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An experimental investigation into hydraulic fracture propagation under different applied stresses in tight sands using acoustic emissions

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ABSTRACT

Hydraulic fracturing is crucial in unlocking tight gas and shale gas and oil resources. The success of any hydraulic fracture depends on the fracture dimensions and proppant placement. Microseismicity (MS) is now a common mapping hydraulic fracture technique. In this paper, we report on the acoustic emission (AE) monitoring during laboratory hydraulic fracture studies conducted on Lyons sandstone samples under different applied external stress. We compute AE hypocenter locations, analyze event frequency content and compute focal mechanisms (FMS). Shear failure reflected in the focal mechanism is more common than tensile failure. AE locations agree well with visual expression of fractures intersection on the sample surface. Fracture orientation and development is controlled by the direction and magnitude of applied stresses. Below a critical stress magnitude, the sample inhomogeneities control the hydraulic fracture development. At lower stresses, the hypocenters indicate a greater stimulated reservoir volume, suggesting stage spacing should consider the magnitudes of in-situ stresses. The sequential acoustic emission activity is found to be episodic and discretized implying fracture propagation is not a simple continuum. SEM fracture morphology studies document a complex and non-planar development of the hydraulic fractures, affirming shearing consistent with the FMS. Furthermore, SEM imaging suggests a surface area creation far more than simple planar models would imply.

1. Introduction

According to Economides (2010) 90% of the natural gas wells in North America are being hydraulically fractured. In the past decade, the total number of hydraulic fracturing jobs across the world is about 2.5 million, a 300% increase compared to the past decade. The estimated size of the fracturing market is as high as 13 billion dollars in North America, alone. So it becomes important to understand the fracturing process through field scale experiments and controlled laboratory experiments. Microseismic monitoring of hydraulic fractures provides remote mapping of the fracture geometry, azimuth, connectivity, density and length. When performed in real-time, this allows changes to be made to the frac program in real-time, including modifications to pump pressure and rate or proppant mesh; operators can also identify the fluid movement patterns and fracture containment. Dynamic feedback provides a mechanism to improve and optimize the stimulation. Of concern is the accuracy of the hypocenter locations and their interpreted stimulated reservoir volumes.

In most field monitoring programs only limited azimuthal coverage of the fracture plane is possible using downhole arrays of sensors. Furthermore velocity models are typically built from perforation shots. The orientation of the hydraulic fractures is often controlled by direction and magnitude of the principal in-situ stresses. Height containment is controlled by treatment parameters, rock moduli and in-situ stresses. The fluid injection in the subsurface reduces the effective stress. If the leak-off is not isotropic, the injection can cause a reorientation of principal stresses.

Our laboratory experiments are simple approximations to the field conditions. For this purpose we used a small hydraulic press to apply a uniaxial horizontal stress to a specimen undergoing hydraulic fracturing. Our experimental configuration allowed nearly complete azimuthal AE sensor coverage of sample. Since our main objective is to understand the changes in the fracture dimensions, characteristics, and orientation caused by changes in the magnitude of the applied horizontal stress, we chose this simple configuration. Conventional theoretical models assume the induced fracture to be pure mode-I tensile opening, but the fault plane solutions obtained from the recorded sensor polarities consistently show shear failure to be the dominant (Baria and Green, 1986; Ishida et al., 1997; Talebi and Boone, 1998; Urbancic et al., 1999; Warpinski et al., 2010). SEM studies of the hydraulic fractures clearly show frequent offsets and jogs in the main fracture which are indications of shearing.

2. Experimental procedure

The experimental setup has been discussed briefly here, but a detailed discussion is reported by Chitrala et al. (2010). The acoustic emission monitoring system consists of 16 piezoelectric

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sensors (bandwidth: 50 kHz–1.5 MHz), broadband preamplifiers, a 16-channel signal conditioning (amplifier and filters) unit and a data acquisition module attached to a personal computer (PC). Each sensor is connected to the signal conditioning unit via a preamplifier. The total amplification for waveforms and the trigger are 70 and 66 dB, respectively. Each captured signal consists of 1024 points with 512 pre-trigger points. The digitizing rate is 5 MHz which makes each recorded waveform 204.8 μs long. Only P-wave arrival times have been used in our hypocenter locations. The system is calibrated and transducer polarities are determined with a series of standard pencil breaks (Hsu and Breckenridge, 1981).

Table 1
Petrophysical properties of test samples and completion geometry.

	Lyons sandstone
Petrophysical characteristics	
Porosity (%)	8
Permeability	10 μd
Mineralogy (wt%)	Quartz, 85
Sample and stimulation properties	
Length (in)	4
Diameter (in)	4
Borehole depth (in)	2
Counterbore depth, (in)	0.4
Perforation depth (in)	1
Fracturing fluid, viscosity (cp)	Oil, 50
Pumping rate (cm^3/min)	10

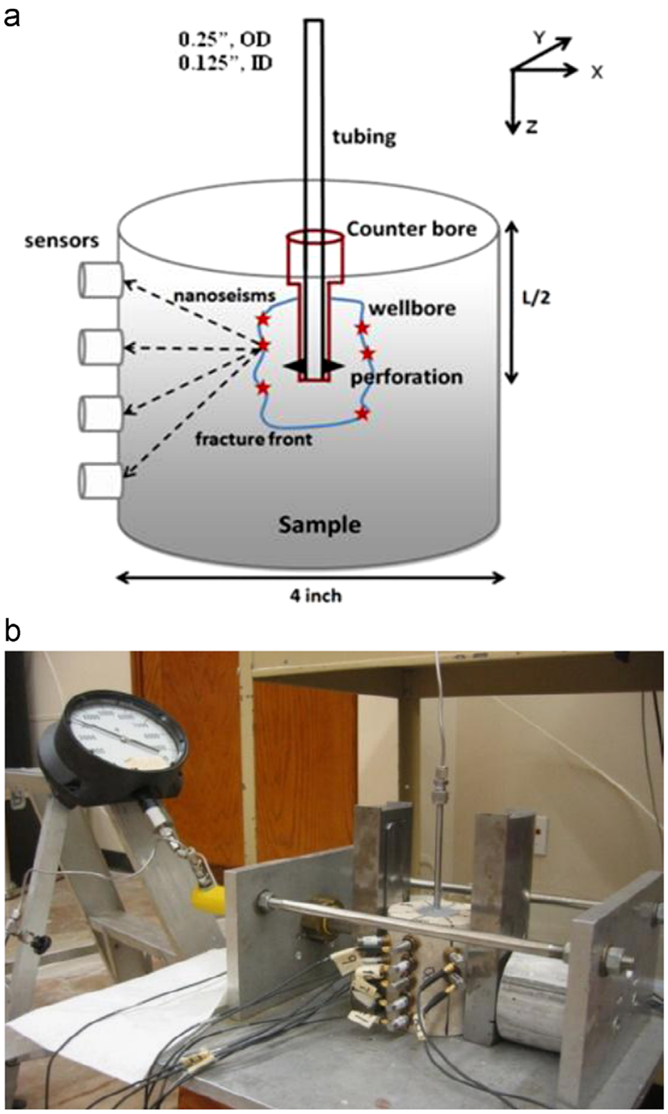

Fig. 1. (a) 3-D plan and side views of a 4-in. diameter sample completed with 0.12 in. ID mini-casing. Fluid ports in the mini-casing are located at the midpoint of the sample (black triangles). (b) Lyons sandstone is shown instrumented and stressed horizontally while undergoing hydraulic fracture stimulation. In the foreground, note the dense vertical subarray of sensors.

2.1. *Sample preparation*

Representative hydraulic fracturing tests on two Lyons sandstone samples at different applied horizontal stresses are presented. Pre-test characterization included circumferential velocity analysis (CVA) which is used to determine azimuthal velocity variation in each sample. CVA is a pulse transmission technique where the velocity is measured as a function of azimuth across the diameter of the sample. The velocity deviation across the samples was less than 4%; therefore, we used an isotropic velocity model for our AE analysis; the average velocity is 4400 m/s. Petrophysical and completion parameters of the sandstone samples are reported in Table 1. A uniaxial horizontal stress is applied mechanically using conformable flat jacks. Two different cases are studied: at horizontal stress values of 1000 psi and 125 psi (Fig. 1b). All other experimental conditions were exactly the same.

A 0.25 in. hole is drilled at the center of the sample along with 0.5 in. diameter counterbore hole. 0.25 in. diameter tubing is cemented into the rock using Conley weld^{TM} epoxy. Sixteen piezoelectric sensors are glued on the outer surface providing azimuthal coverage of the sample. A subarray containing 4 sensors is placed on one edge of the sample (Fig. 1) perpendicular to the fracture plane simulating an observation well. The sample is placed in a small hydraulic press and a far field horizontal stress is applied to control the fracture direction. The sensor arrangement is calibrated using a pencil-break source (Hsu and Breckenridge, 1981) at 8 surface locations. This process provides calibration for velocity models, transducer polarities and hypocenter locations. The best resolution of hypocenters in the Lyons

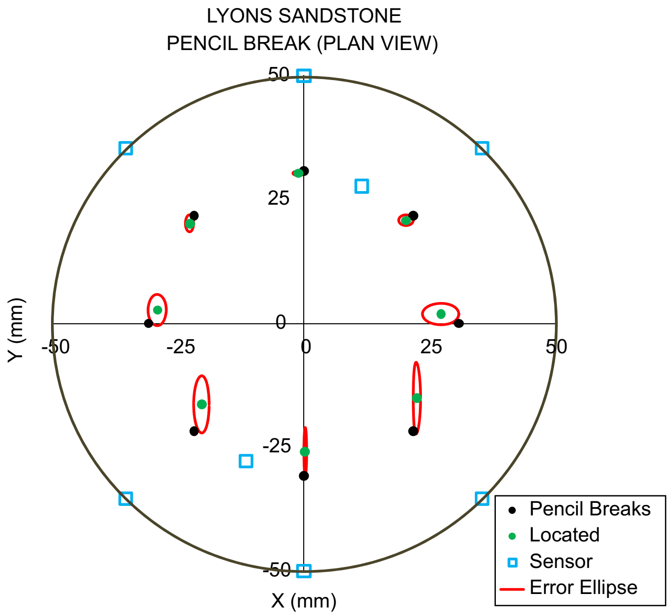

Fig. 2. Calibration showing the location of artificial sources, pencil breaks (black dots) and the calculated locations (green dots). Error ellipses are indicated in red and sensors locations are indicated by cyan squares. The average absolute error is ±3.3 mm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)