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Investigation of Vertical Connectivity between Productive Reservoirs in Kızıldere Geothermal Field with a Numerical Reservoir Model

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ABSTRACT

Geothermal energy is considered one of the renewable and clean energy sources. The sustainability of geothermal reservoirs is dependent on the reinjection of waste brine through a well-designed reinjection program. Reinjection programs are designed based on geothermal reservoir characterization methods. Geothermal reservoirs include natural fractures which have anisotropic properties. Reservoir characterization techniques are typically applied to characterize heterogeneous systems. Reservoir modeling is one of the most comprehensive approaches including many characterization methods. The model is populated with various data sources such as drilling, geology, well testing, reservoir monitoring, and geochemistry. This study mimics the Kızıldere Geothermal Field with a synthetic reservoir model using TOUGH2 software. The study investigates the connectivity between the two distinct producing reservoir sections: Sazak Formation and Menderes Metamorphics. The model involves two production, three reinjection, and two observation wells. Sensitivity analysis was performed for the caprock's permeability laying in between the producing sections to reveal the connectivity in the vertical direction. The study showed that the caprock prevents the hydraulic connection between the two producing sections. Therefore, a separate reinjection program was found essential for the sustainability of both producing reservoirs.

1. INTRODUCTION

Geothermal energy is mined by transferring heat energy towards earth surface with fluids in fractured systems. Reinjection of waste fluid into geothermal reservoir is critical for the sustainability of geothermal production. The reinjection strategy should maintain reservoir pressure, while not cause to significant temperature decline in the production wells. Therefore, configuration of production and reinjection wells play an important role in the development of geothermal fields. Well locations are typically determined by considering the tectonic characteristics of the field, formation characteristics, and temperature distribution in the reservoir.

Kızıldere Geothermal Field, which is located in the western part of the Turkey has mainly two distinct reservoir sections which are called as Sazak Formation and Menderes Metamorphics. Sazak Formation has limestone dominated geothermal reservoir while Menderes Metamorphics is characterized with marble, calcschist and quartzite lithologies along the reservoir section. The field is under operation since 1984. After the privatization of the geothermal field, the total power installed capacity in the field was reached to 260 MWe_{gross} by 2018. With the increased installed capacity, production from the field has increased significantly. Şentürk et al. (2020), reported a substantial pressure decline in the deep production zones (Menderes Metamorphics). A rehabilitation program was implemented in the reinjection strategy. The study showed that appropriate reinjection policy and practices are essential for a sustainable production. Reservoir characterization is critical for determining reinjection strategies. Various reservoir characterization techniques are applied to determine appropriate reinjection and production patterns. Tracer testing, well pressure tests, seismic, drilling mud loss, field geology, chemical monitoring of the geothermal fluid, and production monitoring are the most widely used techniques. These techniques have certain advantages and disadvantages. To illustrate, geometry of the reservoir and fault zones can be determined with seismic, however, it is not possible to estimate permeability of the faults with seismic. This information can be obtained through well tests after the drilling process has been completed. Similarly, outcrop analysis provides crucial information about reservoir rocks, however, outcrops are not at confined pressure, and they are exposed to deformation like weathering.

This study includes how good the connection is between the two distinct reservoir sections, Sazak Formation and Menderes Metamorphics in Kızıldere Geothermal Field, Turkey. A synthetic reservoir model mimicking the Kızıldere Geothermal Field was constructed. The connection between the two distinct production zones was examined under different permeability values of the Kızılburun Formation. The study area is located in the eastern end of Büyük Menderes Graben (western part of Turkey) and it covers an area of around 9 km^2 (Figure 1).



Figure 1: Location of the study area (Google Earth view)

2. GEOLOGICAL SETTING OF THE STUDY AREA

Kızıldere Geothermal field is in the eastern part of the Büyük Menderes Graben. Menderes Metamorphics is the basement formation, which is overlain by sedimentary succession. Core rocks of the Menderes metamorphics are migmatites, paragneiss and orthogneisses, amphibolites, granulites and eclogites (Oberhansli et al., 1997, Candan et al., 2001). According to Göncüoğlu (2010); the core rocks are unconformably overlain by schist-dominated units with few quartzite transitions. In the same study, it was stated that the schist unit is overlain by Mesozoic platform type marbles, calcschist and dolomitic marbles. Paleocene-aged thin-bedded red marbles form the uppermost layer of the Menderes Metamorphics (Dora et al., 1991). Marble, quartzite, and gneiss are brittle rocks. Due to their structures, they have high potential as a geothermal reservoir rock.

Above Menderes metamorphics, sedimentary succession starts with the Kızılburun Formation consisting of mainly red-colored mudstone and transition with sandstone and conglomerate (Aksu, 2019). Menderes Metamorphics is unconformably overlain by the Kızılburun Formation. The unit is known as a cap rock for the geothermal system due to its fine-grained, low-permeable zones. Kızılburun Formation is overlain by the Sazak formation, which is composed of mainly limestone, clayey limestone, and marl. In terms of a geothermal system, this formation is an excellent reservoir rock due to its karstic nature and fragile rheology. Kolankaya formation, which has mostly marl unconformably overlies Sazak Formation. Kolankaya Formation also shows cap rock properties due its low permeable zones. The Tosunlar formation unconformably overlies the older stratigraphy and consists of yellow-brown, polygenic, poorly sorted conglomerate, and occasional mudstone transitions. Tosunlar Formation is unconformably overlain by Quaternary deposits composed of poorly sorted, alluvial fan and fluvial deposits consisting of gravel, sand, and mud (Alçiçek, 2007). Aksu (2019) constructed a stratigraphic columnar section of the study area (Figure 2).

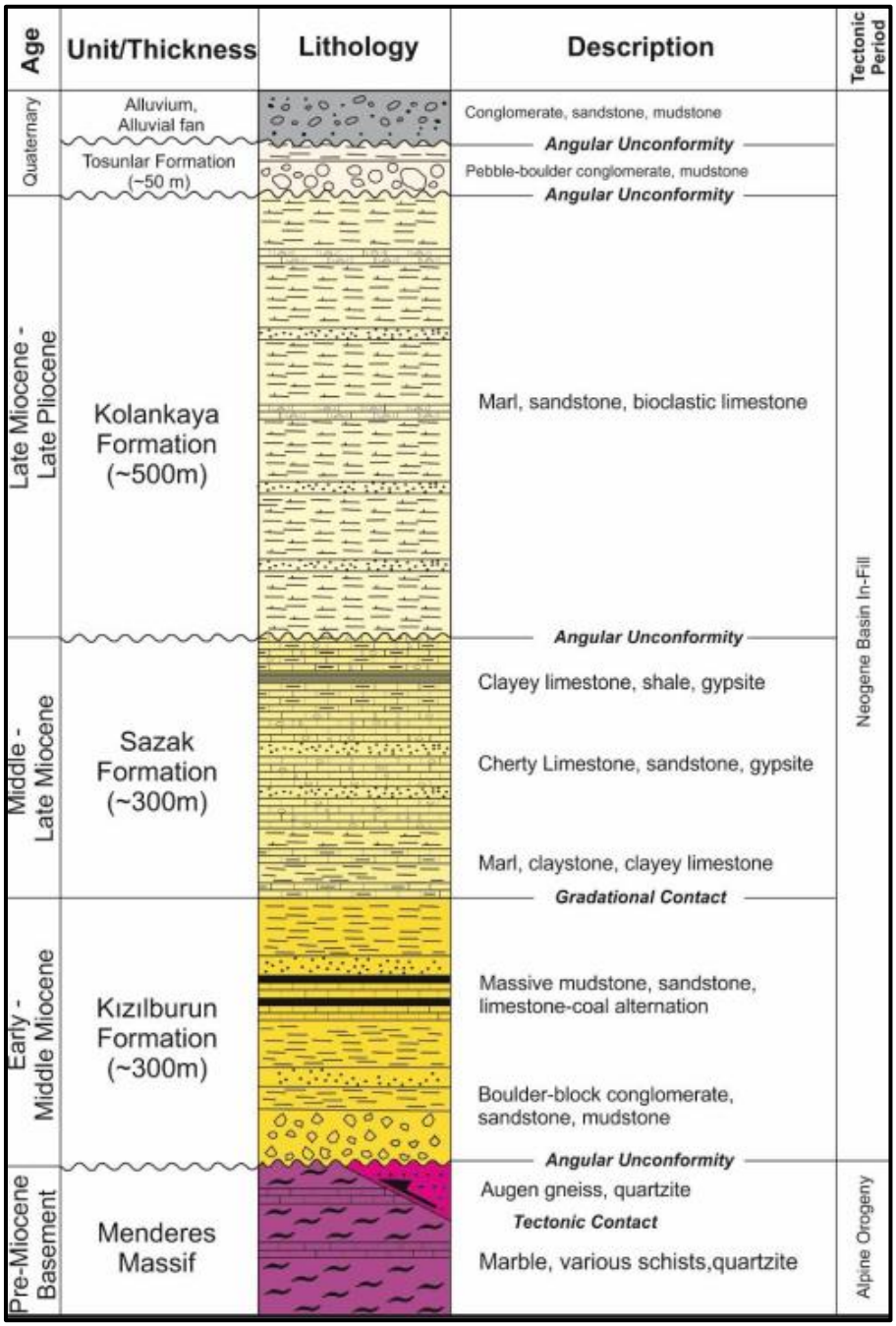

Figure 2: Generalized columnar section of the study area (Aksu, 2019)

3. STRUCTURAL SETTING OF THE STUDY AREA

Kızıldere Geothermal Field, where extensional tectonics is active, has hosted much research on the investigation of structural elements. Among the recent studies, 4 different structural elements were mapped in the study area (Sümer et al., 2020). These are the E-W trending low angle Büyük Menderes Detachment Fault (BMDF), Miocene aged N-NE trending faults, Quaternary aged Gökdere fault containing WNW-ESE trending high angle fault segments, and WNW-ESE trending high angle normal fault systems controlling the formation of the youngest sediments in the graben (Figure 3). The authors stated that BMDF was cut by NW-SE trending faults and inclined towards the north with faults. In addition, it has been explained that the strikes from the fault planes related to the BMDF are changing in between N 21º-80º W. Also, the dips vary between 7º-34º to the S.W., 10º-32º to the N.E. (Sümer et al., 2020). N-S faults have NNE and NNW strikes, and they are strike-slip fault systems with the normal-slip component. Aksu (2019) stated that the rock alterations and fumaroles in the region are widely observed on the N-S faults, so this type of fault in Kızıldere constitutes the main element of the geothermal system and the dip angles vary between 60º and 86º. The Gökdere Fault is defined as an oblique fault with a strike between N60ºW and N75ºW, dipping approximately 70-75º to SW and having >75º rake (Sümer et al., 2020). The E-W faults in the region are normal faults dipping south, varying between 60º-85º (Aksu 2019).

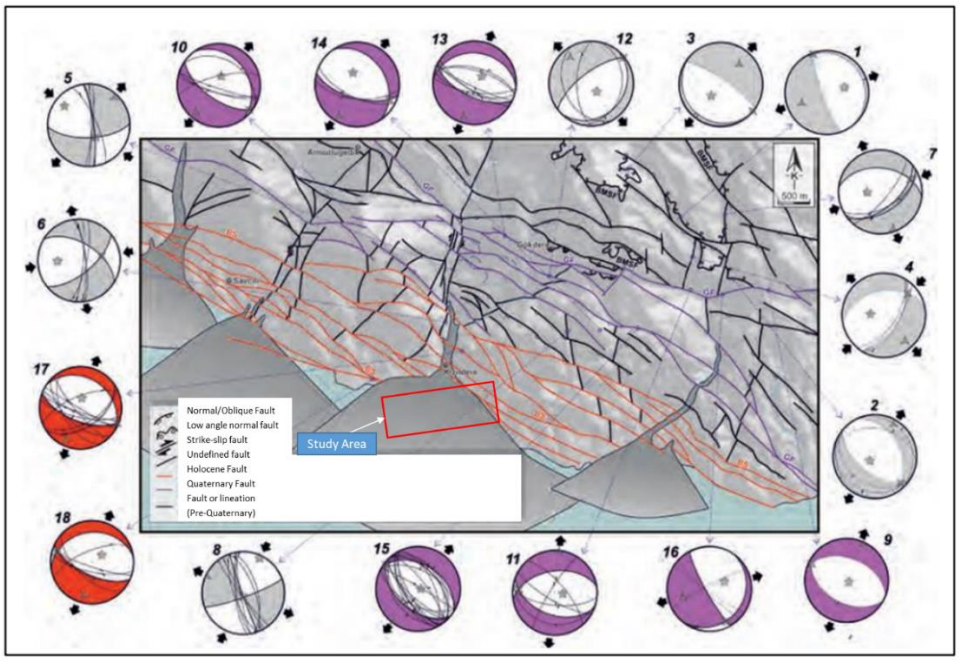

Figure 3: Tectonic map of the study area (Modified after Sümer et al., 2020)

4. METHODOLOGY

Most of the geothermal reservoirs are present in fractured rocks. Defining flow in porous and fractured media plays an important role in geothermal reservoir simulation studies. The main issue here is the identification of fracture-matrix interaction under various conditions (e.g., multiphase flow) (Küçük, 2018). Flow simulation in fractured geothermal systems can be done with three different methods (Figure 4). These are the equivalent continuum approach, dual porosity approach and discrete fracture network approach. The equivalent continuum approach is based on equivalent porosity, and as the number of fractures increases, the system gets closer to the porous system. In the dual porosity approach, permeability of fractures and pores are used separately. Therefore, primary porosity and secondary porosity are introduced into the model. In the discrete fracture network approach; geometric properties of fractures and their communication with each other are used. The geometric properties (direction, slope) of fractures must be known (Aydın and Akın, 2019). In this study, the equivalent continuum approach method was used to define flow in fractured media.

In this study, to create a conceptual model, firstly, the lithological logs of the geothermal wells were introduced into the model to create the stratigraphy of the study area. In addition, structural elements have been defined. Besides, the permeability, porosity and the other rock properties regarding the dominant rocks have been assigned separately. In the numerical modeling phase, initial conditions and boundary conditions were defined and, production and injection flow rates were introduced into to the model. The study includes 7 wells: 3 injection, 2 production, and 2 observation wells. Numerical simulations were performed via TOUHG2, while the Petrasim program was used as a graphical interface.

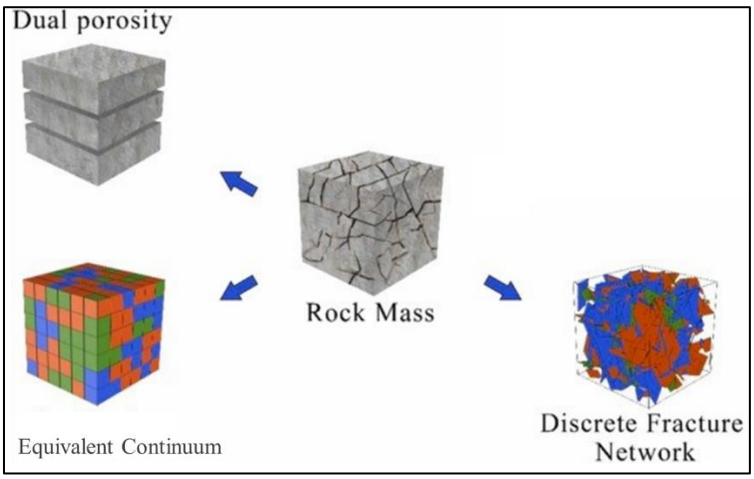

Figure 4: Flow simulation methods in fractured rocks (Modified after Zhang et al., 2022).

5. SIMULATION & RESULTS

5.1 Conceptual Model of the Kızıldere Geothermal Field

In order to reveal the processes occurring in a geothermal system, a conceptual model is created, and an interdisciplinary cooperation is needed in the development of the model. In the model, parameters related to geology, geophysics, temperature and pressure distribution of the reservoir, permeability distributions are used (Akan 2002). Haklıdır et al. (2021) developed a conceptual model for the Kızıldere field (Figure 5). According to this model, rainwater descends to reservoir levels through fractured systems. The fluid is heated by conductive and convective heat transfer. The fluid, which is trapped by the effect of the low permeability cap rock, reaches the surface through the fracture systems by rising with the effect of the pressure gradient. Contrary to the conceptual model below, 2 main reservoir zones are defined in this study. The reason for this is that the reservoir levels in the Menderes metamorphic are thought to have very high communications.

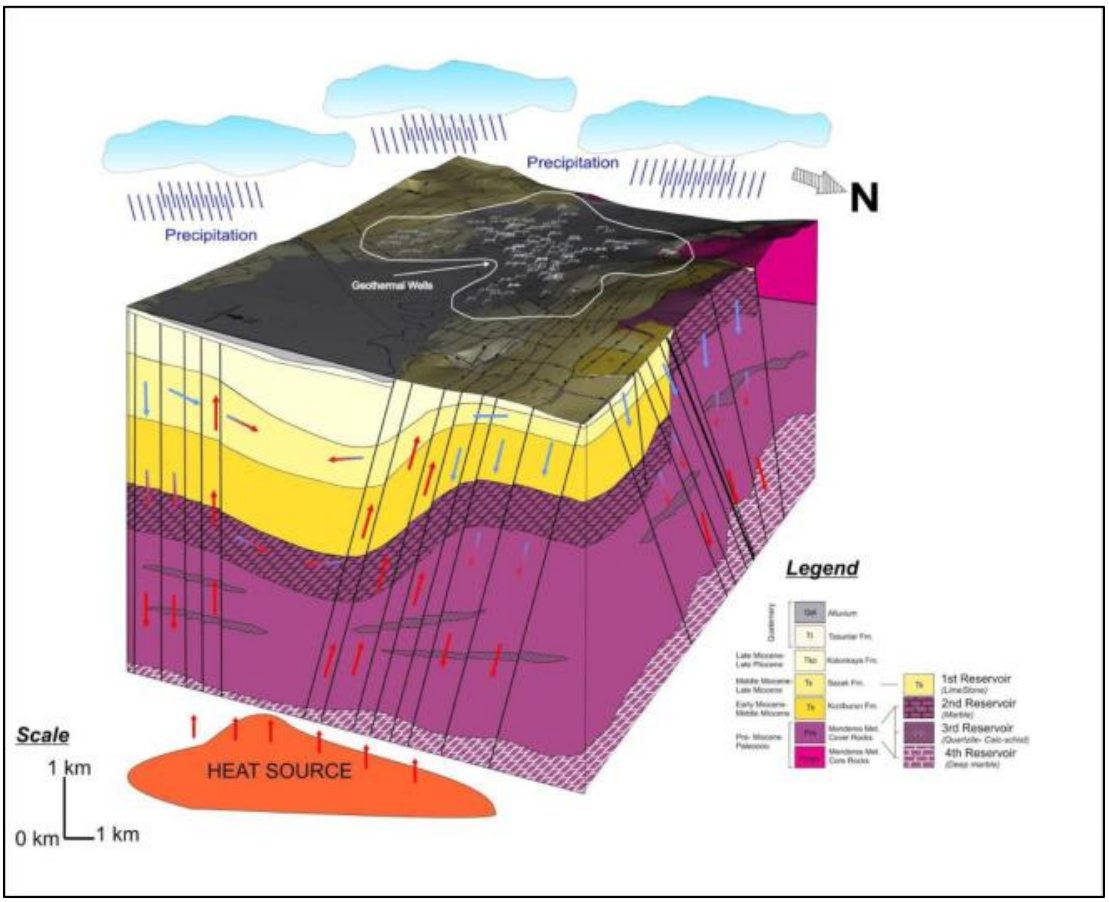

Figure 5: Conceptual model of Kızıldere Geothermal Field (Haklıdır et al., 2021).

5.1.1 Stratigraphy and Structural Elements

As explained in the Geologic Setting part, the study area has mainly two reservoir sections which are Sazak Formations and Menderes Metamorphics. Sazak Formation consists of mainly limestone which forms the first reservoir zone of the Kızıldere Geothermal Field. Above the Sazak Formation, there is a Kolankaya formation, including claystone and marl. Kolankaya Formation has good caprock properties in terms of a geothermal system. Below the Sazak Formation, Kızılburun Formation is found with the cap rock property developed by claystone dominant lithology. Below the Kızılburun Formation, Menderes Metamorphics, the second reservoir zone is found. It includes marble, calcschist, and quartzite in reservoir sections. A 3D lithological model of the study area was created by using the lithological logs of the wells drilled in the region (Figure 6).

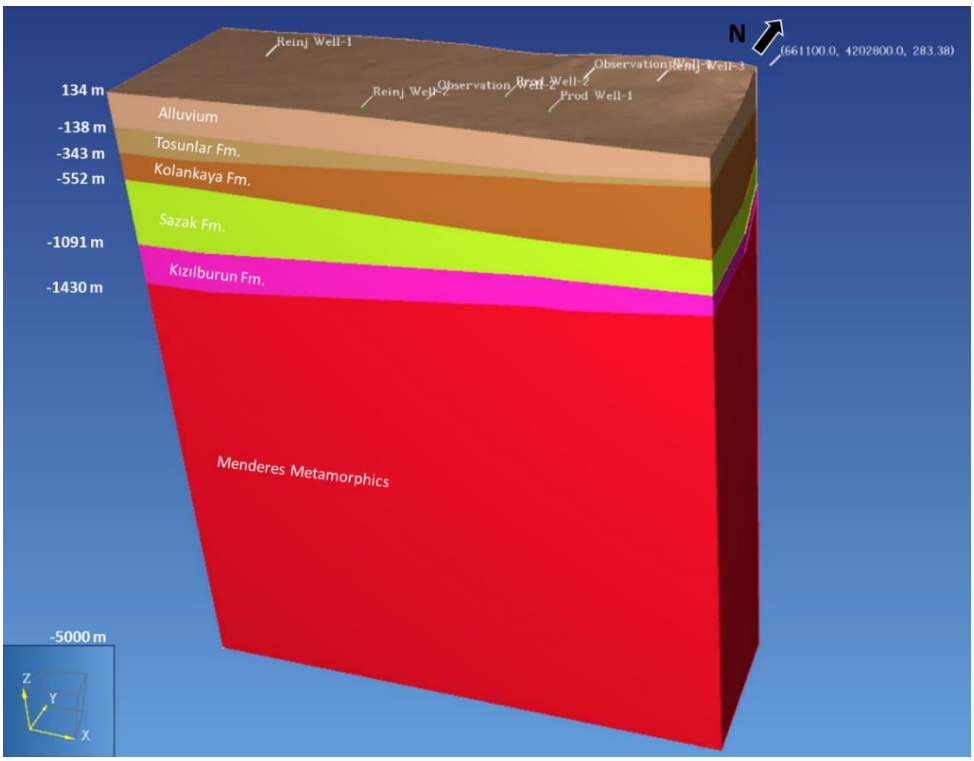

Figure 6: 3D Lithological model of the Study Area

Faults are one of the main components of an extensional geothermal system (Moeck, 2014). Deep geothermal fluid moves towards the surface through faults. Kızıldere Geothermal Field is under the influence of E-W striking normal faults and N-S strike-slip and oblique faults (Aksu, 2019). One of the N-S faults that play an important role in the Kızıldere geothermal system, the Gebeler Fault is a west-dipping fault with a lateral component. In the study area, apart from the Gebeler Fault, there are also N-S faults, Fault-A and Fault-A2 (Figure 7). Fault-A is a normal fault trending between NNW and NNE, dipping towards east (Aksu, 2019). Fault-A2 is a normal fault trending WNW-SE and dipping east. In addition, Fault-2, which is a normal fault dipping to the south, is passing through the study area (Aksu, 2019).

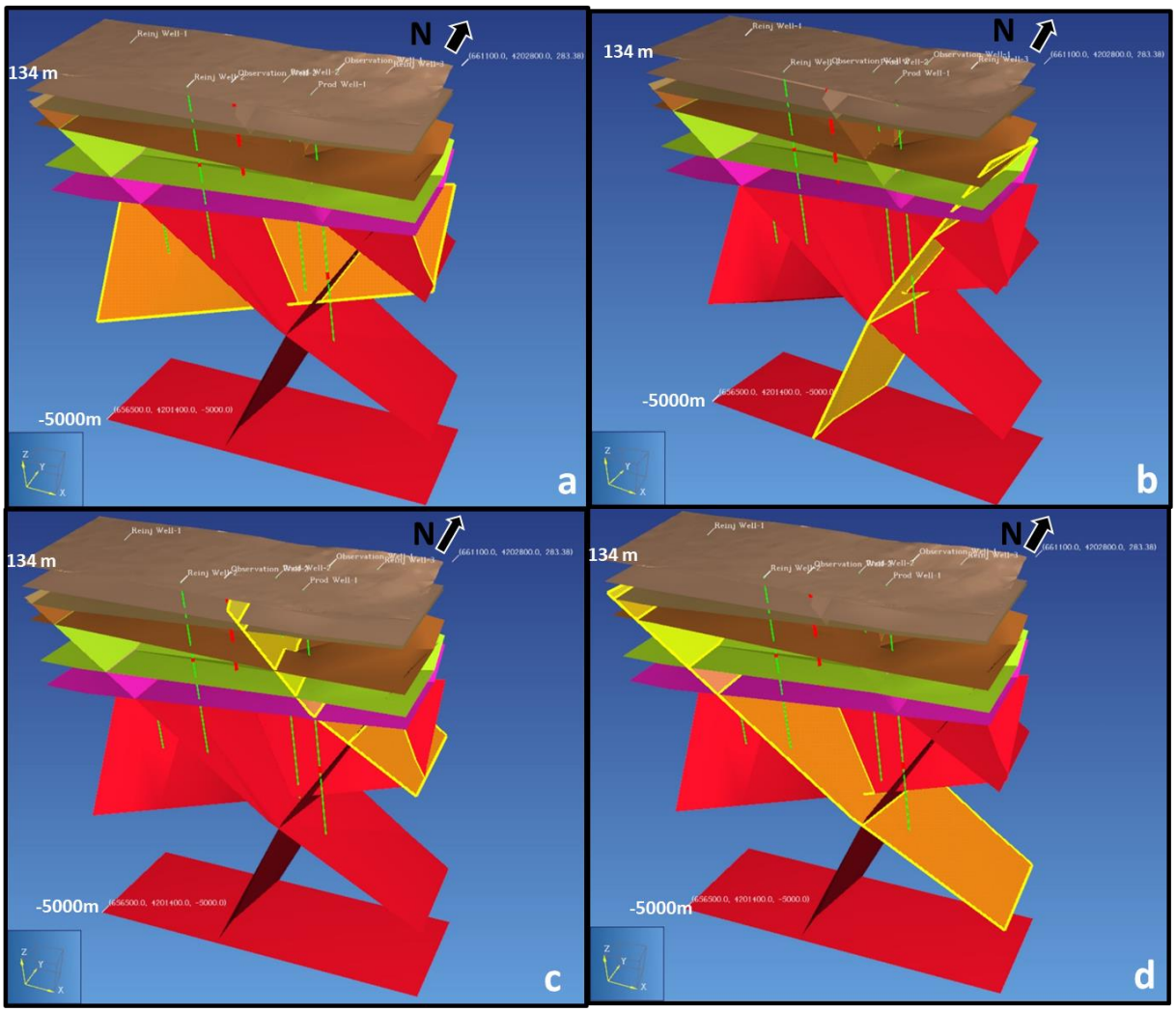

Figure 7: Fault systems related to study area a) Fay-2 b) Gebeler Fault c) Fay-A, d) Fay-A2

5.1.2 Gridding of the Model

The synthetic model based on Kızıldere Geothermal Field was divided into three-dimensional rectangular grids with different sizes. While larger grids were preferred at the outer boundaries of the model, rather small grids were preferred in the areas where wells and faults are located. This is because heterogeneities can be better represented, and more accurate simulation results can be obtained.

In the model, 6400 grids were used. The number and size of grids used along the x, and y axes in the model are shown in Table 1 (x-axis E-W directional; y-axis N-S directional). On the Z axis, the model was divided into 25 grids. Well locations from the top view are as in Figure 8, and the grid system of the model is shown in Figure 9.

Table 1: Grid size distribution along the model area

x, E-W		**y, N-S**		**z**	
Number of Grid	**Grid Size (m)**	**Number of Grid**	**Grid Size (m)**	**Number of Grid**	**Grid Size (m)**
16	312.5	16	112.5	25	Various
Total: 5000 m		Total: 1800 m		Total: 5134 m	



Figure 8: Well locations (Top view)

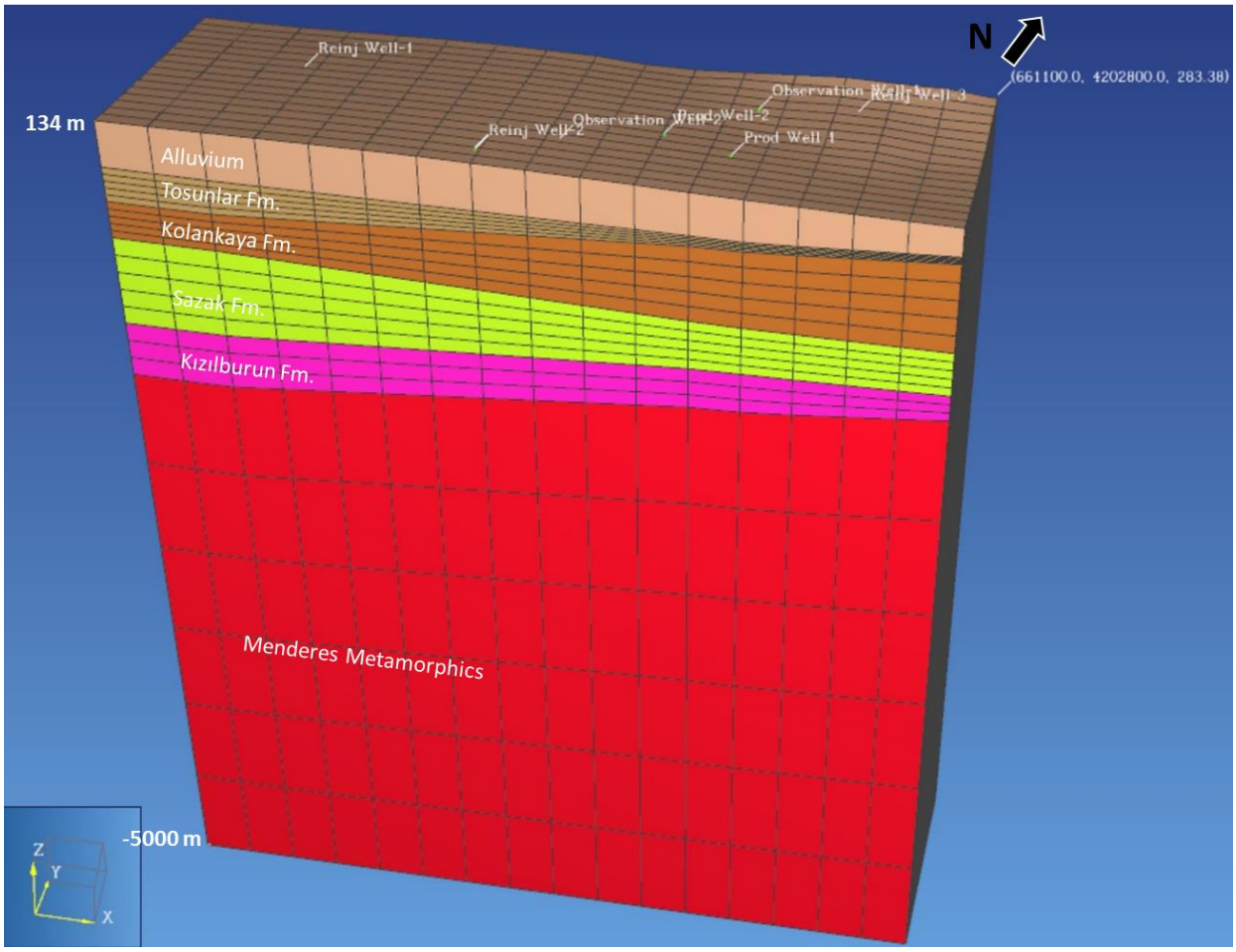

Figure 9: Grid system of the model

5.1.3 Rock Properties

Porosity and permeability values were assigned by considering the dominant lithologies, faults and reservoir characteristics of the formations (Table 2). Grids close to faults were assigned with high porosity and permeability values. In addition, rock features were introduced to the program according to the dominant lithologies of the formations (Table 3).

Table 2: Porosity and permeability values of the formations

Formation	Porosity (%)	Permeability (x-axis) (mD)	Permeability (y-axis) (mD)	Permeability (z-axis) (mD)
Tosunlar Fm.	20	50	50	25
Kolankaya Fm.	20	50	50	25
Sazak Fm.	15	40	40	20
Kızılburun Fm.	10	5	5	5
Menderes Metamorphics	3	30	30	10

Table 3: Rock properties of the model

Formation	Rock Density (kg/m3)	Rock Specific Heat (J/kg ℃)	Wet Heat Conductivity (W/m ℃)
Tosunlar Fm.	2500	920	1
Kolankaya Fm.	2420	920	1
Sazak Fm.	2600	1000	1
Kızılburun Fm.	2420	920	1
Menderes Metamorphics	2600	1000	1

After the porosity and permeability values were assigned to the model, models showing the distribution of parameters were created (Figure 10, Figure 11).

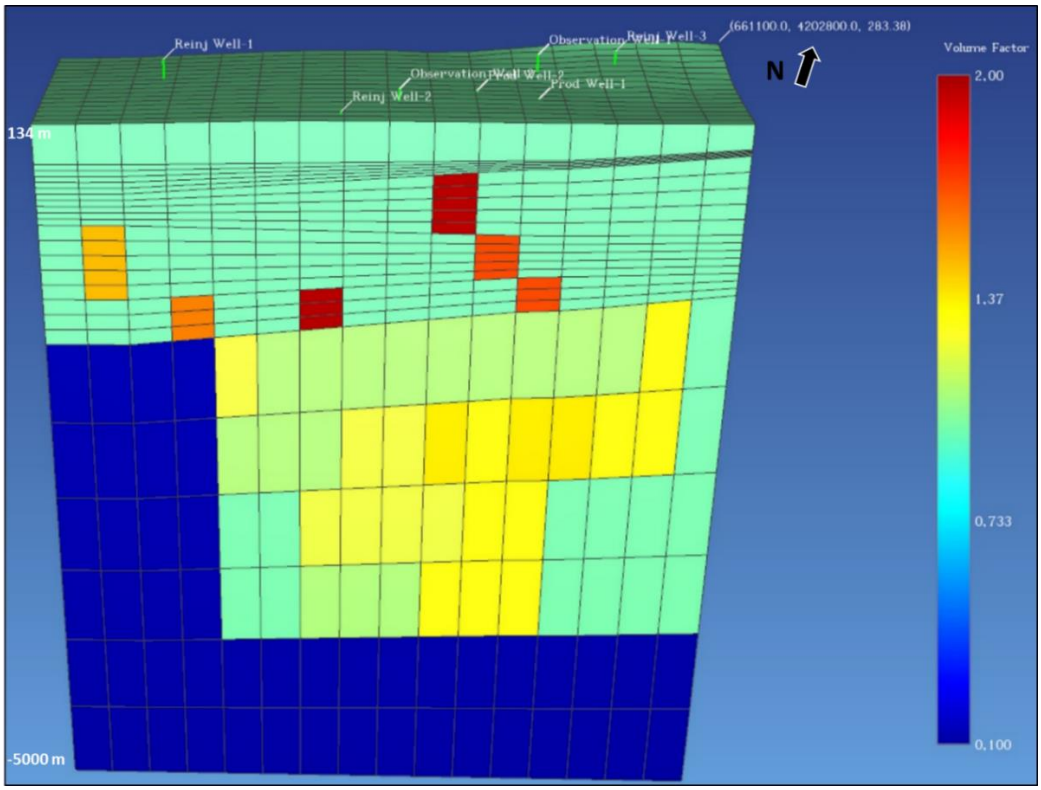

Figure 10: Porosity distribution of the model

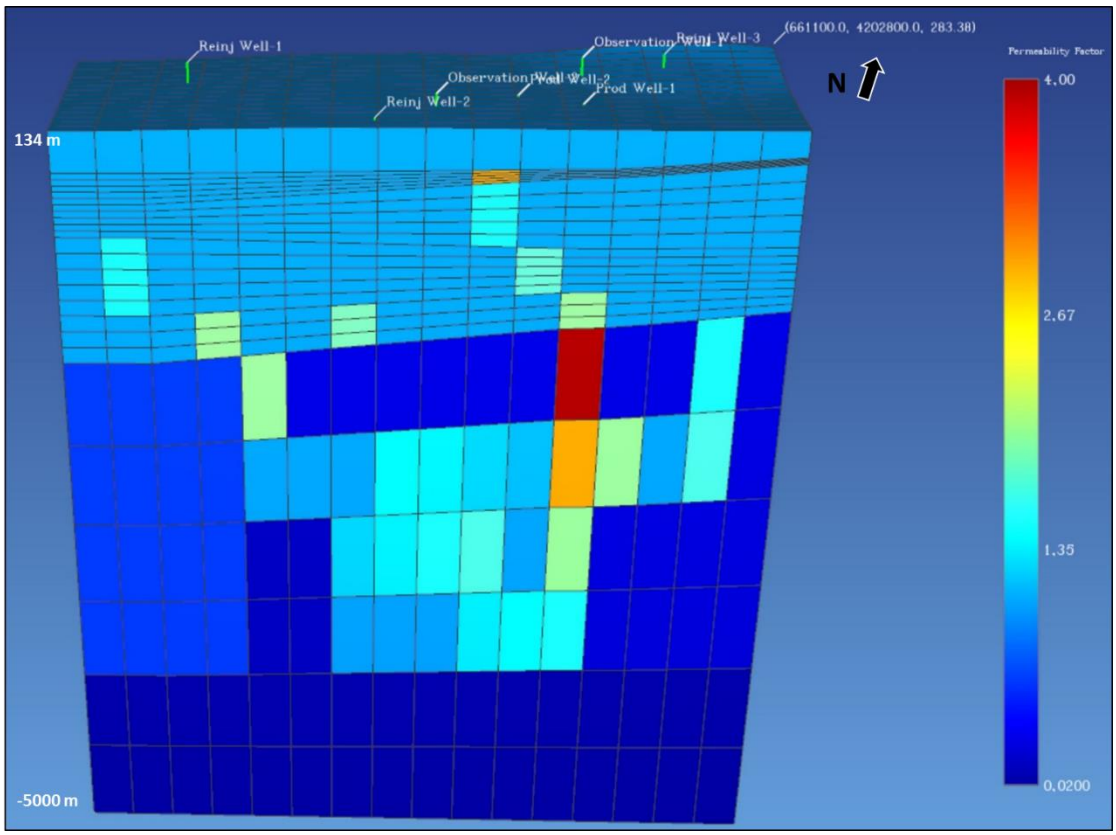

Figure 91: Permeability distribution of the model

5.2 Heat Source

In a geothermal system, heat is transported in three ways: conduction, convection, and radiation. The conductive transfer is the direct transmission of heat without any carrier element, depending on the temperature gradient (Akan, 2002). The convective transfer is the transfer of heat by groundwater movement. Radiation, on the other hand, is the energy emitted by a mass due to its temperature (Domenico and Schwartz, 1990). A single heat source was assigned to the model from the bottom to convey the heat by means of conductive and convective heat transport to the geological formations at the shallower depths.

5.3 Numerical Simulation

The initial and boundary conditions were defined in the model after the conceptual model was created. In the next step, the natural state was captured by running the model for 60,000 years. Then, the model was calibrated by overlaying the natural state modeling with the static temperature/pressure profiles.

5.3.1 Boundary Conditions

Boundary conditions provide mathematical expressions of hydrodynamic and hydrothermal processes along reservoir boundaries. In order to create a dynamic numerical model, it is also necessary to define the initial conditions (Karahanoğlu, 2019). In this study, a fixed boundary condition was assigned to the top layer of the model. Therefore, at this level during the simulation, there will be no pressure/temperature variation. The outer side layers are no flow boundaries. The heat source is assigned to the lowest layer.

The constant pressure and temperature values in the top layer were entered the model as 1 atm and 25°C, respectively. 250°C heat source is placed on an area of approximately 9 km^2 at -5000 m in the lowest layer. The values for this heat source are the flow is 2 kg/s, the enthalpy is 1000 kJ/kg.

5.3.2 Natural State Modelling, Calibration and History Matching

The model needs to be approximated to the natural state before the scenarios are tried. In this study, the model was run for 60,000 years to capture the natural state. The verification of the resulting model was made by superimposing the temperature and pressure profiles of the well called as KD-25B whose temperature and pressure profiles were used previously in a master thesis study, Küçük (2018). In this validation phase, it is a process in which the variations between the data obtained by the simulator and the real field data are compared. Based on these comparisons, the parameters are revised and adjusted on the verification path, and this process is called calibration of the model. Calibration was continued until the difference between the model simulation results and the actual data of the field was less than 10%. While there is overlap at many points in the temperature profile, the maximum margin of error is calculated as 8.8% (Figure 12). In the pressure profile, exact match between simulation and real field data was achieved (Figure 13).

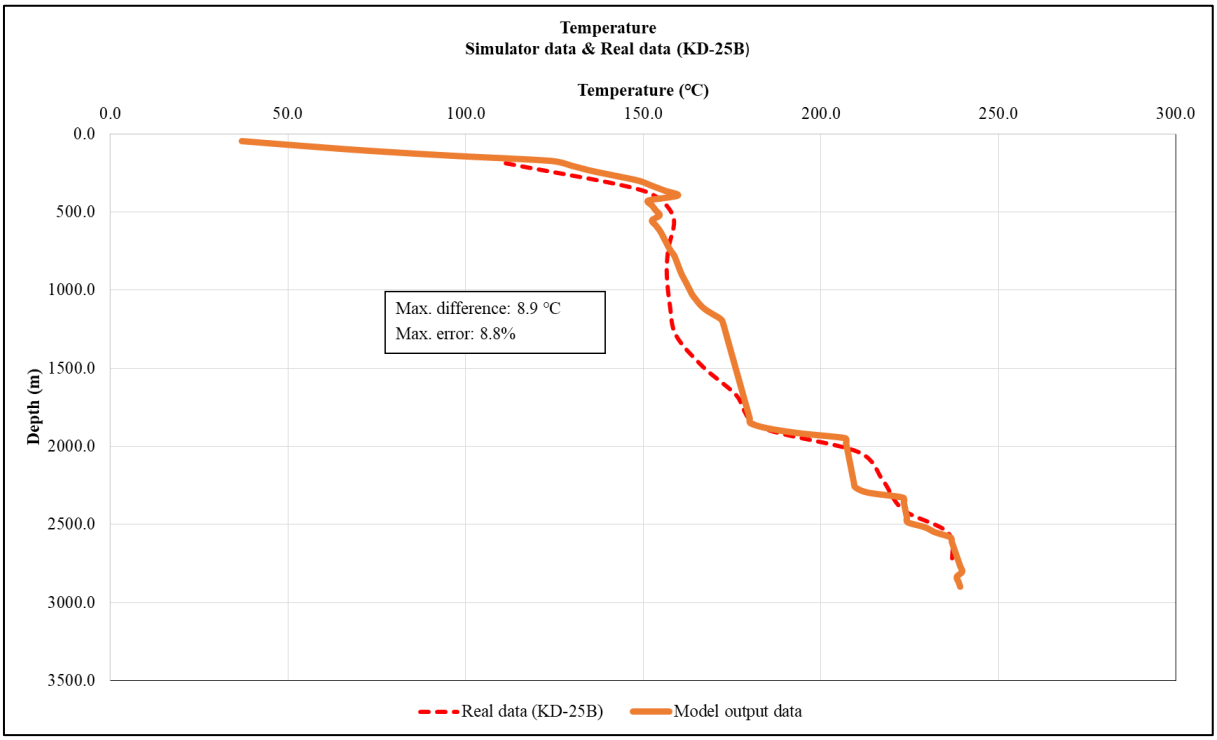

Figure 102: Comparison of simulation and measured temperature data

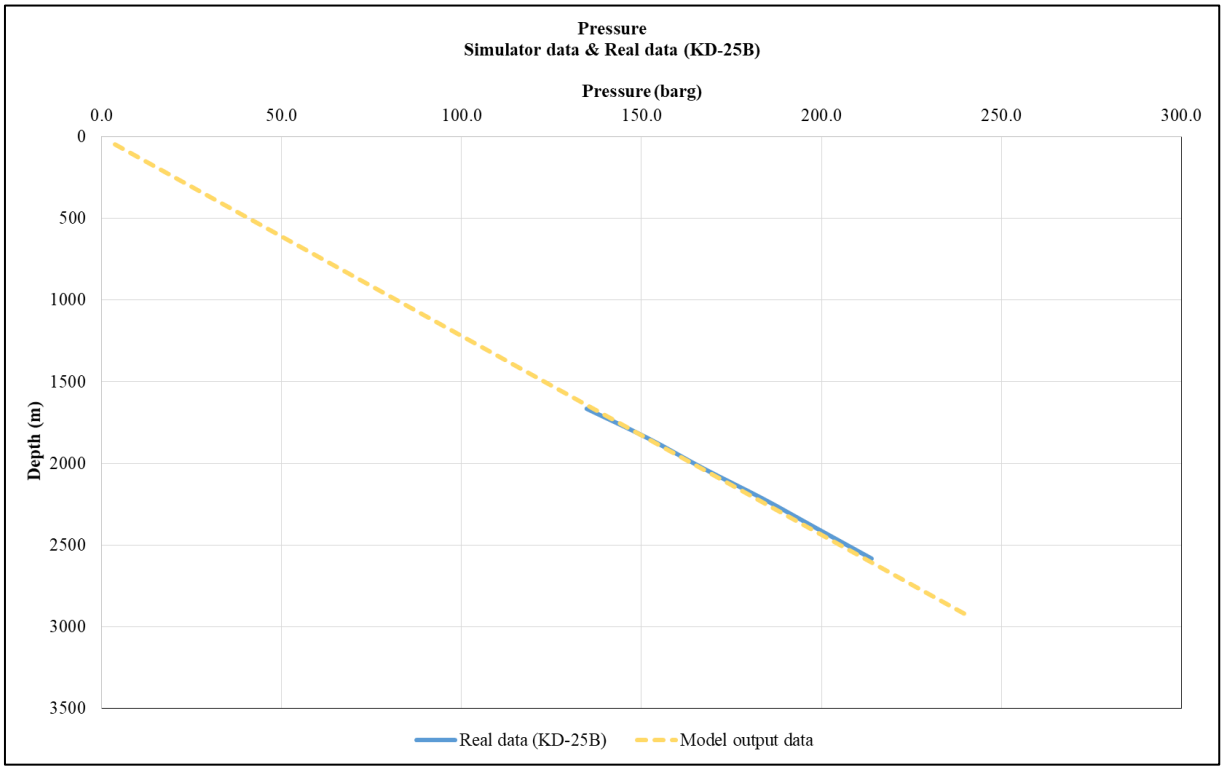

Figure 113: Comparison of the simulator and measured pressure data

5.4 Simulation Results

In this study, the contribution of the injection to the Sazak Formation on the deep reservoir was questioned. The connection between the two reservoirs was studied through the permeability of the Kızılburun Formation. Injection was applied mostly the shallow reservoir zone (Sazak Formation), and the production was from deep reservoir zone (Menderes Metamorphics). 7 wells were used in the model, 2 production, 3 injection and 2 observation wells. The depth and discharge values of the wells are given in the table (Table 4).

Table 4: Well data used in model

Well ID	Depth (m)	Discharge (t/h)
Production Well-1	2100	500
Production Well-2	2500	500
Injection Well-1	2700	300
Injection Well-2	800	200
Injection Well-3	700	200
Observation Well-1	850	
Observation Well-2	3000	

According to the model, production wells are feeding from the Menderes Metamorphics. The waste brine is injected to Sazak Formation and Menderes Metamorphics with three injection wells. One of the injection wells is deeper than the others and that well is used to inject Menderes Metamorphic. The reinjection ratio was assumed 70 % of overall production from the reservoir due to plant technology (wet cooling system). The other two injection wells were finished in the shallow zone (Sazak Formation). So, 57% of the total injection (in terms of discharge) is pumped to the Sazak Formation.

Observation wells are in the Sazak Formation and the Menderes Metamorphics. With five different permeability values assigned to the Kızılburun Formation, the model was run for a 10-year of production, and the reservoir pressures in the observation wells were recorded (Figure 14, Figure 16).

At the end of 10 years, a decrease of 25 barg was observed in Observation Well-1 in the Sazak Formation compared to the initial state, while a decrease of between 55 and 60 barg was observed in Observation Well-2 in the Menderes Metamorphics (Figure 15, Figure 17). The pressure drops in Observation Well-1 was the first finding indicating a hydraulic connection between the Sazak Formation and the Menderes Metamorphics. The high-pressure loss observed in the Menderes Metamorphic can be explained by the fact that the production is only from a deep reservoir, and the injection is mostly to the Sazak Formation, which is the shallow reservoir.

5 mD, 10 mD, 20 mD, 30 mD and 40 mD values were used for the permeability of Kızılburun Formation in x, y, z directions. In the first case, the permeability values in the x,y,z directions were assigned as 5 mD. In the second case, the permeability values in the x, y, z directions were taken as 10 mD. In this way, progress was continued, and five different graphs related to two observation wells were obtained.

The graphs show the change in reservoir pressure with respect to time. When the permeability values of the Kızılburun Formation are increasing, pressure loss regarding to bottom hole pressure (reservoir pressure) of Observation Well-1 is getting higher, whereas the situation regarding the Observation Well-2 is that pressure loss at the reservoir decreases when the permeability values of Kızılburun Formation is increasing. So, different pressure readings in the observation wells were obtained with different permeability values of the Kızılburun Formation. According to the data obtained, it is seen that the Menderes Metamorphics is fed when the waste brine is injected to Sazak Formation. However, although very different permeability values were tested, the pressure readings showed a difference of 1.3 barg between 5 mD and 40 mD cases at the end of 10 years in Observation Well-1, while this situation was observed as 5.9 barg in Observation Well-2 (Figure 15, Figure 17). In other words, although the high permeability value (40 mD) is assigned as in reservoir section, the contribution of the injection to the reservoir pressure in the Menderes Metamorphics is 5.9 barg higher than the case of 5 mD (Figure 17).

According to the average of 10 years, there is a loss of 5.5-6 barg reservoir pressure per year in Observation Well-2 (Figure 16). In this case, according to the graph obtained with the permeability of 40 mD, the annual reservoir pressure loss can be compensated for just a year (Figure 17). However, in the real situation, the permeability value of the Kızılburun Formation is below 40 mD. Therefore, it has been concluded that the contribution of the injection from the Sazak Formation to the Menderes Metamorphics will be at very low level. As a result, according to the synthetic reservoir model, it is thought that the reinjection into the Sazak Formation in the Menderes Metamorphics targeted production scenario does not have a significant contribution to making the geothermal system sustainable.

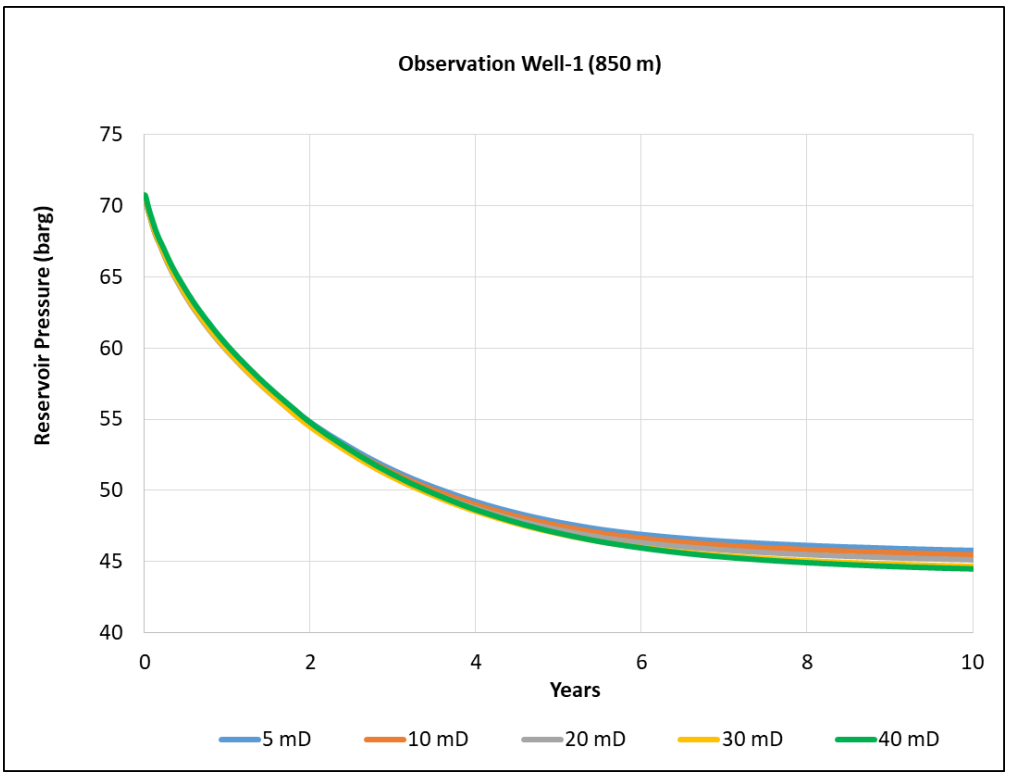

Figure 124: Change in reservoir pressure in Observation Well-1

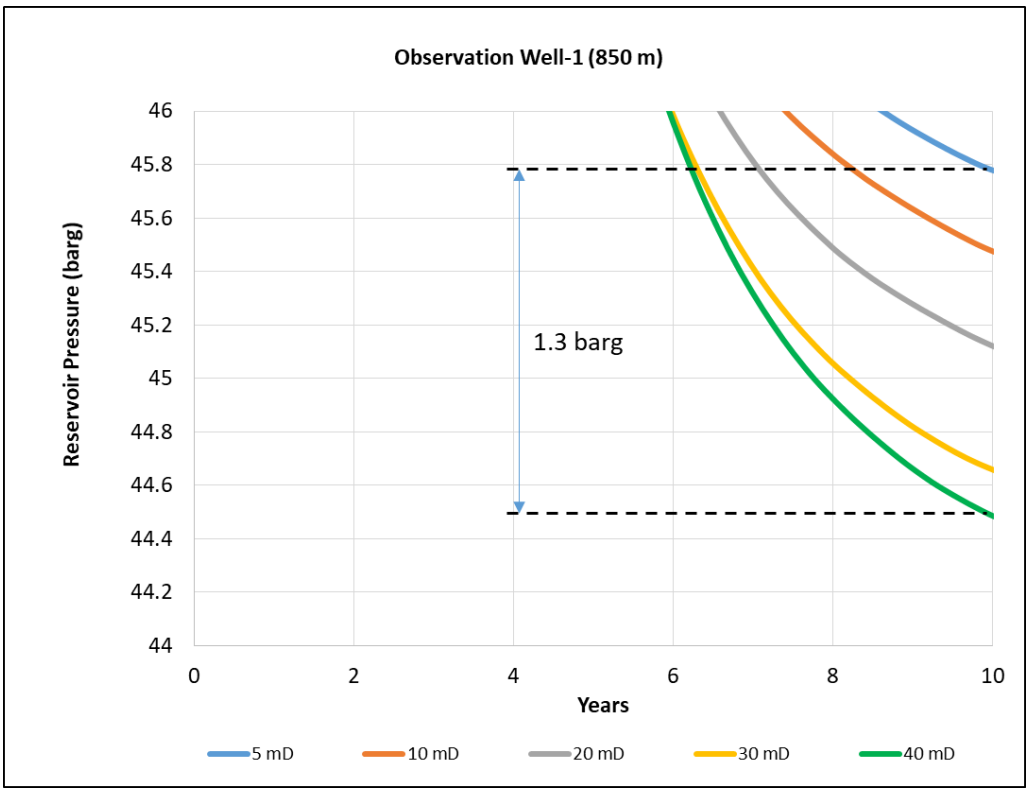

Figure 135: The reservoir pressure difference between the two cases 5 mD and 40 mD in Observation Well-1

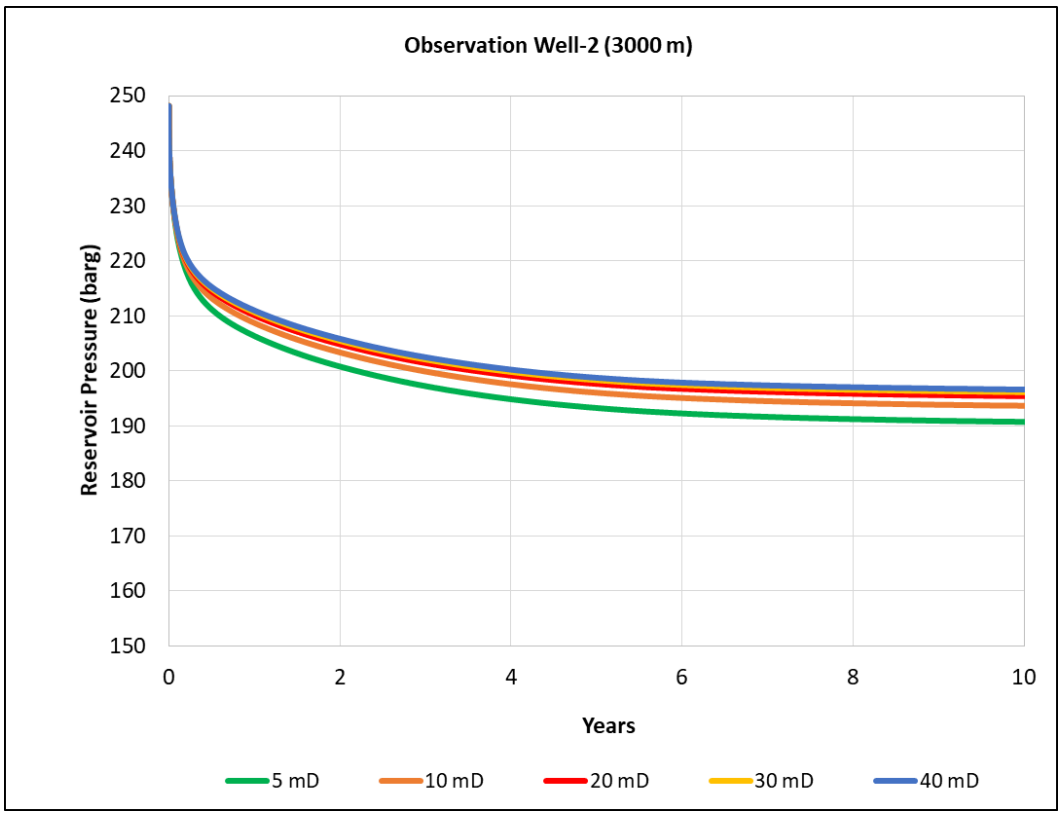

Figure 146: Change in reservoir pressure in Observation Well-2

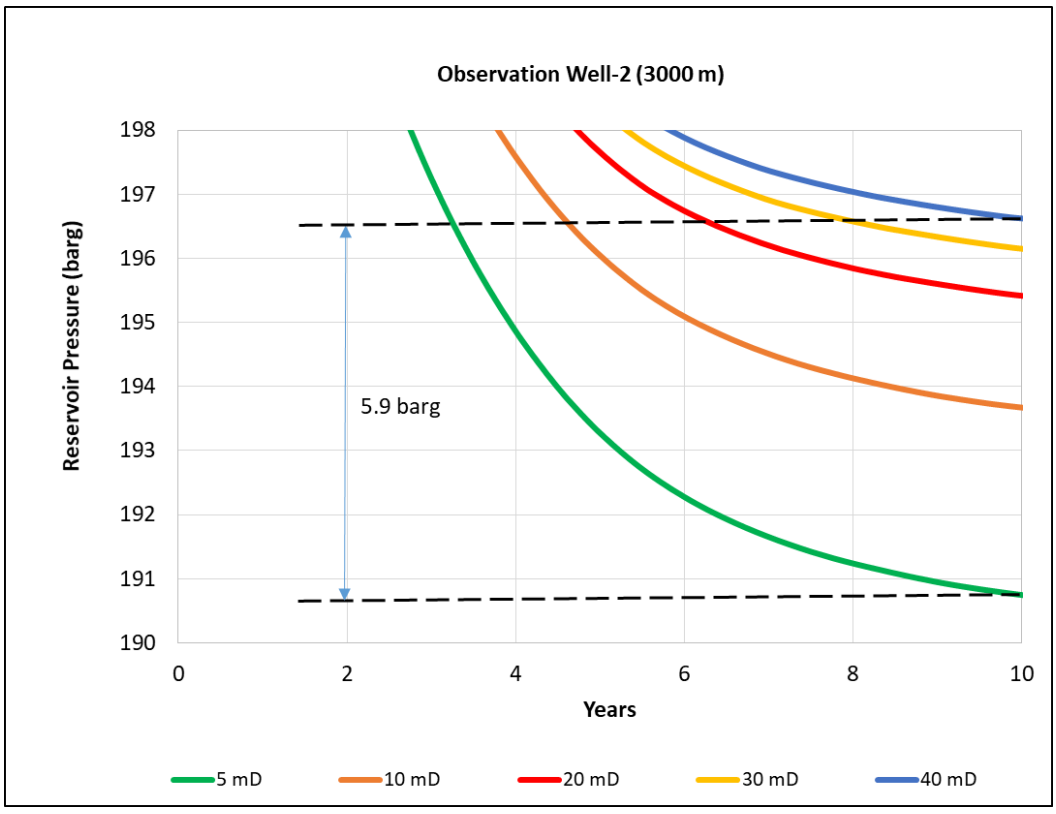

Figure 157: The reservoir pressure difference between the two cases 5 mD and 40 mD in Observation Well-2

6. CONCLUSION

Reservoir management studies are carried out to ensure sustainability in geothermal energy. Within the scope of this study, a synthetic reservoir model has been created for the Kızıldere Geothermal Field. The aim of the study is to investigate the effect of reinjection to the Sazak Formation on the deep reservoir. The effect of injection was studied at different cap rock permeabilities. According to the model results, findings indicating the existence of a hydraulic connection between the Sazak Formation and the Menderes Metamorphic were obtained. However, it was revealed that the Sazak Formation fed the Menderes Metamorphic to a limited extent. As a result, according to the synthetic reservoir model prepared for Kızıldere Geothermal Field, injection to shallow reservoir section (Sazak Formation) and production from deep metamorphic do not play an important role in making the geothermal system sustainable. It is critical to support deep metamorphic rocks with reinjection of waste brine.

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