PROCEEDINGS, 50th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2025
SGP-TR-229

The geochemistry of flowback and produced waters at Utah FORGE and their implications for EGS production

Stuart F. Simmons, Clay Jones, Pete Rose and Joe Moore

EGI, University of Utah, Salt Lake City, UT

ssimmons@egi.utah.edu; cjones@egi.utah.edu; prose@egi.utah.edu; jmoore@egi.utah.edu

Keywords: geochemistry, Utah FORGE, EGS production, water-rock interaction, reservoir monitoring

ABSTRACT

The geochemistry of flowback and produced waters at Utah FORGE were obtained from stimulation-circulation tests between 2022 and 2024, involving a hot dry rock reservoir made of crystalline granitoid and gneiss at 200 to 220 deg C. The collection points for analyzed samples include injection well 16A(78)-32 and production well 16B(78)-32. The dissolution of halide minerals accounts for sharp increases in Na, K, and Cl that were measured in all produced waters, but the size of the increase appears to be diminishing over time as salts are progressively removed from fracture-controlled flow paths. Early interwell connection was established and sustained, although deposition of calcium-bearing minerals (mainly carbonates) in the reservoir due to heating of injected water likely occurred. Temperature-dependent quartz and anhydrite solubilities appear to control the silica and sulfate concentrations in produced waters, which makes these parameters useful for chemical geothermometry. Pipe scale deposition of carbonate minerals and amorphous silica appears to be minimal. Deeply derived gases infiltrate the reservoir, induce weak acidification of produced water, and yield CO_2/Ar and H_2/Ar equilibration temperatures consistent with reservoir conditions.

1. INTRODUCTION

Utah FORGE was established as a field laboratory for advancing enhanced geothermal systems technologies (Moore et al., 2020, 2023). In support of this effort, geochemical analyses were obtained for flowback and produced waters resulting from stimulation and circulation tests in the period 2022 to 2024 and involving wells shown in Figure 1. The first of these occurred in April 2022 following completion of the first deep deviated well 16A(78)-32, in which three closely spaced intervals near the toe were stimulated via pressurized cold-water injection (England and McLennan, 2022; Jones et al., 2023). The second deviated well 16B(78)-32 was completed in June 2023, and short circulation testing a month later provided evidence that an interwell connection was established (England et al., 2023; Xing et al., 2024). In 2024, commercial scale stimulation in April enlarged the EGS reservoir volume as was confirmed by successful completion of the 28-day circulation test in August-September. From these experiments, time-series chemical data of fluid compositions were obtained using analytical services at Brigham Young University and Thermochem (Tables 1-5). The resulting trends and interpretations summarized below are provisional and illuminate the effects of mineral dissolution and precipitation that influence reservoir permeability and underpin chemical geothermometry, and the evidence for influx of deeply derived gases.

2. FLOWBACK OF INJECTED WATERS APRIL 2022

The 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. Following shut-in, the fluid from each hydraulic fracturing stage was returned to the surface through a flow line to reduce well pressure before stimulating the next stage, providing the opportunity to periodically sample and monitor tracer concentrations and fluid chemistry for each stimulated interval. Geochemical data for water samples (Figure 2) in stages one and two both show sharp increases in Na, K, Ca and Cl over short periods of time (< 12 hours), whereas for stage three they show gradual increases in these elements. Collectively such trends suggest dissolution of very soluble phases, whereas the sharp decreases in Mg across all three stages reflect mineral deposition or sequestration. The trends for sulfate and boron in stages one and two are similar, whereas the strong increases in stage three are attributed to additives accompanying the crosslinked polymer. The use of crosslinked polymer in stage three may have also suppressed silica dissolution, whereas in stages 1 and 2 it attains concentrations of 160-200 ppm.

3. FLOWBACK AND PRODUCTION OF INJECTED WATERS JULY 2023

The drilling of 16B(78)-32 followed by a short term circulation test provided the next opportunity to sample and analyze reservoir fluids over a 24 hour period, July 19-20, 2023. This test was designed to assess interwell connectivity, involving injection of about 7,750 bbl of water (4000-4500 psi) at low injection rate of 5 to 7.5 bpm and at low rate of production 10 bph (Xing et al., 2024). The earliest samples were obtained from 16A(78)-32 representing a phase of injection flowback, which lasted ~3 hours and terminated just prior to producing water from 16B(78)-32 (Figure 3). The 16A(78)-32 results reflect trends similar to those from the April 2022 test (Figure 2). Specifically, the injected water shows sharp progressive increase in total dissolved salts, including Na, K, Ca, and Cl; notably silica rises from 20 to 219 ppm. The waters produced from 16B(78)-32 mostly resemble the compositions of 16A(78)-32 flowback waters with the exception of the sample taken at ~800 minutes into production, which shows a significant increase in Na, K and Cl; by contrast silica ranges 78-86 ppm.

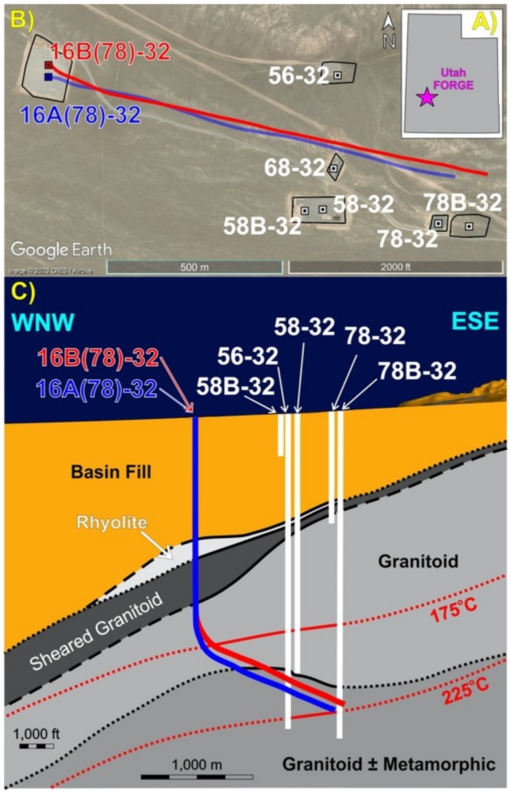

Figure 1. Map (A), plan (B) and cross section (C) views of the location of the Utah FORGE site, wellfield layout and the underlying geology hosting the EGS reservoir, respectively. The reservoir rocks comprise granitoids and gneiss, which are composed mainly of alumino-silicate minerals and quartz (Jones et al., 2024).

Table 1. Chemical compositions (mg/kg) of injected and flowback waters April, 2022 (na=not analyzed).

		pH	Na	K	Ca	Mg	B	SiO2	Cl	SO4	HCO3
Injection											
16A(78)-32	4/19/22	na	59	5.0	33.0	14.00	0.2	24	89	68	na
Flowback											
16A(78)-32	4/17/22	na	2319	403	253	2.45	7.1	181	4643	91	na
16A(78)-32	4/19/22	na	1423	245	107	4.00	3.4	165	2585	159	na
16A(78)-32	4/22/22	na	1966	282	83	2.00	40.0	45	2497	91	na

Table 2. Chemical compositions (mg/kg) of injected, flowback and produced waters July, 2023.

		pH	Na	K	Ca	Mg	B	SiO2	Cl	SO4	HCO3
Injection											
16A(78)-32	7/19/23	7.78	41	3	24	5.46	0.18	20	32	66	78
Flowback											
16A(78)-32	7/19/23	7.83	708	96	95	4.92	2.43	219	1295	169	115
Production											
16B(78)-32	7/20/23	6.69	2871	319	44	0.07	9.05	81	4384	239	383

Table 3. Chemical compositions (mg/kg) of injected and produced waters April, 2024.

		pH	Na	K	Ca	Mg	B	SiO2	Cl	SO4	HCO3
Injection											
Harpoon tank	4/6/24	7.47	1530	181	209	17.30	25.20	94	2770	74	339
Injection											
16B(78)-32	4/27/24	6.50	2640	305	206	10.90	31.10	161	4460	143	423
16B(78)-32	4/27/24	5.99	2930	325	188	10.80	31.50	236	4880	167	398
16B(78)-32	4/27/24	5.97	3020	333	164	3.95	30.90	299	5000	177	310
16B(78)-32	4/27/24	6.03	2970	330	165	4.66	29.30	297	4920	183	355

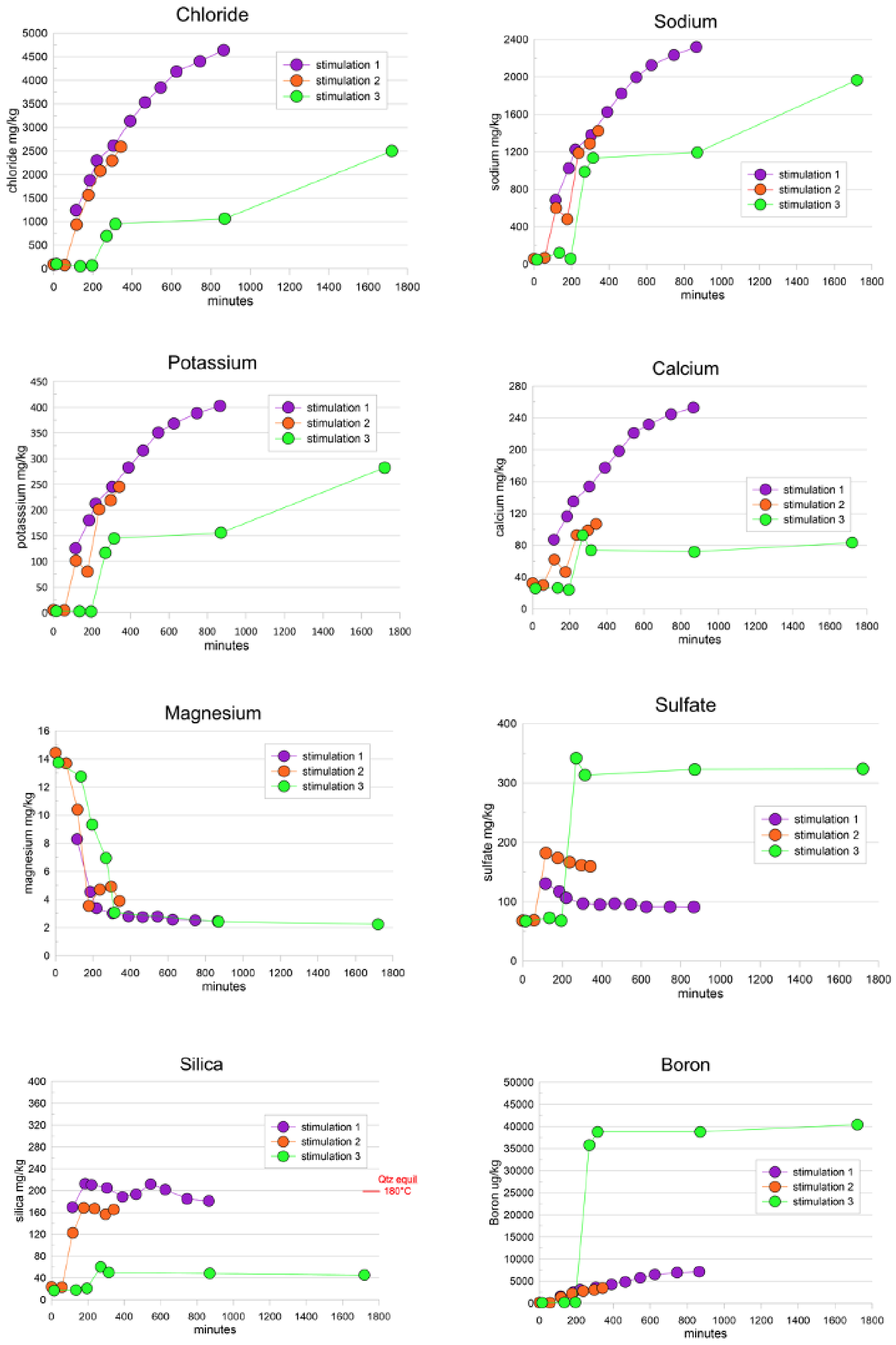

Figure 2. Time series trends for flowback waters from stimulation stages one, two and three, April, 2022.

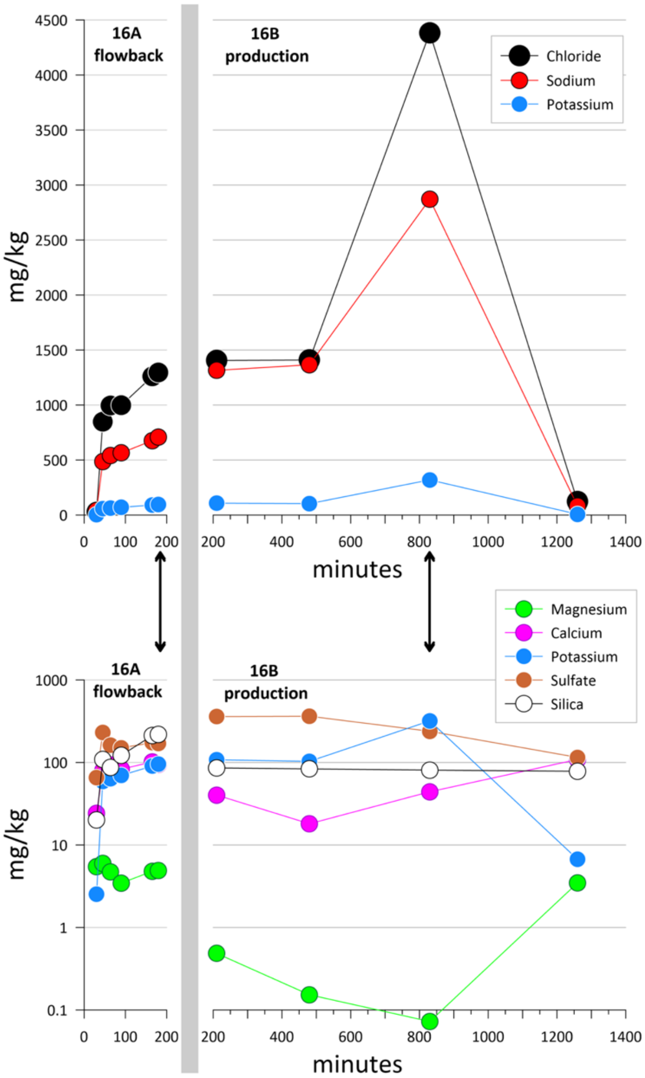

Figure 3. Time series trends for water compositions from flowback of 16A(78)-32 (0-200 minutes) and production from 16B(78)-32 (200-800 minutes), July, 2023. Arrows designate samples that appear to best reflect waters having interacted with the reservoir.

3. PRODUCTION OF INJECTED WATERS APRIL 2024

In April 2024, the commercial 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 with the first sample being collected about 1.5 hours after the start; the injectate was stored on the surface in the Harpoon tank after being produced from 58B-32 but before being injected into 16A(78)-32.

Analytical results over time are shown in Figure 4. The rise in TDS as reflected by sharp increases in Cl, Na, and K parallels trends observed in flowback waters from 16A during the April 2022 stimulation, indicating the waters sampled had traversed the reservoir from well 16A to 16B. Relative to the injected water, Ca decreases about 20% likely due to carbonate deposition in the subsurface, which could also account for the decrease in Mg, whereas sulfate increases suggesting mineral (anhydrite?) dissolution which is widespread but occurs in trace amounts based on examination of drill cores and cuttings (Jones et al., 2024). Noteworthy is the 1.5 decrease in pH, which could affect the concentration of HCO_3 and which is likely due to incorporation of CO_2 gas as discussed further below. Silica gradually increases plateauing in the last two samples at close to 300 mg/kg, reflecting an equilibration temperature of ~210 deg C based on the quartz-silica geothermometer (Fournier, 1991), which is hotter than the maximum produced wellhead water temperature of 139 deg C (McLennan et al., 2024).

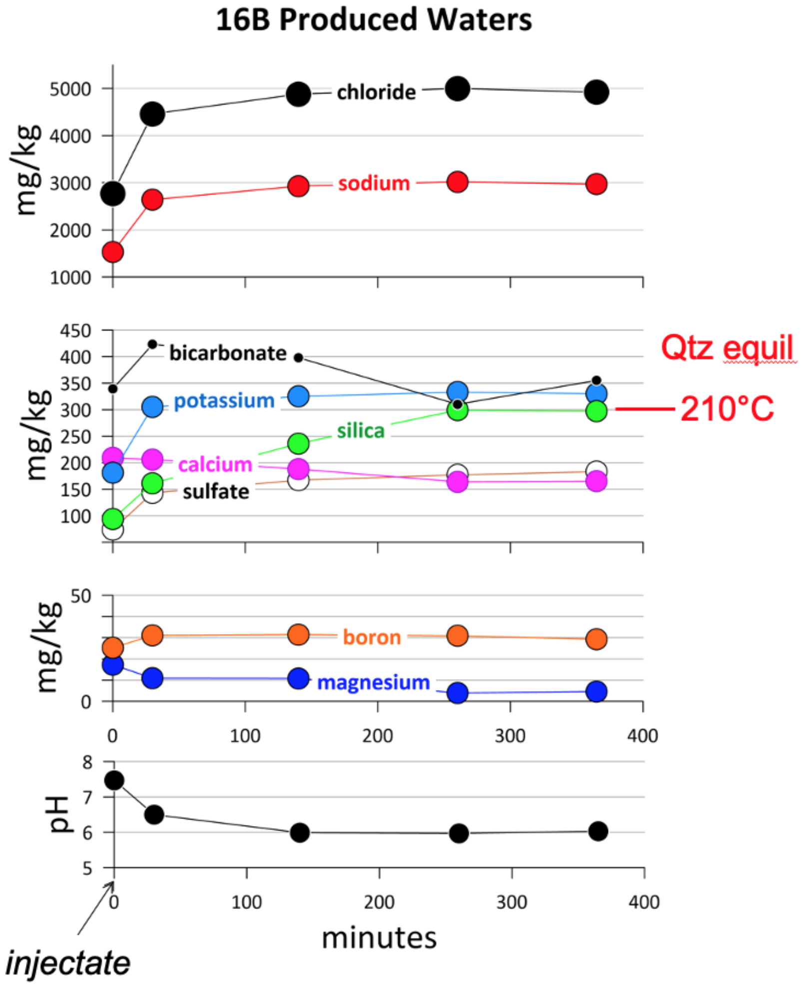

Figure 4. **Time series trends for water compositions produced from 16B(78)-32 during the April 27, 2024 circulation test.**

3. PRODUCTION OF INJECTED WATERS AUGUST-SEPTEMBER 2024

The previous results provide a glimpse of likely reservoir rock-water interactions influencing the compositions of produced geothermal fluids, the interpretations of which were strengthened by data obtained during the 28-day circulation test, August 8 to September 4, 2024. Compositional data described below were sampled weekly starting August 16 and ending September 3. Pressurized single phase liquids from the production well were collected from a stainless-steel condensing coil, whereas gas samples were collected in evacuated glass bottles partially filled with caustic soda using a mini-separator; sample ports were configured into the production pipeline upstream of the separator. The analytical results are plotted in Figure 5

The concentrations of Na, K and Cl in injected waters increase in produced waters over time. As early produced fluid was recycled into the injectate sump, both injected and produced waters also gradually increase in TDS with time. By contrast, the differences between injected and produced water concentrations decrease and converge with time. These suggest that the compositions of injected waters are modified while permeating the reservoir by the dissolution of soluble salts (e.g., NaCl) and that these salts are gradually being removed by dissolution from the fractures over time. Sulfate and SiO_2 in injected waters also increase in produced waters, but over time, the produced water concentrations remain nearly uniform suggesting that have reached mineral saturation with respect to anhydrite and quartz at temperatures of ~195 deg C and ~210 deg C, respectively. Boron shows no significant difference in concentrations between injected and produced waters, and its behavior is generally unaffected by water-rock interaction or mineral dissolution-deposition. Calcium and Mg in the produced waters are lower in comparison to their concentrations in the injected waters; these decreases are attributed to carbonate deposition although some Mg may be incorporated into clay minerals. The pH of the produced water is consistently about 6 whereas the pH of the injected water decreases steadily from 7.4 to 6.7.

The total gas concentrations in the produced waters are between 0.7 and 0.15% and dominated by carbon dioxide, which accounts for the weak acidification of the produced waters (Table 5); the proportions of the other gas species resemble produced fluids from Roosevelt Hot Springs (Simmons et al., 2021). Application of gas geothermometers based on the CO_2/Ar and H_2/Ar (Giggenbach, 1991) yield equilibration temperatures of 245 deg C and 180-200 deg C, respectively.

Although not originally anticipated as a sampling site for deep fluids, well 58-32 was sampled in 2022 using a bailer, when the water level was static, and then again during the August-September 2024 30-day circulation test once it was apparent that the well head pressure had risen to over 1000 psi. From 2022 to 2024, the 58-32 water compositions (Table 4) changed markedly, with increase in total dissolved salts, increase in bicarbonate associated with gassy conditions, and decrease in sulfate; however, so far, there has been no detectable change in thermal gradient, which remains conductive.

Table 4. Chemical compositions (mg/kg) of injected and produced waters August-September, 2024.

		pH	Na	K	Ca	Mg	B	SiO2	Cl	SO4	HCO3
Injection											
16A(78)-32	8/16/24	7.41	2090	238	201	17.00	30.5	133	3670	110	287
16A(78)-32	8/22/24	6.99	2260	250	190	12.60	30.6	151	3920	132	297
16A(78)-32	8/28/24	6.82	2330	257	185	11.30	30.9	156	3980	140	300
16A(78)-32	9/3/24	6.72	2530	276	178	9.59	32.3	167	4310	153	285
Production											
16B(78)-32	8/16/24	6.07	2490	266	90	1.20	29.4	301	4180	177	114
16B(78)-32	8/22/24	6.05	2540	269	108	1.24	30.3	298	4210	179	163
16B(78)-32	8/28/24	5.91	2630	277	108	1.21	31.0	293	4310	184	153
16B(78)-32	9/3/24	5.99	2660	280	113	1.08	31.7	289	4450	183	150
Monitor											
58-32	6/15/22	6.49	214	21.1	94.3	42.4	1.7	10.9	509	19.9	273
58-32	8/22/24	6.38	3550	339	94.6	6.26	36.5	205	5460	4.57	1200
58-32	9/3/24	6.40	3580	340	66.5	6.44	35.8	208	5520	0.4	1190

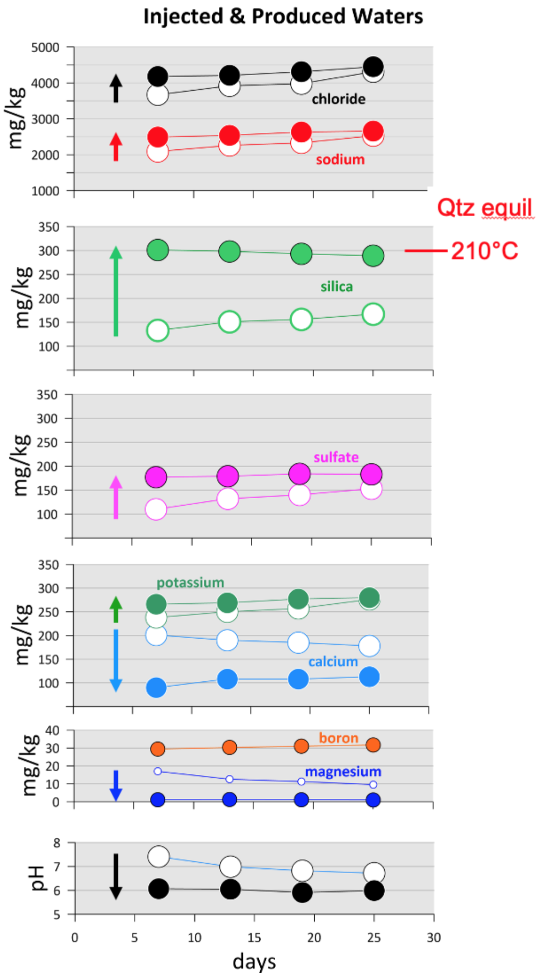

Figure 5. Time series trends for injected (16A(78)-32; open circles) and produced (16B(78)-32; filled circles) water compositions from the August-September 2024 circulation test. Samples were obtained weekly (Aug 16, Aug 22, Aug 28, and Sept 3). Arrows indicate increase or decrease in the produced concentration relative to the composition of the injectate.

Table 5. Chemical compositions (mg/kg) of gases in produced fluids (August-September, 2024) recalculated to a single-phase reservoir liquid.

		CO_2	H_2S	NH_3	Ar	N_2	CH_4	H_2
16B(78)-32	8/16/24	1387	2.27	0.7	0.7	30	0.19	0.045
16B(78)-32	8/22/24	1187	1.93	0.6	0.7	26	0.17	0.039
16B(78)-32	8/28/24	691	1.23	0.5	0.4	16	0.10	0.049
16B(78)-32	9/3/24	1164	2.98	0.9	0.8	27	0.23	0.066

4. SUMMARY OF KEY RESULTS

During stimulation, flowback and circulation testing at Utah FORGE, injected waters were subject to sharp and rapid modification in response to mineral dissolution and precipitation resulting from water-rock interaction in the stimulated EGS reservoir as indicated by time series trends in the compositions of produced fluids (Figures 2 through 5). The dissolution and precipitation of soluble mineral phases comprising halides, carbonates, and sulfates, which have been identified in cuttings and cores (Jones et al., 2024), induced many of the changes described above. The dissolution of halide minerals can account for sharp increases in Na, K and Cl as seen in all the produced waters. Furthermore, as theses phases are being removed from fracture-controlled flow paths, the magnitude of change is decreasing with time (Figures 2 through 6). Across all the tests, produced fluids show increases in aqueous silica that are attributed to dissolution of quartz, which is a ubiquitous phase in the reservoir rocks and was also used for proppant during stimulation campaigns in 2023 and 2024. Time series silica trends tend to plateau, suggesting quartz-silica equilibrium at ~210 deg C. Based on the results presented, over 6 metric tons of solids were dissolved and mobilized by the 2022 stimulation of 16A(78)-32 and over 60 metric tons of solids were dissolved and mobilized by the April 2024 stimulation; these represent quantifiable changes influencing reservoir permeability over short periods of time.

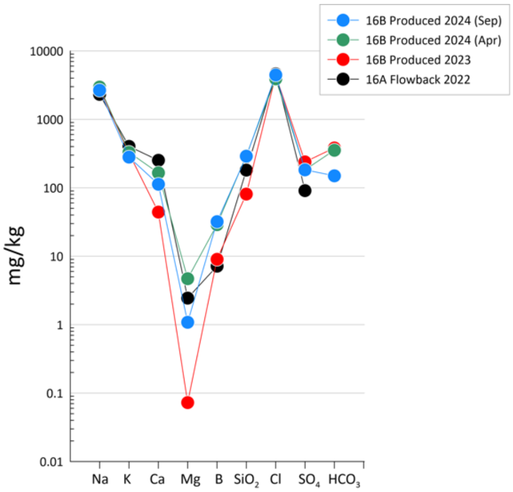

Figure 6. Summary plot of reservoir compositions based on sampling and analysis of flowback and produced waters (2022-2024).

Calcium is subject to the influences of carbonate and sulfate behavior, which both show reverse solubility. Furthermore, as all the known water supply in the Milford valley is at or close to carbonate and sulfate saturation (Simmons and Kirby, 2024), these phases readily attain saturation upon heating. For calcite, saturation can occur at less than 50 deg whereas for anhydrite it can occur at ~200 deg C based on speciation calculations using GWB (Geochemist's Workbench); parameters that affect these chemical thresholds include pH, total carbonate, Ca concentration, and aqueous CO_2. Carbonate deposition is the predominant influence on decreases in Ca (e.g., Figure 5), and it likely also accounts for decreases in Mg in all produced waters. Separately, that Ca and SO_4 converge with time in the April and August-September 2024 circulation tests (Figures 4 and 5) appear to reflect equilibrium with anhydrite at a calculated saturation temperature of ~190 deg C.

The sampling and analysis of gaseous species (Table 5) confirmed suspicions of such components in produced fluids dating back to 2023. Incorporation of CO_2 specifically accounts for the pH drop first detected in April 2024 (Figure 4) and replicated in August-September 2024 (Figure 5). As mentioned, the incorporation of CO_2 also affects pH, carbonate solubility and the sites of carbonate deposition in geothermal reservoirs. One likely site of carbonate deposition is in the reservoir, and another is where phase separation and two-phase flow develops in the production well (e.g., Simmons and Christenson, 1994). In mitigation of such effects, the use of antiscalants during the August-September 2024 circulation test appear to have been effective in sustaining production flow or temperature. So far, pipe scales due to calcite and amorphous silica deposition appear minimal and restricted to the surface where two-phase fluid is discharged at atmospheric pressure. Unlike the composition of the injected fluid, the incorporation of gases has a deep-seated control that is likely magmatic in origin (Simmons et al., 2021; Simmons and Kirby, 2024). A resulting outcome is the availability of two additional chemical geothermometers based on CO_2/Ar and H_2/Ar (Giggenbach, 1991) that give consistent results with reservoir temperatures and equilibration temperatures based on quartz and anhydrite solubility.

Just like conventional geothermal reservoirs, the geochemistry of injected and produced fluids in EGS reservoirs need to be characterized and monitored to understand changes over time that reflect the nature and productivity of the resource. Such understanding helps to mitigate and control mineral deposition, to calibrate chemical geothermometers and to understand the existence and influences of native state reservoir fluids.

5. ACKNOWLEDGEMENTS

Funding for this work was provided by U.S. Department of Energy under grant DE-EE0007080 “Enhanced Geothermal System Concept Testing and Development at the Milford City, Utah FORGE Site”. Thanks are extended to the Utah Geological Survey, the Utah Trust Lands Administration, and Beaver County for their additional support.

REFERENCES

England, K. and McLennan, J.: Hydraulic Fracturing of Well 16A(78)-32 (April 2022), https://gdr.openei.org/submissions/1379, (2022), 39 p.

England, K., Swearingen, L. and McLennan, J.: End of Well Report Utah FORGE Wells 16B(78)-32, https://gdr.openei.org/submissions/1516, (2023), 566 p.

Fournier, R.O.: Water geothermometers applied to geothermal energy, Applications of Geochemistry in Geothermal Reservoir Development, UNITAR-UNDP (1991), 37–69.

Giggenbach, W.F.: Chemical techniques in geothermal exploration, Applications of Geochemistry in Geothermal Reservoir Development, UNITAR-UNDP (1991), 119–144.

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),

McLennan, J., Swearingen, L. and England, K.: Utah FORGE: Wells 16A(78)-32 and 16B(78)-32 Stimulation Program Report—May 2024, https://gdr.openei.org/submissions/1695, (2024), 36 p.

McLennan, J. and Xing, P: Utah FORGE: Well 16A(78)-32/Well 16A(78)-32 Circulation Program: Circulation Program: July 4/5, 2023, and July 18/19, 2023, https://gdr.openei.org/submissions/1575, (2024), 36 p.

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), p. 10.

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 Finnila, A: Current Activities at the Utah Frontier Observatory for Research in Geothermal Energy (FORGE). Proceedings World Geothermal Congress, Beijing, China (2023).

Simmons, S. F. and Christenson, B. W.: Origins of calcite in a boiling geothermal system, American Journal of Science, 294, (1994) 361-400.

Simmons, S. F., Allis, R., Kirby, S., Moore, J. and Fischer, T: Interpretation of hydrothermal conditions, production-injection induced effects, and evidence for enhanced geothermal system-type heat exchange in response to >30 years of production at Roosevelt Hot Springs, Utah, USA, Geosphere 17 (2021).

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).

Xing, P., England, K., Moore, J., Podgorney, R., and McLennan, J.: Analysis of circulation tests and well connections at Utah FORGE, Proceedings, 49th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2024).