Seismic Moment Tensors: A Path to Understanding How Fractures Develop During Hydraulic Fracture Stimulations and Reservoir Injections

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Introduction

Seismic Moment Tensor Inversion (SMTI), especially for microseismicity induced by hydraulic fracturing or other reservoir injection programs, can be used to identify the failure components (shearing – double couple component and isotropic component) of individual events. In turn, their distribution spatially and temporally in response to fluid injections provide an opportunity to track the flow of fluids in the system and the microseismic response. In this presentation SMTI analyses were carried out for data recorded on optimally placed mutli-level multi-well downhole triaxial geophone arrays for events with good focal sphere coverage associated hydraulic fracture stimulations and cyclic steaming operations.

Method

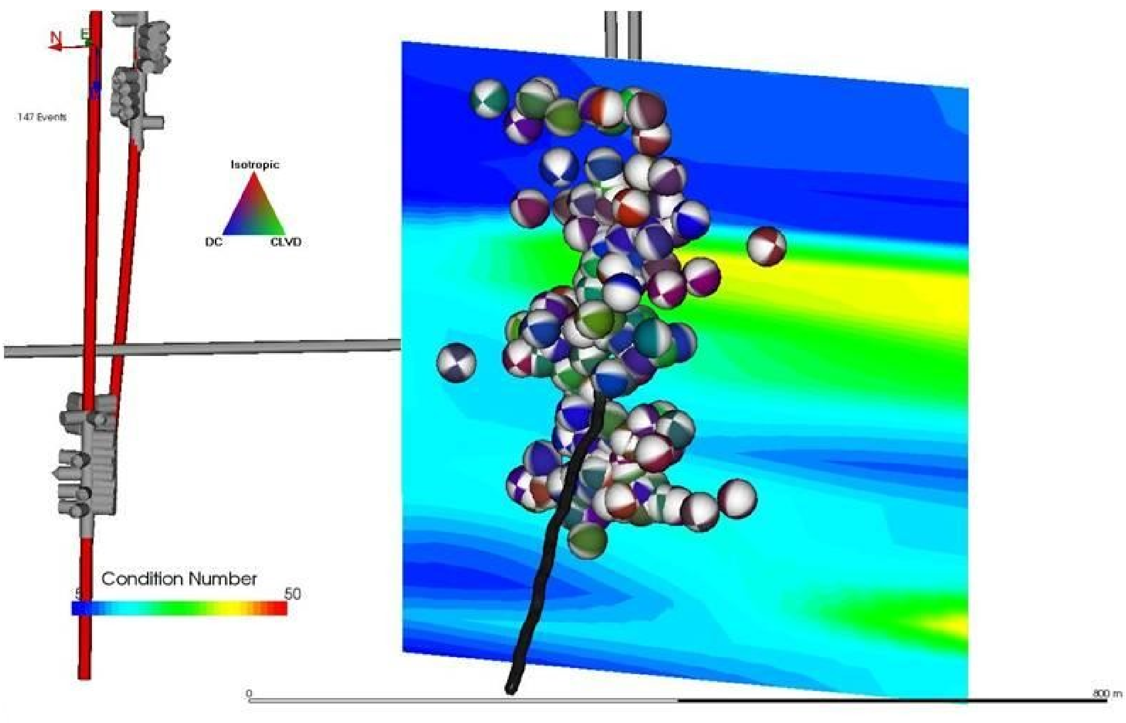

Figure 1: The moment tensors for events plotted with the condition number that determines how well one can invert for the mechanism of the event, scaled according to the colour triangle. The treatment well is in grey, the observation wells, in red and the triaxial sensors are the triads of grey cylinders.

As shown in the hydraulic fracture stimulation example provided (figure 1), the events themselves feature a variety of mechanisms, suggesting that the events cannot be considered as simple shear failures but include volumetric components of failure. To further enhance our understanding, a source mechanism k-T type plot was used, where both k and T vary between -1 and 1 (figure 2). In figure 3, k-T analyses are provided for three different treatments in the same field. In the top left (red), there are a wide variety of mechanisms showing a complex fracture behaviour. To the top right (blue), although the data are sparse, we observe a small cluster of events representing crack openings and a larger cluster representing crack closures. This type of pattern is also seen in the lower-left source-type plot (green). Differences in behaviour for these datasets, as seen in the adjoining histogram, show a higher proportion of double-couple events in the red dataset as compared to the others, indicating that the events here are generated by a different process, suggesting a possible re-activation of a pre-existing fault-fracture set.

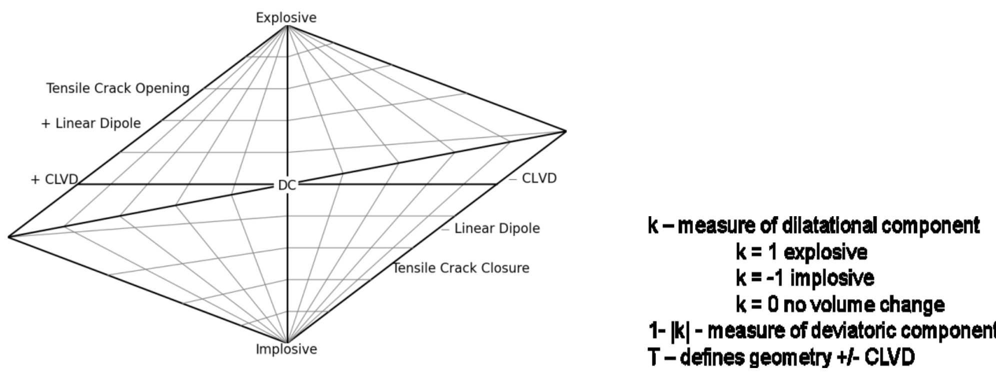

Figure 2: A source-type k-T diagram, which is used to define different the proportion of DC, CLVD and isotropic contributions to the moment tensor.

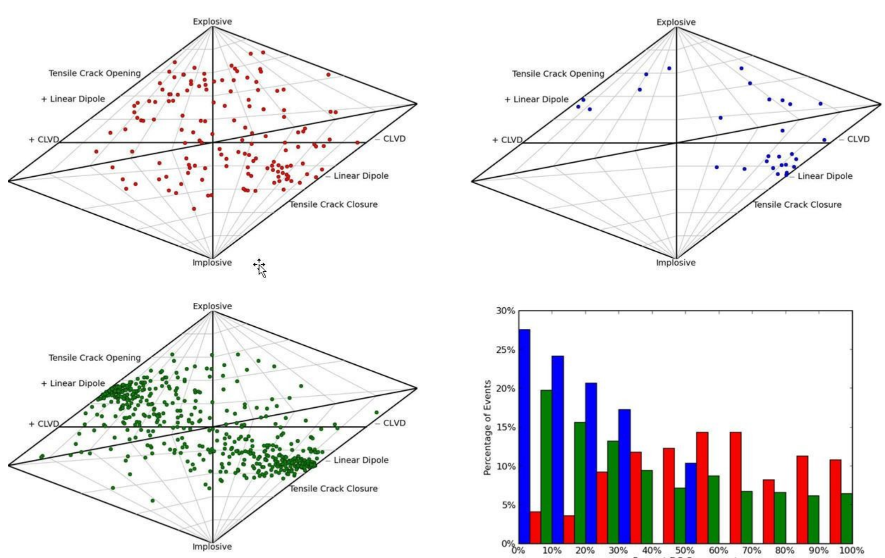

Figure 3. Source-type diagrams for three different hydraulic treatments from the same field. The histogram indicates the proportion of events with a given amount of double-couple component for the three datasets, the colour of the bars corresponds to the colour of the point in the source-type plots.

Examples

In figure 4, four different time windows, roughly corresponding to different proppant injection periods, are used to describe the changing fracture development during the treatment. The events associated with the first proppant injection are dominated by crack opening events. The scatter-plot of events shows that most of the events here are close to the treatment well. Subsequent to this time period, most of the events still cluster to the crack opening axis with some events occurring farther away from the well. However, a significant amount of events begin to cluster around the crack closure axis, close in to the well. The third interval corresponding to the start of a second phase of proppant injection, events cluster near the poles of the crack opening/closure axis, but now the majority are closure-type failures. However, the same trend of is observed in the locations of the events: the events are distributed even farther away from the well, with the farthest opening events still outpacing the closure events. Finally, at the end of the treatment, closure-type events are dominant. The farthest out events in each phase of the treatment are progressing the fracture further away from the well and are uniformly crack-opening type mechanisms. Behind this fracture front, the region in the vicinity of the well shows a transition: initially fractures are expanded generating opening type events and then relax back with closure-type mechanisms. There is also closure front, defined by the maximum offset of the crack-closure events, behind the breakout front that progresses more slowly.

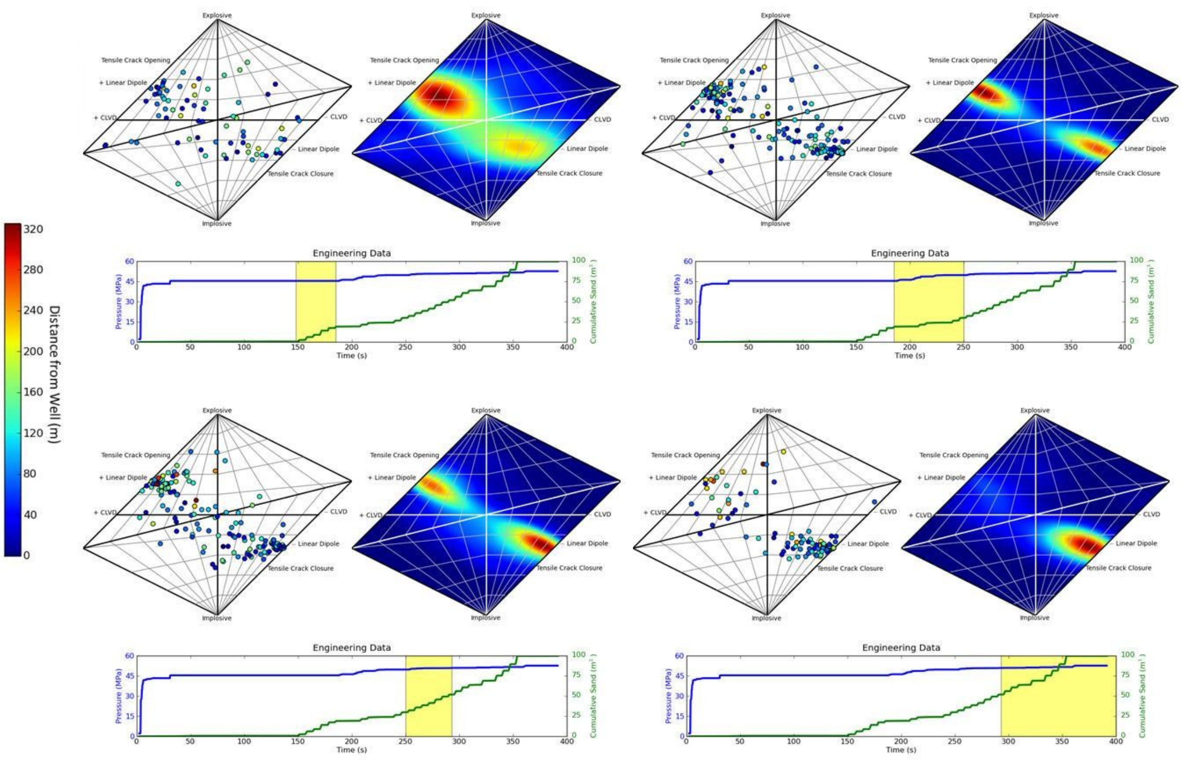

Figure 4. Time based representation of the treatment as scaled by the injection pressure. In the density contour plot red are areas of high density; the scaled pressure and proppant volume are shown along with the time window in yellow.

An SMTI analysis of events recorded during a cyclic steam injection are shown in Figure 5. Similar to observations for the hydraulic fracture treatments, the failure or growth of the steam chamber outline a complex fracturing process, with many events showing isotropic components of failure. Interestingly though, the observed trends show a dominance of explosive mechanisms, that occur early during the steaming cycle, trending towards implosive events later near the end of the steaming cycle. These observations suggest that the complex fracturing process is more volumetric in nature than observed during hydraulic fracturing.

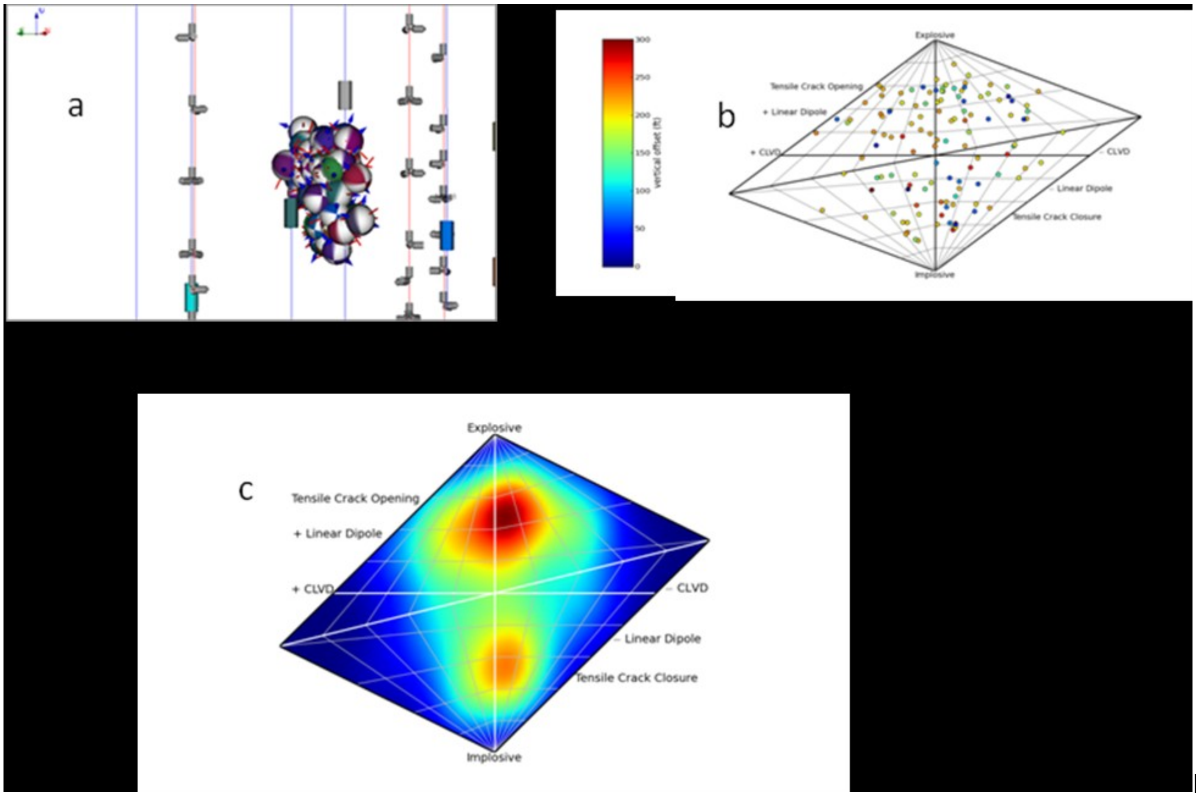

Figure 5. a) Distribution of events and their mechanisms associated with a reservoir based steaming injection program. Colour coding is as provided in Figure 1. b) Distribution of events on k-T source-type plot scaled by vertical position relative to the injection interval for steam injection related events. c) Contoured distribution of observed failure components for events related to a steaming operation.

Conclusions

In summary, the monitoring of microseismicity related to hydraulic fracture stimulations and reservoir injection programs typically focuses on deriving event locations and the relative magnitude of events. As we have shown here, there is a wealth of additional information that can be obtained about the events themselves Further by investigating the spatial and temporal variations of these failure components, a more definitive image of fracture development can be realized. The effective relation of pressure, proppant volume and injection rates, as seen, can be examined in the context of the observed seismic response, providing an opportunity to assess the effectiveness of the prescribed program. Further, these additional analyses provides an opportunity to both validate and calibrate numerical models to enhance production.

Determining the stress-strain state and fracture orientations allows for the resolution of progressive frac growth, such as we suggested by invoking an en-echelon fracture distribution along the maximum horizontal stress orientation. Further investigation of the individual strain components reveals the complexity of the individual failures but more importantly, by looking at the spatial and temporal variations of these failure components, a more definitive image of fracture development can be realized. The effective relation of pressure, proppant volume and rates, as seen, can be examined in the context of the observed seismic response, providing an opportunity to assess the effectiveness of the stimulation program. Further, it provides the opportunity to develop numerical models that can be used to predict the behaviour of the stimulation program. Of course, microseismic monitoring may then provide an approach to both validate and calibrate numerical models to enhance production.