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Utilization of SMTI Approaches to Characterize Fracture Spacing: Significance of Fractal versus Periodic Fracturing in Extending Fracture Networks

Katherine Bosman, Ted Urbancic, Ellie Ardakani, Adam Baig
ESG Solutions

Summary

We apply a methodology developed by Gomez (2007) to analyze the spatial organization of fractures along a scanline. Rather than giving a single value of average fracture spacing, this method compares the fracture set to an equivalent randomly-spaced fracture set to determine the length scale(s) at which it is significantly different from random. This analysis can also provide insight into whether a fracture set displays periodic, clustered or fractal characteristics (or some combination of these). We apply this methodology to a microseismic dataset acquired in a North American shale play to determine the spatial organization of two different fracture sets observed during stimulation of one hydraulic fracturing stage. The resulting information is used to assess the significance of different types of spatial organization in the growth of a stimulated fracture network during hydraulic fracturing treatments.

Introduction

Due to the very low matrix permeability observed in most unconventional petroleum reservoirs, the industry has concluded that reservoir permeability (and thus the most important source of production) is determined by the fracture network in the reservoir. This fracture network may be characterized in a number of ways. Image logs provide a direct measurement of subsurface fractures, but only in the immediate vicinity of logged wellbores. Exploration seismic data can illuminate some larger-scale fracture structures (such as faults), as well as volumes which are likely to contain significant numbers of smaller fractures. Combining some of the advantages of both these methods, microseismic monitoring provides information about the fractures stimulated by reservoir treatments, such as hydraulic fracturing, and the extent of fracture growth away from the wellbore.

By performing moment tensor analysis on high quality microseismic data, we are able to obtain the orientation and size of stimulated fractures, as well as where they occur in the reservoir. Fractures may then be grouped into fracture sets based on their orientation. Subsurface fractures tend to occur in sub-parallel sets throughout a lithological or mechanical unit. Geological description of such fracture sets generally consists of an average orientation and a single value of average fracture spacing in the volume of interest. This implies the assumption that fracture sets are approximately evenly spaced, which is not necessarily true. Using a methodology developed by Gomez (2007), we can further investigate whether the spatial organization of the fracture sets we observe is random, periodic, clustered, fractal, or some combination of these characteristics.

Methodology

To determine the failure mechanisms, we perform Seismic Moment Tensor Inversion (SMTI: Urbancic et al, 1993; Baig and Urbancic, 2010) on microseismic data. For shear and mixed-mode failures, there are two potential fracture planes identified by the moment tensor. To resolve this ambiguity, we perform stress inversion for a collection of events assumed to have failed under a consistent stress state (Gephart and

Forsyth, 1984; Vavryčuk, 2014). By determining the stress state under which this group of events occurred, we can evaluate for each potential fracture plane the slip direction determined from the moment tensor relative to the shear stress imposed on the plane to assess which fracture plane is most likely to have failed for each event. The size of each fracture plane is estimated using the dominant frequency of the recorded seismic signal and a penny-shaped crack model similar to that proposed by Brune (1970, 1971) and Walter and Brune (1993). Figure 1 shows the discrete fracture network (DFN) of penny-shaped fractures determined for the example dataset used in this study. The fracture planes are coloured by their failure mechanisms: warm colours indicate fractures with tensile opening components of failure, green indicates double couple or shear failure, and cool colours indicate fractures with tensile closing components of failure.

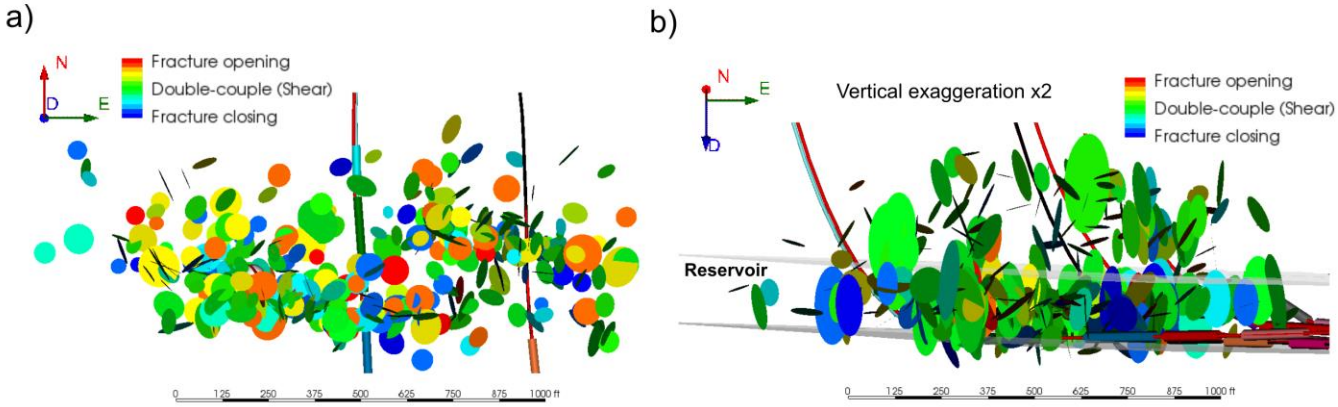

Figure 1: Penny-shaped fractures determined from SMTI analysis of one stage of a hydraulic fracturing treatment. (a) Plan view, and (b) depth view with 2x vertical exaggeration.

For each identified fracture set, we use a scanline sampling method to determine the relative positions of each fracture. These positions along the scanline are used as input for the spatial organization analysis described by Gomez (2007). We determine the distance, perpendicular to the dominant fracture orientation, between each pair of fractures (not solely adjacent fractures). These distances are then binned by length scale to obtain what is termed the correlation count. An analytical expression (given in Gomez, 2007) is used to obtain the correlation count for an equivalent randomly-spaced fracture set, which is then used to normalize the correlation count of the real fracture set, giving the normalized correlation count (NCC). We use a Monte Carlo-type approach to determine ±95% confidence limits for the NCC of a randomly-spaced fracture set. The NCC of the real fracture set is said to be significantly different from random at length scales where it exceeds the +95% confidence limit or is less than the -95% confidence limit.

Case Study Results

For this case study, we have analyzed a microseismic dataset recorded during one stage of a hydraulic fracture treatment in a North American shale play. The DFN resulting from SMTI analysis is shown in Figure 1. The majority of events are well-contained within the reservoir, with a small portion of the dataset showing some growth in to the overlying formation. Detailed analysis of this dataset has been performed in other work (Ardakani et al., 2017; Urbancic et al., 2017) and indicates that the out-of-zone growth is likely due to a buildup of stress in the reservoir during the treatment. The failure mechanisms show a mix of shear and tensile components, with most events showing tensile opening components of failure. Two dominant fracture sets are observed: a sub-horizontal set, and a dipping fracture set with average strike of 120° and average dip of 40°.

As input for the spatial organization analysis, we define a “fracture set” as all fractures with normal vectors (poles) oriented within 30° of the dominant fracture orientation pole. Figures 2a and 2b show the poles to the fracture planes included in each of the two fracture sets.

Figures 2c and 2d show the NCC calculated for each of the two fracture sets, along with the corresponding ±95% confidence limits and the average NCC for a randomly-spaced fracture set, as obtained from the Monte Carlo-type approach described above.

The NCC for the dipping fracture set (Figure 2c) shows a number of significant peaks in fracture spacing, at approximately 4, 12, 24, 38, 60, and 100 ft. This appears to indicate a roughly periodically-spaced fracture set, with the dominant fracture spacing at approximately 4 ft.

The NCC for the sub-horizontal fracture set (Figure 2d) shows elevated values over a wide range of length scale: approximately 3 to 37 ft, with a separate small peak at about 52 ft. The NCC values between 3 and 37 ft gradually decrease in a roughly linear fashion. Comparing to the type-curves given in Gomez (2007), we interpret this fracture set as having a fractal spatial arrangement in clusters up to 37 ft in width. These clusters are interpreted to be spaced approximately 52 ft apart.

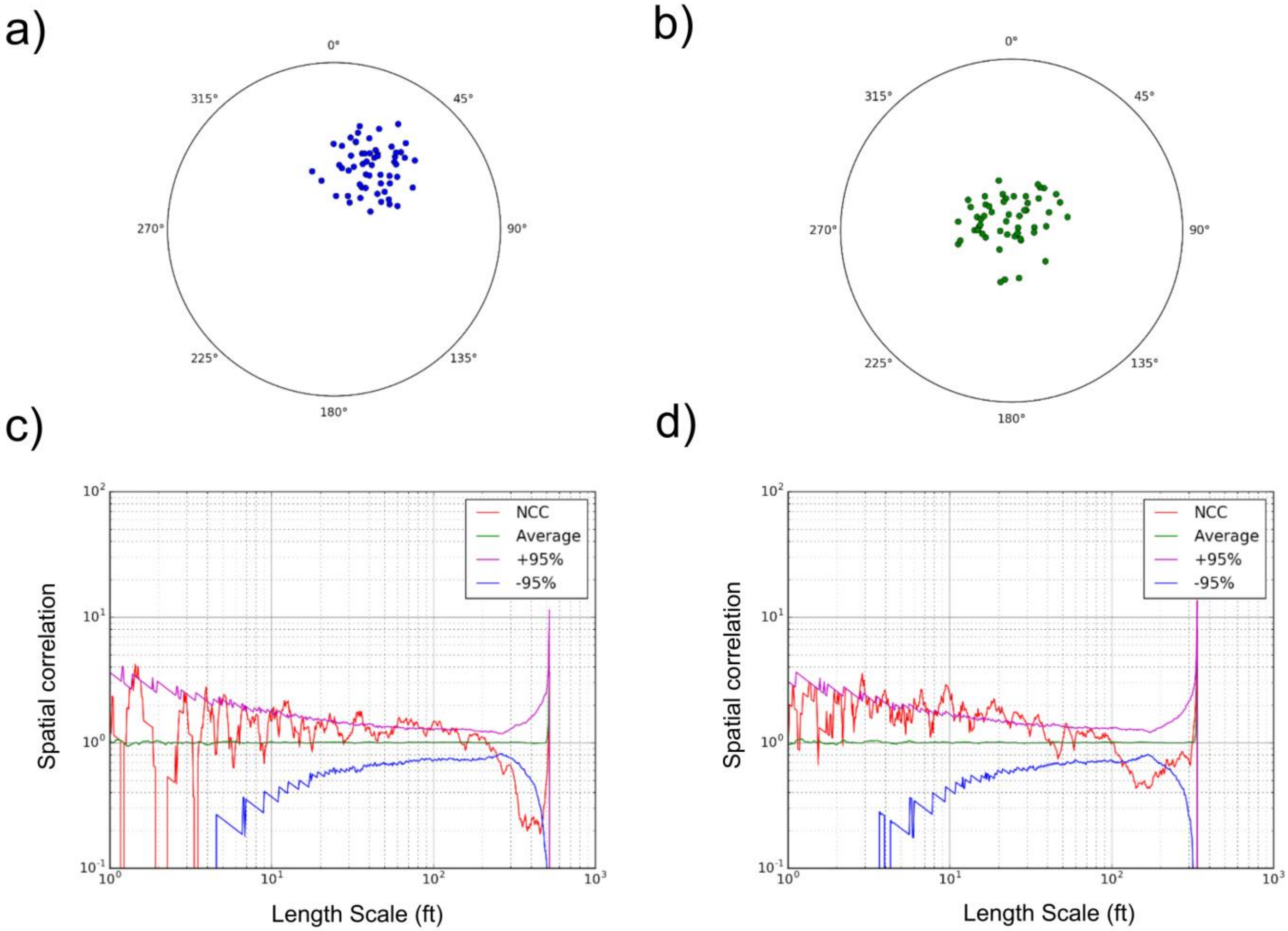

Figure 2: (a) and (b) show the poles to fracture planes included in each of the two fracture sets analyzed. (c) and (d), respectively, show the NCC calculated for each of these fracture sets.

Conclusions

The discrete fracture networks obtained through SMTI analysis of microseismic datasets provide an incredible amount of information about the processes occuring in the reservoir, and are continually proving invaluable in improving inputs for reservoir characterization models. This leads to an improved capability to predict future production, and will assist in optimizing future completions in similar geological setttings.

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