AAPG Search and Discovery Article #90173 CSPG/CSEG/CWLS GeoConvention 2011, Calgary, Alberta, Canada, May 9-11, 2011

Evaluating the Effectiveness of Hydraulic Fracture Staging with Moment Tensors

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Summary

Microseismic moment tensors are determined from a number of stages in a multiwell hydraulic fracture treatment. These moment tensors are point measures of the strain in the reservoir and can be related to volumetric opening and closure of cracks. The data for these stages locate asymmetrically with respect to the treatment well in a region of the reservoir that was recently fractured. The strain from these data show volumetric increase and decrease indicating that this pre-existing fracture network opened and closed as the treatment progressed. The dominance of closure for the later set of events implies that the stages were too proximal as previously stimulated regions were closed reducing the enhancement in permeability in these regions.

Introduction

Hydraulic fracturing is utilized to increase permeability of the reservoir and thus increase the hydrocarbon production. With advances in drilling capabilities, many reservoirs are stimulated through multiple stages in sets of horizontal wells. In many cases, the stages are placed relatively close to each other so that the stimulated reservoir volumes of the individual stages overlap. Such a design attempts to increase fracture density and hydraulic conductivity of the reservoir in between the wells as shown theoretically by Mayerhofer et al. (2008). Their conclusions were that fracturing in the reservoir can be increased if the stress is increased from simultaneously growing opposing fractures.

Microseismic monitoring provides a tool to sample the deformation of the reservoir during stimulation. Advanced analysis of the microseismic data can determine the orientation of newly formed or reactivated fractures as well as their size and time-dependent response to the injected fluid. In this study, we show how microseismic data can be used to study the interaction of the individual stages during hydraulic fracturing and determine if the close placement of the stages is indeed improving the fracture density and hydraulic conductivity.

Data

We analyze the microseismicity recorded from a hydraulic fracture treatment in a shale formation. Monitoring arrays were deployed in three wells surrounding the treatment allowing for full moment tensor solutions to be determined for events in three different stimulation stages. For each of the stages, locations and source parameters were determined for around 300 events. From this dataset, a representative set of seismic moment tensors in each set was chosen based on the frequency-magnitude distribution such that only the events showing self-similar behaviour were selected. This self-similar dataset was assessed on the basis of evaluating over what range of magnitudes was the frequency magnitude distribution linear. Such an approach allows for the comparison of the evolution and deformation within and between the individual stages.

Microseismic Moment Tensors

The moment tensor is a representation of the failure mechanism responsible for initiating the propagation of energy away from the event hypocentre. This energy propagates away with characteristic radiation patterns for *P* and *SV* and *SH* waves. Observing the polarities and amplitudes of the incoming waveforms, and projecting this information back to the source, allows for the moment tensor to be determined. Since there is a strong azimuthal component to these radiation patterns, accurate determination of the moment tensor is highly reliant on the events being recorded at a number of azimuths around the treatment; practically this requirement almost always translates into having a number of sensor arrays in different wells.

The moment tensors can be regarded as point measures of strain. Since the deformation is frequently consistent with that introduced from the opening and closure of fractures (Baig and Urbancic, 2010), this interpretation can be extended to gain estimates of the permeability enhancements due to the opening of fractures during treatments (Guest and Settari, 2010). However, the fact that closure events also occur indicate dynamic stress conditions on previously opened fractures and the permeability enhancement in these cases will be reduced. We shall track the changes in this behaviour by considering the volumetric strain implied by the moment tensors.

Results

In the example discussed, Stage 2 followed immediately after Stage 1, and Stage3 took place several days later in an offset well. However, each studied stage was preceded by about 11 hours with a neighboring fracturing stage. The recorded events for all three stages are shown on Figure 1 together with the location of the injection ports. The events NE and SW from the well is show a strong degree of asymmetry, with the majority of events located preferentially in the reservoir that was already stimulated by an offset horizontal well several days prior to the studied stages took place. Such skewed distributions seem to point to a strong degree of interference from neighbouring injection wells.

The deformation pattern of the three stages is shown in the source-type plots of Hudson et al. (1989) on Figure 2. The majority of moment tensors feature mechanisms representing tensile openings and closures. Stages 1 and 2 show similar distributions of the opening and closure events, and Stage 1 contains higher number of shear events. Stage 3 shows a preference for closing events suggesting that during this stage, the injected fluid redistributed the stress in the reservoir that caused closures of previously opened fractures. This behaviour is possible because the fractures formed during the previous stages would be the weakest parts of the reservoir.

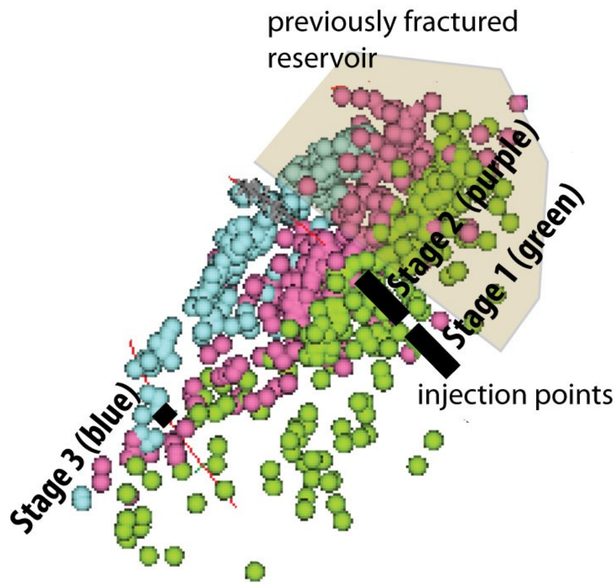

Figure 1: Map of the detected events in the three studied stages. Frequency of the events increases in the previously fractured reservoir (light-brown patch) relative to the un-fractured parts (no background color). Note that the Stage 3 is completely asymmetric.

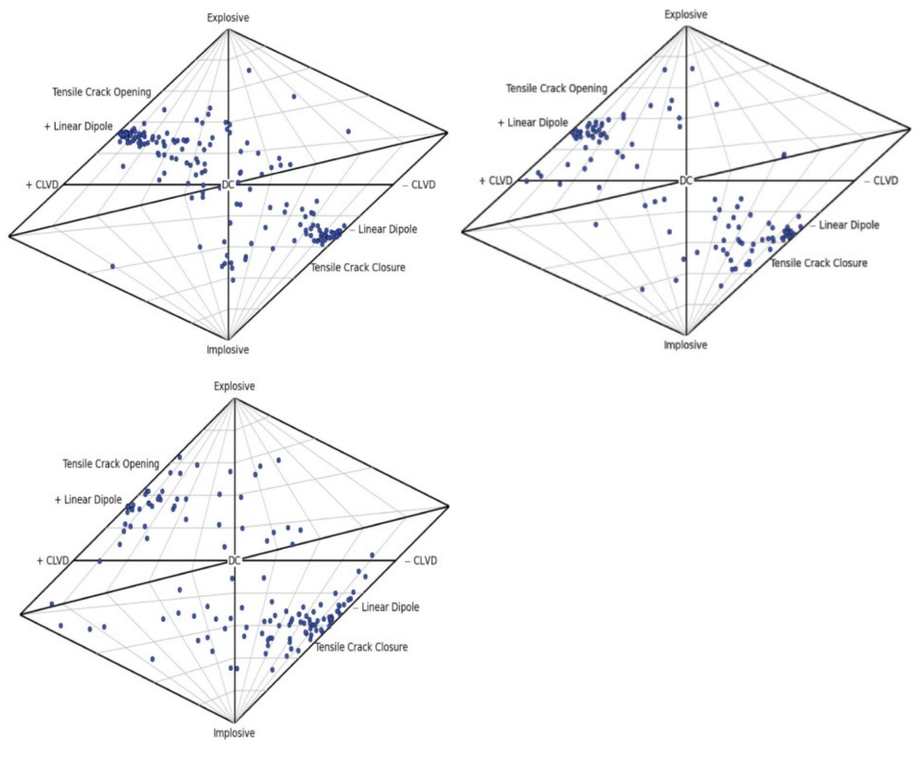

Figure 2: Deformation modes for the Stage 1 (upper left), Stage 2 (upper right) and Stage 3(bottom).

Based on the deformation determined using seismic moment tensor analysis, we calculated the cumulative volumetric strain evolution for the individual stages (Figure 3) in ten minute windows over the duration of the stage. Stages 1 and 2 show three windows of fracture opening that are followed by closures. Whereas the openings are overall more significant in Stage 1, the closures prevail in Stage 2 and 3 so that the final volumetric strain at the end of the treatment is negative. For Stage 3, the final volumetric strain is 4 times higher than the positive volumetric strain from Stage 1, as observed by the increase of collapsing events.

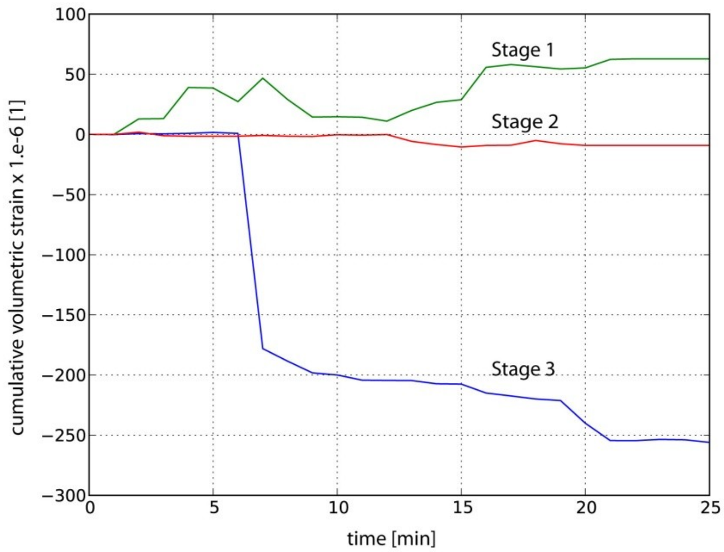

Figure 3: Cumulative volumetric strain during the injection time [min] for each of the three studied stages. Stage 1 shows an overall increase of the opening fractures whereas the Stages 2 and 3 are mainly causing closures of fractures.

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Conclusions

Our results suggest that not all stages successfully increase the fracture density of the reservoir. It is possible that fluid tends to escape into the previously fractured reservoir and instead of forming new fractures, closes and reopens regions of the already stimulated fracture system. Only Stage 1 could possibly increase the permeability of the reservoir, whereas the successive Stages 2 and 3 had the opposite effect. In terms of the total volumetric deformation during injection, the closing deformation of Stage 3 is four times higher than the successful positive volume opening from the Stage 1. It is not clear at this point why Stage 1 would be successful and Stages 2 and 3 not, and it will be subject of our further investigation. However, it does appear that the results of Mayerhofer et al. (2008) are not applicable to this case.

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