# Reservoir Simulation of Balçova Geothermal Field

**By**

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# ABSTRACT

This study investigates the geothermal reservoir of Balçova geothermal field using the program Fluent which is written for general problems of fluid flow and heat transfer in a given complex geometry.

Geothermal reservoir simulation of Balçova geothermal field is made by Istanbul Technical University, Department of Petroleum and Natural Gas Engineering using the program Though2 which is written for geothermal reservoir application in 2001. The results of this study become a starting point of this thesis. Besides, the new techniques applied the geothermal field since that period, and reinjection of the geothermal fluid by the well BD-8 to the reservoir, made it necessary to remodel of the field.

During the modeling study, the conceptual model of the field is developed based on technical data and advices by the Balçova Geothermal Ltd. The fault Agamemnon-I existing in the field is thought the dominated fault of the reservoir and assumed that the heated water from the aquifer is raised to the surface using that fault as a flow path.

The geometry of the conceptual model of the reservoir is drawn and meshed properly using Gambit meshing program and meshed reservoir is exported and run in Fluent program under given boundary conditions and after that 3-D temperature distribution of the reservoir is obtained.

# ÖZ

Bu çalışmada, genel akışkan ve ısı transferi problemleri için yazılmış Fluent programı kullanılarak Balçova jeotermal sahasının rezervuar simülasyonu incelenmektedir.

2001 yılında bu çalışmaya benzer olarak İstanbul Teknik Üniversitesi, Petrol ve Doğal Gaz Mühendisliği Bölümü, Balçova jeotermal sahasının rezervuar simülasyonunu, jeotermal rezervuar uygulamaları için yazılmış Though2 programını kullanarak yapmıştır.

Yukarıda adı geçen çalışmanın sonuçları bu tez için bir başlangıç noktası olmuştur. Ayrıca, o zaman ki tarihten günümüze kadar sahada uygulanan yeni teknikler ki bunlardan en önce geleni BD-8 kuyusundan rezervuara reenjeksiyon yapılması, sahanın yeniden modellenmesini gerekli kılmıştır.

Modelleme çalışması sırasında ilk aşamada, Balçova jeotermal ltd. şirketinden alınan teknik veriler ve öneriler temel alınarak sahanın kavramsal modeli geliştirilmiş, bu kavramsal modelden de sahada bulunan Agamemnon-I fayının baskın fay olduğu ve derinlerden gelen sıcak suyun bu fayı kullanarak yüzeye doğru yükseldiği varsayılmıştır.

Kavramsal modelin geometrisi Gambit mesh programı kullanılarak çizilmiş ve meshlenmiş ve meshlenmiş rezervuar Fluent programına aktarılıp burada verilen sınır şartları altında çalıştırılmış ve sonuçta rezervuarın 3-boyutlu sıcaklık dağılımı çıkarılmıştır.

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# NOMENCLATURE

B = water recharge constant

$C_{vr}$ = specific heat at constant volume of reservoir rock and contained fluids (kj/kgK)

E = internal energy (kJ)

g = acceleration of gravity (m/s$^2$)

$H_s(H_w)$ = enthalpy of saturated steam (water) (kJ)

$H_r$ = rock enthalpy (kJ)

Hp = enthalpy of produced fluids (kJ)

K = thermal conductivity (W/mK)

k = absolute permeability (mD)

$k_{rs}(k_{rw})$ = relative permeability to steam (water) (mD)

$m_g$ = mass of steam (kg)

$\Delta m_g$ = mass of steam produced during a depletion step (kg)

$\rho_s(\rho_w)$ = steam (water) density (kg/m$^3$)

$\rho_r$ = average rock-grain density (kg/m$^3$)

$\rho_r$ = density of rock and contained fluids (kg/m$^3$)

$\mu_s(\mu_w)$ = steam (water) viscosity (N.s/m$^2$)

p = pressure (Pa)

P = reservoir pressure (Pa)

$p_n$ = pressure drop at any time n (Pa)

$Q_D$ $(t_D)$ = dimensionless cumulative recharge, corresponding to dimensionless time, $t_D$ (kJ)

q = mass (source) production rate (W/m$^2$)

$q_{HL}$ = heat loss rate (W/m$^2$)

$q_H$ = enthalpy production rate (W/m$^2$)

$S_s(S_w)$ = steam (water) saturation

T = temperature (°C)

W = initial mass of hot water and steam in reservoir bulk volume, V (kg)

Q = conductive heat loss (kJ)

$\Phi$ = porosity of rock matrix

X = steam quality

# CHAPTER 1

## INTRODUCTION

### 1.1 Introduction to Geothermal Energy

Geothermal energy derived from the heat in the interior of the earth. Since the depths of the earth are very hot due to continuous decay of the long-lived radioactive isotopes, heat from deep regions flows outward toward the surface.

Steadily outward heat flow is permanently lost from the surface by radiation into space. However owing to the nature, by means of several geologic processes occurred, and this earth's heat concentrated in discrete regions surrounding by impermeable rock namely cap rock below the surface and called "geothermal reservoir."

The reservoir is not void space or a cavity below the surface, instead has fractures and porous, and geothermal fluid stored in porous medium in rocks and by interconnection of fractures made a path for heated water to the cooler places near the surface.

The main properties of a geothermal reservoir are porosity and permeability. The porosity of a reservoir rock is used to assess the volume of fluids stored in a reservoir and permeability controls flow rate of the produced fluid. [1]

In Turkey, most of the geothermal reservoirs consist of fracture zones, which occur often as a result of recent tectonic activities. [2]

Deeply-penetrating meteoric waters sweep some heat from the deeper part of the fracture zone and then, due its low gravity, the heated fluids ascend within a segment of the fracture zone. [2]

At that point, it is worth to describe some other definition related with geothermal reservoir,

*Geothermal Field* usually indicates an area of geothermal activity at the earth's surface. In cases without any surface indications, this term can be used to define the surface area corresponding to the geothermal reservoir at depth below.[2]

*Geothermal System* refers to all parts of hydrological system involved, including the recharge and discharge zone, all subsurface parts and outflow of the system. In other words, the whole volume of rocks in which fluids move both inside and outside reservoir, together with the heat source and the natural discharge, constitute a geothermal system. In some reservoirs, natural recharge may be induced by exploitation; in other ones, recharge can be provided artificially by injection of cold water. Figure 1.1 shows a schematic of a geothermal system.[2]
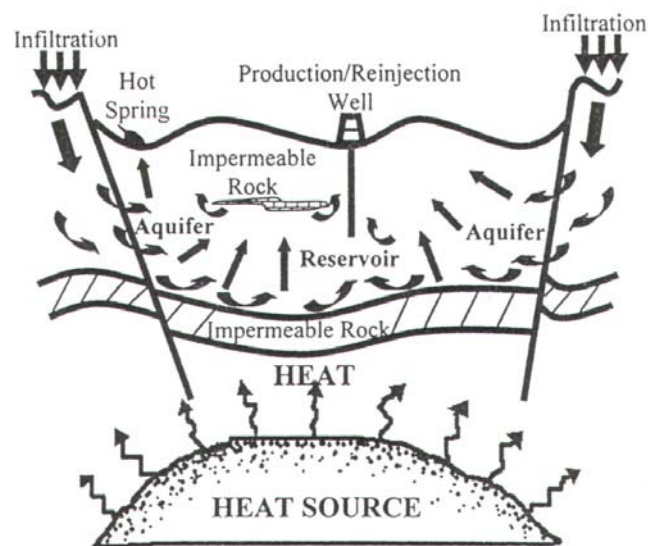


**Figure 1.1** Schematic of a geothermal system.

*Aquifer* is an underground bed or layer yielding ground water in sufficient quantity as a source supply. Some cases geothermal reservoirs are bounded by aquifers. In response to the production, the reservoir pressure drops and aquifer reacting in the way of retarding pressure decline by natural recharge.

*The geothermal gradient* expresses the increase in temperature with depth in the Earth's crust. Roughly in typical continental crust, temperatures will increase by $\approx 3$ ° C for every 100m depth. The ratio of temperature increase $\Delta T$ to vertical depth interval $\Delta Z$ over which it occurs is called "temperature gradient" and is written $gradT = \Delta T / \Delta Z \approx$ 3/100 ° C/m =0.03 ° C/m is an average temperature geothermal gradient in continental crust.

Figure 1.2 shows the relation between the temperature within the earth and depth in the crust of the earth.[1]
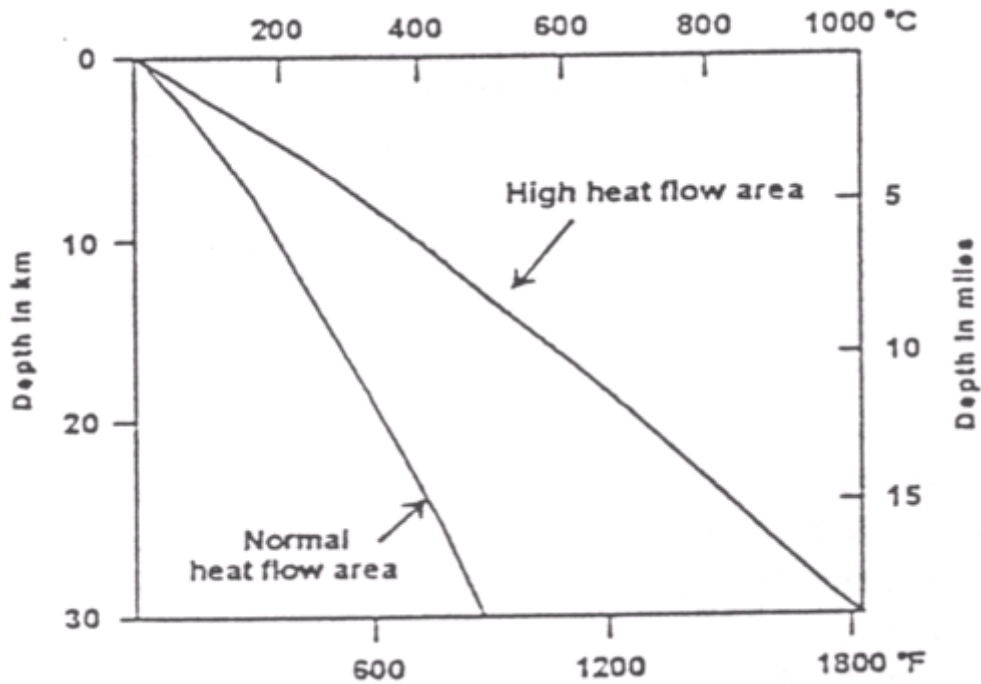


**Figure 1.2** Temperature versus depth in the crust of the earth.

When only average geothermal gradients prevail, one needs to go down to about 6 km depth to reach a temperature of 200 º C. However owing to the nature this value can be enhanced locally or regionally due to special geologic conditions, where the earth's crust is unusually thin, or where hot molten rock has risen to shallower depths, forming magma chambers.[3]

From Fourier's law of heat conduction with an assumption of $k \approx 2$ W/m C º for thermal conductivity which is a typical value for rocks we obtain a typical continental heat flux,

$$q \approx -2 \times 0.03 = 0.06 \text{ W/ m}^2$$

Over an area of 1 km$^2$ ($10^6$ m$^2$), the typical crustal heat flow rate would be $6 \times 10^4$ W, or 60 kW which a small amount compared to heat extraction rates of typically tens to hundreds of megawatts in producing geothermal fields.

Reason for that is heat conduction not the only mechanism of heat transfer in a geothermal field. Due to the deep fluid circulation of hot fluids (liquids and gases) through porous and permeable rocks in a given geothermal region convective mode of heat transfer is developed and convective heat transfer may occur at much larger rates than accomplished by heat conduction.

**1.1.1 Types of Geothermal Systems**

Geothermal systems can be found in regions with a normal or slightly above normal geothermal gradient, and especially in regions around plate margins where the geothermal may be significantly higher than the average value [4].

Geothermal energy is primarily stored in rocks. The mineral waters which are contained in porous rocks and in cracks, fractures and faults provide the necessary medium for the transfer of the heat from the rocks to the surface [5]

Geothermal systems can be divided into five groups as following: [5]

1. Hydrothermal convection systems related to young igneous intrusions,

2. Fault-controlled systems,

3. Radiogenic heat sources,

4. Geopressured geothermal reservoirs,

5. Deep regional aquifers.

Below some of the most common geothermal reservoirs are illustrated in Figures 1.3, 1.4, and 1.5
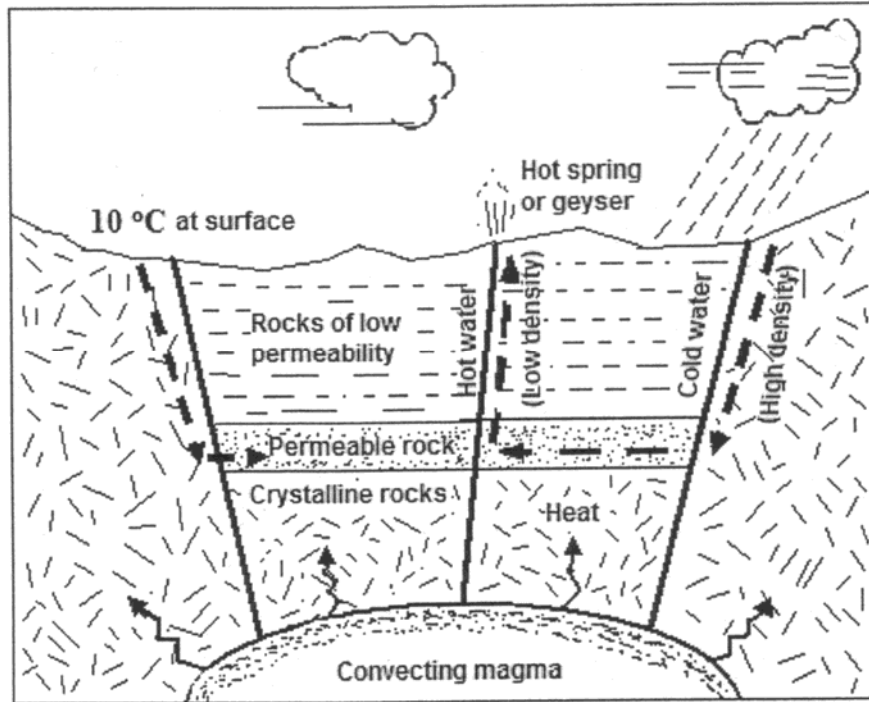
**Figure 1.3** Schematic model of a hydrothermal convection system driven by an underlying young igneous intrusion
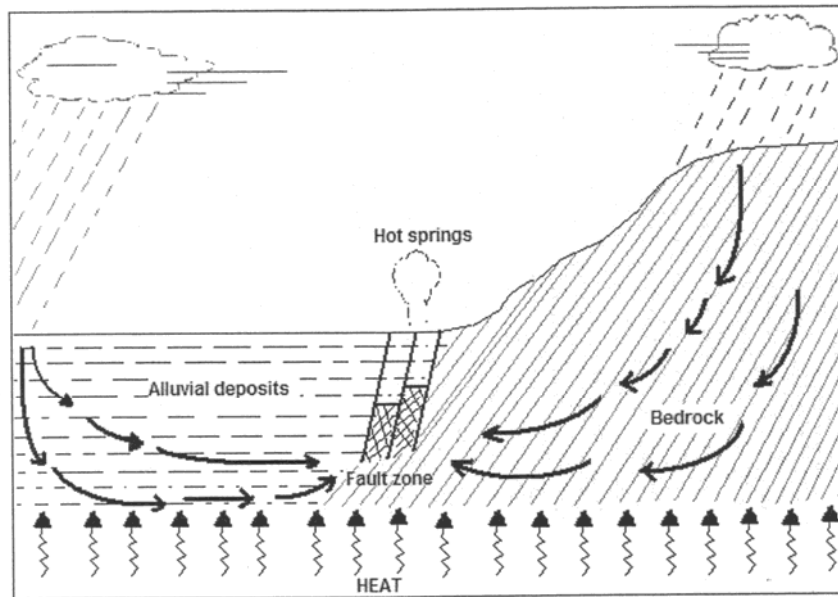


**Figure1.4** Schematic model of a hydrothermal convection system (fault-controlled) related to deep circulation of meteoric water without the influence of young igneous intrusions.
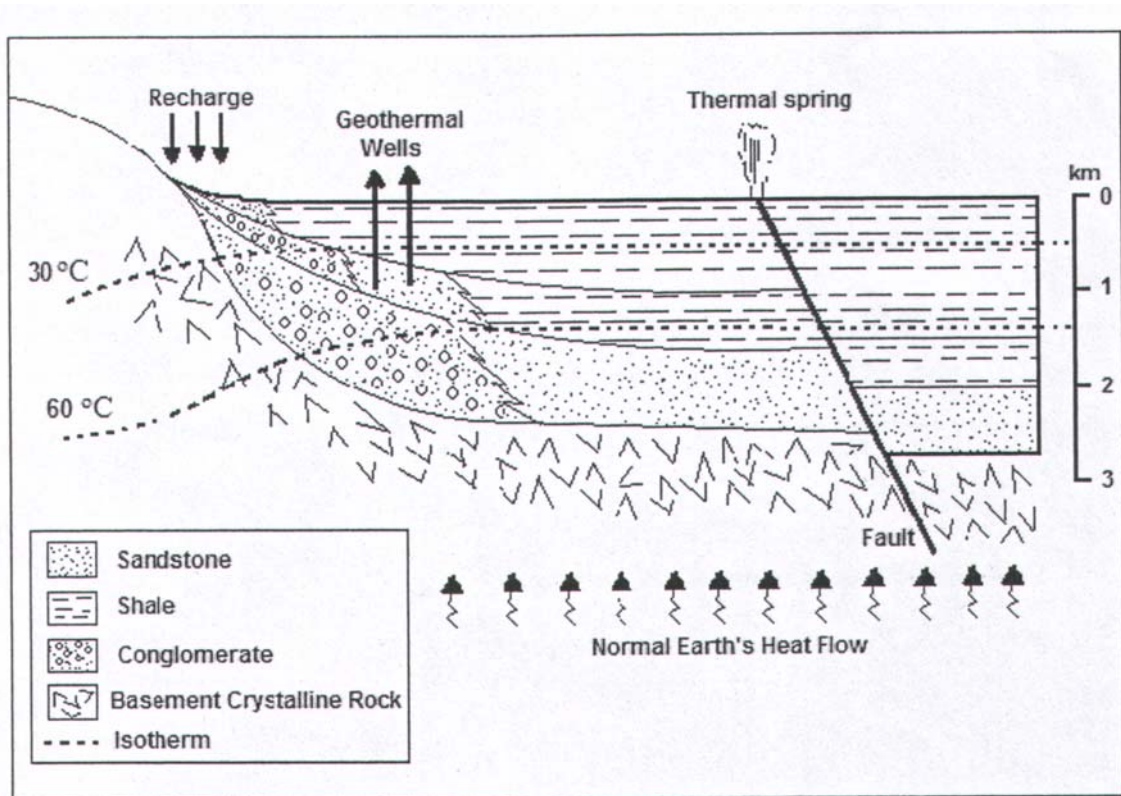
**Figure 1.5** Schematic model of a geothermal reservoir in a deep regional aquifer

## 1.2 Definition and Characteristics of Geothermal Reservoirs

The term reservoir can be defined as a natural underground container of fluids such as geothermal waters or steam at a useful temperature. All geothermal reservoirs commonly have three components [3]:

1. An anomalous concentration of heat (i.e. a heat source)

2. Fluid which transport the heat from the rock to the surface

3. Permeability in the rock sufficient to form a plumbing system through which the water can circulate

### 1.2.1 Heat Sources

In geothermal areas, higher rock and groundwater temperatures are found at shallower depths than is normal. This condition usually results from one or more of the following mechanisms [3]:

1. Intrusion of molten rock (magma) from great depth to high levels in the earth's crust, bringing up great quantities of heat

2. High surface heat flow, perhaps due to thin crust, with an attendant high temperature gradient with depth

3. Ascent of groundwater that has circulated to depths of 1 to 3 miles and has been heated in the normal or enhanced geothermal gradient

4. Thermal blanketing or insulation of deeper rocks by thick formations of such rocks as shale whose thermal conductivity is low

5. Anomalous heating of shallow rock by decay of radioactive elements, perhaps augmented by thermal blanketing

Most high-temperature geothermal reservoirs, usually used for electrical power generation, appear to be caused by the first mechanism, while many isolated low- and moderate-temperature reservoirs appear to result from the second, third and fourth mechanisms, sometimes working together. [3]

### 1.2.2 Geothermal Fluids

In computer modeling geothermal reservoir assuming the fluid as pure water a common approach among scientists. Water naturally is seen as an ideal heat transfer fluid due to its high heat capacity and its capability to pervade pores and fractures in rocks, for that reasons the water brings large quantities of heat to the surface.

The density and viscosity of water decrease with increasing temperatures. Since the density getting lighter as temperature goes up, heated water founded at depth below the surface is lighter than cold water in surroundings rocks. Therefore heated water

subjected to buoyant forces goes up towards the surface at the time it overcomes the flow resistance of the rocks and as it goes up cooler water from the surroundings replace it, by that way deep natural fluid circulation of water occurred. And this naturally occurred water circulation is responsible bringing large quantities of heat within the reach of wells, and make feasible the most widely observed class of geothermal reservoir, called geothermal reservoirs.

In some convective hydrothermal reservoirs governed by the pressure of the fluid, temperature of the water can reach the boiling point and steam is generated. By this way, steam convection currents are set up.

### 1.2.3   Permeability

Permeability is a measure of a rock's capacity to transmit fluid as a result of pressure differences. The flow takes place in pores between mineral grains and in open spaces created by fractures and faults. [3]

Porosity is the term given to the fraction of void space in a volume of rock. Interconnected porosity provides flow paths for the fluids and creates permeability, although there is no simple relationship between porosity and permeability.

Most geothermal systems are structurally controlled (ie. the magmatic heat source has been emplaced along zones of structural weakness in the crust). Permeability may be increased around an intrusion from fracturing and faulting in response to stresses involved in the intrusion process itself and in response to regional stresses. [3]

### 1.3 Classification of Geothermal Reservoirs

Geothermal reservoirs can be classified as which mode of heat transfer encountered in the geothermal system is dominant as shown below,

Conductive Reservoirs

- Geopressured Hydrothermal Reservoirs
- Hot Dry Rock Reservoirs

Convective Hydrothermal Reservoirs

- Vapor dominated
- Hot-water dominated

Although each one of these reservoirs has potential for exploitation, the vapor-dominated system offers the optimum conditions for electricity production. [6]

Based on present knowledge, there are some requirements that have to be met for electricity generation from geothermal steam; however these requirements are not easily meet in the earth's crust:[7]

1. temperature of the reservoir should be high (at least 180 ºC, and preferably above 200 ºC)

2. reservoir depth must be less than 3 km

3. reservoir volume must be adequate

4. the reservoir should contain natural fluids for transferring the heat to surface and power plants

5. permeability of the formation should be adequate to ensure sustained delivery of fluids to wells at high enough rates to meet power production needs

6. there must be no major unsolved technology problems.

## 1.3.1   Conductive Reservoirs:

The conduction-dominated reservoirs are those where the thermal waters do not convect, or the heat transfer is dominated by conduction. It is typical for sedimentary basins, those that contain petroleum as well as those that do not, to contain porous and permeable rock units such as sandstones and limestones that hold water. [3]

Low-temperature geothermal reservoirs of the conduction-dominated type are known to occur in sedimentary basins and beneath coastal sedimentary rocks. Figure 1.6 shows a simple model of recharge in carbonate rock in a basin.[3]
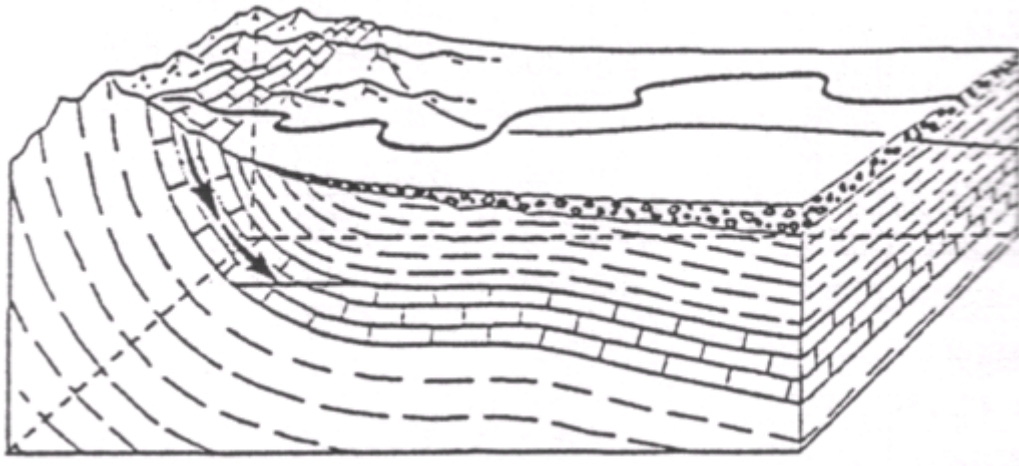


**Figure 1.6** Sedimentary basin model for a low-or intermediate-temperature conduction dominated reservoirs.

Figure 1.7 illustrates a radiogenic reservoir, also called the "coastal plains" reservoir type. In places beneath these sediments, rocks occur that have an anomalously high rate of heat production because of decay of natural radioactive isotopes of uranium, thorium and potassium. These naturally radioactive rocks are old granite intrusions, long since cooled. The heat generated by radio-active decay is trapped by the insulating sediments, and temperatures are much higher in the intrusive rocks than would ordinarily be the case. [3]
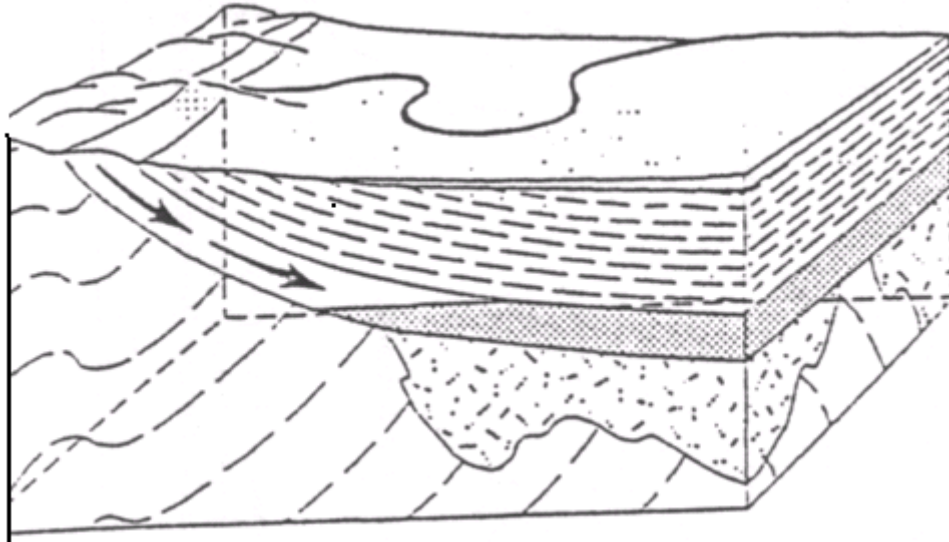
**Figure 1.7** Radiogenic-heat or coastal-plain model of a conduction-dominated reservoir.

## 1.3.1.1 Geopressured Hydrothermal Reservoirs:

Geopressured geothermal reservoirs are closely analogous to geopressured oil and gas reservoirs. Because the reservoirs found are associated with petroleum, the water is generally saturated with methane. Their structure –homogoneus permeability confined by impermeable boundaries- is similar to that of petroleum reservoirs, and such reservoirs are generally fairly deep (over 2 km). In their reservoir engineering aspects they are perhaps more like petroleum reservoirs than true geothermal reservoirs.

Geopressured reservoirs are composed of rocks that contain fluids at pressures far greater than normal (hydrostatic) pressure. These reservoirs have a highly impermeable overlying formation that prevents the migration of fluids out of the zone and, thus, causes the fluids saturating this zone to partially bear the overburden load. This results in an increase in the fluid pressure. [6]

## 1.3.1.2 Hot Dry Rock Reservoirs

In contrast with all other reservoirs, these contain neither permeable channels nor fluid, but they contain heat.

Exploitation of such a system depends on creating permeability so that fluid can contact the rock and extract heat. Water is circulated down one well, through the fractured rock, and up the other well. The reservoir is an artificially created one: heat is extracted from rock sufficiently close to the fractures to allow conductive heat flow to the fluid circulating in the fractures. [6,8]
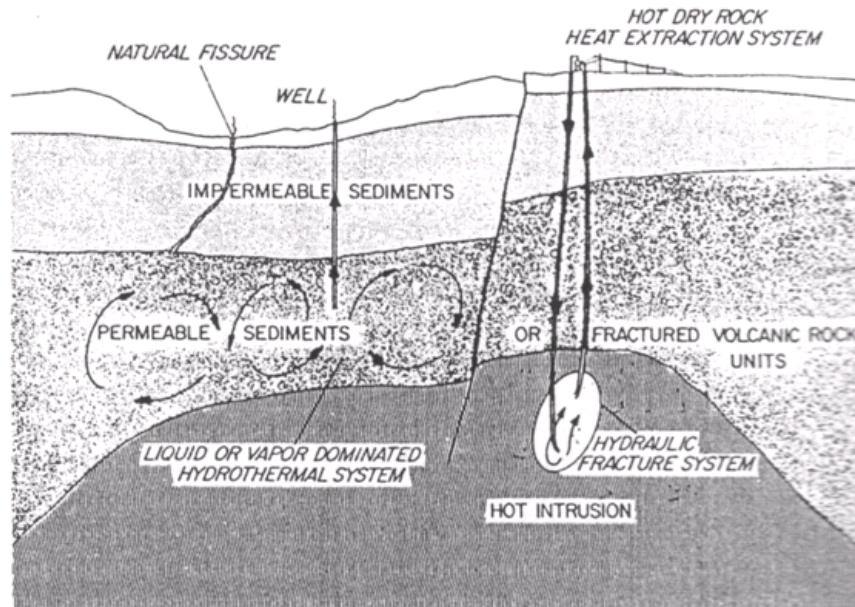


**Figure 1.8** Schematic diagram of a hot, dry rock geothermal system, shown adjacent to a hydrothermal reservoir.
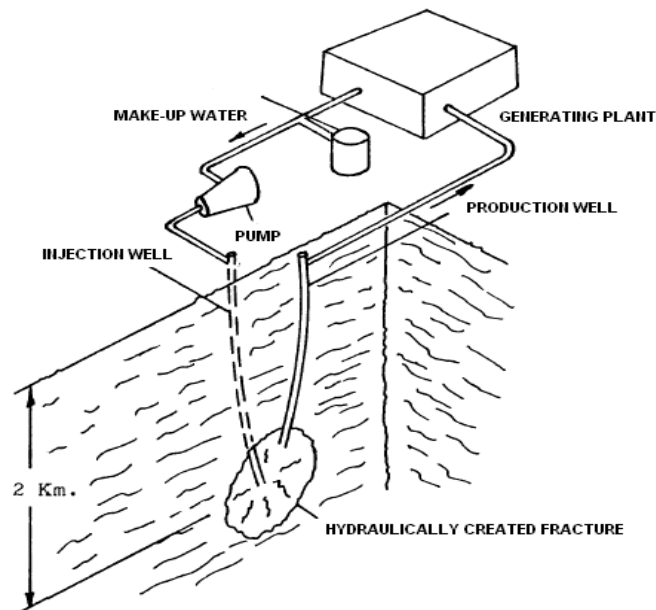


**Figure 1.9** Schematic of hot, dry rock geothermal energy extraction scheme

### 1.3.2   Convective Hydrothermal Reservoirs

All present and planned power stations operate on such fields, and all of the more visible surface features such as geysers and mud pools are associated with such fields.

In contrast to the conductive systems, it is the flow of fluid through the system that determines the temperature and fluid distribution in these reservoirs.

Distinction of two hydrothermal reservoirs depends on the physical state of the water, commonly assumed as pure water. Figure 1.10 shows a pressure-temperature diagram for pure water, indicating critical point and boiling point curve.
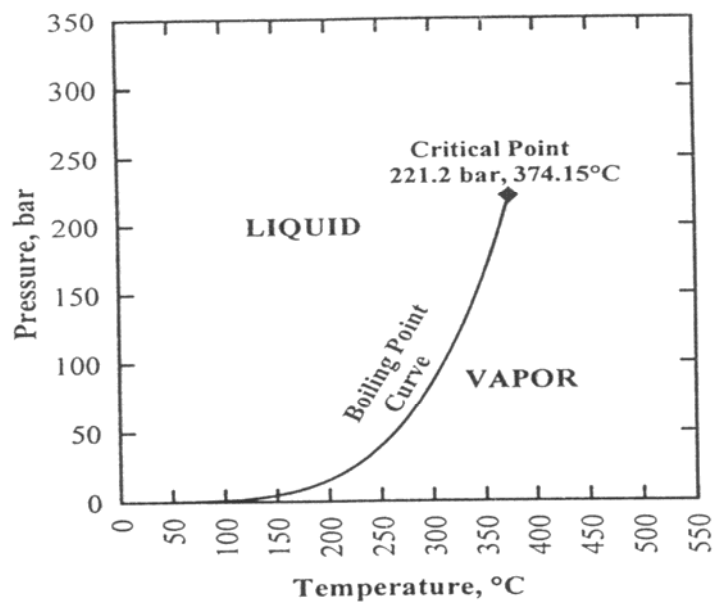
**Figure 1.10** Pressure – temperature diagram for pure water.

As in liquid-dominated geothermal reservoirs, the water temperature is at, or below, the boiling point curve at the prevailing pressure and the liquid phase controls the pressure in the reservoir although some steam may be present. Pressure in the reservoir is close to hydrostatic pressure.

In vapor-dominated geothermal reservoirs; the water temperature is at or above the boiling point curve at the prevailing pressure and the steam phase controls the pressure in the reservoir, some water may, however, may be present. Pressure in the reservoir is close to steam-static pressure.

Hydrothermal reservoirs consist of high temperature water and/or steam, which are stored in porous and permeable reservoir rocks. As a result of the convective circulation of water and/or steam through faults and fractures, the heat is transported to near the earth's surface. The driving force is gravity, owing to the density difference between cold, downward-moving water and hot, upward-moving fluids. Heat stored in the geothermal reservoir rock is produced by bringing to the surface hot water and/or steam.[6]
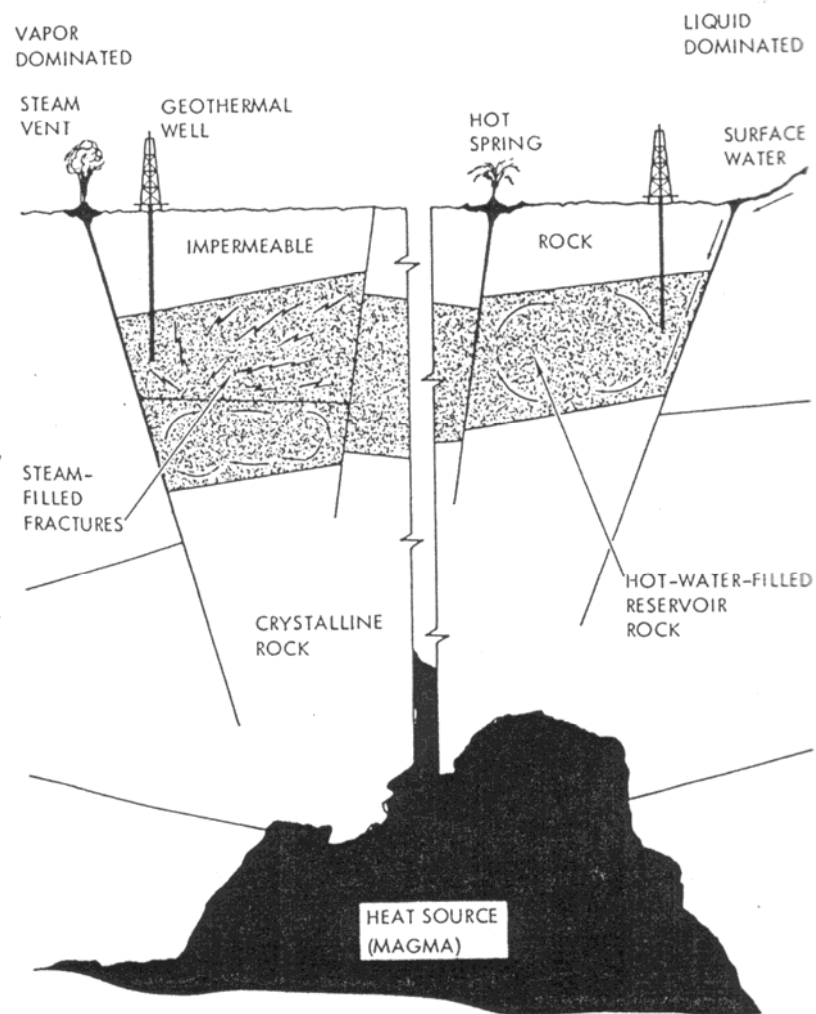


**Figure 1.11** Generalized (simplified) schematic diagram of a hydrothermal reservoir.

Figure 1.11 is a representation of a hydrothermal reservoir and depicts the general geological and thermal features thought to exist in most of these systems.
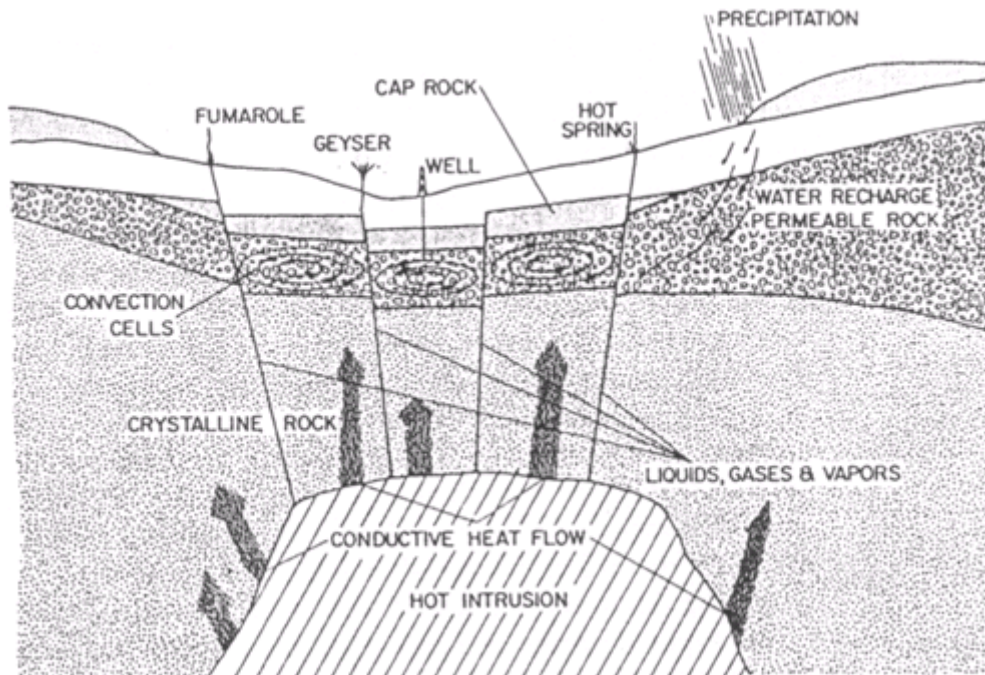
**Figure 1.12** Diagram of convective hydrothermal geothermal reservoir

### 1.3.2.1 Vapor-Dominated Hydrothermal Reservoirs

These systems are the rarest found in nature and the most desirable, because they provide a clean and environmentally safe energy source with minor production problems. [2]

Although this type of hydrothermal systems also known as "dry-steam systems" due to production from vapor-dominated field dry or superheated steam with no associated liquid, liquid water and vapor usually coexist in the reservoir, with vapor being the continuous, pressure-controlling phase.

Vapor-dominated hydrothermal systems contain far less heat than the hot-water hydrothermal systems, but problems related with their utilization are minor.

The conceptual model of the vapor-dominated geothermal reservoir in its natural state, as proposed by white et al. (1971), is shown in Figure 1.11. At the base of the reservoir is a layer of boiling convecting brine, presumably heated by magma. The steam coming off this boiling brine ascends through the reservoir. Since most of the

upward mass flow is stopped at the top of the reservoir by the impermeable cap rock, fluid must flow back down to the brine as condensate. [7]
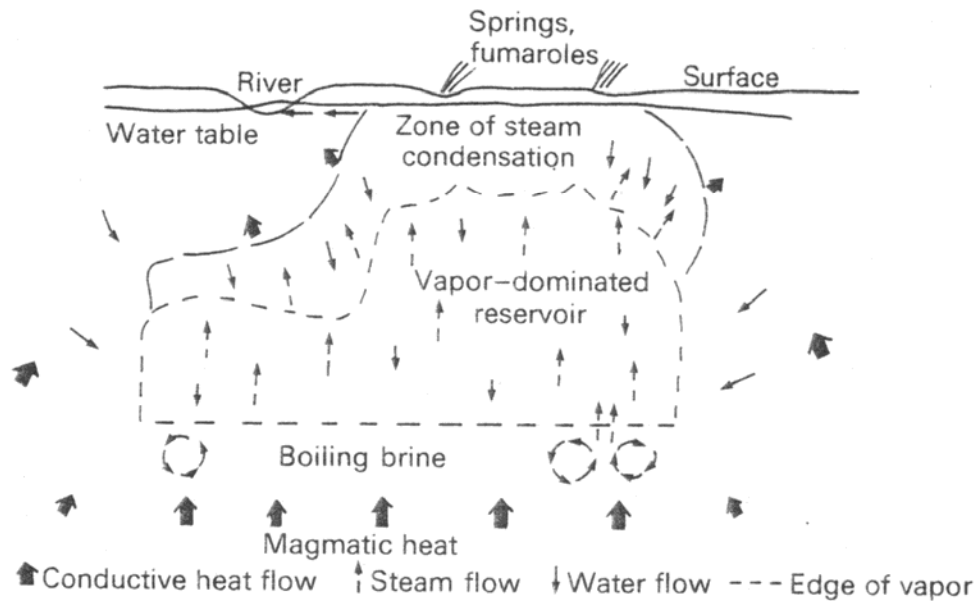


**Figure 1.13** Conceptual model of the fluid flow in the natural state of a vapor-dominated reservoir. (After White *et al*, 1971)

**Water-Dominated Hydrothermal Reservoirs**

Of all geothermal systems discovered to date, hot liquid-dominated reservoirs are far more common than vapor-dominated systems. In these systems, water is the continuous, pressure-controlling fluid phase, although system may contain some vapor, found as discrete bubbles in the shallow, low pressure zones.

Some simple models of convective hydrothermal reservoirs are shown in Figures 1.14 and 1.15.
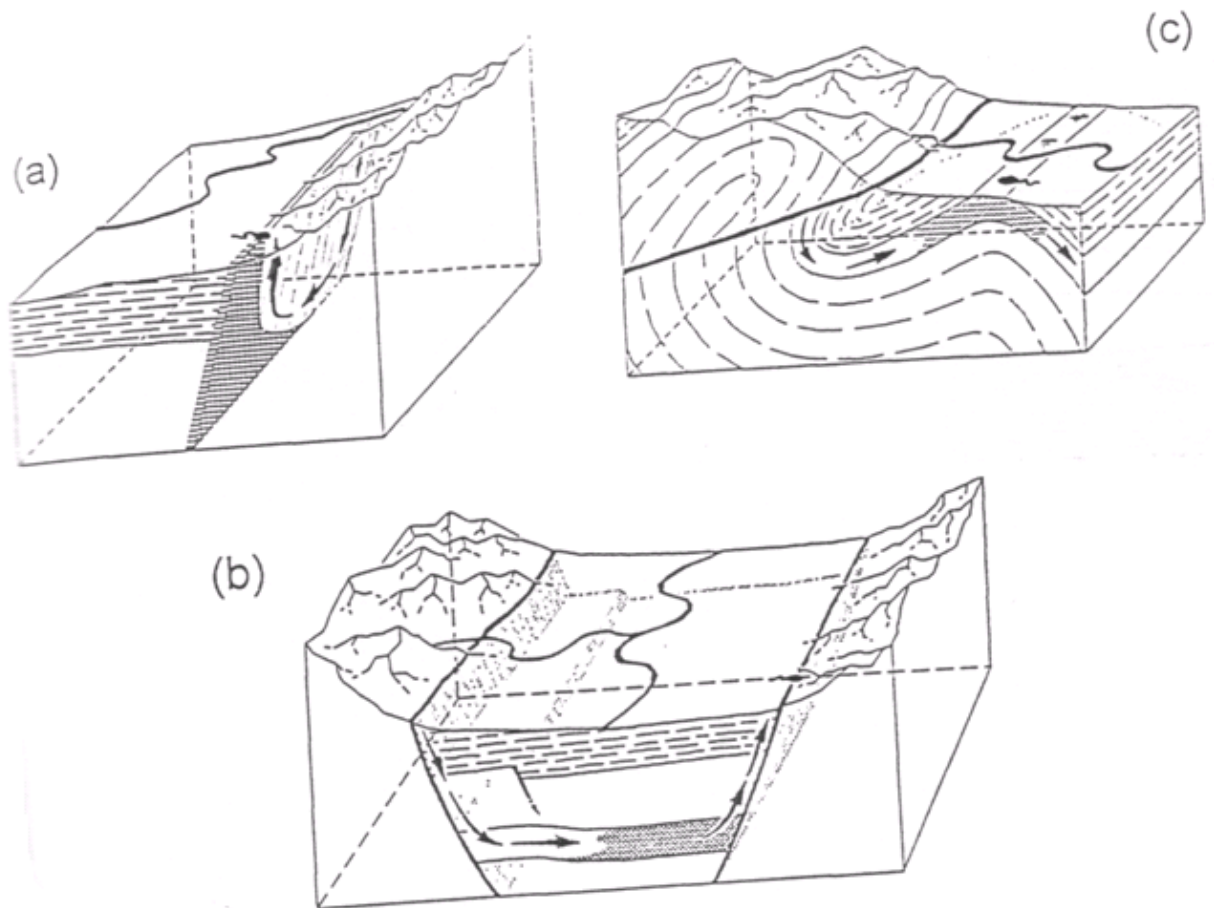
**Figure 1.14** Models for low-and intermediate –temperature hydrothermal reservoirs:
(a) fault-plane model, (b) deep-basin model, and (c) permeable bed in folded strata
model.

Figure 1.14a shows a reservoir located along a fault zone. The water sinks in one part of the fault zone to a depth where it is sufficiently heated that it can rise along another part of the same fault zone. This simple model is believed to represent the basic mechanism for many fault related, low-and moderate- temperature reservoirs.[3 ]

Figure 1.14b represents a possible mechanism for certain convective hydrothermal reservoirs in areas of fault-block valleys separated by up-faulted mountain ranges. Water sinks along a fault zone on one side of the valley, moves laterally in an aquifer at depth where it is heated, and discharges on the other side of the valley by movement up a second fault zone. For such a system, the aquifer at depth may or may not be close enough to the surface to be economically tapped by wells.[3]

Figure 1.14c shows a situation where water infiltrates into a permeable bed in a mountain block and sinks deeply enough to be heated. Folding of the rock strata brings the permeable aquifer near the surface at another location, and the thermal fluid is channeled upward, where it can be reached by wells or thermal springs.
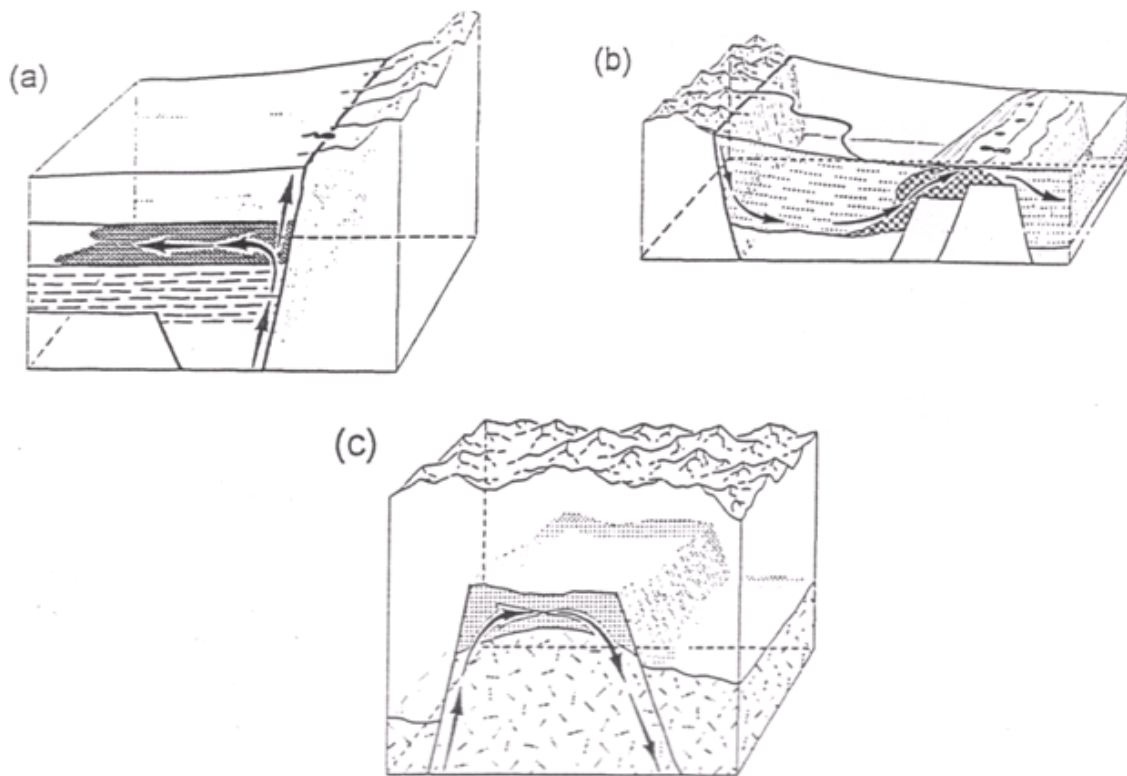


**Figure 1.15** Models for low-and intermediate-temperature hydrothermal reservoirs: (a) lateral-leakage model, (b) basin-construction model, and (c) bedrock-high model

Figure 1.15a demonstrates the possibility of lateral leakage from a fault-related zone of upwelling. Thermal water rises along a fault zone and forms springs at the surface, but much of the thermal fluid also flows laterally away from the fault in an underground aquifer. [3]

Figure 1.15b illustrates the case of water sinking along a basin-bounding fault and flowing laterally while being heated, much as in the case of Figure 1.14b. However, in this model, the thermal fluid is brought near the surface by uplift in the basement rock of the basin, which causes a constriction in the horizontal water flow.

Figure 1.15c illustrates a case where thermal fluid rises along faults bounding subsurface bedrock high and flows laterally within fractured rocks at the upper margin of the bedrock high. The thermal fluid may be cooled and sink, as illustrated, or it may be continue to flow laterally in poorly consolidated valley fill at the right margin of the bedrock high.[3]

## 1.4 Balçova - Narlıdere Geothermal Field

### 1.4.1 The Field History and Recent Situation

Balçova-Narlıdere geothermal field, which is known as the oldest geothermal systems in Turkey, is situated 10 km away from the west of İzmir.

Balçova Geothermal Field always has been an attractive place for settlers over the ages. The field is also known as Agamemnon Spas and in antiquity, was used for the therapeutic qualities of its water.

According to a legend, Agamemnon was advised by an oracle to bring soldiers who had been wounded during campaign against Troy to the sulphur-rich waters of these natural hot springs. The periods that Ionians passed to Aegean Coasts, a part of Alexander the Great's army's injured soldiers were cured in these hot springs. It had a wide usage in that period, constructions were brought and progressed. [9]

Today, the ancient ruins are not seen in the area. Only information about springs are available from the historical sources in 1763. After that period, Agamemnon Spas are reconstructed by a Frenchman called Elfont Meil with adding the staying units and they endured to our country. Today there is a modern spa complex with a total capacity of 1000 person/day providing hot springs pools and baths, therapy pool. [9]

The reconnaissance and exploration studies started in Balçova in 1963 by General Directorate of Mineral Research and Exploration (MTA). The first well was 40 m deep and producing two phase fluid at 124 ℃. Then 3 exploration wells were drilled after the first evaluation of geological, geophysical and geochemical data. Because of high calcite precipitation problem, the field could not be developed until 1981.

The milestones of geothermal development in Balçova-Narlıdere have been given in Table 1.1.

**Table 1.1**: Chronogical improvement of geothermal utilisation in Balçova-Narlıdere

| Year | Improvement |
|------|-------------|
| 1963 | The first geothermal well was drilled in the field. |
| 1983 | Down hole heat exchanger (DHE) was used to heat Balçova thermal facilities. |
| 1983 | DHE was used to heat Dokuz Eylul University medical Faculty (DEUMF). |
| 1992 | The use of plate type heat exchangers was started in (DEUMF). |
| 1994 | Geothermal heating of Princess Hotel was started. |
| 1995 | Adjudication of the first stage geothermal heating and cooling works with 2500 And 500 dwellings for cooling. |
| 1996 | Increasing the capacities from 2500 to 5000 dwellings for heating and from 500 To 1000 dwellings for cooling. |
| 1996 | Balçova GDHS was commissioned. |
| 1996 | Reinjection was started. |
| 1997 | The capacity was increased to 7680 dwellings. |
| 1998 | Narlıdere GDHS was commissioned for 1500 dwellings. |
| 2001 | Modernisation and enlargement of DEUMF geothermal heating centre. |
| 2001 | Izmir Economy University was connected to the Balçova GDHS |
| 2001 | Geothermal reservoir was modeled by ITU Petroleum and Natural Gas Eng. Dept. |
| 2002 | Energy economy and automation studies were started. |
| 2002 | Feasibility studies for the geothermal heating of 5000 dwellings were started. |
| 2002 | Re-injection to the shallow wells was stopped and re-injection to the deep wells was started. Geothermal fluid temperature increased in the field. |
| 2002 | Complete modeling of pipe networks in the system was completed. |
| 2003 | Dokuz Eylul University Fine Arts Faculty has been connected to the system. |
| 2003 | Özdilek Hotel and shopping centre was connected to the system. |

The geothermal water with the temperature ranging from 80 to 140 ºC is produced from the wells with the depths between 48.5 m and 1100 m. There are about 50 wells drilled up to date and they are classified as gradient, shallow and deep wells. The field started to feed a district heating system with a capacity of approximately 5000 residences in 1996.

A total of 21 wells (9 deep and 12 shallow wells) are operated since 1996. The deepest well is BD-5 with a depth of 1100 m and the shallowest well is B-9 with a depth of 48.5 m. Six deep wells, BD-2, BD-3, BD-4, BD-5, BD-6, and BD-7, and four shallow wells, B-4, B-5, B-10 and B-11 are being continuously or periodically used for production.

The deep wells were produced in winter and the shallow wells were produced in summer months in general. Until September 2002, three shallow wells, B-2, B-9 and B-12 were used for reinjection. However in 2002, the reinjection was switched to deep wells and a new well, BD-8, drilled in 2001 has been used for reinjection since then.

The depths and the temperatures of the shallow and deep wells are given in Table 1.2, and the locations of the wells are shown in Figure 1.16
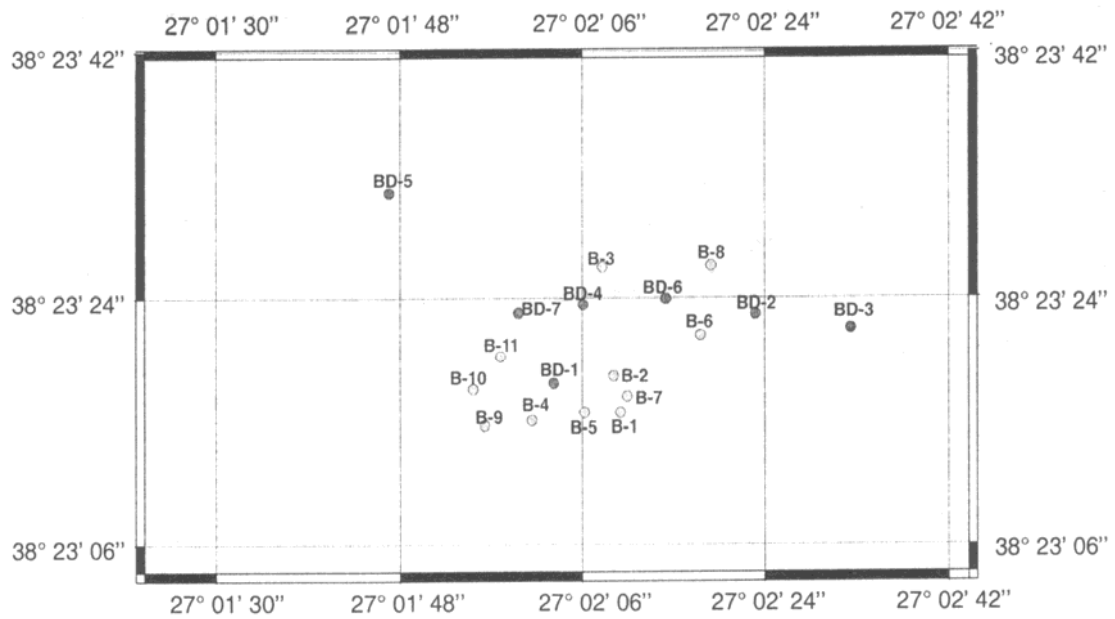


**Figure 1.16** Locations of the wells in Balçova-Narlıdere geothermal field.

**Table 1.2**: Recent situation of wells in Balçova-Narlıdere

| Well | Date | Length (m) | Temperature (°C) | Flow Rate (m$^3$/h) | Position |
|------|------|------------|------------------|---------------------|----------|
| BD-1 | 1994 | 200 | 110 | 50 | Production |
| BD-2 | 1995 | 677 | 132 | 180 | Production |
| BD-3 | 1996 | 750 | 120 | 85 | Production |
| BD-4 | 1998 | 624 | 135 | 140 | Production |
| BD-5 | 1999 | 1100 | 115 | 80 | Production |
| BD-6 | 1999 | 605 | 135 | 100 | Production |
| BD-7 | 1999 | 1100 | 125 | 60 | Production |
| BD-8 | 2002 | 630 | | 2500 | Re-injection |
| B-1 | 1982 | 104 | 115 | 100 | Production |
| B-2 | 1989 | 150 | 95 | - | No Production |
| B-3 | 1983 | 160 | 110 | - | No Production |
| B-4 | 1983 | 125 | 117 | - | Production |
| B-5 | 1983 | 109 | 120 | 135 | Production |
| B-6 | 1983 | 150 | 95 | - | No Production |
| B-7 | 1983 | 120 | 115 | 140 | Production |
| B-8 | 1983 | 250 | 95 | - | No Production |
| B-9 | 1983 | 48 | 95 | - | No Production |
| B-10 | 1989 | 125 | 105 | 100 | Production |
| B-11 | 1989 | 125 | 109 | 40 | Production |
| B-12 | 1998 | 160 | 95 | - | No Production |
| ND-1 | 1996 | 800 | 115 | - | No Production |
| N-1 | 1997 | 150 | 95 | - | No Production |
| BTF-2 | | | | | |
| BTF-3 | | | 100 | 30 | No Production |
| Bh-1 | | | 80 | 15 | No Production |

# CHAPTER 2

# GEOTHERMAL RESERVOIR SIMULATION: AN OVERVIEW

## 2.1 Introduction to Simulation of Geothermal Reservoirs

The term reservoir simulation means the process of deducing the physical behavior of a real reservoir from the performance of a model. Since the beginning of study for simulating geothermal reservoirs two kinds of approach are developed;

(a)     Physical Model,

which is conducted experimentally in laboratory, for example a laboratory sand back

(b)     Mathematical Model,

A mathematical model of a physical system consists of a set of partial differential equations subject to certain simplifying assumptions, together with an appropriate set of boundary conditions, which describe the physical processes active in the reservoir.

Reservoir simulation applies the concepts and techniques of mathematical modeling to the analysis of the behavior of geothermal reservoir systems.

Most often, the term reservoir simulation is used with regards to the hydrodynamics of flow within the reservoir, but in a more general sense it refers to the total geothermal system, which includes mainly the reservoir itself, the tubing, and the surface facilities.
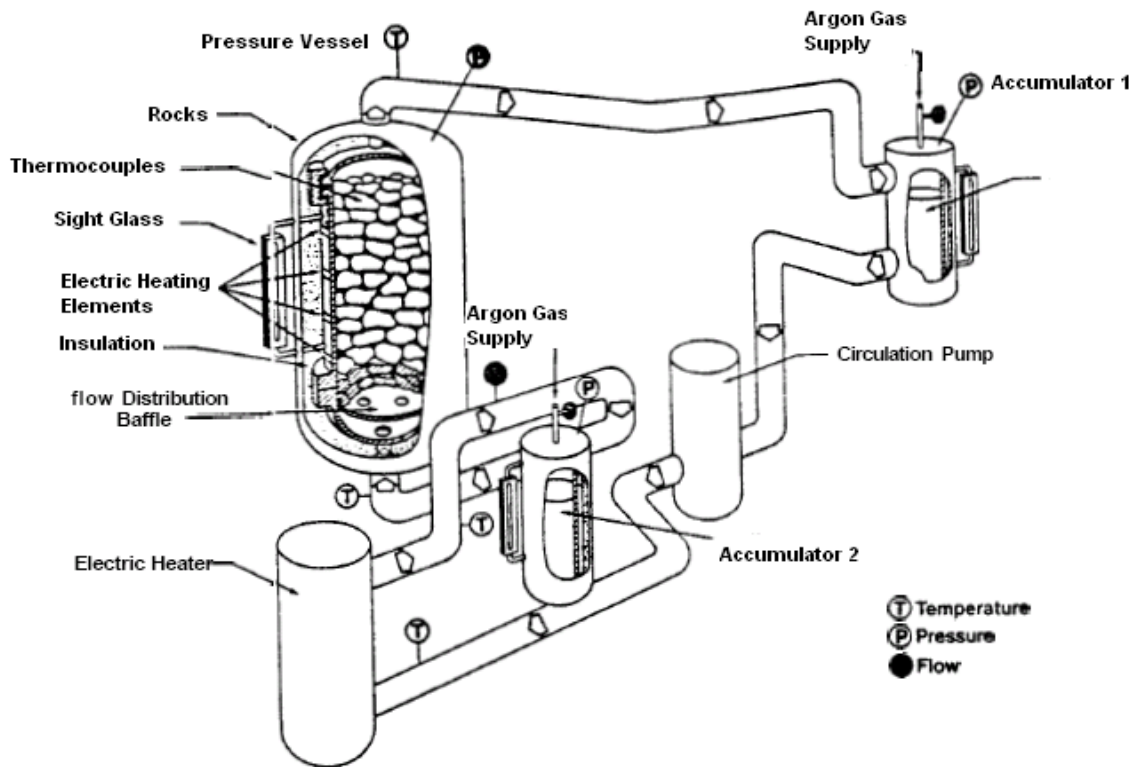
**Figure 2.1** Diagram of SGP Large Reservoir Model

The experimental reservoir model conducted in Stanford Geothermal Program is shown in Figure 2.1, it has been used to study fundamental nonisothermal production methods and heat transfer from the rocks to the produced fluids.

Since more than 70% of the energy available in a geothermal reservoir resides in the reservoir rock, the development of techniques to enhance the fraction of energy extracted from the rock itself is imperative for efficient exploitation of a geothermal reservoir. [10]

The rate of energy extraction from a geothermal reservoir is limited by slow conductive heat transfer from the large reservoir rocks to the convecting fluid and by the resistance to the flow of fluid through the formation. Total energy extraction is limited by finite stored heat capacity of the reservoir.

The main purpose of simulation is to estimate the behavior of a geothermal reservoir under a variety of exploitation schemes. From observation of model performance, under a variety of producing conditions, the optimum exploitation conditions for the reservoir can be selected. Some of the information that can be obtained from reservoir simulation studies is given below [6];

1. The capability of a reservoir of producing significant quantities of energy over meaningful periods of time.

2. The number of wells and spacing required for optimum development of the reservoir.

3. The effect of the rate of production of the wells on total energy recovery.

4. Variation of fluid temperature with time.

5. Feasibility of implementation of an enhanced recovery process to recover additional heat.

Reservoir models range in complexity from simple ones for fairly homogenous systems, where average values for reservoir properties, such as permeability and porosity, are adequate to describe their behavior, to those used for highly heterogeneous systems.

Mainly, three methods are currently available in literature for modeling the behavior of geothermal reservoirs. They are "Whiting and Ramey's Model (1969)" (or Lumped Parameter Model), "Brigham and Morrows's Model (1977)" and Numerical Models.

## 2.2 Whiting and Ramey's Model (Lumped Parameter Model)

This model is described as zero dimensional due to the rock and fluid properties and pressure values are not a function of location in the reservoir. These parameters are calculated as average values for the whole reservoir. This type of models has also been called lumped-parameter models.

This model can be used for performance forecasting of reservoir behavior, where some field development already exists and production is in progress, a mathematical model for fluid flow in the reservoir can be postulated.

The reservoir size and its productivity can be determined by matching measured production data (mass produced, enthalpy produced, reservoir pressure and temperature,

etc.) with the corresponding parameters of the mathematical model. Once all model parameters and their relationships have been identified, the model can be used for performance production forecasting under different assumed exploitation schemes.[6]

The model of the reservoir system developed by Whiting and Ramey is shown in Figure 2.2. The system contains rock, water, and steam. The reservoir system has a bulk volume V and a porosity of $\Phi$. The cumulative fluid production at any given time id $W_p$, whereas the cumulative heat production associated with this fluid production is $Q_p$. The model also considers heat loss, $Q_L$, and mass fluid loss, $W_L$, due to convection in, for example, hot springs, fumaroles, etc. According to the theory, heat loss, Q, at the reservoir boundary is negligible and should not significantly affect reservoir behavior. Water recharge, $W_e$, and its associated energy (cumulative enthalpy, $H_e$) are also considered.[6]
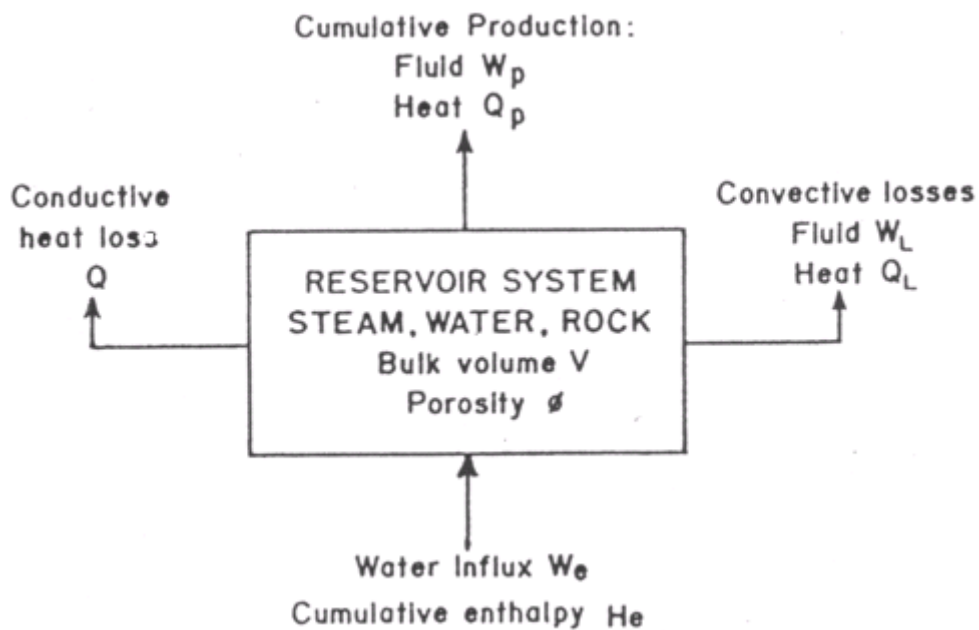


**Figure 2.2** Schematic diagram of reservoir model

The model of Whiting and Ramey considers the following basic assumptions:

1. Thermodynamic equilibrium (temperature of rock, water, and steam are equal)

2. Pressure and saturation are uniform throughout the reservoir

3. Uniform fluid production, which implies that fluid production comes from all parts of the reservoir.

In model generally two blocks are used to represent the entire system. One of the blocks represents the main reservoir and the other acts as a recharge block or aquifer. Average properties are assigned to reservoir and aquifer blocks, and the changes of reservoir pressure, temperature, and production are monitored. The mass and/or heat entering and leaving are used in mass and/or energy balance equations. The governing equations under idealized conditions can sometimes be reduced to ordinary differential equations that can be solved semi-analytically.[6]

Lumped parameter models are generally calibrated against a pressure history. After a history match is obtained, the model is used to predict future average reservoir pressure.

A combined mass, energy and volumetric balance gives the following expression:

$$W_P(H_P - E_C) + W_L(H_L - E_C) + Q$$

$$= W\{E_i - E_C + [(1-\phi)/\phi][x_i v_{si} + (1-x_i)v_{wi}]\rho C_{vr}(T_i - T_C)\} + (H_e - E_C)(B/v_{we})\sum Q_D(t_D)\Delta p_n$$

Where:

Hp = enthalpy of produced fluids (kJ)

W = initial mass of hot water and steam in reservoir bulk volume, V (kg)

E = internal energy (kJ)

Q = conductive heat loss (kJ)

Φ = porosity of rock matrix

X = steam quality

v = specific volume (m$^3$/kg)

$\rho_r$ = density of rock and contained fluids (kg/m$^3$)

$C_{vr}$ = specific heat at constant volume of reservoir rock and contained fluids (kJ/kg.K)

T = temperature (°C)

B = water recharge constant

$Q_D$ ($t_D$) = dimensionless cumulative recharge, corresponding to dimensionless time, $t_D$

$\Delta p_n$ = pressure drop at any time n (Pa)

The subscripts p, L, c, i, r, s, w, and e indicate produced, loss, current, initial, reservoir, steam, liquid water, and recharge values, respectively.

The model given by equation above can be simplified, according to the situation of a specific reservoir. For example, for a reservoir containing only hot water, this equation reduces to:

$$(W_P + W_L)v_w = W(v_w - v_{wi}) + B\sum Q_D(t_D)\Delta p_n$$

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 of the model are:[2]

1. they do not consider fluid flow within the reservoir and neglect spatial variations in thermodynamic conditions and reservoir properties,

2. they cannot simulate fronts such as phase or thermal fronts because of coarse space discretization,

3. they cannot consider questions of well spacing or injection well locations.

## 2.3 Brigham and Morrow's Model

Brigham and Morrow have presented a zero-dimensional model for vapor-dominated systems. They considered three cases regarding the distribution of hot water and steam.

According this model the geothermal system is closed and energy within the system is derived from the rock mass itself.

The first system is completely filled with steam with no water present. Flow in this system is essentially isothermal, because the heat capacity of the rock is large compared with that of steam. Then, in order to study the system's behavior only a mass balance needs to be taken.

Under these reservoir flow conditions, a steam reservoir can be treated as an ordinary petroleum gas reservoir, where average reservoir pressure divided by the gas deviation factor, p/Z, is plotted versus cumulative production, resulting in a straight line. The intercept on the abscissa is equal to the original mass of fluid in place, $m_{gi}$. The equation can be presented as follows:

$$P_f / Z_f = (p_i / Z_i) \frac{(m_{gi} - \Delta m_g)}{m_{gi}} = (p_i / Z_i) \frac{(m_{gf})}{m_{gi}}$$

Where:

P = reservoir pressure (Pa)

$m_g$ = mass of steam (kg)

$\Delta m_g$ = mass of steam produced during a depletion step (kg)

i = subscript for the initial conditions of a depletion step

f = subscript for the end conditions of a depletion step

The second model considers that the steam zone is separated from an underlying liquid zone by a horizontal interface at which boiling takes place. As steam is produced, water boiling will take place, resulting in a liquid level drop; thus its name, the *falling liquid level model*. Flow in the steam zone is assumed to be isothermal, whereas on the water zone non-isothermal flow conditions would prevail. A mass and energy balance is made for the water zone.[2]

The third model also considers that the steam zone has an underlying liquid zone, but assumes that liquid boiling takes place throughout the whole liquid zone, and that liquid level does not drop. This model is called the *constant liquid level model.* Consequently, in this system steam saturation will continuously build up within the liquid zone. The energy equation for this system resembles that of Lumped parameter model(1969), with the exception that only steam flows out of the system.

In order to show simulation quality of above mentioned two kinds of model, namely, the falling liquid level and the constant liquid level model, have solved for three hypothetical reservoirs, having porosities of 0.05, 0.10, and 0,20. It was assumed that the volume of the steam zone was the same as the volume of the liquid zone.

Figure 9-16 shows the results of solution for a steam falling liquid level system. From the results of this Figure and from other results shown by Brigham and Morrow, the following conclusions have been made:[6]

- For low-porosity reservoirs, an extrapolation of the p/Z versus cumulative production plot will be too optimistic, whereas for high-porosity reservoirs it will be pessimistic.

- A porosity of about 0.10 will give approximately correct predictions.

- The constant liquid level model predicts higher recovery for a given reservoir pressure than the falling liquid level model.

- The presence of even a small water zone in the lower portion of the system is an important fraction of total system's mass, and can significantly affect p/Z prediction procedure.

- From results one concluded that the steam zone of the reservoir remains isothermal whether or not there is a water boiling zone below the steam. This causes characterization problems, because pressure, temperature, and enthalpy measurements are not sufficient to determine the original state of the reservoir fluid system.

## 2.4 Numerical Geothermal Reservoir Simulation

Numerical models are very general models that can be used to simulate reservoirs with few or many (>100 to 1000) grid blocks. They can be used to simulate entire geothermal system, including reservoir, caprock, bedrock, shallow cold aquifers,

recharge zones, etc. They allow spatial variations in rock, fluid, and well properties and thermodynamic conditions.[2]

The principal advantage of numerical models is that they have all mathematics built into computer code and allow the user to decide how detailed the simulation should be and which physical processes should be considered. Disadvantages of the numerical models are the need for more input data.

When important heterogeneities exist in the reservoir, rock and/or fluid properties (permeability, saturation, pressure, viscosity, etc.) vary in space, then simple zero-dimensional models can no longer be used for prediction of reservoir performance.

A model that considers the variation of rock and fluid properties is called a distributed-parameter model. A reservoir where properties vary in space, is usually divided in blocks (cells), assigning to each one of them average values for rock and fluid properties.[6]

A mathematical model for describing fluid flow in a geothermal reservoir includes equations for the conservation of mass, momentum, and energy for water and steam, and for specifying the state of the system.

These models differ from each other according to the assumptions implied. A model for the flow of hot water and steam, written for a general coordinate system, consists of the following equations:

$$\Delta \left[ \frac{k k_{rw} \rho_w}{\mu_w} (\Delta p - \rho_w g) + \frac{k k_{rs} \rho_s}{\mu_s} (\Delta p - \rho_s g) \right] - q = \frac{\partial}{\partial t} (\Phi q_w S_w + \Phi q_s S_s)$$

Energy balance for the water-steam-rock systems can be presented as follows:

$$\Delta \left[ \frac{k k_{rw} \rho_w H_w}{\mu_w} (\Delta p - \rho_w g) + \frac{k k_{rs} \rho_s H_s}{\mu_s} (\Delta p - \rho_w g) \right] + \Delta (K \Delta T) - q_{HL} - q_H$$

$$= \frac{\partial}{\partial t} \left[ (\Phi \rho_w H_w S_w + \Phi \rho_s H_s S_s) + (1 - \Phi) \rho_r H_r \right]$$

Where:

k = absolute permeability (mD)

$k_{rs}(k_{rw})$ = relative permeability to steam (water) (mD)

$\rho_s(\rho_w)$ = steam (water) density (kg/m$^3$)

$\mu_s(\mu_w)$ = steam (water) viscosity (N.s/m$^2$)

p = pressure (Pa)

g = acceleration of gravity (kg/m$^3$)

q = mass (source) production rate (W/m$^2$)

$\Phi$ = porosity

$S_s(S_w)$ = steam (water) saturation

$H_s(H_w)$ = enthalpy of saturated steam (water) (kJ)

K = thermal conductivity (W/mK)

T = temperature (ºC)

$q_{HL}$ = heat loss rate (W/m$^2$)

$q_H$ = enthalpy production rate (W/m$^2$)

$\rho_r$ = average rock-grain density (kg/m$^3$)

$H_r$ = rock enthalpy (kJ)


In the derivation of two equations above, the following assumptions have been made:[6]

1.  The reservoir is treated as a porous medium.

2.  Capillary pressure effects are negligible. This means that the pressure in the water and steam phases is equal.

3.  Thermal equilibrium exists among all phases; hot water, steam, and rock.

4.  Validity of Darcy law for two-phase flow.

5.  Thermal conductivity is a property of the medium.

6.  The geothermal fluid is pure water

# CHAPTER 3

# NUMERICAL GEOTHERMAL RESERVOIR SIMULATION

## 3.1 Current State Of Practice

Computer modeling of geothermal systems is today a mature technology with application to more than 100 fields worldwide and on this topic researchers continue to carry out new modeling techniques in order to simulate complex physical processes occurred in geothermal systems better.

Geothermal reservoir engineering is related in many aspects to oil and gas reservoir engineering, which began receiving attention in the 1930s and fundamentals theories background them well-established. Developed techniques on the experience of underground groundwater and petroleum reservoirs employed properly in geothermal reservoir technology, especially in cases where the characteristics of the geothermal and petroleum systems are alike.[11]

However geothermal reservoirs differ from their groundwater and petroleum counterparts with their considerably more complex nature and requiring some difference in approach and outlook.

Some distinctive features of geothermal reservoirs are the following [3 ] [6]:

1. The primary permeability is usually in fractured rock.

2. The reservoir is of great vertical extent.

3. Many reservoirs are uncapped and hence allow free flow to the ground surface.

4. The vertical and lateral extent of the reservoir may be unknown, and the hot fluid core may be in direct connection with cooler surrounding fluid.

5. Heat transport as well as mass transport is important.

6. Very high reservoir temperatures

7. Formations containing the fluid in many cases are highly fractured and of volcanic type

8. Chemical deposition of solids during flow of fluids in the reservoir; and steam flashing.

A common thread through all these problems in analysis is the observation that everything that happens in a geothermal field is the result of fluid flow. The flow of fluid –water, steam or gas- through rock, fractures, or a wellbore is the unifying feature of all geothermal reservoir analysis. The historic flow of created the reservoir; the modification of this flow due to exploitation is what the science of geothermal engineering is all about.

In the late 1960s using digital computers, became possible to solve numerically complex non-linear partial differential equations, however the application of these techniques to modeling the behavior of geothermal reservoirs lagged behind their usage in groundwater, oil and petroleum reservoir modeling because of the coupling between mass and energy transport in a geothermal reservoir adds considerable complexity.

The earliest work on the numerical reservoir simulation began to appear in the early 1970s. But the effective starting point on the subject was in 1980 by studies conducted in Stanford Geothermal Program granted by US Department of Energy. During the program several geothermal simulators tested on a suite of six test problems. The results of the study were reviewed during that year's Stanford Reservoir Engineering Workshop. Since then, the experiences of developing site-specific models and carrying out generic reservoir modeling studies has led to a steady improvement in the capabilities of the geothermal reservoir simulation codes. [11]

The computer power available in the 1980s limited the size of the computational meshes used and many of them were based on geometrically simple models. For example, often 2-dimensional models were used, either vertical slices, or single layer models. In some cases radial symmetry was assumed. Most of the early 3-dimensioanal models were simplified in some way, usually by omitting low-permeability zones entirely or by using a relatively small number of blocks. [11]

## 3.2 Conceptual models and data collection

Before a simulation model of a given geothermal field can be set up, a conceptual model must be developed. A good understanding of the important aspects of the structure of the system and the most significant (physical and chemical) processes occurring in it is referred to as its "conceptual model". It is usually represented by two or three sketches showing a plan view and vertical sections of the geothermal system. On these sketches are shown the most important features such as; surface manifestations (i.e., hot springs, steaming grounds, etc.), flow boundaries, main geologic features such as faults and layers, zones of high and low permeability, isothermes, location of deep inflows and boiling zones, etc. [11]

Setting up a conceptual model requires the synthesis of information from a multi-disciplinary research team composed of geologists, geophysicist, geochemists, reservoir engineers and project managers.

## 3.3 Design Model Structure

Recent models have a complex 3D structure and often consist of as many as 3000-6000 blocks or elements. Even with these large site-specific models, the smallest block size is still quite large. A typical minimum horizontal dimension is 200 m and minimum vertical dimension is 100 m. [11]

The use of large blocks in a geothermal model makes the task of matching well-by-well performance difficult. Some modelers have overcome this difficulty by introducing embedded sub-grids around each well.

The most common simulators which have been used to implement these complex 3D models are STAR (Pritchett, 1995), TETRAD (Vinsome and Shook, 1993) and THOUGH2 (Pruess,1998) and FEHM. [11]

Currently, these four simulators that are used to model hydrothermal reservoirs. Each of them has the capability of handling multiphase, multi-component flows, and several models have included a reservoir fluid which is a mixture of water and NaCl or both.

A regular rectangular mesh structure is required by TETRAD and STAR, whereas THOUGH2 can handle general unstructured meshes. However, most geothermal models set up using THOUGH2 have some structure such as layering.

## 3.4 Boundary Conditions

Two important matters to be decided in setting up a model of a geothermal system are its size and the boundary conditions to be applied on the sides of the model.

Geothermal systems, apart from low-temperature systems, involve large-scale convection of heat and mass, driven by deep heat (and fluid) recharge. Usually the whole of this convective system is not included in a model and therefore aspects of the system must be represented by a suitable source of heat and mass. The only exception to this procedure is the special case of vapor-dominated systems where it is not possible to set up a stable natural state using by flow boundary conditions. Instead constant pressure and vapor saturation boundary conditions must be applied. [11]

Constant pressure and temperature boundary conditions instead of flow boundary conditions have been used for modeling hot water or liquid-dominated, two phase systems.

At the lateral boundaries of the model in general it is advisable to have the side boundaries of the model sufficiently remote from the production and injection zones so that the choice of boundary conditions does not significantly affect the performance of the model. Most often no flow (heat and/or mass) conditions are used at the side boundaries.

For the top boundary probably the most common approach is to assume a constant atmospheric pressure and temperature at the top of the model. For temperature soil temperature can be taken (10 ºC) [11]

Boundary conditions for all THOUGH2 models are as follows [12]:

1. Top set at a constant pressure of 1E05 Pa(atmospheric) and temperature of 20 ºC

2. Sides set at no heat or fluid-flow

3. Bottom set at no fluid-flow, with constant heat flux into the model.

# CHAPTER 4

# GEOTHERMAL RESERVOIR SIMULATON USING SOFTWARE PROGRAM (FLUENT)

## 4.1 Background

FLUENT is a package computer program written in C computer language for modeling fluid flow and heat transfer in complex geometries. FLUENT provides complete mesh flexibility for solving the flow problems with unstructured meshes that can be generated in order to simulate complex geometries with relative ease.

In FLUENT, according to the geometry that studied, wide range of mesh types can be used, include 2D triangular/quadrilateral, 3D tetrahedral/ hexahedral/ pyramid/ wedge, and mixed (hybrid) meshes.

As in general procedure, at the beginning of this study the geometries are created with some idealization and appropriate assumptions and meshed using GAMBIT modeling program. Then fully meshed and made readable geometries are exported to the FLUENT program. Once a grid model has been read into FLUENT, the next remaining operations in order setting boundary conditions, defining fluid properties, executing the solution and finally viewing and checking the results.

## 4.2 Definition of The Problem Under Consideration

In order to develop computer simulation of any geothermal field, it is required to get many data from different disciplines, such as geological, geophysical, geochemical characteristics of the field, production history of wells for matching output data of computer program with the real measured values.

Of all the required information for the field, the conceptual geological model is on first place. Besides, area and mass flow, temperature and depth of recharge zones, permeability distribution, rock properties and total heat transfer rate input to the reservoir, included conductive and convective parts must be known.

As seen above, although too many information required to know, in fact, there is a little data about the conceptual model of the reservoir and most of them gained from the report of ITU Petroleum and Natural Gas Engineering Department under contract with Balçova Geothermal Field in 2001.

This report is a starting point of this thesis and based on gaining experiences from that project it is aimed to develop three dimensional temperature distribution of the field. Some modifications has been made since that time, most important of them the drilling reinjection well of BD-8, has should effected the reservoir somehow.

Although the disadvantages of the Fluent, it is capable to mesh the reservoir in small interval size compared with the Though2, (typical block size minimum horizontal dimension is 200 m and minimum vertical dimension is 100 m), number of the mesh elements gives more accurate and closely results.

During the modeling process, the general, conceptual picture of the field taken from Balçova Geothermal Limited gave valuable information at initial state of the thesis. This illustration is shown in Figure 4.1 [14]
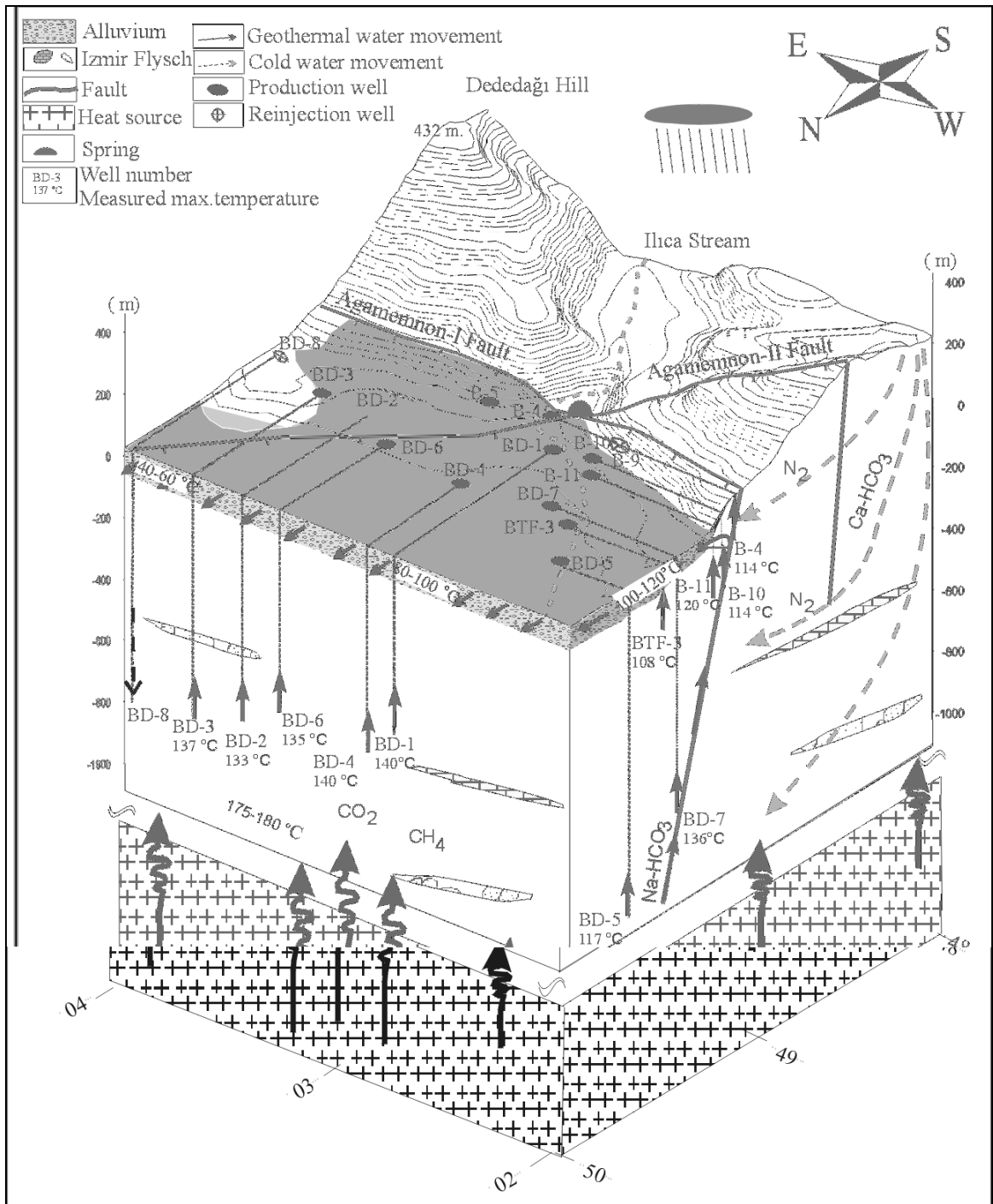
**Figure. 4.1** Conceptual model of the Balçova geothermal field [14]

As seen from the Figure reservoir volume contain two faults, namely Agamennon-I and Agamemnon-II, it is a common acception among the scientists that heat and fluid transport within the reservoir are dominantly controlled by Agamemnon-I, which has an inclination of 75 degree and stretches in direction of east-west.

Since Balçova geothermal field fault-controlled water-dominated reservoir, it is required that the wells intersect the faults somewhere at depth, otherwise hot geothermal water could not be extracted.

Another point that encountered during the process is shallow wells and depth wells have different mechanism of fluid transportation process.

It is believed that shallow wells are fed by nearby water recharge zone, however, wells at deep are fed by deep aquifer.

Due to geological structure of the Anatolia, all of the geothermal reservoirs within the Turkey water-dominated and fault-controlled, so this assumption may also be used in initial conceptual modeling phase.

Measuring values taken from field indicated that the saltiness of the water is very low, and the working geothermal fluent can be assumed pure water without major error. In modeling process this common approach is used.

## 4.3 Modeling the Problem

Before solving the problem with Fluent program, it is required to create the model and its volume meshes using Gambit modeling program.

In this study, in order to develop computer simulation of Balçova geothermal field two kinds of models are created and these models are meshed and run separately under same boundary conditions.

First model meshed without faults and wells were lengthened to the aquifer, and this extension of the wells is thought to describe the heated water rising along the faults.

Second model meshed with two faults each of them represents the long small part of the Agememmon fault.

It is assumed that heated water from the deep surface using these faults as a path, rising towards the reach of the wells, as in close to real process in the field.

If the faults and wells are intersected at a point beneath the surface, the hot water can be raised from the wells.

Initially, by creating first model of the Balçova reservoir field in Gambit program, reservoir geometry is drawn with the dimensions 2 km length, 1.5 km depth and 1 km wide as taken from the model created by Istanbul Technical University Petroleum and Natural Gas Engineering under contract with Balçova Geothermal Limited in 2000.

The wells are taken in square shape for easing the meshes purpose and its dimensions are 50cm * 50 cm.

In the field there are 13 wells in production and another well BD-8 using for reinjection purpose. Therefore 14 wells are taken by modeling the geothermal reservoir.

The following Figure represents basic geometry of the reservoir includes 14 mentioned wells with their volume density.

It is assumed that geothermal water at a temperature of 400 K and 500 $m^3$/h volume density entered the aquifer and exited it with at a temperature of 350 K. At that point, since the aquifer outlet conditions are unknown, the outlet ratio definition was applied. The outlet ratio equal to 0.25 means that %25 percent of the incoming geothermal water from the aquifer inlet, exited from the aquifer outlet.

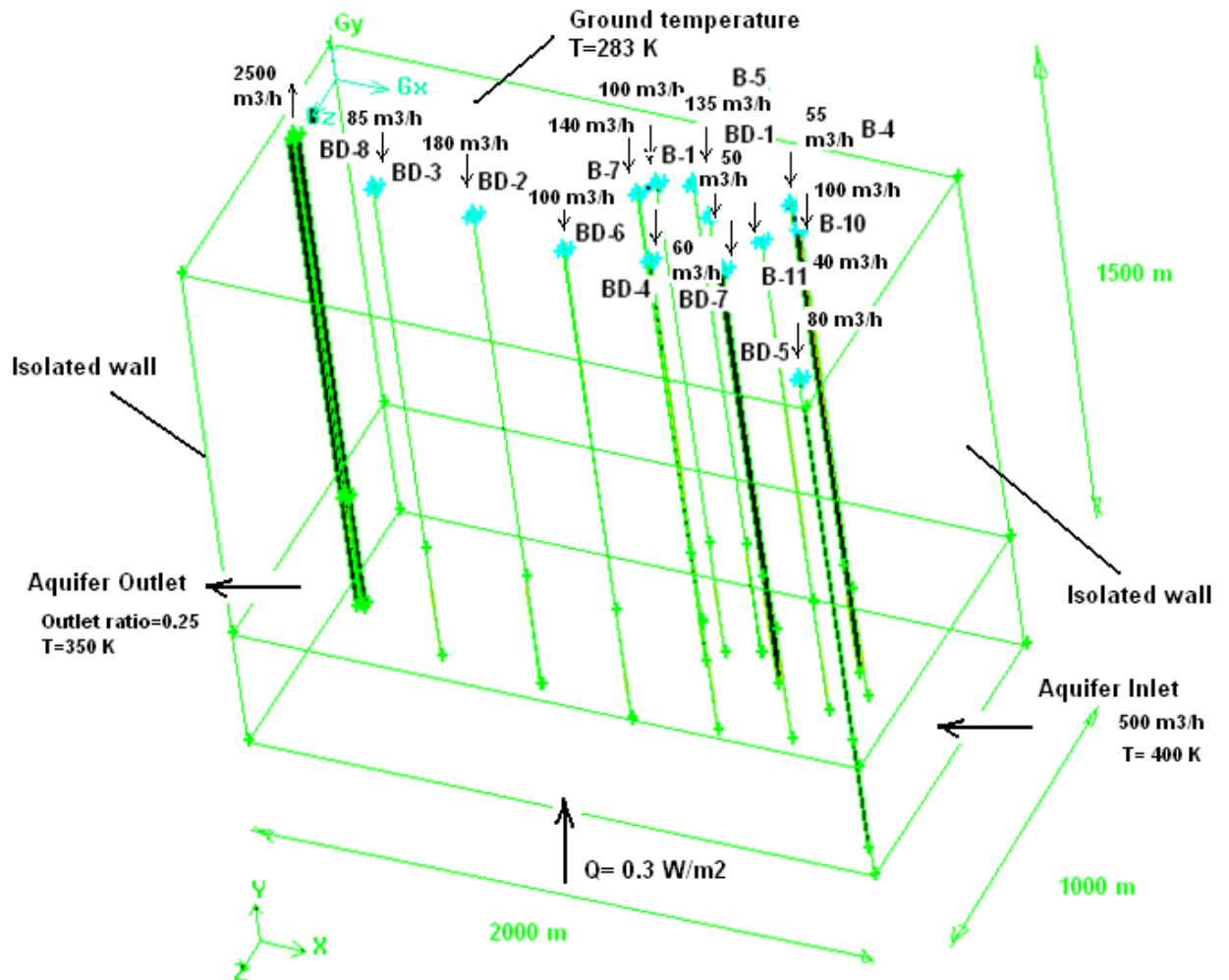The height of the aquifer is 300 meter and extends 2 km along the reservoir bottom.

**Figure. 4.2** Base geometry of Model 1 created in Gambit Program

Since the model reservoir geometry has two different extreme dimensions, namely 50 cm in well and 2 km in the reservoir, meshing process of the modeling in Gambit program created many difficulties.

By meshing the geometry, wells are meshed densely, in contrary other dimensions of the reservoir volumes meshed in bigger mesh interval. This assumption not only eases the meshing process, but also save the computer running time.

In Figure 4.3 the top and bottom of the reservoir are shown in face meshed, the other meshes are made invisible for pretending confusion.
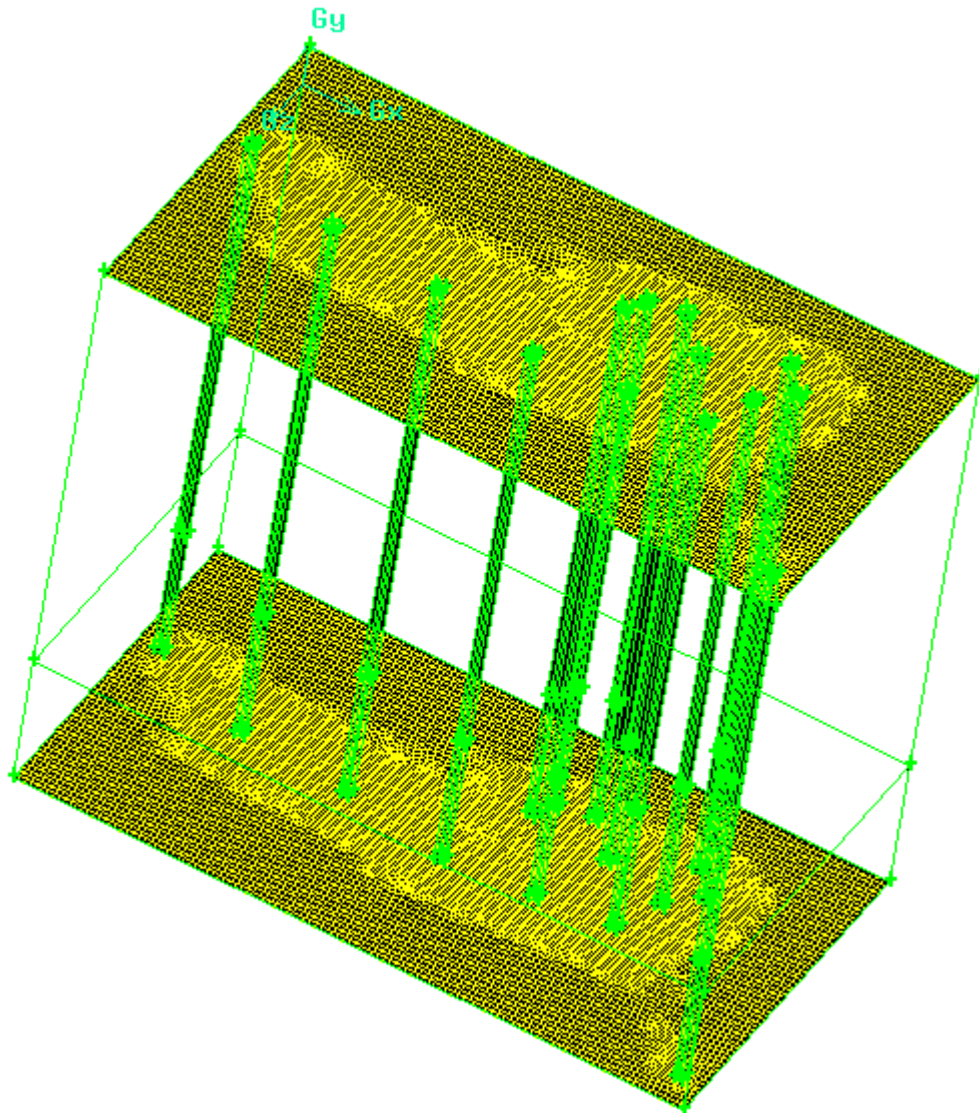
**Figure. 4.3** The top and bottom of the surface are shown in face meshes.

In below, Figure 4.4 the whole reservoir is shown in volume meshes and the following Figure 4.5 shows the top surface and locations of the wells from z-view.

As can be seen from the two Figures the meshes around the wells more dense than the surrounding rocks, since after the meshes created in Gambit whole volumes exported to Fluent program. While Fluent program is running, the continuity, momentum and energy equations are solved for each mesh volumes, the number of the meshes in given area describes the accuracy of the results. That's why the path which water flow is required to mesh more densely to close real process and get better results.
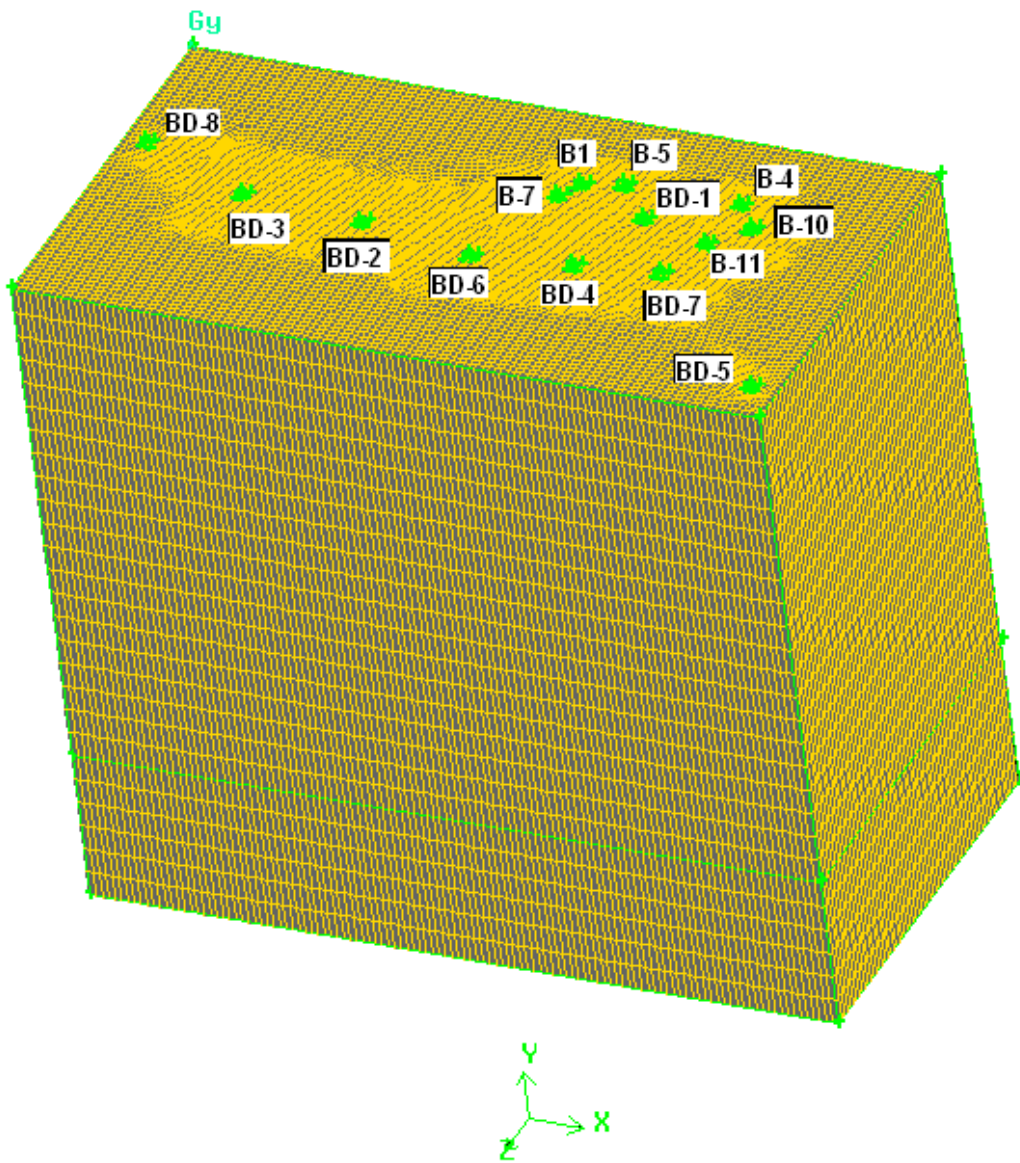
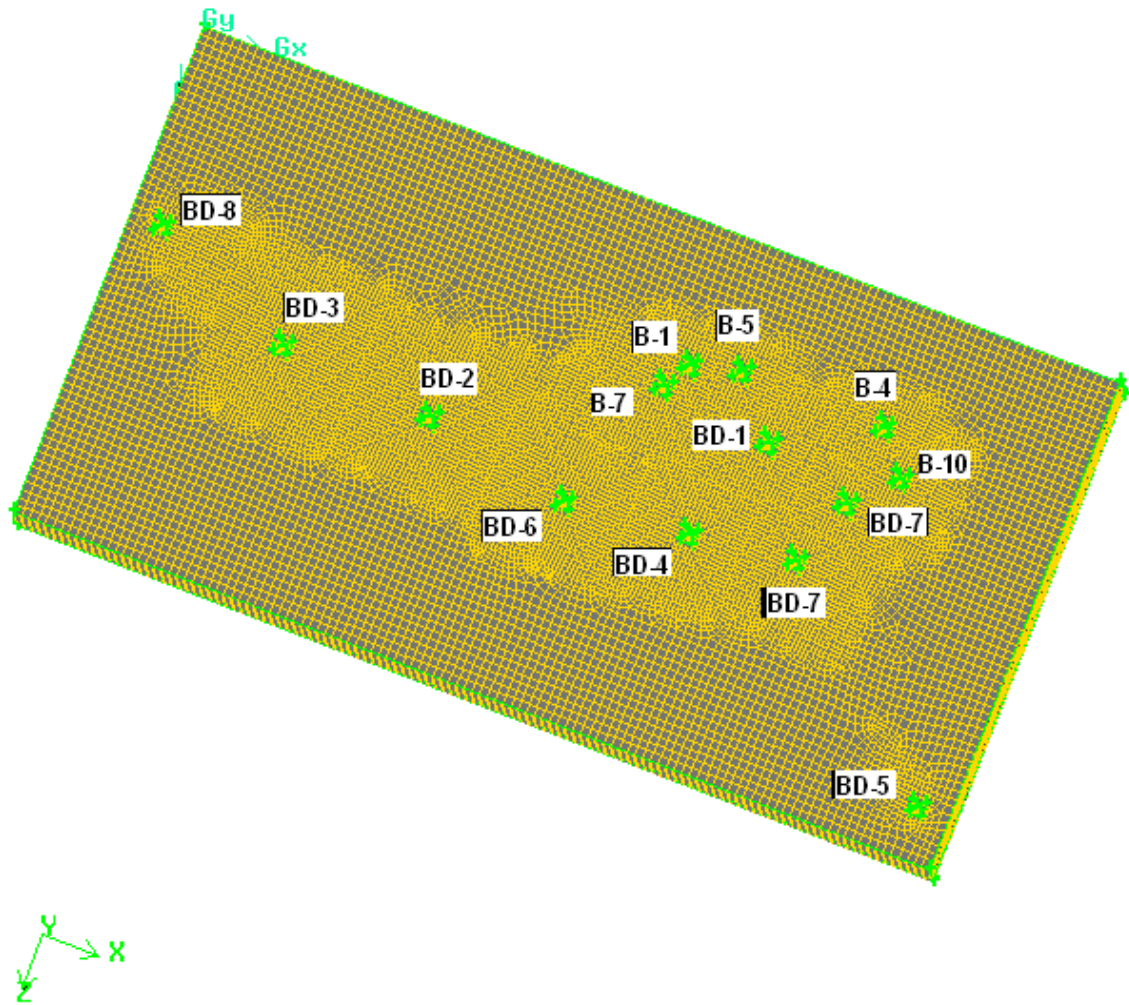**Figure. 4.4** Model 1 of the reservoir is shown volume meshes.

**Figure. 4.5** Locations of the wells from the top view in Model 1.

The design routine done while modeling of the reservoir 1 is also applied second model reservoir.

In Figure 4.6 the basic geometry of the second reservoir model is shown. From the Figure 4.6 it can be easily seen the fault Agamemnon I, the heated water from the aquifer is raised towards to the surface using Agamemnon I as a path. The extraction mechanism of geothermal fluids from the deep wells is explained according to this theory.

It is believed that shallow wells fed from the nearby water recharge zone, in modeling reservoir model 2 by using Gambit program for the part of this wells another small fault which branched from the Agamemnon I is used.
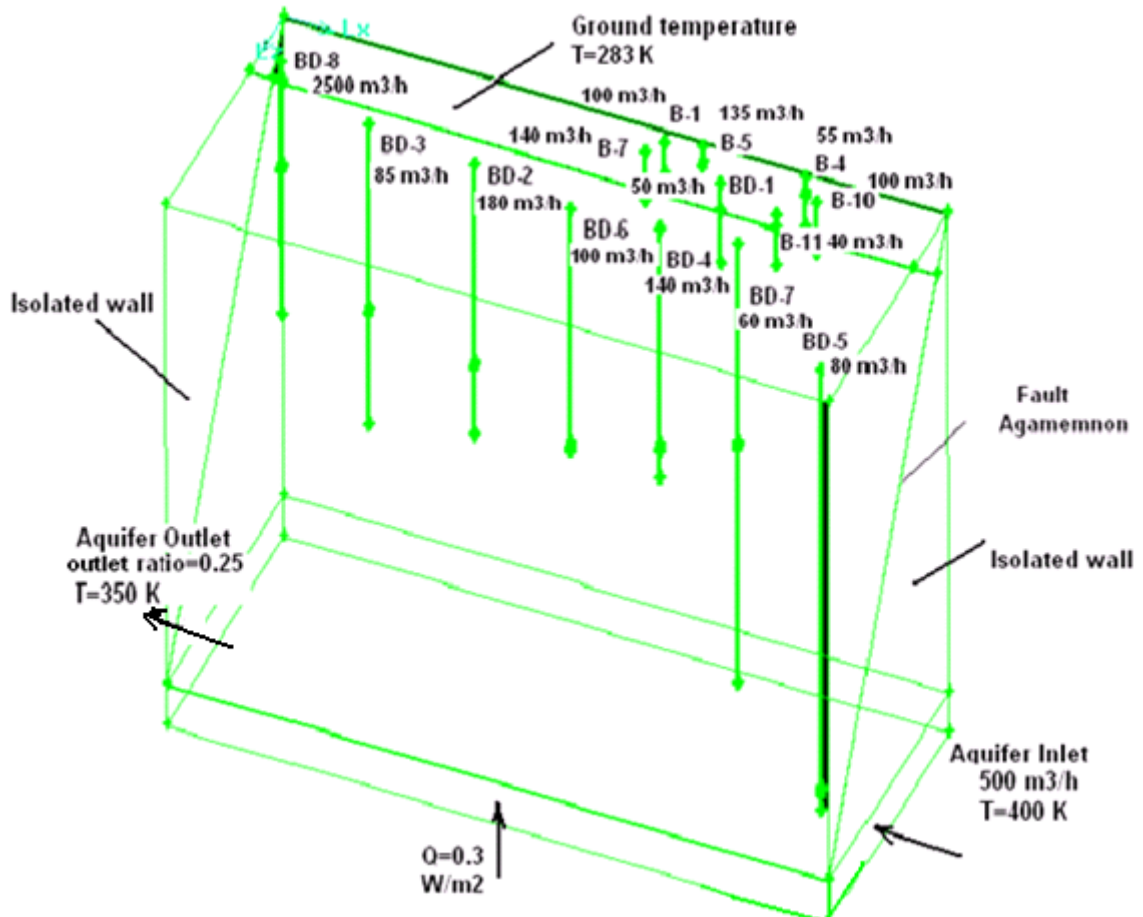
**Figure. 4.6** The basic geometry of the second model created by Gambit program

After geometry of the reservoir was drawn in Gambit program, faces and volumes of the each element were meshed.

For the complex nature of the model Tet./ Hybrid TGrid was used, according to algorithm the interval size of the each volumes are given. Due to huge geometry of the model, after meshing process the total number of mesh volumes is reached to 6,662,523 volumes which beyond the capacity of the PC computer. So in order to overcome this difficulty, the diameter of the wells is raised to 5 meter. It is thought that, this increase does not affect so much the final temperature distribution in the field because of the big sizes of the reservoir.
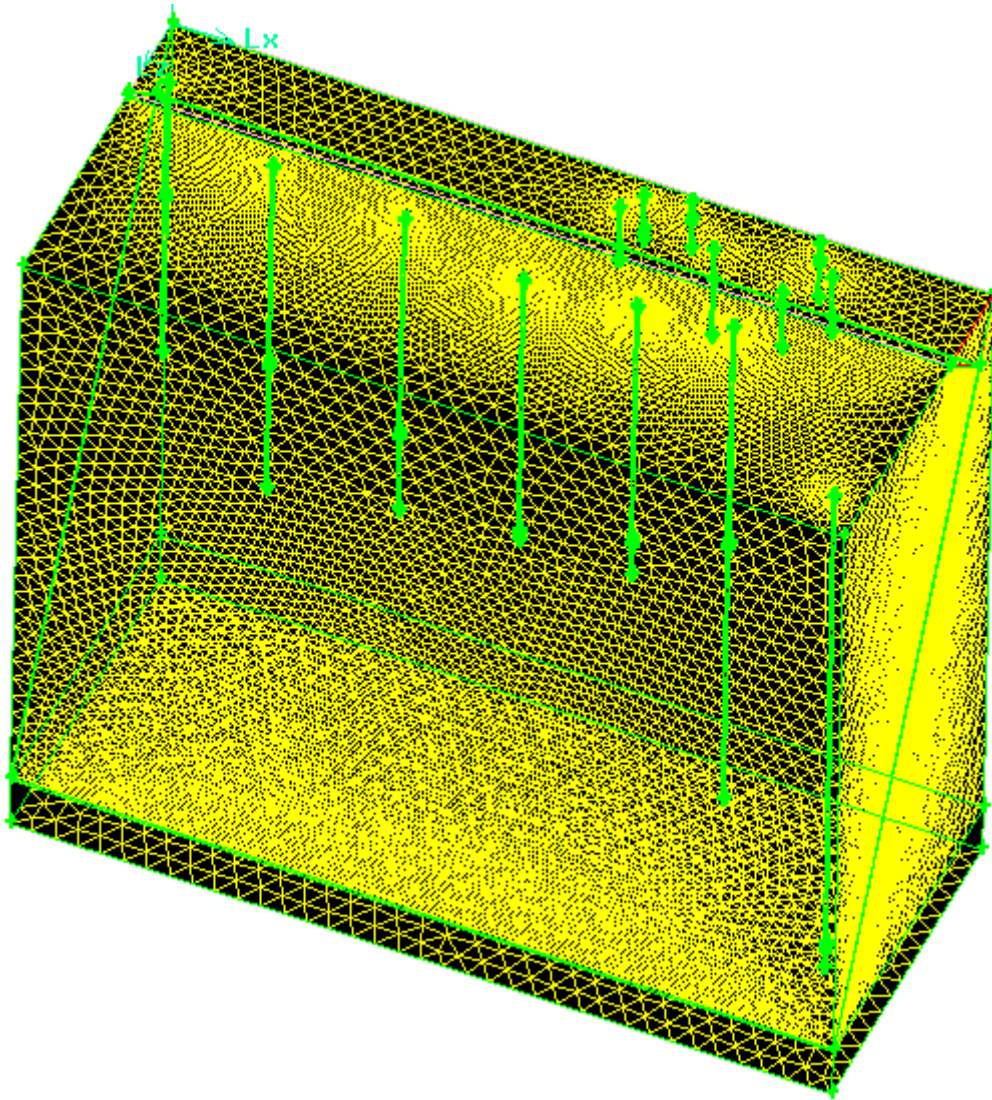
**Figure. 4.7** The second reservoir model in faced meshes.

The total numbers of the meshes caused also some interconnections to the adjacent meshes, after first export of the meshed geometry to the Fluent, some negative volumes are occurred for that reason and meshed model could not be read by the Fluent program.

To overcome these difficulties some modifications and rendering are made over the generated meshes. In Figure 4.8 detailed and zoomed views of the meshes close to the nearby wells is seen.
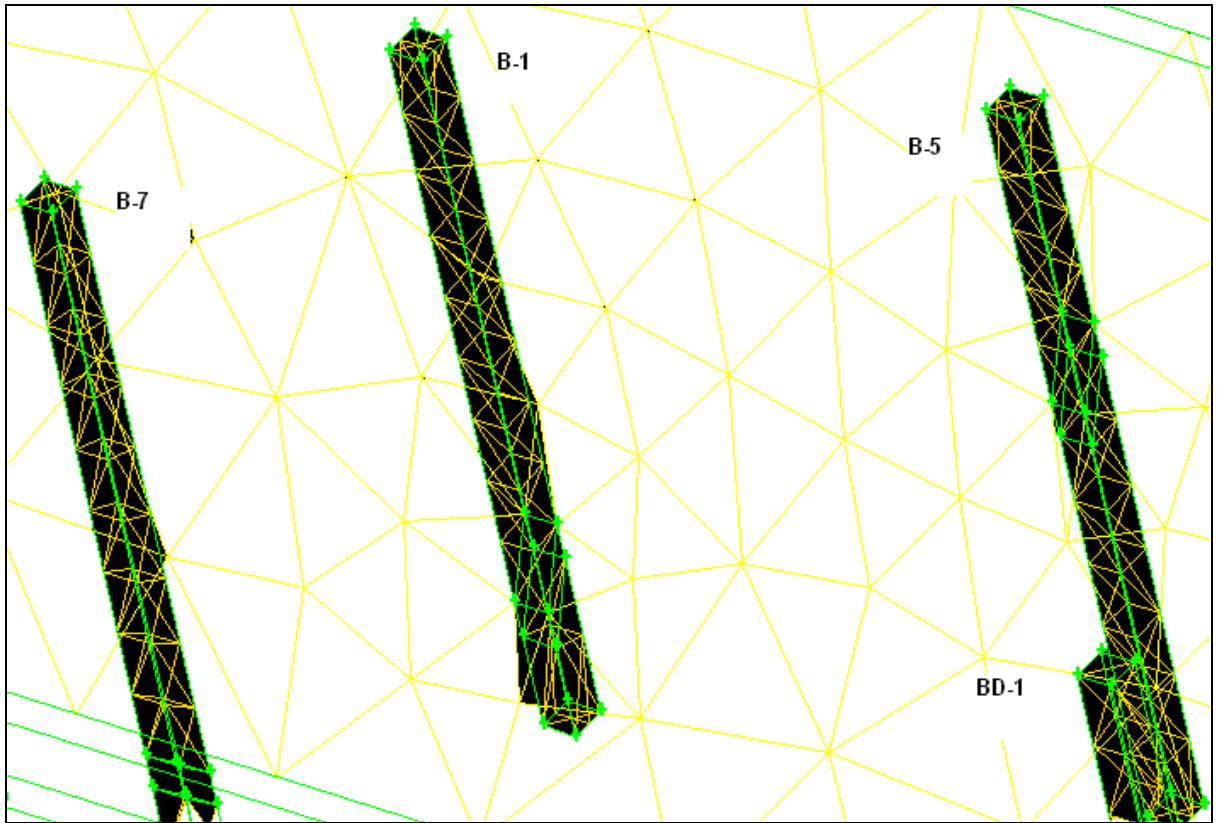
**Figure. 4.8** Volume meshes detail near the wells

After meshing all of the volumes of each model, the boundary conditions assigned to surfaces, these conditions are taken as following,

Heat is transferred from the bottom to the aquifer, the mass flow rate of wells are given according to the tabulated values measured from the reservoir by Balçova Geothermal Field.

The lateral boundaries are taken as insulated because of the amount of laterally transferred heat is very small compared to the flow of heat from the below by convection.

The top surface temperature is taken as 10 °C, which is a typical ground temperature.

# CHAPTER 5

# RESULTS AND DISCUSSION

## 5.1 The Output Temperature Distributions of the Reservoir Models

Two reservoir models created in Gambit program are exported to the Fluent separately, and run 500 iterations under same boundary conditions until the continuity, momentum and energy equations are converged and real mass values of the wells are satisfied.
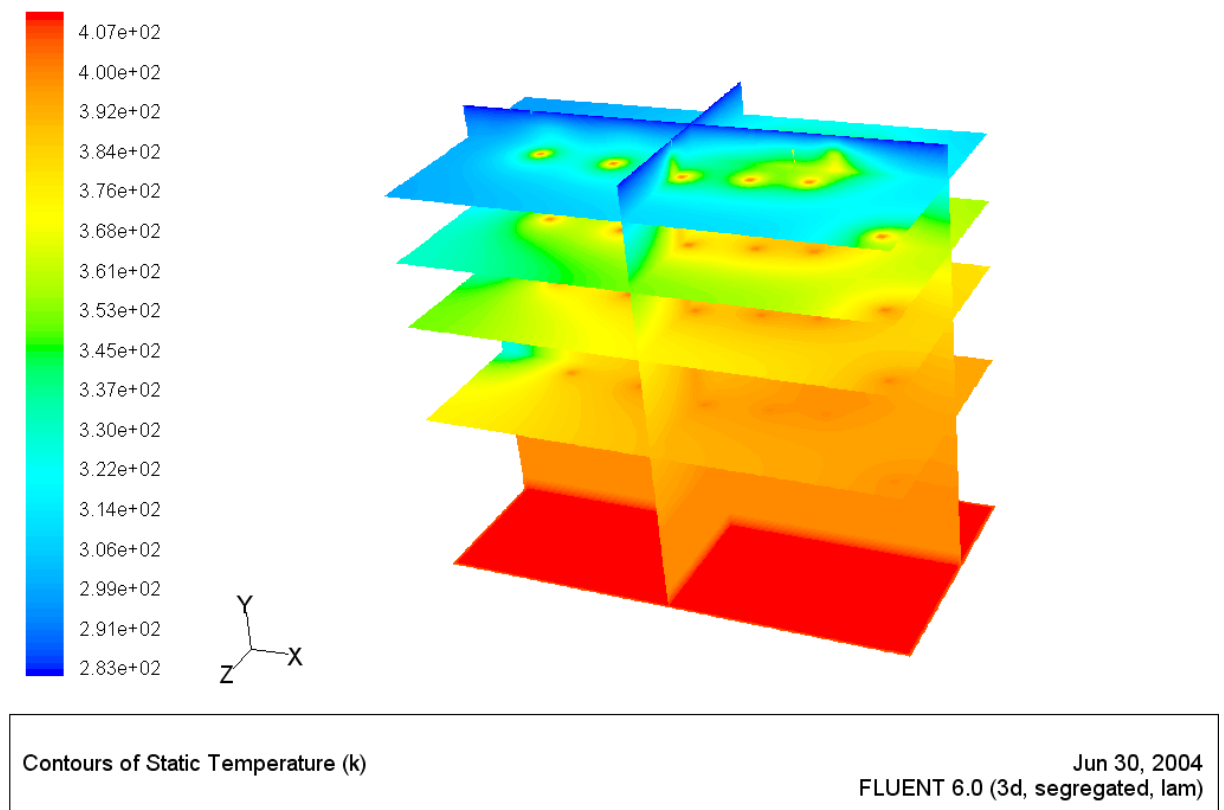
Contours of Static Temperature (k)                         Jun 30, 2004
                                        FLUENT 6.0 (3d, segregated, lam)

**Figure 5.1** Temperature distribution in model 1 with the interfaces in 100, 300, 500, and 800 meters and in middle plane.

In Figure 5.1 the temperature distribution of Balçova geothermal field is shown by the interfaces at the 100, 300, 500, and 800 meters and in middle plane. At the top interface the wells can be seen.
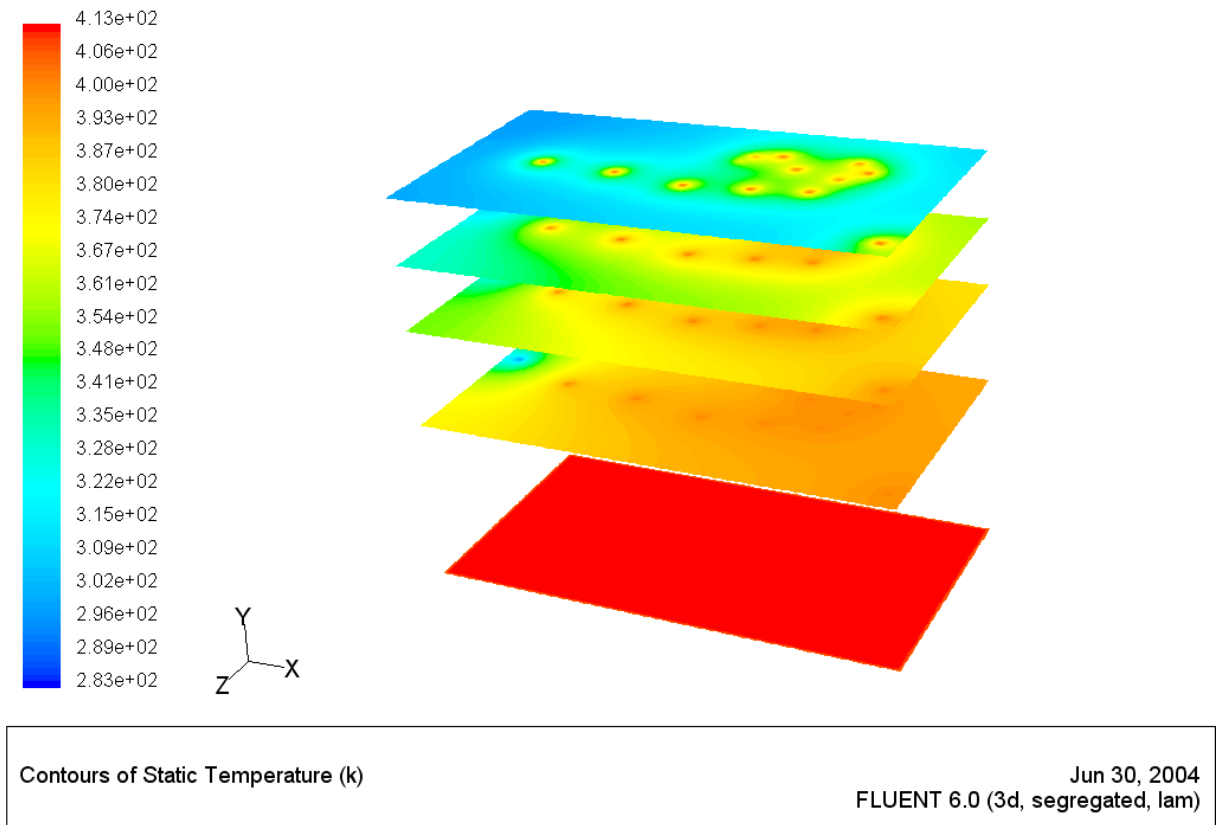


| |
|---|
| 4.13e+02 |
| 4.06e+02 |
| 4.00e+02 |
| 3.93e+02 |
| 3.87e+02 |
| 3.80e+02 |
| 3.74e+02 |
| 3.67e+02 |
| 3.61e+02 |
| 3.54e+02 |
| 3.48e+02 |
| 3.41e+02 |
| 3.35e+02 |
| 3.28e+02 |
| 3.22e+02 |
| 3.15e+02 |
| 3.09e+02 |
| 3.02e+02 |
| 2.96e+02 |
| 2.89e+02 |
| 2.83e+02 |

Contours of Static Temperature (k)                    Jun 30, 2004
                                        FLUENT 6.0 (3d, segregated, lam)

**Figure. 5.2** The contour interfaces at the depth 100, 300, 500, and 800 meters.
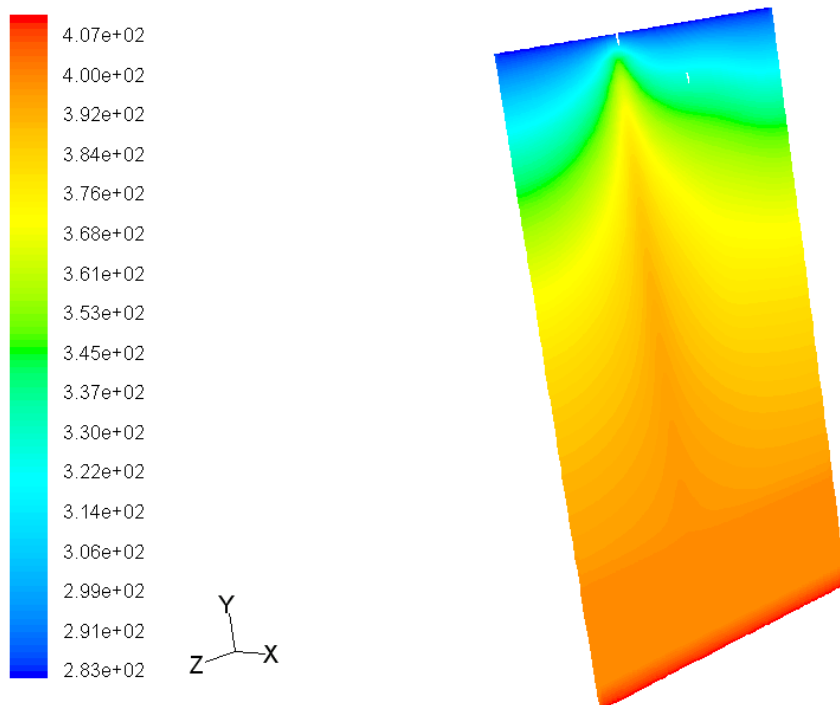
In Figure 5.2 interfaces are shown at the depth 100, 300, 500, and 800 meters.

In the following Figures 5.3 and 5.4 two different temperature distribution taken form two middle plate are shown.
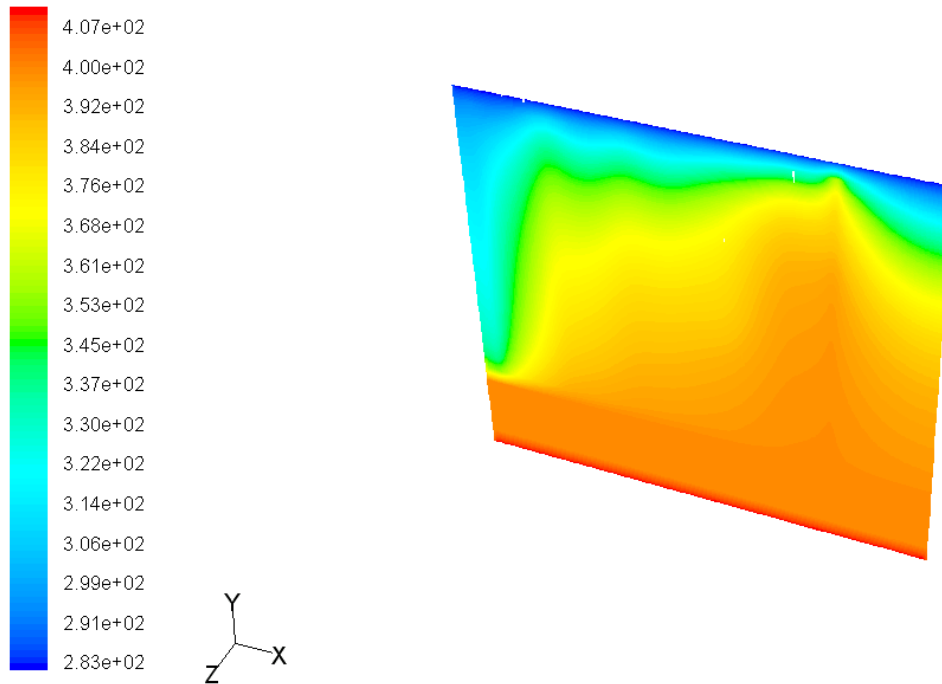
Contours of Static Temperature (k)

Jun 30, 2004
FLUENT 6.0 (3d, segregated, lam)

**Figure. 5.3** Middle plane along the direction of East / West



Contours of Static Temperature (k)

Jun 30, 2004
FLUENT 6.0 (3d, segregated, lam)

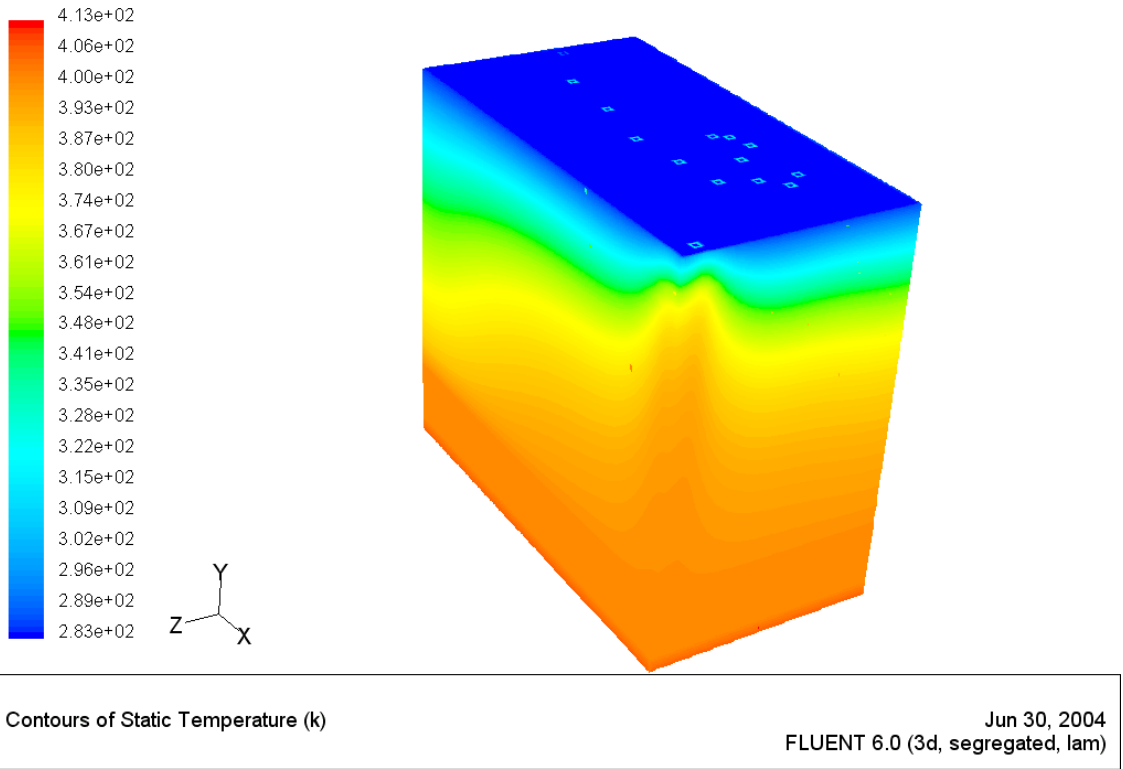**Figure. 5.4** Middle plane along the direction of North / South.

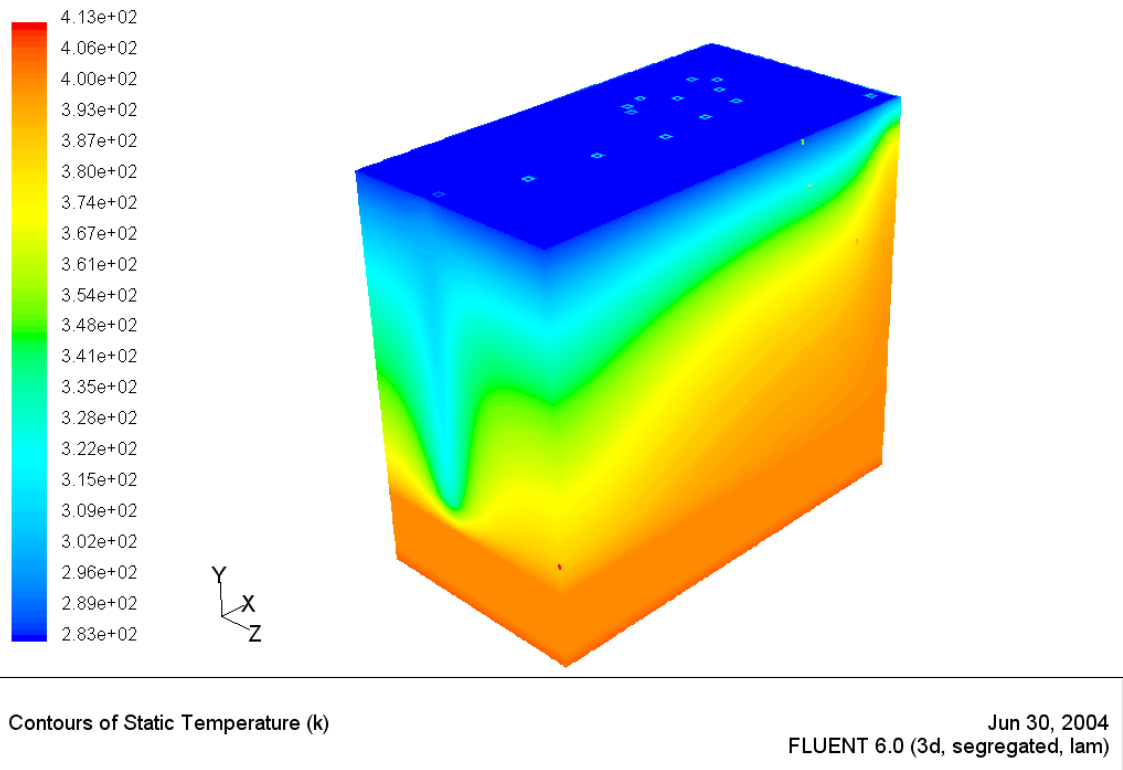**Figure. 5.5** 3-D reservoir temperature distribution from the west view.



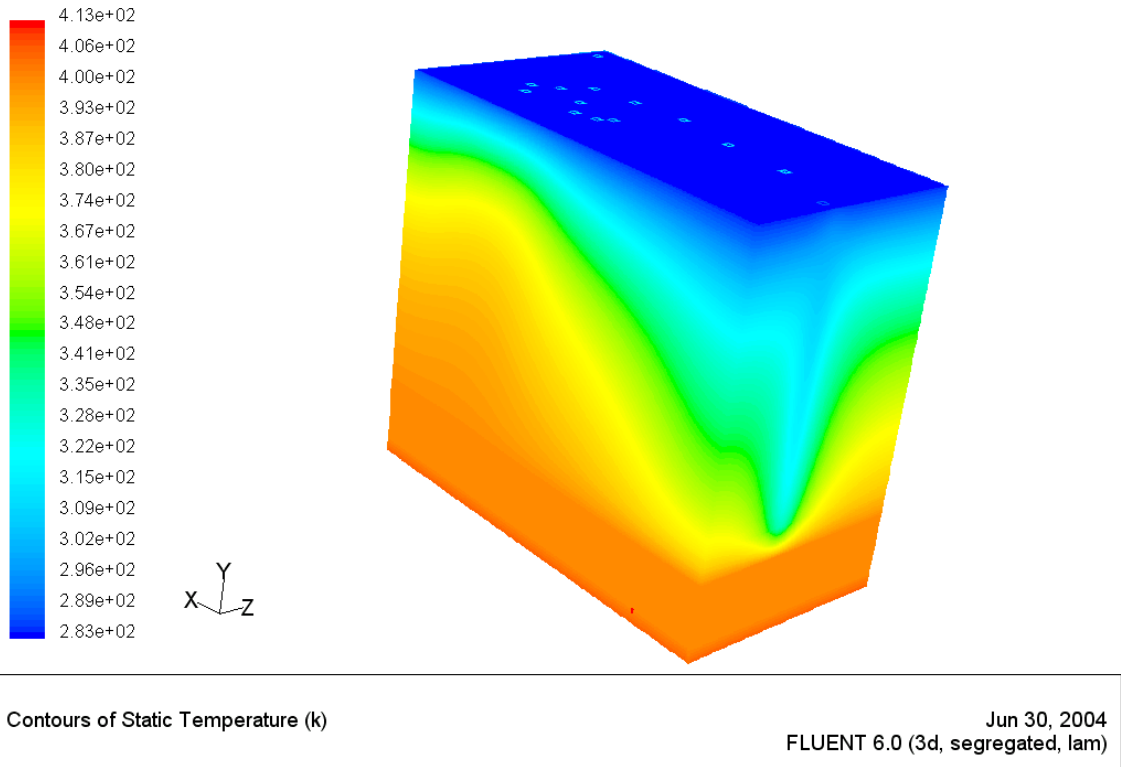**Figure. 5.6** 3-D reservoir temperature distribution from the east, showing the effects of reinjection from BD-8

**Figure. 5.7** 3-D reservoir temperature distribution from the east.
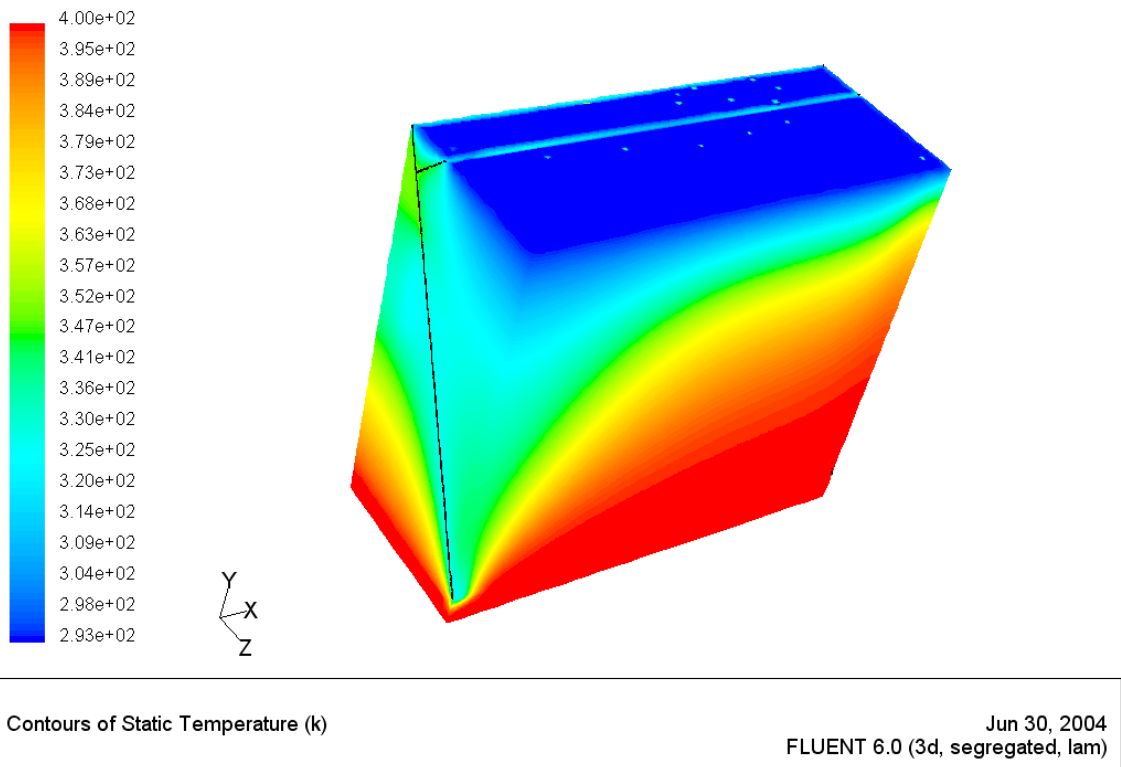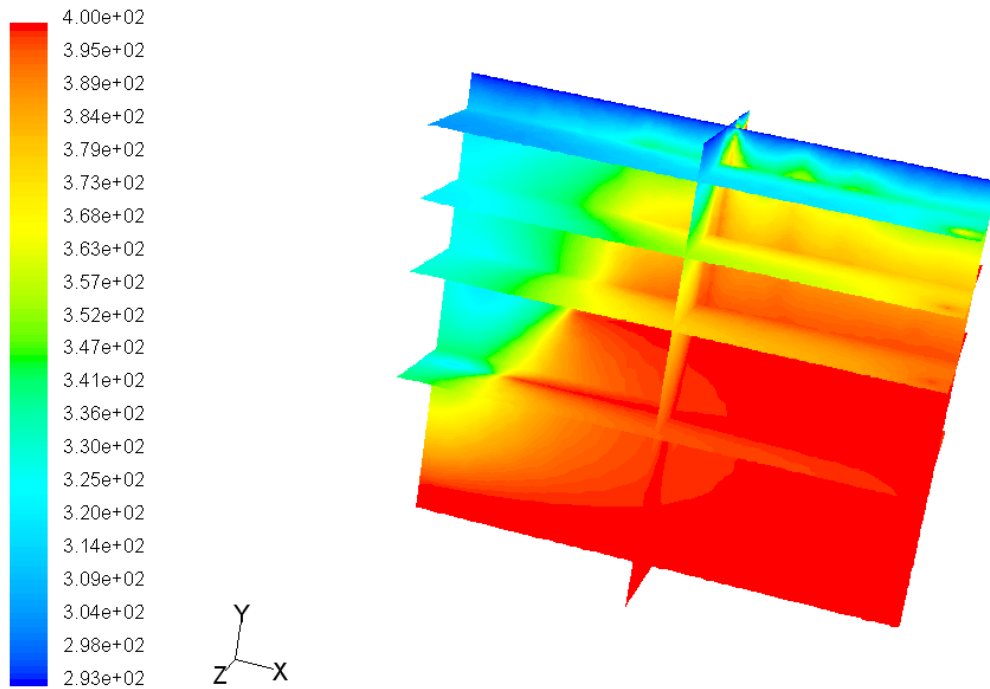
**Figure. 5.8** 3-D reservoir temperature distribution from the west according to the

second model of the reservoir.

Contours of Static Temperature (k)                                    Jun 30, 2004
                                                        FLUENT 6.0 (3d, segregated, lam)

**Figure. 5.9** The interfaces of second reservoir models taken from second model of the reservoir.

In Figure 5.5, 5.6, and 5.7, 3-D temperature distribution of the reservoir is shown from NW, NE and SE views respectively.

In Figure 5.8 3-D temperature distribution of the reservoir according to the second model is shown. Temperature distribution in model 2 with the interfaces in 100, 300, 500, and 800 meters are shown.

# CHAPTER 6

## CONCLUSIONS

In this study, initial conceptual model of the reservoir is created as a first step based on current measured data and previous modeling study of Balçova geothermal field.

From the conceptual model of the Balçova Geothermal Field, it is thought that the Agamemnon-I fault exist in the field dominate geothermal fluid transport. It is assumed that heated water from the below aquifer due to its decrease in its density goes up towards the surface by using Agamemnon-I fault as a path.

The model of the reservoir is created by using Gambit mesh program; two kinds of reservoir model are developed. One of them without Agamemnon-1 fault, however the extension from the depth of the wells to the aquifer represents the up flow of heated water along the Agamemnon fault. The other model includes Agamemnon-1 fault with its small parts. It is assumed that the heated water rising up using this small part of the Agamemnon-1 fault explain the hot geothermal water extraction from the shallow wells.

After the geometry is drawn in Gambit meshing program, all of the elements are splitted up each other and due to complex nature of the geometry, the reservoir are meshed by tetrahedral grids with proper interval and mesh size.

The boundary conditions are applied to meshed geometry; the top surface is taken at a constant ground temperature, lateral boundaries are isolated due to low values of the heat transfer to the lateral surfaces compared to the convective heat transfer from the deep of the reservoir and the heat given from the bottom is assumed as 0.3 W/m$^2$. [13]

After the creation process by using Gambit program the meshed reservoir exported to the Fluent program, mass flow rates of the each wells and the aquifer are entered to the program. Moreover, thermal properties of the rocks are taken from the previous reservoir study. [13]

The models are run and iterated by Fluent program until the mass flow rates, well temperatures are converged. From the simulation of the models two kinds of temperature distribution of the field are obtained.

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