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Structural controls on permeability and fluid flow in the high-temperature Þeistareykir geothermal system in northern Iceland

Aastha[1]*, Dave Healy[1], Emma Bramham[1], Andy Nowacki[1], Nick Shaw[1], Anette Mortensen[2]
[1] Geosolutions Leeds, School of Earth and Environment, University of Leeds, United Kingdom
[2]Landsvirkjun, Reykjavik, Iceland
*aastha1@leeds.ac.uk

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1 INTRODUCTION

Structures such as fractures and faults play an important role as fluid flow pathways in geothermal reservoirs located in active tectonic regions. Fracture networks regulate the permeability, heat flow and associated geothermal activity in the subsurface (Rowland and Sibson, 2004). The Þeistareykir geothermal system in the Northern Volcanic Zone (NVZ) of Iceland is known to be structurally controlled. Geothermal drilling results reveal substantial variations in temperature and permeability across the field, with temperature reversal observed in some wells drilled within the main fault and fissure system (Jóhannsson, 2011; Kajugus, 2012). Fracture analysis based on borehole televiewer interpretation highlights the diverse structural character of the permeable feed zones, and fractures with similar characteristics but exhibiting no active fluid circulation in wells (Aastha et al., 2025). These observations strongly indicate that geothermal fluid movement in Þeistareykir is constrained by the fault and fracture networks. The detailed mechanisms of these structural controls can further refine our understanding of the distribution of heat and fluid flow within the geothermal system.

It is widely recognised that subsurface stress and stress heterogeneity play a critical role in controlling the permeability of fractures and faults in geothermal systems. Variations in the orientation and magnitude of regional stresses can strongly influence whether fractures act as conduits or barriers to fluid flow (Barton et al., 1995; Becker et al., 2019). Laboratory and field studies show that fracture permeability is highly sensitive to effective stress and may change dynamically with stress perturbations (Li et al., 2021; Min et al., 2004). In geothermal reservoirs, where permeability is largely fracture-controlled, understanding these stress–permeability relationships is essential for predicting fluid flow and reservoir performance. In this context, this study employs a simplified stress modelling approach to investigate the potential for fracture dilation and slip in the Þeistareykir geothermal field. Specifically, we focus on evaluating how the regional stress environment of the Þeistareykir fissure swarm affects fracture dilation and slip tendencies, which serve as proxies for permeability in the fractured geothermal reservoir.

2 METHODS AND RESULTS

Stress analysis is conducted under three representative tectonic stress regimes: (1) normal faulting, (2) transtensional faulting, and (3) strike-slip faulting (Figure 1). These regimes are selected to reflect the range of tectonic conditions expected in the Þeistareykir fissure swarm, situated within the Northern Volcanic Zone of Iceland. A strongly simplified stress model is adopted, in which principal stress magnitudes are estimated from typical geothermal reservoir depths and faulting styles rather than direct measurements. The vertical stress (σ_v) is approximated from the overburden pressure at a depth of 2 km, assuming an average rock density of 2,600 kg m^{-3}. The horizontal principal stresses (SH_{max} and Sh_{min}) are defined according to the assumed faulting regime (Zoback, 2007). Because this study focuses on relative stress effects rather than absolute magnitudes, only the ratio of principal stresses ($\sigma_1 : \sigma_2 : \sigma_3$) and their orientations are considered important for subsequent analyses.

The orientations of the maximum and minimum horizontal stresses are assigned in accordance with regional tectonic observations, including microseismicity and the dominant rift-parallel extension direction in Þeistareykir. The maximum horizontal stress (SH_{max}) is oriented approximately NE–SW, consistent with the spreading direction across the Northern Volcanic Zone and P-axis of the earthquake focal mechanism solutions in Þeistareykir (Drouin et al., 2017; Guðnason et al., 2023; Ziegler et al., 2016).

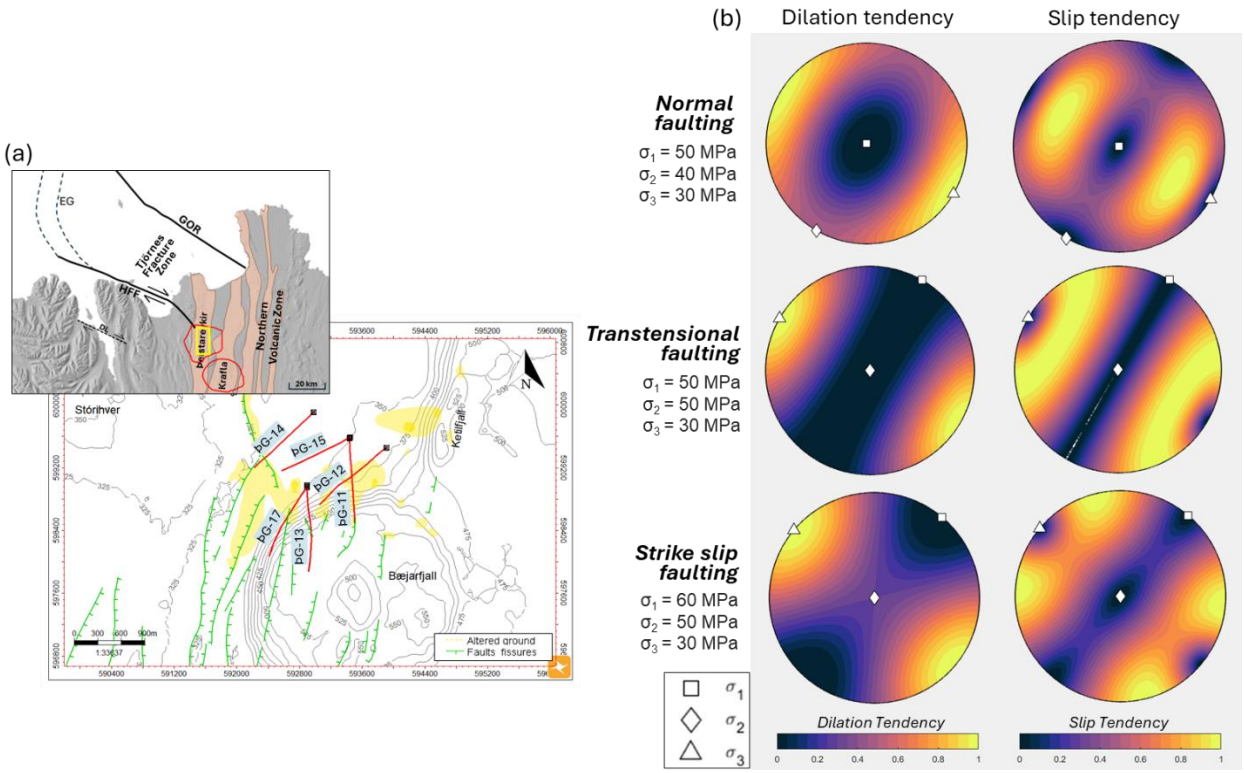


Figure 1. (a) Map showing location of the studied wells in the Þeistareykir geothermal area, located within the Northern Volcanic Zone, and intersected by the Húsavík-Flatley Fault (HFF). (b) Lower-hemisphere, equal-area stereonets showing modeled dilation tendency and slip tendency under the expected tectonic regimes in Þeistareykir.

Fracture orientation data are obtained from borehole televiewer image logs from six wells within the Þeistareykir geothermal field (Figure 1a, Aastha et al., 2025). This fracture dataset is analysed using the FracTend MATLAB toolbox (Healy, 2018) to compute dilation tendency (T_d) and slip tendency (T_s):

$$T_d = \frac{\sigma_1 - \sigma_n}{\sigma_1 - \sigma_3} \qquad T_s = \frac{\tau}{\sigma_n - P_f}$$

Dilation tendency quantifies the potential for fracture opening under a given stress state, indicating where tensile or extensional fluid pathways are most likely to form (Ferrill, 1999). Normalised slip tendency indicates the potential for shear reactivation along pre-existing fractures, representing zones where shear-induced permeability enhancement may occur (Morris et al., 1996). Both parameters range from 0 to 1, with higher values suggesting greater likelihood of fracture reactivation or opening, hence providing proxies for relative fracture permeability under different stress scenarios (Rogers, 2003).

The computed T_d and T_s values are plotted on lower-hemisphere, equal-area stereonets to visualize fracture orientations relative to the principal stress axes (Figure 1b). The stereoplots show a reasonable fit between the calculated stress regimes and the observed fracture orientations. In all wells, a large proportion of fracture planes exhibit elevated values of both dilation tendency (T_d) and slip tendency (T_s), indicating that many fractures are favourably oriented for either opening or shear reactivation under the imposed stress fields. Warm colour zones on the stereonets correspond to fractures with high T_d and T_s values (> 0.5), representing orientations most conducive to fluid flow. Under the normal faulting stress regime, the majority of fracture poles (> 70 % in most wells) show T_d > 0.5, implying a strong potential for extensional dilation (Figure 2). Conversely, the transtensional to strike-slip regimes yield the best correlation with slip tendency, with more than 80 % of fracture poles showing T_s > 0.5 (Figure 3). A combined analysis of both parameters reveals that over 50 % of the fracture poles exceed the threshold T_s,T_d > 0.5 in the normal faulting regime, except in well ÞG-15, where the proportion is lower indicating local stress heterogeneity (Figure 4). This indicates that fractures in most wells have a likelihood for both dilation and slip, suggesting conditions favourable for enhanced permeability and geothermal fluid circulation.

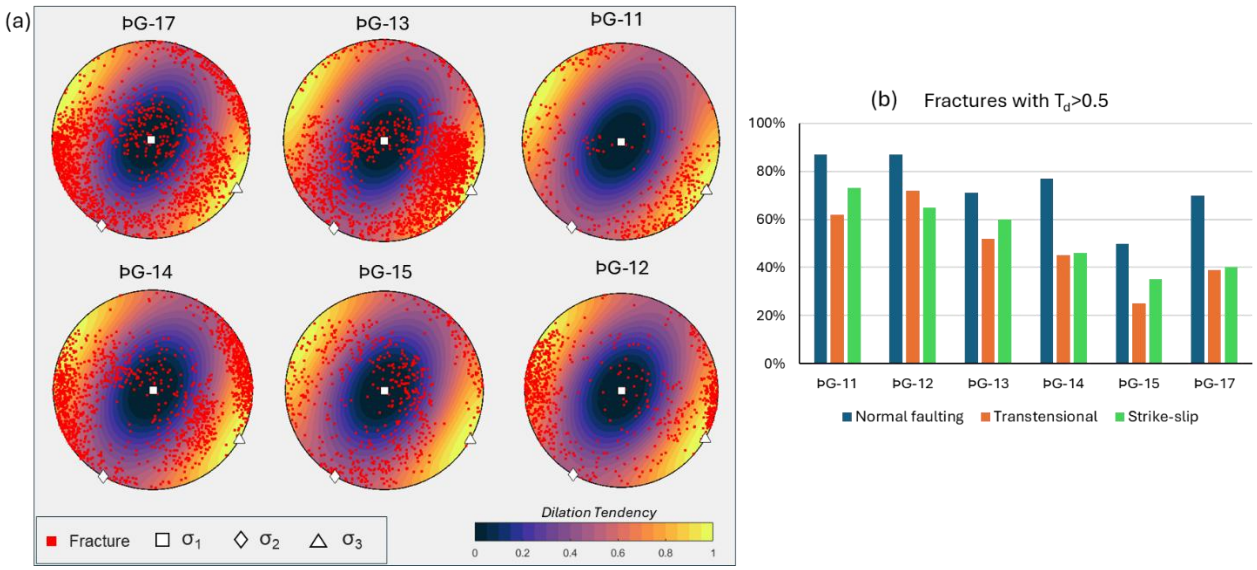


Figure 2. (a) Dilation tendency analysis of interpreted fracture data from six wells in the Þeistareykir geothermal field under normal faulting stress regime. (b) Plot illustrating the percentage of fractures in each well that are favourably oriented for dilation (T_d > 0.5) under the three different stress regimes considered in this study: (1) normal faulting, (2) transtensional, and (3) strike-slip faulting.

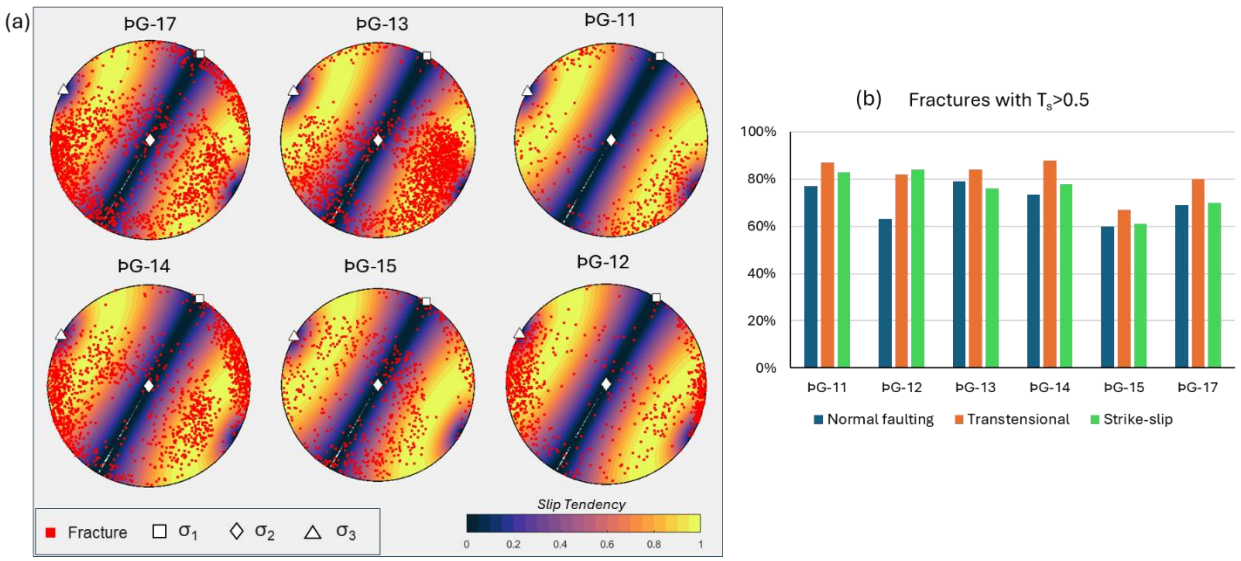


Figure 3. (a) Slip tendency analysis of interpreted fracture data from six wells in the Þeistareykir geothermal field under transtensional faulting stress regime. (b) Plot illustrating the percentage of fractures in each well that are critically stressed for slip (T_s > 0.5) under the three different stress regimes considered in this study: (1) normal faulting, (2) transtensional, and (3) strike-slip faulting.

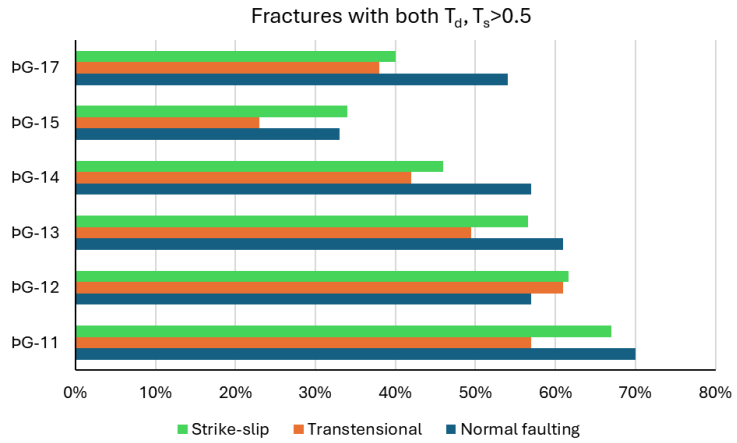


Figure 4. Percentage of fractures in each well exhibiting both high dilation and slip tendencies (T_s > 0.5 and T_d > 0.5).

3 DISCUSSION AND CONCLUSION

The results highlight the probable dominant role of the regional stress field in controlling fracture permeability and fluid flow in the Þeistareykir geothermal system. High correlations between fracture orientations and both dilation and slip tendencies indicate that the current tectonic regime promotes both fracture opening and shear reactivation. The normal faulting scenario best predicts dilation potential, while transtensional to strike-slip regimes align best with slip tendencies.

Despite the general agreement, some shallow-dipping fractures remain permeable despite being unfavourably oriented for either dilation or slip. These anomalies are not well explained by our stress models, and may result from additional mechanisms including chemical alteration and mineralisation that maintain or enhance fracture apertures (e.g. Laubach et al., 2004). These observations highlight the complex nature of permeability development governed by an interplay of tectonic, lithologic, and geochemical factors. While regional stress is a dominant control on fluid pathways, permeability in Þeistareykir cannot be explained solely by stress-controlled mechanisms. To better constrain the bulk permeability within the Þeistareykir geothermal system, future work will focus on integrating these findings into a 3D discrete fracture network model. Such modeling would incorporate fracture geometry, orientation, apertures and connectivity derived from borehole and field data, together with the present stress field, to improve predictions of fluid pathways and support sustainable resource management.

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