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What Does Microseismic Tell Us About Hydraulic Fractures?

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Summary

Microseismic imaging has proven valuable in imaging hydraulic fracture geometry. However, the relationship between the microseismic deformation and the geomechanical response of the rock to the hydraulic fracturing process needs to be properly understood in order to exploit additional microseismic attributes to better characterize the hydraulic fracture. Here, observations are given that shows that the microseismic deformation represents a high-frequency, predominantly shearing and small proportion of the deformation in contrast with the slow, predominantly aseismic, tensile hydraulic fracture opening. A common engineering interpretation of the hydraulic fracture effectiveness is the total stimulated volume of the reservoir, typically based on the microseismically active volume. The volume of the microseismic cloud is shown to represent an overestimation of microseismic deforming volume depending on the microseismic location uncertainties, which in turn can include stress induced deformation and so is an upper limit on the hydraulically created fracture volume. The microseismic does describe the relative proportion of the geomechanically deforming rock and when interpreted in light of a complex fracture mechanics model can be used to estimate the extent and effectiveness of the open, flowing hydraulic fracture.

Introduction

Microseismic (MS) imaging of hydraulic fractures has become a routine engineering tool to assess hydraulic fracture geometry. Typically the MS locations are used to interpret the fracture height, length, azimuth and fracture complexity in terms of a simple, planar fracture or a complex fracture network. However, the MS source characteristics can also potentially provide more insight into the fracturing process. In order to extract additional fracture information from the MS data, it is critical to have a contextual framework to interpret the MS relative to the geomechanical deforming rock around the hydraulic fracture. Nevertheless, little information existing about the rock physics of MS deformation relative to the hydraulic fracture. In this paper, a number of general observations are given to help clarify the relationship between the hydraulic fracture and MS, and attempt to clarify how much can be interpreted directly from just the MS as well as how it can be used in conjunction with other data sets such as geomechanical fracture mechanics models.

Hydraulic Fracture Stimulation Characteristics

The MS activity is a representation of the geomechanical deformation of the hydraulic fracture stimulation. Stimulations designs vary widely using injections of various fluids and proppants material of various types (intended to keep the fractures open after the injection stops) at various injection rates and treating pressures. At the start of the stimulation, increasing treating pressure result in very low injection rates until the pressure reaches the tensile stress slightly exceeding the minimum principal stress at which time the injection rate suddenly rapidly increases at approximately constant pressure (so-called 'breakdown pressure'). At the breakdown pressure, the resulting fracture is most likely a tensile parting of the rock. Consider the frequency spectra of a typical injection pressure record from a two hour long stimulation

(Figure 1). Notice that most of the power corresponds to very low frequencies relative to normal MS bandwidths (few to several hundred Hz). The geomechanical deformation around the hydraulic fracture will be driven by the treating pressure first breaking the rock and then slowly pushing the fracture faces apart, with the fracture opening a direct hydraulic linkage to the treating pressure. Based on the frequency spectra this would likely be a 'slow', low frequency process relative to 'fast', higher frequency MS bandwidths, and likely be 'aseismic' (i.e., not seismically recorded). While the initial parting of the rock at the fracture tip could be localized and 'fast' (i.e. within the MS bandwidth), most rocks are weak in tension and unlikely to produce significant instantaneous movements required to cause detectable MS signals. Conversely, after the end of the stimulation, the fracture will partially close and could be associated with post-injection MS activity. However, very little MS activity is typically recorded post-injection and the activity rate generally tends to quickly decline. Furthermore, the hydraulic fracture remains fluid filled post-injection and would naturally resist 'fast' localized closing events, in the same way that it is difficult to make noise by rapidly clapping hands underwater. Further evidence of significant aseismic deformation can be inferred by comparing total MS energy with the hydraulic energy of the injection. Fracture models show that the hydraulic injection energy is approximately the same as the energy associated with the geomechanical deformation of the fracture opening (Maxwell et al., 2009). However, comparisons of total MS energy with the hydraulic energy result in ratios as high as 10^{-5} but more commonly around 10^{-9} (Maxwell et al., 2009). The implication of these low ratios is that MS represents only a small component of the total deformation, and most occurs aseismically.

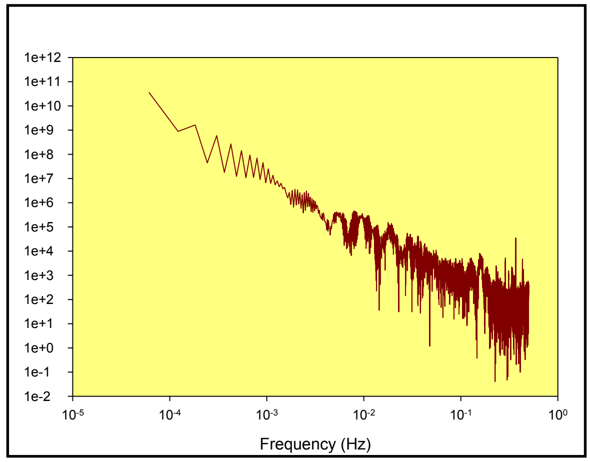

Figure 1. Frequency spectra of a typical injection pressure record.

Microseismic Mechanisms

Further insight into the geomechanical response of MS deformation can be gained by considering the source mechanisms. Recently there has been growing investigation of moment tensor inversion where the MS directionality of the source radiation pattern is used to determine the coseismic source deformation. Moment tensor quantifies if the MS source represents shearing, tensile parting, and/or a volumetric expansion (see for example Leaney and Chapman, 2009). While seismic moment tensor inversion is common for tectonic earthquakes monitored with seismographs deployed around the source, hydraulic fractures are often monitored with sensors in a single monitoring borehole. Even in cases where multiple observation wells exist, robust moment tensor estimation remains a challenge due to signal-to-noise ratio, location uncertainties, transmission and recording characteristics. Despite the attractiveness of using moment tensor inversion to reconcile the MS with the tensile hydraulic fracturing and improve the understanding of the geomechanical response, little effort so far has been made to quantify the confidence in moment tensor inversion results. While moment tensor inversion may appear attractive in terms of assessing hydraulic fracture effectiveness and potentially the ability to quantify the fracture opening and closing, it is important to remember that

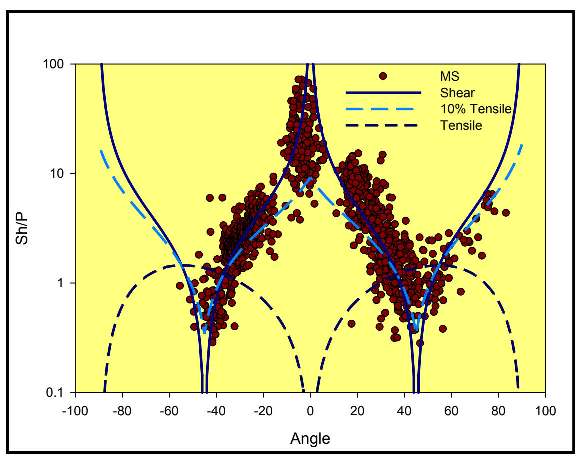

Figure 2. Composite amplitude ratio plot with various source mechanism models.

the actual hydraulic fracture opening/closing is probably aseismic.

Rutledge et al. (2004) describe forward modeling of s to p-waves amplitude ratios for a collection of events. Assuming that the mechanism is consistent for the events, these composite amplitude ratio plots are an effective means of both increasing the directional coverage of the radiation pattern and allowing simple assessment through the quality-of- fit of the mechanism model with the observed data. In other words, a composite mechanism plot offer the advantage of easy visual assessment of model fit which is something that is lacking in the majority of most full moment tensor inversion investigations. Furthermore, the s/p amplitude ratio is a robust attribute, since the normalization tends to cancel many of the conventional challenges of moment tensor. Figure 2 represents horizontal s- to p-wave amplitude ratio of high signal-to-noise ratios signals from several hydraulic fractures from different projects in a variety of sites. For each the azimuth relative to the main trend of the MS cloud is used. Also shown is the forward model results for various source mechanisms: a strike-slip shear fault with a fracture plane along the direction of the main trend of the MS cloud, a mixed strike-slip shear fault with 10% tensile opening, and a pure tensile opening. Notice that the strike-slip shear mechanism provides a good fit to all the data, and that the 10% tensile mechanism is not able to model the highest observed amplitude ratios. The pure tensile mechanism is inconsistent in amplitude ratio at most angles and in particular inconsistent with the high s/p amplitude ratios. While not all projects are well modeled by a single strike-slip model, the high observed s/p amplitude ratios is indicative of a shear MS mechanism being prevalent in a number of projects.

The shear MS deformation mechanism raises a paradox with respect to the tensile hydraulic fracturing (although again remember that the MS only represents a small percentage of the deformation). Furthermore, the hydraulic fracture will tend to form orthogonal to the minimum principle stress direction and by definition should have no resolved shear stresses in that direction. Three possible mechanisms can be conceived to reconcile the shear MS mechanism with a tensile hydraulic fracture and likely each account for some component of the MS deformation in any given project: stress induced failure near the fracture tip, fluid leak-off into pre-existing fractures, or 'dog-legs' created by interaction of the hydraulic fracture with pre-existing fractures. Note that these mechanisms could be associated either with shearing along planes sub-parallel to the hydraulic fracture or orthogonal to that direction in the conjugate fracture direction. Nevertheless the MS deformation provides a valuable constraint to geomechanical simulations, along with information about the orientation(s) of fracture planes to help interpret fracture complexity.

Stimulated Versus Deforming Reservoir Volume

Several fracture models are available to completion engineers to simulate simple, planar hydraulic fractures. However, MS images often show complex fracturing which require more sophisticated models including the ability to simulate the geomechanical interaction between the hydraulic fracture and pre-existing fractures. While these complex fracture models are now becoming available, several earlier studies focused on quantifying the total simulated reservoir volume (SRV) from the MS active volume and empirically relating these values to the well production. While reservoir simulations showed that the SRV was related to surface contact area with the reservoir and ultimately production rates and reservoir drainage, although other factors including the fracture density are also important. Consider various fracture dimension realizations that are relevant to interpreting hydraulic fractures as shown in Figure 3 (here shown simply as length for a simple planar fracture but 3D equivalent dimensions are relevant for a complex fracture network). The longest

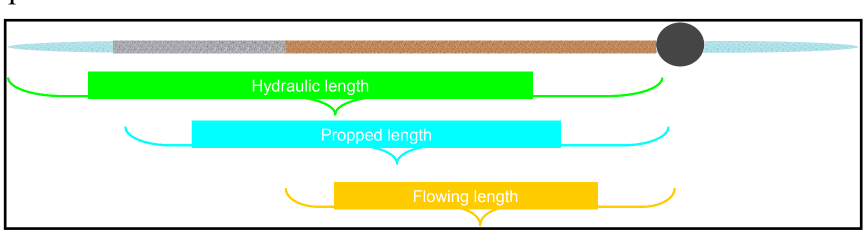

Figure 3. Relationship of various fracture dimensions.

dimension is the total hydraulic fracture dimension created during the stimulation, but only a portion of this would be filled with proppant defining a propped dimension. After the stimulation, as the injection pressure equilibrates allowing the surrounding rock to close on the proppant, only a portion of the proppant dimension will be conductive and allow fluids to flow. In terms of the objective of the hydraulic fracture to enhance hydraulic conductivity, the relevant aspect is this flowing dimension. As stated above the MS is unlikely to be able to distinguish the fracture closing. Also the geomechanical deformation will be insensitive to presence of proppant in the fracture, although the viscosity changes associated with proppant does change the hydraulic characteristics within the fracture network. However, the MS can be used to calibrate the hydraulic dimension against a complex fracture model, and enable estimation of the other dimensions (e.g., Cipolla et al., 2010).

Generally SRV is quantified by some measure of the volume of the MS cloud. The MS active volume will reflect the larger hydraulic dimension, since the total hydraulically created dimension will cause geomechanical and associated MS deformations. Indeed, the hydraulic fracture opening can also induced stress induced MS activity along structures not hydraulically connected (e.g., Maxwell et al., 2010a), and hence the corresponding MS active volume could exceed the hydraulically created volume. The volume of the MS cloud will also have associated measurement uncertainties and a tendency to overestimate the underlying deforming volume as shown in Figure 4, such that the larger the individual MS source location uncertainty the larger the MS cloud volume (Maxwell et al., 2010b). Therefore the MS location volume will be an overestimate of the MS deforming volume, and an upper limit on the hydraulic fracture volume.

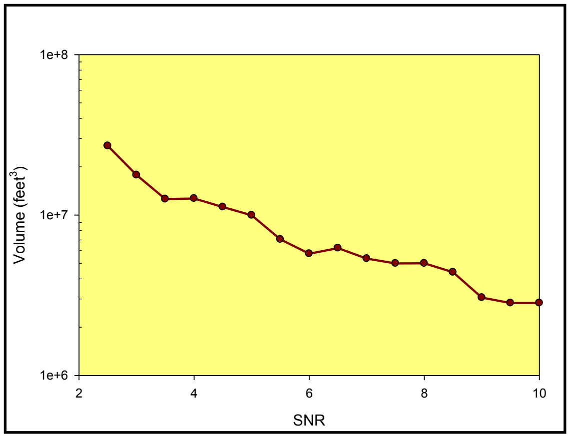

Figure 4. MS volume versus data confidence (SNR) (after Maxwell et al., 2010b).

Finally, consider how the volume of the MS cloud is estimated. Initial attempts relied on a simple, rectangular box but evolved into more complex shapes to describe the extent of the MS cloud (Maxwell et al., 2006). Contours of event density can also be used, with the advantage that a threshold of event density can be used to deemphasise sparsely spaced and potentially mislocated events. Alternatively, seismic moment (source strength) density can be used to quantify the MS deformation density (e.g., Maxwell et al., 2003). Figure 5 shows a comparison of event density and deformation density. Deformation density is a more meaningful attribute than the event density and can help interpret fault activation and relative fracture density within the MS volume.

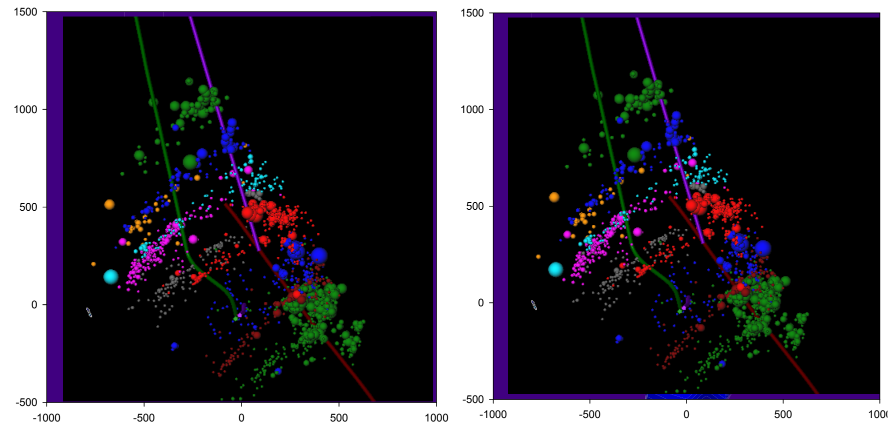

Figure 5. Event density (left) and seismic moment density (right) (after Maxwell et al., 2011).

Conclusions

MS has proven to be a useful tool to determine the hydraulic fracture geometry. However, the MS deformation represents a high-frequency, predominantly shearing and small proportion of the slow, aseismic, tensile, hydraulic fracture opening. The MS deforming failure planes also may not directly represent the complete hydraulic fracture failure planes. The volume of the MS cloud represents an overestimation of MS deforming volume depending on the MS location uncertainties, which in turn can include stress induced deformation and so is an upper limit on the hydraulically created fracture volume. Therefore, the MS deformation has limitations in terms of directly assessing the complete effectiveness of the hydraulic fracture, or completely defining the fracture network directly from the deforming MS fractures. However, the MS does describe the relative proportion of the geomechanically deforming rock and when interpreted in light of a complex fracture mechanics model can be used to estimate the extent and effectiveness of the open, flowing hydraulic fracture.

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