# Natural fractures and their implications for geothermal fluid flow: A case study from the Þeistareykir Geothermal Area, NE Iceland

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## ABSTRACT

The aim of this study is to characterise the natural fracture network and provide a thorough understanding of the structural character in the high-temperature Þeistareykir geothermal system in NE Iceland. All the natural fractures observed in 300 m of shallow core and acoustic image logs in six wells from the Þeistareykir geothermal field were examined geologically to understand and analyse the occurrence, distribution and relative orientation of fracture development in the reservoir. Structural logging of core reveals the variation in fracture population in different segments of core depending on rock characteristics such as lithology and alteration intensity. Fractures occur as single, open fractures or as clusters in fragmented zones. The highest fracture density is observed in basalt (up to 9 frac/m), whereas intensely broken or fragmented zones seem to dominate in altered volcanic breccia. Analysis of acoustic image logs also provides good insights into the attitude of fractures and fracture distribution pattern across the geothermal field. The information obtained from this structural analysis is correlated to feed zone indications from temperature, spinner logging, drilling and completion testing data to assess the contribution of fracture network to permeability and preferential fluid pathways for the geothermal fluid. The results of this study will be incorporated into fracture and flow models to determine the control of fracture occurrence and distribution on permeability and fluid flow in the geothermal system.

## 1. INTRODUCTION

Fractures and faults regulate subsurface fluid flow in geothermal reservoirs, particularly in tectonically active regions (Rowland and Sibson 2004). Depending on their properties, fracture networks may enhance or restrict fluid movement, thus directly influencing reservoir permeability and overall productivity (Chen et al. 2021; Narr et al. 2006). Therefore, understanding the structural complexity, hydraulic behaviour, and distribution of fractures is vital for predicting fluid pathways and permeability patterns, aiding in efficient reservoir management.

This study focuses on the Þeistareykir geothermal system in northeastern Iceland (Figure 1). The Þeistareykir geothermal field, located within the Northern Volcanic Zone (NVZ) of Iceland, is a prime example of a structurally controlled geothermal system. The area is shaped by a complex interplay of rift-related structures and transform faults, particularly at the intersection of the Þeistareykir fissure swarm with the Tjörnes Fracture Zone, resulting in an extensively fractured reservoir (Figure 1a; Sæmundsson 2007). Geothermal drilling indicates significant variability in temperature and permeability across the field (Guðmundsdóttir et al. 2018). Well ÞG-8 drilled on the western side of the main fault and fissure system is a cold well (Kajugus 2012). Well ÞG-2 and lower part of ÞG-5 and ÞG-5B also show relatively cooler temperatures than the other wells in the field (Jóhannsson, 2011). These observations clearly suggest that geothermal fluid flow in Þeistareykir is constrained by the fault and fracture networks, but the actual structural controls are poorly understood. To better understand the mechanisms constraining heat and fluid flow in this structurally complex environment, we integrate data from six production wells and one shallow exploration well in the Þeistareykir geothermal field. Borehole image logs, cores, geophysical logs, and drilling data are analysed to characterise natural fractures in terms of their orientation, density, thickness, and distribution. This fracture analysis is then correlated with the permeable feed zones to identify the fractures and fracture characteristics which support fluid flow in the subsurface.

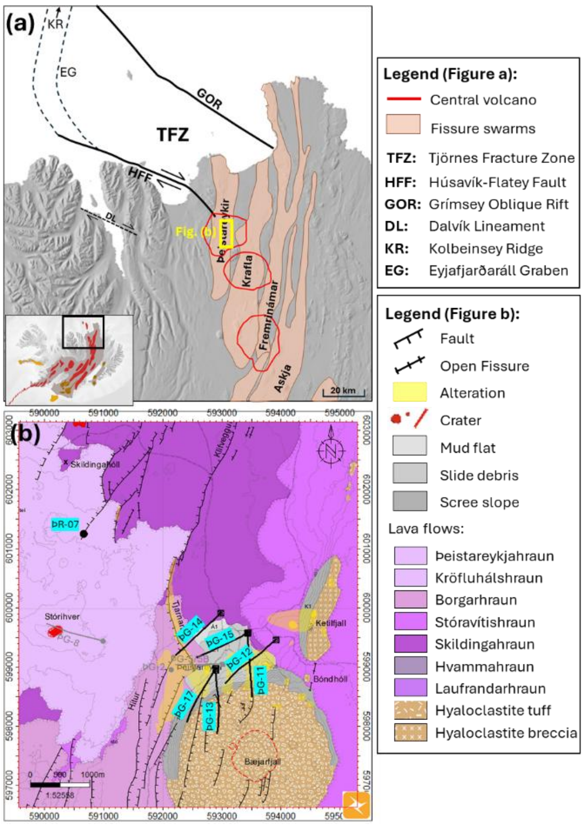


**Figure 1: (a) A simplified tectonic map of the Northern Volcanic Zone of Iceland. (b) Geological map of the Þeistareykir geothermal area (from Sæmundsson et al. 2012) showing locations of the studied wells.**

## 2. DATA AND METHODS

This study utilizes acoustic image logs from six production wells in the Þeistareykir geothermal field and around 300 m of core samples from an exploration well, ÞR-07, located 1.5 km from the main production area (Figure 1). Core is available from a depth of 150 m to 458.1 m, which is used to analyse the structural characteristics and fracture development.

Fracture interpretation is carried out on approximately 9900 m of borehole televiewer (BHTV) image data from six wells. Fractures appear as sinusoidal patterns on the images and are classified based on image characteristics such as acoustic amplitude, visibility in travel time image, and the confidence level of the interpretation. Fracture analysis is further studied in combination with additional borehole data including wireline logs (gamma ray, resistivity, neutron-neutron), cuttings lithology and feed zone indications from temperature spinner and circulation losses. Fracture density is calculated as the number of fractures per metre depth, with corrections applied for borehole deviation. Fracture thickness is measured directly as the width of the feature on the acoustic image and corrected for dip and borehole inclination to determine the true thickness (Mutonga and Fujimitsu, 2024).

## 3. RESULTS

### 3.1 Structural logging of core

A detailed structural analysis is carried out on 300 m of core samples from well ÞR-07 (Figure 2), focusing on identifying and characterizing natural fractures. The core primarily comprises three volcanic facies: basalt, volcanic breccia, and volcanic tuff, interbedded with each other and exhibiting different levels of hydrothermal alteration. Fractures are recorded throughout the entire core length, and fracture density calculated as the number of fractures per metre length of core. In some sections, the rock is so intensely fractured that individual fractures cannot be distinguished, forming dense clusters or highly fragmented zones, as illustrated in the core images in Figure 2. These highly fractured sections are separately marked in the fracture density log. From the analysis, 161 fractures were recorded in 135 metres of basalt, 21 fractures in 85 metres of breccia, 19 fractures in 26 metres of tuff, and 63 fractures in 59 metres of interbedded breccia and tuff intervals. Among these, basalt show the highest fracture density, reaching up to 9 fracs/m. In contrast, breccia units, especially those with high alteration, tend to exhibit broken and fragmented fracture clusters rather than isolated fractures. This suggests that rock characteristics such as lithology and the extent of alteration significantly influences both the distribution and nature of fractures across the core. Moreover, many fractures appear to be mineralised, primarily filled with secondary minerals like quartz and zeolite, the core altered and separated along the fracture plane. Only a limited number of open fractures were identified in basalt units, which allowed direct measurement of fracture width, ranging from 0.5 to 4 mm. Additionally, some fractures also display well-developed slickensides along the fracture plane.

### 3.2 BHTV image interpretation

Analysis of Borehole Televiewer (BHTV) logs from six wells in the Þeistareykir geothermal field reveals significant spatial variability in fracture occurrence, distribution, and orientation. Around 7000 natural fractures are identified from the BHTV images, and the characteristics of these fracture picks logged to assess the structural character of the geothermal field (Figure 3, 4). Despite their limited areal extent, fracture density varies notably between wells. Wells in the western part of the field (ÞG-13, ÞG-14, and ÞG-17) contain nearly double the number of fracture picks compared to those further east (Figure 3b). Fracture orientations also vary across the field and within individual wells. For example, wells ÞG-12 and ÞG-13 show well-defined N-S to NNE-SSW trending fractures, while ÞG-14 and ÞG-17 feature N-S to NNW-SSE trends with both easterly and westerly dips. In contrast, ÞG-15 displays a random distribution of orientation and dips (Figure 3b).

Fracture properties also differ within different lithologies. Hyaloclastites, including basaltic breccia and tuff, generally show lower fracture density than basalts or intrusive units. This may be partly due to the poor image quality in hyaloclastites in most wells (Figure 4). Most fractures, where fracture width measurements could be made, are in the range of 1–50 mm thickness, but thicker fractures also occur, notably in wells ÞG-14, ÞG-15 and ÞG-17 (Figure 4).

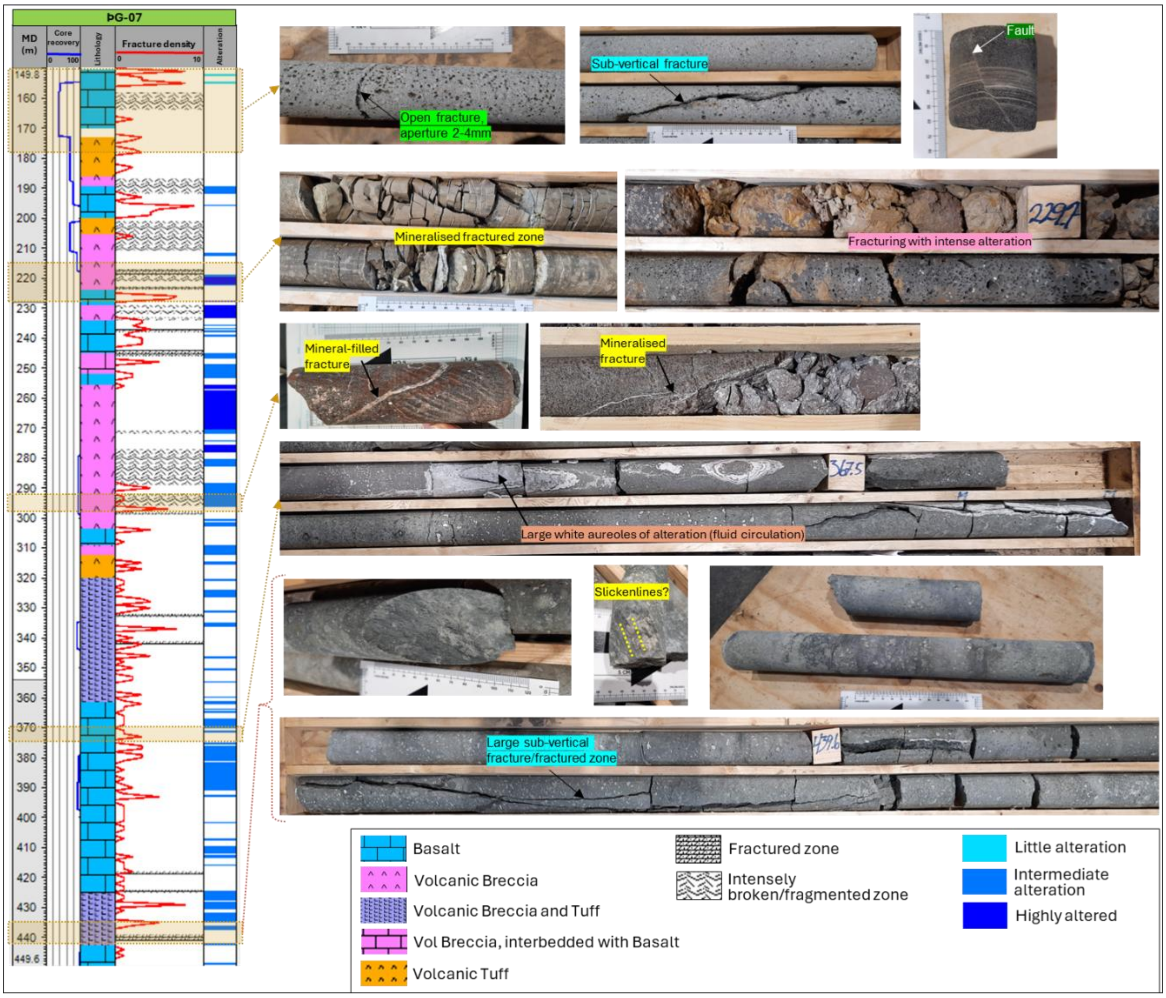


**Figure 2: Core analysis in well ÞR-07 showing the major rock types, degree of fracturing and alteration intensity through the entire length of core (left), along with photographs of structural features observed in the core samples (right).**

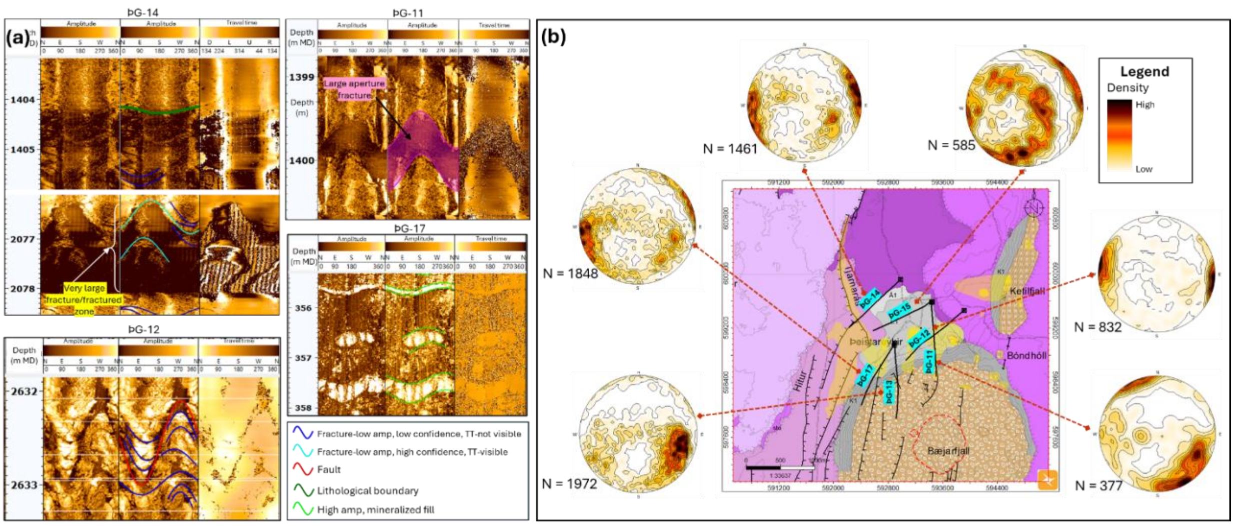


**Figure 3: (a) Examples of interpreted fracture picks and their structural characteristics in the televiewer amplitude and travel time logs from the studied Þeistareykir wells. (b) Contoured stereo-plots of poles to planes in Schmidt's projection, lower hemisphere. "N" is the total number of fractures interpreted.**

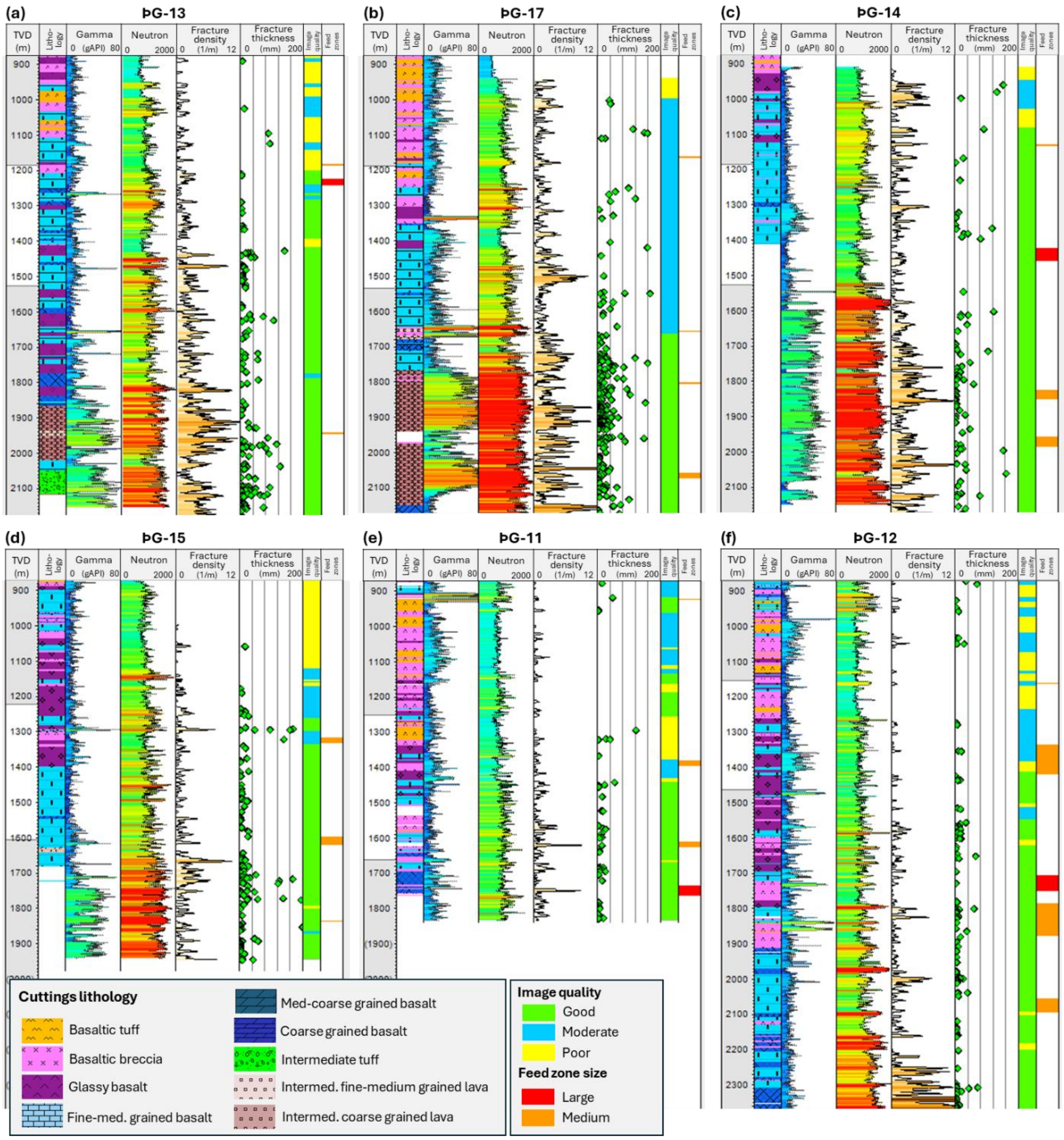


**Figure 4: Plot of wells (a) ÞG-13, (b) ÞG-17, (c) ÞG-14, (d) ÞG-15, (e) ÞG-11, (f) ÞG-12, along True Vertical Depth (TVD) showing cuttings lithology, geophysical logs (gamma ray and neutron), BHTV-interpreted fracture density, fracture thicknesses and image log quality. Permeable feed zones in each well identified by Guðmundsdóttir et al. (2018) are shown on the right.**

### 3.2 Fracture characteristics in feed zones

To better understand the structurally-driven fluid pathways in Þeistareykir, the fracture datasets from BHTV logs are correlated with the permeable feed zones identified in wells by Guðmundsdóttir et al. (2018). A case study is shown in Figure 5, highlighting the medium to large feed zones in ÞG-14: FZ1 and FZ2 within fine-medium grained basaltic lava flow units, and FZ3 and FZ4 within intermediate-acidic intrusive unit. FZ2 is the largest in the well. Although fracture density around FZ2 appears low in the fracture density log in Figure 5, zoomed in televiewer images provide indications of a highly fractured or damage zone that possibly correlate with increased permeability. A similar amplitude response is noted around FZ3, with fracture densities between 4–8 fractures per metre and thicknesses up to 8 mm. In contrast, FZ4 shows moderate fracture density (2-5 fracs/m), but features a large 160 mm thick fracture below it. Most fractures near the feed zones have a general N-S orientation with variable dip angles. However, it is observed that many fractures with similar characteristics and orientation also occur outside the permeable zones (Figure 5). This suggests there is potentially more to play, particularly the role of faults, in this structurally complex geothermal setting that controls fluid flow in the reservoir. Further detailed structural analysis across all wells is necessary to fully understand the role of faults and fractures and the complex permeability structure of the field.

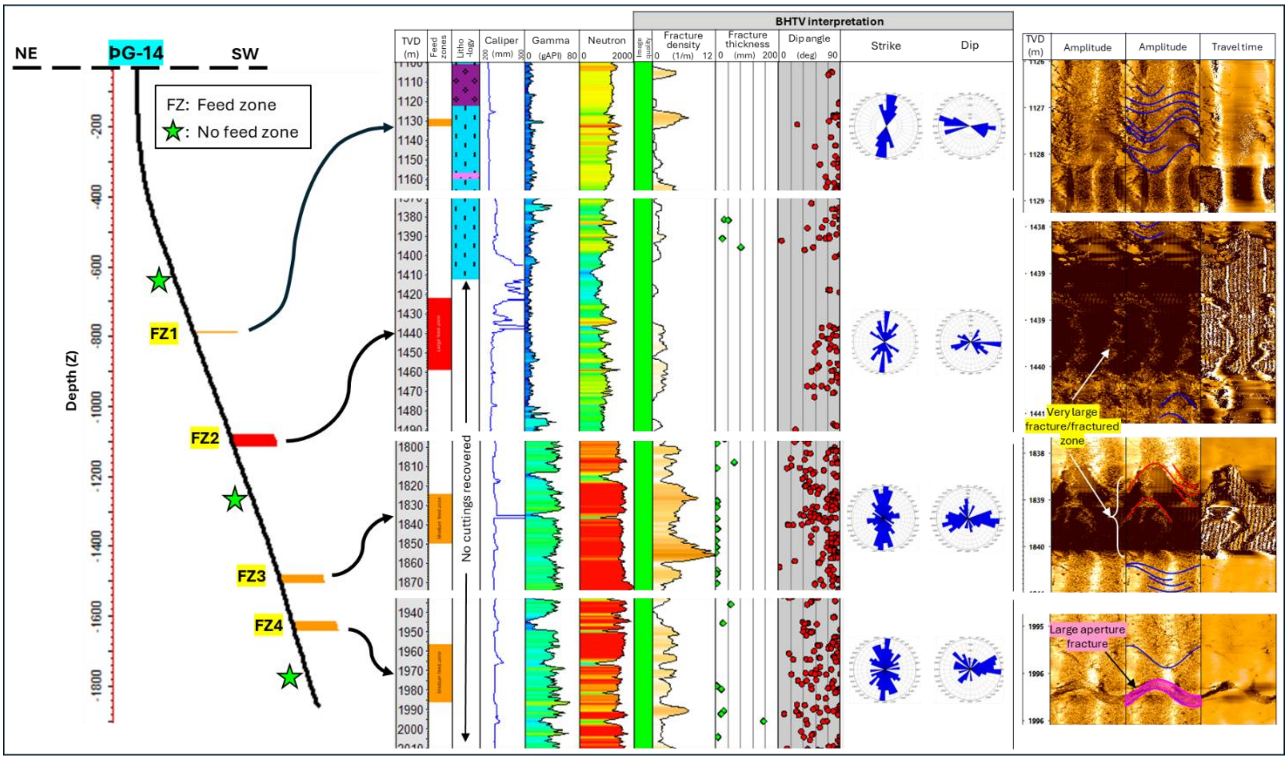

**Figure 5: Detailed analysis of the permeable feed zones in ÞG-14.**

## 4. CONCLUSIONS

This study provides a detailed analysis of the natural fracture system in the Þeistareykir geothermal field, focusing on their structural characteristics and influence on reservoir permeability. Using core observations, borehole image log interpretations, drilling, and well logging data, we characterise the fracture networks and permeable zones. Acoustic image logs reveal significant variability in fracture population, orientation, and density across different wells, lithologies, and depths. Fractures range in orientation from NNW-SSE, N-S, NNE-SSW to NE-SW, with dip angles varying from 0° to 90°. Hyaloclastites generally show lower fracture densities compared to basalts and intrusive rocks. The highest fracture densities are noted in deeper sections dominated by coarse basaltic lava flows or acidic intrusions. Fracture thickness across the field typically ranges between 1–50 mm. The analysis of fracture corridors in permeable flow zones highlights the complex and heterogeneous nature of structural controls on permeability. These initial findings will be refined through further structural analysis across other wells in the study area, along with the integration of field observations to better understand the structural controls on permeability and fluid flow in this geothermal system.

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