Can Microseismics Provide the Answers Frac Engineers Require?

Ted Urbancic*, Adam M. Baig, Kaitlyn Mace
Engineering Seismology Group, Kingston, ON, Canada
urbancic@esg.ca
and
Eric von Lunen, Jason Hendrix
Nexen Inc., Calgary, AB, Canada

Summary

Most microseismic monitoring of hydraulic fractures entails determination of the event locations and magnitudes. This "first-order" analysis has been very successful in determining fracture trends and sizes but is limited in approach. We illustrate a number of examples of how higher-order seismic moment tensor inversion (SMTI) analysis can provide more detailed answers to questions in the fracture engineering community. Determination of the fracture planes from the SMTI data shows the development of an interconnected fracture network that provides conduits for the treatment fluids into formation. From here, the spatial variation of opening and closure modes of the moment tensors yields a map of the regions of the treatment zone where permeability has been enhanced by the opening of fractures. That this region of enhancement does not simply form an envelope around the microseismic events has important implications for the ideas of stimulated reservoir volume. Finally, we show how temporal analysis of the SMTI data together with the treatment parameters can be used to determine where the fracture treatment has reached points of diminishing returns, where further treatment does not enhance the permeability of the reservoir, can be used to optimize future fracture treatments.

Introduction

Microseismic monitoring has been shown to be an effective tool providing insight into the dynamic behavior of a reservoir during hydraulic fracture stimulations. Simplistically, by utilizing the timing and hodograms of first arrivals of different signal phases, estimates of event locations can be obtained. By further examining the spatial and temporal variations in the event locations, basic overall geometric measures such as orientation, fracture extent, and fracture growth can be obtained.

From the perspective of traditional fracture models, data based on these microseismic parameters fit the accepted understanding; fractures are generally considered to develop along a single fracture azimuth or along a plane of fracturing controlled by regional stresses (i.e. along the direction of maximum principle stress), even within the context of a three-dimensional fracture network. The recorded waveforms, however, provide further insight into the nature of the fracturing process. Advanced analysis of the microseismic data, such as seismic moment tensor inversion (SMTI) and source parameter calculations can be used to determine the orientation of newly formed or reactivated fractures as well as their size and time-dependent response to the injected fluid. Based on nearest neighbor statistics, events can be grouped into behavioral domains, such as near treatment well and fracture extension regions, and used to outline a Discrete Fracture

Network (DFN) and the spatial- temporal development of the DFN within the volumes. These results can further be used to assess the fracture connectivity and enhanced permeability associated with the treatment.

Based on these analyses, engineers can assess the effectiveness of different stimulation programs, and the "effective fracture zone" associated with the stimulation. This can further be used to estimate the Stimulated Reservoir Volume (SRV) associated with the treatment program and allow enhanced calculations of productivity. Additionally, as identified through SMTI analyses, changes in fracture behaviour from an extension type regime to an ineffective closure-dominant regime, allow for the identification of Points of Diminishing Returns (PDR). This can then used to achieve better proppant distributions and higher fracture conductivities in future fracture designs.

Although the analysis of microseismic data in isolation provides insight into the dynamic response of the reservoir to stimulations, when combined with known geology and measured engineering parameters value can be added to stimulation programs. Here, we explore these ideas and provide examples of the early work being used to establish the link between microseismicity and engineering parameters, leading to predictive reservoir models or the calibration – validation of reservoir models.

SMTI Analysis

In essence, the seismic moment tensor (SMT) is a mathematical representation of forces acting at the seismic source. The components of the SMT could be seen as dipoles of forces acting on the surface of the crack in the opposite directions. If a pure shear crack is considered, only two components of the SMT will have non-zero values. To satisfy the condition of torsion absence, those components must be pairs from above and below the SMT diagonal e.g. second component in the first row and second component in the first column. In practice, an obtained SMTI solution is decomposed in isotropic, double-couple (DC), and compensated linear vector dipole (CLVD) components. This decomposition is not unique, nevertheless, it allows for geophysical interpretation of the failure mechanism.

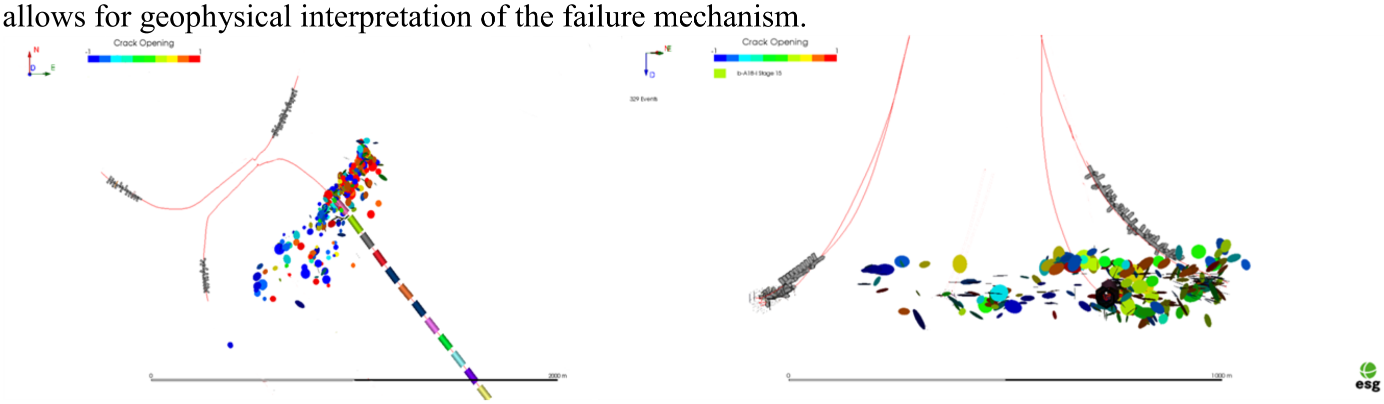

Figure 1: Example DFN for a stimulation showing connectivity of fractures where fractures are coloured by a parameter that governs the type of fracture observed, with positive numbers represent crack opening events and negative numbers represent closure events. Fracture orientation is defined by the apparent eccentricity in the representative ellipses, i,e., in plan view, ellipses for horizontal fractures tend to be more circular.

DFN Analysis

Utilizing approaches similar to that proposed by Gephart and Forsyth (1984), ambiguity in failure plane orientation can be reduced to identify the most likely fracture orientation associated with the DC events. By invoking seismic source models such as defined by Brune (1970), an effective measure of fracture dimensionality can be defined for DC events and similarly for non-shear tensile failures. In the example provided in Figure 1, event fracture types and dimensions are represented as a series of coloured discs. The overlap of the fractures can be used to define the degree of connectivity and further used to define the DFN. Together with the opening nature of the events, it is possible to show that the fluid migrates along these fractures.

Enhanced Permeability and SRV

As indicated above, by obtaining an estimate of fracture dimension and the general moment tensor, the orientation and magnitude of the fracture opening can be determined. To obtain a relative estimate of permeability of the DFN, a nearest neighbour statistical approach is utilized that considers both the individual fracture openings and fracture density. Permeability enhancement of the DFN generally can be shown to increase with the fracture opening and spacing between fractures. As shown in the example in Figure 2, permeability enhancement (greater than zero) is not seen over the observed volume of seismicity, suggesting that all events do not effectively contribute to an enhancement in permeability. In this case, the enhanced permeability represents the likely volume ($1.6x10^6$ m^3) for production. In essence, this volume represents the stimulated reservoir volume or SRV and is a better representation of the stimulated volume than just considering the overall dimensions as defined by the event distribution.

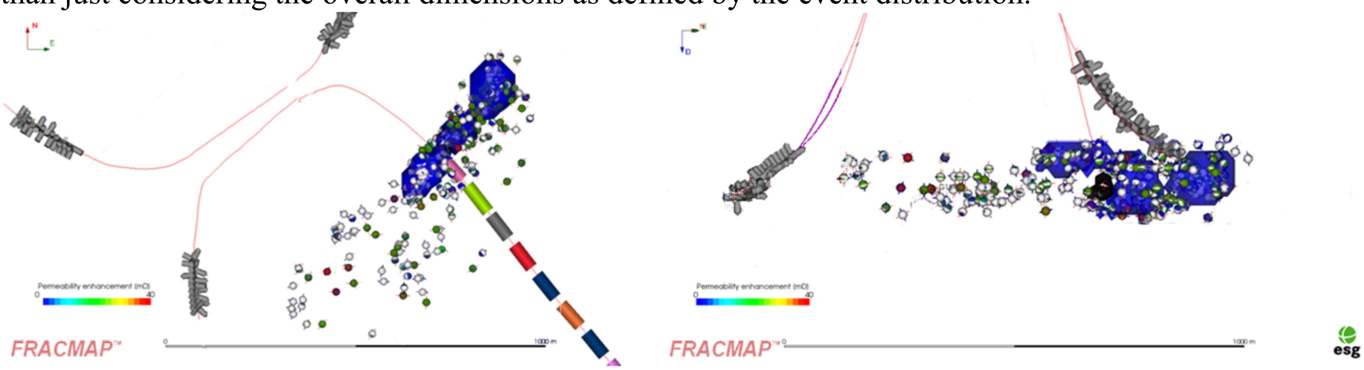

Figure 2: Iso-surface representing the enhanced permeability for a stimulation in both plan and cross-sectional views.

PDR

As shown, spatial patterns in stimulation derived from SMTI modes in combination with treatment data can help optimize fracture design for future fracture designs. Temporally, changes in SMTI behaviour can also be considered to provide information on the effectiveness of the stimulation program. Here, we define Points of Diminishing Return which are temporal points within the fracture when further pumping of the same treatment style is no longer effective in, for example, extending the fracture length. PDR also therefore defines the point where leak-off conditions dominate the fracture system. By identifying the PDR, an opportunity exists to maximize operations by changing the treatment program to, for example, a filling type treatment to improve proppant distribution and increase fracture conductivities. In the example provided in Figure 3, three time periods are shown representing different points in the stimulation program. In the first time interval, the pad stage, the fracture network was established with events dominated by crack opening failures. As the stimulation proceeds, the inter-connectivity of the fractures is established and natural leak-off conditions exist. As a result, the majority of observed failures are crack closure events. In the third time period, the addition of a mesh proppant was used to re-establish an opening regime (an increase in the number of observed opening failures). These observations suggest that the pad stage was too large, and the stimulation program could have benefited from the introduction of a low concentration of proppant earlier in the fracture treatment.

Conclusions

SMTI analysis offers a window into the treatment of a hydraulic fracture that is unavailable in the first-order analysis of location and magnitudes of microseismic events. In the examples of this paper, the moment tensors imply a discrete fracture network through which fluids and proppant travel through to enhance the permeability of the reservoir. Careful interpretation of the spatial variability of these mechanisms leads to the conclusion that the true SRV is not simply the envelope of the microseismicity, but only where there is a dominance of opening events. Furthermore, the temporal behaviour of these mechanisms can be compared to the treatment parameters to infer how fracture stimulations may be optimized.

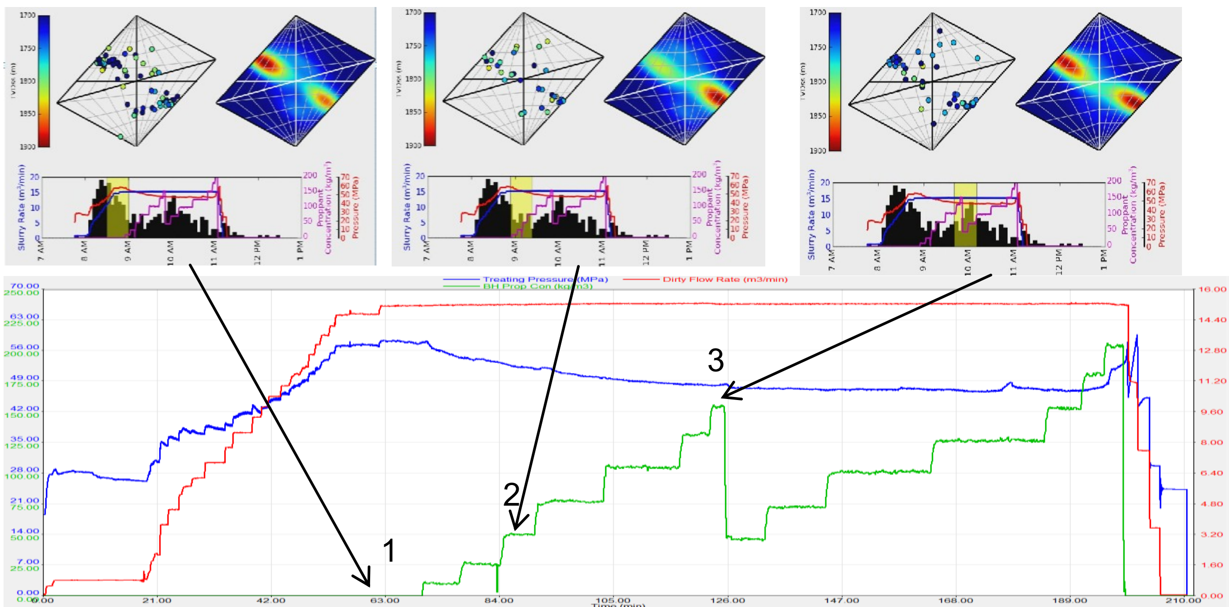

Figure 3: Top views showing the failure types at three time periods of the stimulation corresponding to different PDR. Event failures types are shown on Hudson plots where events plotted to the upper left represent crack opening dominated failures whereas events to the lower right are are indicative of crack closure dominated failures. The lower view provides the engineering data (pressure, flow rate, and proppant concentration) for the stimulation.

References

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