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A Numerical Model of the Kizildere Geothermal Field, Turkey

Sabodh K. Garg, Jill Haizlip, Kevin K. Bloomfield, Ali Kindap, Fusun S.T. Haklidir, and Aygun Guney

Leidos Inc., 10260 Campus Point Drive, MS C2E, San Diego, CA 92083, USA

gargs@leidos.com, jhaizlip@geologica.net

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ABSTRACT

Commercial power generation at Kizildere began in 1984 with the installation of 17.4MWe (gross) Kizildere I power plant. Fluid production (and hence electric generation) gradually fell due to reservoir pressure decline related to little or no injection. More rapid production declines due to calcite scaling in production wells were periodically reversed after mechanical cleaning and acidization creating cyclical production behavior. Zorlu Energy Group acquired the geothermal field in 2008 and initiated wellfield and power plant modification to restore Kizildere I to capacity, and drilling deep wells (up to 2700 m) to supply fluid requirements for Kizildere II, a 80 MW geothermal power plant commissioned in late 2013. This paper presents a numerical reservoir model which was developed as a tool to support the management of the Kizildere reservoir which includes the intermediate depth reservoir in Igdecik marbles which supplies Kizildere I and a deeper reservoir in Menderes Metamophics which supplies the Kizildere II plant.

The natural state numerical model developed herein correctly reproduces the presently available data for pre-production feedzone temperatures and pressures. The numerical model was used to history-match the available production and injection data for the period January 1984 – March 2013; the agreement between the computed and measured pressures in the six (6) observation wells is satisfactory. After history-matching, the numerical model was employed to investigate the feasibility of producing sufficient fluid to supply the fluid requirements for both the Kizildere I and II power plants. The model results for the investigated scenario indicate that a system of 20 production and 8 injection wells should be adequate for producing the required fluid supply. The latter conclusion is of course predicated on the assumed behavior of the deeper reservoir.

Acquisition of data in the future on the response of the deeper Paleozoic reservoir to large-scale production and injection will significantly enhance our understanding of this reservoir. After approximately one year of operating Kizildere II, the quantitative results of production, injection and reservoir monitoring will provide a record of the initial reservoir response. The numerical model will then be refined and revised as needed to reflect the enhanced knowledge about the deeper reservoir.

1. INTRODUCTION

In the 1960s, a Turkish government agency -Mineral Research & Exploration General Directorate (MTA) - explored the fumarole area east of the village of Kizildere in Western Turkey. Geological, geochemical and geophysical investigations were performed, temperature gradient holes were drilled and in 1968, a 198 ^{o}C geothermal reservoir was discovered with the drilling of KD-1. Over the next few years, approximately 20 wells were completed to develop the resource. In 1984, the first geothermal power generation in Turkey began at Kizildere I with an installed capacity of 17.4 MW. Zorlu Energy Group (Zorlu) acquired the Kizildere field in 2008, and began wellfield and power plant modifications and maintenance to restore Kizildere I to capacity and resource investigations and drilling deep wells (up to 2700m) to supply Kizildere II, a 80 MW geothermal expansion power project. Kizildere II power plant project started operation in the fall of 2013.

The Kizildere Geothermal project is located at the eastern end of a Plio-Quarternary east-west trending extensional tectonic valley in Western Turkey known as the Büyük Menderes Graben (e.g. Şimşek, 2003) which hosts several other geothermal systems. Within the Kizildere geothermal area, the Paleozoic metamorphic rocks are downthrown along a series of semi-parallel east-west trending normal faults with vertical throws of a few hundred meters at the edge of the graben to possibly thousands of meters in the center. These faults appear to be cut by northeast trending faults. The combination of the eastern edge of the graben bounding faults and the cross faults creates extensive fracturing (Faulds, 2009). The graben is filled with Tertiary sediments, which are overlain by alluvium. Recent seismic activity suggests that the area is still tectonically active and is extending in the north-south direction . . Although major faults cut formations from the Tertiary to the Paleozoic, variations in the brittle fracturing of different lithologic layers give the reservoir a layered permeability structure. There is a shallow reservoir in Mesozoic limestones (Sazak formation), an intermediate depth reservoir in the uppermost Paleozoic carbonates (Igdecik formation) and a deep reservoir in fractures primarily in the brittle sections of the Menderes Paleozoic rocks. The sediments with higher clay content or metamorphics dominated by mica form impermeable cap rocks above and between the permeable reservoir zones hosted in more brittle formations. Impermeability of the zone between the intermediate and deep reservoirs is supported by pressure interference testing within the newly drilled Kizildere II area as well as high temperature gradients in these zones in temperature logs of the new wells (Haizlip and Tut, 2011). However, there may be some connection between the intermediate and deep reservoirs in the Kizildere I area (Yeltekin, personal communication 2012).

The heat source for the geothermal system is related to the high heat flow of extensional tectonic regimes such as the Menderes Graben. No magmatic contributions to geothermal fluids have been identified. Reservoir temperatures of 200°C at ~500m and 240°C below ~1200m are most likely due to the circulation of meteoric water in fractures within the high heat-flow region.

While brine chemistry between the Kizildere reservoirs is almost identical, the average noncondensible gas (NCG) concentration in the deep reservoir (0.03 kg NCG/kg brine) is approximately twice the intermediate reservoir (0.015 kg NCG/kg brine). Geothermal

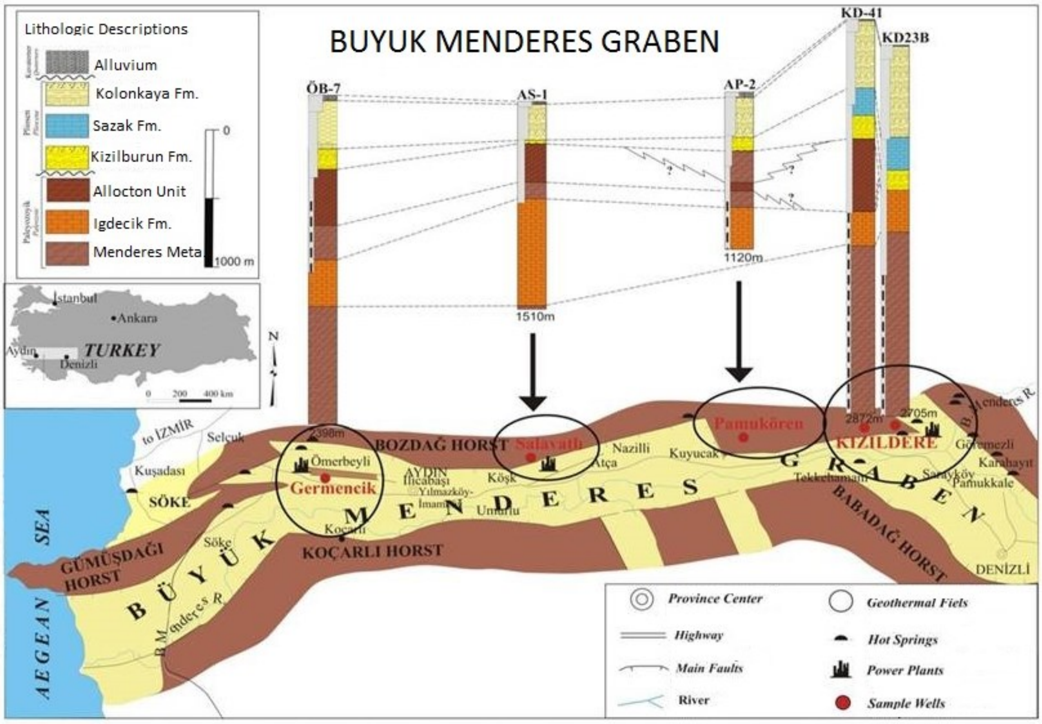

Figure 1: Location of Kizildere geothermal field in Buyuk Mendres Graben. After Simsek (2003).

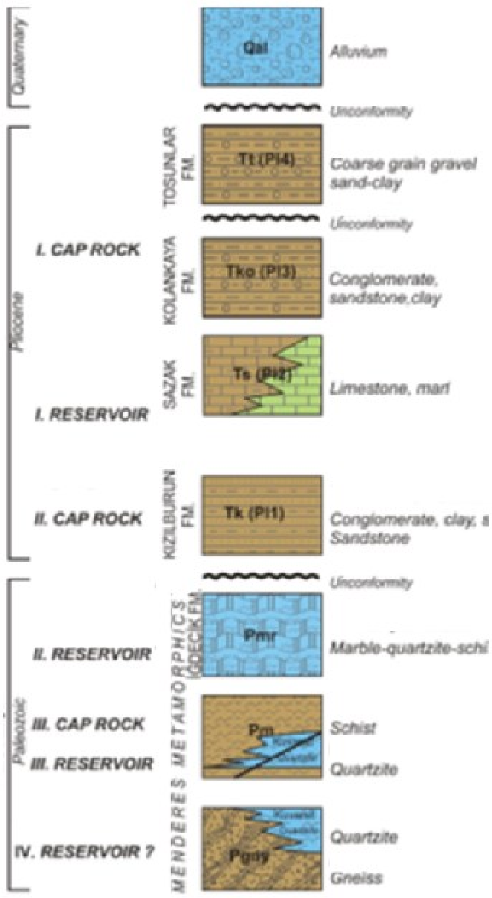

Figure 2: Stratigraphy at Kizildere.

reservoir liquid (brine) is characterized by high sodium, sulfate and bicarbonate and low chloride. Geochemical differentiation in brine chemistry between the intermediate and deep reservoirs is limited to temperature dependent constituents such as (SiO2), Sodium (Na) and potassium (K) and noncondensible gas concentration. Gas composition is almost the same in both reservoirs with 98 to 99% carbon dioxide (CO_2) and very low hydrogen sulfide (H_2S).

This paper presents a numerical reservoir model which was developed as a tool to support the management of the Kizildere reservoir which includes the intermediate depth reservoir in Igdecik marbles which supplies Kizildere I and a deeper reservoir in Menderes Metamophics which supplies the Kizildere II plant.

2. NATURAL STATE

A hydrothermal system such as the Kizildere geothermal field contains a convecting fluid mixture that is heated at depth and then rises towards the surface as a consequence of buoyancy. The system is not only nonisothermal but is also in a continuous state of flow. To make realistic predictions of reservoir performance under exploitation, it is accordingly necessary to first establish the natural (*i.e.*, pre-production) state of the system; that is, the distribution of temperature, pressure, and fluid flow that prevailed prior to human intervention. This description may then be used as a set of initial conditions for history-matching, and for predictive time-dependent calculations of the effects of fluid production and reinjection upon the reservoir. During the exploration and early development stage, the natural pre-production flow of the fluid will be dominant, except in the immediate vicinity of operating exploratory wells. As the development of the field takes place, the natural flow pattern is likely to be overwhelmed by perturbations caused by production and injection well operations associated with mining of heat from the geothermal system.

It is not sufficient to merely prescribe a “natural state” based, for example, upon interpolation between measured, or inferred, pressures and temperatures. It is essential, in fact, that the natural state itself represents a quasi-steady solution of the partial differential equations that govern flow in the reservoir. Otherwise, solution of the production/injection phase of the problem is likely to produce changes in underground pressures and temperatures that are unrelated to exploitation, but are instead fictitious consequences of the initial (*i.e.*, pre-production or natural) conditions being inconsistent with steady behavior. Since transient processes associated with initiation of convection occur over time scales of the order of 10^4 years, the natural state can be regarded as stationary over the 10–50 year period required to exploit a geothermal reservoir. Thus, the requirement that the natural state be itself a nearly steady solution of the governing equations is a critical test of the model of the reservoir.

Commercial operations at Kizildere started in 1984. Till the drilling of deep well R-1 in late 1990s, discharge was from relatively shallow wells completed in Sazak and Igdecik formations (see Figure 3 for locations of various Kizildere wells). Injection of waste brine was initiated in 2002 with the drilling and completion of well R-2 but remained relatively small (<25%) in proportion to production until 2008. In recent years, deeper wells have been drilled and completed in the Paleozoic formation underlying the Sazak and Igecik formations. These deeper wells will be used to supply the fluid requirements for the just completed 80 MW power plant. The bottom of the deepest well drilled to-date at Kizildere (KD-25A) is at about 2522 meters below sea-level. The elevation of the ground surface in the Kizildere area varies from about 140 mASL (meters above sea level) to about 400 mASL. The model grid extends from -3000 mASL (3000 meters below sea level) to 250 mASL.

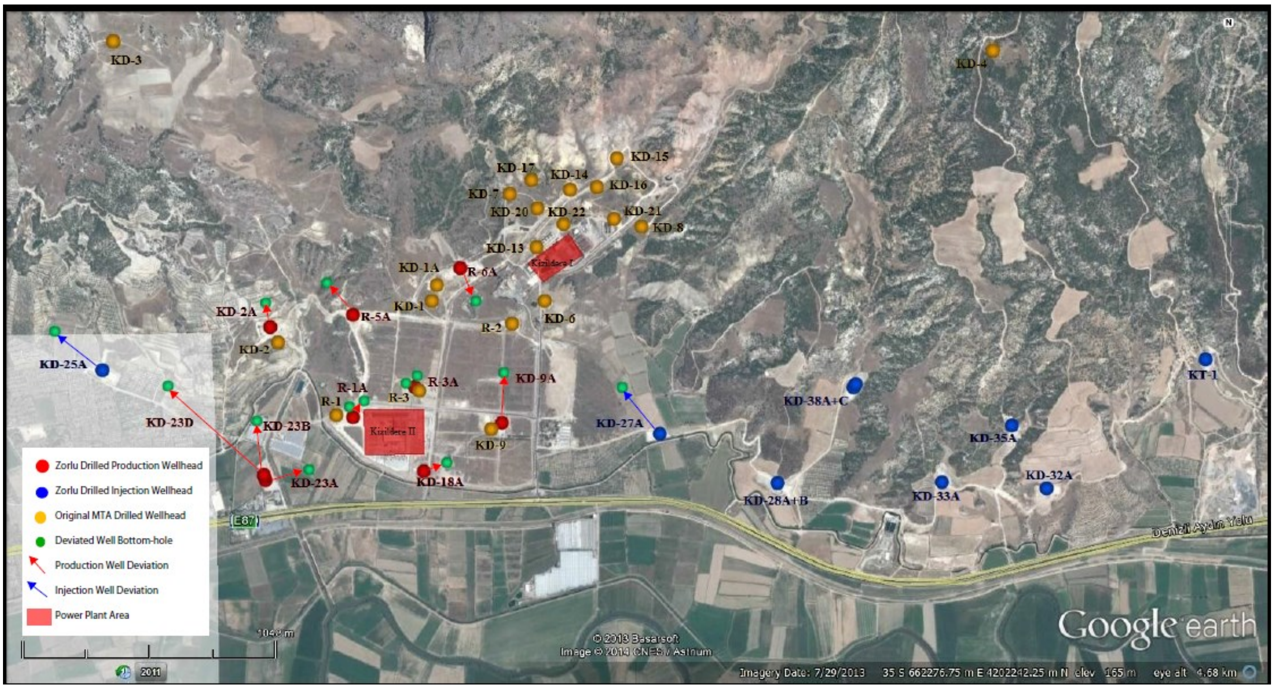

Figure 3: Kizildere wellfield. Red (green) circles denote the wellhead (bottomhole) for deep production wells. Injection wells are shown as blue circles, and shallow/intermediate wells are indicated by orange circles. Power plants are shown as red rectangles.

The model volume is divided in to a 50x34x21 grid in the x- and y- and z-directions respectively. In the z-direction, the grid blocks range in size from 100 m to 500 m; the single 500 m grid block is deployed along the bottom boundary. In the x- and y-directions, grid blocks are either 100 m or 250 m in size. The fine grid blocks (100 m) are used to cover the region where the majority of the wells are located, and the coarsest resolution (250 m) is employed to model the region near to the model boundaries. An overlay of the areal grid (area 6.5 km by 5.8 km) over the Kizildere geothermal field is shown in Figure 4. The vertical grid is displayed in Figure 5.

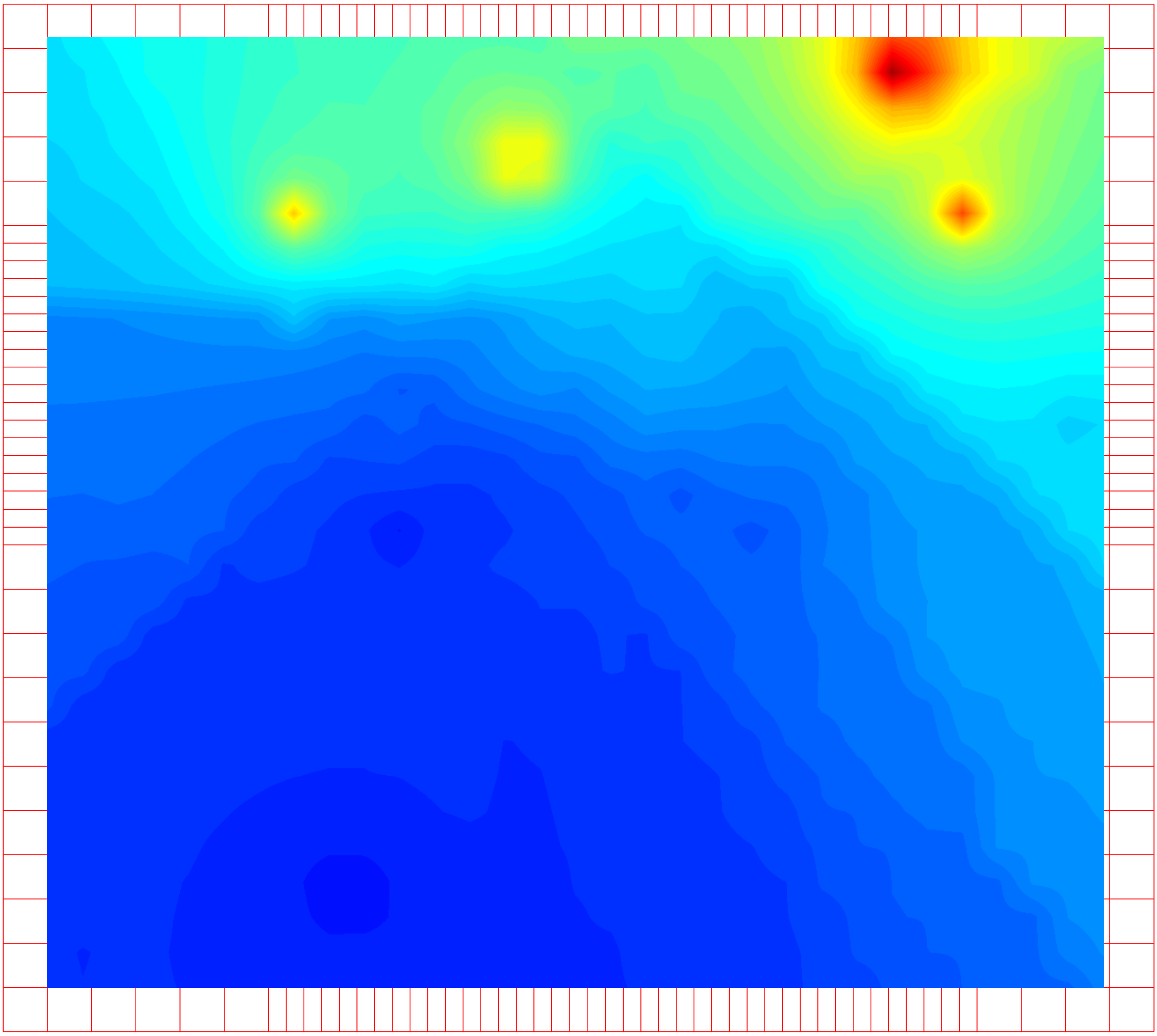

Figure 4: Numerical grid in the x-y (horizontal) plane. The origin of the grid is at 658,550 mE and 4, 198, 950 mN. The grid covers an area of 6.5 km by 5.8 km. The warmer (red) colors denote higher elevation areas.

The 3-D numerical model was constructed using Leidos's STAR geothermal reservoir simulator (Pritchett, 2004). To carry out model computations, distributions of thermo-hydraulic properties (*e.g.,* permeability, porosity, thermal conductivity, specific heat, etc.) for the entire grid-volume, and boundary conditions along the faces of the model grid are prescribed. During the development of the natural-state model for the Kizildere geothermal field presented below, the formation properties (i.e. permeabilities) and the boundary conditions (*i.e.,* mass and heat flux along the bottom boundary, water level surface along the top boundary) were freely varied in order to match (1) the distribution of feedzone pressures (*i.e.,* pressure at the main fluid entry in a well), and (2) observed temperature profiles in wells. Numerous such calculations were carried out; in the following, we will only describe the final case.

Formation properties utilized for the Kizildere model are given in Table 1. Distribution of the formation properties within the model grid along two x-z cross-sections passing through the wellfield are displayed in Figure 6. Sazak, Igdecik, and Paleozoic formations are assumed to have high permeabilities. Other formations have relatively low (especially vertical) permeabilities. Little or no direct measurements are available on properties for Kizildere formations other than the Paleozoic. Based on a pressure interference test carried out in April 2011, the deeper part of the Paleozoic formation is estimated to have a transmissivity of ~170 darcy-m, and a storage of (2 to 3) 10^{-8} m/Pa. The average temperature in the Paleozoic formation is about 230 ^{o}C; the corresponding compressibility for liquid water is about 1.2 10^{-9}/Pa. Assuming a permeable formation thickness of (1000 to 1250) m, we obtain a horizontal permeability of about 150 millidarcies, and a porosity of about 0.02.

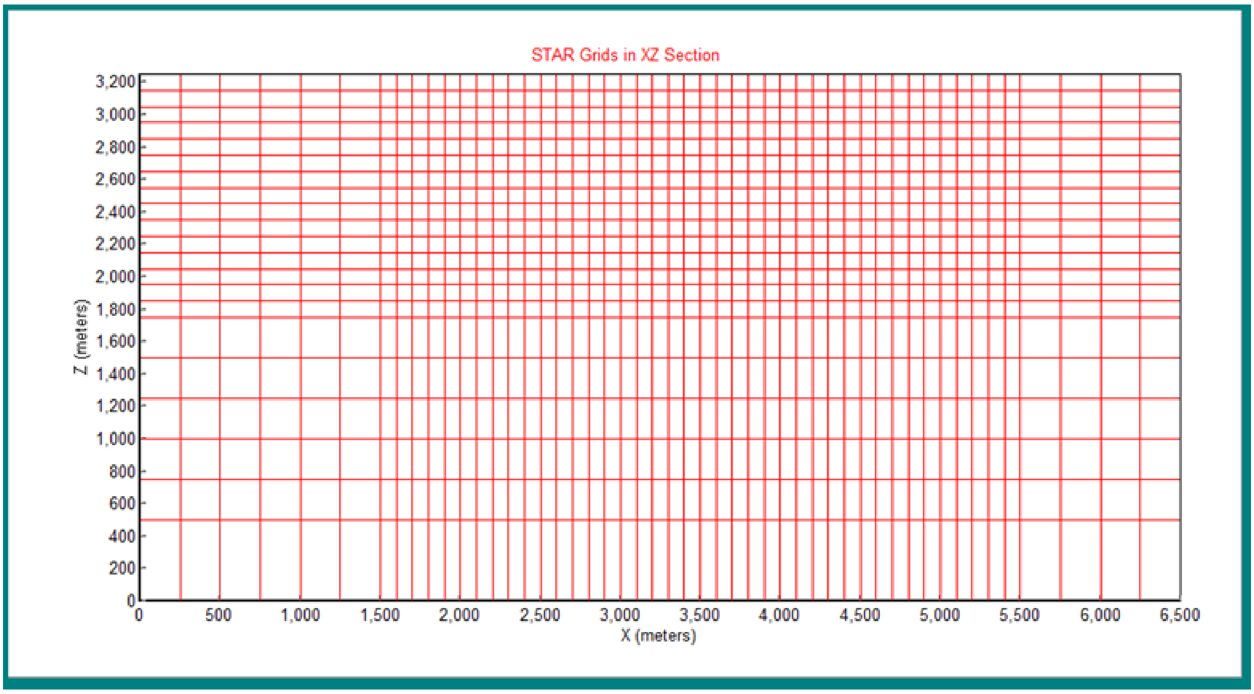

Figure 5: Vertical (x-z plane) grid. The bottom of the grid is located at -3000 mASL, and the top is at 250 mASL.

Table 1: Formation properties.

Formation Name	Intrinsic rock density (kg/m^3)	Rock grain specific heat (J/kg .°C)	Global Thermal Conductivity (W/m °C)	Porosity	Permeability in x-direction (mdarcy)*	Permeability in y-direction (mdarcy)*	Permeability in z-direction (mdarcy)*
Paleozoic	2800	1000	3	0.02	150	150	5
Igdecik	2800	1000	3	0.05	100	100	5
Kizilburun	2800	1000	3	0.02	10	10	0.5
Sazak	2800	1000	3	0.10	100	100	5
Kolankaya	2800	1000	3	0.01	1	1	0.5
Tosunlar	2800	1000	3	0.10	1	1	0.5
Alluvium	2800	1000	3	0.10	1	1	1
Paleozoicimp	2800	1000	3	0.02	150	150	0.5

*It is assumed here that 1 millidarcy is exactly equal to 10^{-15} m^2

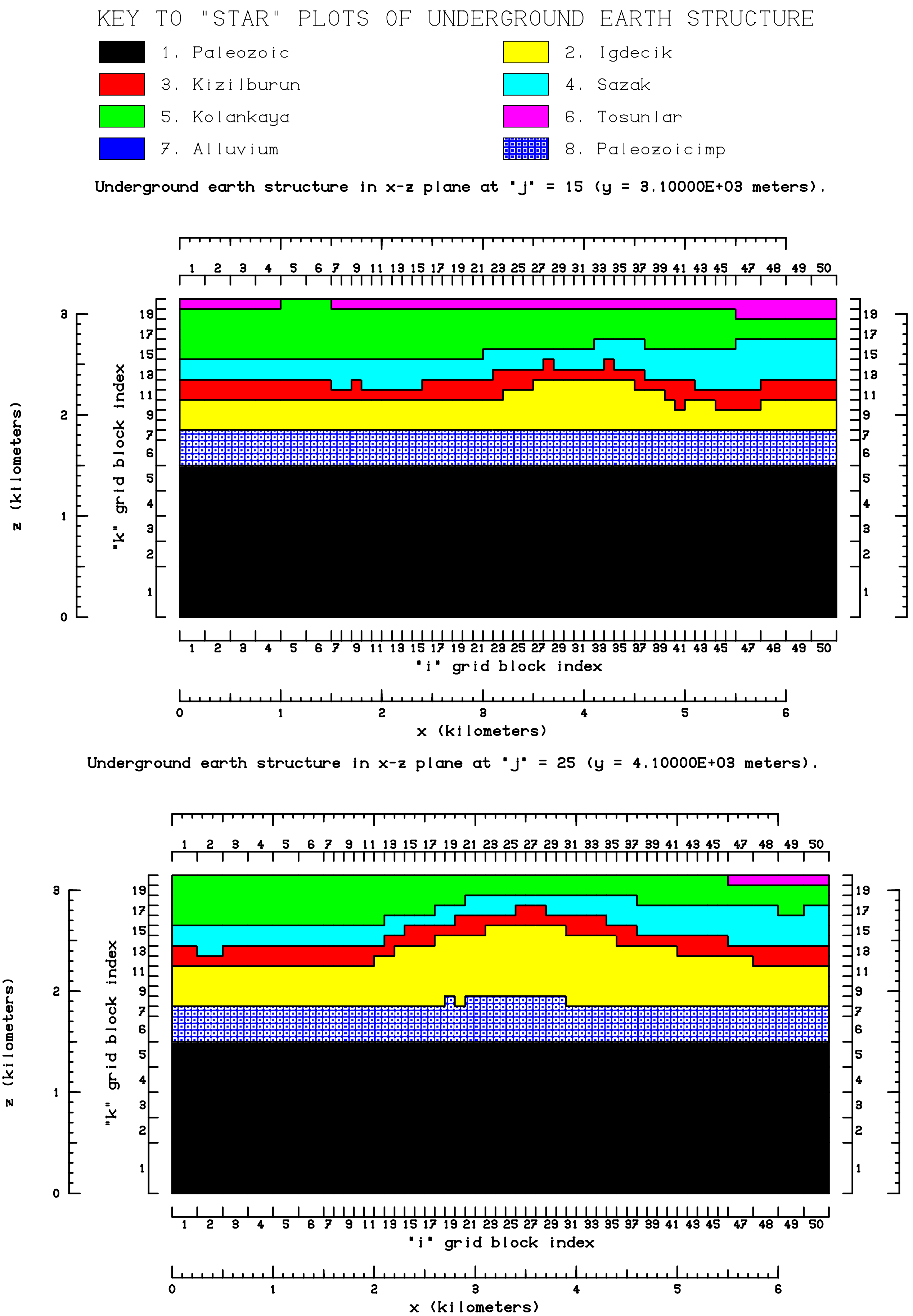

Figure 6: Formation distribution along two selected x-z planes.

Along the top boundary, the water table (i.e. 1 bar surface) is assumed to be at an elevation given by:

$$z_w = 0.25(z - 90) + 90 \quad (1)$$

where z_w denotes the water table elevation (mASL) and z is the local ground surface elevation. The ground surface temperature and shallow subsurface temperature gradient are assumed to be 20 ^oC and 30 ^oC/km, respectively. If the water table given by Eq. (1) falls below the mid-point of a grid block, the grid block is flagged as void. Use of Eq. (1) renders all of the k=21 layer empty. Sources and sinks are imposed in all the grid-blocks in layer k=20 to maintain the pressures and temperatures consistent with Eq. (1), and the assumed surface temperature and subsurface temperature gradient. Along the bottom boundary, a uniform conductive heat flux of 0.22 W/m^2 is imposed along the entire surface. In addition, a uniform mass influx (total mass flux =56.25 kg/s, internal energy = 0.9845 10^6 J/kg, CO2 mass fraction = 0.03, NaCl mass fraction = 0.005) is introduced along a portion (i=12, …,26; j= 11, …, 21; total surface area = 1.875 km^2) of the bottom boundary. Except for layer k = 5, all the vertical faces of the grid are assumed to be impermeable and insulated. Sources and sinks are introduced in all the exterior facing grid blocks in layer k =5 to maintain a constant pressure of 162.4 bars. Any fluid entering the grid along this boundary as well as the top surface is assumed to have negligible amounts of CO2 and NaCl (1 ppm by mass).

Starting from an essentially arbitrary cold state, the computation was marched forward in time for about 250,000 years. The maximum time step used was 25 years. The thermal energy continues to increase and the fluid mass declines during the entire computational period. Initially the change is rapid; it moderates over time. After 50,000 years, the change is quite small over a time scale of 50 to 100 years. The computed pressure and temperature values at several computational times were compared with available data. Based on these comparisons, it was decided to use the computed state at 100,000 years for history match computations.

The computed feedzone pressures are compared with measured values in Figure 7. Although the pressure data display some scatter, the fits to measured and computed values are in excellent agreement. The close agreement between the two fits shows that the vertical temperature distribution (and hence the pressure gradient) is correctly reproduced by the model.

The measured temperatures in three representative Kizildere wells are compared with calculated results from the model in Figures 8-10. The temperature profiles for deep wells were recorded after the field had been in production for over 25 years; it is, therefore, possible that the temperatures at intermediate depths in these boreholes may have been affected by past production and injection. Also because of possible cross-flow between multiple fluid entries along a wellbore path, the measured temperatures in wells do not necessarily reflect formation temperatures (i.e., rock temperatures away from the wellbore). The measured temperature may equal the formation temperature only at the deepest (or shallowest) fluid entry in case of upflow (downflow) in the well. Accordingly, in this work, emphasis was placed on matching the feedzone temperatures in both the shallow and deep wells. Taken as a whole, the computed temperature profiles are in reasonable agreement with the measurements. Therefore, it is concluded that the natural state model provides a satisfactory basis for history match calculations reported in the next section.

3. HISTORY MATCH

Reservoir models are best calibrated by matching historical production and injection data. Kizildere geothermal system has been in production since 1984. Unfortunately, most of the historical discharge and injection data prior to the acquisition of the field by Zorlu are unavailable. Accordingly, an approximate production history was constructed using records for power generation. A total of 12 production and 6 injection wells were used in the period from January 1984 to March 2013 (29.25 years. At various times during the historical period, downhole pressures were recorded in 6 wells (KD-1A, KD-2, KD-6, KD-7, KD-8, KD-9); these pressure data are the primary targets for matching.

The final natural state simulation model was used as the initial state for the history-match. For the history-match computation, pressures computed for the grid blocks adjoining the vertical faces of the grid were imposed as constant pressure boundaries along these faces. All other boundary conditions were left unchanged. Using a maximum time step of 1 week and the production (discharge and injection rates) history, the pressure response of wells KD-1A, KD-2, KD-6, KD-7, KD-8, and KD-9 was computed. A comparison between the observed pressure changes and the results of the numerical simulation for two wells is displayed in Figures 11 and 12; a similar match was obtained for the other four observation wells. Considering the data quality, the agreement between the data and the simulated results is considered satisfactory. Thus, the history-match validates the natural state model and the constant pressure boundary condition imposed along the lateral boundaries. To the extent that only a little of the historical production was derived from the deeper Paleozoics, the latter conclusion (constant pressure boundary condition along the vertical faces) must be regarded as tentative as far as the deeper reservoir hosted by Paleozoics is concerned.

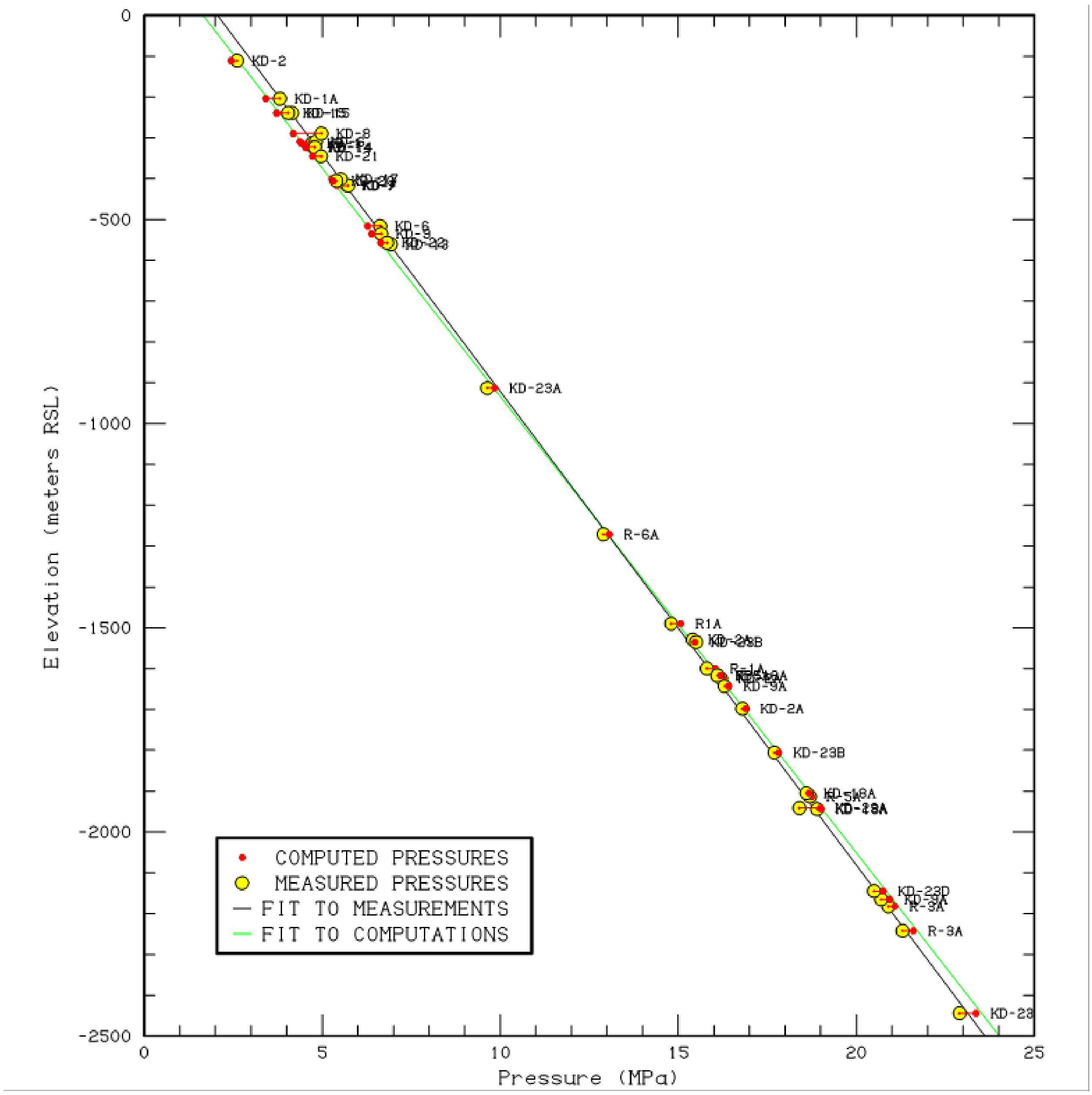

Figure 7: Comparison of computed feedzone pressures with measured values. Although the pressure data display some scatter, the fits to measured and computed values are in excellent agreement.

4. A PRODUCTION AND INJECTION SCENARIO

According to a scenario (Scenario 1) provided by Zorlu, a total of twenty (20) production and eight (8) injection wells will be used to supply both the Kizildere I and II power plants. For Scenario 1, the total discharge (or injection) rates for the various wells are assumed to be constant for the entire 30-year period. Starting with the end of the history-match period (March 2013), the numerical model was run forward in time for 30 years using the flow rates and well properties provided by Zorlu. A maximum time step of 1 week was employed for these predictive calculations. The model output for each production well consists of datum level pressure, discharge enthalpy and fluid composition as a function of time. For the injection wells, the relevant model output is datum level pressure. The model results for a couple of production wells (one deep and one shallow) are displayed in Figures 13 and 14. All of the production and injection wells undergo little or no pressure change after the initial transient period at t = 0 years; this is a result of constant pressure boundary condition along the lateral boundaries.

The computed enthalpy decline in all the production wells is modest (<50 kJ/kg). The CO_2 mass fraction, especially in deeper wells, declines significantly over time presumably as a result of the injection of water depleted in CO_2. Note that the inflowing water from the lateral boundaries also has much lower CO_2 than the water in the production zone.

Long-term production and injection data from the wells drilled in the Paleozoics are needed to confirm or refute the model predictions such as little or no pressure decline after the initial transient period, a modest fall-off in the discharge enthalpy, and a very significant decrease in CO_2 .

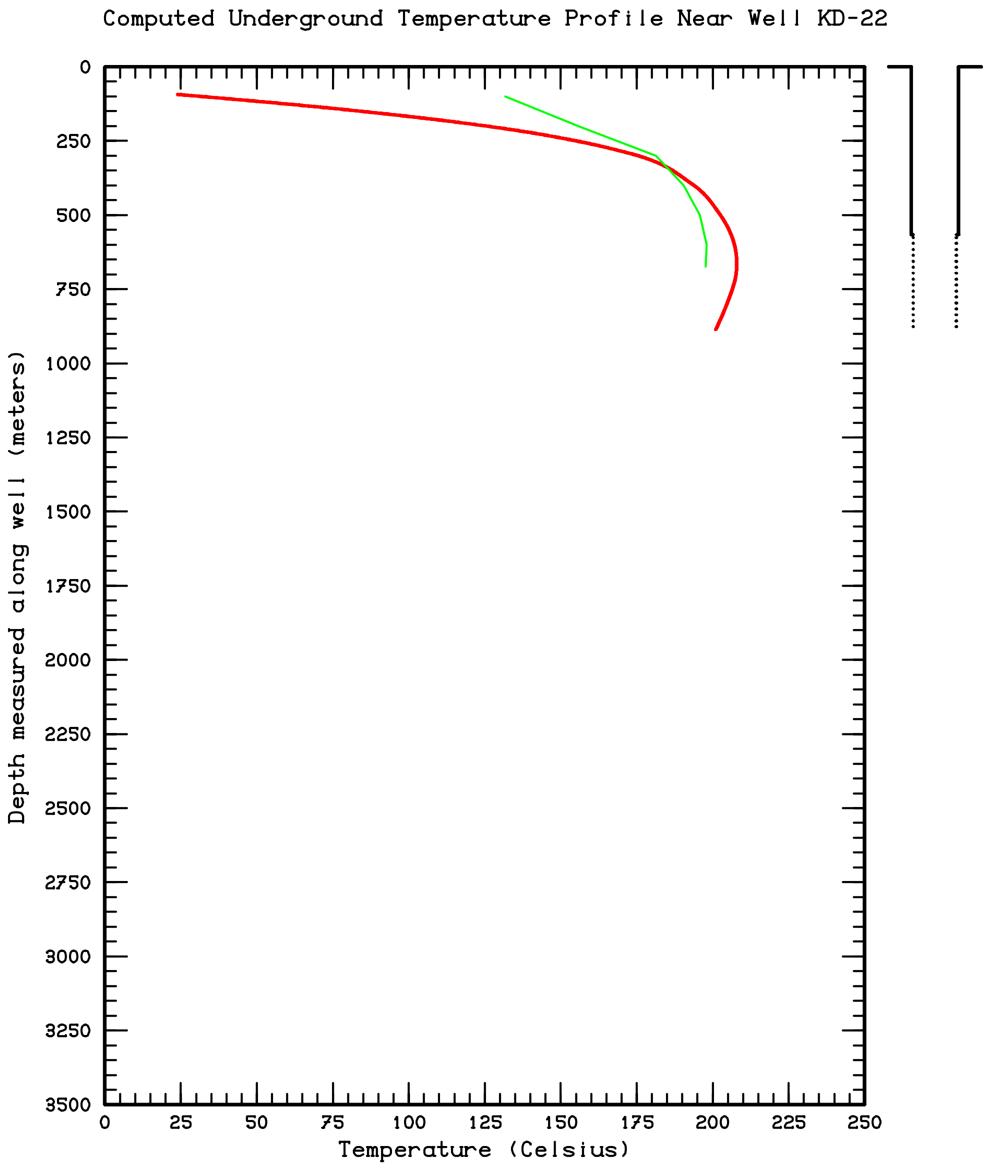

Figure 8: Comparison of measured temperature profile (green) with computed profile (red) for well KD-22.

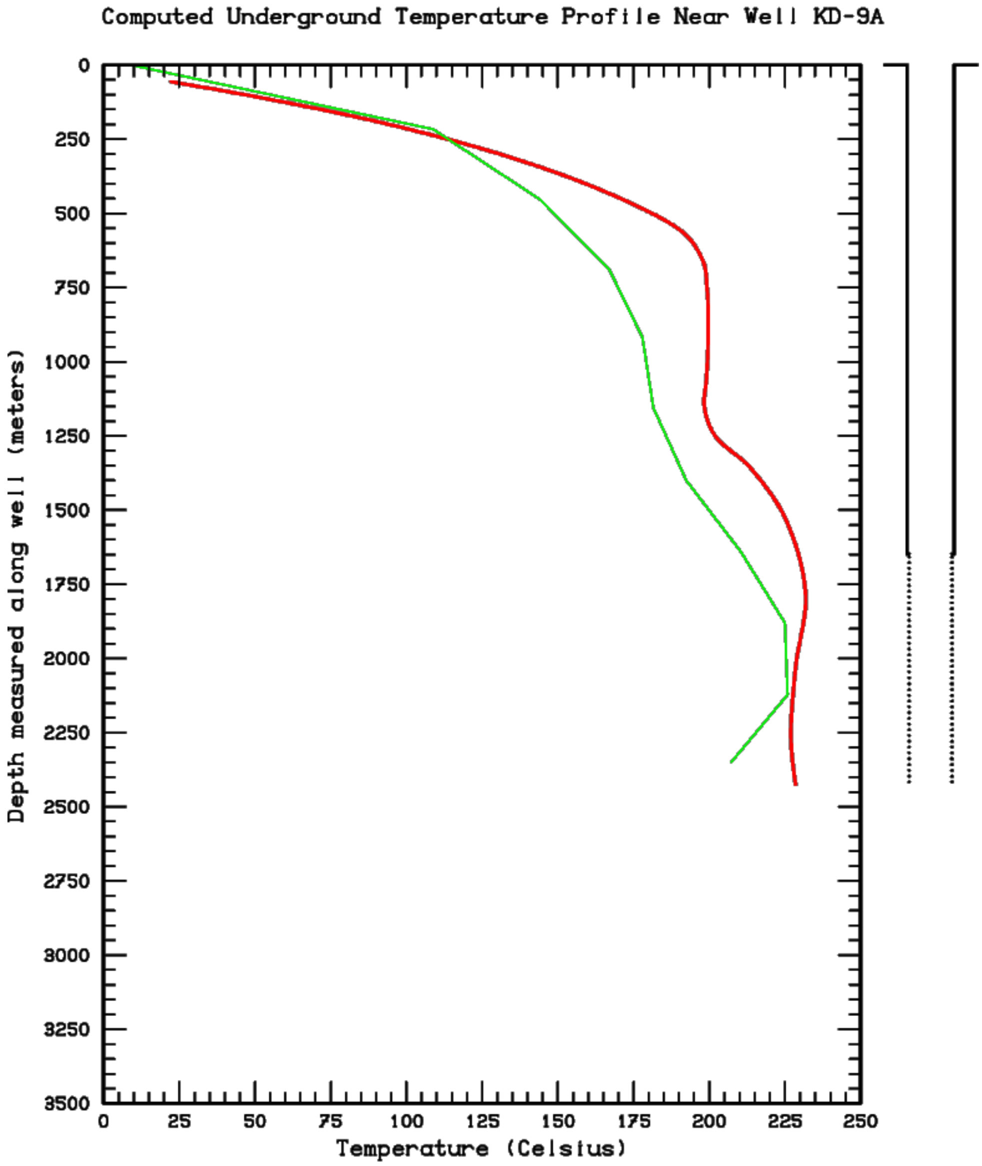

Figure 9: Comparison of measured temperature profile (green) with computed profile (red) for well KD-9A.

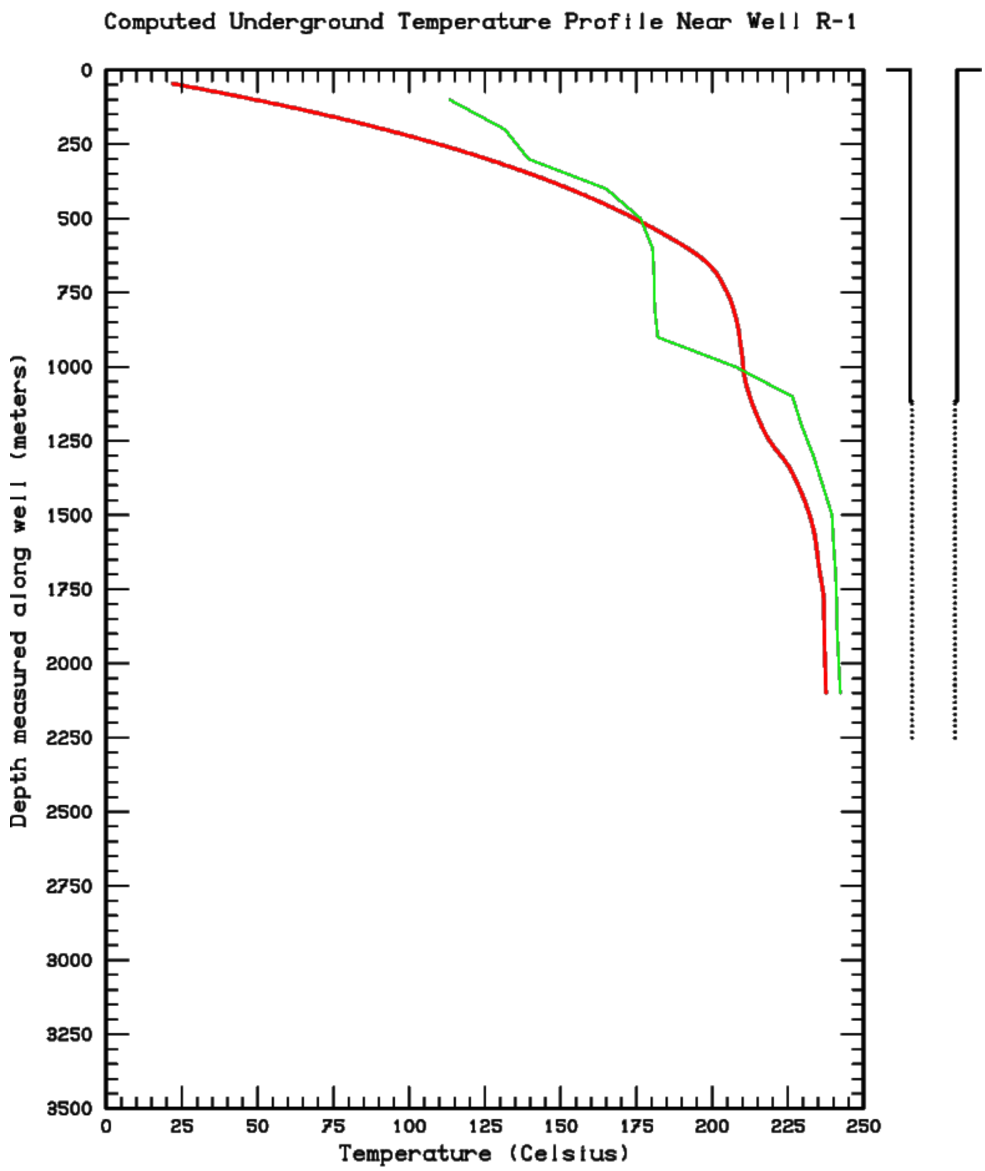

Figure 10: Comparison of measured temperature profile (green) with computed profile (red) for well R-1.

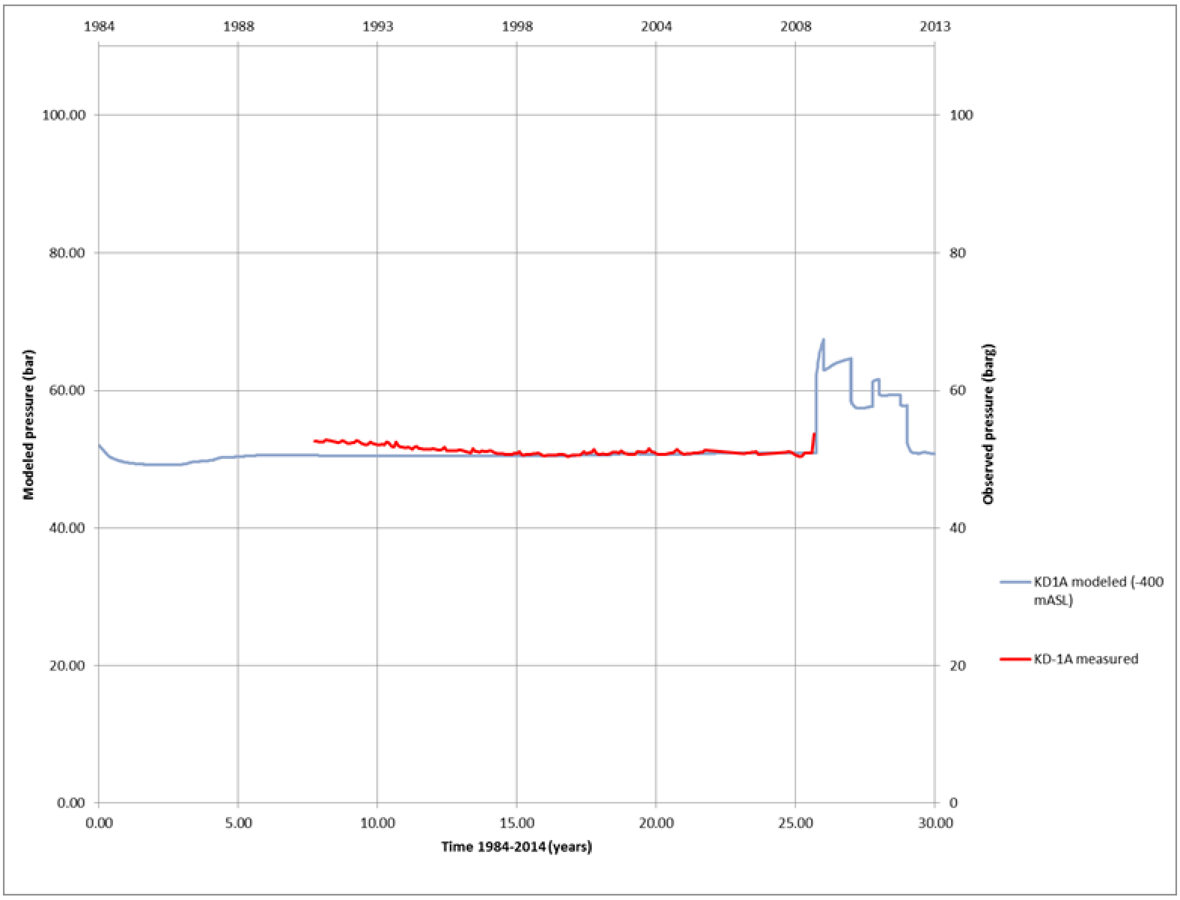

Figure 11: A comparison between measured and computed pressure response for well KD-1A.

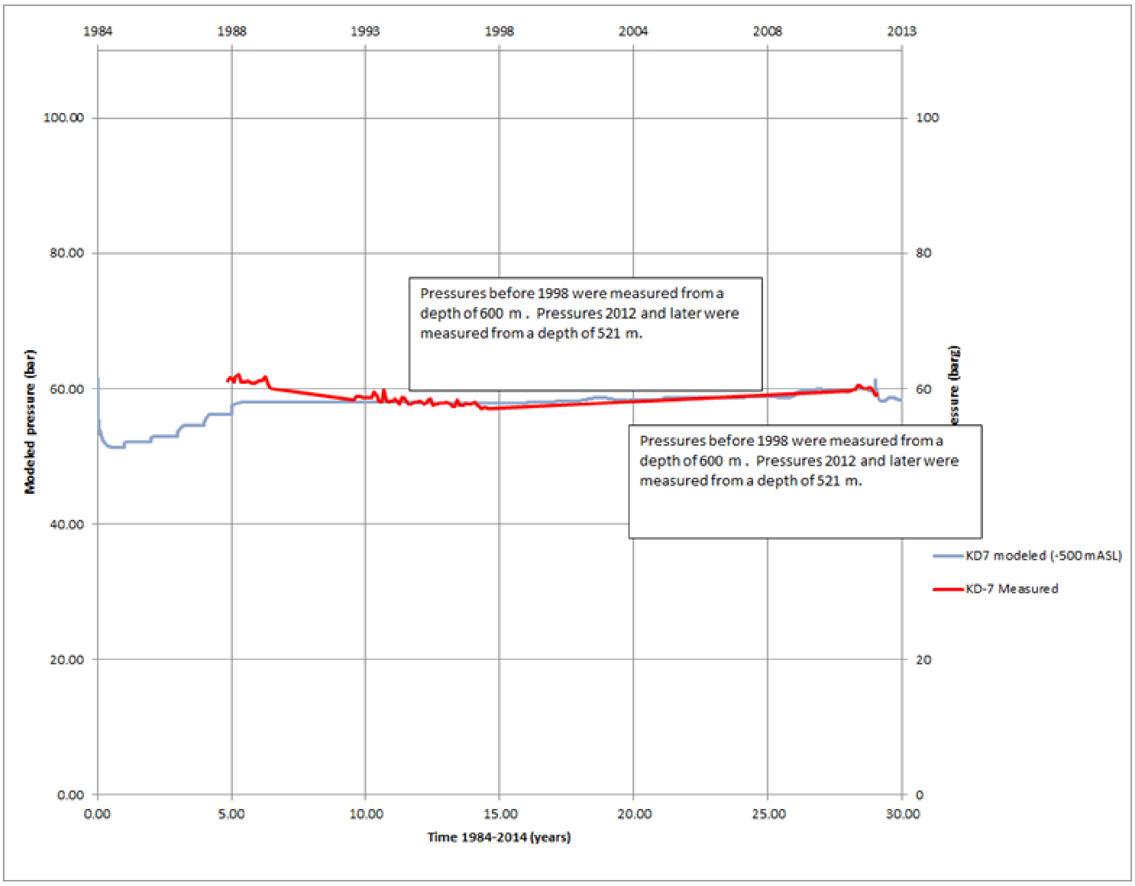

Figure 12: A comparison between measured and computed pressure response for well KD-7.

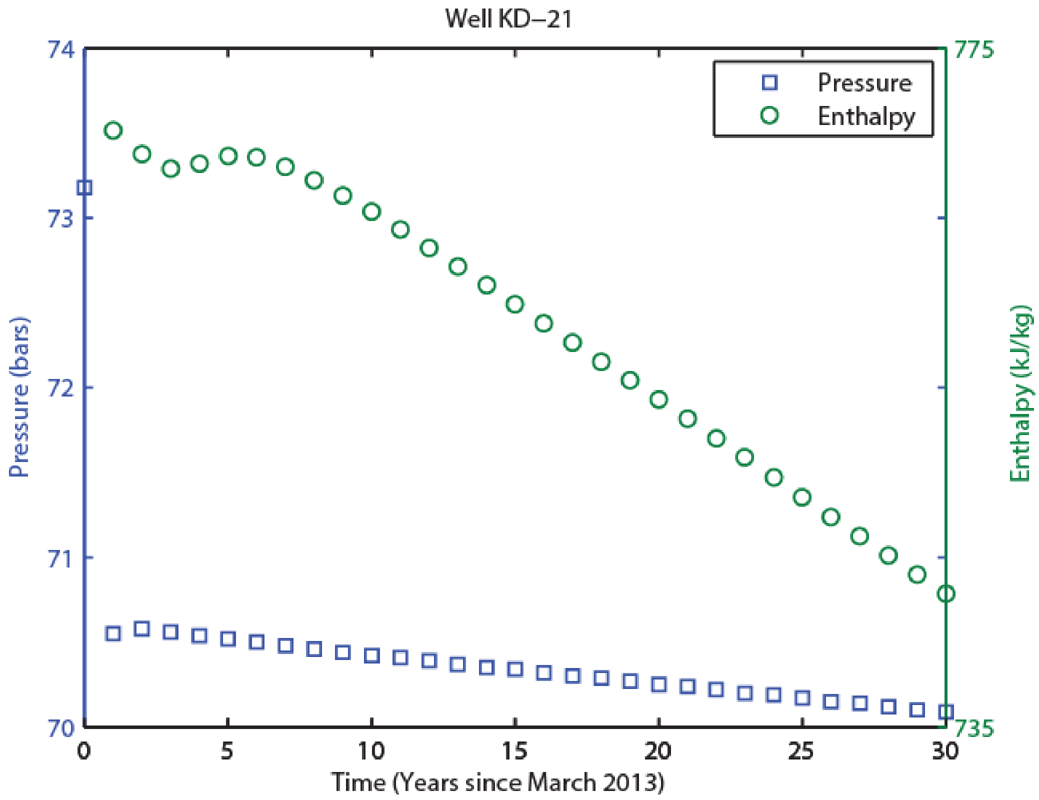

Figure 13a: KD-21 (shallow well) simulated datum pressure and discharge enthalpy.

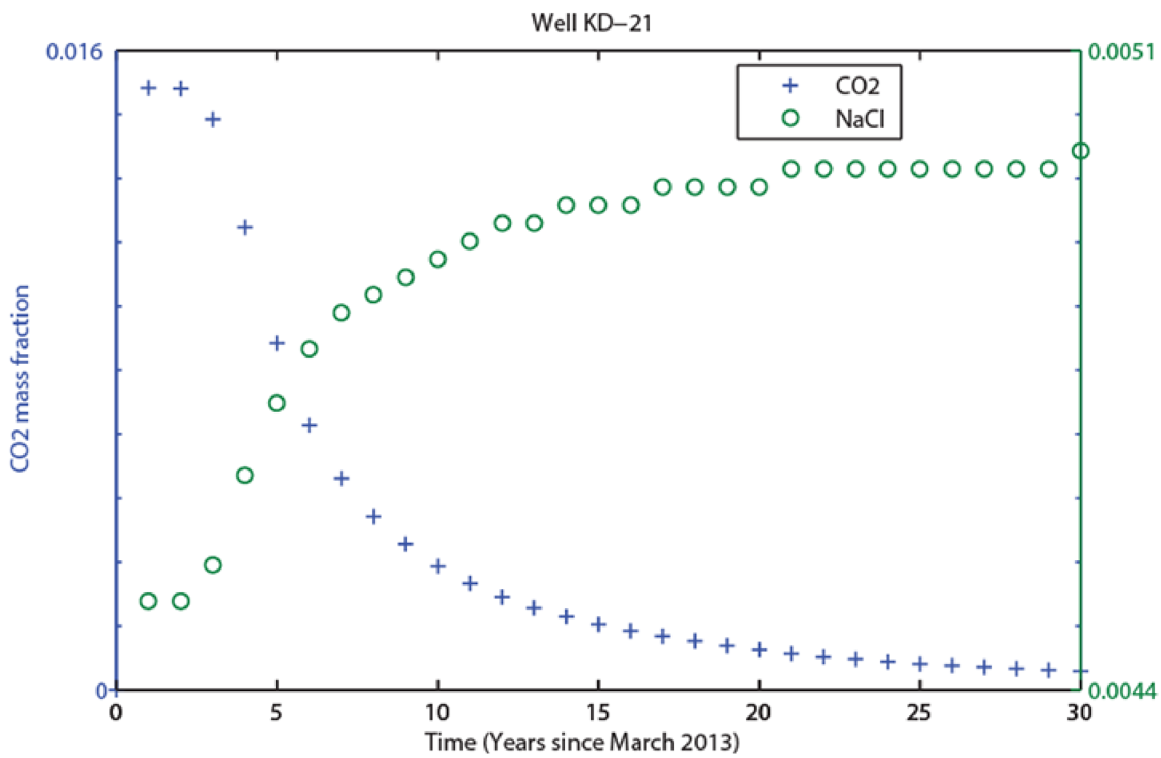

Figure 13b: KD-21 (shallow well) simulated CO2 and NaCl mass fraction.

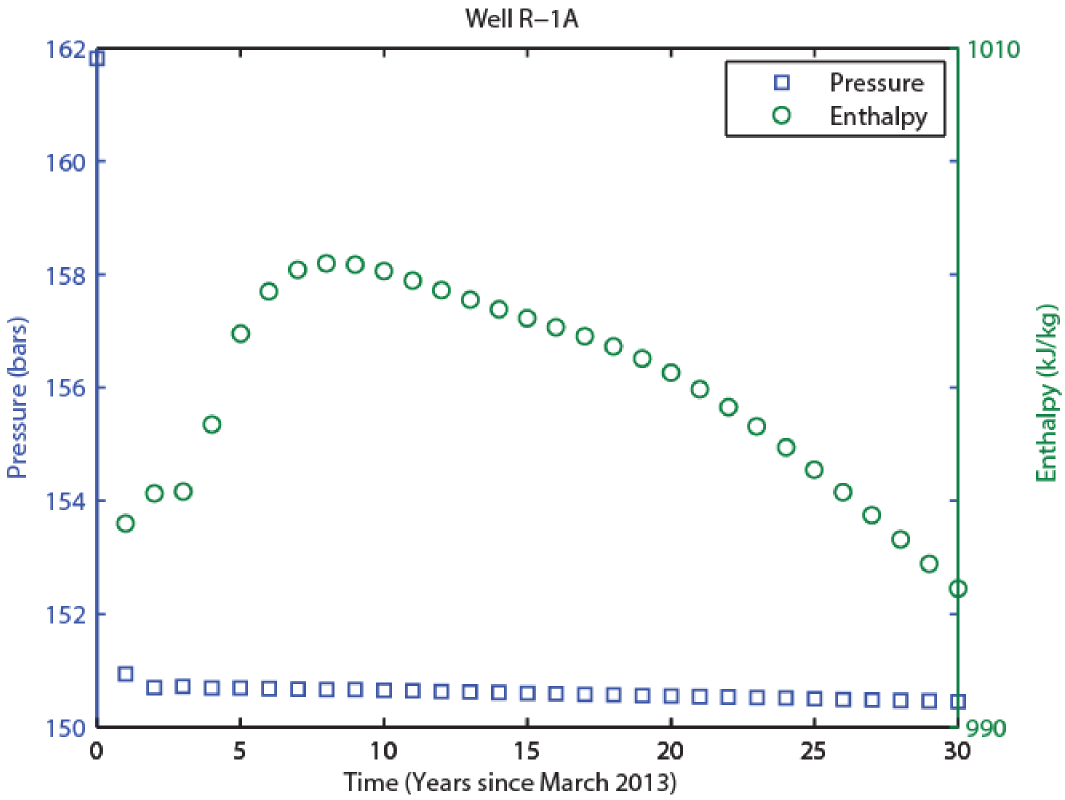

Figure 14a: R-1A (deep well) simulated datum pressure and discharge enthalpy.

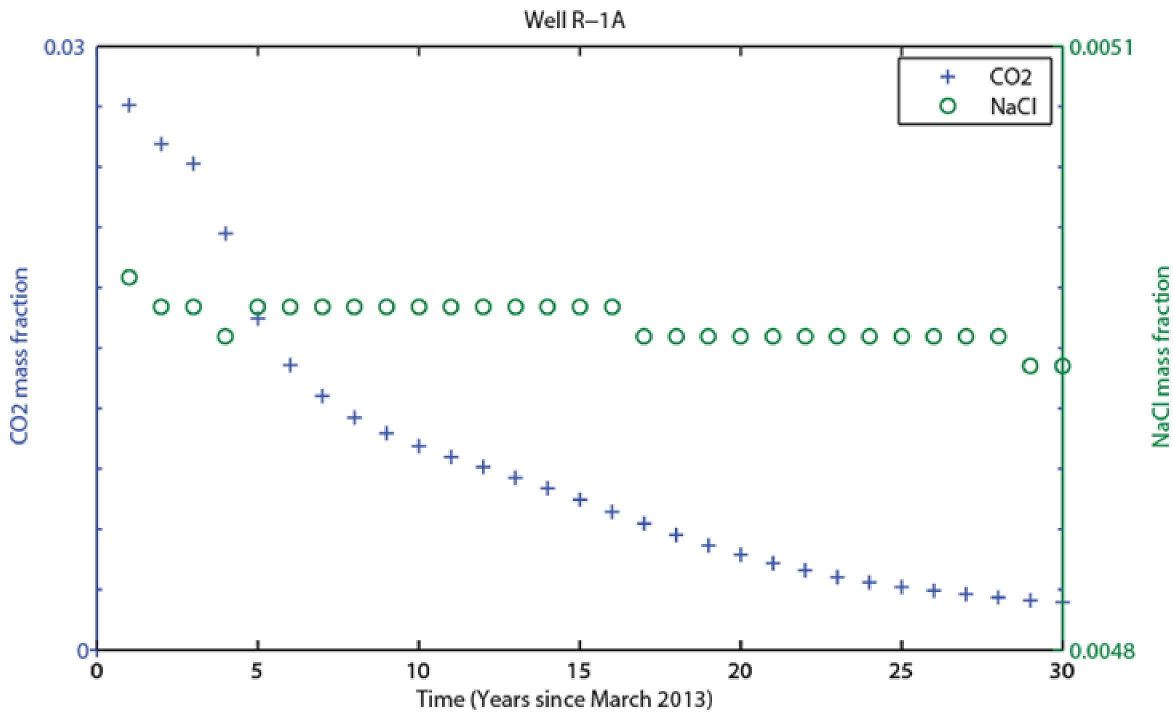

Figure 14b: R-1A (deep well) simulated CO2 and NaCl mass fraction.

5. CONCLUDING REMARKS

The natural state numerical model presented above correctly reproduces the presently available data for pre-production feedzone temperatures and pressures. The numerical model was used to history-match the available production and injection data for the period January 1984 – March 2013; the agreement between the computed and measured pressures in the six (6) observation wells is satisfactory. For the latter history-match calculations, a constant pressure boundary condition was imposed along the lateral surfaces. To the extent that the model results are in accord with the pressures recorded in the six observation wells, the constant pressure boundary condition has been validated at least for the reservoirs hosted by the Sazak and Igdecik formations. Till the present time (early 2014), there has been little production from and injection into the deeper Paleozoic reservoir; therefore, the validity of a constant pressure boundary condition for the deeper Paleozoic reservoir cannot be ascertained at this time.

After history-matching, the numerical model was employed to investigate the feasibility of producing sufficient fluid to supply the fluid requirements for both the Kizildere I and II power plants. The model results for the investigated scenario (Scenario 1) indicate that a system of 20 production and 8 injection wells should be adequate for producing the required fluid supply. The latter conclusion is of course predicated on the assumed behavior (specifically constant lateral pressure condition) of the deeper Paleozoic reservoir.

Acquisition of data over the next year or two on the response of the Paleozoic reservoir to large-scale production and injection will significantly enhance our understanding of this reservoir. The numerical model can then be refined and revised as needed to reflect the enhanced knowledge about the Paleozoic reservoir. The refined model can then be employed to examine other possible production and injection scenarios.

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