Field Deployment Updates on Geochemistry-based Wireline Tool to Characterize Fractures in Enhanced Geothermal Systems (EGS) Wells

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ABSTRACT

This paper presents updates on the field deployment of a chloride-based wireline tool designed to detect and quantify inflows from feed zones in geothermal wells. The Stanford Geothermal Program and Sandia National Laboratories are developing a geochemistry-based wireline tool and methodology to more accurately characterize fracture presence and inflow rate from geothermal wells compared to a pressure-temperature-spinner (PTS) tool. The tool uses an ion-selective electrode (ISE) to measure primarily chloride concentration. A mass balance of different chloride concentration readings around the feed zone can be used to calculate the feed zone inflow rate.

The recent developments of the chloride tool focused on preparing and conducting the field deployment at the Utah FORGE site. Laboratory experiments involving single fracture inflows were performed to test different parameters, including chloride concentrations, tool positioning, and feed zone inflow rates. The results showed different behaviors of probes, one exhibiting gradual changes in molarity readings while another displayed faster responses. It was found that while the presence of bromide and sulfate ions in the feed zone fluid caused interference, the combination of these ions stabilized the chloride tool readings. Dynamic experiments were also conducted, simulating field operations by moving the tool vertically. These laboratory tests correctly registered the higher chloride concentrations in the feed zone fluid, and were found to produce more accurate inflow rate inferences in the pull-out of hole (POOH) direction. The tool showed more accurate readings moving from lower chloride into higher chloride concentrations, compared to moving from high to low – which contributed to the results being more accurate in the pull-out-of-hole (POOH) direction than the run-in-hole (RIH) direction.

Field deployment occurred in wells 58-32 and 16B(78)-32 on June 12-14 and August 16, 2024, respectively. In both field deployments, measurements were noticeably better during the POOH run than the RIH run, as had been seen in the lab. At 58-32, the measurements suggest there were no internal flows in the well during the logging, which was not unexpected as the well was not producing at the time. To analyze 16B(78)-32 measurement results, several reading points were selected at Stage 5 and Stage 4 to provide information on chloride concentration above, at, and below the feed zones. The calculation yielded flow rates of 4326.49 BPD for Stage 5 and 7822.83 BPD for Stage 4, respectively. Compared to the flow rate calculation from the PLT log obtained a week later, the flow rate values calculated using the chloride method are within the expected range of agreement.

1. INTRODUCTION

Enhanced Geothermal Systems (EGS) use artificial fractures to increase fluid extraction in less permeable geothermal reservoirs (Huenges, 2016). These artificial fractures are created through hydraulic stimulation and may close over time, reducing the productivity of the EGS wells (Fei et al., 2023). Therefore, it is important to characterize these fractures to monitor the productivity of the feed zones

Feed zones productivity is inferred from the fluid inflow rate; the pressure-temperature-spinner (PTS) tool is typically used to measure the flow rate (Sisler et al., 2015). PTS tools demonstrate limitations in wells with low fluid velocity, low enthalpy, and large diameters, leading to an overestimation in the vertical section compared to the nonvertical section of the well (Acuña and Arcedera, 2005). Moreover, variations in hole diameter outside of slotted liners will affect spinner rotation, potentially leading to a misinterpretation as an actual change in flow rate.

The Stanford Geothermal Program and Sandia National Laboratories have been developing a geochemistry-based wireline tool and interpretation method that can more accurately characterize fracture presence and inflow rates from EGS wells compared to a pressure-temperature-spinner (PTS) tool. The tool was initially developed at Sandia and used by Gao et al. (2017) to measure the flowing enthalpy from feed zones in two-phase geothermal wells (containing both steam and liquid water). Chloride was chosen specifically because it can only exist in the liquid phase of geofluid. An increase in the chloride concentration in the liquid phase indicates an increase in steam fraction, which can be used to calculate the enthalpy. Building upon that previous work, this study further developed the tool and methodology for quantifying the inflow rate of the feed zone in single-phase geothermal wells for field tests at Utah FORGE.

The wireline tool uses an ISE to measure chloride concentration and adjacent chemical species in the well fluid via electrical voltage. The voltage is measured between a sensor formed from a combination of pressed AgS and AgCl powder and a reference electrode formed

from pressed AgCl powder (Hess et al., 2014). Different chloride concentration readings around the feed zone are then used to calculate the feed zone inflow rates using Equation (1), which is derived from chloride mass balance:

$$\dot{m}_{\text{liquid,in}} = \dot{m}_{\text{above,in}} \cdot \frac{Cl_{\text{above}} - Cl_{\text{below}}}{Cl_{\text{in}} - Cl_{\text{below}}} \tag{1}$$

where (x denotes relative position to the feed zone):

- Cl_x: Chloride concentration (kg/m^3)

- $\dot{m}_{cl\ x}$: Mass flow rate of chloride (kg/s)

- $\dot{m}_{liquid\ x}$: Mass flow rate of the liquid phase (kg/s)

Numerical simulations and laboratory experiments informed tool design and deployment, as reported previously in Schneider et al. (2024), Judawisastra et al. (2022, 2023), Judawisastra (2023), Sausan et al. (2022; 2024), and Sausan (2023). The current paper reports the tool development leading up to the field deployment, data acquisition results, and analysis from the wireline logging performed at well 58-32 and well 16B(78)-32 at the Utah FORGE site in mid-2024.

3. LABORATORY EXPERIMENT UPDATES

New calibration curves were established for the latest version of the probes to assist a series of laboratory experiments in preparation to the field deployments. The first set of experiments involved the chloride tool being held in a static vertical position in the artificial wellbore while a series of two one-minute feed zone flows occurred.

The first variables tested were the chloride concentration of the feed zone fluid and the vertical location of the chloride tool relative to the feed zone jet. The most notable result was the different behavior of the ISE probes when the chloride concentration of the surrounding fluid changed. Specifically, ISE sensor #2 exhibited smooth and gradual changes to its molarity readings that then plateaued. In contrast, the molarity readings of ISE probe #3 spiked immediately when the chloride concentration of the surrounding fluid changed. Then, the molarity readings of ISE probe #3 decreased, even though no changes to the surrounding fluid occurred. Additionally, these experiments suggested that higher feed zone chloride concentrations produced the most accurate and repeatable responses for both ISE probes.

Additional static experiments with the chloride tool were conducted to determine the effect of varying the feed zone inflow rate and the presence of additional chemical species in the feed zone fluid. The first set of additional experiments found that higher feed zone inflow rates led to higher accuracy when inferring the chloride concentration of the feed zone. The second set of experiments suggested that a significant amount of interference occurred when bromide, and to a lesser extent sulfate, were present in the feed zone fluid. This interference resulted in the ISE probes massively overestimating the concentration of the individual ions. However, the presence of bromide and sulfate ions stabilized the readings of the chloride tool when compared to a feed zone fluid containing only bromide, chloride, or sulfate ions separately. These findings for ISE probe #2 are shown in Figure 1.
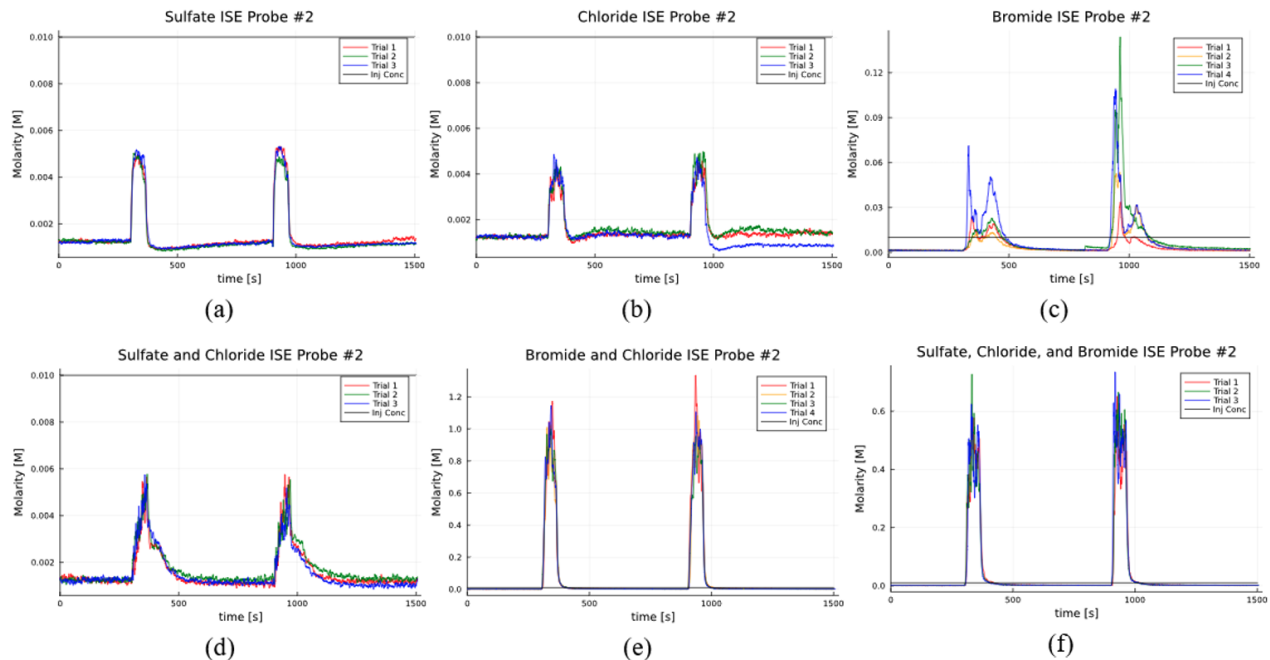

Figure 1: Molarity time series for ISE probe #2 for feed zone fluid containing 1×10^{-2} mol/L solutions of (a) sulfate, (b) chloride, (c) bromide, (d) sulfate and chloride, (e) bromide and chloride, and (f) sulfate, chloride, and bromide

In subsequent experiments, it was found that when bromide was present in the feed zone fluid, the magnitudes of the molarity readings were significantly greater than other experiments. However, the relative changes to the measured concentration still provided accurate feed zone inflow rate estimations. In contrast, the presence of sulfate ions in the feed zone fluid did not affect the chloride concentration readings of the ISE sensors nor the ability of the chloride tool to infer feed zone inflow rates.

To better imitate field operations, laboratory experiments were conducted in which the chloride tool was moved vertically in both directions to measure the chloride concentration across the depth of the artificial wellbore. These dynamic experiments provided insight into the performance of the chloride tool as it was actuated in the run-in hole (RIH) and pull-out of hole (POOH) directions. The first series of dynamic experiments tested various chloride concentrations of the feed zone fluid and the direction of motion of the chloride tool. These experiments found that feed zone fluids with higher chloride concentrations resulted in the most accurate feed zone inflow rate inferences. However, these accurate inferences were seen only for ISE probe #3 in the POOH direction (Figure 2). This is likely because the behavior of ISE sensor #3 caused it to capture the rapid changes in chloride concentration best when the chloride tool moved through the feed zone jet. Additionally, Table 1 shows the estimates of mass inflow rate $\dot{m}_{in}$ for a single feed zone averaged across the three trials and the percentage error between the actual and inferred inflow rates.
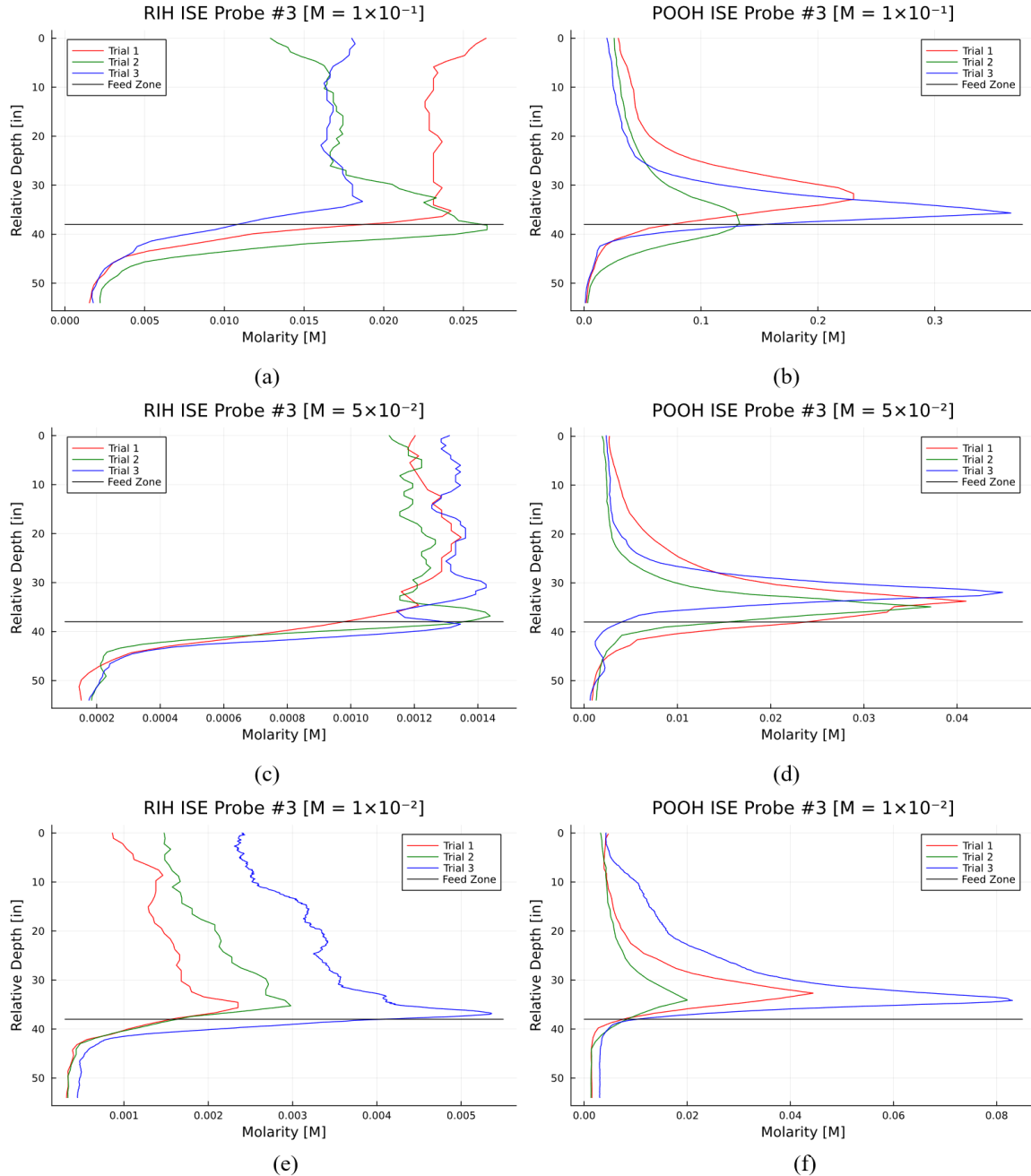

Figure 2: Molarity vs. Depth for ISE probe #3 in the RIH and POOH directions for feed zone fluids with chloride concentrations of (a and b) 1×10^{-1} mol/L, (c and d) 5×10^{-2} mol/L, and (e and f) 1×10^{-2} mol/L

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Table 1: Average inferred feed zone inflow rates and percentage error for the various scenarios at different chloride concentrations of the feed zone fluid

Feed Zone Chloride Concentration	Scenario	ISE Probe	Average Inferred Flow Rate (kg/s)	Percentage Error
1×10^{-1} mol/L	RIH	#2	1.256	993%
1×10^{-1} mol/L	POOH	#2	1.010	778%
1×10^{-1} mol/L	RIH	#3	0.730	535%
1×10^{-1} mol/L	POOH	#3	0.109	-5%
5×10^{-2} mol/L	RIH	#2	1.131	884%
5×10^{-2} mol/L	POOH	#2	0.877	662%
5×10^{-2} mol/L	RIH	#3	0.773	572%
5×10^{-2} mol/L	POOH	#3	0.031	-73%
1×10^{-2} mol/L	RIH	#2	0.866	653%
1×10^{-2} mol/L	POOH	#2	0.886	670%
1×10^{-2} mol/L	RIH	#3	0.393	242%
1×10^{-2} mol/L	POOH	#3	0.078	-33%

3. FIELD DEPLOYMENT AT 58-32

The well 58-32 deployment at Utah FORGE occurred on June 12-14, 2024, and was intended as a test run to assess the capabilities and limitations of the field-scale tool in preparation for the main deployment, which was at well 16B(78)-32. The schematics of the wireline tool assembly used in the field test at well 58-32 are depicted in Figure 3. A wire guide component was developed to adapt the PTS tool to the chemical sensor housing. The sensor wires from both the Mitco PTS tool and the chemical sensors pass through a wire feedthrough in the chemical sensor housing to the high-temperature logging tool in the electronics housing. The electronics housing connects to the wireline via a 4-conductor feedthrough adapted to a 7-pin conductor feedthrough that matches the wireline connection.

Well 58-32 is a vertical pilot well of 7,536 ft depth with two cased and perforated zones (Zones 2 and 3) and an open hole section (Zone 1) with a 7-inch casing. The logging was paused in five test locations above, below, and within the cased and perforated zones to gather stronger indicators of inflow, if any, as shown in the deployment plan in Figure 4. The logging was planned to stop short of entering Zone 1, as a component in the open hole section could potentially get stuck. Figure 5 shows the chemical sensor housing (i.e., the geochemistry-based tool) and the wireline assembly lifted by the Sandia wireline truck and ready to trip into well 58-32. The first two tools encountered issues due to leaks in connections and a problem with the microcontroller board, thus were unable to collect any data. Logging worked successfully during the third attempt.
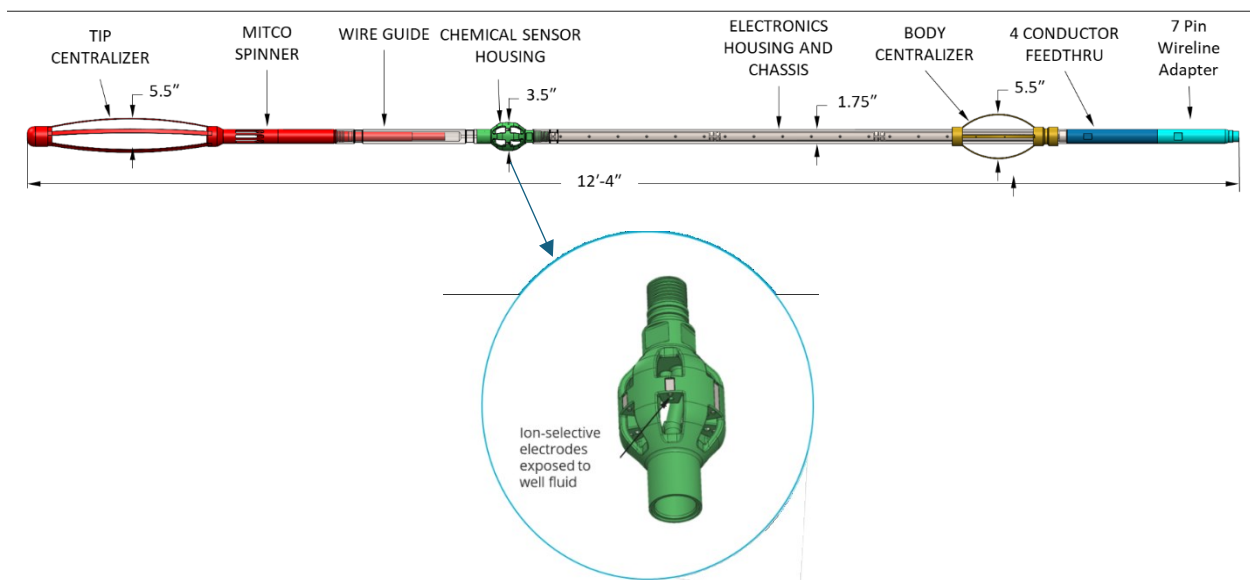

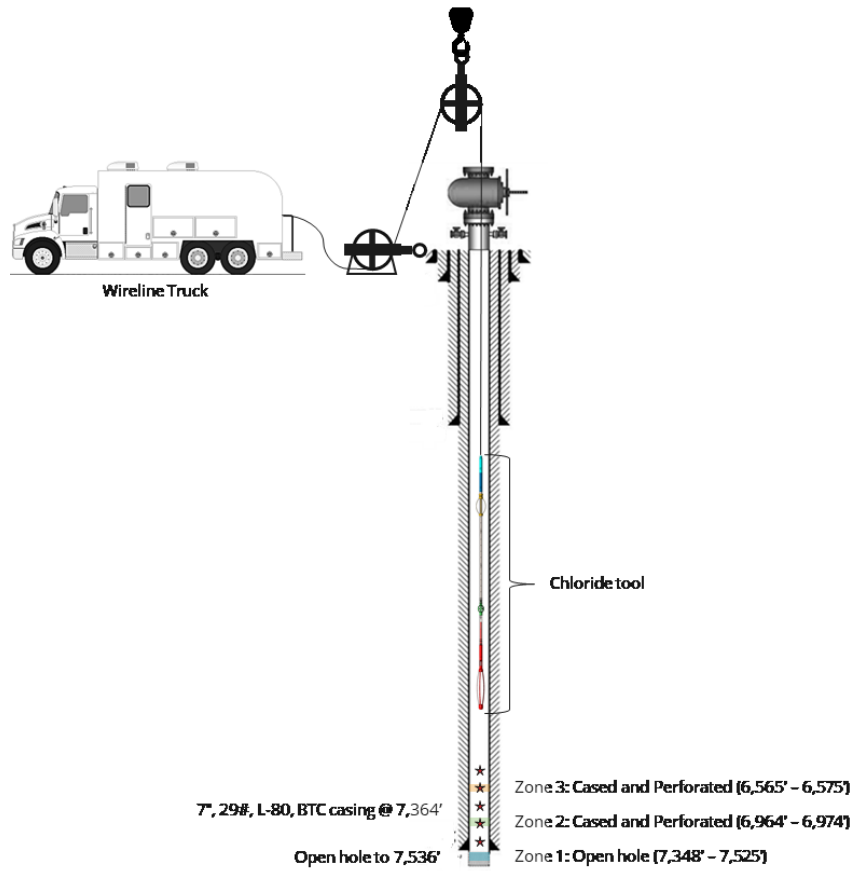**Figure 3: wireline tool assembly diagram deployed at well 58-32.**

Figure 4: Illustration of tool deployment plan at well 58-32.

(a) Field tool component   (b) Wireline tool ready to trip in

Figure 5: (a) the chemical sensor and housing as part of the wireline tool assembly, and (b) the assembly ready to trip in.

The logging results are shown in Figure 6 for the run-in hole (RIH) and Figure 7 for the pull-out of the hole (POOH). The first two columns display data from two chemical sensors, while the following two columns show the PTS and CPU temperature data. The CPU temperature data is considered more accurate in magnitude for this particular run despite the lag in heating up caused by its position inside the electronics component rather than in direct contact with the fluid. The last three columns represent the flow data from the PTS sensor. The perforated zones are marked with yellow regions; the short interval creates the appearance of a line.

A decrease in voltage (i.e., a spike to the left) would correlate with an increase in chloride concentration, indicating inflow presence. If accompanied by a temperature spike coming from geofluid entering the wellbore, the voltage spike will strongly indicate inflow presence. The RIH data shows no firm indication of such a spike around Zone 2 and 3. Meanwhile, spikes in both directions are observed in the chloride voltage columns near Zone 1, which also correlates with a temperature increase. However, the PTS counter did not increase, even with a location pause. Thus, the interval is not interpreted as flowing or experiencing notable internal flow.

The POOH run provides much cleaner data than the RIH run, which is consistent with results from the laboratory experiments. However, chemical sensor voltage data from the shallower part of the POOH, as indicated in Figure 7, is erroneous and cannot be used for interpretation. Similar to RIH, spikes are seen near Zone 1 but are not interpreted as flow because the PTS counter did not change at all. There is a voltage spike near Zone 3, which is also accompanied by a temperature spike. However, the spike was only caused by one data point; again, no corresponding counter or direction change from PTS was present. Thus, it is concluded that the logged interval did not indicate the presence of any inflow. If there were any internal flow happening, it may occur within the open hole section, which was not covered by the logging runs.

The voltage signals from the two chemical sensors appear to resemble each other. Thus, the readings from the first sensor were used to evaluate converting the chemical sensor voltage into chloride concentration. Calibration for the field tool used at 58-32 was performed with KCl solution in distilled water and fluid samples from well 16A(78)-32 and 16B(78)-32. The molarity result using the best available calibration curve is shown in Figure 8, showing a range of around 0.2 M for RIH data and between 0.25 to 0.75 M for POOH data. However, this calibration curve is unreliable due to a discrepancy in the bench calibration after acquisition.
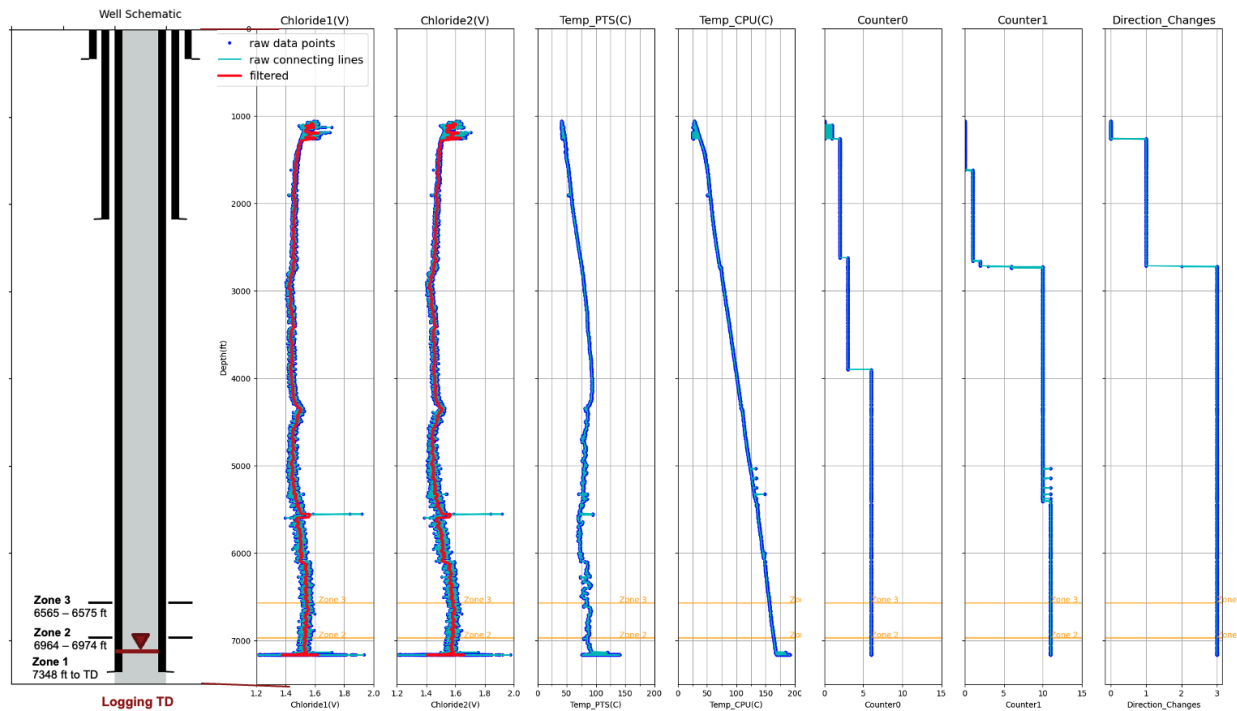

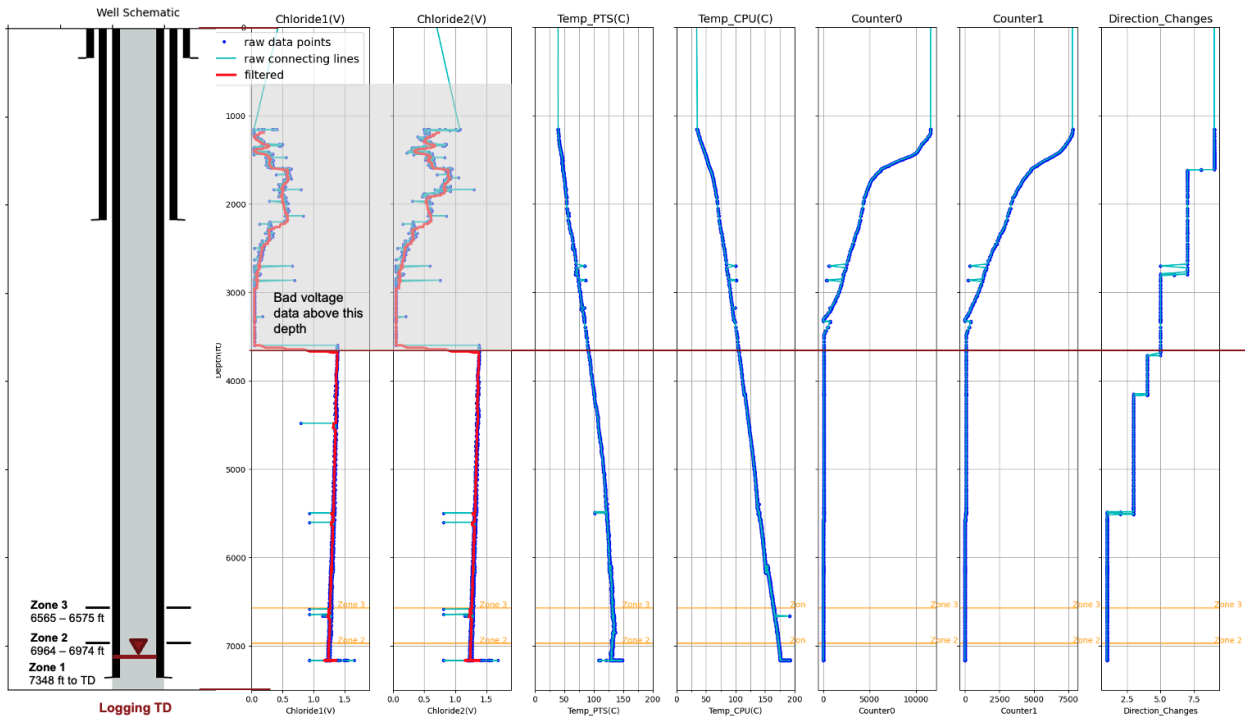**Figure 6: logging results during Run in Hole (RIH) at well 58-32.**

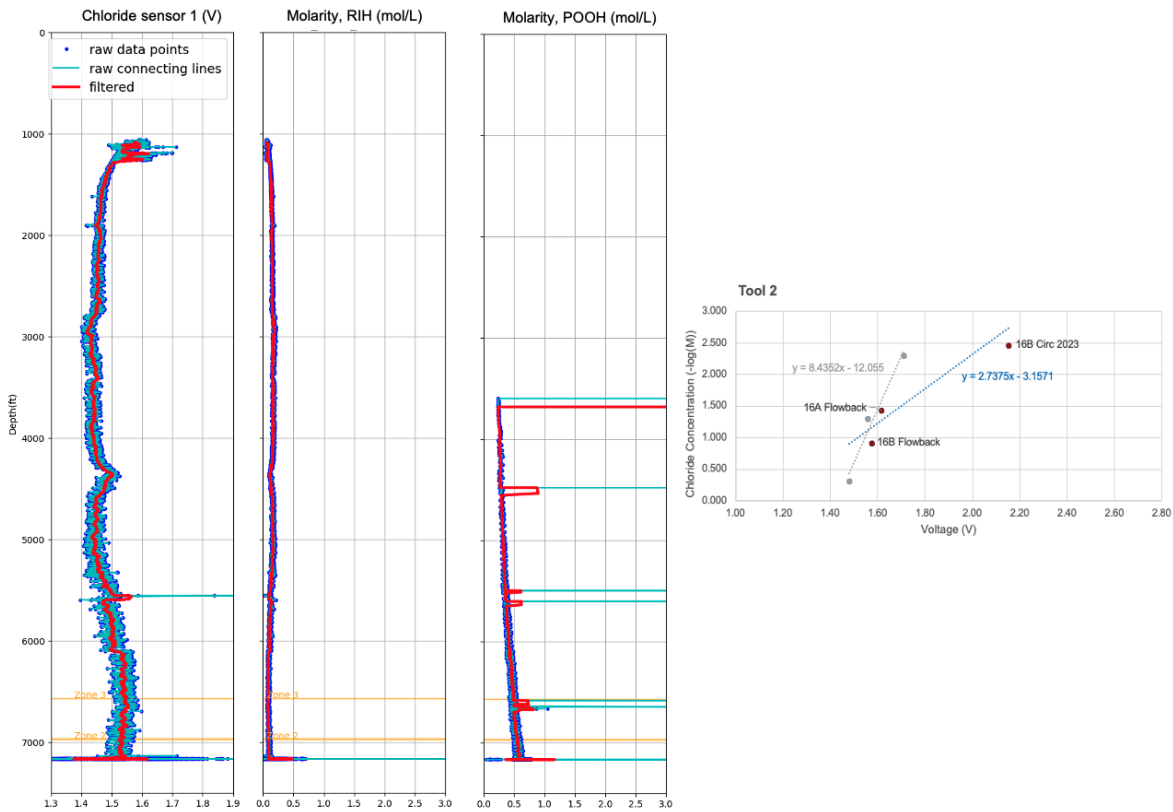**Figure 7: logging results during Pull Out of Hole (POOH) at well 58-32.**

Figure 8: converted molarity from the chemical sensor 1 voltage data during RIH and POOH using Tool 2 calibration curve (blue line on the right chart).

In Table 2, the sum of the molarity of relevant chemical species that the chemical sensor would pick up ranges from 0.0046 to 0.12 M. Recent laboratory experiments have shown that in addition to chloride, the ISE is sensitive to bromide (Br) and a lesser extent, sulfate (SO4). While chloride is more common in brine water and often determines the molarity, the ISE reacts to bromide and sulfate to varying degrees. Compared to the molarity in Table 1, the chemical concentration obtained from the logging data (Figure 8) indicates that the ranges of molarity derived from the chemical sensor are generally higher than what was found in the nearby well samples 16A(78)-32 and 16B(78)-32. Some anomalous points are present and exhibit erroneous railing behavior and, therefore, may be excluded.

Table 2: Relevant chemical species of well samples from Utah FORGE Wells 16A(78)-32 and 16B(78)-32

DATE & TIME	WELL	Concentration (mg/l)			Molarity (mol/l)			Sum of molarity (mol/l)
		Br	Cl	SO4	Br	Cl	SO4	
7/19/2023 20:00	16A(78)-32	2.07	1300	162	2.59E-05	3.66E-02	1.69E-03	0.0383
7/20/2023, 7:50	16B(78)-32	9.05	4384	239	1.13E-04	1.23E-01	2.49E-03	0.1261
7/20/2023, 15:00	16B(78)-32	0.32	122	115	4.01E-06	3.44E-03	1.20E-03	0.0046

4. FIELD DEPLOYMENT AT 16B(78)-32

While the field test at 58-32 demonstrated the practical application of the geochemistry-based wireline tool, a meaningful inflow signal was absent because the well was not flowing. In contrast, well 16B(78)-32 was undergoing flow through the five stimulation stages and multiple feed zones along the deviated section. The field test at this well investigated the sensor's feasibility, tool design, and capability of data acquisition under challenging well conditions.

The second deployment occurred on August 19, 2024, at Utah FORGE Well 16B(78)-32 during a 30-day circulation test. Figure 9 depicts the deployment plan. Well 16B has five stages, each with 3-5 guns, allowing for mapping up to 20 fractures. For this deployment, ten test locations were planned to target measurements at and between perforations. The tool would be stationed at each test location to enable stationary measurements of the chloride sensors and PTS tool. The logging between each test location would provide a blind "fly by" measurement to assess the feasibility of mapping fractures using a running log. Two chemical tool assemblies were prepared as a contingency in the field. The tool was deployed using a Schlumberger wireline truck, weight bars, and Petromac rollers to convey it through the flowing and deviated well. Figure 10 shows the full chemical tool assembly attached to weight bars and being loaded into lubricators. Figure 11 shows the wireline tool assembly tripping in.

The tool was successfully deployed to approximately 9,480 ft, passing through Stage 5, Stage 4, and part of Stage 3, with a maximum measured temperature on the tool of 210°C. The logging results from well 16B(78)-32 are presented in Figure 12 for the run-in hole (RIH) and in Figure 13 for the pull-out hole (POOH). The first three columns display chloride voltage readings from the three sensors installed in the wireline tool. The following three columns represent the chloride concentration in mol/L, calculated using the calibration curve (Figure 14) to convert voltage to concentration. Subsequently, the Pressure-Temperature-Spinner tool readings are displayed in the following three columns, and the velocity log is derived from the spinner readings. The stages are marked in differently colored zones, and guns are marked as green lines throughout the logs.
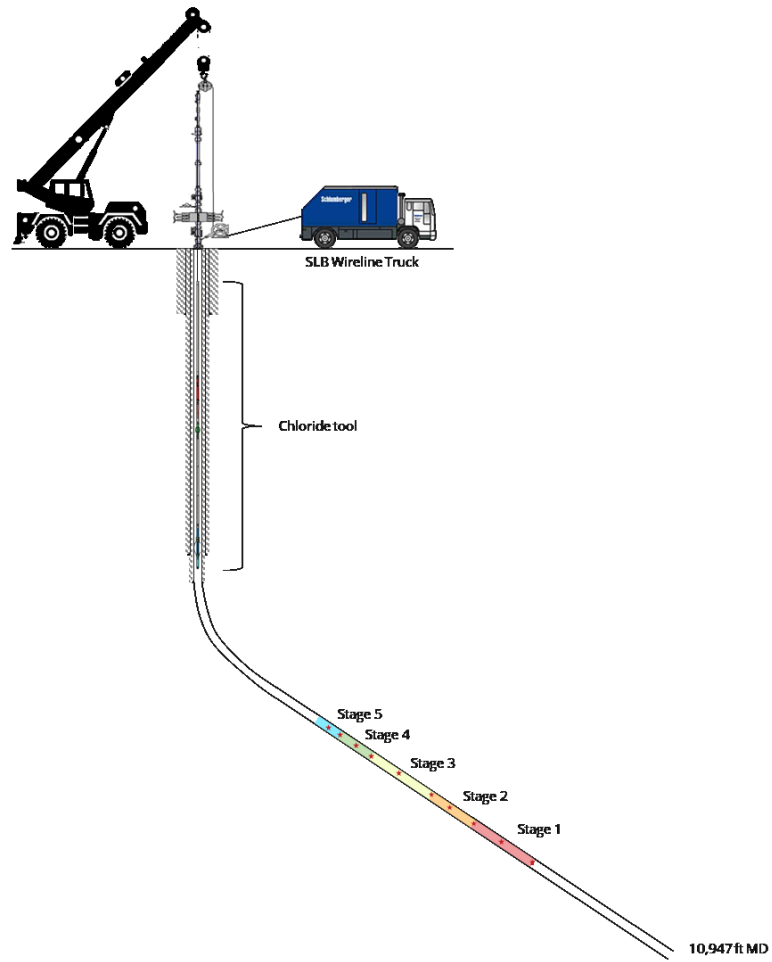
Figure 9: Illustration of tool deployment plan for Utah FORGE Well 16B(78)-32. Perforation stages are shown in highlighted zones, and planned test locations are shown as red stars.

Figure 10: Full chemical tool assembly attached to weight bars and being loaded into lubricators.

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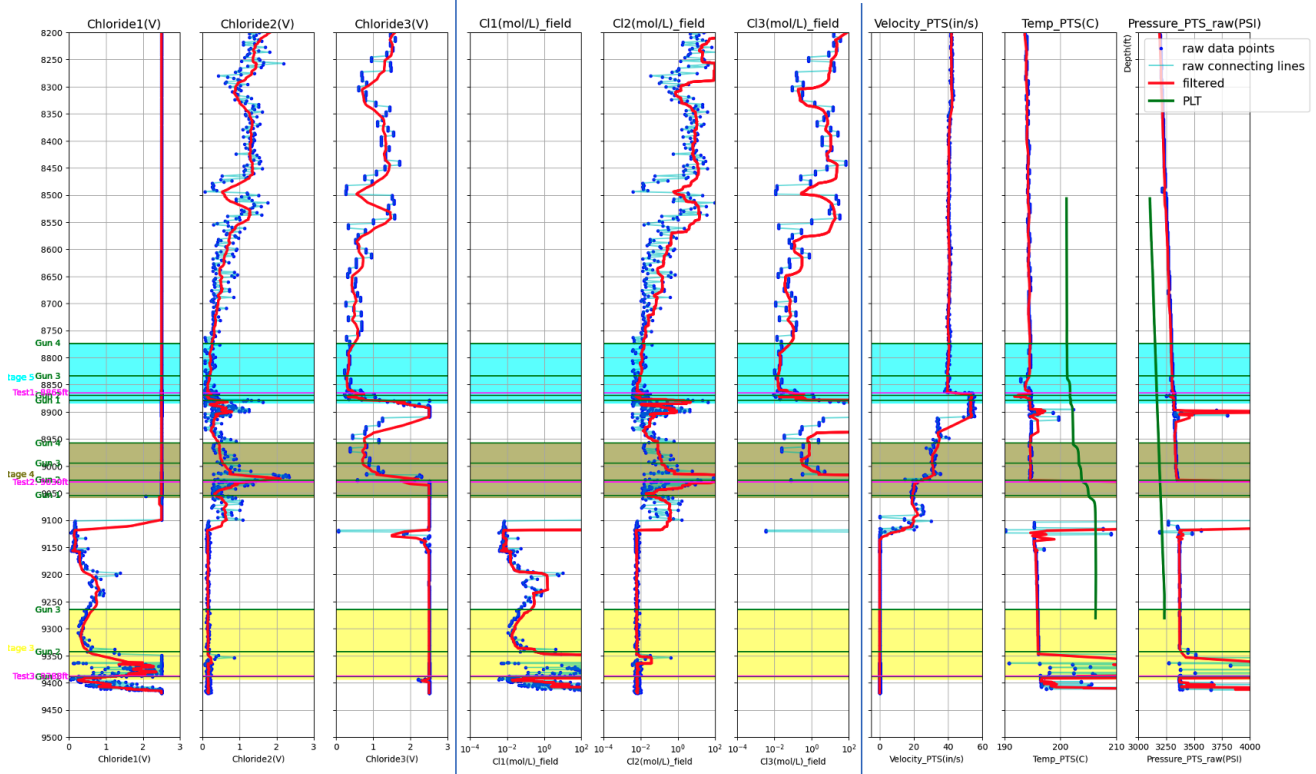**Figure 11: Utah FORGE Well 16B test site with lubricator stacks for chemical tool.**

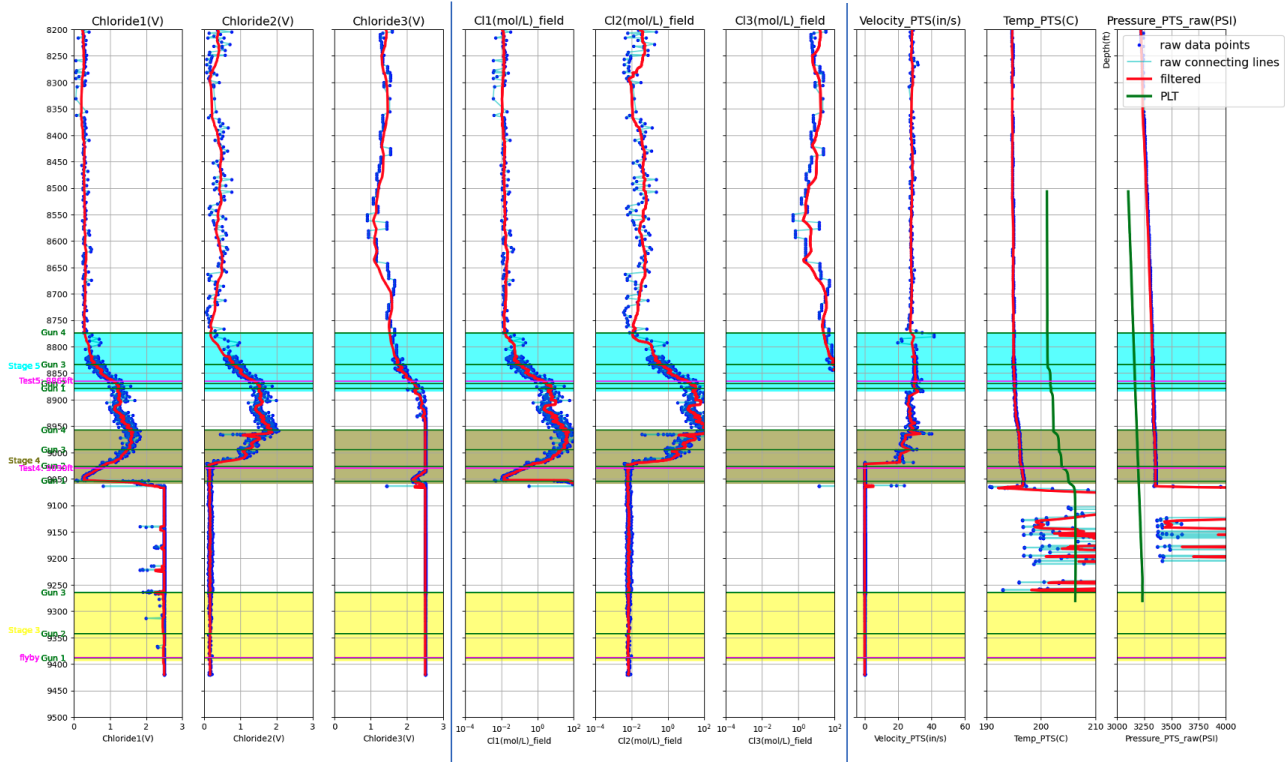**Figure 12: well logs from Run in Hole (RIH) run at 16B zonal depths.**

Figure 13: well logs from Pull out of Hole (POOH) run at 16B zonal depths.
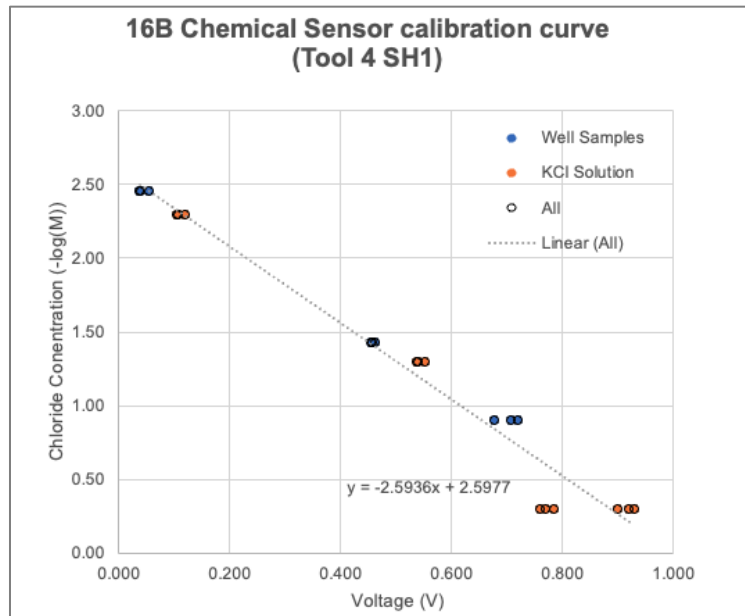
Figure 14: calibration curve for the chloride sensors used for 16B logging.

Similar principles apply to reading the results, which show that a spike in voltage correlates with an increase in chloride concentration, indicating inflow presence. If accompanied by a temperature spike from the geofluid entering the wellbore, the voltage spike indicates inflow. Such spikes can be observed in Stage 5 and Stage 4 in both RIH and POOH. Moreover, similar to the observations in wells 58-32 and laboratory experiments, chloride measurements at 16B(78)-32 are noticeably more stable and consistent during the POOH run than in the RIH run. Therefore, the inflow analysis was conducted using POOH data (Figure 15).

Utilizing the formula developed earlier in the project to convert chloride concentration readings into flow rates, several reading points were selected at Stage 5 and Stage 4 to provide information on chloride concentration above, at, and below the feed zones, indicated by arrows in Figure 4. The calculation yields flow rates of 4326.49 BPD for Stage 5 and 7822.83 BPD for Stage 4, respectively. Compared to the flow rate calculation from the PLT log obtained a week later by SLB, the flow rate calculated using the chloride method is within

the expected range of agreement. However, a caveat is the somewhat arbitrary selection of reading points for the chloride flow rate formula; we are exploring ways to make the selection process more replicable and robust.
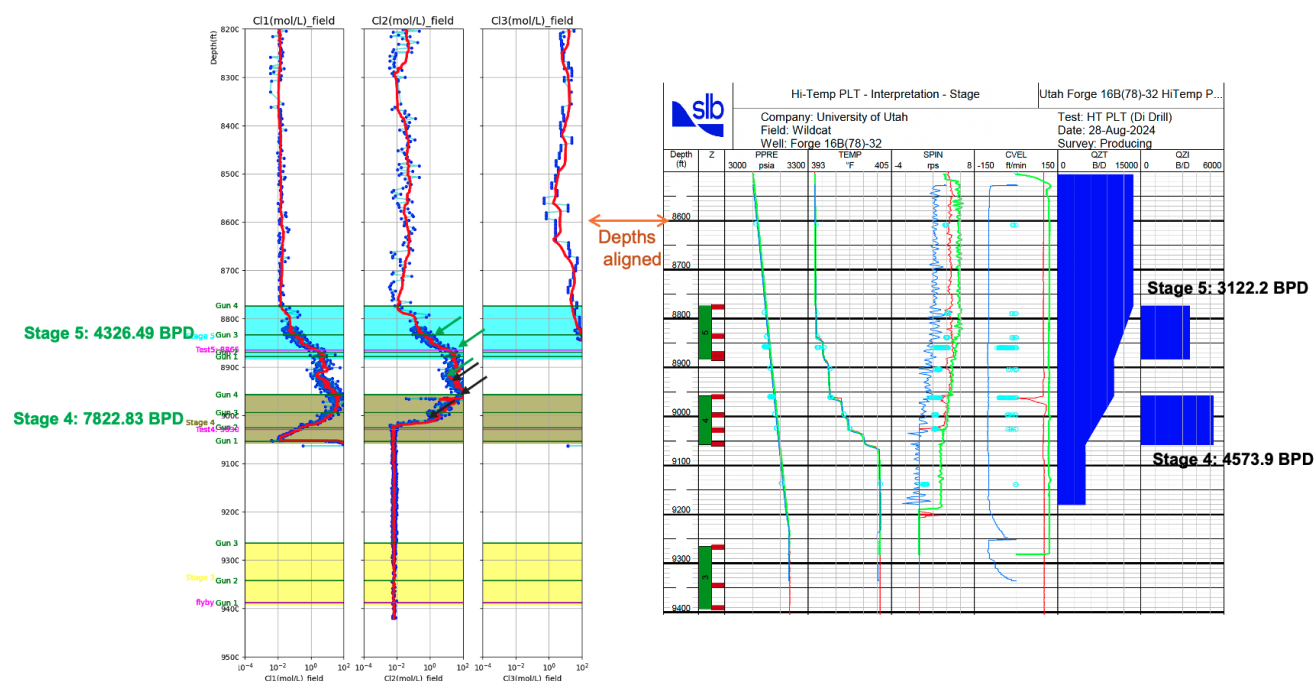

Figure 15: Comparison of POOH chloride signal and PLT interpretation performed by SLB on 28 Aug 2024 (around one week later).

5. CONCLUSION

Laboratory experiments involving single fracture inflows were performed to test different parameters, including chloride concentrations, tool positioning, and feed zone inflow rates. The results showed different behaviors of probes, one exhibiting gradual changes in molarity readings while another displayed faster responses. It was found that while the presence of bromide and sulfate ions in the feed zone fluid caused interference, the combination of these ions stabilized the chloride tool readings. Dynamic experiments were also conducted, simulating field operations by moving the tool vertically. These tests showed higher chloride concentrations in the feed zone fluid, which produced more accurate inflow rate inferences in the pull-out of hole (POOH) direction. The tool showed more accurate readings moving from lower chloride into higher chloride concentrations, compared to moving from high to low – which contributed to the results being more accurate in the pull-out-of-hole (POOH) direction than the run-in-hole (RIH) direction.

The tool was successfully deployed at FORGE Well 58-32, an open, vertical well, in June 2024, and FORGE Well 16B(78)-32, a pressurized and flowing deviated well, in August 2024. Both deployments demonstrated the tool's capability to withstand Utah FORGE conditions and the feasibility of a geochemistry-based approach to map fractures in a flowing well (16B), with no false positives in a nonflowing well (58-32). In both deployments, measurements were noticeably better during the POOH run than the RIH run. At well 58-32, the measurements suggest there were no internal flows in the well during the logging, which was not unexpected as the well was not producing at the time. Conversion from the voltage data into chloride concentration used calibration curves established using KCl solution and fluid samples from nearby wells. The converted molarity values were higher than the sum of relevant chemical species in available samples, which ranged from 0.0046 to 0.12 M. As a result, improvements to the chemical sensor were planned for future tests to ensure more accurate readings.

To analyze well 16B(78)-32 measurement results, several reading points were selected at Stage 5 and Stage 4 to provide information on chloride concentration above, at, and below the feed zones. The calculation yields flow rates of 4326.49 BPD for Stage 5 and 7822.83 BPD for Stage 4, respectively. Compared to the flow rate calculation from the PLT log obtained a week later, the flow rate calculated using the chloride method is within the expected range of agreement.

In summary, these findings demonstrated the effectiveness of the geochemistry-based approach for mapping fractures in geothermal wells and showed the chloride ISE tool's potential to enhance subsurface characterization.

ACKNOWLEDGMENTS

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