Acoustic Emission and Ultrasonic Transmission Monitoring of Hydraulic Fracture Initiation and Growth in Rock Samples

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Abstract
In this paper we report laboratory experiments conducted to study initiation and growth of hydraulic fracture in low permeability sandstone blocks loaded in a poly-axial test frame to representative effective in-situ stress conditions. Fracture propagation was monitored by means of Acoustic Emission (AE), Ultrasonic Transmission (UT) and volumetric deformation techniques. We used initially intact rock blocks, as well as blocks with saw cut discontinuities oriented orthogonally to the expected direction of fracture propagation. Hydraulic fracturing was initiated by injection of silicone oil into a borehole drilled in the block. Analysis of AE results shows an increase in AE activity and spatial correlation coefficient, reliably indicating a process of microcracks coalescence during hydraulic fracture initiation. This early stage of fracturing correlates strongly with the onset of volumetric deformation of the rock. Detailed analysis of AE localizations allowed us to identify initiation of hydraulic fracture and also various stages of hydraulic fracture propagation, including interaction with the preexisting interface, propagation away from the interface, and fracture closure. We found that the onset of borehole pressure breakdown correlates closely to the time, when the hydraulic fracture crosses interface and not with the fracture initiation, reliably indicated by AE technique earlier than the breakdown. Analysis of the combined AE and volumetric deformation data allow us to estimate near-wellbore fracture width and in combination with UT data analysis provided additional insight into the fracturing process and significantly improved our understanding of the dynamics of hydraulic fracture propagation. These results also give us a reference for interpretation of microseismic monitoring data recorded in the field.

Keywords: acoustic emission, ultrasonic testing, crack detection, crack propagation, localization of damage, hydraulic fracturing, rock deformation

1. Introduction

It is well known that hydraulic fracturing is required for successful oil and gas production from ultra-low permeability unconventional reservoirs. However, very often these reservoirs are highly heterogeneous, and their heterogeneity leads to high degree of geometrical complexity of hydraulic fracturing. Therefore, laboratory study of hydraulic fracture initiation, growth and propagation through pre-existing interface is important. One successful technique for monitoring of hydraulic fracture in the laboratory is acoustic emission (AE), which is considered to be a high-frequency analogue of induced microseismicity in the field [1]. A few decades ago, Lockner and Byerlee [2] demonstrated that AE, generated during hydraulic fracturing in the laboratory, could be used to map fracture orientation and infer its propagation rate. Hydraulic fracturing of granite blocks was investigated in laboratory conditions using different fluid viscosities [3, 4] and injection rates [5]. Ishida et al. [4] have demonstrated that injection of high viscosity fluid tends to generate thick and planar cracks with few branches, while injection of water tends to generate thin and wavelike cracks with many secondary branches. Zoback et al. [5] observed increase of breakdown pressure with increase of injected fluid viscosity and proposed conceptual model explaining test results. In other laboratory researches it has also been demonstrated that in addition to AE analysis, ultrasonic velocity measurements [6] and volumetric deformation measurements [7] can be successfully used for monitoring the process of fracturing.

In this paper we report results of four laboratory experiments conducted to study criteria of hydraulic fracture initiation and also the effect of pre-existing discontinuities on hydraulic
fracture propagation initiated by injection of different viscosity fluids in low permeability sandstone blocks.

2. Experimental Setup

Hydraulic fracturing was investigated using blocks extracted from an outcrop of Colton Sandstone. The blocks were loaded in a polyaxial load frame made by TerraTek, a Schlumberger Company. Photo of loading frame is shown in Figure 1.

![Photo of polyaxial loading system build by TerraTek, a Schlumberger Company.](image)

Stresses were applied to the rock blocks independently in three directions using flat jacks, and fluid was injected into the borehole, simulating the stress conditions existing in the field. Measurements of the volume of fluid pumped inside each flat jack allowed the volumetric deformation of the rock in each direction to be independently monitored.

<table>
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<tr>
<th>Direction</th>
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<th>Stress, psi</th>
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<td>$\sigma_h$</td>
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<td>Horizontal Maximum</td>
<td>$\sigma_H$</td>
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<td>Vertical</td>
<td>$\sigma_V$</td>
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Table 1. *Stresses applied to rock blocks by polyaxial loading frame.*

Applied stresses are specified in Table 1. We investigated hydraulic fracturing on two kinds of sandstone blocks.

(i) Initially intact rectangular shape blocks having dimensions of 279 x 279 x 381 mm with borehole of 25.4 mm diameter and 260.35 mm deep drilled in the center of the block. During these tests, hydraulic fracturing of the rock was conducted by injection of viscous silicone oil (2.5x10^6 cSt viscosity) into the borehole at a flow rate of 5 cm^3/min. A synoptic illustration of the sample, borehole and hydraulic fracture geometry, as well as the loading conditions is shown in Figure 2a. A 260.35 mm long steel casing with two 50.8 mm slots oriented northward and southward was glued inside the borehole. Two longitudinal scribes were created along these slots to facilitate the initiation of a hydraulic fracture in the direction of maximal horizontal stress (North-South direction, Figure 2a). The main goal of these tests was to study reliable criteria indicating hydraulic fracture initiation.

(ii) We also tested the blocks, which were initially cut in two parts parallel to the direction of minimum horizontal stress to create an artificial interface orthogonal to the fracture propagation path, as shown in Figure 2b. The faces of the interface were
During this series of tests, we studied hydraulic fracturing by injection of high viscosity (2.5x10^6 cSt) and low viscosity (1450 cSt) fluids. The borehole was 25.4 mm in diameter and 260.35 mm deep; and was drilled offset from the block center as shown in Figure 2b. A 260.35 mm long steel casing with a 50.8 mm slot oriented southward was glued inside the borehole. A single longitudinal scribe about 6 mm deep was made along the slot using a sand blaster in the South direction to facilitate the initiation of a hydraulic fracture toward the discontinuity. In these tests the objective was the investigation of the effect of artificially created interfaces, modeling natural rock heterogeneity, on the fracture initiation and propagation.

In all tests ultrasonic velocities and AE signals were monitored by 20 to 24 SE-150-M sensors made by DECI (Dunegan Engineering Consultants Inc.) embedded into pockets drilled in the rock. The sensors have sensitivity range from 50 to 300 kHz, and were used for registration of both AE signals and periodical ultrasonic transmission measurements (UT) of time-dependent P-wave velocity in the rock. Signals were amplified by 49 dB using Vallen AEP3 preamplifiers with high-pass filtering of 50 kHz and low-pass filtering of 1000 kHz. Fully digitized waveforms of AE and UT signals were recorded by an AMSY-6 data acquisition system made by Vallen GmbH with 5-MHz sampling rate and 16-bit amplitude resolution. The evaluation of AE hypocenter coordinates was carried out using sophisticated software package that includes: (i) automatic picking of P-wave onset time based on the Akaike Information Criterion (AIC criterion) [8]; and (ii) minimization of travel time residuals using the downhill simplex algorithm [9], considering time-dependent changes of heterogeneous anisotropic velocities periodically measured during the tests [10]. Application of this software package allows us to reach accuracy of the AE hypocenter localization of about 6 mm.

3. Experimental Results

3.1 Hydraulic Fracturing of Initially Intact Rock Blocks.

3.1.1 Mechanical Characteristics Recorded During Hydraulic Fracturing

In this paper at first we report results of two tests studying hydraulic fracture initiation and propagation in intact sandstone blocks induced by injection of high fluid viscosity (2.5x10^6 cSt). During the first test we interrupted fluid injection right after borehole breakdown, which means -- right after the maximum of applied borehole pressure has been reached. Analysis of this test data shows that the hydraulic fracture was initiated significantly earlier than borehole...
breakdown. Therefore, in the second test we decided to interrupt fluid injection soon after fracture initiation and before the breakdown. In order to validate reliability of our fracture initiation criteria, we used the second test to visualize the conditions of fracturing by saw cutting the block after the test orthogonally to the plane of expected hydraulic fracture and confirmed the presence of the fracture. We also compared the shape of the actual hydraulic fracture observed after cutting the block with localized AE hypocenters.

The wellbore pressurization histories of two tests are presented in Figure 3. All flat jacks in all tests were maintained at the constant pressures specified in Table 1, during injection and fracture. The fluid volume pumped or withdrawn from each flat jack to maintain the prescribed stress was measured, which allows the volumetric deformation of rock in each direction to be monitored. Figures 3a and 3b show the time histories of wellbore pressure (red), of East-West volumetric deformation (green) perpendicular to the fracture plane, and the response of the North-South (pink) and Top-Bottom (blue) volumetric deformations, for each test. In all reported tests, before the borehole pressure breakdown (corresponding to the maximum borehole pressure) we observed the onset of East-West flat jack volume decrease, indicating an increase of rock size in the East-West direction. In all tests the hydraulic fracture propagated in the North-South direction, therefore the change in flat jack volume in the East-West direction is an indication of hydraulic fracture propagation and opening. This effect provides us with a mechanical criterion of hydraulic fracture initiation. This assumption will be confirmed below by comparison of mechanical characteristics with the results of acoustic emission and ultrasonic transmission monitoring.
3.1.2 Combined Analysis of AEs and Mechanical Characteristics

Additional confirmation of hydraulic fracture initiation and propagation is obtained directly from the analysis of AE hypocenter localizations. Figures 4 (a)-(b), 4 (d)-(e), 5 (a)-(b) and 5 (d)-(e) show 2 orthogonal projections of AE hypocenters, and Figures 4(c), 4(f), 5(e) and 5(f) show the loading histories of two samples fractured by injection of 2.5x10^6 cSt viscosity fluid. Fluid injection was interrupted right after borehole pressure breakdown in the first test (Figure 4) and sooner after hydraulic fracture initiation in the second test (Figure 5). To demonstrate the evolution of AE signals appearance during the fracturing, the loading interval in both tests was separated into two stages. In the first test, initial Stage (i) corresponds to the time interval of loading before the borehole pressure breakdown, indicated in Figures 4 (a)-(c); second Stage (ii) corresponds to the time interval of hydraulic fracture propagation after breakdown, indicated in Figures 4 (d)-(f). For the second block (Figure 5) the initial Stage (i) corresponds to the fluid injection interval, as indicated in Figures 5 (a)-(c) and Stage (ii) corresponds to the fluid withdrawal interval, as indicated in Figures 5 (d)-(f).

The color of the dots in Fig. 4 and Fig. 5 corresponds to the time sequence of AE events: violet color indicates the earliest AE events and red indicates the latest AE events, according to the color bar presented at the bottom of each plot. Localizations of AE hypocenters marked by violet color in Figures 4(a)-(b) and Figures 5(a)-(b) show that in both tests the initiation of the hydraulic fracture occurred near the wellbore slots. The early localized AE hypocenters (violet dots) in Figures 4a and 5a, and the change in the slope of cumulative number of localized AE events (blue color curves in the Figures 4c and 5c) occurred approximately at the same time as the onset of East-West flat jack volume decrease (Figures 4c and 5c). Therefore, the combined analysis of AE rate increase, AE localization and volumetric rock deformation allows us to identify reliably the moment of hydraulic fracture initiation. This criterion of hydraulic fracture initiation will be described more detailed below. It should be mentioned that initiation of the hydraulic fracture happened significantly earlier than the peak of applied bore pressure has been reached (breakdown moment is marked by red arrow and dash line in Figure 4c). After initiation, we observe hydraulic fracture growth in the direction of maximum horizontal stress (indicated by change of hypocenter dots color in Figures 4(a)-(b) from violet to red), and at the same time we see a decrease in the East-West flat jack volume (Figure 4c, green curve), indicating volumetric rock deformation. Close to the borehole pressure breakdown the non-linearity of the applied bore fluid pressure could be observed (red color highlighting of curves in Figure 4c), indicating fluid penetration into an opened hydraulic fracture. Figures 4 (d)-(e) demonstrate that after the beginning of borehole fluid withdrawal, the front of the acoustic emission activity continued propagation toward the block boundaries in the first test, while in the second test, AE propagation stopped significantly earlier, as indicated in Figures 5 (d)-(e).

In Figures 4 and 5 we plotted only the highest amplitude AE hypocenters. We calculated Adjusted Amplitude of AE hypocenters (AdjAmp) by taking into account the geometrical spreading of elastic waves [11]. Figure 4 shows the selection of AE hypocenters with AdjAmp > 75 dB and Figure 5 with AdjAmp > 70 dB. To enhance the rendering of a significantly higher number of AE hypocenters without adjusted amplitude selection, we calculated the density of these within a sliding cube of dimensions 5 x 5 x 5 mm. These results are subsequently calculated as a normalized fraction of the maximum number of AE hypocenters counted, and then plotted on each orthogonal projection. Results are shown in Figure 6 (first test), and in Figure 7 (second test). The separations of Stage (i) and Stage (ii) in both tests are the same as in Figures 4 and 5. AE hypocenter density maps show that in both tests the hydraulic fracture surfaces indicated by AE activity have pancake-like shape, growing from the borehole wall in the direction of maximum horizontal stress.
Figures 6 (c)-(d), representing the first test, show that the hydraulic fracture continues to propagate towards block boundaries even after fluid withdrawal at a rate of \(-30\) ml/min. This process is accompanied by the continuous East-West Flat jack volume decrease (Figure 4f), indicating continuous opening of hydraulic fracture during this stage. In the second test we interrupted fluid injection much sooner after the hydraulic fracture initiation and before the borehole pressure breakdown moment. Also, we withdrew fluid from the borehole at a much faster rate of \(-1000\) ml/min than in the first test. This allowed us to arrest fracture propagation and map AE activity associated with the Stage (ii). The second test clearly indicates localization of AE activity closer to borehole during fluid withdrawal stage (Figures 7 c-d) than during fluid injection stage (Figures 7 a-b).
3.1.3 Criteria Indicating Hydraulic Fracture Initiation

As we mentioned above, combination of the results of mechanical and acoustic emission data indicates initiation of hydraulic fracture. In addition, we propose to use statistical analysis of the spatial distribution of AE hypocenters for indication of hydraulic fracture initiation. We investigated the spatial distribution of AE, calculating the correlation integral [12]:

\[
C(R) = \frac{2}{N(N-1)} N(r<R)
\]  

where \(N(r<R)\) is the number of AE hypocenter pairs separated by a distance smaller than \(R\). \(C(R)\) is a measure for the degree of clustering and localization varying between 0 and 1. The correlation coefficients, plotted in Figures 8b and 8e (green) for Test#1 and Test#2, correspondingly, are calculated by (1) for \(R = 25.4 \text{ mm}\), similarly to the technique described in [13]. Drastic increase of correlation coefficient indicates AE nucleation coinciding with the increase in AE activity (Figs. 8b and 8e, red). Here we use a combination of rock volumetric deformation, indicated by East-West flat jack volume (Figs. 8a and 8d, red), and AE parameters (Figs. 8b and 8e) for indication of hydraulic fracture initiation.
Figure 8 shows that borehole pressures of hydraulic fracture initiation in both tests are very similar, however the volume of fluid expelled out of East-West flat jack is about 7 times higher during the first test than during the second test (Figures 8a and 8d, red). Below it will be demonstrated that this volume characterizes the volume of opened hydraulic fracture. There is correspondence of volumetric deformation measurements with AE results confirming about 3 times smaller size of hydraulic fracture at maximum borehole pressure in Test #2 (Figure 8f) than in Test #1 (Figure 8c).

3.1.4 Comparison of Acoustic Emission Results with Actual Fracture Geometry

After the first test #1, the fractured block was split up along the expected hydraulic fracture plane. The photo of half-block is shown in Figure 9b. Dark red color of oil in this photo indicates pancake-like shape of hydraulic fracture, confirming that fluid reached the block boundary at the end of the test. Figure 9a shows spatial distribution of AE hypocenters localized up to the moment of the beginning of fluid withdrawal. Similarity of Figures 9a and 9b confirms that the AE technique was successfully applied for monitoring the hydraulic fracturing of the rock.

After the second test #2, the partially fractured block was cut by saw horizontally in the middle, to expose the fracture shape. The photo of the block section is shown in the Figure 10b. Dark color of the oil in Figure 10b indicates the part of the rock where the fluid penetrated the rock along the created hydraulic fracture. Figure 10a shows the position of 213 AE hypocenters localized during injection stage within ± 10 mm distance from the position of the saw cut. Comparison of distribution of AE hypocenters along X axis (Figure 10a) with the photo of fractured rock (Figure 10b) confirms that accuracy of the most of hypocenters localization is about 5 mm. Note that spatial distribution of AE hypocenters along Y axis (Figure 10a) indicates appearance of AE events at distances up to 10-15 mm farther from the
wall of borehole, than could be indicated as position of fluid front in Figure 10b. This discrepancy could be explained by existence of certain lag between the position of fracture process zone tip, indicated by AE technique and the position of viscous fluid front tip, directly indicated by photo of fractured rock section.

Fig. 9. (a) YZ distribution of AE hypocenters localized during fluid injection in Test #1. The color of the balls indicates time sequence of AE events appearance according to color bar at the bottom of Figure 9a. The diameter of the balls is proportional to the logarithm of AE amplitude; (b) the photo fracture surface reviled after completion of Test #1, dark red color of oil indicates position of fluid front.

Fig. 10. (a) XY distribution of AE hypocenters localized within horizontal slice of the block at 180 < Z < 200 mm during fluid injection in Test #2. The color of the dots corresponds to the time sequence of AE events: violet color indicates the earliest AE events, red color – the latest AE events; (b) photo of fractured sample cut in horizontal direction at the position Z=190 mm. Dark line in the photo indicates position of fluid penetrated the hydraulic fracture.
3.2 Propagation of Hydraulic Fracture through the Pre-existing Discontinuity.

3.2.1 Combined Analysis of AEs and Mechanical Characteristics

We also tested two blocks, which were initially cut in two pieces parallel to the direction of minimum horizontal stress to create an artificial interface orthogonal to the expected fracture propagation path, as shown in Figure 2b. We studied propagation of hydraulic fracture through artificially created discontinuity during Test #3 by injecting high viscosity fluid (2.5x10^6 cSt), and during Test #4 we injected significantly lower viscosity fluid (1450 cSt).

Figures 11 (a), (b), (d) and (e) show 2 orthogonal projections of AE hypocenters, and Figures 11 (c) and (f) show the loading histories of the sample #3, which was fractured by injection of 2.5x10^6 cSt viscosity fluid. Figures 11 (a)-(c) show the time interval of hydraulic fracturing up to borehole pressure breakdown, and Figures 11 (d)-(f) show the time interval after breakdown. Localizations of AE hypocenters marked by violet color in Figures 11 (a)-(b), show that fracture initiation occurred near the perforations at approximately the same time as the onset of East-West flat jack volume decrease (Figure 11c). Also, one can see that the initiation of the hydraulic fracture happened significantly earlier than the peak of applied bore pressure. Combined analysis of AE and volumetric deformation of the rock #3 and #4 allows us to identify reliably the moment of hydraulic fracture initiation, similarly to the intact rock tests #1 and #2 described above. After initiation, we observe hydraulic fracture growth towards the discontinuity, and at the same time we can see a decrease in the East-West flat jack volume (Figure 11c, green curve), indicating volumetric deformation of the rock. Close to the breakdown pressure, spatial distribution of AE events shows that at this time the cloud of AE events approached the discontinuity, marked as blue dash line in Figure 11. The shape of AE hypocenter localization presented in Figures 11b shows a slight migration of AE cloud along discontinuity in East-West direction and we assume that this AE activity indicates migration of fluid along discontinuity, causing the onset of bore pressure decrease (Figures 11c and 11f).

Figures 12 (a), (b), (d) and (e) show AE hypocenter spatial distributions for the test with significantly lower viscosity fluid (1450 cSt) and lower fluid injection rate. Figures 12c and
12f show the test loading histories. Similarly to all previous tests, AE hypocenters marked by violet color in Fig. 12 (a)-(b) show that the initiation of hydraulic fracture occurred near the perforations and significantly earlier than the peak of the bore pressure time history curve (Figure 12c).

Similarly to the previous test, Figure 12b shows migration of the fluid along discontinuity in East-West direction, but in the case of lower fluid viscosity we also observe migration of the fluid in Top- Bottom direction (red color dots in Fig. 12a). One can see that loading curves recorded during injection of lower viscosity fluid (Figs. 12c and 12f) significantly differ from loading curves recorded during injection of high viscosity fluid (Figs. 11c and 11f). Two consecutive drops of bore pressure and East-West flat jack volume are observed (Figs. 12c and 12f). Analysis of AE hypocenter localizations presented in Fig. 12a and 12b indicates that at the breakdown pressure we observe spreading of AE hypocenters in Top- Bottom direction (red dots in Figure 12a) and in East -West direction (red dots in Figure 12b). This indicates fluid leak-off along the discontinuity, causing a bore pressure to decline (the breakdown pressure is marked by arrow and red dash line in Figure 12c). Analysis of Figure 12 indicates that after the breakdown the fluid continues spreading along the discontinuity in Top- Bottom direction (blue color dots in Figure 12d), as well as in East-West direction (blue color dots in Figure 12e). At approximately 5550 seconds we observed the hydraulic fracture crossing the interface (green--yellow color dots in Figs. 12d and 12e). This closely corresponds to the beginning of the second drop of bore pressure and decrease of East-West flat jack volume (green-yellow highlighting of curves in Fig. 12f). Later, we observed the propagation of the hydraulic fracture from the borehole toward the North side of the block (red color dots in Figs. 12d and 12e) and this corresponds very closely to the moment of flattening of bore pressure and East-West flat jack volume curves, indicating that the fracture reached the boundary of the rock.

Therefore, combined analysis of AE localizations and volumetric deformation of the rock allows to identify the initiation of the hydraulic fracture. The AE localization also allows visualization of the interaction between the hydraulic fracture and the preexisting interface, and helps us understand the flat jack volume behavior.
3.2.2 Combined Analysis of AEs and Ultrasonic Transmissions, to Monitor Hydraulic Fracture Propagation through Pre-existing Discontinuity.

In addition to registration of AE, we performed Ultrasonic Transmission (UT) measurements by applying a 100-V electrical pulse to transducer number 20, installed at the West face of the rock. The geometry of the ray traces associated with UT along the various paths in Test # 4 is shown in Figure 13a. The loading history is shown in Figure 13d, and the results of P-wave velocity and amplitude measurements are presented in Figures 13b and 13c, respectively.

The velocities and amplitudes recorded along the different traces are almost constant during the initial stage of loading. During the fracture propagation stage, we observed about 3 to 5% increase of velocities and decrease of amplitudes close to the moment when hydraulic fracture intersects certain ray-path. Figures 13b and 13c clearly demonstrate certain delays in the onsets of velocity increase and amplitude decrease for the different ray-paths. This also closely correlates to the spatial distribution of AE events. One of the examples is the ray-path (20-12) demonstrating onset of velocity increase at about 300 seconds after breakdown (blue color curves in Fig.13b and Fig.13c). This corresponds very closely to the beginning of hydraulic fracture propagation from the borehole toward the North face of the block (Figs. 12d and 12e). Therefore, combined analysis of AE and UT gives us additional independent information about dynamic of hydraulic fracture propagation.
3.2.3 Estimations of Hydraulic Fracture Width

Detailed analysis of the mechanical characteristics of hydraulic fracturing presented in [14] allows us to assume that volume of fluid squeezed out of the flat jack characterizes the volume of the opened hydraulic fracture. Therefore, combining the volumetric deformation and the AE localization results we can estimate the fracture width. Comparison of loading curves presented in Figures 11c and 12c shows that for higher viscosity fluid, at breakdown we recorded few times higher volume of fluid expelled out of East-West flat jack (Fig.11c) than in case of lower viscosity fluid (Fig. 12c). This allows us to assume that opening of hydraulic fracture was wider with the higher viscosity fluid. According to AE hypocenter localizations of Test #3 and Test #4 (Figs.11a-b, Figs.12a-b), at the moment of breakdown the fracture tip reached discontinuity interface, so that AE analysis enables us to estimate the length of fracture at the breakdown moment equal to 76.2 mm. If we assume that shape of hydraulic fracture surface is close to half-ellipsoid, and that experimentally measured volumes of fluid squeezed out of the flat jacks (4.85 ml and 0.74 ml for high and low injection fluid viscosity, correspondingly) are equal to the volumes of half-ellipsoidal shape of the opened hydraulic fractures, we can calculate the width of hydraulic fracture opening equal to 798 µm and 121 µm for high and low injection fluid viscosities, correspondingly. It means that in case of $2.5 \times 10^6$ cSt viscosity fluid injection (Test #3), hydraulic fracture is about 6.5 times wider than in case of 1450 cSt fluid injection (Test #4).

4. Conclusions

We investigated the initiation of hydraulic fracture in initially intact rock blocks and propagation of hydraulic fracture through artificially created discontinuities, modeling natural boundaries of the rock heterogeneity. In all four reported tests AE analysis confirmed formation of hydraulic fracture propagated in the direction of maximal horizontal stress. In case of blocks with discontinuities we observed hydraulic fracture crossing the interface of preexisting discontinuity. We found a strong correlation between flat jack deformation, indicating rock dilatancy, and the spatial distribution of AE events. We propose to use statistical analysis of AE spatial distributions (correlation coefficient) for identification of hydraulic fracture initiation. Flat jack deformation was applied for estimation of hydraulic fracture volume. Both techniques allowed us to define the initiation of hydraulic fracture in tested blocks. In all four tests this initiation was determined to occur prior to the borehole pressure breakdown.

AE analysis confirmed that for the blocks with discontinuities, the onset of borehole breakdown pressure closely correlates to the time when hydraulic fracture crosses the discontinuity. The AE technique allowed us to monitor the interaction of hydraulic fracture with preexisting interfaces, fluid penetration along the interface and hydraulic fracture crossing the interface. We expect that in natural conditions the boundaries of rock heterogeneity would also act as the barriers for hydraulic fracture propagation and onset of the borehole pressure breakdown could be associated with fluid penetration along heterogeneity interfaces. We found that viscosity of the injected fluid has a strong influence on hydraulic fracturing process; i.e., injection of high-viscosity fluid results in wider fractures and higher breakdown pressures, while injection of low-viscosity fluid results in narrower width of fractures developed at lower injection pressure. Analysis of the combined AE and UT data provides additional insight into the fracturing process and gives significant information that improved our understanding of the dynamics of hydraulic fracture propagation. These results also give us a reference for understanding and interpretation of microseismic monitoring data recorded in the field.
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