

The Influence of Carbon Dioxide on Reservoir Fluids at Utah FORGE

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ABSTRACT

A key component of the Utah FORGE field program has been chemical monitoring of flowback and produced fluids. In this regard, the ability to confirm and quantify the presence of gaseous species in circulated fluids dominated by carbon dioxide was first achieved in 2024. However, the effects of carbon dioxide are interpreted to have been present since the earliest phases of reservoir stimulation in April 2022 when flowback waters showed sharp increases in solutes accompanied by significant enrichments in oxygen and hydrogen. The possibility that two-phase conditions had developed in response to boiling was inconsistent with injection pressures that greatly exceeded vapor saturation. Later, when halite was identified along fractures in granitic rocks, it was evident that dissolution of soluble salts was most likely responsible for the increases in total dissolved solutes. The next significant observation followed the completion of 16B(78)-32 in July 2023 when during the first short term circulation test there was evidence of slugging flow and effervescing water indicating gas in the produced fluid. As a result, the flow lines for the Aug-Sept 2024 circulation test were designed to accommodate temporary installation of a mini-separator via which steam and gas could be collected and analyzed. The resulting produced water contained 0.07 to 0.13 wt. % CO₂, inducing weak acidification, and the total carbon dioxide production was ~220 metric tons. Monitoring of well waters in 2025 continued to show infiltration of carbon dioxide and isotopic evidence of a deep upper mantle origin. Speculatively and drawing on experience from carbon dioxide injection for enhanced oil recovery and sequestration, carbon dioxide infiltration is linked to the drying out of waters, accounting for the stable isotope trends and salt deposition in fractures. This appears to be an active process that is associated with reservoir development, and one that also occurred naturally in the geologic past.

1. INTRODUCTION

Utah FORGE was established as a field laboratory for advancing enhanced geothermal systems (EGS) technologies (Moore et al., 2020, 2023). In support of EGS reservoir development and field experiments, geochemical analyses were obtained for flowback and produced waters resulting from stimulation and circulation tests in the period 2022 to 2025 (Simmons et al., 2025). These results have illuminated the potential for mineral deposition and dissolution, and they have been used to calibrate chemical geothermometers. But there has also been long-standing interest in characterizing and quantifying the inputs of native state fluids, particularly gaseous species, and to understand the nature of any effects they might have on geothermal production from an EGS reservoir. The first dissolved helium samples for isotope analysis were thus obtained in 2023, and the first gas-steam samples were obtained August 2024 as part of a four-week long circulation experiment. In 2025, additional gas samples were obtained during two short circulation tests. These results and the interpreted effects of interactions with carbon dioxide in the reservoir represent the focus of the current report.

2. RESERVOIR CHARACTERISTICS

The setting of the Utah FORGE EGS reservoir is shown in Figure 1. Reservoir rocks are made of coarsely crystalline granitoids and banded gneiss that are dominated by alumino-silicate minerals and quartz (Jones et al., 2019; 2024). They are transected by a large population of fractures, with wide ranging azimuths and dips, that formed during tectonic uplift and exhumation (Bartley, 2019; Finnila and Jones, 2024).

Secondary minerals comprise epidote, actinolite, carbonate, and clays, and they appear to mainly occupy fracture fillings although a proportion occurs as incipient country rock alteration (Jones et al., 2024). Some chlorite-smectite lined structures contain traces of halite, and the occurrence such a highly soluble mineral accounts for the sharp increases in the TDS concentrations of flow back waters during the stimulation of well 16A(78)-32 (Jones et al., 2024; Simmons et al., 2025).

Core sample measurements indicate very low porosity of <1% and very low permeabilities of <0.1 mD (Gywnn et al., 2019; Podgorney et al., 2021; Iyare et al., 2025), and these attributes are corroborated by field measurements including micro-hydraulic fracture and DFIT tests conducted in Utah FORGE wells (Xing et al., 2020). The regional geothermal gradient is hot, linear (>70°C/km) and conductive as shown in Figure 1 (Allis et al., 2019).

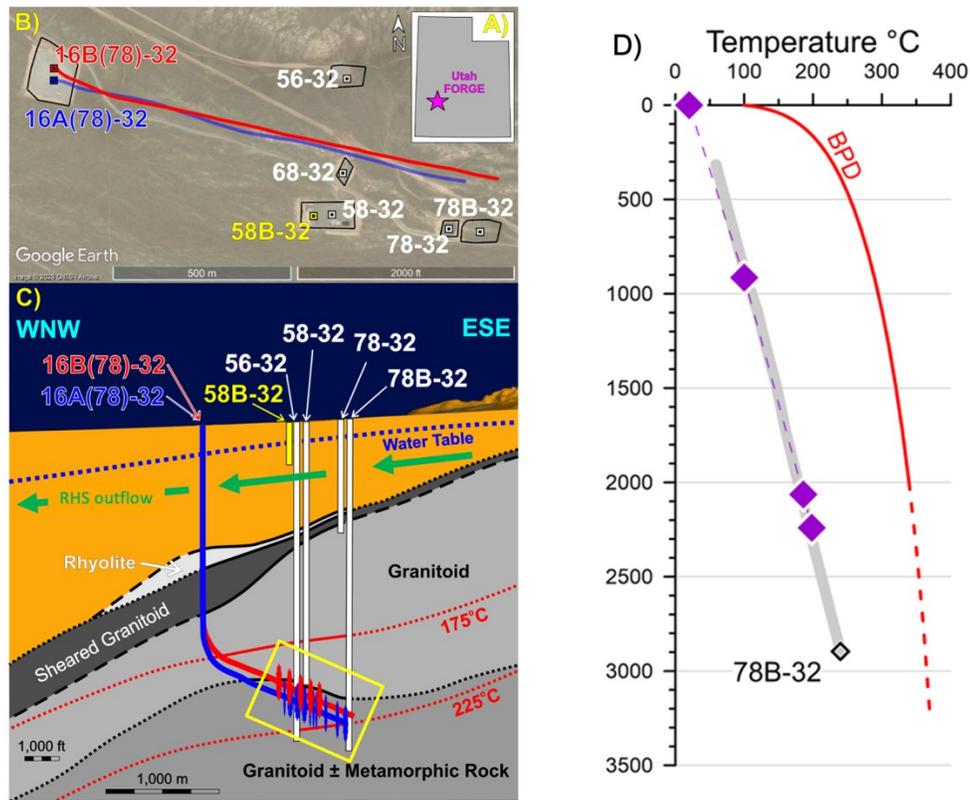


Figure 1. Map (A), plan (B) and cross section (C) views of the location of the Utah FORGE site, wellfield layout and the underlying geology hosting the EGS reservoir outlined in yellow. The reservoir rocks comprise granitoids and gneiss, which are composed mainly of aluminosilicate minerals and quartz (Jones et al., 2024). The green arrows mark the outflow of thermal waters from Roosevelt Hot Springs (RHS), which is pumped from well 58B-32 for water supply during circulation testing. The geothermal gradient (D) surrounding Utah FORGE is shown by the gray line, and the purple diamonds represent measurements in 58B-32 obtained late August, 2025; the hydrostatic boiling point for depth (BPD) curve is shown for comparison.

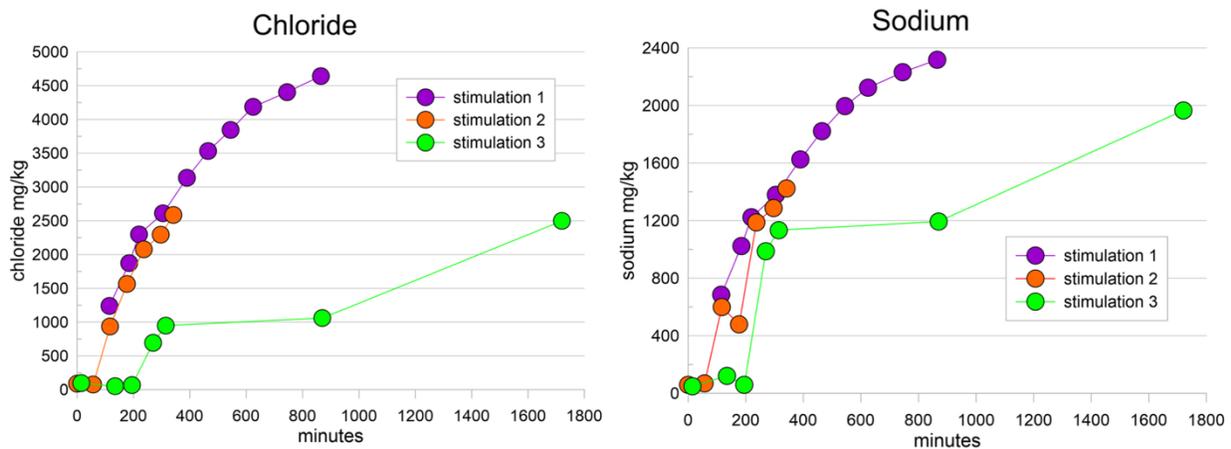


Figure 2. Trends in chloride and sodium versus time during the first stimulation and flowback of stages 1, 2 and 3 in 16A(78)-32, showing sharp increases in solute concentrations, April 2022.

3. COMPOSITIONAL EVOLUTION OF FLOWBACK AND PRODUCED FLUIDS

A concise summary of observations and measurements pertaining to the evolution of fluids and the detection of carbon dioxide follows. Time series data that are referred to appear in Figures 2-5, and they are based on reported values (Simmons et al.; 2025).

April 2022. The initial hydraulic stimulation of the toe of well 16A(78)-32 involved injection of slickwater in stages one and two, and the addition of a crosslinked polymer in stage 3. Apart from the additives, injectate was made of culinary grade water obtained from a deep supply well in Milford, Utah, and in total, ~10,000 bbl were injected. The sharp increases in Na and Cl (Figure 2) reflect the dissolution of very soluble phases with an estimated 6.2 metric tons being mobilized.

July, 2023. A short term (24-hour) circulation test followed the drilling of 16B(78)-32 to assess interwell connectivity that involved injection of about 7,750 bbl of water. The produced waters showed significant increase in Na and Cl (Figure 3) and based on the net change in total dissolved solutes an estimated 9.9 metric tons were mobilized via salt dissolution. During water sampling from a stainless-steel condensing coil, there was evidence of slugging flow and effervescing water indicating gas in the produced fluid, consistent with the decrease in pH from 7.8 to 6.7 (Figure 3).

April, 2024. Large scale stimulation involving injection of ~117,000 barrels of non-potable water that originated from aquifer well 58B-32 (Figure 1) enlarged the EGS reservoir and improved interwell connectivity (England et al., 2024). About 85% of the total injected fluid was used to stimulate 10 stages between the heel and toe of the deviated leg in 16A(78)-32, and the remainder was used to stimulate frac hits and perforated intervals in well 16B(78)-32. During the 9-hour circulation test (April 27, 2024), produced waters (16B(78)-32) were sampled in two-hour intervals and sharp increases in Na and K were detected (Figure 3). An estimated 76 metric tons of soluble salts were dissolved through interaction of injected waters, and the pH decreased from 7.5 to 6.0.

August-September, 2024. Data obtained during the 27-day circulation test (August 8-September 4, 2024) are related to injection of >350,000 barrels of water that originated from aquifer well 58B-32 of which nearly 240,000 barrels were produced (England et al., 2024). Pressurized single phase liquids from the production well were collected weekly from a stainless-steel condensing coil, and the gas samples were collected in evacuated glass bottles partially filled with caustic soda using a mini-separator. The analytical results are plotted in Figure 5. As observed previously, the concentrations of Na and Cl in injected waters increase in produced waters over time; the total dissolved solutes of both injected and produced waters also gradually increase as reflected by the sodium and chloride trends which is likely due to partial recycling of produced water. Furthermore, the differences between injected and produced water concentrations decrease and converge with time indicating that salts are being depleted from the fracture-controlled flow paths. In support of this concept, the total estimated mobilized mass of dissolved solutes decreased to 32 metric tons. The dissolved gas in the produced waters is dominated by carbon dioxide, which ranges 0.7 and 0.14 wt.%, verifying the cause of weak acidification to pH ~6 in the produced waters; the total carbon dioxide production was ~220 metric tons. Although helium is a trace gas ($\text{CO}_2/\text{He} > 10^6$) in produced fluid (Figure 5), the helium isotope values range from 2 to 2.5 R/Ra and provide evidence of a deep-seated origin similar to values occurring at Roosevelt Hot Springs (Simmons and Kirby, 2024).

June, 2025. Following cleanouts of well 16A(78)-32 and 16B(78)-32, a 3-day circulation test (June 20-22, 2025) provided opportunity for the last set of analytical data and involved injection of 30,600 barrels of water stored in the sump. The solute concentration difference for sodium and chloride between the injected and produce waters is even smaller than in August-September, 2024, suggesting that the flow path has been almost completely rinsed free of salts; the total estimated mobilized mass of dissolved solutes is 1.1 metric tons. By contrast, the dissolved carbon dioxide has increased to >0.2 wt% with pH~6 and helium isotope value of 2 R/Ra.

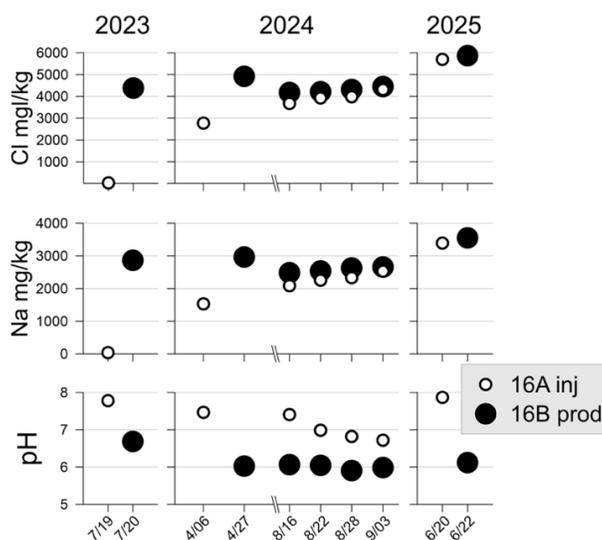


Figure 3. Time series data comparing pH, sodium and chloride values for injected water into 16A(78)-32 (small open circles) with produced water from 16B(78)-32 (large black filled circles) between 2023 and 2025.

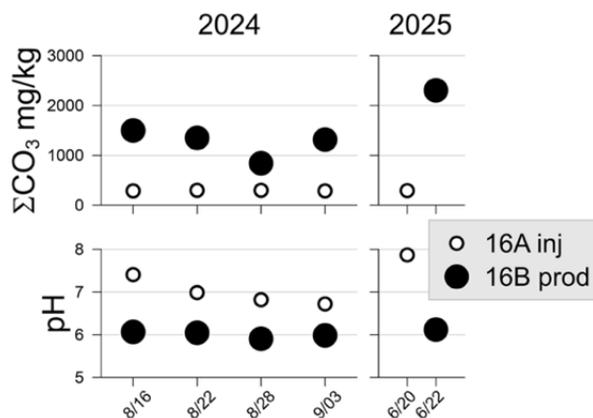


Figure 4. Time series data comparing pH and total carbonate values for injected water into 16A(78)-32 (small open circles) and produced water from 16B(78)-32 (large black filled circles) in 2024 and 2025.

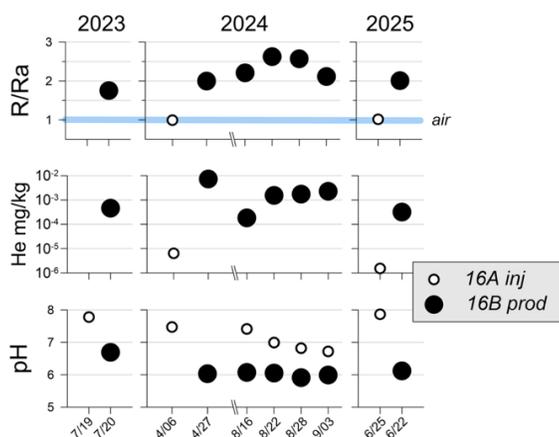


Figure 5: Time series data comparing pH, aqueous helium, and helium isotope (R/Ra) values for injected water into 16A(78)-32 (small open circles) and produced water from 16B(78)-32 (large black filled circles) between 2023 and 2025.

4. COMPOSITIONS OF 58-32 BORE WATERS

Well 58-32 is offset 200 m south from the injection-production doublet comprising 16A(78)-32 and 16B(78)-32, and it has been used mainly for seismic monitoring during stimulations. Recent downhole sampling of the water column shows that deep samples contain ~0.3 wt% aqueous CO₂ (Simmons et al., 2026). Specific to 58-32 has been the opportunity to sample dry gas at the surface on which measurements of carbon and helium isotopes could be obtained. The δ¹³C values for carbon dioxide range -4.19 to -4.99 per mil and helium isotope values are 2 R/Ra, indicating that both contain components originating in the upper mantle. Like the data for 16B(78)-32, these support the indication that the EGS reservoir is being infiltrated by gaseous species that are dominated by carbon dioxide and that have a deep origin.

5. STABLE ISOTOPE TRENDS

Stable isotope data obtained on injected and produced waters in 2022 and 2024 are shown in Figure 6, and they are compared with compositions of thermal waters from Roosevelt Hot Springs and shallow groundwaters from the Milford Valley. The groundwater from 58B-32 represents subsurface thermal outflow from Roosevelt Hot Springs, and it was used for injection during the 2024 stimulation and circulation tests. Notable is the tight grouping of isotopic compositions that separate the April 2022 stimulation-flowback waters from 16A(78)-32, the April 2024 waters produced from 16B(78)-32, and the August-September 2024 waters produced from 16B(78)-32 from one another. Also significant is the range of values within each of the three subgroups, and the direction of temporal evolution shown by the dashed arrows.

The April 2022 stimulation-flowback waters from 16A(78)-32 labeled stages 1, 2 and 3, form a positively sloping linear array and the purple dotted arrow indicates the order in which samples were obtained at the wellhead on each of the three successive injection-flowback stages. All three show the same evolution that start bottom left near the meteoric water line and with time progress in isotopic composition upward and to the right. These are the same waters that are plotted in Figure 2, and they were the first waters to be produced from the

stimulated reservoir. Furthermore, stages 1, 2 and 3 represent separate injection-flowback cycles between which there was nil interaction based on tracer results (Jones et al., 2023); the stable isotope data reflect this too. Since the isotopic compositions evolved quickly over a few hours, involving progressive enrichments in both oxygen and hydrogen isotopes, the trends are best attributed to mixing or loss of water vapor through evaporation or boiling (e.g., Giggenbach and Stewart, 1982; Sharp, 2017). Boiling can be discounted as reservoir conditions were too cool (225°C max) to reach vapor saturation at injection pressures, and mixing can be discounted based on the positions of the 2024 stable isotope results. This leaves evaporation as an explanation of the isotopic trends, and based on available evidence is tentatively related to infiltration of dry carbon dioxide as discussed further below.

The April 2024 waters produced from 16B(78)-32 form a tight cluster having strongly similar isotopic compositions. They are significantly offset to the right being the most enriched in the heavier oxygen isotope (^{18}O) compared to all the other data. The blue dotted arrow (Figure 6) connects the composition of the produced water with the injected water, which has a positive slope paralleling the April 2022 trend. On this basis, the April 2024 produced waters may reflect evaporative effects. There could also be a component of hydrothermal water-rock interaction (e.g., Sharp, 2017), assuming residual water from earlier injections had sufficient time to exchange significant amounts of ^{18}O with rock-forming minerals.

The August-September 2024 waters form a much different trend, in part due to the effect of evaporation on the water sitting in the sump over the summer before being used for injection and in part due to the very large overall mass of injected fluid. The former seems to account for the inverted sequence of temporal evolution (i.e., downward and to the left), and the latter may account for the small differences between the coeval compositions of injected and produced waters. Localized mixing could account for some of the tie lines connecting the coeval compositions of injected and produced water that have negative slopes.

In summary, the stable isotope data in Figure 6 form three distinct groups that directly reflect the three separate and specific periods of injection and production. Furthermore, for each period, the compositions of the injected waters represent the strongest influence on the compositions of produced waters, and this accounts for the wide spacing separating each group. The trends in April 2022 and April 2024 data are tentatively best explained as products of evaporation of injected water, whereas the trend in August-September 2024 data are best explained by changes in the composition of injectate and minor mixing in the reservoir (most likely with an end-member water composition similar to produced water in April 2024). There is no evidence of mixing with any isotopically characterized natural waters. If mixing with previously unidentified natural waters is important, then their compositions vary and shift with each specific period of injection and production.

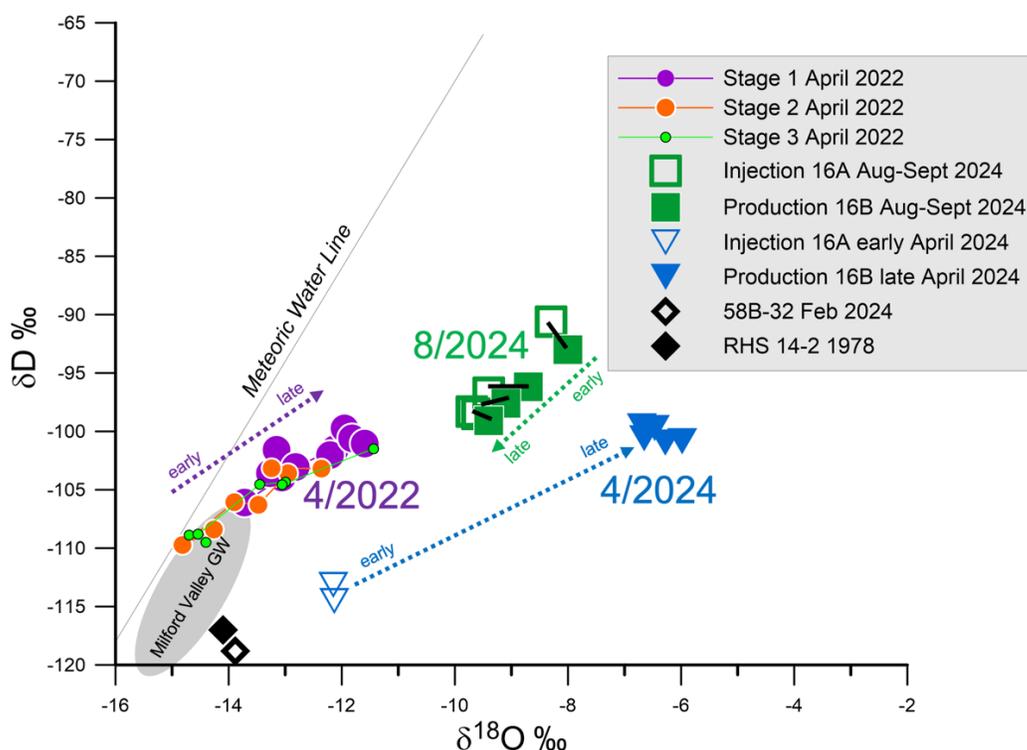


Figure 6: Stable isotope compositions for injected and produced water at Utah FORGE obtained between 2022 and 2024, compared to values for Roosevelt Hot Springs (RHS) and Milford Valley groundwaters (Simmons and Kirby, 2024). Dotted arrows are colored coded and show the temporal evolution of isotopic compositions for specific test periods. The short black lines connect injected and produced water samples collected on the same day.

6. SYNTHESIS

The main aim of this report is to highlight the data and information covering temporal patterns in produced water compositions, focusing on effects associated with carbon dioxide infiltration into the reservoir. The interpretations that follow are at an embryonic stage of development for which revisions and refinements are expected. With these caveats, the predominant effects considered important include: 1) sharp increases in dissolved solutes due to dissolution of soluble salts; 2) weak acidification of injected and produced waters; 3) incorporation of gaseous species dominated by carbon dioxide; 4) the carbon and helium isotope data that trace their deep origin; and 5) linear trends of stable isotope enrichment due to evaporation.

Although a challenging concept geologically, the distribution of halite and related soluble salts along fractures is likely much greater than what might be inferred from their occurrence identified in drill core alone (Jones et al., 2024), as simple mass transfer calculations imply mobilization of >100 metric tons of solids. Declines in the net solute loads (Figure 3) suggest that flushing of injected water is effectively removing salts from the dominant flow paths. Beneficially, the early removal these soluble phases led to enhancements in rock permeability.

Weak acidification is inextricably linked to the infiltration of carbon dioxide, which based on carbon and helium isotope analyses is deep sourced and derives from the upper mantle. Although its concentration was not quantified until 2024, carbon dioxide was likely present and influencing the pH compositions of produced waters since the first stimulation of 16A(78)-32 and possibly earlier. Magmatic processes and partial melting of the lower and middle crust facilitate carbon dioxide ascent through to shallow level (Simmons and Kirby, 2024), including via stimulated fractures in the EGS reservoir. Consequently, the production of carbon dioxide is significant and similar to Roosevelt Hot Springs (Simmons et al., 2025). From a mineral scaling perspective, acidification helps to inhibit carbonate deposition at reservoir depth and silica deposition at the surface.

Speculatively and drawing on experience from carbon dioxide injection for enhanced oil recovery and sequestration (e.g. Pruess and Müller, 2009; Bernsten et al., 2019), infiltration of dry carbon dioxide through basement rocks also accounts for evaporative effects. The first, which extends into the recent geological past, is related to salt deposition on fractures when natural seismicity created short-lived pathways through which shallow groundwaters temporarily leaked downward into hot basement rocks and ultimately evaporated to dryness, leaving a residue of salt crystals. Being encapsulated along sealed fractures, the salts remained preserved until the start of Utah FORGE. The second begins with the drilling and stimulation of wells, when the injection of fresh water resulted in rapid dissolution of salts, while interaction with dry carbon dioxide induced evaporation accounting for stable isotope trends in April 2022 data (Figure 6). It is unknown if these early injections of water completely evaporated to halite saturation or dryness, but if they did, they would have deposited a new generation of salt. With significantly greater volumes of water being injected in the subsequent tests, liquid spread radially, inflating fractures while a reservoir water composition evolved as reflected by the April 2024 and August-Sept 2024 data. Conceptually, only the fringes of this water saturated domain are vulnerable to evaporation, and within the flow network, heating and salt dissolution predominated. The overall impression gained is that of a geochemically dynamic setting and one that will continue to evolve in response to utilization and growth of the reservoir.

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REFERENCES

- Allis, R., Gwynn, M., Hardwick, C., Hurlbut, W., Kirby, S., and Moore, J.N.: Thermal characteristics of the Roosevelt Hot Springs system, with focus on the FORGE EGS site, Milford, Utah, Utah Geological Survey Miscellaneous Publication 169-D, (2019).
- Bartley, J.M.: Joint patterns in the Mineral Mountains intrusive complex and their roles in subsequent deformation and magmatism, Utah Geological Survey Miscellaneous Publication 169-C, (2019).
- Berntsen, A., Todorovic, J., Røphaug, M., Torsæter, M., Chavez Panduro, E., and Gawel, K.: Salt clogging during supercritical CO₂ injection into a downscaled borehole model, *International Journal of Greenhouse Gas Control*, 86, (2019), 201-210.
- England, K., Swearingen, L., and McLennan, J.: Extended Circulation Test Report Utah FORGE 16A(78)-32 and 16B(78)-32, EGI, University of Utah, (2024), Geothermal Data Repository, <https://doi.org/10.15121/2475065>.
- Finnila, A., and Jones, C.G.: Updated reference discrete fracture network model at Utah FORGE, 49th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2024).
- Giggenbach, W. F. and Stewart, M. K.: Processes controlling the isotopic composition of steam and water discharges from steam vents and steam-heated pools in geothermal areas. *Geothermics*, 11, (1982), 71-80.
- Gwynn, M., Allis, R., Hardwick, C., Jones, C., Nielsen, P., and Hurlbut, W.: Compilation of rock properties from FORGE well 58-32, Milford, Utah, Utah Geological Survey Miscellaneous Publication 169-L, (2019).
- Jones, C.G., Moore, J.N., and Simmons, S.: Petrography of the Utah FORGE site and environs, Beaver County, Utah, *in* Allis, R., and Moore, J.N., editors, Geothermal characteristics of the Roosevelt Hot Springs system and adjacent FORGE EGS site, Milford, Utah, Utah Geological Survey Miscellaneous Publication 169-K, (2019).

- Jones, C. G., Simmons, S., and Moore, J.: Geology of the Utah Frontier Observatory for Research in Geothermal Energy (FORGE) Enhanced Geothermal System (EGS) site, *Geothermics*, 122, (2024), <https://doi.org/10.1016/j.geothermics.2024.103054>.
- Moore, J., McLennan, J., Pankow, K., Simmons, S., Podgorney, R., Wannamaker, P., Jones, C., Rickard, W., and Xing, P.: The Utah Frontier Observatory for Research in Geothermal Energy (FORGE): A laboratory for characterizing, creating and sustaining Enhanced Geothermal Systems. *Proceedings 45th Workshop Geothermal Reservoir Engineering*, Stanford University, Stanford, CA, (2020).
- Moore, J., McLennan, J., Pankow, K., Podgorney, R., Rutledge, J., Meir, P., Byer, B., Karvounis, D., Bethmann, F., Xing, P., Barker, B., Jones, C., Simmons, S., Damjanac, B., and Finnilla, A.: Current Activities at the Utah Frontier Observatory for Research in Geothermal Energy (FORGE). *Proceedings World Geothermal Congress*, Beijing, China (2023).
- Podgorney, R., Finnilla, A., Simmons, S., and McLennan, J.: A reference thermal-hydrologic-mechanical native state model of the Utah FORGE enhanced geothermal site, *Energies*, 14, 4758, <https://doi.org/10.3390/en14164758>, (2021).
- Pruess, K. and Müller, N.: Formation dry-out from CO₂ injection into saline aquifers: 1. Effects of solids precipitation and their mitigation, *Water Resources Research*, 45, doi:10.1029/2008WR007101, (2009).
- Simmons, S. F. and Kirby, S.: Formation of a large cold groundwater mantle helium anomaly and high temperature geothermal resources in response to bimodal magmatism near Roosevelt Hot Springs and Utah FORGE, Milford valley, southwest Utah, *Geochemistry, Geophysics, Geosystems* 25 (2024).
- Simmons, S. F., Jones, C. G., Rose, P., and Moore, J.: The geochemistry of flowback and produced waters at Utah FORGE and their implications for EGS production, *50th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, CA (2025).
- Sharp, Z.: *Principles of Stable Isotope Geochemistry*, 2nd Edition, University of New Mexico Digital Repository, <https://doi.org/10.25844/h9q1-0p82>, (2017).
- Xing, P., Moore, J., and McLennan, J.: In-Situ Stress Measurements at the Utah Frontier Observatory for Research in Geothermal Energy (FORGE) Site, *Energies*, 13 (21), (2020).