Differentiating Between Shear and Tensile Events Using Spectral Parameters

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Summary

Determining the source mechanisms of microseismic events that occur during hydraulic fracturing is important for understanding fracture evolution. Source mechanisms are typically determined via moment tensor inversion, which is a computationally expensive procedure. Tensile and shear events can have significantly different spectral characteristics, therefore it may be possible to differentiate between seismic source mechanisms based on their spectral content. In this study, we aim to differentiate between shear and tensile events using corner frequency analysis. Corner frequency ratio does not appear to be a strong discriminant between tensile and shear events, however two clusters of predominantly tensile and predominantly shear events can be identified from their S-wave corner frequency alone.

Introduction

Microseismic events recorded during hydraulic fracturing can have source mechanisms that range from shear to tensile in nature. As both types of mechanisms play a significant role in reservoir deformation, it is important to distinguish between events with different types of rupture mechanisms in order to understand how the fracture, and the corresponding stress field, evolves with time (Baig and Urbancic, 2010).

Source mechanisms are usually determined via moment tensor inversion (MTI) which is a computationally expensive and time-consuming process. In order to obtain a well-resolved moment tensor (MT) solution, the focal sphere of the event needs to be sufficiently sampled. However many hydraulic fracturing operations are typically monitored by only one downhole monitoring array; the aperture of which can only sample an extremely limited portion of the focal sphere. Therefore many monitoring set-ups are ill-posed for carrying out reliable MTI (Eaton and Forouhideh, 2011).

Various studies suggest that events generated by tensile and shear mechanisms may be distinguishable via their spectral content. For example, in comparison to shear events the spectra of tensile events are expected to have a lower frequency content with a more rapid high-frequency spectral falloff (Majer and Doe, 1986), higher S/P spectral amplitude ratios (Walter and Brune, 1993) and lower S/P corner frequency ratios (Kwiatek and Ben-Zion, 2013). These proposed spectral characteristics are likely a reflection of reduced rupture velocity and lower seismic efficiency. Spectral analysis could therefore potentially provide a faster and more reliable method to identify tensile sources than conventional focal mechanism inversion.

Spectral parameters can be determined in a variety of ways. In this study, corner frequency values obtained using the method of Snoke (1987) are used to try to distinguish between shear and tensile microseismic events recorded during hydraulic fracturing. A microseismic dataset with moment tensor solutions included in the microseismic catalog is used. The moment tensor solutions can be decomposed into source parameters that can aid in differentiating between the different modes of deformation. The source parameters obtained from the MTI are compared with the corner frequency values to determine whether shear and tensile events can be suitably identified.

Data

Microseismic data acquired during multistage hydraulic fracturing of two horizontal wells in the Barnett Shale, Fort Worth Basin, Texas is presented. The horizontal treatment wells were fractured in 18 sequential stages using a "zipper-frac" sequencing technique, and monitored by two vertical downhole arrays, with 40 three-component 15 Hz geophones in each vertical array. Over 7000 microseismic events (MSEs) were detected by the monitoring array and subsequently processed and analyzed by the microseismic vendor. Figure 1 shows the treatment and monitoring layout together with the microseismic event locations.

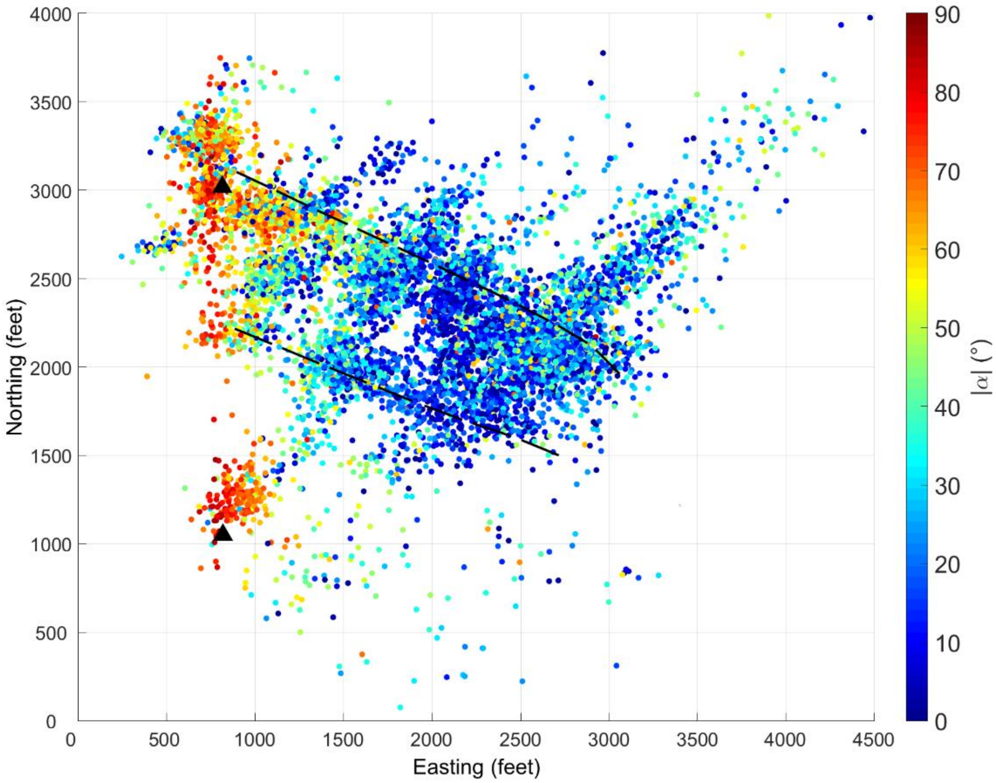

Figure 1: *Map view of the treatment stages (black lines) and monitoring array (triangles) layout together with the microseismic event locations (dots). The microsiesmic events are color-coded according to the angle α derived from the moment tensor solutions, which describes the inclination of the slip vector from the fracture plane.*

P- and S-wave corner frequencies (determined using the method of Snoke (1987)), moment magnitudes (M_w), and moment tensor (MT) solutions obtained via MTI are included in the catalog for each event. The MT solutions are decomposed into various source parameters using the methods of Vavryčuk (2001) to determine the source mechanism. A useful source parameter for distinguishing between tensile and shear events is the angle α, which describes the inclination of the slip vector from the fracture plane (Figure 2); A pure shear source, with slip parallel to the fracture plane is described by $\alpha = 0°$, whereas a pure tensile source with slip/opening occurring perpendicular to the fracture plane is defined by $\alpha = 90°$. Using α as a proxy for the type of source mechanisms, the MSEs can be described as ranging from being predominantly shear to predominantly tensile and exhibit a spatially distributed pattern across the reservoir (Figure 1). A zone of predominantly tensile MSEs can be observed at the toe of the wells suggesting significant extension within the reservoir in that region. A zone of predominantly shear MSEs is found mid-way along the well followed by a "hybrid" zone at the heel of the wells. This observed spatial variation is consistent with a transition in lithologic facies type within the reservoir midway between the toe and heel of the completion wells, with a carbonate submarine fan to the west and the primary reservoir rock (siliceous mudstones) to the east (Roy et al., 2014).

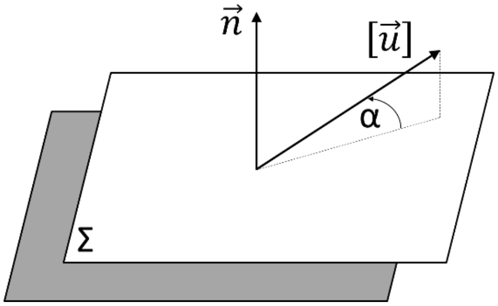

Figure 2: *Schematic model for a tensile earthquake. Σ is the fracture plane, $\vec{n}$ is the normal to the fracture, $[\vec{u}]$ is the slip vector at the fracture, α is the inclination of the slip vector from the fracture plane.*

The decomposed MT can also be divided into double-couple (DC), isotropic and CLVD (compensated linear vector dipoles) components. Tensile events are expected to have a small DC component, whereas shear events are expected to have a large DC component; therefore, the DC component should decrease with increasing α and should be another useful discriminant for differentiating between modes of failure.

Analysis and Results

An idealized far-field body wave spectra from a seismic dislocation on a small penny-shaped crack, has three distinguishing features: a low-frequency amplitude plateau, Ω_0, a corner frequency, F_c, and a high frequency spectral fall-off, n. Ω_0 is proportional to the seismic moment, and f_c can provide information about seismic efficiency as well as the rupture time/velocity at the source.

Magnitude inversely scales with F_c, so that F_c increases with decreasing magnitude. Figure 3 shows the relationship between the S-wave corner frequency, F_c^S , and M_w for the MSEs recorded during hydraulic fracturing. Two distinct clusters of events can be observed, which suggests that the source processes may differ between the clusters. Events in cluster 1, shown in red in Figure 3, have lower S-wave corner frequencies than events with similar magnitude values in cluster 2, shown in blue, suggesting that events in cluster 1 are less seismically efficient than events in cluster 2.

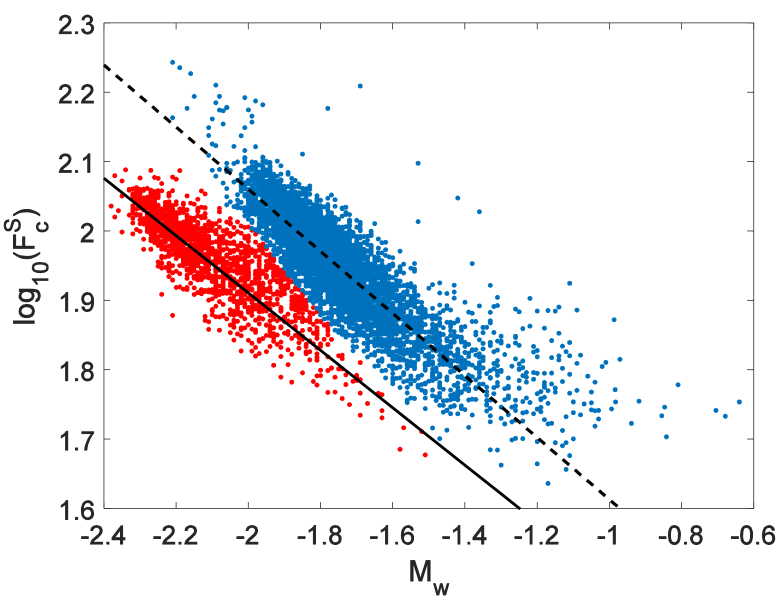

Figure 3: *Relationship between S-wave corner frequency, F_c^S , and moment magnitude, M_w, for over 7000 microseismic events. Two separate clusters can be identified; cluster one is shown in red and cluster two is shown in blue. The black solid line and black dashed line are the line of best fits for cluster one and cluster two, respectively.*

In order to further understand the difference between the two cluster of events, the source parameters α and DC, obtained through MT decomposition, are analyzed for the events in each cluster . Figure 4 demonstrates that MSEs in cluster 1 tend to have a higher α value and a smaller DC component than events in cluster two; thus suggesting that the MSEs in cluster 1 are predominantly tensile events and the MSEs in cluster 2 are predominantly shear events. Although there is some scatter in the observed source parameters for each cluster, this is to be expected due to the composite nature of MSEs.

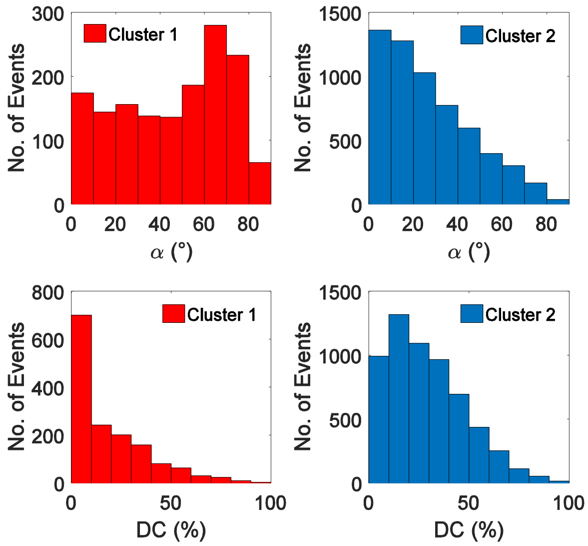

Figure 4: *Histogram of different source parameters for events in cluster one (left panels) and cluster two (right panels). Top panels: distribution of α, the inclination of the slip vector from the fracture plane. Bottom panels: distribution of the double-couple component (DC).*

Contrary to the hypothesis of Kwiatek and Ben-Zion (2013) and Walter and Brune (1993), the P/S corner frequency ratios do not appear to vary between the two clusters, and is therefore not a good discriminant.

Discussion and Conclusions

In this case study, the S-wave corner frequency alone is a better discriminant for differentiating between shear and tensile events than the P/S corner frequency ratio. Using the relationship between S-wave corner frequency and moment magnitude, two clusters of events can be identified and are subsequently analyzed both spatially and with respect to their source parameters (derived from MT solutions). The two clusters are differentiated into predominantly tensile and predominantly shear MSEs. The line of best fit that describes the linear trend between the $\log(F_c^S)$ and M_w for the predominantly tensile cluster of events (cluster 1) has a gradient of -0.41 and an intercept of 1.08, whereas the gradient and intercept for the predominantly shear cluster of events (cluster 2) is -0.44 and 1.16, respectively (Figure 3). Therefore for similar magnitudes the tensile cluster has lower S-wave corner frequencies than the shear cluster; hence, tensile events expend more energy in deforming the medium than radiating seismic energy and are thus deemed less seismically efficient (Walter and Brune, 1993).

Spectral analysis, specifically corner frequency analysis in this case, appears to be a useful tool for quickly differentiating between tensile and shear MSEs.

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