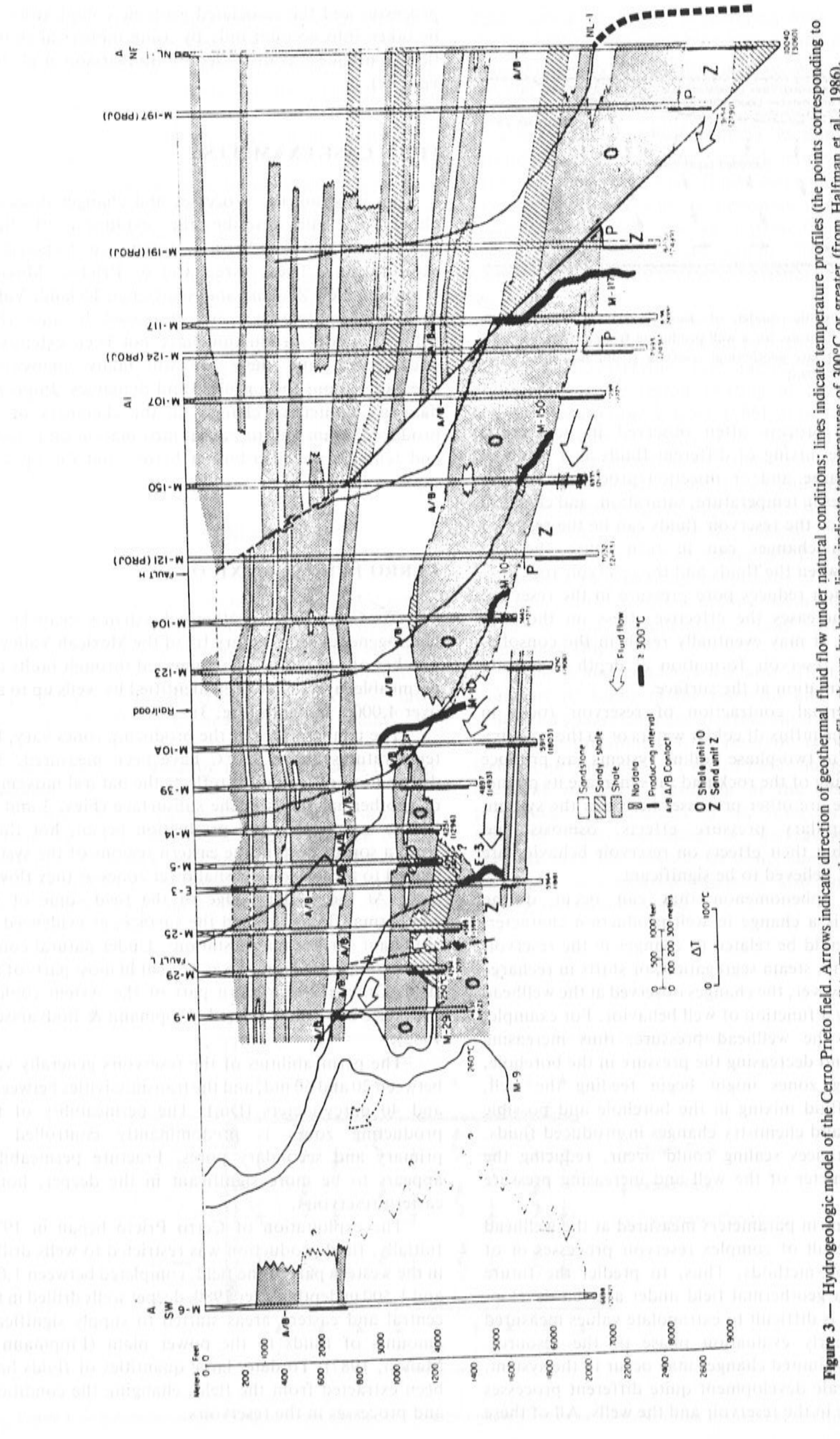

Figure 3 — Hydrogeologic model of the Cerro Prieto field. Arrows indicate direction of geothermal fluid flow under natural conditions; lines indicate temperature profiles (the points corresponding to 300°C are located below the respective wells). The parts of the temperature profiles shown by heavy lines indicate temperatures of 300°C or greater (from Halfman et al., 1986).

The pressure in the shallow α reservoir (only found west of the railroad tracks shown in Fig. 4) declined by about 23 bars between June 1973 and December 1979 (Bermejo et al., 1979). For the same period the temperature drop was less than 10°C (Lippmann & Mañón, 1987). No data have been published on the changes in the deeper (below 1,500 m depth) reservoirs.

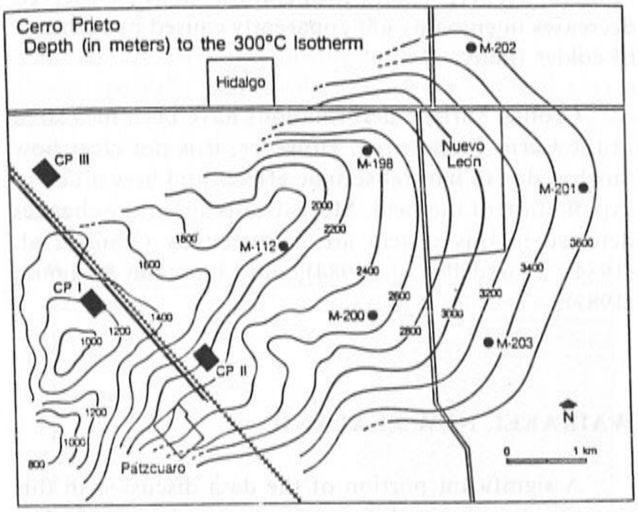

Figure 4 — Cerro Prieto. Depth to the 300°C isotherm (from Lippmann and Mañón, 1987).

Most Cerro Prieto wells produce from single-phase liquid reservoirs, however, local boiling occurs close to many of the wells. Because of the strong recharge of colder waters from shallow groundwater aquifers and from the western edge of the field (Fig. 5); no extensive boiling zone has developed in the α reservoir in response to fluid production. Initially, boiling around the wells produces an excess in flowing enthalpy, which later diminishes or disappears as the boiling front stabilizes (Grant et al., 1984; Truesdell et al., 1984). As reflected by a silica deficiency in the produced fluids, boiling causes mineral precipitation around the wells, possibly reducing the permeability of the reservoir and the productivity of the wells.

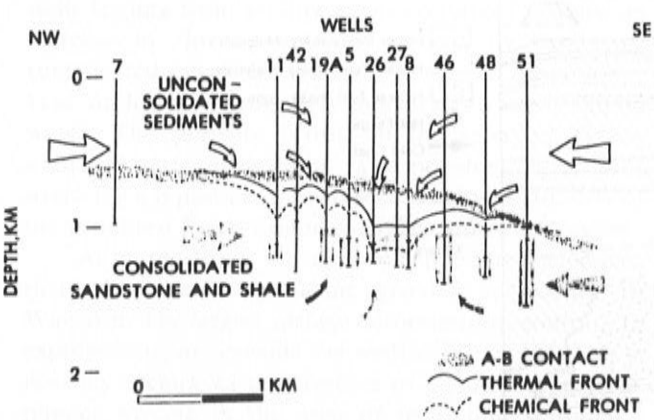

Figure 5 — Schematic section across the western Cerro Prieto reservoir showing flows of hot (stippled) and cold water toward the producing wells, the chemical and thermal fronts, and zones of near well boiling (from Grant et al., 1984).

The strong cold water recharge in the reservoir is inferred from physical and geochemical data, such as the reduction in chloride content in the produced fluids (Fig. 6). A plot of enthalpy versus chloride content suggests the existence of "cold sweep" in the reservoir in response to exploitation (Grant et al., 1984). The time of detection of "chloride breakthrough" in the western wells clearly indicates cold fluid recharge to this reservoir along a normal fault (Figs. 7 and 8). The temperature decline is retarded by heat conduction from the reservoir rocks. The hot influx from the east does not appear to change significantly with exploitation. The rate of recharge from the east seems to be limited by the presence of the two-phase zone located to the east of the α reservoir (Fig. 8). The associated fluid mobility decrease due to relative permeability effects restricts the mass recharge from the deeper parts of the geothermal system (Lippmann & Bodvarsson, 1983; Truesdell & Lippmann, 1986).

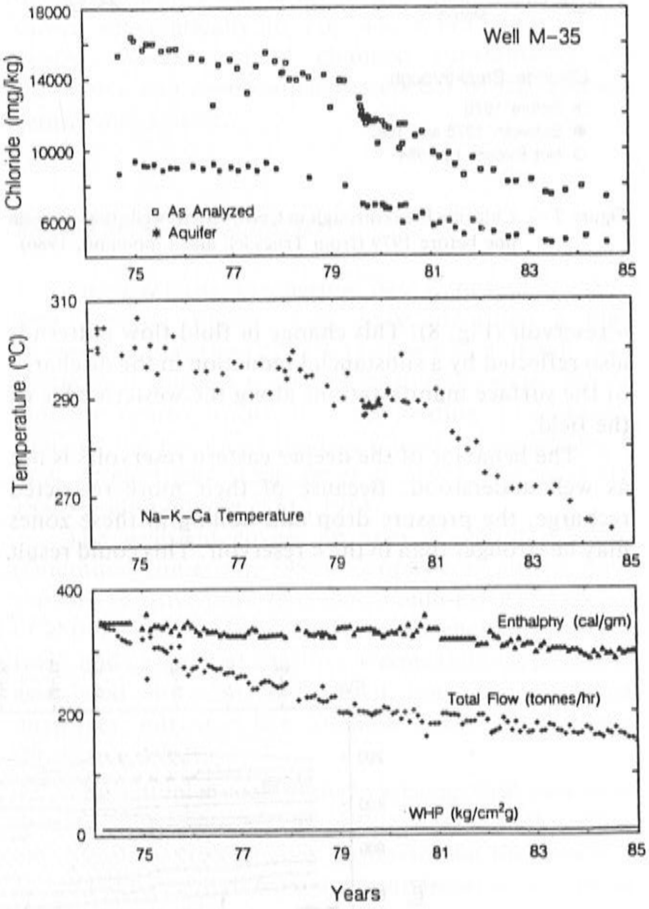

Figure 6 — History of Cerro Prieto well M-35 showing chemical and thermal breakthrough (from Truesdell and Lippmann, 1986).

The convective pattern in the western part of Cerro Prieto has radically changed in response to exploitation. Under natural-state conditions the geothermal fluid flowed westward and upward, some of it discharging at the surface and the rest mixing with local groundwaters west of the field (Fig. 3). With the drawdown in reservoir pressure due to the development of the system, colder ground waters now flow east, and down fault L, into the

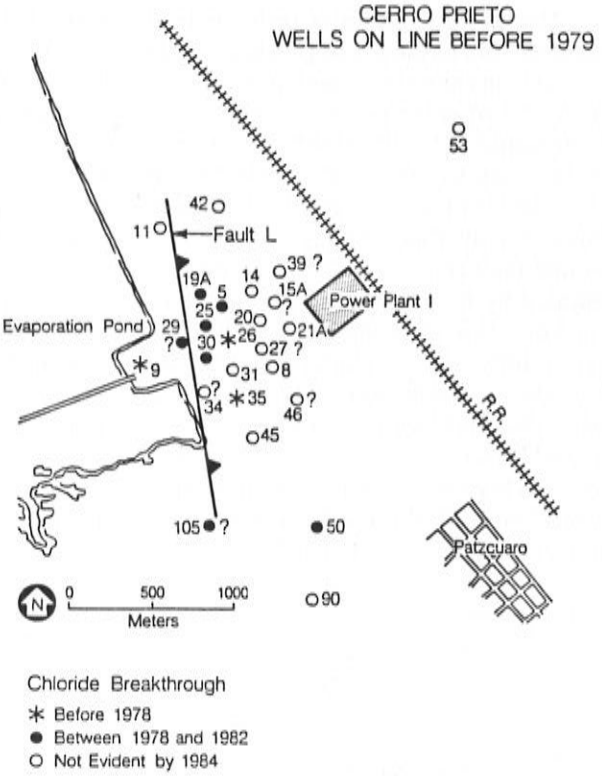

Figure 7 — Chloride breakthrough in Cerro Prieto wells that were on line before 1979 (from Truesdell and Lippmann, 1986).

α reservoir (Fig. 8). This change in fluid flow pattern is also reflected by a substancial reduction in the discharge of the surface manifestations along the western edge of the field.

The behavior of the deeper eastern reservoirs is not as well understood. Because of their more restricted recharge, the pressure drop and boiling in these zones may be stronger than in the α reservoir. This could result in more extensive mineral precipitation in the producing horizons, reducing well productivities (Truesdell et al., 1984).

The average (mass weighted) enthalpy of the produced fluids has also changed significantly with time. The enthalpy rise is related initially to the excess steam produced by some of the wells and later to the introduction of deeper, higher-temperature wells. Observed decreases in enthalpy are apparently caused by recharge of colder fluids.

Ground surface deformations have been measured in the Cerro Prieto area. However, it is not clear how much is due to natural seismic effects and how much to exploitation of the field. More details about the changes detected in this system are discussed by Grant et al. (1984), Truesdell et al. (1984), and Lippmann & Mañón (1987).

WAIRAKEI, NEW ZEALAND

A significant portion of the data discussed in this section was obtained from Grant et al. (1982). The Wairakei power plant, on the North Island of New Zealand, began generating electricity in 1959. The producing horizons are at about 500 m depth, and are generally associated with a contact between a volcanic breccia and an ignimbrite. These zones tend to have high horizontal permeabilities; the permeability-thickness product for the reservoir tends to vary between 10 and 100 Dm. The initial base temperature of the reservoir was about 260°C. Before large-scale fluid production a boiling zone existed above 400 m depth.

In response to exploitation and the resulting pressure drawdown, the two-phase zone expanded

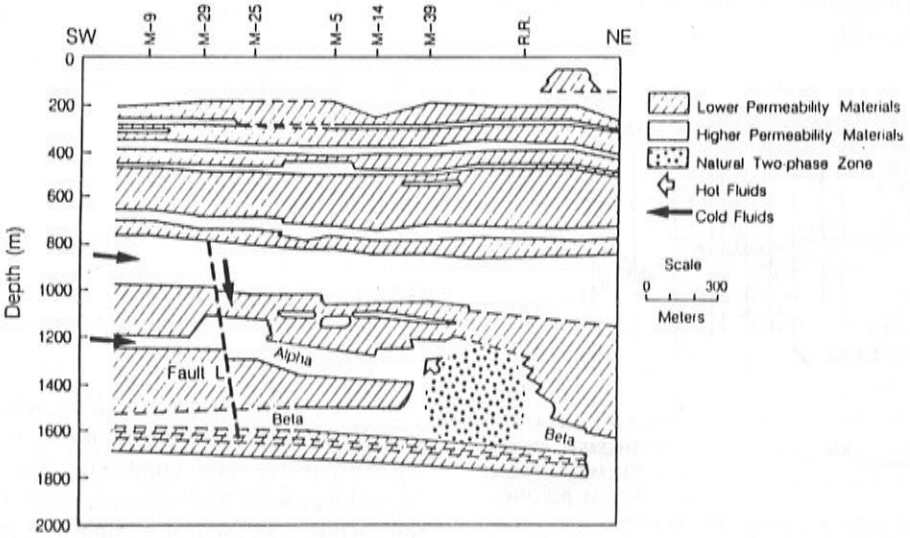

Figure 8 — Postulated fluid recharge pattern in the Cerro Prieto α reservoir resulting from its exploitation (from Truesdell and Lippmann, 1986). This figure covers only the western (left) part of the section shown on Figure 3.

downward. The upper part of this zone became vapor-dominated, while the lower part remained liquid-dominated. Fig. 9 illustrates the changes observed in the reservoir. The lack of pressure stabilization in the two-phase zone, results from interference between producing wells. The overlap of their zones of influence does not allow the lateral recharge of steam that would maintain pressures in this upper zone.

With increased fluid extraction, the size and vapor saturation of the steam zone have increased at Wairakei. In 1960, the flowing enthalpy of the produced fluids generally increased; most wells showed excess steam. At that time the water columns in the wells tended to disappear, and internal fluid flow within the wells between different feed zones became common (Grant et al., 1982).

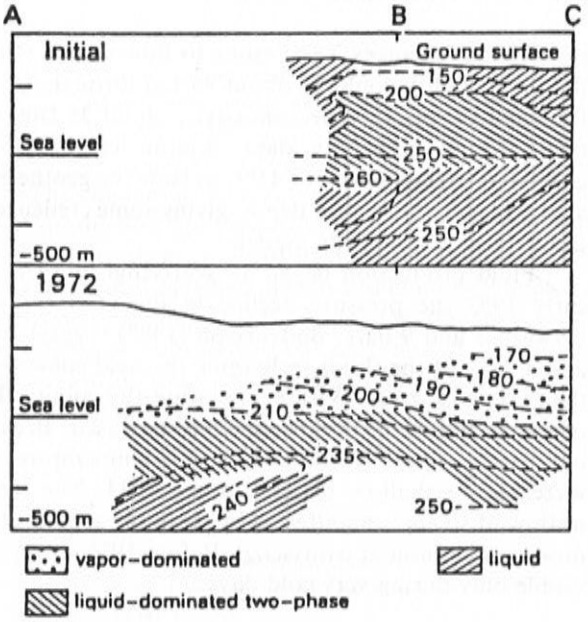

Figure 9 — Section through the Wairakei reservoir in its natural state and in 1972 (from Grant et al., 1982).

In 1962, the behavior of the field stabilized. Some wells feeding from shallow zones continued to show an increase in flowing enthalpy, eventually producing superheated steam. However, in most wells the enthalpy kept declining, finally reaching nearly that of liquid water. The pressure profile in the reservoir clearly indicated the existence of a vapor-dominated zone overlying a liquid-dominated region. More than 95% of the produced fluids originated from this lower region.

As a result of the reservoir pressure reduction, there has been significant ground subsidence at Wairakei. The largest surface deformations, contrary to expectations, are outside the wellfield (Fig. 10). This is possibly because of the presence of highly compressible pumice breccia in the area of maximum subsidence (Allis, 1982b).

Presently, the Wairakei reservoir is being recharged by deep hot waters and by colder shallow groudwaters. Since 1966 the mass extracted from the system has been replaced almost totally by natural recharge (Grant et al., 1982).

The pressure reduction in Wairakei has caused considerable hydrologic and geochemical changes in the nearby Tauhara geothermal system, about 6 km to the southeast (Allis, 1982a; Henley & Stewart, 1983). Fig. 11 compares the fluid movement and characteristics within the system in 1962 and 1978. In 1962 (under natural-state conditions), hot springs discharged deep chloride waters along the margins of the Tauhara system. Steam rising from a deep two-phase system generated sulfate-bicarbonated waters by absorption in shallow groundwater and chloride-sulfate waters by mixing with chloride water.

During 1978-1981, as a result of pressure reduction related to Wairakei production, the chloride springs along the western flanks of Tauhara disappeared. In addition, the upflow of steam increased 5 to 10 times, substantially increasing the volume and temperature of the steam-heated waters (Henley & Stewart, 1983). As shown schematically in Fig. 11, exploitation of the nearby Wairakei field changed substantially the convective and chemical characteristics of the Tauhara geothermal system.

SVARTSENGI, ICELAND

The Svartsengi geothermal field is located in southwest Iceland. Eleven wells have identified a high temperature reservoir (240°C) below 600 m depth. The geothermal fluids are used to heat fresh water that is piped to nearby towns for space heating. In addition, some of the produced fluids are used for generating 8 MW_e of electricity (Eliasson et al., 1977; Kjaran et al., 1980; Gudmundsson et al., 1984).

The wellfield covers an area of about 0.6 km^2 (Gudmundsson et al., 1984). Geophysical surveys have shown a resistivity low (less than 5 ohm-m) over a region of about 7 km^2. In the subsurface one encounters basalt flows and basalt hyaloclastites. Permeability is primarily associated with contacts between flows, fractures, and intrusives; intrusives are common below 800 m depth (Franzson, 1983).

Conceptual models of the Svartsengi field have been developed by Eliasson et al. (1977), Kjaran et al. (1980), and Regalado (1981). They postulate that the system is recharged by rainfall from a mountainous area some 20 km to the east. The water percolates to about 3 km depth and is heated as it flows west. The fluids ascend in the Svartsengi area because of buoyancy, developing a convection cell (Fig. 12). This explains the near-isothermal conditions in the reservoir. According to Regalado (1981), the upflow zone could be confined to a major near-vertical fault located near wells 2, 3, and 10 (Fig. 12). A small boiling zone is inferred to exist between 200 and 400 m in the vicinity of this fault. Counterflow of steam and liquid water occurs in this two-phase region.

A caprock between 300 to 500 m depth, formed by

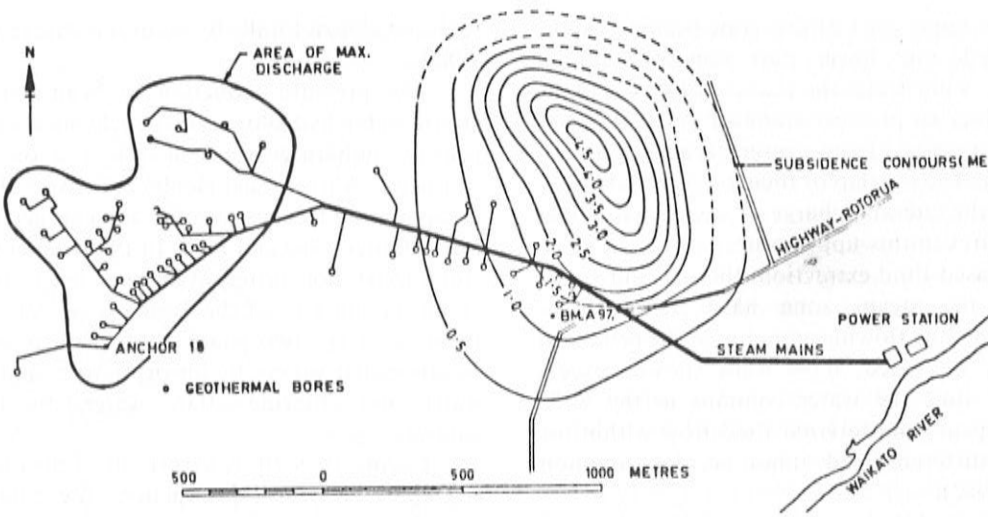

Figure 10 —Total subsidence (in meters) at Wairakei, 1964-1974 (from Stilwell et al., 1976).

hydrothermal alteration, hinders further fluid ascent. Most fluids spread laterally below the caprock, cool by conductive heat losses, and descend. Some of the upflow fluids recharge aquifers in shallow regions. This and the presence of the two-phase zone strongly suggests that the caprock is leaky, perhaps because of the presence of near-vertical faults. The reservoir is believed to extend to about 2,500 m depth, bounded below by a low-permeability bedrock.

Numerical modeling studies (Bodvarsson, 1987) indicate that the reservoir has a 0.5 to 1.0 km-radius high-mobility inner zone surrounded by a low-mobility outer zone. The contrasting mobility could be due to temperature effects on the fluid properties rather than permeability changes. (According to Bodvarsson (1987) the permeability could be about 85 md throughout the field and the reservoir transmissivity about 35 Dm) On the basis of resistivity data, Kjaran et al. (1980) estimated a temperature of 41°C outside the geothermal anomaly and at reservoir depth, giving some credence to Bodvarsson's composite model.

Fluid production began at Svartsengi in 1976; by early 1983 the pressure decline in the reservoir was between 8 and 9 bars. Bodvarsson (1987) suggests that about 25% of the fluids recharging the field come from the two-phase zone. With exploitation the counterflow of steam and water in this zone has increased. Because now more steam is condensing the temperature has increased in shallow regions of the field. The larger upflow of steam is manifested by steaming grounds that now are common at Svartsengi. Before 1976 steam was visible only during very cold days.

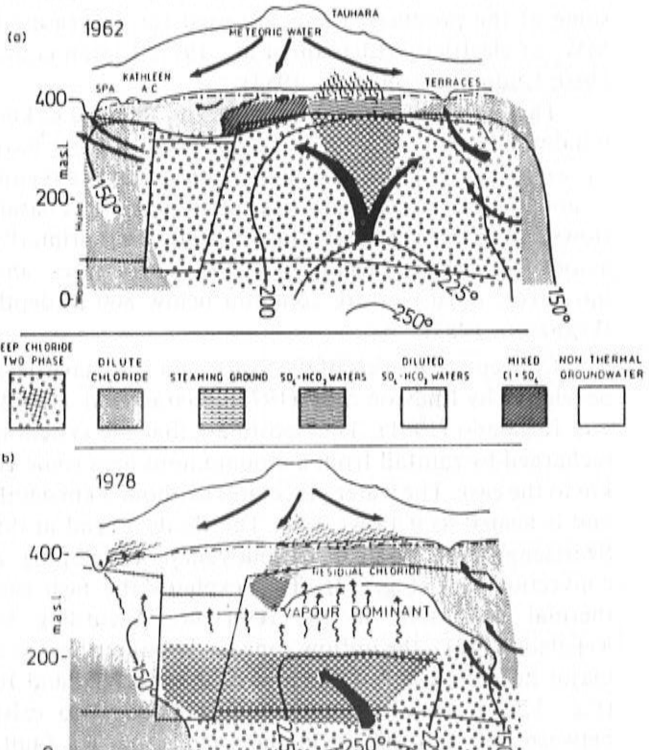

Figure 11 —Schematic models showing features of the Tauhara geothermal system in 1962 and 1978 (from Henley and Stewart, 1983).

FINAL REMARKS

The main characteristics, processes, and changes observed in three liquid-dominated, convective geothermal systems have been described. There is no general purpose model that can be applied to all these systems. Each has particular features that need to be considered when predicting their behavior under exploitation. However, only a few complexities of geothermal systems have been discussed. We have not included fields having high concentrations of dissolved solids or noncondensible gases. Brines with higher concentrations of these constituents make it more difficult to handle the fluids at the surface, and add complexities to the processes occuring in the geothermal reservoir. For example, higher salinities increase the boiling and critical points of the geothermal brines and increase the solubility of calcite. High concentrations of noncondensible gases alter the boiling curve of liquid water significantly and tend to expand two-phase zones in geothermal systems (Sutton & McNabb, 1977; O'Sullivan et al., 1985).

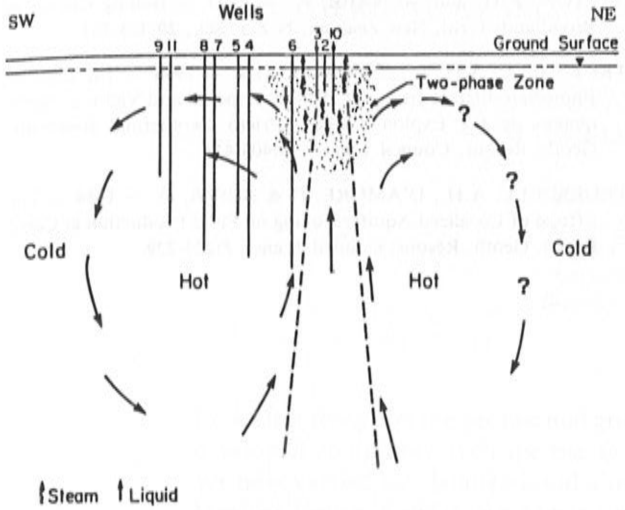

Figure 12 —Plausible conceptual model of the Svartsengi geothermal system showing steam-liquid counterflow in the two-phase zone overlying a liquid reservoir (from Bodvarsson, 1987).

The changes in a geothermal system in response to fluid production are the result of coupled physical and chemical processes, most of them highly nonlinear. The complexity of these phenomena, and that of the geologic structures controlling the heat and mass transport in the hydrothermal convective systems, requires the use of mathematical tools to simulate and predict their behavior under given reservoir management plans. Mathematical models of increasing sophistication could be applied to the study of these systems if an adequate data set were available. When data are scarce, simple models can be applied, as discussed in an accompanying paper (Bodvarsson et al., *this volume*).

As more complete field data sets become available it will be possible to validate the conceptual models being developed for individual hydrothermal systems. A carefully designed monitoring program, including geochemical and reservoir engineering measurements, will be necessary to obtain the required information. Mathematical models, especially numerical computer codes, could then be used to establish the importance of given reservoir processes in the geothermal system and develop a conceptual model that reflects the data measured in the field. The next step would be to evaluate several fluid production/injection scenarios and to establish the reservoir management plan that optimizes the recovery of the heat stored in the subsurface.

ACKNOWLEDGMENTS

We would like to thank Leslie Fairbanks and Mary Bodvarsson for their help in producting this paper. This work was supported through U.S. Department of Energy Contract No. DE-AC03-76SF00098 by the Assistant Secretary for Conservation and Renewable Energy, Office of Renewable Technology, Division of Geothermal Technology.

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