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No Gas Left Behind: Reactive Transport Modelling of CO_2 Reinjection in Mt Apo Geothermal Field, Philippines

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ABSTRACT

This study presents a one-dimensional (1D) radial and two-dimensional (2D) cross-sectional model to investigate the reactive transport behavior in the Mt Apo Geothermal Production Field, focusing on Well K1's major feedzone, subject to various reinjection scenarios including neutral brine, binary brine, and a proposed non-condensable gas (NCG)-charged binary brine using TOUGHREACT v4.13 EOS 1. It explores the geochemical and mineralogical changes induced by NCG-charged fluid injection under reservoir conditions. The simulation captures key processes such as dissolution, mineral alteration, and secondary mineral precipitation within the feedzone-to-reservoir flow path. The 1D model results provided insights into potential impacts on injectivity and showed permeability enhancement due to thermal effects, with calcite, dolomite, epidote, illite, and anhydrite undergoing consistent dissolution at different magnitudes under low-pH injection. The 1D model provided an initial assessment of porosity-permeability evolution and geochemical responses near the injection zone, while the 2D model allowed spatial analysis of thermally and chemically driven changes across injection and production well areas. The 2D model highlighted the importance of incorporating spatial heterogeneity and boundary condition influences to predict long-term geochemical behavior and permeability evolution under future injection strategies. The comparison underscores the limitations of simplified 1D approach and supports the use of more detailed 2D modeling for scenario planning, particularly when evaluating the feasibility and long-term effects of NCG co-injection on reservoir performance and sustainability.

1 INTRODUCTION

Geothermal energy is one of the energy sources that we can harness primarily for power production and direct use. Although renewable, it is not free from greenhouse gas emissions as production of non-condensable gases (e.g., CO_2, H_2S, H_2, NH_3, CH_4) are inherent when dealing with hydrothermal systems (Altar and Kaya, 2020). The recent global estimate of GHG emissions from geothermal is averaging at 122 gCO_2/kWh (Fridriksson, 2017). In the Philippines, EDC reported to have around 105 gCO_2/kWh emission on its combined geothermal capacity nationwide in 2023. This is significantly lower than coal, oil, and natural gas (DOE, 2023); and although geothermal's carbon dioxide emissions are slightly higher than wind, solar, and hydro, it is still within the "low carbon" category (McClean and Richardson, 2024).

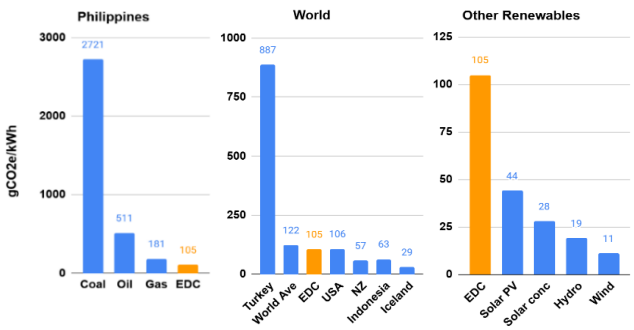


Figure 1. (a) Philippines' GHG Emissions From Fossil Fuels and EDC (b) Worldwide Geothermal Emission Comparison (c) Comparison to Other Renewables.

1.1 NCG reinjection worldwide comparison

An emerging method to reduce GHG emissions from geothermal is through co-injection where NCG is mixed with the condensate or brine for reinjection back into the reservoir. Several countries such as Iceland (Sigfusson

et al., 2018; Ratouis et al., 2022), Turkey (Erol et al., 2022; Yucetas et al., 2018), Japan (Yanagisawa, 2010; Kaieda et al., 2009), USA (Adams et al., 2000) and New Zealand (Ruiz et al., 2021; McClean and Richardson, 2024; Abd Ghafar et al., 2022) have been doing this; however, each geothermal field has unique characteristics and may have different response to this reinjection scheme. Some of these projects have reported problems like scaling in production lines, NCG breakthrough to adjacent production wells, and increased operational costs (Siahaan, 2024).

Table 1. Comparison of Different Geothermal Fields with NCG reinjection.

Site	Rock type	Year started	Amount CO_2 injection	Issues encountered / Notable Results
Puna, USA (Bonafin et al., 2019; DePippo, 2016)	Basalt	1984	Total fluid and gas reinjection	No issue on corrosion
Coso, USA (Kolar et al., 2015)	Granite	1989	H_2S injection	High maintenance cost
Ogachi/Hiroji, Japan (Ueda et al., 2010; Kaieda, 2021)	Granite (EGS)	2007	1% w/w CO_2 (dry ice)	Calcite precipitation
Te Huka, New Zealand (Richardson et al., 2023)	Greywacke	2011-partial	100% reinjection (2022)	No issues regarding gas breakout
Hellisheidi/Nesjavellir, Iceland (Ragnarsdottir et al., 2023; Levy et al., 2021)	Basalt	2014	12 Mt/yr CO_2 6 Mt/yr H_2S	Mineralization occurred in reservoir
Umurlu, Turkey (Yucetas et al., 2018)	Carbonate	2017	1.2 Mt CO_2 for 20 days	CO_2 breakthrough in production wells
Kizildere, Turkey (Sevindik et al., 2024)	Carbonate	2022	985 tCO_2 for 6 months	No CO_2 increase in produced fluid
Ngā Tamariki, New Zealand (Abd Ghafar et al., 2022)	Greywacke	2022	100% reinjection (3/4 units)	No scaling/NCG changes in production wells

In the Philippines, there's no NCG reinjection that has been operationally done yet among the geothermal fields except for the pilot testing conducted in Tongonan-I in 2005 (Villena et al., 2005). For this study, the Mindanao Geothermal Production Field located in Mt Apo is considered. It was originally composed of two units (Mindanao 1 and Mindanao 2) with a 701-hectare concession and 104 MW capacity which started production in 1997. In 2022, a third power plant was commissioned (Mindanao 3 Binary) with a 3.6 MW capacity utilizing the separated brine from Mindanao 1 (Frassinetti et al., 2022). With the lower brine temperature at the outlet of the binary plant, it increases the scaling potential down the reinjection wells. Hence, this study aims to investigate the effect of mixing non-condensable gases to the brine and to check the changes in porosity, permeability, mineral volume fraction, chemistry, and other parameters around the reinjection well using 1D and 2D models.

1.2 Well K1 in Mt Apo Geothermal Production Field

Well K1 is one of the reinjection wells in the Mindanao Geothermal Production Field located in Mt Apo. The field is geographically divided into three sectors: Matingao-Kullay, Marbel, and Sandawa; the latter two sectors are feeding the flash power plants (Mindanao 1 and 2) while the former serves as the injection sink (Aragon and Sambrano, 2010; Malibiran and Zarrouk, 2014) (see Figure 2).

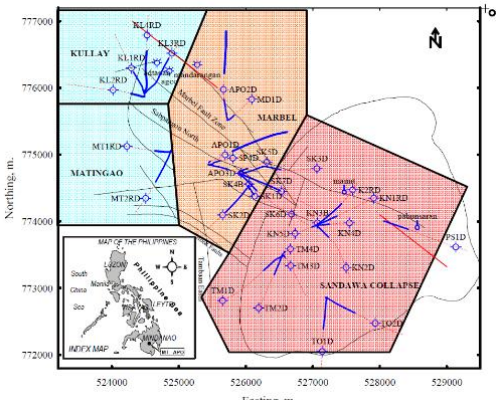


Figure 2. Map of MGPF Showing Geographical Boundaries (Aragon & Sambrano, 2010).

The feedzones of Well K1 as viewed in Leapfrog is shown in Figure 3. Well K1 was originally one of the hot reinjection wells in the Kullay sector before it was dedicated to the binary operations. It was drilled in the outflow region with a shallow major feed zone (at around 114mRSL with 40m thickness) along with four more permeable zones at greater depths. It intersects three structures, namely N-NW Sisiman, Sisiman Splay, and Sisiman Fault at depths of 175 to -625mRSL (Sambrano et al., 2010).

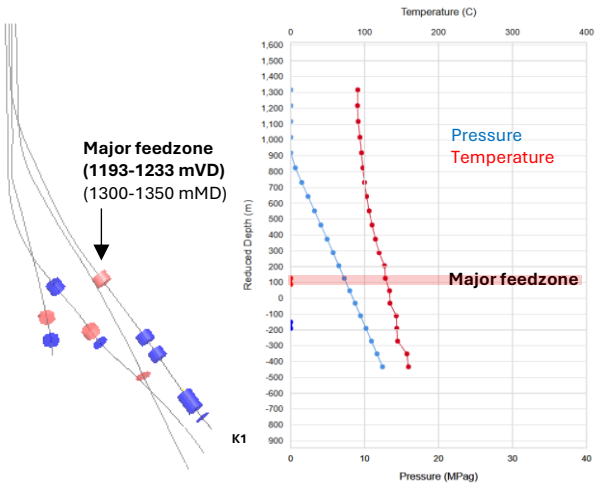


Figure 3. Well K1's Feedzones and Shut Pressure and Temperature Plot.

2 METHODOLOGY

2.1 1D and 2D Model Setup

A 1D radial model grid was generated using PyTOUGH scripts with only one layer at 40m thickness to match Well K1's major feedzone contributing 50% of the total flow rate (see Figure 3). It was set up with a 0.1 m well radius (removed from the blocks) and the next 3.338 m as skin zone, another zone up to 2049 m for the reservoir, and extended up to 28.5 km representing the outer reservoir boundary as shown in Figure 4. The block sizes were increasing logarithmically and the last gridblock was made large enough to accommodate the fluid flow and avoid boundary effects. MINC approach was used to setup the skin and reservoir zone up to 2049m with 98% matrix and 2% fracture volume fraction because the nearest production well feedzone is at around 2000 m from the injection feedzone being modelled, while the outer reservoir boundary layer was only set as single porosity.

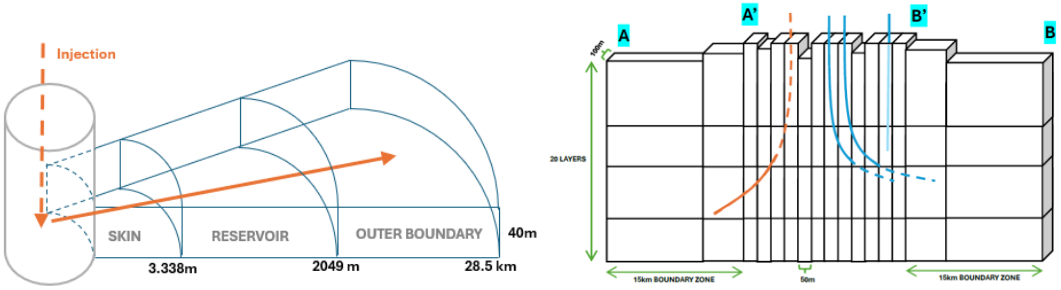


Figure 4. Unscaled Illustration of the 1D Radial and 2D Cross-sectional Model.

As for the 2D model, it has 20 layers in total incorporating the topography (atmospheric blocks added on the top layer) with varying thicknesses along the z-axis following the existing 3D reservoir model and a thickness of 100m in the y-axis as a slice (see Figure 4). Grid blocks of varying thicknesses spanning 15 km on both ends of the model (A to A' and B' to B) are included and set as boundary zones to allow continuous lateral flow of fluids and avoid boundary effects. The grid blocks in between the injection and production zones are set at 50m thickness to discretize the changes around the area of concern for this study. There is one reinjection well and three production wells intersected in the 2D slice model (100% of the feedzone of the two production wells are included and one feedzone with 17% contribution for the third production well is also included).

2.2 Reactive Surface Areas

The reactive surface areas for the fracture and matrix were calculated using the equations given in the TOUGHREACT manual (Sonnenthal et al., 2018).

$$A = \frac{\pi A_{f-m}}{2\varphi_f} \tag{1}$$

$$RSA = A\, V_{frac} \tag{2}$$

For the fracture, Equation 1 above was used to get the reactive surface area (RSA) where π/2 serves as the roughness factor, Af-m is the fracture-matrix interface area/volume ratio (considering the 98% matrix, 2% fracture setup), and ϕf is the true fracture porosity, then taking the RSA per mineral using Equation 2.

$$A = \frac{0.5}{r} \tag{3}$$

For the matrix, a simple cubic packing of 8 spheres was assumed and dividing the total area by the cube volume results in Equation 3. The radius is assumed to be 5.00E-04, then the same process is taken for the RSA per mineral as in Equation 2. The RSA used in the model is divided by 1000 because based on the compiled kinetic models they are usually 10-1000 times lower than the calculated (White and Peterson, 1990). Shown in Table 2 are the mineral volume fractions and calculated reactive surface areas used in the model.

Table 2. Mineral Volume Fractions and RSA of Well K1's major Feedzone.

Mineral	Volume fraction	Fracture		Matrix	
		RSA	RSA/1000**	RSA	RSA/1000**
Hematite	0.092783	1.09E+03	1.09E+00	18.55670	1.856E-02
Chlorite	0.185567	2.19E+03	2.19E+00	37.11340	3.711E-02
Goethite	0.072165	8.50E+02	8.50E-01	14.43299	1.443E-02
Smectite	0.072165	8.50E+02	8.50E-01	14.43299	1.443E-02
Calcite	0.164948	1.94E+03	1.94E+00	32.98969	3.299E-02
Dolomite	0.164948	1.94E+03	1.94E+00	32.98969	3.299E-02
Quartz	0.072165	8.50E+02	8.50E-01	14.43299	1.443E-02
Illite	0.025773	3.04E+02	3.04E-01	5.15464	5.155E-03
Epidote	0.051546	6.07E+02	6.07E-01	10.30928	1.031E-02
Am silica* **	0.000001	1.00E-03	1.00E-06	1.00E-03	1.00E-06
Anhydrite* **	0.000001	1.00E-03	1.00E-06	1.00E-03	1.00E-06

***RSA/1000 used in the model input*
****added in the model input to check if there is precipitation*

2.3 Fluid Chemistry and Reaction Kinetics

Data from drilling geology, injection and reservoir chemistry, and feed zone parameters were collected and processed to generate the input for the chemical, flow, and solute files used for TOUGHREACT. The rock parameters used for the model setup were derived from the existing 3D reservoir model but with modified porosity and permeability upon rendering very high pressures during calibration.

Three periods in sequence were modelled. The first 23 years being neutral brine injection only (Scenario 1). After that are 2 years of binary utilization (Scenario 2), where the brine is dosed with acid and injected at a lower temperature. Then three future scenarios of 10 years forecast for those mixed with CO_2 co-injection—Mindanao 1 and Mindanao 2 NCG mixing with the binary brine (Scenarios 3a and 3b), and lastly the continued binary brine injection (Scenario 3c). Since no actual geochemistry data are available for the future scenarios, SOLVEQ-XPT and CHIM-XPT were used to simulate the mixing process of the binary brine and the NCG from the respective steamline gas chemistry.

Meanwhile, the dissolution and precipitation of minerals are kinetically controlled, and the kinetic rates (r_n) are a product of the rate constant (k_n) and reactive surface area (A_n) with factors for mineral saturation (Ω) as shown in Equation 4 (Sonnenthal et al., 2021). A positive value means dissolution while negative indicates precipitation.

$$r_n = \pm k_n A_n \left|1 - \Omega_n^{\theta}\right|^n \tag{4}$$

The kinetic rate constants are usually reported at 25 °C, hence this is converted to the desired temperature using Equation 5 (Sonnenthal et al., 2021).

$$k_n = k_{25} \exp\left[\frac{-E_a}{R}\left(\frac{1}{T} - \frac{1}{298.15}\right)\right] \tag{5}$$

The main parameters in equations 4 and 5 are summarized in Table 4 taken from the compiled comprehensive report of Palandri and Kharaka (2004).

Table 4. Kinetic Reaction Parameters for Minerals.

Minerals	Dissolution / Precipitation	
	log k_{25}	E_a
Hematite	-14.6	66.2
Chlorite	-12.52	88
Goethite	-7.94	86.5
Smectite	-12.78	35
Calcite	-8.79	41.87
Dolomite	-8.6	95.3
Quartz	-13.98	87.7
Illite	-12.6	14
Epidote	-11.99	70.7
Am silica	-7.98 / -9.42	39 / 49.8
Anhydrite	-3.19 / 1.11	14.3 / 60.2

3 RESULTS AND DISCUSSIONS

3.1 1D Radial Model Calibration

The model was calibrated using downhole pressure to reflect the flowing or continuous injection condition observed in the field, however, there are limited shut and flowing surveys conducted on Well K1. The actual downhole pressure collected is recorded at 8.6 MPa when the well is at shut condition while 12.8 MPa at flowing condition. Nevertheless, the modelled pressure at around 12 MPa (Scenarios 1 to 3a/b/c) gives a reasonable match with the actual data while the shut pressure reflects the reservoir's static pressure (see Figure 5).

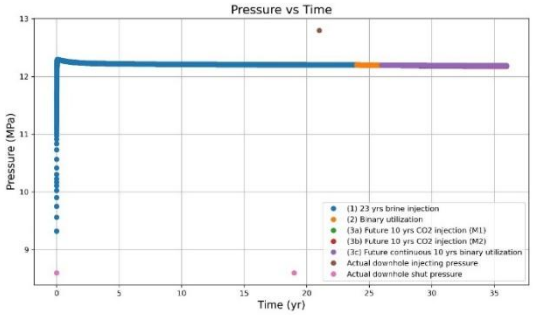


Figure 5. Modelled pressure over time with actual downhole pressures.

To validate the chemical behavior, the chemistry at the first gridblock (nearest the wellbore) was also calibrated to see if the model is giving similar results to that of the actual injected chemistry on the well (see Figure 6). The actual chemistry is from the surface and analyzed at lab conditions, so it was run with WATCH software to increase its temperature to 140°C for comparison to the model results. Based on the sulfate and silica plots, there is a good match in the model and the actual chemistry. Constant injection flow rate was implemented in the model hence a very linear modelled chemistry is reflected per period. The injection fluid pH drop after binary utilization due to the acid dosing in the brine to avoid scaling with its lower temperature reinjection was also matched with the model.

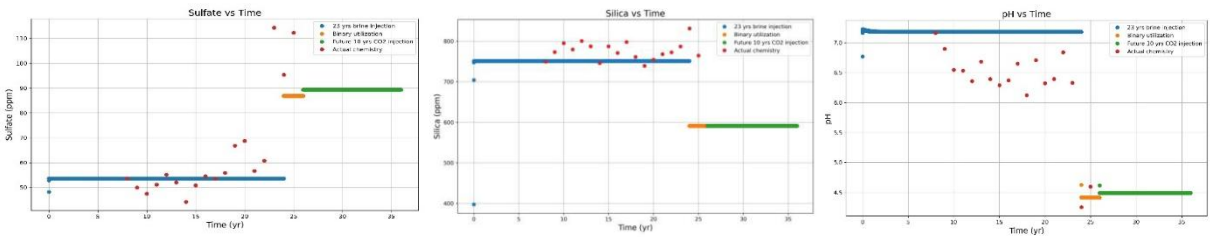


Figure 6. Modelled and Actual Chemistry Comparison Over Time.

3.2 1D Permeability and Porosity Changes

The extent of permeability changes is significant up to the skin and reservoir zone only for the fracture as shown in Figure 7 and no changes all throughout for the matrix.

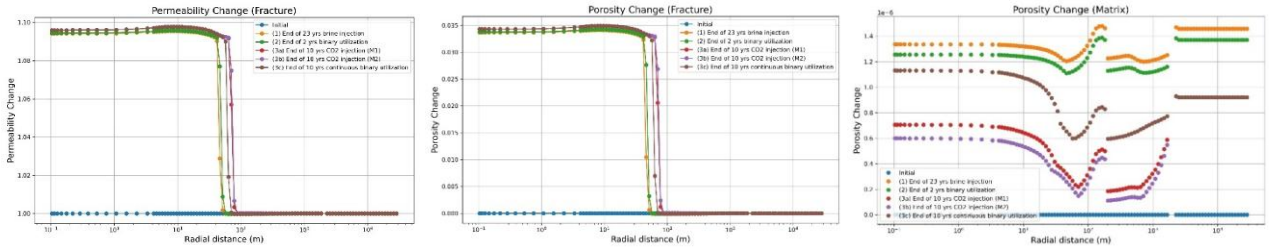


Figure 7. Permeability and Porosity Changes in the Fracture and Matrix.

Both the fracture skin and reservoir zone's permeability exhibited an increase after 23 years of brine injection and further enhancement was observed during binary utilization and the mixed CO_2 injection forecast. The maximum increase in fracture's permeability reached approximately 10% but localized only up to around 60m to 80m radial distance, beyond this zone there is no significant change observed. The permeability change in the fracture also reflects in the changes in mineral volume fractions.

Porosity has less pronounced changes than permeability for both the fracture and the matrix as shown in Figure 7. Although, the same trend is observed where fracture porosity change (3.5% maximum increase) is higher than the matrix (0.00014% maximum increase). Hence mineral volume fraction changes are more apparent in the fracture. The extent of porosity changes in the fracture is only up to around 60m to 80m consistent with that of permeability changes, while changes in the matrix are seen up to the outer reservoir boundary. Despite its greater radial extent, the magnitude of the matrix porosity changes is very small, and it has little to negligible manifestation in the matrix's mineral volume fraction changes.

3.3 1D Mineral Volume Fraction Changes

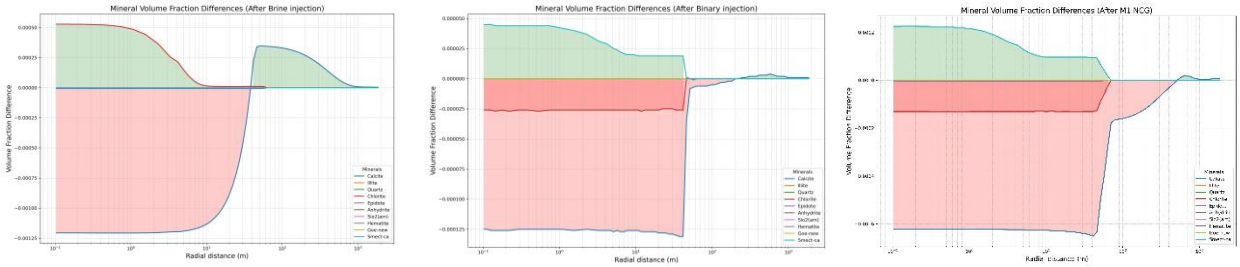


Figure 8. Mineral Volume Fraction Differences After Different Reinjection Scheme

Given that there are higher changes in the fracture in terms of permeability and porosity, the mineral volume fraction changes are also more evident in the fracture than that in the matrix.

Calcite reaction rates are set to be kinetically controlled in the model. Calcite has a retrograde solubility, the temperature drop promotes a slight dissolution hence a decrease in mineral volume fraction up to 3.61% following prolonged injection of neutral brine (Scenario 1). This also manifests in the increase of calcium and bicarbonate concentration in the fluid as a product of calcite dissolution. At around 25m, there is an increase in pH which coincides to a localized precipitation of calcite as it favors a more basic environment for deposition. Dolomite volume fraction also behaved similar to calcite.

For chlorite, precipitation is observed from near the wellbore up to around 8m in the reservoir zone with more prominence in the skin zone while further dissolution from its initial volume is observed around the reservoir zone up to around 30m after the lower pH injection (NCG and continuous binary injection scenario). Beyond 30m, there are no observed changes indicating stable reservoir conditions in terms of chlorite. The switch from neutral brine injection to binary utilization dissolved some of the precipitated chlorite as expected due to a lower pH.

Meanwhile, following binary utilization, smectite mineral volume fraction increased indicating precipitation (see Figure 8b). Since the binary brine injected is acidic, mixing of this fluid to the near neutral in situ water rendered the smectite supersaturated hence precipitation occurred (Ajima et al., 1998), then this precipitation is further

enhanced with the introduction of more CO_2-rich water (NCG reinjection). The lower pH promotes dissolution of primary minerals leading to precipitation of secondary clay minerals like smectite (Xu et al., 2008). Although minimal, the extent of precipitation is up to around 60m from the wellbore.

Epidote and anhydrite had negliglibe dissolution while for the rest of the minerals such as amorphous silica, hematite, and goethite, there are no changes observed across all the changes in chemistry and injection temperatures. For amorphous silica, this stability is consistent with suppressed polymerization under low pH conditions.

3.4 2D Permeability and Porosity Changes

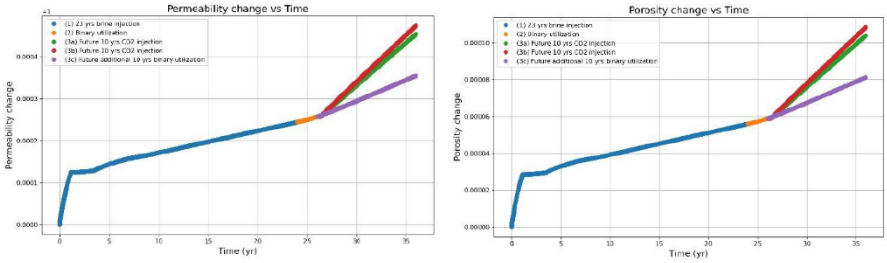


Figure 9. Permeability and Porosity Changes over time.

The permeability changes in the x and z directions are similar with a very steep increase in the first two years. After 23 years of neutral brine reinjection, the permeability increased up to around 0.025% and further increased after two years of binary utilization. Continuing the binary utilization for another 10 years slightly changed the slope of this increase but a significant rate change is observed when doing CO_2 injection, doubling the increase in half the time. This could be attributed to the lower pH under this potential reinjection scheme. In terms of porosity at the injection gridblock, although lower, it showed a similar trend of permeability with a maximum increase of around 0.01%.

3.5 2D Mineral Volume Fraction Changes

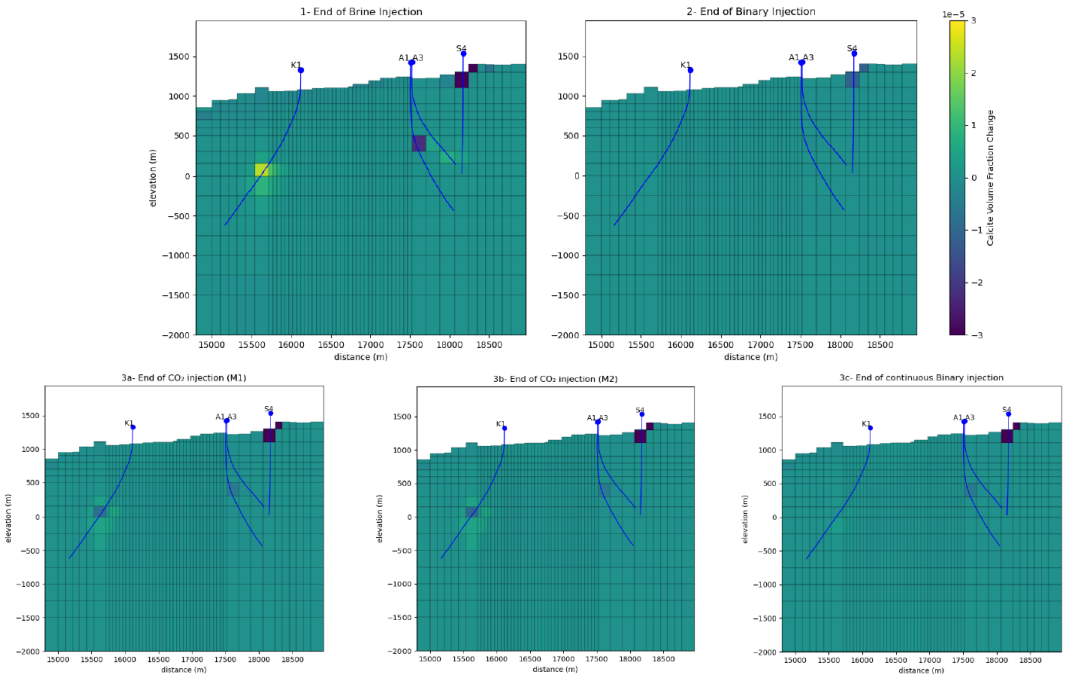


Figure 10. Changes in Calcite Mineral Volume Fraction at Different Scenarios.

Calcite precipitation is observed around the injection point at the end of 23 years of brine reinjection. Although this is very minimal in magnitude, at the order of 5, it should be noted that this is a different trend when compared to the 1D radial model result which had calcite dissolution. The opposite trend could be attributed to the more realistic representation of the pressure and temperature gradients in the 2D cross-section since in the 1D model, a uniform initial temperature and pressure distribution is set across the radial distance. The gradient could impact the mineral saturation or solubility added with the effect of the surrounding chemistry and changes

around the injection gridblock. Also, the 1D model has closed boundaries and assumed homogeneous mineralogy whereas the 2D model included depth-dependent variations in its mineralogy assumptions and spatial heterogeneity farther from the injection well. The interaction between these varied mineral assemblages—induced by both in-situ and injected fluids—may lead to different outcomes. Due to different boundary conditions, perhaps flows in the production wells induce fluid entrance from other boundaries.

There is no significant change observed from the brine injection period up to the end of two years binary utilization (Figure 10-2). However, in the forecast scenarios, the injection feedzone gridblock had a decrease in calcite volume fraction. This is due to the lower pH of the injection fluid, and this dissolution is also manifested by the increase in bicarbonate and calcium concentrations (see Figure 11).

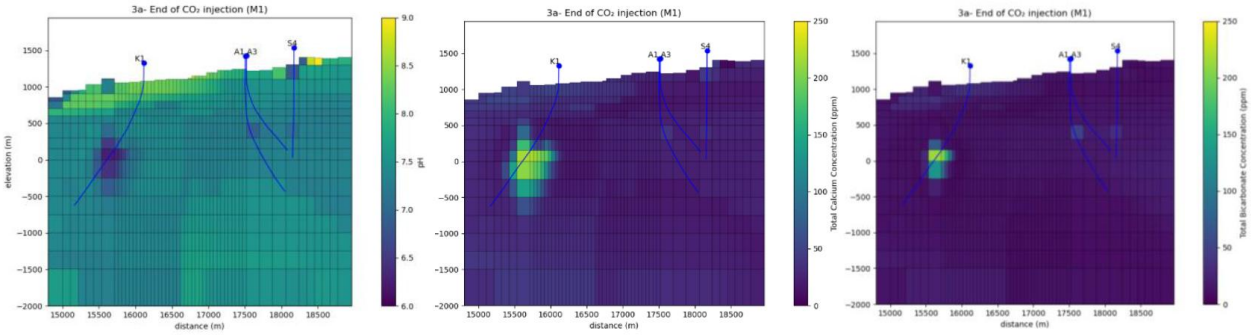


Figure 11. pH, Calcium, and Bicarbonate Concentration at the End of NCG reinjection scenario.

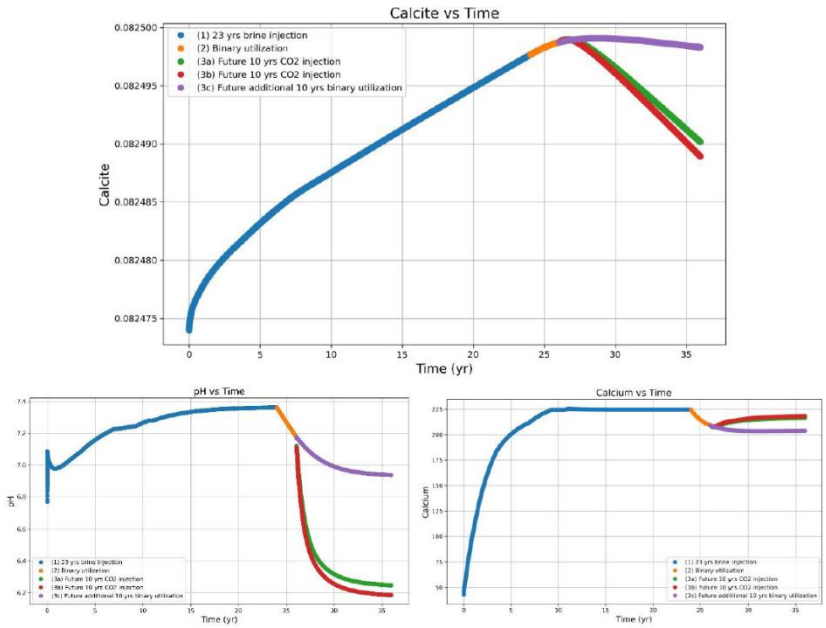


Figure 12. Calcite Volume Fraction, pH, and Calcium Concentration at the Injection Gridblock Over Time.

Although rendering different trend for Scenario 1, results of the subsequent scenarios/periods are consistent with the 1D model. Comparing the parameters on the injection gridblock over time (Figure 12), we can see that there is a lower dip in pH for Scenarios 3a and 3b where the injection was with an NCG-charged binary brine hence the dissolution of calcite is more apparent than when the binary utilization is continued (Scenario 3c). Although the same trend, the pH drop values is again not the same with the 1D model. This could be due to the influence of the in-situ fluid from the surrounding gridblocks diluting the injected brine. There is a very high increase in calcium concentration in the first 10 years and the eventual plateau could be an indication of supersaturation, thus precipitation occurred (Figure 12).

4 SUMMARY AND CONCLUSIONS

This study investigated the coupled hydraulic and geochemical responses of Well K1 in Mt Apo Geothermal Production Field under long-term neutral brine, binary brine, and a proposed non-condensable gas (NCG)-charged binary brine reinjection using reactive transport modeling in 1D and 2D domain.

The 1D radial model was calibrated with the actual downhole pressures at shut and flowing conditions as well as the actual injected chemistry and gave reasonable matches. It captured the near-wellbore dynamics effectively, including permeability increases within a radial distance of up to approximately 60m at the end of neutral brine injection for 23 years and at the end of binary utilization for two years. Whereas permeability increases were up to around 70m at the end of the future scenario of continuous binary utilization for another 10 years while the extent of increase was up to 80m at the end of both future scenarios of NCG-charge binary brine for 10 years (M1 and M2). These changes were more apparent in the fracture (at the maximum of ~10%) than in the matrix. Out of the three future scenarios, results indicate that the NCG-charged binary brine has a greater degree of changes across the radial distance. This is also reflected in the mineral volume evolutions particularly dolomite which had dissolution and smectite which had precipitation, both up to 80m at most. Calcite undergone dissolution for the first 40m and precipitation from 40m to 900m while chlorite had the opposite with precipitation in the first 50-70m and dissolution up to 650m under CO_2-enriched scenarios, indicating the strong influence of fluid chemistry on reservoir permeability.

Porosity changes in the 2D followed a similar trend to permeability but with smaller magnitudes. Porosity increase of up to ~0.01% in the injection zone were recorded while permeability increase of up to 0.04% in both x and z directions were observed. Geochemical alterations were generally consistent across models, with notable differences in spatial manifestation. For calcite, while dissolution was predicted in the 1D radial model around the injection zone during prolonged neutral brine injection, the 2D model initially showed precipitation at the injection area. This discrepancy is attributed to the presence of spatial temperature and pressure gradients in the 2D setup, unlike the uniform temperature distribution in the 1D model. However, both models agree in terms of the binary and NCG-charged injection scenarios where dissolution occurred due to a lower pH reinjection.

Comparing the future scenarios, NCG-charged reinjection resulted in a higher dissolution than purely binary brine reinjection. This indicates that NCG-charged injection could preserve the injection capacity of the well even with the inherent lower binary brine injection temperature which is prone to scaling. However, this study does not include the corrosion potential associated with lower pH injection hence it is recommended to evaluate the pre and post NCG-charged brine chemistry with Fe-CO_2-H_2O stability diagrams. Thus, injecting NCG-charged binary brine shows positive effects in terms of permeability enhancement, porosity evolution, and mineral volume changes with provision of further studies in terms of corrosion risks and execution of the injection strategy. This is to ensure an optimal process that leaves no gas behind.

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