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Modeling of Chloride and Carbon Dioxide Injection at Kızıldere Geothermal Field

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ABSTRACT

Re-injection process of the produced fluids back into the reservoirs is a widely recognized method to maintain the reservoir pressure and prolong the life-cycle of the geothermal fields. In addition, environmental awareness throughout the world requires returning the effluent geothermal fluids into the reservoir back to protect both surface and subsurface freshwater resources. Under geothermal conditions, chloride typically behaves as a conservative species remaining in the liquid phase during boiling thus, it can be treated as a tracing element for the injectate. Due to pressure drop along the fluid gathering systems boiling and gas formation occurs in produced fluids, which yields a gradual enrichment in the re-injection fluid in terms of chloride concentration. Therefore, the chloride contents of produced fluids and injectate significantly increase over the lifetime of the field, which indicates substantial returns of injectate to the production wells, enabling the treatment of the conservative chloride species as a continuous tracer injection process. In this work, our aim is to track the carbon dioxide injection by modeling chloride concentration change in the Kizildere geothermal field, located in the west of Turkey, which is performed by using the TOUGH2 simulator. The reservoir model parameters are calibrated with measured static pressure-temperature values and fitted through monitored water chemistry. In the absence of tracer tests, modeling chloride concentration change becomes beneficial to understand the connectivities between wells and the estimation of parameters such as permeability and porosity thus, it provides a reliable model for tracking the carbon dioxide injection process.

1. INTRODUCTION

Geothermal energy is gaining popularity as an alternative energy source for providing future clean electricity demand (Chandrasekharam and Bundschuh, 2002). Although the adopted opinion about the geothermal energy is that it would be a part of the energy transition to reduce the greenhouse gas emissions, presence of high amount of CO_2, up to 4% by weight (Akın, 2020), in hydrothermal reservoirs can be observed in Turkey. It is a well-known fact that high amount of CO_2 may adversely affect the efficiency of the geothermal power plant while increasing the greenhouse gas emissions. Thus, proper actions are needed to be taken in account.

Through the CarbFix1 project, the mineral sequestration method was carried out by injecting $CO_2$with the effluent fluid which the injected fluid disperses through the formation leading the sequestration process of carbon-dioxide in solid minerals by various chemical reactions. The project has achieved to immobilize 95 % of the injected CO_2 as calcite mineral in a low temperature shallow reservoir, which was followed by the CarbFix2 project where the mineralization process was achieved by injecting 23000 tons of carbon dioxide at 60% rate of mineralization (Clark et al., 2020). In order to generalize the CarbFix method even further, GECO project was initialized in 2018 to test the method in different reservoirs where one of the pilot sites is the Kızıldere Field located in Western Anatolia.

In order to achieve these goals, the characterization of the injection site must be properly conducted to understand the flow paths that the injected CO_2 would follow. In this regard, multi-well tracer tests are great options however, in the occasions where tracer tests are absent or do not fully cover the whole reservoir domain, characterization of the flow paths may become challenging. In this work, we present a localized numerical model for the CO_2 injection site in Kızıldere field where chloride has been treated as a conservative tracer in order to characterize the reservoir section between the injection and production wells. The study includes calibration of a natural state model using the static pressure and temperature observations, fitted chloride concentration breakthrough curves and dynamic pressure calibration of the planned CO_2 injection well. Lastly, a predictive model has been developed for the current carbon-dioxide injection strategy and the produced amount of CO_2 has been forecasted.

2. CONCEPTUAL MODELING

The Kızıldere Geothermal Field located in the Saraköy-Buldan area, Denizli Province, of the Western Anatolia at the western part of the Büyük Menederes Graben. The field was discovered in the 1960's when the first well was drilled in 1968 at 540 m depth and 198°C bottom-hole temperature. In terms of the origin of the heat source, no young volcanism was not observed since the last volcanic eruption occurred approximately 12,000 years ago (Ercan, 1979). In the northern part of the Gediz Graben, the volcanic formation is young (Şimşek, 1984) whereas in the western part of the Büyük Menderes Graben, the volcanism is aged to Plio-Quaternary (Şimşek, 1980) for which both volcanism formations are closely related with the rift system (Ercan, 1981). The heat flow map of the field indicates heat anomalies along the graben (Tezcan, 1979), which is an indication of a possible magmatic source. Şengör and Yılmaz (1981) indicated that the origin of the magmatic source is possibly the granite intrusions beneath the Menederes Massif. The orientation of the fault systems are mainly E-W and SE-NW alongside with some N-S trends. The dominating faults are the E-W oriented faults linked with the Büyük Menderes Graben (Şimşek, 2005).

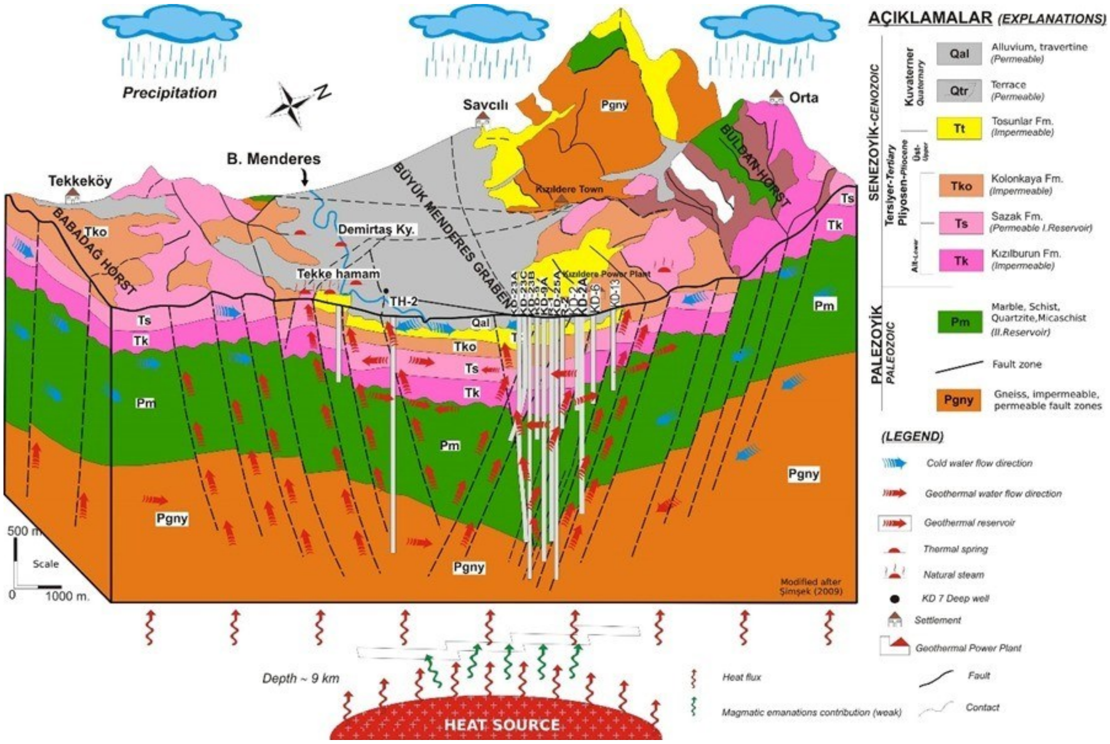

Figure 1 Conceptual Model of Kızıldere Field, (modified after Şimşek et al, 2009).

The Kızıldere Geothermal field consists of two reservoir sections. A general schematic drawing of the conceptual model can be observed in **Figure 1**. The first formation over the shallow reservoir is the Kolankaya formation, which consists of yellowish and brown sandstones, green marls and siltstones. The Tosunlar formation consists of poorly consolidated conglomerate, sandstone and mudstone with fossiliferous clayey limestone (Şimşek, 1985). Sazak formation underlies the Tosunlar formation, which is composed of gray limestone marl and siltstone forms the shallow reservoir section of the geothermal system. Below the Sazak formation, a second cap rock, Kızılburun formation, consists of well-consolidated conglomerates, sand stones and clay stones. The İğdecik formation is composed of marble-quartzite-schists whereas the deep metamorphic reservoirs consists of gneisses and quartzites. These two formations are named as the second and third reservoir sections where the maximum temperature values were recorded as 212°C and 236.5°C respectively. Using the information gathered from the well-log interpretations, geophysical surveys and previous conceptual model knowledge, the 3-D geological model of the Kızıldere Geothermal Field has been constructed (**Figure 2**). Kolankaya and Tosunlar formations form the shallow caprock bounding the shallow reservoir (Sazak formation). The deeper Kızılburun formation and the İgdecik and the deep metamorphic reservoir sections form the cap rock and the deep reservoir respectively.

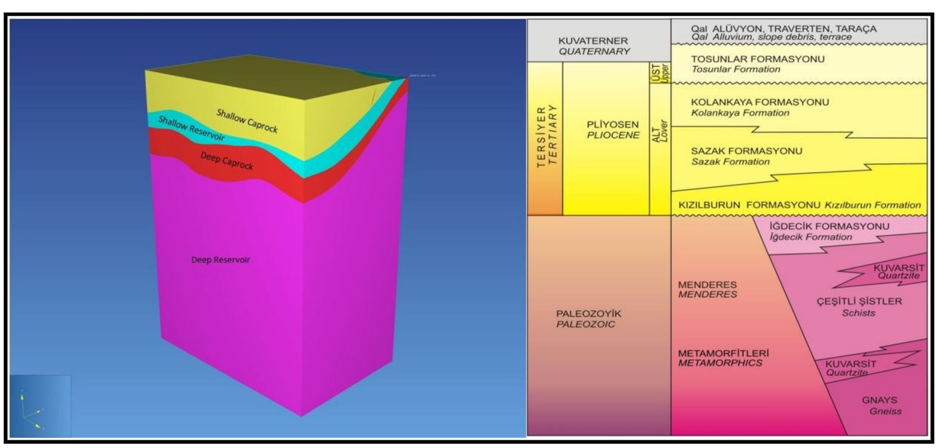

Figure 2 3D Conceptual Model of the Localized Model (left), General Statigraphy of Kızıldere Field (right), (Şimşek et al, 2009)

3. NUMERICAL MODELING

3.1 Model Construction and Natural State Modeling

As the main aim of the study is to characterize the flow field in the reservoir domain, a sector model of the injection site containing 6 production wells and 4 injection wells centered along the carbon-dioxide injection well has been developed. The advantages of constructing such a local model are reduced computational cost of the numerical simulation and increased resolution of the injection site. Erol et al., (2022), showed that for two separate slug tracer injections, the tracers arrived only at the production wells, which are within the localized model boundary. Furthermore, Akın et al., (2016) reported 3 separate tracer tests in the field with which the results do not contradict with the localized model boundary. For the numerical simulation, the EOS1 module of the TOUGH2 (Pruess et al., 1999), which solves both tracer and fluid flow problem in a non-isothermal fashion has been used. The constructed model bounds an area of 5.18 km² with a maximum depth of 3850 meters. A polygonal mesh system consisting of 13584 grid blocks (**Figure 3**) with additional mesh refinements near the well coordinates has been used. Fixed state boundary condition has been applied at the top of the model. In order to represent the heat flux from the reservoir, a heat source has been used at the lower section of the model. The natural state simulation has been run for 500,000 years until the pressure and temperature values converged in all of the grid blocks. Satisfactory pressure and temperature matches were obtained at the 9 5/8" casing setting depths (**Figure 4**). It should be noted that static pressure and temperature observations may not represent absolute static values since the field has been producing for the last 10 years.

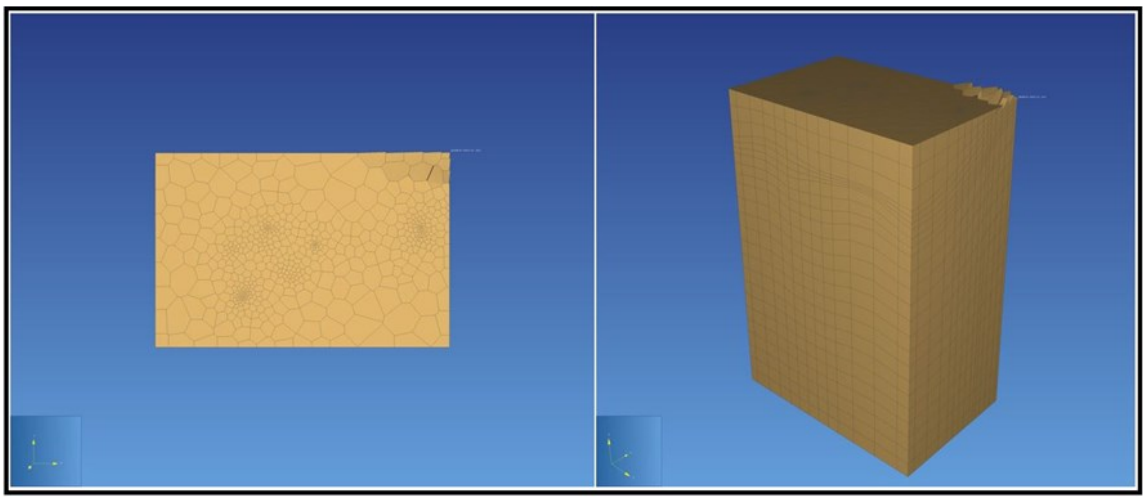

Figure 3 Mesh System of the Localized Model

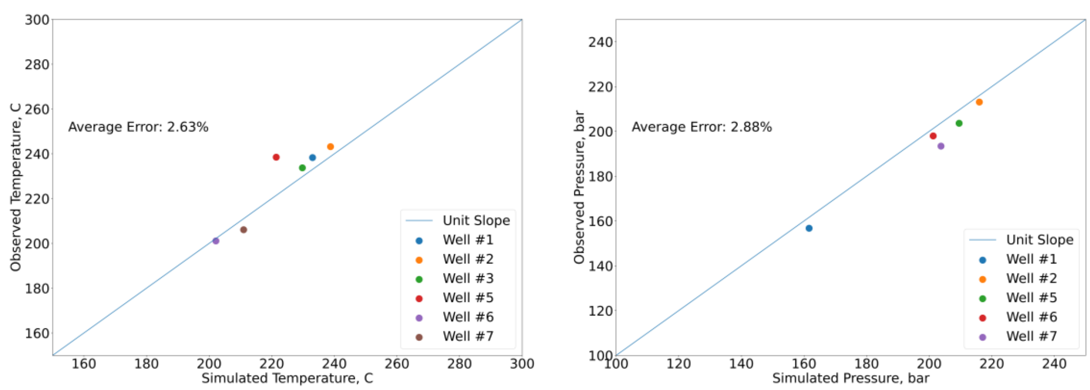

Figure 4 Natural State Temperature and Pressure Matches at 9 5/8" depths

3.2 Chloride Tracer

Non-volatile chemical components such as chloride do not take part in any precipitation reaction in a geothermal system. This means that the concentration of chloride in the reservoir fluid will remain constant over time, making it useful tracer for studying fluid flow and mixing in the reservoir. Several simulation studies where conservative species have been used as tracers were conducted in the past. Kissling et al (1996) constructed a transport model where chloride was treated as conservative, non-reacting species for the Wairakei geothermal field. Ratouis et al (2022) used boron as conservative species in the Husmuli geothermal field. In Kızıldere Geothermal Field, although the reservoir fluid is water dominated, a gradual enrichment of the chloride concentration occurs due to the pressure drop along the wellbores and separator units, which results in gas formation with boiling and adiabatic cooling. The enriched fluid is reinjected into the reservoir hence, continuous injection breakthrough curves, which enables us to define the flow path characteristics, can be observed in the production wells in terms of chloride concentration. The chloride concentration from the production wells were continuously measured at surface conditions. The surface measured concentration data was then adjusted to the reservoir conditions for model comparison. As it has been stated, 4 injection wells and 6 production wells are present within the model boundary. In order to model the tracer breakthrough curves, artificial flow paths (**Figure 5**) were defined into the model along the direction of the fault zone. Similar approaches for modeling tracer breakthroughs have been developed by Tómasdóttir (2018), Erol et al (2022) and Ratouis et al (2022). In all of these studies, modeling slug injection tracer breakthrough curves have yielded satisfactory results. Different from those works, the developed model uses all possible flow paths originating from all injection wells by using the chloride concentration breakthrough curves.

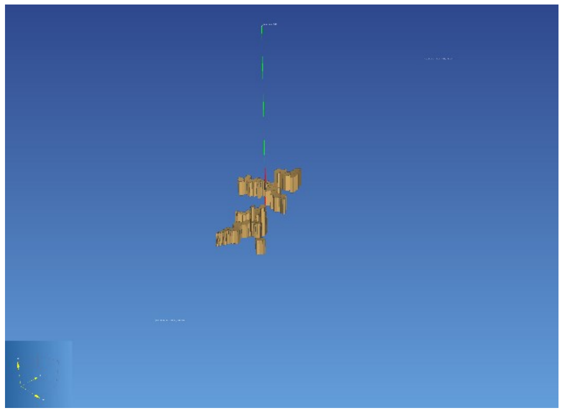

Figure 5 Flow Path Representation of Well #7

Permeability, porosity, anisotropy ratio and grid volume multipliers of the fault zones have been used as calibration parameters for the flow paths. An important consideration is that the observed data may not resemble the production concentration at a specific reservoir depth but the whole feed zone thickness of the production wells for which every well in the domain crosses through multiple grid blocks. By using a simple flow-averaging formula through the grid blocks of the production wells, the chloride concentrations were calculated. If the initial distribution of the chloride concentration in the reservoir varies across regions convergence problems in the natural state modeling may arise. To overcome this issue, the initial concentration of the chloride has been taken as constant and the observation data has been normalized around the initial concentration. **Figure 6** shows the chloride matches obtained for the production wells. It can be observed that the model captures both the magnitude and the behavior of the chloride concentration change. An excellent pressure match (**Figure 7**) was obtained for Well #7 when it was used as an observation well prior to brine reinjection. This shows that the developed model accurately represents the deep reservoir behavior of the Kızıldere field. After dynamic calibration natural state model is revisited for possible temperature and pressure deviations. It was concluded that an excellent dynamic calibration has been achieved.

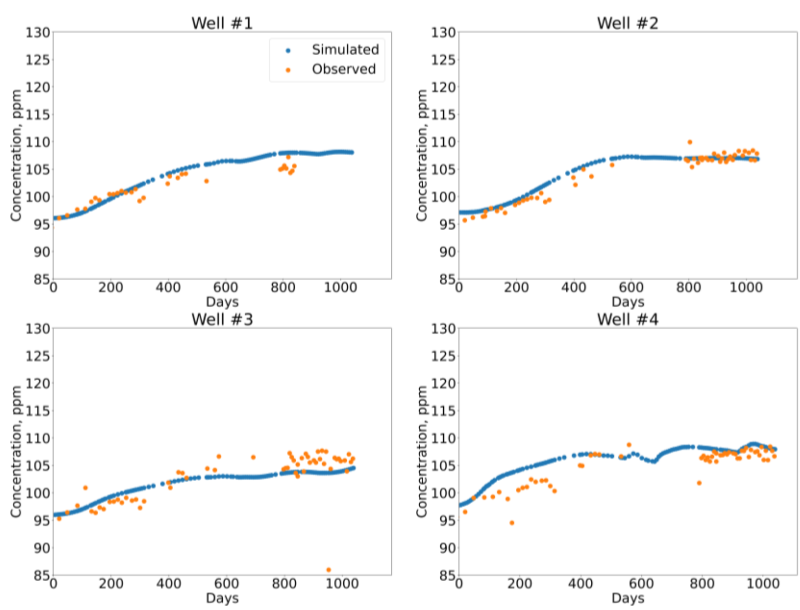

Figure 6 Calibration Results of Chloride Breakthrough Curves

Figure 7 Dynamic Pressure History Matching Results for Well #7

4. PREDICTION OF THE CARBON-DIOXIDE INJECTION

As stated before Kızıldere Geothermal resevoir contains high amount of NCG (approximately %3 percent by weight) at reservoir conditions. Furthermore, 98% of the NCG is composed of CO_2. Under the GECO Project, an injection plan has been constructed to inject NCG from Well #7. According to this plan 250 kg/hr of NCG and approximately 150 ton/hr of brine will be continuously injected at Well #7 at approximately 30 bar pressure for a period of 6 months. Previously, Küçük (2018) developed a field scale simulation model for the Kızıldere field to study the impact of CO_2 injection. Alkan and Satman (1990) developed a lumped parameter model to estimate the reservoir performance of the Kızıldere field. More recently, Erol et al (2022) constructed a reactive transport model to study the impact of CO_2 injection on mineral deposition and dissolution for various injection schemes. The findings of this reactive transport model indicated that the carbonization process of CO_2 is limited in the Kızıldere field. Thus, a mass and heat transfer model can be considered satisfactory for predicting the fate of carbon-dioxide injection. In this regard, the calibrated model can be used for the prediction of the CO_2 weight fractions of the production wells after the injection has commenced. In terms of modeling, the EOS2 module of TOUGH2 (Pruess et al 1999), which couples flow of brine with the non-ideal behavior of carbon-dioxide in gaseous phase and the dissolution of it in the aqueous phase in non-isothermal conditions has been used. For the partial pressure calculations, the Henry's Law Coefficient is calculated by a correlation developed by Battistelli et al. (1997). A similar procedure has been followed for simulating the NCG injection. First of all, a natural state model has been developed by using the EOS2 module followed by the dynamic simulation of the sector model. In both of these models fluid and rock properties of the aforementioned chloride calibrated model was used. No significant changes in terms of pressure and temperature were observed compared to aforementioned model results. The model shows a significant decrease of CO_2 content near the injection well after degassed brine injection (**Figure 9**). The results of the CO_2 content of the produced brine of several wells after NCG injection can be observe the **Figure 8**. The model results show that NCG injection does not increase CO_2 content of the produced brine. This is expected due to limited amount of NCG injection. There are minor changes in terms of CO_2 content both in the produced fluid (**Figure 8**) and CO_2 remaining in the reservoir (compare **Figure 10** with **Figure 11**). This behavior is possibly related to limited amount of NCG injection rather than limited hydraulic connectivity between the injection and production wells, since the calibrated model chloride breakthroughs indicate arrival of sufficient amount of injectate. To observe a significant alteration in CO_2 content, higher amounts of CO_2 needed to be injected.

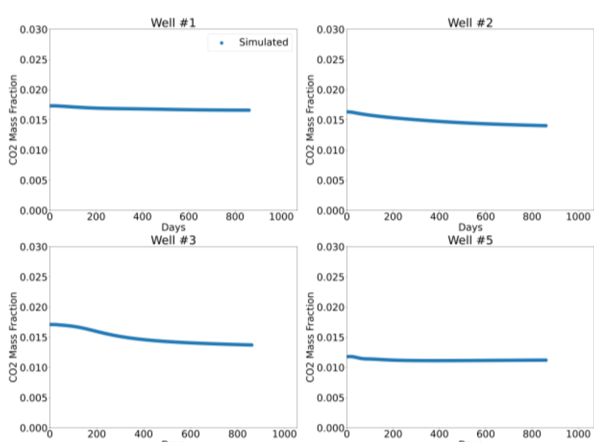

Figure 8 Carbon-Dioxide Mass Fractions of Production Wells after NCG injection

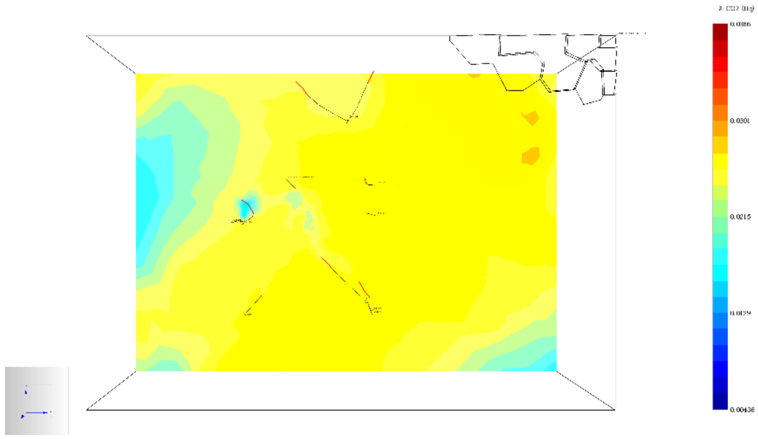

Figure 9 CO_2 Mass Fraction @Reservoir Depth (2200 BSL), Prior to Brine Injection.

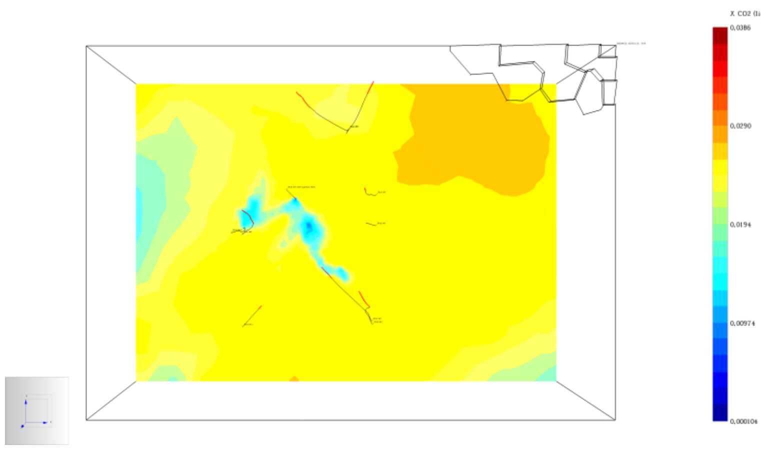

Figure 10 CO_2 Mass Fraction @Reservoir Depth (2200 BSL), at CO_2 Injection Date

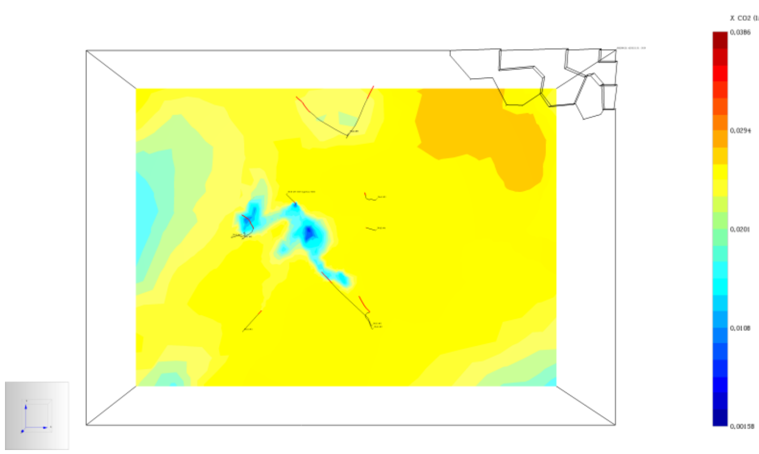

Figure 11 CO_2 Mass Fraction @Reservoir Depth (2200 BSL), 2 Years After CO2 Injection

5. CONCLUSION

In this work, a 3D sector model of the Kızıldere geothermal field has been constructed using TOUGH2 to study pilot field NCG injection. The model is calibrated using static pressure and temperature data, chloride concentration time data obtained at the production wells and dynamic observation well pressure data. As a result a comprehensive characterization of the flow paths for a carbon-dioxide injection site, Kızıldere Geothermal Field, has been achieved. The developed sector model was used to predict CO_2 distribution in the reservoir and the CO_2 content of the produced brine at the production wells. The following conclusions were depicted.

1) The model results show that NCG injection does not increase CO_2 content of the produced brine, due to limited amount of NCG injection.
2) There are minor changes in terms of CO_2 content both in the produced fluid and CO_2 remaining in the reservoir, which is a consequence of injecting limited amount of NCG injection rather than limited hydraulic connectivity between the injection and production wells
3) In order to observe a significant alteration in CO_2 content, higher amounts of CO_2 needs to be injected.

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REFERENCES

Akın, S., Örücü, Y., & Frıdrıksson, T. (2020). Characterizing the declining CO2 emissions from Turkish geothermal power plants.

Akın, S., Şentürk, E., Şengün, R., & Kılınçarslan, S. (2016 0). Tracer Testing at Kizildere Geothermal Field Turkey Using Nap htalene Sulfonates. https://hdl.handle.net/11511/84774.

Alkan, H., & Satman, A. (1990). A new lumped parameter model for geothermal reservoirs in the presence of carbon dioxide. Geothermics, 19(5), 469–479. https://doi.org/10.1016/0375-6505 (90)90059-k

Alkan, H., & Satman, A. (1990). A new lumped parameter model for geothermal reservoirs in the presence of carbon dioxide. Geothermics, 19(5), 469–479. https://doi.org/10.1016/0375-6505 (90)90059-k

Chandrasekharam, D., & Bundschuh, J. (2002). Geothermal Energy Resources for Developing Countries. https://doi.org/10.1201/9780367803353

Clark, D. E., Oelkers, E. H., Gunnarsson, I., Sigfússon, B., Snæbjörnsdóttir, S. Ó., Aradóttir, E. S., & Gíslason, S. R. (2020). Carbfix2: CO2 and H2s mineralization during 3.5 years of continuous injection into basaltic rocks at more than 250 °C. Geochimica Et Cosmochimica Acta, 279, 45–66. https://doi.org/10.1016/j.gca.2020.03.039

Ercan, T. (1979) Bati Anadolu, Trakya ve Ege adalarmdaki Senozoyik volkanizmas). Jeolojii Müh. Odası. Yayini,

sayi 9, Ankara.

Ercan, T. (1981) Kula yöresinin jeoloji ve volkanitlerinin petrolojisi, (PhD Thesis), I.U. Earth Sciences Faculty, 165 pp.

Erol, S., Bayer, P., Akın, T., & Akın, S. (2022). Advanced workflow for multi-well Tracer test analysis in a Geothermal Reservoir. Geothermics, 101, 102375. https://doi.org/10.1016/j.geothermics.2022.102375

Erol, S., Akın, T., Başer, A., Saraçoğlu, Ö. & Akın, S. (2022). Fluid-CO2 Injection Impact in a geothermal reservoir: Evaluation with 3-D reactive transport modeling. Geothermics, 98, 102271. https://doi.org/10.1016/j.geothermics.2021.102271

Kissling, W. M., Brown, K. L., O'Sullivan, M. J., White, S. P., & Bullivant, D. P. (1996). Modelling chloride and CO2 Chemistry in the Wairakei Geothermal Reservoir. Geothermics, 25(3), 285–305. https://doi.org/10.1016/0375-6505 (96)00009-0

Küçük, S. (2018). Simulation of geothermal reservoirs with high amount of carbon dioxide (Master's thesis, Middle East Technical University).

Pruess, K., Oldenburg, C. M., & Moridis, G. J. (1999). TOUGH2 user's guide version 2 (No. LBNL-43134). Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States).

Ratouis, T. M. P., Snæbjörnsdóttir, S. Ó., Voigt, M. J., Sigfússon, B., Gunnarsson, G., Aradóttir, E. S., & Hjörleifsdóttir, V. (2022). Carbfix 2: A transport model of long-term CO2 and H2S injection into basaltic rocks at Hellisheidi, SW-Iceland. International Journal of Greenhouse Gas Control, 114, 103586. https://doi.org/10.1016/j.ijggc.2022.103586

Şengör, A. C., & Yilmaz, Y. (1981). Tethyan evolution of Turkey: a plate tectonic approach. Tectonophysics, 75(3-4), 181-241.

Şimşek, Ş. (1985). Geothermal model of Denizli, Sarayköy-Buldan area. Geothermics, 14(2-3), 393–417. https://doi.org/10.1016/0375-6505 (85)90078-1

Şimşek, Ş., Yıldırım, N., & Gülgör, A. (2005). Developmental and environmental effects of the Kızıldere Geothermal Power Project, Turkey. Geothermics, 34(2), 234–251. https://doi.org/10.1016/j.geothermics.2004.12.005

Şimşek, Ş., Parlaktuna, M., & Akin, S. (2009). Data Gathering and Evaluation of Kızıldere Geothermal Field.

Tezcan, A. K. (1979) Geothermal Studies, Their Present Status and Contribution to Heat Flow Contouring in Turkey.

Springer, Berlin.

Tomasdottir, ´ S., 2018. MSc. Thesis. Uppsala University, Sweden.