Chapter 2

Concepts of Geothermal Systems

Chapter Outline

2.1. INTRODUCTION

This chapter discusses fluid distribution, pressure, and temperatures that can occur in geothermal reservoirs. These concepts provide a background for the following chapters, which describe the testing of wells and reservoirs, the construction of a conceptual model of the resource, and then a quantitative model.

Much of the following discussion relates to unexploited fields in which the thermodynamic state of the field is determined by the natural processes of heat and fluid transport. This is because the results of testing done early in a new field development are the most challenging to interpret and because the natural state of the field influences its subsequent response to exploitation. As a geothermal field is developed and information from more wells, along with the system response to production and injection, becomes available, the conceptual model and the numerical simulation model can be further refined.

Anyone who has ever watched a geyser in action or a hot pool bubbling and wondered where the water and heat came from has some sort of mental picture of this small part of a geothermal system. The accuracy of such a mental picture depends to a great extent on the available data and on the individual's interpretation of that data based on preconceived ideas and past experience. Each of

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these mental models is thus unique to the individual concerned and is closely linked with that person's background and experience.

In the scientific arena, such mental models, which are based on a range of data from various disciplines, together with experience in related research, form the basis for the development of *conceptual models* that should bring together all the available information into a single coherent model. Of course, these conceptual models will vary from one expert to another, depending on the individual's background and the weight given to specific data. However, since a model should be consistent with all the observable aspects of the system, they should all give very similar basic results. These models will vary among individuals, depending on their need. For example, the fine detail that is essential in a model of flow around a particular well will become insignificant as the scale increases to include the complete geothermal resource.

2.2. CONDUCTIVE SYSTEMS

2.2.1. The Thermal Regime of the Earth

Over almost the entire surface of the Earth is a flux of heat through the crust upward to the ground surface. This heat is transported to the surface by conduction through the crustal rocks. The average geothermal gradient in the shallowest part of the crust is around 30°C/km. Since the heat flux varies from place to place over the Earth's surface, and the thermal conductivity varies with different strata, conductive gradients of up to 60°C/km can be encountered. Thus, higher temperatures are encountered when drilling or mining deep into the crust, and temperatures more than 100°C are often found in deep oil or gas wells. One means of prospecting for geothermal reservoirs that is not evident from surface discharge of geothermal fluids ("blind systems") is identifying areas of anomalous heat flow by measuring temperature gradient in wells—either shallow "temperature gradient" wells or existing deep oil, gas, or groundwater wells. A region of potential geothermal resource may be associated with high heat flow. The near surface temperature gradients can be extrapolated through impermeable strata to obtain deep temperatures. Such extrapolation cannot be continued through permeable strata because the presence of permeability means that convection will determine the temperature distribution (Benoit, 1978; Salveson & Cooper, 1979).

2.2.2. Warm Groundwater Basins

One source of water at temperatures above mean surface is from aquifers that are so deep that their temperature is raised by the normal geothermal gradient. The mechanism heating the water in such systems is then simply the vertical conduction of heat through the crust. The fluid flow in the aquifer must be sufficiently slow that there is time for the water to be heated by this conductive heat flow. The general reduction of permeability with depth implies that successful production from greater than a few kilometers requires anomalously high permeability, and the chance of such anomaly decreases with increasing depth.

In some large groundwater basins, a fraction of the heated water circulates back up to the surface where there is suitable permeability and structure. Otherwise the heated fluids may be confined within a particular stratum.

2.2.3. Deep Sedimentary Aquifers

Deep sedimentary aquifers heated by the normal thermal gradient are found in many continental environments. These aquifers are usually not part of a currently active circulation system. Figure 2.1 shows such a system. This simple two-well system in an aquifer is very common in groundwater or petroleum engineering. The only difference is that the fluid is warm. Figure 2.1 in its simplicity makes a sharp contrast to the figures that follow, which show active geothermal systems. A typical example of this type of system is a carbonate/sandstone aquifer that was developed using production-injection well pairs for district heating in the Paris Basin. Other examples are found in most larger-scale basin areas where elevated temperatures are encountered around the world.

2.2.4. Warm Springs and Fracture and Fault Systems

Many warm springs are found along major fault and fracture lineations throughout the world, suggesting that these major fault systems provide the channels for the flows of warm water that feed the springs. Such channels provide the means for circulation of cold meteoric water to depths where it is heated by the normal geothermal temperature gradient and then returned to the surface to form warm springs. These are a form of convective system, with convection along the plane of the fault being heated by conductive heat transfer into the fault zone. The driving force for the circulation is the density difference between the cool descending water column and the hotter rising column. This mechanism differs from a full convective systems discussed later in this chapter in that it is confined to a narrow fault plane with no extensive reservoir and is

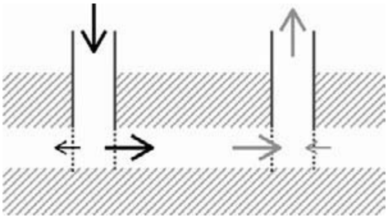

FIGURE 2.1 Injection well (dark) and production well (gray) in sedimentary aquifer.

located in an area with a normal geothermal gradient. An example of a fault-controlled spring system is the hot spring area around Banff, Canada.

2.2.5. Geopressured Systems

Geopressured geothermal reservoirs are closely analogous to geopressured oil and gas reservoirs. Fluid caught in a permeable stratigraphic trap may, by crustal motion over millions of years, be raised to lithostatic pressure. Such reservoirs are generally relatively deep, at least 2 km, so that the geothermal gradient ensures reservoir temperatures over 100°C. A number of such reservoirs have been found in petroleum exploration.

Where these reservoirs are found associated with petroleum, the water is generally saturated with methane, and the methane may be a more important energy source than the heat in the water. Reservoir engineering of such a system is more like a petroleum reservoir than a hydrothermal reservoir or groundwater aquifer. Experiments were conducted on existing wells, originally drilled for petroleum exploration, in the 1980s in the U.S. Gulf Coast, including power generation using an experimental "hybrid power system," but the results were discouraging, with operational problems due to high salinity and high CO_2 content. No further studies have been done since that time (Griggs, 2005). EGS exploration in the Cooper Basin (see Chapter 14) has revealed similar abnormally high pressures in the ancient granite terrain that is overlaid by about 4 km of more recent sediments. Successful development of the deep geothermal resource would operate at similar high pressures.

2.2.6. Hot, Dry Rock or Engineered Geothermal Systems

In some locations, rock of low permeability that has been heated to useful temperatures can be found. The heat source may be from volcanism or an abnormally high geothermal gradient, or there may be impermeable rock on the flanks of a hydrothermal system. Compared with the other systems, these do not have sufficient intrinsic permeability, but they do contain heat.

Exploitation of such a system depends on creating permeability by controlled fracturing such that fluid can be circulated through the rock and heat can be extracted. The fracturing creates a reservoir that did not previously exist. This subject is discussed further in Chapter 14.

2.3. CONVECTIVE SYSTEMS: LIQUID DOMINATED

2.3.1. Introduction: The Dominance of Convection

Hydrothermal convective systems are geothermal systems with high temperatures and usually with surface activity. At the present time, all major geothermal power stations operate on such systems.

In contrast to conductive systems, it is the flow of hot fluid through the system that determines the temperature and fluid distribution. The natural state of the geothermal reservoir in a convective system is thus dynamic, and knowledge of the natural fluid flow is needed to understand how this natural state was formed. Surface features such as geysers, springs, fumaroles, cold gas vents, and mudpools may be associated with this type of reservoir, and they are the end points for some part of the natural thermal flow.

Such natural flows play a dominant role in establishing the state of the fluid within the reservoir, and an understanding of them provides information about reservoir parameters such as vertical permeability, which cannot be determined by other means. Because new flow patterns created by exploitation will usually overwhelm the natural flows in the reservoir, it is important that appropriate information and data be collected early in the exploration program of a new resource.

In low-temperature systems the reservoir fluid is always liquid water, while in higher-temperature systems, steam can also be present. All geothermal reservoirs located to date can be divided into two types—liquid dominated and vapor dominated—depending on whether liquid or steam is the mobile phase. A few reservoirs have separate regions of both types. The majority of reservoirs are liquid dominated and have a vertical pressure distribution that is close to hydrostatic. In vapor-dominated reservoirs the vertical pressure distribution is close to steam-static. In each case the dominant mobile phase, either liquid or steam, controls the pressure distribution, although the other phase may be present in significant amounts. The remainder of this section considers only liquid-dominated reservoirs. Vapor-dominated reservoirs are discussed later in this chapter.

2.3.2. Deep Circulation and Magmatic Heat

Conductive geothermal systems do not require a great deal of heat at depth and can occur anywhere in the world. High-temperature convective systems demand some additional heat above the normal conductive gradient.

One of the earliest conceptualizations of a geothermal system to be built on a detailed analysis of technical evidence was by Bunsen in the 1840s (Björnsson, 2005), who showed that the water discharged by springs in Iceland was meteoric water. For his description of the hot spring system in west Iceland, Einarsson (1942) visualized something akin to a deep groundwater basin. His geothermal flux had to be higher than normal to produce the higher-temperature spring discharge, and his aquifers were factures and fissures in the otherwise impermeable basalts. Variations of Einarsson's model are still accepted for some hot springs in Iceland. For the more intensely active areas of central Iceland, Bödvarsson (1964) allowed deeper circulation and called on a magmatic source for the heat energy.

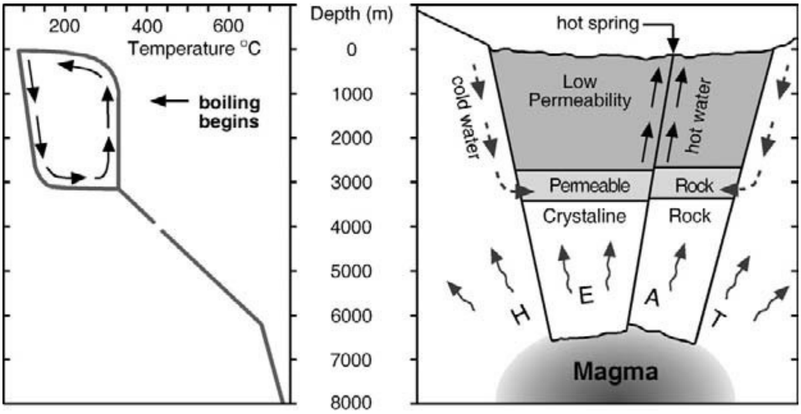

FIGURE 2.2 Model of the large-scale circulation of fluid in the natural state of a geothermal system. *Source: White, D.E., 1967 "Some principles of geyser activity, mainly from Steamboat Springs, Nevada" Am. J. Sci. 265, pp641–684.*

A model similar to Bödvarsson's was produced by White (1967, 1968) for the system associated with Steamboat Springs, where isotopic evidence indicated that about 95% of the water discharged in the springs was of meteoric origin. White produced the model shown in Figure 2.2, where water originating at the ground surface percolates downward through faults and fissures or structures in otherwise impermeable rock to considerable depth.

In Figure 2.2, a circulation depth of 3 km is indicated. White suggested a possible range of 2 to 6 km. A significant number of geothermal fields have now been drilled beyond 3 km without finding a bottom to the system, so the fluid circulation depths would appear to be larger rather than smaller. In White's model the water is heated at depth, probably by close contact with some magmatic body, to the high temperatures encountered in reservoirs associated with such systems. The buoyancy imbalance between the hot and cold columns drives this fluid back up to the surface through other permeable channels.

These systems, which require large amounts of heat compared to the normal crustal heat flux, are generally found in regions of relatively recent volcanism. This accounts for the large number of geothermal fields associated with volcanic arc and crustal rifting. The fractures or flow paths for the water circulation appear to be associated with structures such as regional rift zones or calderas. The total amount of heat transported out of convective geothermal systems over their lifetimes is large—so large, in fact, that not only must circulating water make close contact, but this magma itself must be convecting or replenished by mechanisms such as crustal spreading. Some geothermal fields are long-lived. Browne (1979) imputes a lifetime of hundreds of thousands of years for Kawerau. At Coso a lifespan of 300,000 years has been suggested, at least intermittently (Adams et al., 2000). Silberman and colleagues (1979) suggest that Steamboat Springs may have existed for 3 million years, and Villa and Puxeddu (1994) suggest that Larderello may be as much as 4 million years old. In contrast, some fields have much shorter lifetimes. The Salton Sea geothermal field has an estimated lifetime of 3,000 to 20,000 years (Kasameyer et al., 1984; Heizler & Harrison, 1991).

Long lifetimes of geothermal systems cannot be sustained by a single emplacement of magma. Simulations of single magmatic intrusions in aquifers show that the thermal disturbance lasts only about 10,000 years (Cathles, 1977; Norton & Knight, 1977). For long-lived fields, even if the magma was extensive, many cubic kilometers would be required to supply the cumulative heat discharged (White, 1968; Lachenbruch et al., 1976). Larderello would have required 32,000 km^3 of magma to maintain activity over 4 million years (Villa & Puxeddu, 2004). Similarly Banwell (1957) estimated that over its lifetime Wairakei required at least 10,000 km^3 of magma for its heat supply. For both Wairakei and Larderello the magma volume is too large to be stored under the field. This suggests that the magma source itself must be convecting, so molten rock remains near the zone where heat is exchanged between the magma and the fluid in the geothermal system.

2.3.3. Exploitation and System Circulation

The deep circulation feature of geothermal systems implies that in general the changes induced by exploitation will not greatly affect the natural upflow from depth. Consider the case of a field with a natural flow of 100 kg/s and a base temperature of about 300°C. Assuming a depth of 5 km to the base of the geothermal system, this flow is driven by the pressure difference due to the fluid density between the hot and cold columns, which in this case is about 100 bar. An additional pressure difference of 25 bar due to drawdown in the reservoir would increase the natural flow by 25%, or 25 kg/s. This is not a significant contribution in relation to the typical production flows of about 1000 kg/s.

Thus, the natural state of the reservoir is dynamic, and the fluid distribution is controlled by a dynamic balance of mass and heat flow. Once exploitation occurs, fluid flow to and from wells is generally much greater than the natural flow. This may create a significant flow from parts of the reservoir beyond the depth or areal extent of the wells. With large-scale production and reinjection, the primary induced flow is from the injection wells to the production wells, and induced flow changes outside this area are significantly smaller.

2.3.4. The Vertical Upflow Model and Boiling Point for Depth Models

Having considered the processes in the geothermal system as a whole, this section focuses on the smaller, relatively shallow part of the system that contains the reservoir: the area where fluid rises within an exploitable depth from the surface. The simplest case is when the upflow rises vertically from greater depth to ground surface. The upflow at great depth consists of water or supercritical fluid. As this fluid ascends, the pressure decreases, and at some point, depending on the temperature and fluid chemistry, the ascending fluid forms two phases, gas and liquid, which both rise to the surface. The upflow continues toward the surface as gas and liquid. From conservation of mass and energy it is possible to estimate the form of this upflow. The following assumes that the fluid at depth is liquid and boils when it reaches its saturation pressure, as illustrated in Figure 2.2.

For most purposes, conduction can be ignored as a means of heat transport. For an example, before development, the Wairakei field discharged 400 MW thermal to the ground surface over an area of about 11 km^2—a heat flux of 40 W/m^2. The upflow at depth was most likely confined to a smaller area of 2–3 km^2, and in this case the convective heat flux in the deep recharge area would have been about 180 W/m^2. The original temperature at 400 m was about 250°C, giving a gradient of $250/400 = 0.6$ K/m. Assuming a conductivity of 2 W/m.K, the conductive heat flux would have been about 1 W/m^2, two orders of magnitude less than the conductive heat flow.

Assuming that the pressure at the boiling level depends on the temperature in the upflowing liquid zone, as boiling commences, saturation conditions must apply. Below the boiling level, the temperature distribution is given by

$$T = T_b \tag{2.1}$$

where T_b is the constant "base temperature." Above the boiling level, temperature is given by the saturation relation

$$T = T_{sat}(P) \tag{2.2}$$

The pressure gradient at any depth is equal to the local hydrostatic gradient plus the dynamic gradient caused by the upflow. In most cases the latter is less than 10% of the static gradient (Donaldson et al., 1981), and it may be much less. In a field where the mass flux density (upflow per unit area) is low, the excess dynamic gradient is correspondingly small. This excess gradient is present only in the area of upflow, and toward the margins where there is lateral flow, the pressure gradient will be close to hydrostatic. Ignoring the dynamic gradient, the BPD approximation is obtained from

$$\frac{dP}{dz} = \rho_w g \tag{2.3}$$

The BPD pressure profile is that of a static column of water whose temperature is everywhere at saturation for the local pressure. The BPD approximation implies that steam saturation is close to residual (see Appendix 2). The BPD approximation thus not only approximates the pressure and temperature in the reservoir, but it also specifies something about the reservoir fluid: that little mobile steam is present in the boiling zone. Figure 2.3a shows the fluid

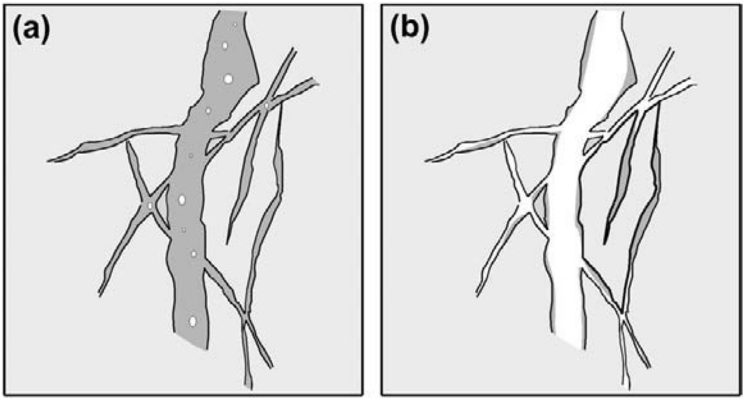

FIGURE 2.3 Distribution of liquid (dark shading) and steam (no shading) in liquid-dominated and vapor-dominated reservoirs. Matrix denoted by pale shading.

distribution in the reservoir fracture network (the higher-permeability paths). Figure 2.3b shows the complementary situation for a vapor-dominated reservoir. In the liquid-dominated reservoir in Figure 2.3a, the fractures are occupied by water, with occasional steam bubbles. The matrix is water-saturated. In the vapor-dominated reservoir in Figure 2.3b, the fractures are occupied by steam, with a film of water clinging to the fracture walls and in dead-end spaces, and the matrix is fully or partly saturated with water.

As a model, BPD—that is, a static fluid column everywhere at boiling point (until the constant-temperature liquid-water section is reached)—is for many purposes a good approximation of the initial state of the upflowing core of the reservoir. Note that this is only an approximation; pressures and temperatures can be higher or lower, and it is incorrect to regard BPD as any sort of theoretical maximum temperature. The BPD profile is naturally of less value where flows are relevant and actual reservoir pressure gradients are necessary, as in comparing pressures between different wells to determine a lateral pressure gradient.

In reality, the rising fluid is cooled by dilution and conduction as much as it would be by boiling, which reduces the amount and extent of boiling. The BPD model is still valid as long as there is some boiling. Typically, boiling conditions will be found in the core of the upflow, with cooler conditions toward the margins.

In all high-temperature geothermal systems, noncondensable gases (NCGs) are present in the reservoir fluids. The presence of these gases together with dissolved salts changes the saturation relation for the reservoir fluid from that for pure water, with the effect that the pressure at which the liquid phase first boils is greater than that for pure water; in other words, boiling starts deeper. A modified boiling curve can be computed by adding conservation of gas to conservation of mass and energy.

2.3.5. Systems with Lateral Outflow

The assumption that the natural flow is entirely vertical is an idealization. Structural control by permeability variation and topographic effects will usually impose some degree of lateral flow. The BPD approximation requires a component of upflow, since boiling conditions can only be maintained if there is some continued upflow of fluid. Most two-phase geothermal fields have associated nonboiling lateral flows away from the boiling upflow region. If the natural flow is horizontal or turns downward, boiling ceases and liquid reservoir conditions are encountered.

Thus, the BPD profile may be applicable only in the upflow region of this type of reservoir. The lateral outflows from this region will be liquid water (although there will usually be some shallow boiling in places along the top of the outflow tongue). Exploration wells will be expected to encounter different regimes within the reservoir, depending on their location. In the upflow region, boiling conditions should be expected, and in outflow regions, high-temperature liquid conditions with temperature inversions (declining temperatures with depth) can be expected. Usually the outflow region of a field is initially explored, and with further drilling, the flow is traced toward the high-temperature source area. For example, at Ahuachapan, El Tatio, Wairakei, Yangbajan, and Tiwi, the outflow region was initially investigated. Some examples follow.

Tongonan

The Tongonan field is located on the island of Leyte in the Philippines. It is a large field with an installed capacity of 703 MW in the greater Tongonan area, which includes the adjacent Mahanagdong field. An overview of the development history is given by Gonzalez and colleagues (2005). Figure 2.4 shows a conceptual cross section.

Tongonan is a liquid-dominated field with a base temperature of over 320°C and chloride content of up to 11,000 ppm. Before development, steam-heated

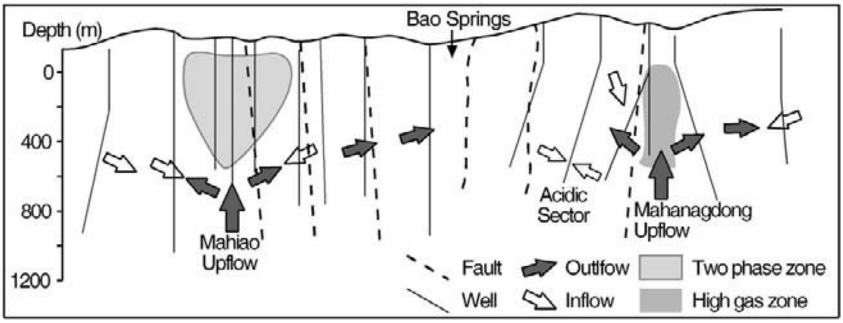

FIGURE 2.4 Conceptual model of Greater Tongonan. *Source: Seastres et al., 1996. © Geothermal Resources Council*

waters existed near the surface. The Tongonan upflow rises under Mahiao toward one end of the reservoir. Here, steam and water rise, creating a limited region of two-phase conditions in the natural state. Water flowed laterally away from the upflow area to ultimately discharge at the Bao Springs and possibly elsewhere. This combination of upflow and horizontal outflow is very common. The surface activity in a field of this type is a guide to reservoir fluid distribution. The principal springs are at Bao, but the highest temperatures are beneath the steam-heated activity at Mahiao, and it is such steam-heated activity that indicates the area of upflow. There is an impermeable region separating Tongonan proper from the separate upflow at Mahanagdong. Under production, large pressure drawdown has occurred in the Tongonan area, and the upper part of the reservoir here has become vapor dominated.

Dixie Valley

Dixie Valley is a high-temperature field in the Basin and Range province of the western part of the United States. As is typical of many Basin and Range fields, it is associated with permeability developed along a fault zone that provides the primary source of deep recharge. The reservoir is on the fault zone rather than an outflow from it. Figure 2.5 shows a cross section through Dixie Valley. The reservoir is a region around the fault zone.

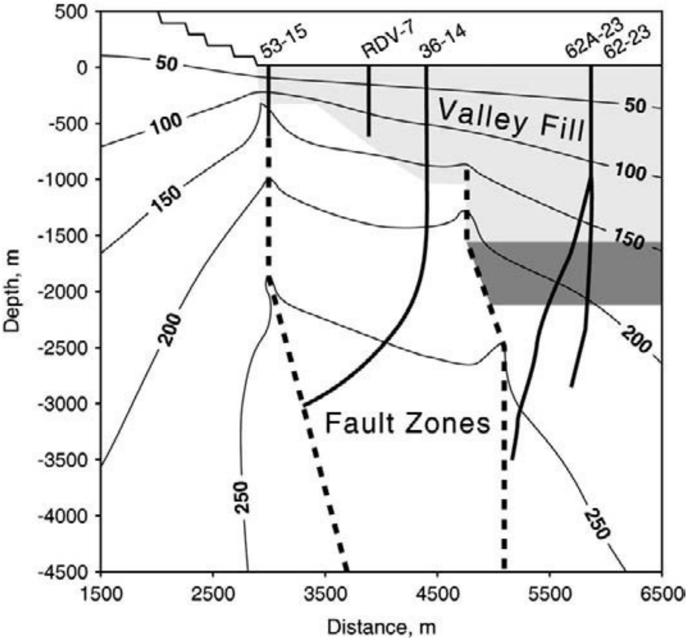

FIGURE 2.5 Dixie Valley thermal cross section. *Source: Blackwell et al., 2000. © Geothermal Resources Council*

2.3.6. Inferences from Pressure Distribution

The discussion of systems with outflow introduced the effects of permeability contrasts on the pattern of the natural flow. The presence or absence of permeable or impermeable features is of great importance in assessing the possible effects of exploitation. The temperature profiles measured in exploration wells, together with geological information, provide a guide to the permeability structure of the reservoir, but pressure distribution (when this is available) gives more definite and direct information about how different parts of the reservoir are interconnected. Often there is little or no information about reservoir pressures above the casing depths during the early stages of field development. Such information is vital to predicting the response of the reservoir to development, and in particular to evaluating the potential interconnection between the high-temperature resource and surrounding cool aquifers. Stage testing of exploratory wells, or drilling specific wells to gain this information once the deeper reservoir has been identified, can provide this essential data.

In petroleum or groundwater resources, a pressure difference between two reservoirs or aquifers at different depths that is significantly different from hydrostatic normally implies that the two reservoirs are not connected by permeable structures. This inference is not always valid for geothermal reservoirs and can be difficult to evaluate due to the variation of the vertical pressure gradient with temperature. Because the natural state of a geothermal reservoir is dynamic, its pressure distribution is as well, and pressure differentials may be caused by the natural flow, the temperature difference, or some combination of these factors.

Figure 2.6 illustrates the natural state (predevelopment) pressure distribution with depth in three New Zealand fields. The depth is measured from the highest surface elevation of discharge of chloride water. At Wairakei and Kawerau, the pressure profile is smooth and extrapolates to atmospheric at surface. No large-scale surface confining layer is apparent. Pressures deep in the reservoir are overpressured compared to surface (for a hydrostatic column allowing for temperature). This overpressure is caused by the natural upflow through the reservoir, not by any confining bed. Because of the coarse nature of the data, this conclusion is only valid on the large scale. With more details, the effects of lower-permeability capping structures can be observed.

Data from Ngawha illustrate a truly confined geothermal field, with only a very small flow of liquid from the reservoir to the surface; a larger flux of gas seeps through the confining formations. Beneath the caprock, production is found in fractured greywacke, and within this reservoir, pressure gradients are near hydrostatic for the reservoir temperature, 225–230°C. The reservoir is overpressured with respect to ground surface. In this case the overpressure is due to the confining layer rather than the dynamic pressure gradient due to vertical flow.

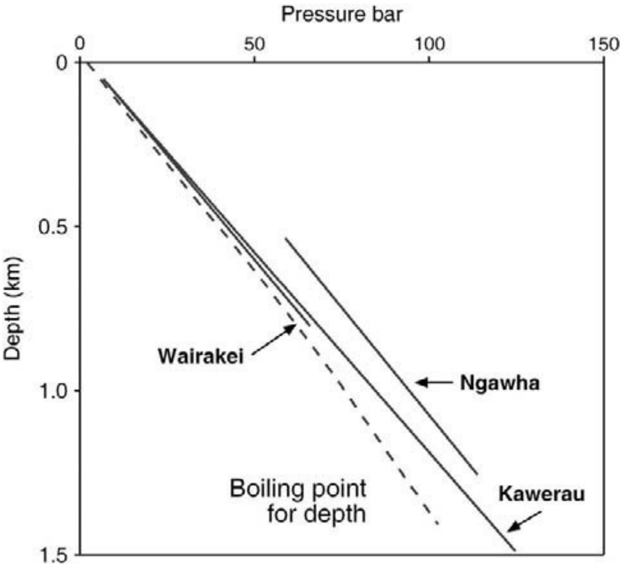

FIGURE 2.6 Pressure distribution with depth in three New Zealand geothermal fields. *Source: Grant 1981.*

2.3.7. Summary

In its natural state the basic components of the geothermal *system*, of which the reservoir is the hot, exploitable part, are: (1) an aquifer or fracture network containing hot fluid, (2) a path through which cold water can flow to recharge the *system* or an input of magmatic fluid, and (3) a source of heat. In the finer details of the *reservoir,* there is often also a reduced permeability zone or cap, or at least a partial aquiclude over the aquifer or channel network (that comprise the *reservoir*), but these elements are not essential. The hot recharge into the geothermal system is perhaps the main feature, apart from the difference in energy that distinguishes this system from its groundwater counterpart. The pressure drive that sustains the hot recharge or upflow is the buoyancy difference between the columns of descending cold and ascending hot water. This difference may be modified by topographic effects. In their natural—predevelopment—state, high-temperature liquid-dominated reservoirs must be considered as a dynamic body before any downhole measurement can be properly evaluated or interpreted.

2.4. CONVECTIVE SYSTEMS: VAPOR DOMINATED

In all the systems discussed so far, the dominant fluid has been water and the pressure distribution approximately that of a static body of water. It has also been implied that fluid can move relatively freely into, through, and out of the system.

This contrasts with vapor-dominated systems and the associated reservoir. In its natural undeveloped state, a vapor-dominated reservoir appears to contain a static column of steam, and any associated surface thermal activity consists of steam or steam-heated water with little chloride content. Four such fields are presently known to exist: The Geysers, the world's largest field by production; Lardarello; Kamojang; and Darajat. (Other hybrid fields are discussed in Chapter 12.) In liquid-dominated reservoirs, vapor-dominated zones of limited thickness are sometimes found, and in several cases, extensive vapor-dominated zones have been formed in response to exploitation—for example, Wairakei, Awibengkok, Miravalles, Ahuachapan, and Tongonan.

The natural vapor-dominated reservoir was first reported by Ramey (1970), who described a reservoir containing steam, with pressure close to steam-static and temperatures near saturation. Figure 2.7 shows pressure profiles as determined in the early period of exploration at Kamojang and Darajat, The Geysers, and Travale. Profiles have been constructed for various sections of Larderello (Celati et al., 1978) showing a mixture of vapor-dominated zones at varying pressures and liquid-dominated zones.

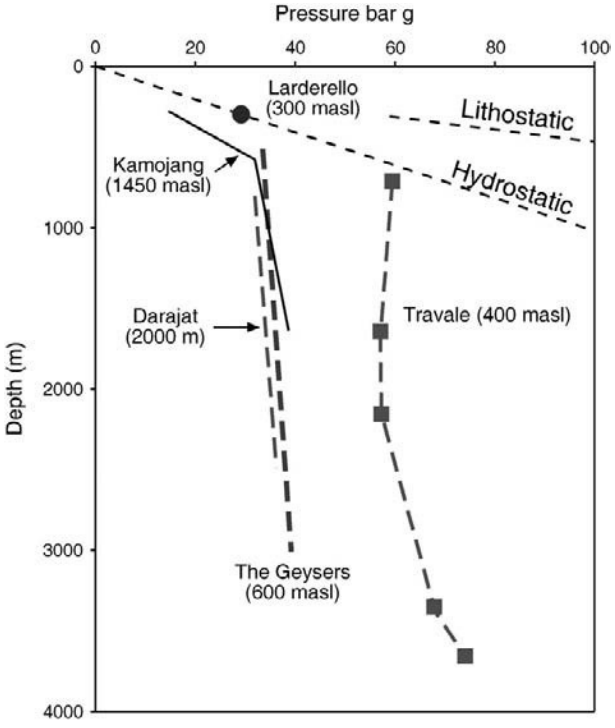

FIGURE 2.7 Reservoir pressure in vapor-dominated systems (Travale is part of greater Larderello). *Source: Allis, 2000.*

In a vapor-dominated reservoir the pressure increases only slowly with depth, implying that a low-permeability boundary exists around the sides of the reservoir, isolating the relatively low pressures inside the reservoir from regions outside the reservoir, where pressures near hydrostatic are expected (see Figure 2.7). Similarly, there must generally be poor permeability above the reservoir except in the limited areas where natural discharges occur.

2.4.1. The Conceptualized Fluid Flow System

Over the years, several models of vapor-dominated systems have been proposed. Early models proposed either a dry steam chamber or a steam zone overlying boiling water. It is now known that in the natural state, the vapor-dominated reservoir contains significant amounts of liquid water held in the rock pores. At both Larderello and The Geysers, reservoir conditions were initially those of saturated steam. Simple volumetric analysis has shown that much more steam has been produced from these fields than could be stored as steam alone. Therefore, the additional steam must have originally been stored as (immobile) liquid.

A qualitative description of the physical processes leading to the development of a vapor-dominated reservoir was first given by White and colleagues (1971) and later refined by D'Amore and Truesdell (1979). In the initial phase of development, there is a natural upflow of steam and gas from a deep boiling zone. The steam spreads laterally through the reservoir, and as it spreads, heat is lost through the caprock, and some of the steam condenses, absorbing some of the gas. This condensate migrates down through the reservoir under gravity, wetting the matrix rock and increasing the permeability by dissolving some of the rock minerals. The steam condensation results in changes in the steam chemistry with distance from the upflow zone. Liquid-mobile species present in the steam are removed with condensate, and vapor-mobile species are concentrated in the remaining steam. This model provides a good fit to the variation in steam chemistry at Larderello and The Geysers.

In a steam-dominated reservoir, the counterflow system of steam moving up and water moving down controls the fluid distribution. If the mass fluxes of steam (up) and water (down) are roughly similar, and the vertical pressure gradient is near steam-static, the relative permeability to water must be low. The flowing steam occupies most of the fracture space, and water occupies the remaining pore space. The reservoir has a saturation such that water is just mobile—that is, just above residual saturation (see Chapter 3). This implies that the mass of water in the reservoir is much greater than the mass of steam. To obtain the best match to the measured response, reservoir simulation of The Geysers requires application of dual porosity models, with liquid saturation in the matrix typically as much as 85% (see Chapter 12). Deeper drilling in Larderello and part of The Geysers has found superheated regions at over 300°C, rather than the hypothesized deep liquid (Bertani et al., 2005; Walters et al., 1991), so the water-steam counterflow may describe only the upper part of the field.

D'Amore and Truesdell also observe that the downflowing water, being acidic condensate, is chemically reactive and will in time erode the rock through which it flows. This may help to explain the high permeabilities typically found in vapor-dominated reservoirs despite the poor permeability found in cooler rock outside the steam reservoir.

Studies of the reservoir mineralogy indicates that all of the four vapor-dominated fields were at one time liquid dominated (Allis, 2000) and have somehow "boiled dry" to produce their current state. The model of Larderello-Travale (Barelli et al., 2010b) simulates this process from an initial state when the rock was filled with cold water. Thus, D'Amore and Truesdell's model represents the present state of the reservoir but not how it was created.

2.5. CONCEPTS OF CHANGES UNDER EXPLOITATION

Exploitation of a geothermal reservoir means that heat and (almost always) mass are withdrawn, and some fraction of this may be reinjected. Additional recharge fluid, hot or cold, may flow into the reservoir. Some conceptual models of reservoirs under exploitation describing the changes in distribution of heat and mass throughout the reservoir and its surroundings are described in the following sections.

2.5.1. Flow of Liquid

The simplest concept of the flow of geothermal fluid in the reservoir is the analogy of the flow of liquid water in a confined aquifer. If the reservoir is at a fairly uniform temperature, the flow is isothermal. If there is a distribution of temperature or if there is reinjection of cooled fluids, it is necessary to compute the motion of thermal changes along streamlines. Figure 2.8 illustrates such a flow.

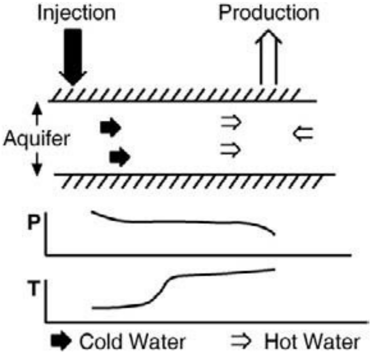

FIGURE 2.8 Flow of liquid in an exploited liquid reservoir.

Distinctive geothermal features are introduced if the reservoir is not a confined aquifer of a conductively heated system, but is part of an active geothermal field. The reservoir may have homogeneous permeability and great thickness, such as those found in the Imperial and Mexicali Valleys in North America. More usually in fractured rock, little is known about the reservoir thickness except that it is probably large. In addition, the fact that the reservoir is part of an active hydrological system makes it more likely that fluid recharge will occur from other parts of the system.

The great thickness of the reservoir causes few conceptual problems. It means that reservoir modeling must describe three-dimensional rather than two-dimensional flow, but transmission of pressure and thermal changes is conceptually the same. One possible complication is that the reservoir may be unconfined rather than confined, with a free surface above the zone of withdrawal. With the possible entry of surface groundwaters, or with reinjection of cooled fluids, the efficiency of thermal sweep through the reservoir becomes important. This is particularly true of a fractured reservoir, where there may be preferential flow along a few paths of high permeability.

In this liquid model, if there is a net mass loss of fluid in the reservoir, there will be a resultant decline in pressure. If the reservoir contains compressed liquid, this pressure decline causes expansion of water and the rock matrix; if there is a free surface, then there is a fall in this surface. Rocks cooled by the advance of colder water account for the net heat loss.

2.5.2. Liquid-Dominated Reservoirs with Boiling

In high-temperature geothermal reservoirs, a decline in pressure caused by exploitation may initiate boiling in part or all of the reservoir. In this case the changes in the reservoir caused by exploitation will include changes in the steam/water ratio, as well as pressure and temperature changes.

One concept is to regard the reservoir as uniformly mixed, containing steam and water throughout—the simplest two-phase lumped parameter model. A second is to assume that water drains from the upper parts of the reservoir, forming a “steam cap”—a vapor-dominated zone overlying a liquid-dominated zone. The first approach ignores gravity; the second assumes gravity is dominant. Both assume steam and water in thermal equilibrium. Figure 2.9 shows the drainage model of the formation of a steam cap. In its initial state there was a near-hydrostatic pressure profile. With production, pressure in the reservoir falls, and above the level of production the vertical gradient is less than hydrostatic. Water will now drain downward. As the water drains, liquid saturation decreases and steam becomes more mobile. Steam then drains upward. Where there is appropriate vertical permeability, the two phases, steam and water, segregate with time. In the upper part of the underlying liquid-dominated region, boiling occurs as the pressure declines, and steam is formed. This steam also drains upward. With time, there is usually sufficient

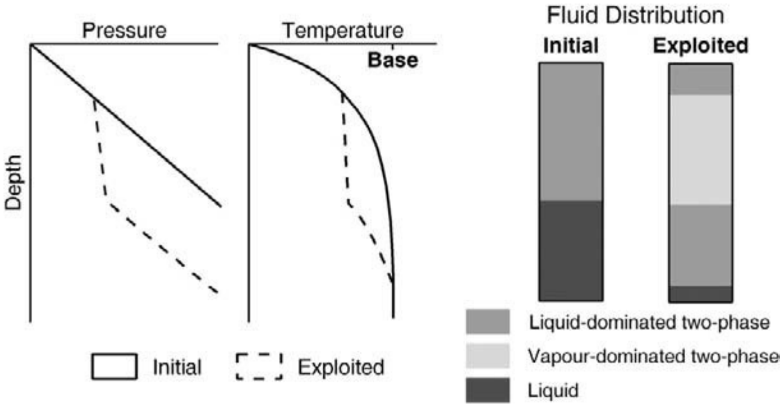

FIGURE 2.9 Fluid distribution in natural and exploited states of a liquid-dominated reservoir.

segregation that nearly all mobile water drains out of the top of the reservoir, and a distinct vapor-dominated region forms at the top—a *steam cap*. The top of the steam cap is normally defined by a capping stratum, a layer of lower permeability. Note that thermal equilibrium between steam and water is required throughout the two-phase zones, but compressed liquid remains at the bottom of the reservoir.

The assumption that the boiling fluid will segregate into vapor-dominated and liquid-dominated zones depends on the vertical permeability and the vertical extent of boiling conditions. High vertical permeability and a small temperature range of boiling conditions are expected to give more rapid segregation of the liquid and steam phases.

In addition to the boiling effects, there are likely to be a lateral or vertical inflow of hot or cold water, together with associated thermal and chemical changes. Under production conditions, the net mass loss from the boiling reservoir is a result of the replacement of liquid by steam and possibly a fall of a free surface on the groundwater above if that groundwater is connected to pressures in the deeper liquid reservoir. The net heat loss of the reservoir is the cooling of the rock as a result of water boiling and the advance of peripheral cooler waters.

2.5.3. Vapor-Dominated Reservoirs

The essential components of a vapor-dominated reservoir are the stored steam and immobile (or nearly immobile) water, the heat stored in the rock, an overlying condensate layer, and a possible deep zone of boiling brine. The boundaries of the reservoir, at the sides and top, must have poor or very poor permeability to prevent the reservoir from being flooded with water. Some boundaries are effectively impermeable; others have low permeability,

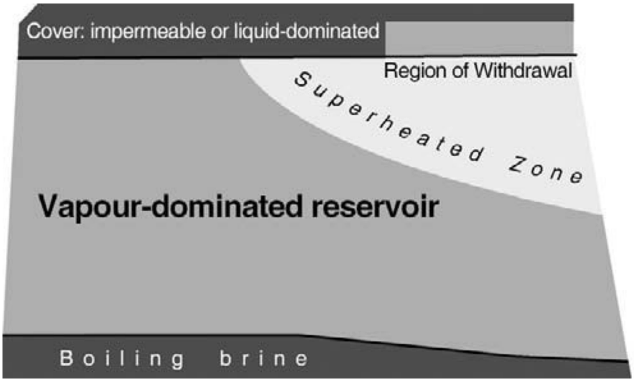

FIGURE 2.10 Fluid distribution in a vapor-dominated reservoir under production.

allowing some communication with liquid-dominated regions above or beside the reservoir. Under exploitation, the immobile water is gradually evaporated (using the heat stored in the rock), and the vapor-dominated reservoir becomes depleted of water, eventually forming a dry (superheated) zone, as shown in Figure 2.10. As production continues, the superheated zone around the area of exploitation expands into the (saturated) vapor-dominated region. There may be a recharge of steam from the deep boiling zone if one exists and possibly also from the condensate layer. The net heat and mass loss are as for the previous case.

2.6. CONCLUSIONS

In this chapter, the first analyses of reservoir information have been presented, dealing with reservoirs in their undisturbed state. The information obtained at this stage is limited but important to collect and evaluate, as it often cannot be obtained once exploitation is underway. In high-temperature convective systems, the flows stimulated by exploitation may overwhelm the original natural flows. These natural flows, continuing for tens or hundreds of thousands of years, have established the heat and fluid reserves available to be exploited.

In simple terms, it is the vertical movement of hot fluid up and through the various types of geothermal systems that established the geothermal reservoirs. To the geothermal developer, the system as a whole and the source of the heat energy are probably of little relevance. It is the flow and the way in which it relates to the reservoir's hydrogeologic structure that set the form for the reservoir. The preceding discussion concentrated on the role and form of these flows in the two main types of high-temperature geothermal reservoirs: liquid dominated (both liquid and two-phase) and vapor dominated.

For both types of reservoirs, simple conceptual models have been described that can be useful in both developing an understanding of these reservoirs and estimating some of their vital field parameters. An understanding of these basic possible models provides a starting point to appreciate more complex real systems.

The discussion in this chapter has been in general terms. In later chapters there is more focus on specific issues. Consequently analyses will be more detailed and take into account a wider range of data. Physical and structural information should not be the only items considered when conceptualizing a reservoir. All the data are relevant, and it is essential to bring together information from many disciplines to build the most robust conceptual models.