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Using Distinct Chemical Ratios of Wells' Geothermal Brine to Determine Connectivity Between Faults and Fractures in Þeistareykir Geothermal Field in Northeast Iceland

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ABSTRACT

A tracer test initiated in June 2024 at the Þeistareykir Geothermal Field investigated fracture and fault connectivity associated with the recently drilled production well ÞG-19. The well intersects two major aquifer intervals: an upper aquifer at depths of 1200–1500 m (~150 °C) and a deeper aquifer at 2200–2800 m (~180 °C). During shut-in periods of ÞG-19, crossflow from the upper aquifer to the lower aquifer was observed, potentially facilitating fluid migration into surrounding fractures and faults.

To trace this movement, chemical ratios (Na/K, Na/Cl, and Cl/F) were monitored in multiple production wells across the geothermal field. These ratios serve as indicators of fluid mixing because each borehole exhibits a distinct chemical signature. Preliminary results show that the water chemistry of certain wells, particularly ÞG-04, has shifted toward the chemical composition of ÞG-19, suggesting fluid flow connectivity along a shared fault structure.

Although the tracer test remains ongoing, these findings demonstrate that monitoring chemical ratios in geothermal brine provides a simple and effective method for identifying subsurface flow pathways. Such insights are valuable for improving reservoir characterization and informing geothermal reservoir management strategies

1 INTRODUCTION

Characterizing subsurface fluid flow is a central challenge in geothermal reservoir management. Fluid pathways within geothermal systems are largely controlled by networks of fractures and faults, and understanding the connectivity of these structures is essential for predicting reservoir behaviour and ensuring sustainable production.

Geochemical monitoring provides a powerful approach for investigating subsurface connectivity because changes in fluid chemistry can reveal interactions between aquifers, production wells, and structural features within the reservoir. Natural variations in geothermal brine chemistry may therefore serve as effective tracers of fluid movement within the subsurface.

The Þeistareykir Geothermal Field in northeast Iceland has undergone significant drilling and development in recent years. Production well ÞG-19, drilled in 2023, intersects two major aquifer intervals at different depths and temperatures. Early testing of the well revealed crossflow between these aquifers during shut-in periods, suggesting that fluids from the upper aquifer may migrate into surrounding fractures and faults (Jóngeirsdóttir et al., 2023).

To investigate this potential fluid migration, a tracer study was initiated in June 2024. Rather than using injected tracers, this study relies on naturally occurring chemical ratios in geothermal brine to identify mixing between wells. Ratios of major chemical species (Na/K, Na/Cl, and Cl/F) were monitored across multiple production wells while ÞG-19 alternated between shut-in and production periods.

This paper presents the methodology, results, and interpretation of this tracer test. Particular attention is given to chemical changes observed in wells ÞG-04 and ÞG-11, which provide insight into subsurface connectivity and reservoir processes within the Þeistareykir geothermal field.

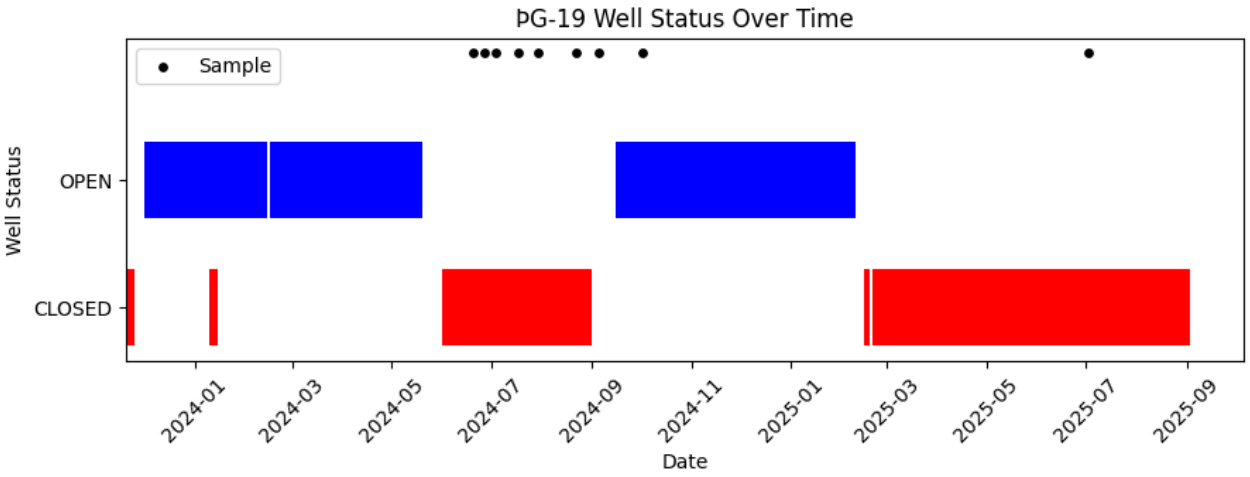


Figure 1. Status of ÞG-19 Over Time, Depicting Intervals of Production, Closure, and Sampling Dates

When the project began in June 2024, sampling was conducted weekly for the first three weeks, after which it shifted to every two to three weeks depending on staff availability. The first sample following this schedule was collected on 20 June 2024, and the final sample on 2 October 2024. Laboratory analysis was carried out during the fall and winter, and the results of these initial samples prompted further investigation and additional sampling. This included two samples from ÞG-04 collected in February and June 2025, as well as samples from all other wells involved in the tracer test collected on 1 and 2 July 2025. At the time this paper was written, sampling for the tracer test was still ongoing; however, the sampling frequency had decreased due to weather conditions, staff availability, and other project commitments.

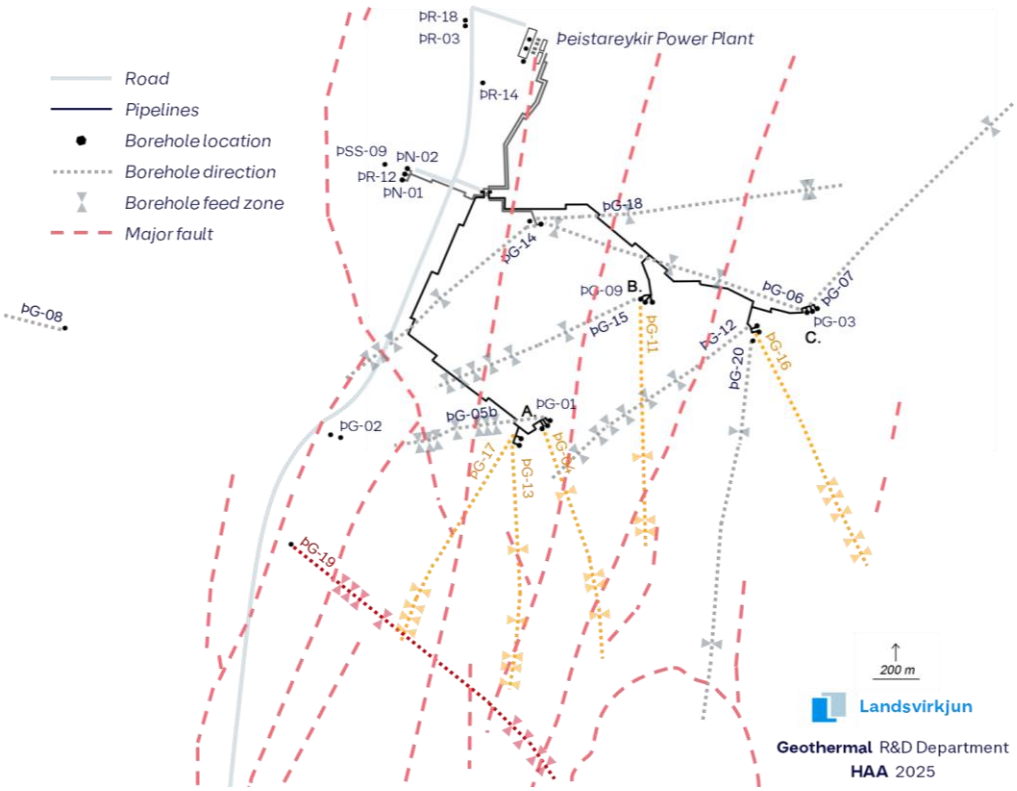


Figure 2. Overview of Þeistareykir Geothermal Field with Borehole Paths and Major Faults

The above figure is a simplified rendering of Þeistareykir geothermal power plant as seen from above. Production wells that were selected to be monitored as part of the tracer test are depicted in yellow dotted lines, ÞG-19 is depicted by a red dotted line, and the feed zones of these production wells are indicated by small bowties along each well's drill path. Finally, major faults in the geothermal field are indicated by dashed red lines. Faults that intersect both ÞG-19 and other production wells along their drill paths are the object of this study, as they could serve as fluid pathways between the production wells.

2 METHODOLOGY

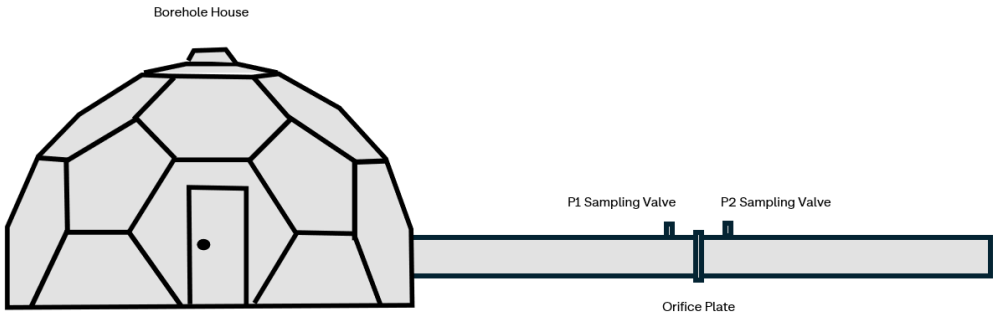


Figure 3. Sketchup of Sampling Valve Location in Relation to Well

The above image shows the location of the sampling valves on the production wells in Þeistareykir. All samples were taken at the "P2 Sampling Valve" point due to the ease of separation of the water phase at this point on the pipeline (Arnarssón, S., 2000).



Figure 4. The image on the Left shows the sampling valves of Borehole ÞG-04. The image on the right shows a standard Weber separator setup on the P2 sampling valve.

At each well, samples were collected using a standard separator setup (Figure 4), with a filtering device attached at the sampling point (Arnórsson, S., 2000). Three sample types were prepared:

- **Major/minor chemistry:** A filtered, untreated sample (Fu), and a filtered, untreated, degassed sample (Fud). Fu samples were collected in 100 mL polypropylene bottles using a 45µm filter paper and a filtering device, rinsed three times with filtered sample before being filled, and analysed for anions and cations at Krafla laboratory using ion chromatography (Metrohm 850 Professional IC). Fud samples were collected in the same way as Fu samples and then degassed by Argon-blowing each sample for approximately 20 minutes or until any sulphur odour was no longer detectable. Fud samples were preserved for possible trace metal analysis at ALS Scandinavia.

- **Isotope chemistry:** A filtered and untreated sample (iso,v). These were collected in 60 mL amber glass bottles using a 45µm filter paper and filtering device, rinsed three times with filtered sample before being filled, and closed carefully to ensure the sample bottle was void of air. Samples were stored for possible isotope analysis at ÍSOR or the University of Iceland.

Three chemical ratios were calculated for each sample: sodium-to-potassium (Na/K), sodium-to-chlorine (Na/Cl), and chlorine-to-fluorine (Cl/F). These chemicals were chosen as they represent the major anions and cations present in Þeistareykir geothermal field (Arnórsson, S., 2000). Ratios were used instead of absolute concentrations to minimize potential errors caused by incomplete steam separation during sampling. If a separator cannot perfectly separate the condensate out of the geothermal brine while collecting a sample, the condensate will dilute the sample and lower the concentrations of the chemical species. Ratios, however, will remain unchanged.

3 RESULTS AND ANALYSIS

The samples collected from ÞG-19 were analysed and compared. It was decided that one sample from ÞG-19 would serve as the representative sample of ÞG-19's upper aquifer. The representative sample was chosen based on the pressure of the borehole head at the time of sample collection. It is thought that a lower pressure allows the upper aquifer reservoir to circulate to the borehole's surface, while a higher pressure partially restricts this aquifer and only allows the lower aquifer to flow (Jóngeirsdóttir et al., 2023). Therefore, the sample that was taken while the wellhead's pressure was operating at its lowest point (excluding samples from the well's warm-up period) was chosen to be the representative sample.

Each well's chemical ratios were compared individually to that of ÞG-19. If there was fluid interaction or mixing in the subsurface with ÞG-19's low enthalpy water, then we could expect to see an increase in the Na/K, Na/Cl, and Cl/F ratios in ÞG-04 and ÞG-16. We would also expect to see a decrease in the Cl/ F ratios in ÞG-13 and ÞG-17, along with increases in the Na/K and Na/Cl ratios. In ÞG-11, mixing would be indicated by a decrease In the Na/Cl ratio and increase in the Na/K and Cl/F ratios.

The chemical ratios of the wells were plotted on ternary diagrams to clearly observe the changes in chemical ratios (see figures 5-12). While the ternary plots are disadvantaged in that it is difficult to demonstrate these changes through time, visually separating data collected from production wells prior to ÞG-19's drilling from data collected during the tracer test was thought to rectify this. On the ternary plots, each borehole's chemical ratios from previous annual sampling (plotted as stars), the tracer test samples (circles), and ÞG-19's representative sample (red X), were plotted. This way, fluid mixing would be indicated by a directional trend in tracer test samples from where the annual samples are plotted towards where ÞG-19 is plotted.

The first ternary plot (Figure 5) shows the chemical ratios of all wells, except for ÞG-11, on one plot. The figure illustrates the unique water chemistry of each borehole.

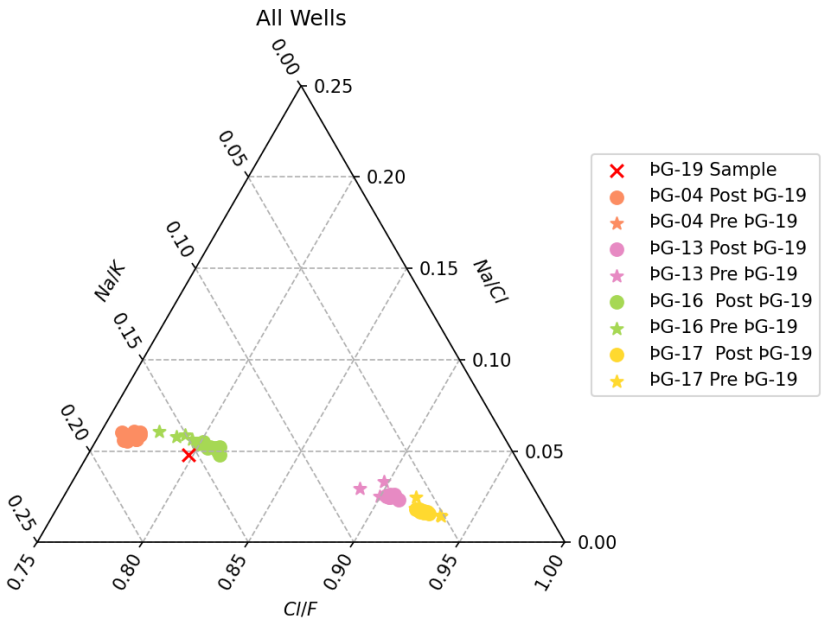


Figure 5. Ternary plot of all production wells' chemical changes in relation to ÞG-19 between June and October 2024. Note that ÞG-11 is not observed due to its vastly different chemical profile.

3.1 Borehole ÞG-19

The sample chosen to represent ÞG-19 was taken with a well-top pressure of 30.3 bar.

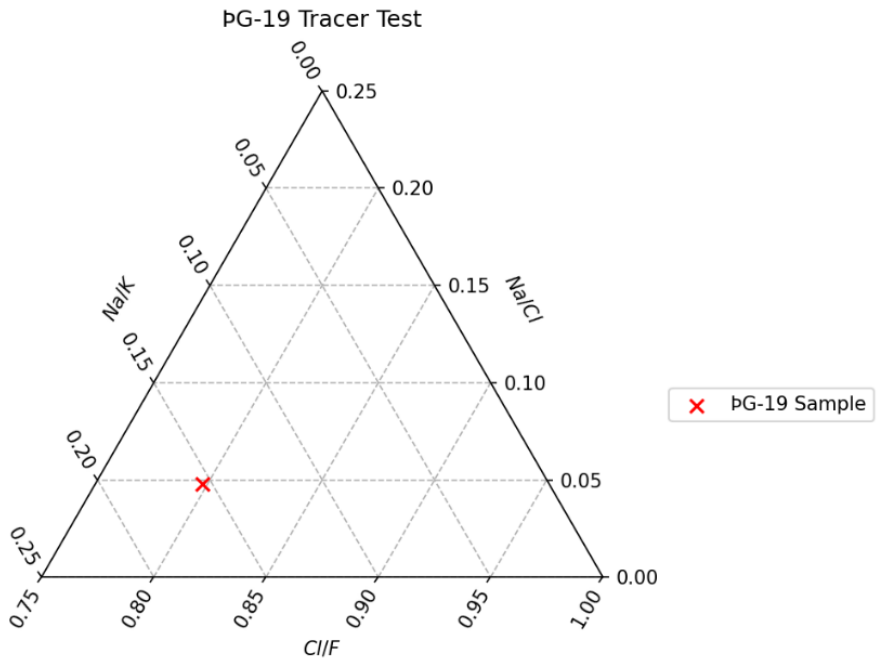


Figure 6. Ternary plot of ÞG-19's chemical ratios

3.2 Borehole ÞG-04

The water chemistry of ÞG-04 shows a distinct shift towards the water chemistry of ÞG-19.

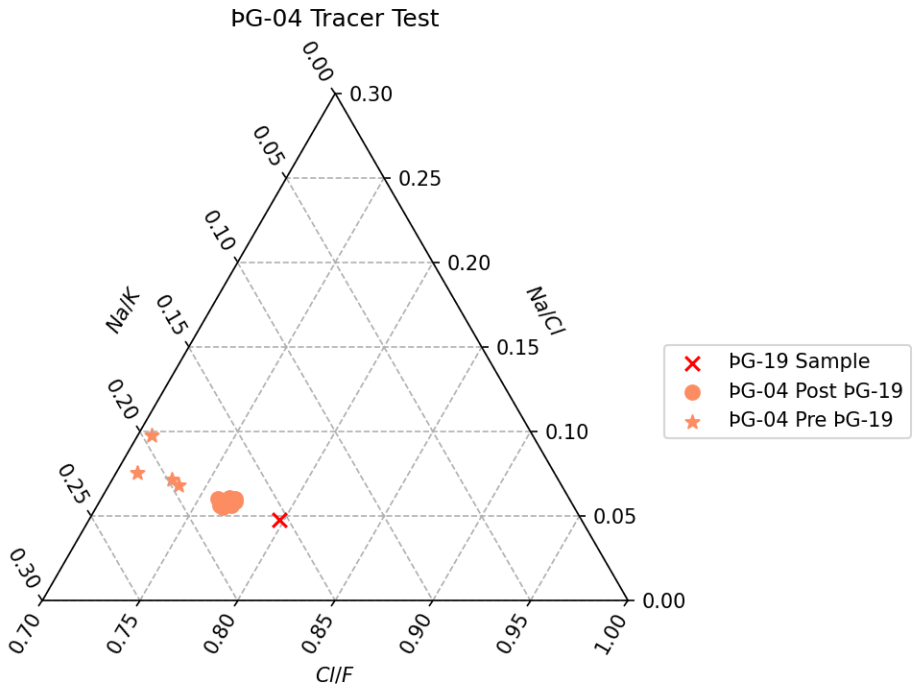


Figure 7. Ternary plot of ÞG-04's chemical ratios in relation to ÞG-19

3.3 Borehole ÞG-11

ÞG-11's water chemistry is vastly different from the other wells sampled during this experiment. Note the difference in scale on this ternary plot.

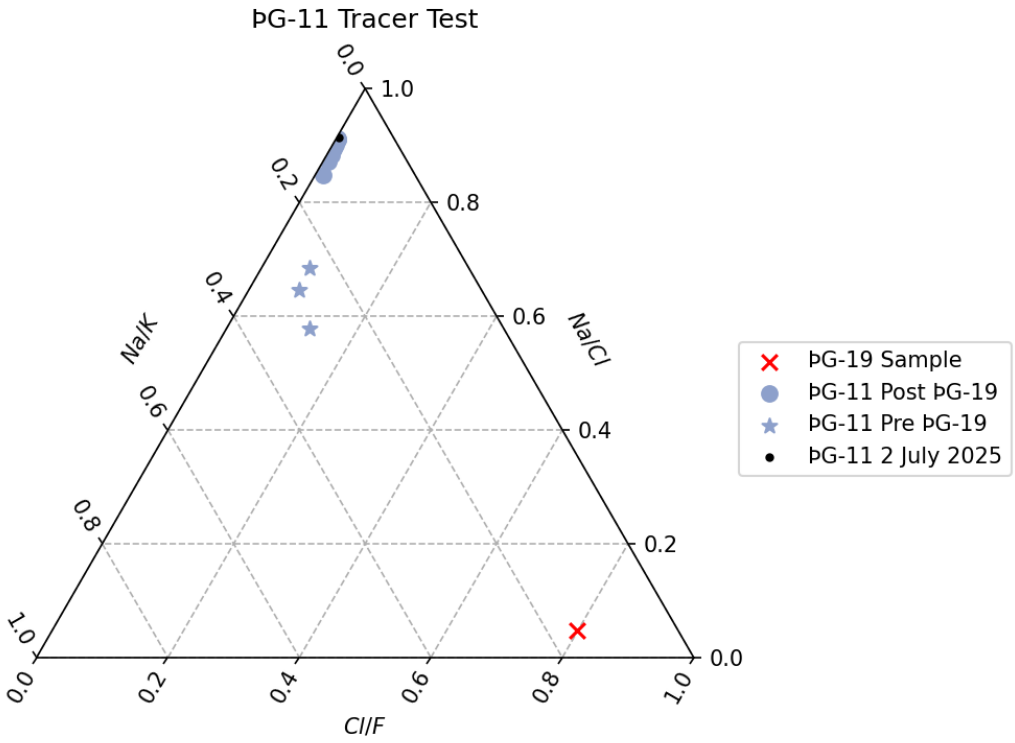


Figure 8. Ternary plot of ÞG-11's chemical ratios in relation to ÞG-19

3.4 Borehole ÞG-13

No significant change in ÞG-13's brine chemistry is observed.

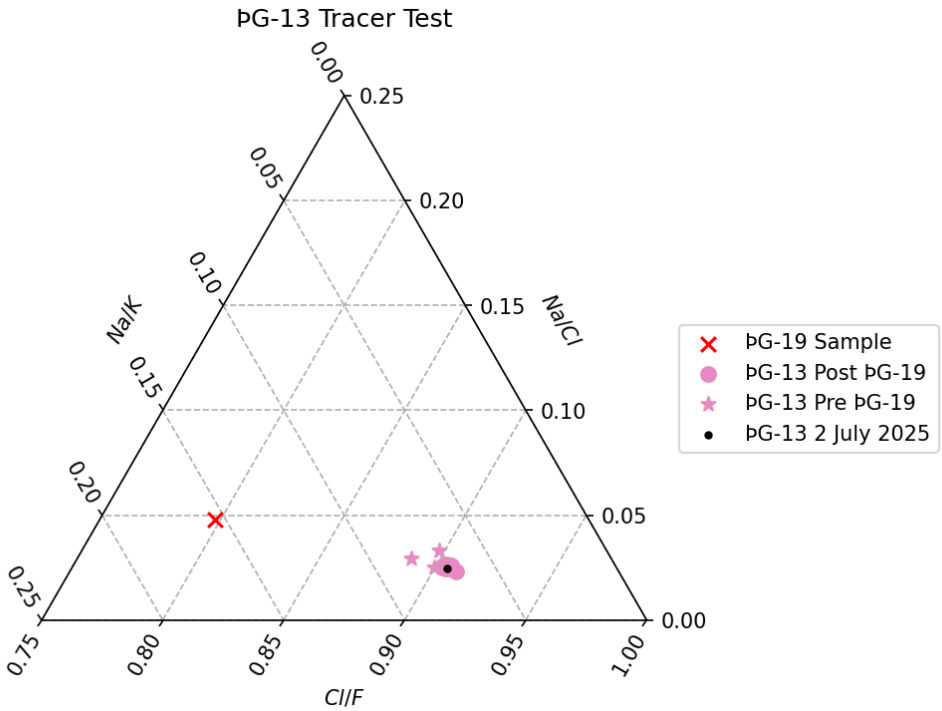


Figure 9. Ternary plot of ÞG-13's chemical ratios in relation to ÞG-19

3.5 Borehole ÞG-16

No significant change in ÞG-16's brine chemistry is observed.

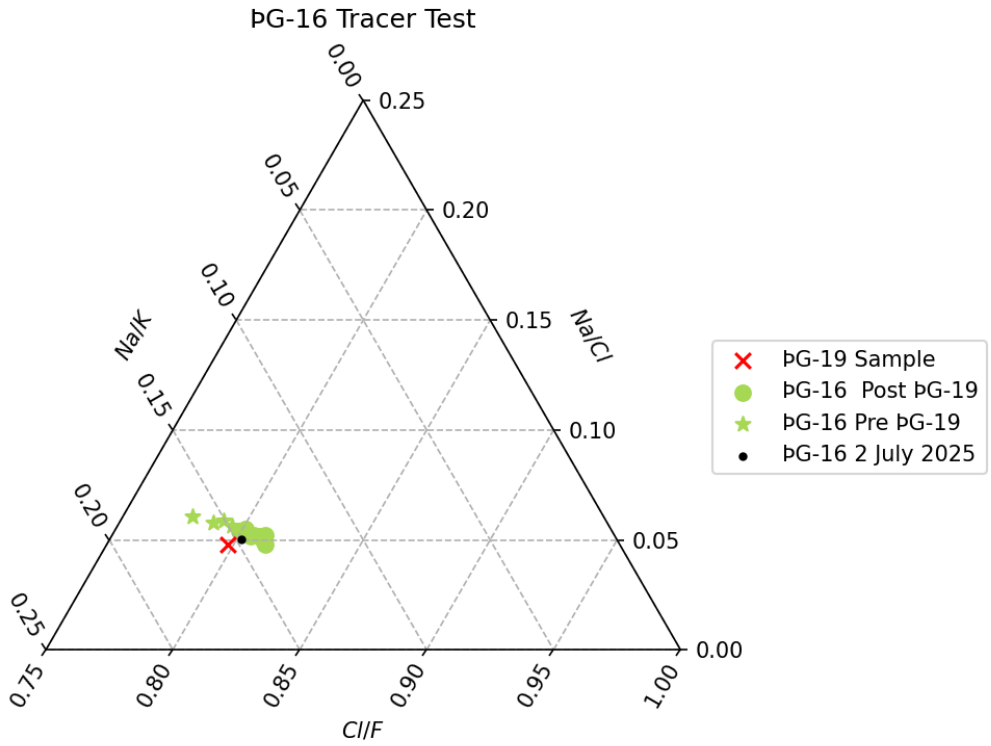


Figure 10. Ternary plot of ÞG-16's chemical ratios in relation to ÞG-19

3.6 Borehole ÞG-17

No significant change in ÞG-17's brine chemistry is observed.

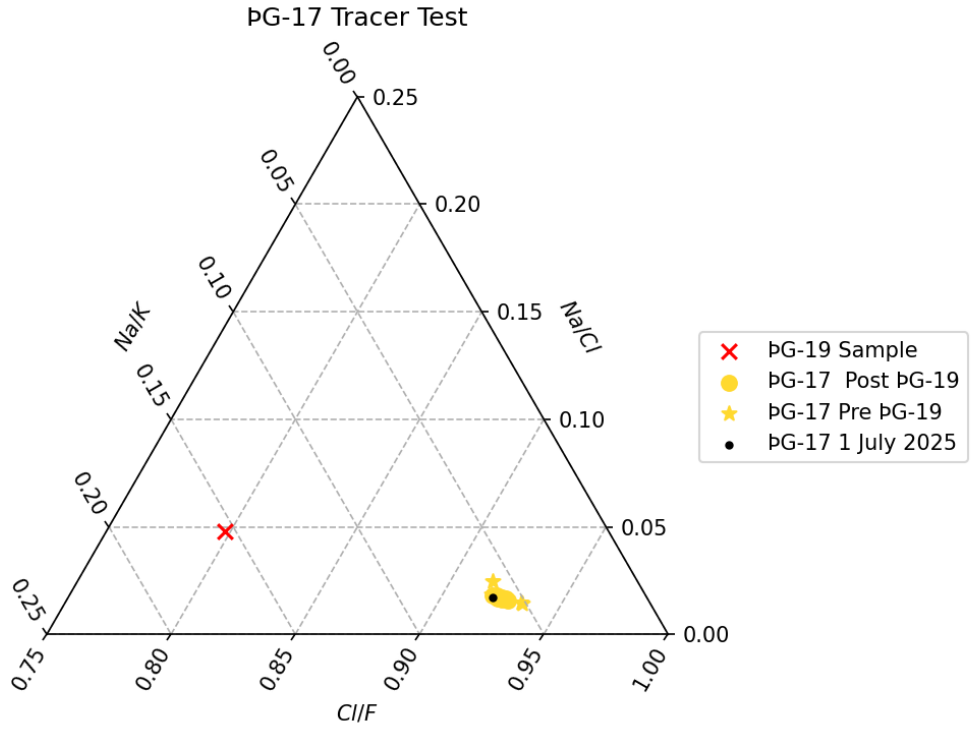


Figure 11. Ternary plot of ÞG-17's chemical ratios in relation to ÞG-19

3.7 Overall Interpretations

The ternary diagrams provide a clear visualization of potential mixing trends. Figure 7 shows the chemical ratios of ÞG-04 relative to ÞG-19. The tracer test samples from ÞG-04 display a consistent shift toward the chemical composition of ÞG-19, suggesting subsurface mixing between the two wells.

One possible explanation for this trend is fluid movement associated with a fault intersecting the terminal sections of the wells' drill paths. As shown in Figure 13, a mapped fault structure intersects both wells and may act as a preferential pathway for fluid transport.

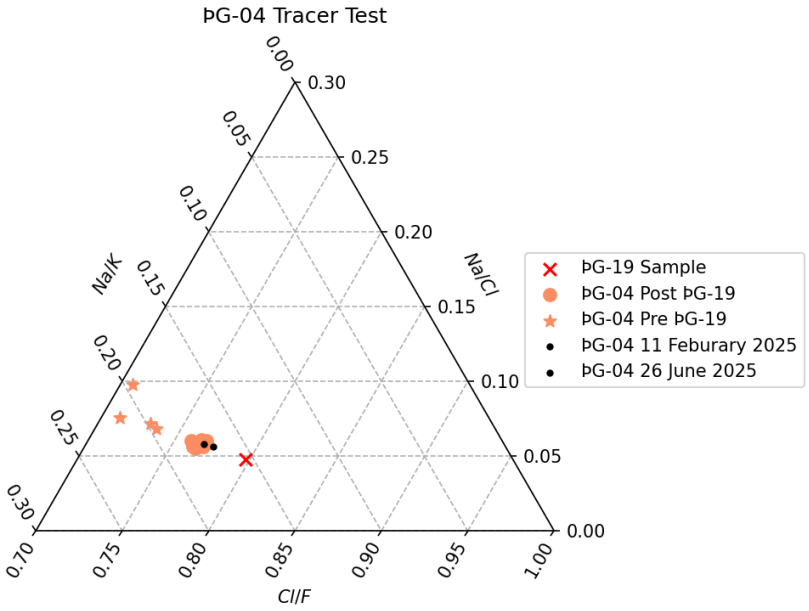


Figure 12. Ternary plot of ÞG-04 with additional sample from February indicated by black dot.

To evaluate whether the chemistry of ÞG-04 would return to its original state, additional samples were collected on 11 February 2025 and 26 June 2025 (Figure 12). These samples do not show any return toward the pre-tracer-test chemical ratios. This persistence may indicate that fluids associated with ÞG-19 during shut-in periods influenced the local reservoir chemistry near ÞG-04.

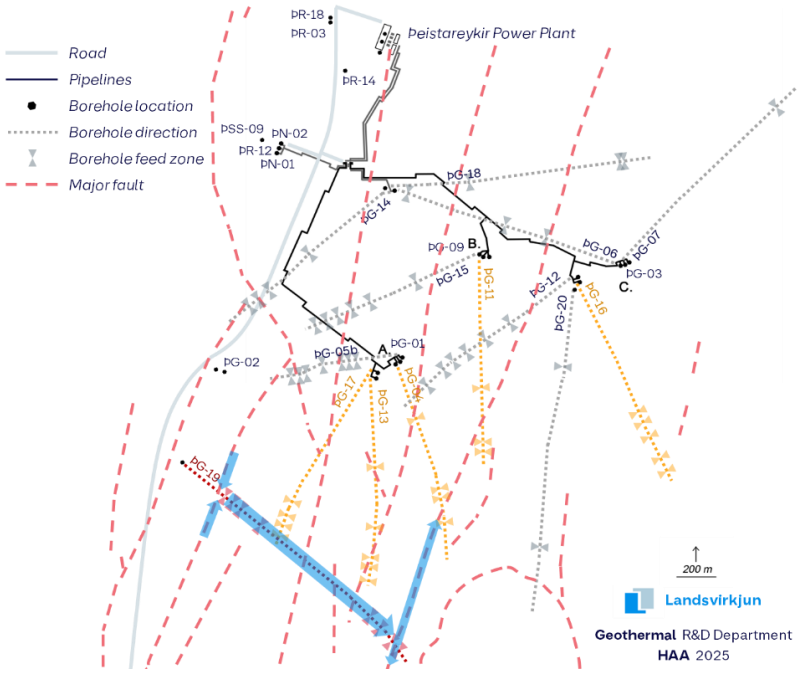


Figure 1313. Adaptation of Figure 2 showing the hypothesised fluid movement between ÞG-19 and ÞG-04. Fluid transport is indicated by blue arrows.

The behaviour of ÞG-11 is also noteworthy. Although this well does not show evidence of mixing with ÞG-19, its chemistry trends away from the chemical composition of ÞG-19. Similar trends were already present in past sampling data of ÞG-11 prior to 2022, indicating that the observed changes are unrelated to the drilling of ÞG-19.

A potential explanation for these changes in ÞG-11 is increasing phase segregation and aquifer boiling associated with long-term production (Scott et al., 2014). Such processes may explain the supersaturation of secondary minerals observed in the well's chemistry. This interpretation is further supported by measurements of excess enthalpy in the well's discharge.

4 CONCLUSION

The tracer test conducted at the Þeistareykir Geothermal Field provides new insight into possible subsurface connectivity within the reservoir, particularly regarding the influence of well ÞG-19 on surrounding production wells. Changes observed in the chemical ratios of geothermal brine indicate that interactions between wells may be occurring within the reservoir.

The chemical ratio data show that the water chemistry of ÞG-04 shifted toward that of ÞG-19 during the tracer test period. This trend suggests the possibility of a fluid flow pathway between the two wells, potentially associated with a fault intersecting the ends of their respective drill paths. However, these results should be regarded as preliminary indicators rather than definitive evidence of a direct fluid migration pathway.

The chemical behaviour observed in ÞG-11 highlights the complexity of the geothermal reservoir. The chemical trends in this well differ from those observed in ÞG-04 and other wells. Data from previous years indicate that these changes in ÞG-11 began prior to the drilling of ÞG-19. The observed trends may therefore be related to processes such as phase segregation or aquifer boiling associated with long-term production.

Overall, the results demonstrate the potential usefulness of monitoring chemical ratios as tracers of subsurface processes in geothermal systems. Because the approach relies on standard sampling procedures and existing analytical capabilities, it provides a practical and cost-effective method for identifying possible changes in reservoir behaviour.

Further sampling and continued monitoring will be necessary to determine whether the chemical trends observed in this study persist over time and to better understand the mechanisms driving these changes. Additional analyses, including isotopic and trace metal measurements, may help clarify the extent of connectivity between wells and the role of structural features within the Þeistareykir geothermal field.

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