Can Hydraulic Fractures in Granitic Rock Remain Permeable Without Proppants?

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Keywords: Stimulation, hydraulic fracturing, EGS, FORGE, shear slip, dilation, permeability, self-propped, proppant

ABSTRACT

An alternative design in multi-stage hydraulic fracturing for EGS is to create closely-spaced fractures that undergo shear deformation due to their mutual stress shadow. It is shown that by sequentially placing a number of hydraulic fractures close to one another, the induced shear leads to self-propping. The primary motivation for this approach is to avoid proppant use, which is a challenge under high temperature conditions. A few field and laboratory cases are presented to illustrate that fractures in hard granite rocks remain permeable even when they experience high stress conditions. The data shows that if shear deformation can be induced on neighboring hydraulic fractures, it can promote self-propping, lowering the near wellbore pressure drop and providing a permeable pathway between the injection and production wells. This would avoid the challenges associated with proppant availability and potential complications related to proppant transport into the surface facilities.

1. INTRODUCTION

Multi-stage hydraulic fracturing from multiple isolated perforation intervals provides an opportunity for systematic stimulation of geothermal reservoirs. The technique is in contrast to stimulation injections at pressures below the minimum stress into a long openhole section aimed at rock mass stimulation via primarily shear slip on natural fractures. However. many field observations from petroleum and geothermal as well as mining cases show that even during plug and perf hydraulic fracturing jobs, natural fractures and faults across different scales are activated leading to the formation of a stimulated reservoir volume with enhancement permeability. Recent experience at Utah FORGE and elsewhere shows evidence of unintended or unplanned shear stimulation, whereby activated shear fractures make a major contribution to flow rate and path (RESMAN Report, 2024, Lee and Ghassemi, 2025).

2. THE CASE FOR PROPPANT AND NEW DEVELOPMENTS

Whether hydraulic fractures can remain self-propped and permeable without proppant use is a significant question with important practical consequences in geothermal reservoir development This is because the experience in unconventional resources (Coulter and Wells, 1971; Cook, 1973, Montgomery and Smith, 2010; Shah, 2010, Kurz et al., 2013) suggest that proppants are needed to keep hydraulic fractures open to sustain production from the reservoir. Although the selection and use of proppants in lower temperature geothermal wells is an economic factor of concern, the issue becomes highly critical when developing higher grade and higher temperature geothermal resources. This is because many challenges arise, such as lack of proppant material that can survive and function at high temperatures under stress and corrosive hydrothermal conditions. Research is under way to test available products and to potentially develop new solutions for enhanced geothermal systems (Mattson et al. 2016, Jones et al., 2014; Ko and Ghassemi, 2023; Sutrahdor and Ghassemi, 2025; Rahman et al. 2026). Such efforts can yield solutions to proppant selection challenges; however, the associated costs do impact projects economically. It is therefore of interest to concomitantly explore other novel approaches to permeability retention, including revising the multi-stage HF to intentionally create shear displacement on closely-spaced neighboring fractures to promote dilation.

3. SHEARING OF HYDRAULIC FRACTURES CAN LEAD TO SELF-PROPPED PERMEABLE FRACTURES

Numerous studies in different geomechanics areas have shown that slip on natural fractures and faults generates dilation that can lead to permeability increase and its retention over long periods of time. Evidence suggests this can occur, even under prevailing thermo-chemo-mechanical conditions in EGS. If hydraulic fractures can be designed to undergo shearing, then the potential for permeability by self-propping can be considered as a permeability conservation mechanism to supplement proppant or negate their usage.

To illustrate the concept of induced shearing on neighboring fractures, consider the simultaneous propagation of 3 fractures from perforation clusters as simulated in Kumar and Ghassemi (2016). Consider three fracture clusters each having one initially planar fracture orthogonal to the wellbore axis with initial radius equal to 1 meter. The separation distance between the fractures is kept equal to 3 m and the rock properties and the in-situ stresses condition are as listed in Kumar and Ghassemi (2016).
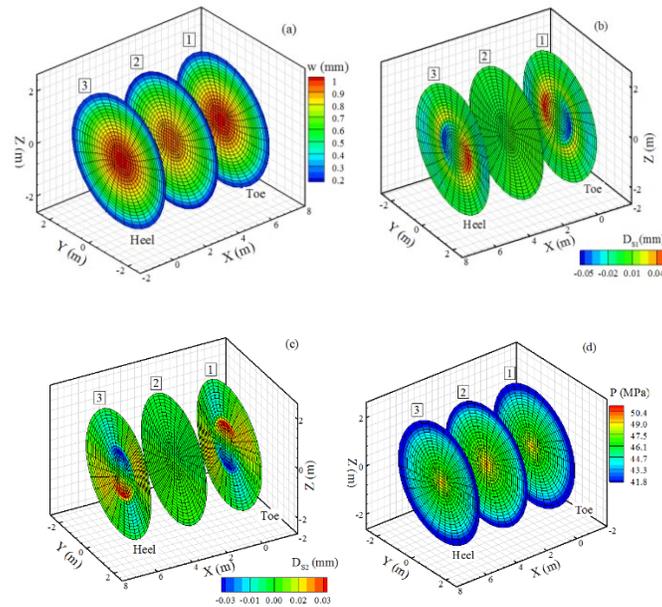
Figure 1. Simultaneous propagation of three fractures: (a) distribution of fracture opening, (b) distribution in-plane shear displacement, (c) distribution out-of-plane shear displacement, (d) distribution of fluid pressure (simulated time = 27 min).

The total fluid injection (slick water of viscosity 0.005 Pa.s) was at a rate of 0.48 m³/s. The fluid is dynamically distributed among the fractures depending on their transmissibility, relative locations, and perforation condition at the wellbore. Figure 1 shows the results, after the 14th propagation step, in terms of fracture opening, in-plane shear displacement, out-of-plane shear displacement, and the fluid pressure distribution. It can be observed from figure that the outer fractures (Frac.1 and Frac.3) are experiencing shear deformation (the induced shear stresses on the middle fracture by exterior ones cancel).

The mutual interaction and produced shear stresses also occur when the fractures are created sequentially. This has been observed experimentally (Kear, et al., 2013) and in modelling of the experimental results (Sesetty and Ghassemi, 2017). The experiments had created sequentially 4 hydraulic fractures spaced at 15 mm with initial half-length of 3 mm. Two cases were considered to study the behaviour of hydraulic fracture near a pre-existing fracture. In the first case, fractures open against zero minimum in-plane principal stress and, in the second case minimum in-plane principal stress is kept at 14.4 MPa, with the differential stress in both cases being equal. Experimental results (Figure 2) for case-1 show that, initiating Fracture-2 in the presence of Fracture-1 lead to "curving in" of Fracture-2 and eventual coalescence with Fracture-1 (Bunger, et al., 2011 and Kear, et al., 2013). Numerical results (Figure 2, right) also indicate similar behaviour.
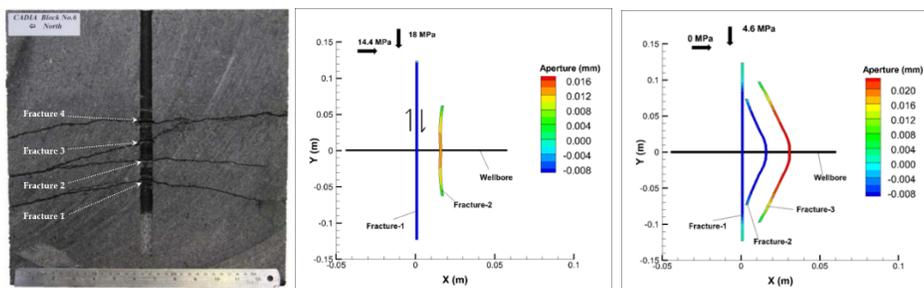

Figure 2. Experimental result (Kear, et al., 2013) shows Fracture-2 and Fracture-4 coalescing with Fractures 1& 3, respectively. Numerical results of block experiment for case-2 shows Fracture-2 turning away from Fracture-1 due to slip induced dilation on Fracture-1 (b) Experimental results (Kear, et al., 2013) show fractures growing nearly parallel to each other.

In case-2, the applied minimum stress suppressed shear slip and re-opening of older fractures. So, fractures 1, 2 & 4 grow almost parallel to each other. The results obtained from numerical model are shown in Figure 2a; minor shear slip occurs on fracture 1 due to induced shear stresses from fracture-2. Shear induced dilation on fracture 1 is likely the cause of the slight curving of Fracture-2. The above experimental and modelling results do suggest that it is not only feasible to create closely spaced hydraulic fracture but also, they induced

shear displacement on each other which can potentially lead to self-propped hydraulic fractures. In addition to modelling, field and laboratory data provide additional support for the concept.

3. Field Data: Cases of Conductive Faults in Crystalline Rock

Three case histories are presented below that describe   major fractures or faults, having experienced shear, remaining hydraulically permeable. One case is given that demonstrates how opening of a hydraulic fracture can induce shearing on offset portions of the fracture plane. These cases support the idea that if unpropped hydraulic fractures are generated at the Utah FORGE site with sufficient conductivity to support economic circulation, they can be expected to remain conductive for extended periods of time.

The first case involves a fault that was intercepted by drilling at a geothermal site in a deep granite and the second case involves a fault that was sufficiently permeable to blunt hydraulic fracture growth at a mining preconditioning test site in an andesite orebody. Both cases are evidence that conductive fractures / faults exist in nature in crystalline rock masses.

Case 1: The circulation between vertical wells at the Habanero site of Geodynamics occurred through a sub-horizontal faulted zone that was highly conductive. This case shows that shear in granite, if sufficiently strong, can produce high conductivity fractures and fracture zones. This size and conductivity are likely not reproducible by using HF, but it shows unpropped structures at 4.2 km depth in granite can be highly conductive.

After stimulation, the circulation between two of the Habanero wells achieved rates of up to 53 L/s (20 bbl/min). The stimulation involved injecting water at pressures up to but not exceeding the minimum in-situ stress and resulted in thousands of microseismic events being generated in a cloud along the fault zone. The fault zone connecting between the vertical wells dipped at 10° to the west south-west from horizontal. The fault was determined by acoustic logs to consist of a conductive zone approximately 1 m thick and was located at 4,180 m (13,710 ft) depth in Habanero 1 (Hogarth et al., 2016). The fault and circulation test were modelled in a geothermal reservoir simulator using a permeability of 600 millidarcy (mD) in the x direction and 1,200 mD in y direction (Llanos et al., 2015). Figure 3 (from Llanos et al., 2015) shows the well layout and the stimulated fracture extent as determined from microseismic events. The x-y principal permeability grid direction is also shown. The main grid is in meters and is the state grid system in the area of the wells. The blue fault shown is a low-permeability subvertical fault that limited stimulation to the south and east. The mud ring shown in Figure 3 was generated by drilling fluid lost into the fault as the well was drilled.
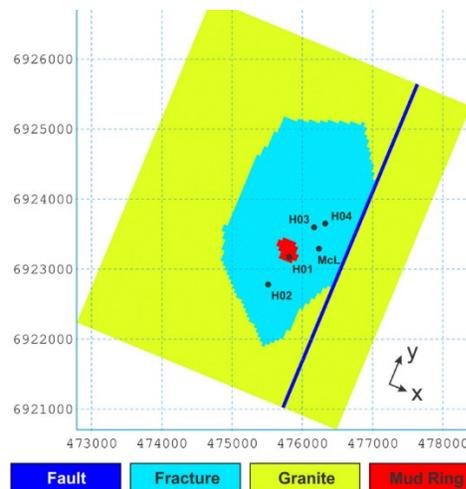

Figure 3: Plan view of Layer 7 in the numerical model showing the stimulated fracture, mud damage zone, and impermeable fault. (For interpretation of the references to the colors in the text, the reader is referred to the web version of this article) From Llanos et al. (2015).

Figure 4 is from Bendall et al. (2014) and shows the overall shape of seismic events recorded during stimulation at the Habanero site. The events are associated with the Habanero Fault which was enhanced in conductivity by the shear stimulation, as modelled in Figure 3 (Llanos et al., 2015), and provided the conductive connection during later circulation testing.
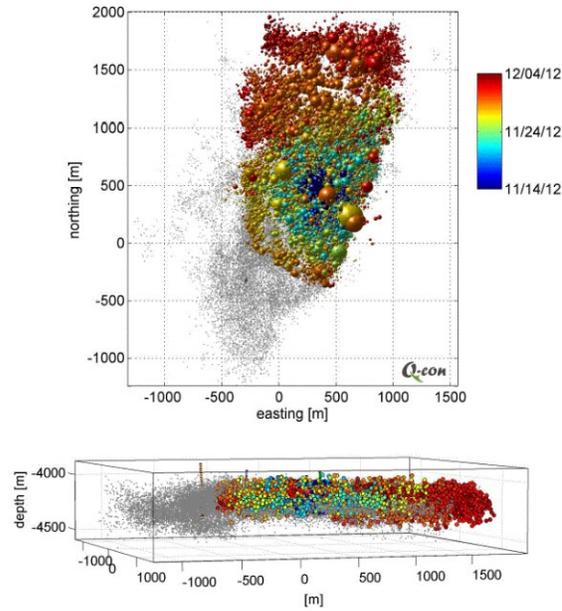
Figure 4: (top) Hypocenter locations of the induced seismicity from the 2012 stimulation in Habanero 4. Each seismic event is displayed by a globe scaled to the event magnitude. Colour encoding denotes occurrence time according to legend. Previous seismic activity is indicated by grey dots. (bottom) Hypocenter locations in side-view looking from ESE. Seismic events are displayed as dots with colour encoding denoting the origin time. (From Bendall et al., 2014).

Case 2: At Salvador mine, the HFs were placed in the central borehole, HF02. They were determined to be subvertical, dipping at 75 degrees to the west and grew with a north-south strike direction. Their growth and orientation were measured by monitoring boreholes (the M holes) containing instrumentation as shown in Figure 5 below. To the south, no fracture growth was detected by monitoring holes M3 and M4. A fault existed to the south and one HF at least intersected this fault. The fracturing fluid, which was a crosslinked gel, was carried along this fault to the east and was found leaking from the fault into a tunnel approximately 120 m away, as shown in Figures 5. It seems this conductive fault served to block HF growth to the south. This site was in the andesite orebody at Salvador mine. Figure 5 (right) contains a photo of the red crosslinked gel on the floor of the tunnel where it leaked out of the fault with this location indicated by the green circle in Figure 5 (left).
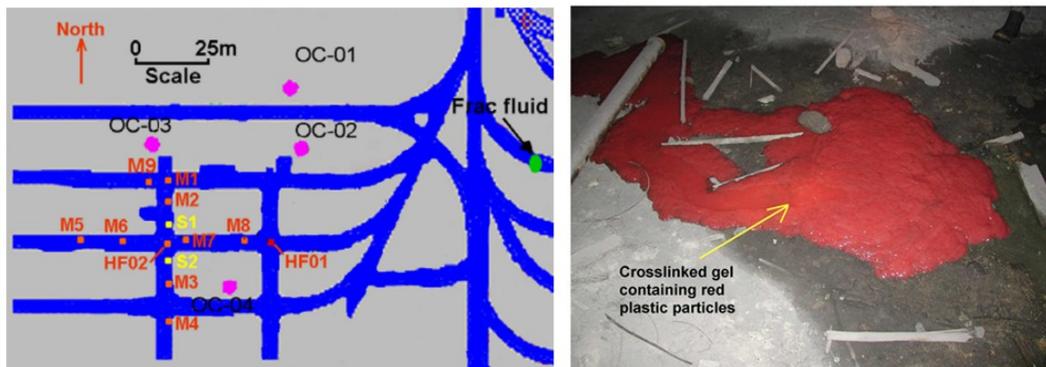

Figure 5: Left: Plan view of site on 2600 level showing injection and monitoring holes. (From Chacon et al., 2004). Right: Crosslinked gel coming from the floor at a location about 120m east of HF02. (From Chacon et al., 2004).

Case 3: A mineback and fracture mapping project was completed in the naturally fractured orebody at Northparkes mines. The fractures that formed were mapped along the tunnel walls after mining (Jeffrey et al., 2009) and were found to contain offsets or steps where they were diverted by and eventually crossed natural fractures in their path. Fracture 8 at this site was analysed numerically in some detail to better understand how such a fracture geometry responds mechanically when pressurized (Jeffrey et al., 2010). One finding of this analysis was that the primarily opening portions of the fracture induce shear deformation on the offset portion and the opening of the offset portion

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induces shear on the primarily opening mode portion of the fracture. Figure 6 shows a sketch of Fracture 8 as mapped and the numerically calculated deformation and coupling between opening and shear. This mechanism is expected to act along any hydraulic fracture growing through a naturally fractured rock mass.
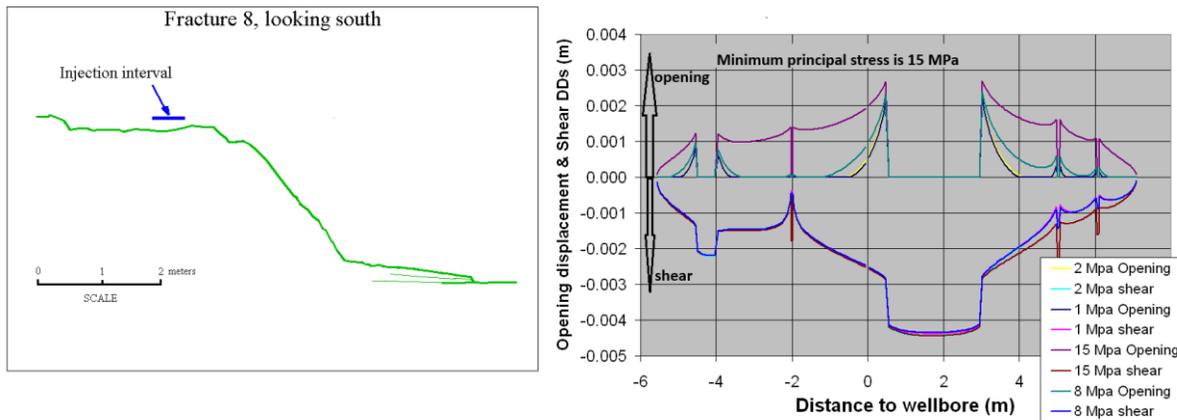

Figure 6: Left: View of fracture 8 as mapped on south wall of tunnel. Right: Numerical simulation of Fracture 8 inflated by uniform pressure as indicated in legend. Opening and shear displacements are shown (After Jeffrey et al., 2010).

We have also carried out a laboratory experiment to study the impact of a small amount of shear deformation on fracture permeability and its evolution with time. The test used a cylindrical Sierra White granite sample (length of 84mm and diameter of 38mm). The specimen is instrumented with two axial LVDTs and one radial LVDT. Based on these measurements and knowing the applied stress, the normal and shear stresses and the corresponding displacements during the test are calculated. The sample geometry and test setup is shown on the right side of Figure 7 (Ye and Ghassemi, 2018). The sample was placed in the chamber and the confining pressure was increased to 4000 psi. Steady fluid flow in the fracture was established and the baseline permeability was measured at room temperature. The differential stress was increased gradually until the dilation point was reached. The axial stress was then lowered some to ensure dilation would not further occur. The temperature was then increased to 180–200 °C at a controlled rate while maintain constant confining pressure/axial stress and flow conditions.
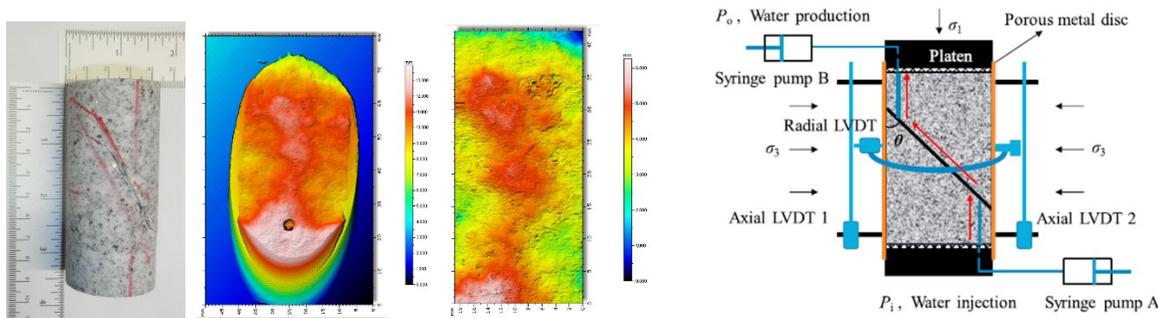

Figure 7. The fracture sample and test configuration. The fracture tested has a JRC of 16, similar to a hydraulic fracture in granite.

Permeability was measured in stages as temperature increased. Changes in permeability reflect the fracture response to thermal loading while mechanical conditions remained steady.

As shown in Figure 8, two axial-stress drops were observed during the test, both associated with fracture-sliding events. The first occurred at approximately 20,000 s (5.5 hours) and at that point the actuator was immediately switched to displacement control by stopping the actuator pump. After further reducing the applied force to maintain a safe condition, the actuator pump was resumed in constant-stress control mode. The second stress drop occurred later, around 50,000 s, during evening hours when no personnel were present. At that point, the syringe pump (actuator pump) had quickly depleted its available fluid, causing an automatic transition from constant-stress control to displacement-control mode.

Fracture slip and dilation significantly increased permeability. When dilation was triggered by the temperature increase to 160–170 °C, a sharp spike in permeability was observed, reflecting the sudden opening and sliding of fracture surfaces. Over time, however, permeability gradually declined, but it remained higher than pre-dilation values, indicating that slip and dilation resulted in stimulation.

After remaining dilated for ~8 hours at high temperature (180–200 °C), the fracture surfaces did experienced softening, likely associated with weakened asperity contacts, and because the axial load was still high, additional shear dilation is observed. However, post-mortem observation suggest that the produced rock fines plugged the exit hole in the lower sample platen so that the measured permeability continuously declined until the test ended with sample failure and seal breakage.
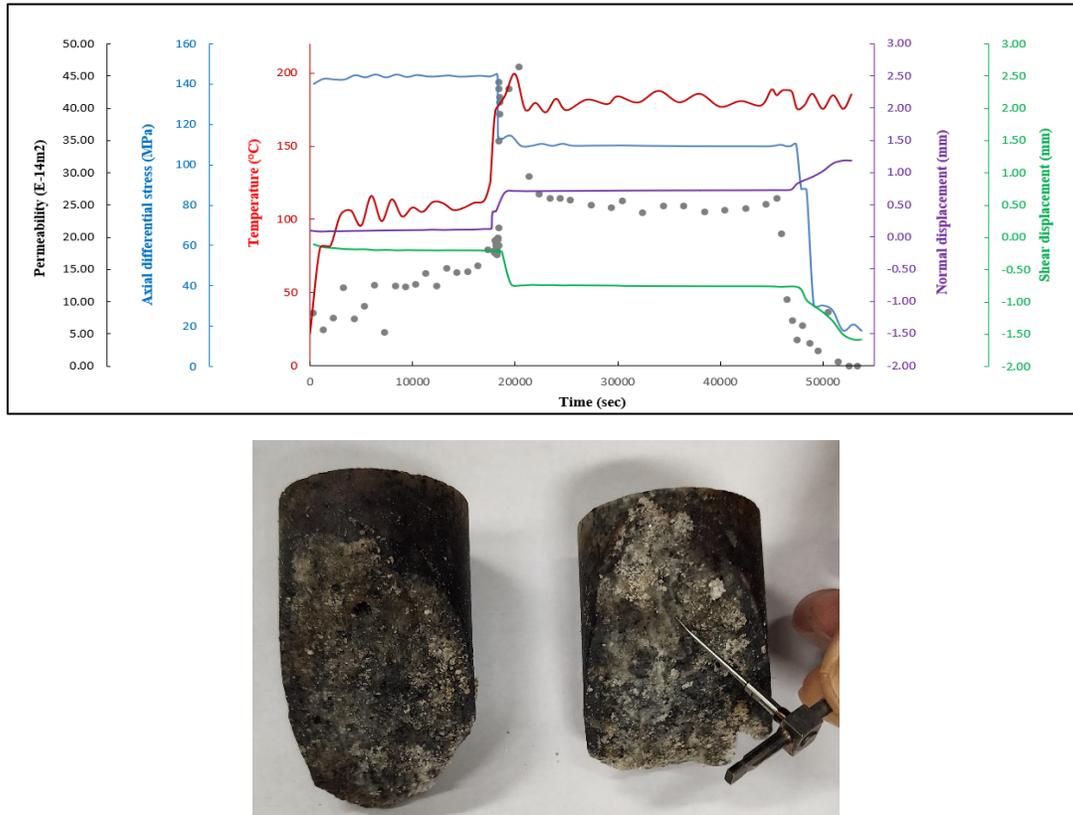

Figure 8. Results of a heated shear test on Sierra White granite. Red curve: Temperature changes over time; the curve fluctuates slightly due to thermal stabilization, first increasing from 22 °C to 100 °C and stabilized at 100 °C for ~5 hours, then rising to 180 °C ~ 200 °C and remaining stable until the end. Blue curve: Axial differential stress, initially held constant at 140 MPa, below the rock's dilation strength. Previous triaxial tests show that under room temperature, the rock remains stable under this stress. Normal (purple curve) and shear (green curve) displacement: Represent fracture deformation. Permeability values are shown using black dots. Note that permeability is retained for the test duration. The drop in permeability near the end of the test is caused by rock fines plugging the exit hole as shown in the lower figure. A longer experiment is planned to further assess the long-term retention of the shear-induced permeability.

4. CONCLUSIONS

Hydraulic fractures generate shear as they form, both along themselves and along offset hydraulic and natural fractures. By sequentially placing a number of hydraulic fractures close to one another, we propose to induce sufficient shear along them to produce self-propping. The primary motivation in avoiding proppant is to avoid production problems that arise as it crushes or is geochemically altered and degraded. Three field cases are discussed to illustrate that fractures and faults can exist, with natural or induced permeability, in hard granite rocks, even at great depth where such fractures are subject to high stress conditions. In addition, results from a laboratory test show permeability increase with shear deformation over a range of temperatures. Therefore, if shear deformation can be induced on neighboring hydraulic fractures, it can promote self-propping, lowering the near wellbore pressure drop and providing a permeable pathway between the injection and production wells. This would avoid the challenges associated with proppant availability and potential complications related to proppant transport into the surface facilities. The operational needs for creation of closely-spaced and sheared hydraulic fracture do provide for some challenges but laboratory and field test in mines indicate its feasibility. Aspects of the stimulation and the resulting flow path and heat extraction potential are discussed in an accompanying paper (Ratnayake et al., 2026).

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