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Towards Using Seismic Moment Tensor Inversions to Infer Reservoir Rock Properties

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Summary

Seismic moment tensor inversion is a tool used for high quality microseismic data that reveals the mechanisms responsible for the observed events. Not only do these mechanisms have styles that tend to be consistent with the opening, closure and slip of fracture planes, but careful analysis of the data will suggest different fracture plane orientations that are present in the data. These orientations can be used to define a discrete fracture network, together with an estimate of the size of the events. The variety of these orientations can also show how the rock is breaking, and the more distinct orientataions that are activated can relate to the overall brittleness of the rock.

Introduction

Hydraulic fracturing of low-permeability formations seeks to enhance the reservoir drainage characteristics through the creation of a discrete fracture network, propped open with sand or other proppants. The complexity of these fracture networks is very dependent on the rock properties of the formations: ductile formations are thought to generate more linear fracture geometries compared to more brittle formations favourable to the creation of a complex and interconnected discrete fracture network. The degree of brittleness in a formation is largely controlled by the Poisson's ratio, with lower numbers being considered more brittle and higher more ductile. Variations in this quantity (or more generally, the stress-strain tensor) through the reservoir have been invoked to explain the variations in microseismic activity observed in treatments with a strong event asymmetry or complicated geometries.

Seismic moment tensor inversion is a method that is being increasingly used to characterize the microseismic events recorded during such stimulations. By taking the microseismic signals recorded across a number of different azimuths, and back-projecting these signals to the event's source, the failure mechanism representing that source may be attained. Careful interpretation of these mechanism can determine the style of failure as well as the geometry of the failure plane allowing for the determination of the dominant fracture sets that a treatment is activating and the degrees of connectivity shown in the dataset. The determination of these fracture sets can provide constraints on the rock properties controlling the growth of these fractures in the reservoir.

Seismic Moment Tensor Inversion and Fracture Orientations

A waveform from a microseismic event can be considered to be the convolution of a source and a Green's function, describing the propagation of the event away from the source. The source term contains a directivity described by the moment tensor that, in turn, describes the radiation pattern of the P and S waves away from the event's hypocentre. The careful measurement of the amplitudes and polarities of the P, SV, and SH waveforms across a well-distributed array of geophones samples each of these waveform's radiation patterns after back-projecting these observations to the microseismic source.

The moment tensor itself can be represented as a 3X3 symmetric matrix of force couples, meaning that any other decomposition of moment tensor must require 6 independent parameters. One alternate decomposition is to describe the size of the event with one parameters, the moment; the orientation of the moment tensor with three parameters describing the angles comprising the orthogonal set of strain axes, compressional (P), tensional (T) and intermediate (B); and two parameters that control the deformation style or source type of the event. These source-type parameters, k and T, control the volumetric component of the deformation and the sense of the compensated linear vector dipole (CLVD), and detail how the deformation style varies from the double-couple (DC) model of motion that successfully described the vast majority of tectonic earthquake mechanism. These last two source type parameters are frequently plotted on the source-type plot introduced by Hudson et al. (1989). Most events involving the activation of a fracture plot on this representation in the corridor from “tensile crack opening” through “DC” to “tensile crack closure”. In other words, simple mechanisms involving opening, slip or closure of a fracture plane are easily distinguished on these plots, and these plots provide a link to the model of failure and the moment tensor.

The process of going from a moment tensor to the orientation of the fracture or fault that was activated to cause the event is problem that involves consideration of the source-type as well as the angular orientations of the moment tensor. For double-couple events, there has been much discussion on how this process is best accomplished since for any single event, two possible solutions are equally valid. In order to disambiguate these fracture planes, Gephart and Forsyth (1984) considered the best fitting stress orientations implied form the moment tensors in a given volume and period of time and further considered then for each candidate fracture plane, which one was most likely to fail under those stress conditions. For opening and closure events, the situation is simplified: the fracture plane will be normal to the T and P axis of the moment tensor, respectively. This decomposition (together with a description of the source radius by reference to the penny-shaped crack models described by Brune(1970) and Walter and Brune (1993)) allows the construction of a discrete fracture network as shown for a single stage in a hydraulic fracture treatment.

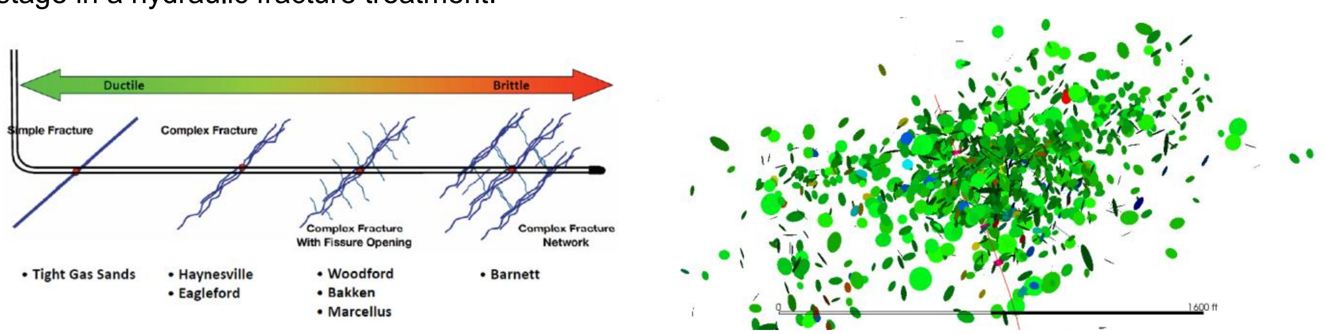

Figure 1 (left) After McKeon (2011). A cartoon showing how brittleness affects the induced fractures in a number of US shale plays and tight gas sands. (right) The discrete fracture network from a stimulation of a shale reservoir as constructed from the SMTI interpretation of the microseismicity.

Relating Moment Tensors to Mechanical Brittleness and Fracture Sets

McKeon (2011) relates the complexity of the induced fracture network to the brittleness of the reservoir, noting that the complexity of the fracture network is favourable for the drainage characteristics of the reservoir (see Figure 2). On the right side of the figure, we show in plan view the induced fracture network from one stage of a hydraulic fracture treatment of a shale formation. Each event is depicted by as a penny-shaped crack so, in plan view, if the event is activating a vertical fracture, we are looking edge-on to the fracture and it appears highly elliptical. Horizontal fractures, in contrast, look circular in this viewpoint. The variation in fracture orientations from this particular stimulation shows that the rock is undergoing brittle deformation. Figure 2 shows the stereographic projection of the contour densities of fracture azimuths showing that two fracture sets are dominant: one with a strike of 340° and dipping 50° and the other oriented 60°/50°. A sub-horizontal set of fractures is also evident in this view, potentially representing the role of bedding planes in contributing to the Discrete Fracture Network (DFN), as are a couple other clusters.

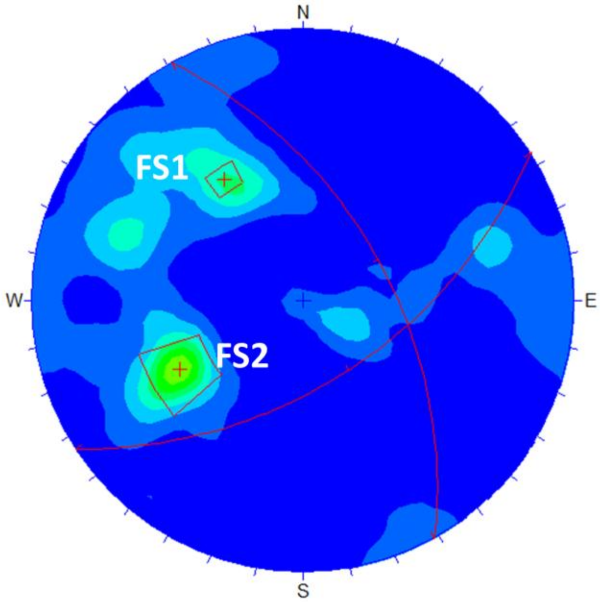

Figure 2 A stereographic project of the poles to the planes of the DFN shown in figure 1. Two dominant fracture orientations are shown, enclosed in red boxes and the fracture planes normal to these clusters of poles is shown as well. These fracture sets are FS1: 60°/50°, FS2: 340°/50° in strike/dip.

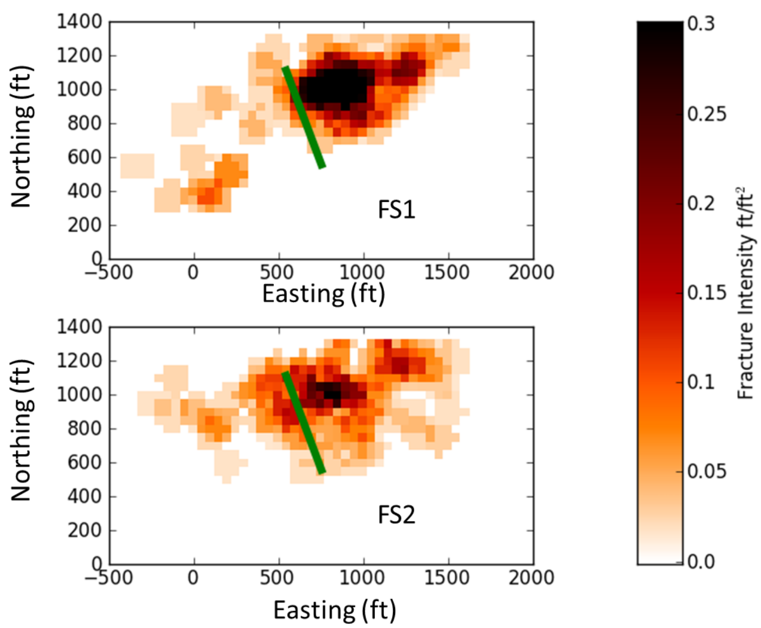

Figure 3 Fracture intensities for FS1 and FS2 in relation to the perforation interval (marked in green) for the treatment shown in figure 1.

In order to better estimate the role of a variable fracture network in a brittle formation, we can show the fracture intensity for these dominant fracture sets. The fracture intensity is defined as the total fracture length per unit aera in a volume. In Figure 3, we show this fracture intensity for the two fracture sets identified in Figure 2. Both of the intensity plots for these fracture sets show the highest intensities to the east of the perforation cluster, therefore indicating that the most brittle deformation is in this area. FS1 also appears to be more intense than FS2 in this area which could indicate a difference in fracture spacing in this area; more fracture length for FS1 is being activated here suggesting that the fracture spacing for this set is longer than that for FS2 which has a lower fracture intensity. Comparing fracture intensities in this way may give us insights into the key block sizes in the reservoir.

Conclusions

Moment tensor inversion allows for a link to be made between rock properties like brittleness and the recorded microseismic waveforms through the creation of a discrete fracture network. The example examined shows how the fracture intensities of different fracture sets shows where the most brittle deformation is being generated in the reservoir and therefore where the most effective drainage should be taking place during production. The relative intensities between the fracture sets also may indicate the key block sizes involved in the deformation.

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