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Reexamining In-situ Stress Interpretation Using Laboratory Hydraulic Fracturing Experiments

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ABSTRACT

Knowledge of in-situ stress is important to many subsurface science and engineering problems. The magnitude of minimum principal stress (S_3, or S_{hmin} in most cases) is generally measured through hydraulic fracturing tests. Several methods have been suggested to interpret S_{hmin} using the pressure data during the injection and/or shut-in phases of a hydraulic fracturing test. However, S_{hmin} interpreted from different methods are often not consistent with each other and could lead to large uncertainty in net pressure determination. In this paper, we present a laboratory hydraulic fracturing experiment conducted on a granite block with a side length of 13 inches under controlled true-triaxial stress conditions. In the experiment, the injection scheme includes a hydraulic fracturing cycle followed by a few fracture propagation cycles and several diagnostic fracture-injection/falloff tests (DFIT). The wellbore pressure and the acoustic emission (AE) activities during fluid injection and shut-in were concurrently measured to monitor fracture initiation, propagation, and closure within the span of fluid injection and shut-in. The pressure data were used to interpret S_{hmin} using different HF-based methods. The results show the spatial-temporal evolution of AE activities is well associated with fracture propagation. In addition, the overall geometry of the hydraulic fracture created in our experiment is planar, however, a clear non-uniform topography is evident with heterogeneous distribution of asperities. The stress interpretation results from DFIT test demonstrate fracture reopening pressure generally provides a very good estimate of $S_{hmin.}$ Fracture closure was observed using the so-called tangent method in all DFIT tests and the 1st, earlier signature tends to offer a better stress estimate when compared to the traditional tangent method using a signature close to the highest point on the GdP/dG curve. The signature corresponding to the change in the system stiffness or compliance is observed although not consistently. It is found that the non-uniform fracture topography significantly impacts fracture closure behavior and the associated stress interpretation. Considering the complex nature of hydraulic fracturing in the subsurface, multiple techniques may need to be integrated for the determination of S_{hmin}, nevertheless, the results demonstrate that the traditional tangent method clearly underestimates the stress value thus overestimating the net pressure.

1. INTRODUCTION

Understanding the magnitude and orientation of in-situ stress is important to many subsurface science and engineering problems. In the development of an Enhanced Geothermal System (EGS), the knowledge of in-situ stress impacts several aspects from drilling and hydraulic stimulation to induced seismicity. In most geological settings within the Earth's upper crust, we can assume that the three principal stresses are vertical stress (S_v), and two horizontal principal stresses (S_{hmin} and S_{Hmax}). The magnitude of minimum principal stress (S_3, or S_{hmin} in most cases) is generally measured through hydraulic fracturing tests, such as DFIT, minifrac test, leakoff test, and the extended leak-off test (XLOT). In hydraulic fracturing (HF) based stress estimation, a relatively small volume of high-pressure fluid is injected into the wellbore to create a hydraulic fracture, and then the well is shut in. The wellbore pressure data during the injection and/or shut-in phases are monitored to interpret the S_{hmin}. Fracture reopening pressure (P_r), instantaneous shut-in pressure (ISIP), and closure pressure (P_c) are widely used to determine the magnitude of S_{hmin}. Conventionally, closure pressure is estimated from the pressure fall-off data during the shut-in phase by determining the signature of fracture closure on the semi-log derivative of pressure with respect to the G-function or G-time (Mukherjee et al., 1991; Barree & Mukherjee, 1996). As an alternative to the conventional tangent method, several studies have used the change in system stiffness (Raaen et al., 2001; Raaen et al., 2005) or compliance (McClure et al. 2016; McClure et al. 2019) at fracture closure to determine the closure pressure. Often, stress estimations from the tangent method and the compliance method are not consistent with each other (e.g., McClure et al. 2016; Craig et al., 2017; Ehlig-Economides & Liu, 2018; McClure et al. 2019), resulting in uncertainty in net pressure determination and hydraulic fracturing design. In some field DFIT tests the tangent method tends to underestimate closure pressure (e.g., McClure et al. 2019), while in many other cases, there is no clear signature of the fracture closure (e.g., Virues et al., 2022). In addition, it is also found the interaction of natural fractures and hydraulic fracture likely complicates fracture closure and causes difficulty in the associated stress interpretation (Kamali & Ghassemi, 2019), especially in highly fractured rock masses such as geothermal reservoirs with abundant natural fractures.

In order to explore the underlying physics and address the inconsistencies in HF-based stress estimation, we conducted a series of laboratory hydraulic fracturing experiments under true-triaxial stress conditions. The pressure data and the acoustic emission response during the injection and shut-in phase of an injection cycle are concurrently monitored to determine fracture closure and estimate the closure pressure for stress estimation. In this paper, we present the results from one laboratory hydraulic fracturing experiment conducted on a granite block with a side length of 13-inch to examine the following key points: (1) monitoring fracture growth through high-resolution acoustic emission or seismic activities; (2) examining S_{hmin} determination through various HF-based methods; (3) deciphering the impact of fracture surface topography on fracture closure and its signature in the pressure fall-off data.

2. EXPERIMENTAL METHODS

The sample used in this experimental study is a Sierra White granite block with a side length of 13 inches (Figure 1(a)). The relevant geomechanical properties of Sierra White granite can be found in our previous papers (Ye & Ghassemi, 2018). The experiment was performed in our in-house true-triaxial testing system (Figure 1(b)) under controlled stress conditions of 1250 psi minimum principal stress, 2000 psi intermediate principal stress, and 3000 psi maximum principal stress (Figure 1(c)). More details regarding the testing system and general testing procedure can be referred to by Hu and Ghassemi (2020, 2021). Due to the minimum principal stress being in the vertical direction with a value of 1250 psi, it is expected to induce a horizontal fracture during hydraulic fracturing and achieve S_{hmin} estimations close to 1250 psi. The injection fluid used in this experiment is low-viscosity mineral oil. In the experiment, the injection scheme includes one hydraulic fracturing cycle followed by two fracture propagation cycles and several diagnostic fracture-injection/falloff tests (DFIT). The wellbore pressure and the acoustic emission (AE) activities during fluid injection and shut-in were concurrently measured to monitor fracture initiation, propagation, and closure for each cycle. The pressure data were then used to interpret S_{hmin} based on different HF-based methods. After the test, the two surfaces of the created hydraulic fracture were scanned to describe the fracture surface topography.

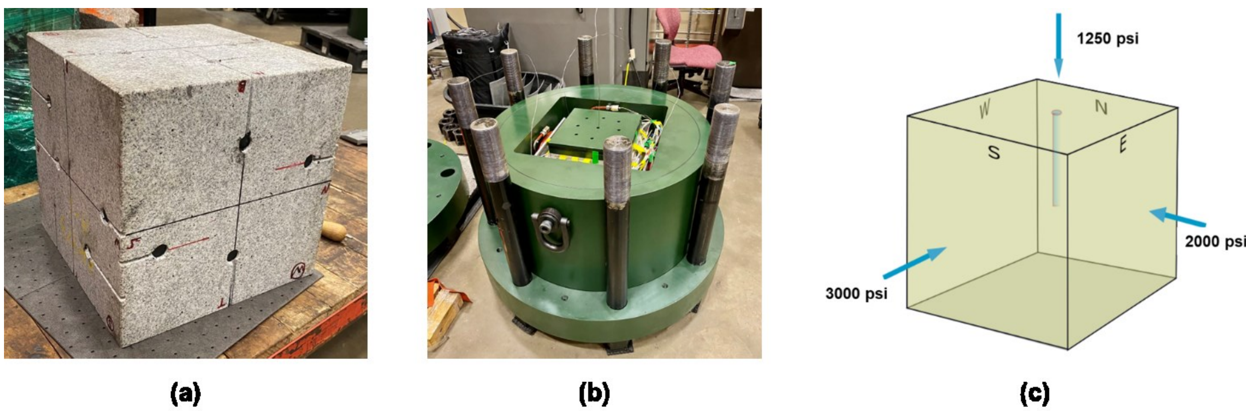

Figure 1: (a) cuboid Sierra White granite sample used for laboratory DFIT experiment; (b) in-house true-triaxial testing system; (c) the controlled stress conditions.

3. EXPERIMENTAL RESULTS

3.1 Hydraulic Fracturing in Cycle 1

The pressure data and AE response during the hydraulic fracturing cycle (Cycle 1) are shown in Figure 2. Fracture initiation suggested by induced AE events occurred at 226 s with an injection pressure of 1790 psi, while breakdown occurred at 353 s with an injection pressure of 3524 psi. This indicates the hydraulic fracture initiated significantly earlier than the borehole breakdown. In addition, most of the AE events were induced at the interval between breakdown and fracture closure (roughly indicated by ISIP in Figure 2), which suggests the fracture continued to propagate during the shut-in stage until the fracture was closured.

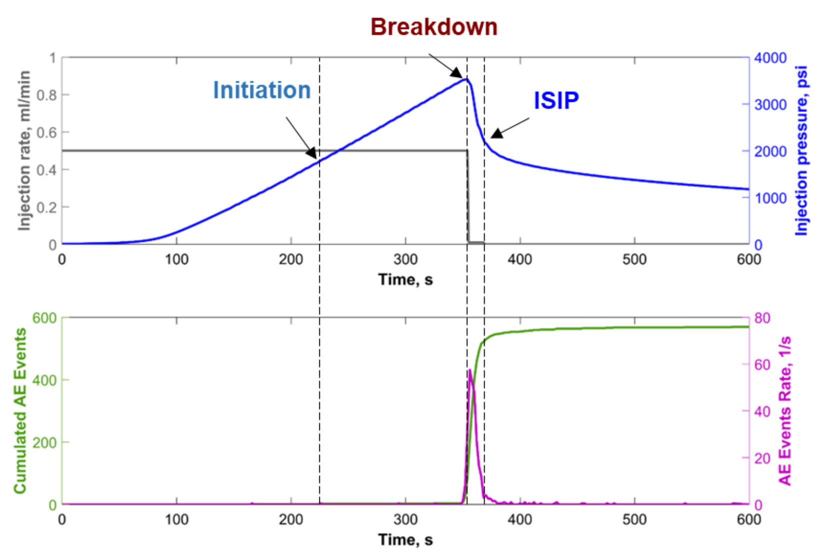

Figure 2: The temporal evolution of injection pressure (blue), injection rate (gray), cumulated AE events (green), and AE event rate (purple) during the 1st hydraulic fracturing cycle.

3.2 Fracture Propagation in Cycle 2 and Cycle 3

After the 1st hydraulic fracturing cycle, another two fracture propagation cycles were performed to propagate the hydraulic fracture from the wellbore for DFIT tests and stress analysis. The pressure transient and AE responses of Cycle 2 and Cycle 3 are illustrated in Figure 3 and Figure 4 respectively. The overall hydro-seismo responses of the two fracture propagation cycles are quite similar. It is noticed that two rollovers on pressure transient curves. The 1st rollover on the pressure curve indicates the slope decline of pressure increase due to the reopening of the hydraulic fracture, while the 2nd rollover on the pressure curve suggests the "breakdown" caused by the new fracture area created or propagated. It is noticed that no AE events were induced during fracture reopening process until fracture propagation was initiated. The initiation of fracture propagation is indicated by the initiation of AE events. From the pressure curve and AE rate curve, it is observed that fracture starts to propagate before the breakdown. In addition, most of the AE events are induced between fracture propagation and shut-in. However, compared to the hydraulic fracturing cycle, more AE events were induced during the shut-in phase, which is likely related to more fluid leaking off from the fracture and causing microcracking in the matrix with the accumulated fluid leak-off during the three cycles of injection. The fracture propagation pressure is about 1611 psi in Cycle 4, while the fracture propagation pressure is around 1530 psi.

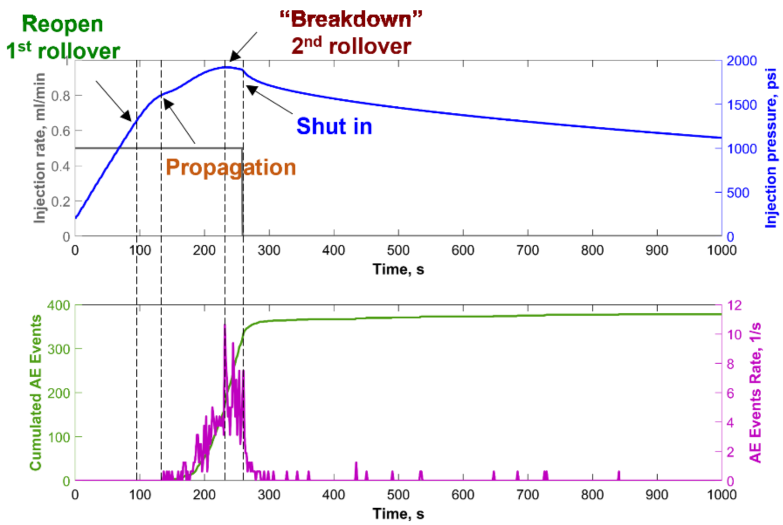

Figure 3: The temporal evolution of injection pressure (blue), injection rate (gray), cumulated AE events (green), and AE event rate (purple) during the 2nd fracture propagation cycle.

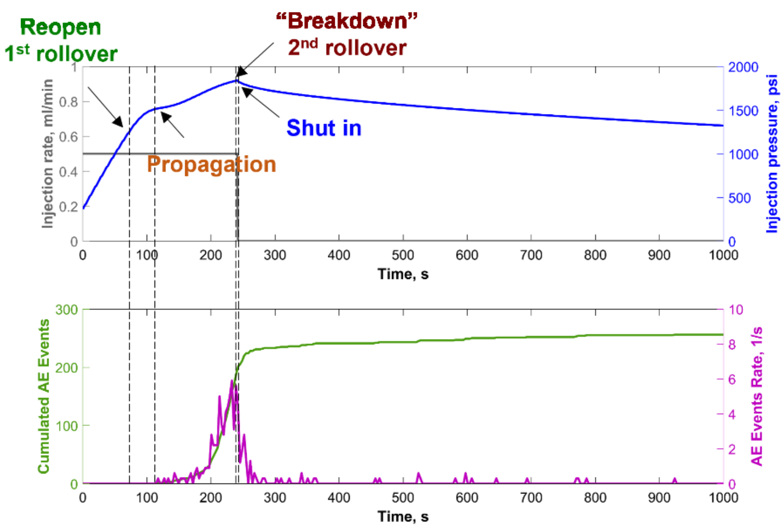

Figure 4: The temporal evolution of injection pressure (blue), injection rate (gray), cumulated AE events (green), and AE event rate (purple) during the 3rd fracture propagation cycle.

3.3 Fracture Initiation and Propagation Inferred from Acoustic Emissions

Acoustic emission (AE) is a widely used technique for monitoring hydraulic fracture in the laboratory and the location of AE events can reflect fracture growth and the overall fracture geometry. The location of AE events in the hydraulic fracturing cycle (Cycle 1) and the two fracture propagation cycles (Cycle 2 and Cycle 3) are shown in Figure 5. It is found that the overall geometry of the hydraulic fracture is flat and planar. In Cycle 1, a near penny-shaped hydraulic fracture was created by fluid injection. In the following fracture propagation cycles, fracture propagation is asymmetric and tends toward the northwest direction.

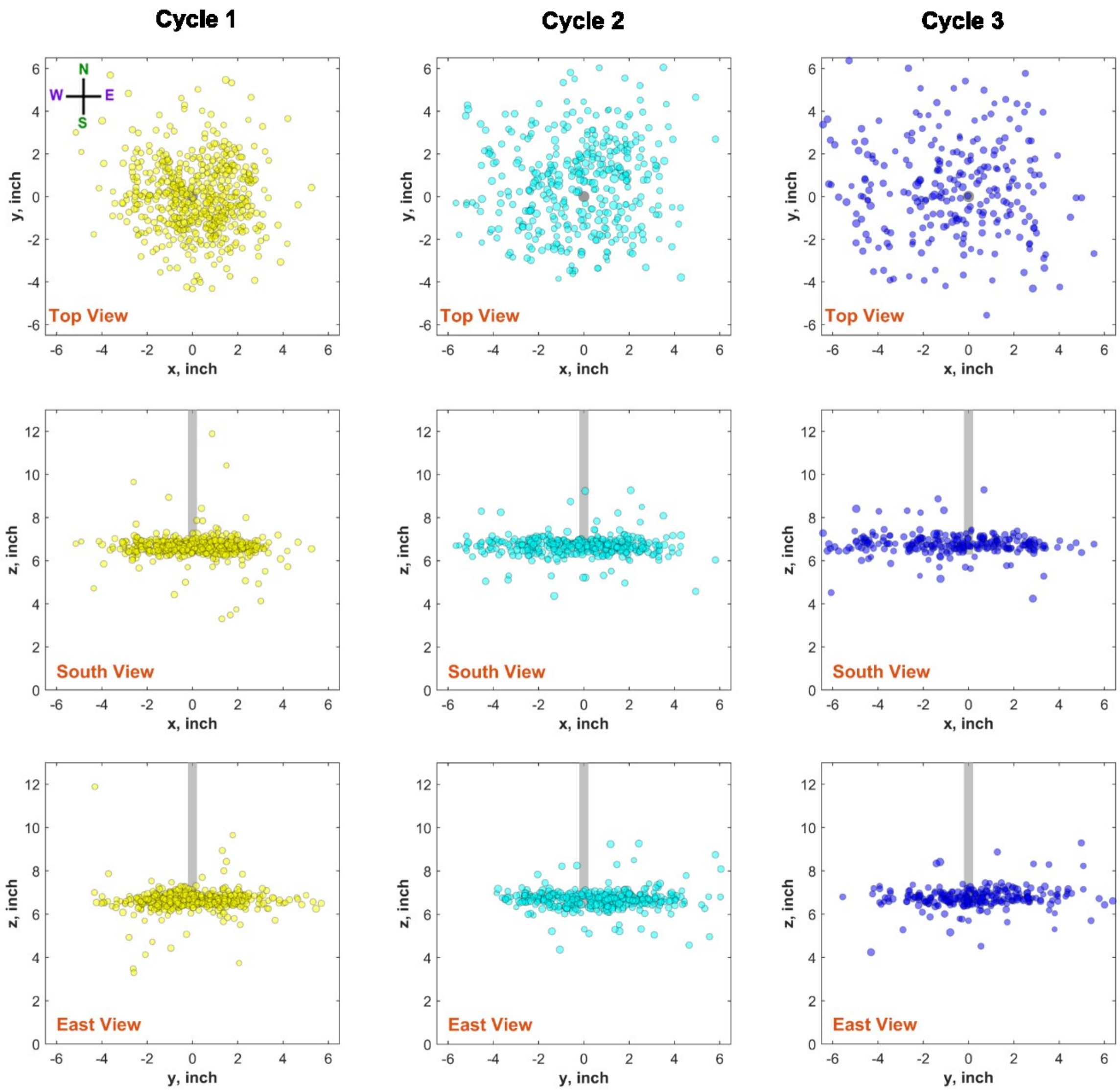

Figure 5: Monitoring hydraulic fracture propagation by the location of AE events. The location of AE events suggests an overall planar fracture perpendicular to minimum principal stress was created by fluid injection.

3.4 S_3 Determination in DFIT Cycles

After the three injection cycles for fracturing and propagation, three DFIT tests were conducted and the pressure transient data during injection and shut-in phases were recorded for stress analyses. Figure 6 illustrates the fracture reopening process of the three DFIT cycles. In Cycle 4, a relatively large injection pressure (1512 psi, but less than fracture propagation pressure) was used to reopen the entire fracture area without inducing further fracture propagation (as monitored by acoustic emissions). While in Cycle 5 and Cycle 6, relatively low injection pressures (around 1400 psi) were used to reopen the fracture. It is found that in all three DFITs, fracture reopening pressure provides a very good estimate of minimum principal stress (S_3 = 1250 psi).

The interpretations of closure pressure by the classic tangent method are shown in Figure 7. It is found that there are signatures in all the DFIT tests. In Cycle 5 and Cycle 6, the closure pressures based on 1st signature from the GdP/dG curve are 1263 psi and 1265 psi respectively, which are very close to the minimum principal stress of 1250 psi. However, the closure pressure determined by the 1st signature in Cycle 4 overestimates the minimum principal stress as 1362 psi. In addition, in all the DFIT tests (Cycles 4-6), the 2nd signature on the GdP/dG curve likely tends to underestimate minimum principal stress. The fracture closure is also examined using the compliance method but using the dP/dG plot (Figure 8). It is found that only Cycle 4 has a clear signature in this plot. On the other hand, Cycle 5 and Cycle 6 show a monotonical decrease in dP/dG curve and hence lack a signature for determining fracture closure. In the comparative analysis of 62 DFITs from nine different shale plays, McClure et al (2022) noted that 52% of DFITs showed good indication of closure using the compliance method, 32% indicated adequate indication of closure, and 16% showed no compliance signature. In another comparative analysis of 83 DFIT tests from the Canadian Duvernay basin pursued by Virues et al. (2022), 41% of the DFITs showed no compliance signature while 22% of the DFITs presented strong compliance signature and 23% showed adequate signature. The inconsistent compliance signature/indication observed in both our lab tests and the field tests (McClure et al., 2022; Virues et al., 2022) suggests a complex fracture closure process impacted by rock type and fracture surface morphology.

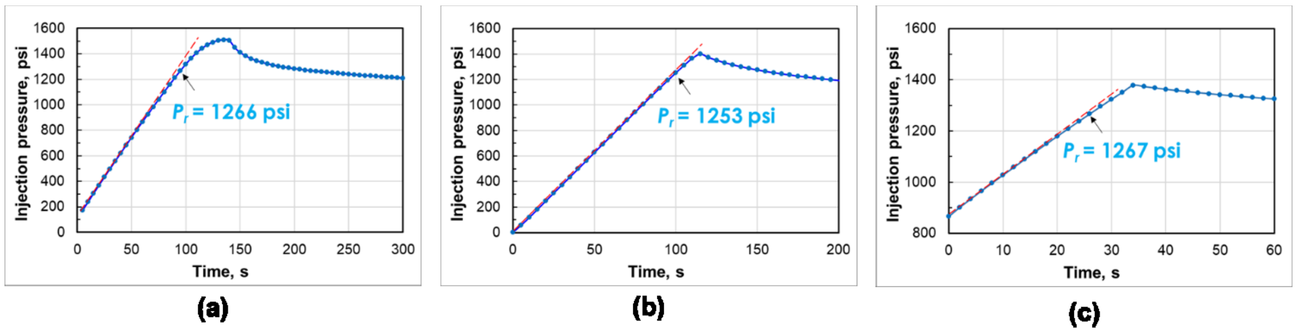

Figure 6: Fracture reopening pressure determination for the three DFIT tests (a) Cycle 4; (b) Cycle 5; (C) Cycle 6.

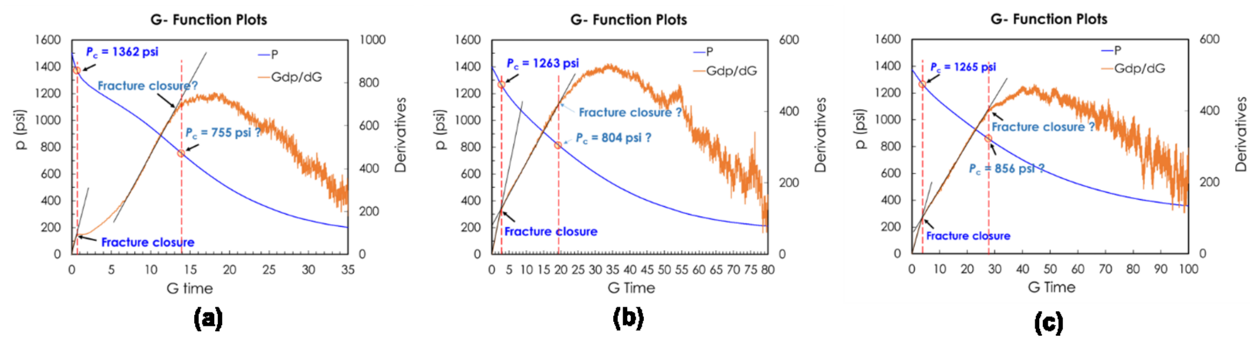

Figure 7: The interpretation of fracture closure pressure according to the tangent method for the three DFIT tests (a) Cycle 4; (b) Cycle 5; (C) Cycle 6.

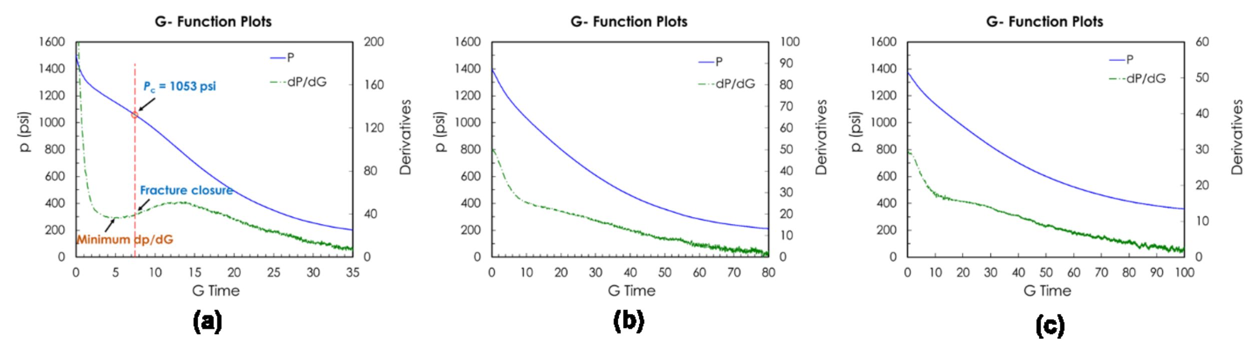

Figure 8: The interpretation of fracture closure pressure according to the compliance method for the three DFIT tests (a) Cycle 4; (b) Cycle 5; (C) Cycle 6.

4. DISCUSSIONS

In the three DFIT tests conducted in the laboratory, fracture reopening pressure provides a very good estimate of minimum principal stress, while the pressure falloff data analysis using the tangent method and the compliance method leads to inconsistent stress estimation due to various fracture closure signatures. The surface topography of the hydraulic fracture created in the experiment was described by surface scanning after the experiment and is shown in Figure 9. It is found the overall fracture geometry is flat with a maximum surface relief is around 0.5 inches (Figure 9(b)). However, local surface heterogeneity exists, and the near wellbore region is relatively flat compared to the fracture area far from the wellbore. During fluid injection, the near wellbore will reopen first and then gradually open the whole fracture area until the extension/propagation of the fracture under high injection pressure. Therefore, fracture reopening pressure provides a very good estimate due to it only being impacted by the near wellbore region that is perpendicular to minimum principal stress. In Cycle 5 and Cycle 6, the injection pressure is relatively and much smaller than the fracture propagation pressure, and hence a relatively small and much flatter area near the wellbore was reopened. Therefore, stress estimation from Cycle 5 and Cycle 6 provides a better estimate. On the other hand, in Cycle 4 a relatively large injection pressure close to the fracture propagation pressure was used, and almost the entire uneven fracture area was reopened. Due to the fracture surface being inclined at the region far from the wellbore, the stress estimate in Cycle cannot reflect minimum principal stress but the normal stress acting on the inclined section of the fracture.

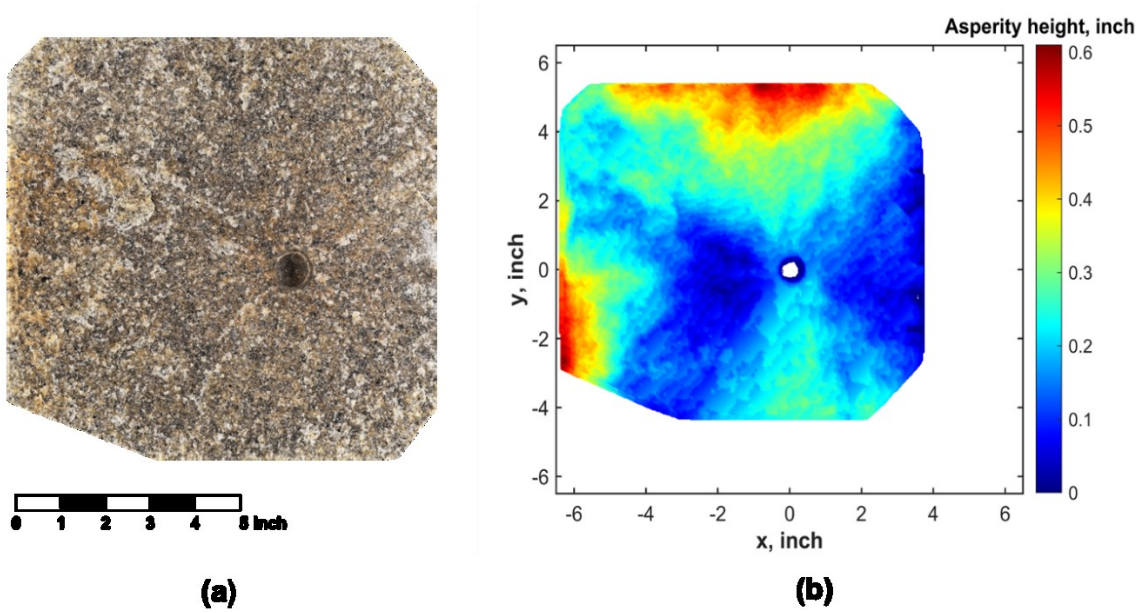

Figure 9: (a) The bottom side of hydraulic fracture created in the experiment; (b) fracture surface contour showing local surface heterogeneity.

5. CONCLUSION

In this study, we conducted a laboratory hydraulic fracturing experiment including several DFIT tests on a granite block to reexamine in-situ stress interpretation using pressure transient data. Acoustic emission was applied to monitor fracture initiation and propagation, and help generate a nearly flat hydraulic fracture. Results demonstrated fracture reopening pressure provides a very good estimate of minimum principal stress, while the pressure falloff data analysis using the tangent method and the compliance method leads to inconsistent stress estimation due to various fracture closure signatures. Two signatures of fracture closure were observed using the so-called tangent method in all DFIT tests and the 1st signature tends to offer a better stress estimate. The required signature for the system stiffness or compliance method is observed in one DFIT test although not consistently. According to the AE monitoring and the surface scanning, it is observed the overall geometry of the hydraulic fracture created in our experiment is planar, however, a clear non-uniform topography is evident with heterogeneous distribution of asperities. Results demonstrate fracture surface topography has significant impacts on fracture closure and the associated stress determination. Considering the complex nature of hydraulic fracturing in the subsurface, we recommend integrating multiple techniques for S_{hmin} determination rather than relying on a single interpretation method.

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