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Investigating Proppant and Fluid Influence During Hydraulic Fracturing with Rock Properties from AVO and Microseismic Mechanisms

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Summary

The success of a hydraulic fracture program depends knowledge of the rock properties of the reservoir to target the more brittle zone. Static estimates of these properties are availble at very large and very small scales from AVO surveys, well logs and core samples. Microseismic monitoring is used to assess the effectiveness of the stimulation and the region stimulated after compeltion of the treatment. However, with mulitple arrays, we can estimate not only the location, magnitude of the event, but the seismic moment tensor and the mechanism of failure. From the seismic moment tensor of a set of shear/tensile failures we can estimate the apparent Vp/Vs ratio, which is sensitive to rock properites, of a small region of the reservoir at at particular time within the fracture treatment. We apply this technique to a set of microseismic events from four stages in the Horn River Basin, all treating the Otter Park Formation, and show that in general the apparent Vp/Vs from the inversion isreduced from the AVO-determined values. One possible explanation for this is that the influence of fluids in the failure process is resulting in a strain ellipsoid that is not volume conserving. To test this hypothesis, we investigate the behaviour of this mechanism signal with other source parameters that connect to the fluid lubrication of the fracture, namely seismic efficiency. Our results show an anti-correlation between seismic efficiency and apparent Vp/Vs ratio after proppant injection: high apparent Vp/Vs ratios are associated with lower seismic efficiencies - suggesting that the proppant alters the observed rock properties. This technique shows promise for tracking the penetration of proppant throughout the treatment.

Introduction

The goal of hydraulic fracturing is to increase permeability of a reservoir to maximize the recovery of hydrocarbons. In order to successfully stimulate the reservoir, the mechanical characteristics of the rock must be known. These properties are constrained using 3-D amplitude-versus-offset (AVO) seismic surveys, well-logs and core samples- each piece reflecting the mechanical properties at large (AVO) or very small scales (core samples and well logs). Each piece of information provides a static view of the reservoir before stimulation. However, during a stimulation, the injection of high pressure fluid and proppant into the reservoir will alter these mechanical properties in a variety of ways. Understanding how the mechanical properties change during a stimulation can provide a great deal of insight into the state of the reservoir for long-term modeling of the hydrocarbon recovery.

Microseismic montioring of the hydraulic fracture provides a large amount of information about the effectiveness of the stimulations. During a hydraulic fracture stimulation, microseismic events are generated. Each event represents some deformation of the reservoir at a specific location. The source characteristics of the event can provide further constraints on the amount of stress released, the length of the fracture stimulated and as well as other characteristics of the source such as the seismic efficiency. All such source estimates rely on accurate, unbiased measurements of the spectral properties of the microseismic waveform (corner frequencies, low-frequency plateaus, and an accurate accounting for attenuation).

Seismic efficiency or Savage-Wood Efficiency, the ratio of apparent stress to static stress drop, estimates the efficiency of the seismic event at generating seismic radiation. It is an estimate of the amount of energy radiated relative to the total energy released during the rupture process. If the rupture is stopped or slowed by a barrier or occurs in a region that is harder to rupture, then more energy will be radiated and less energy will be used to continue the rupture process, resulting in a higher seismic efficiency. Lower seismic efficiency could be a result of fluids lubricating the failure plane or the generation of fracture surfaces (see Kanamori, H., & Rivera, L. (2006) for further details). Regions with lower seismic efficiency are likely to be more fluid saturated than regions with higher seismic efficiencies. Comparing variations in seismic efficiency within a reservoir as fracturing proceeds can constrain the region influenced by fluid injection.

In addition to constraining the regions stimulated, a microseismic monitoring program with multiple arrays can provide the source mechanism of the observed deformation from the seismic moment tensor of the event (Baig & Urbancic**,** 2010). The seismic moment tensor represents a decomposition of the observed deformation in terms of the three end-members of failure – shear slip along a plane, isotropic volumetric change, and a compensated linear vector dipole (compresion in one direction balanced out by extension in a perpendicular direction.) The eigenvalues and eigenvectors of the moment tensor yield information about the strength and direction of compressional and tensile stresses that generated the earthquake. For tectonic events, the net effect of the stresses results in slip along the fault and no change in volume - so the sum of the eigenvalues of the moment tensor must equal zero.

For microseismic events, fluid interactions can result in slip at an angle to the fault- representing a crack opening or closing and a change in the volume of the focal sphere. This model is referred to as a tensile source. For such tensile events, the moment tensor is directly sensitive to the Vp/Vs ratio, the ratio of P-wave to S-wave velocity at the fault, which is controlled by the bulk (K) and shear modulus (μ) of the focal sphere. Using the methods suggested by Vavryčuk (2011) and the eigenvalues of the moment tensor, we can invert for an estimate of Vp/Vs from a small set of shear/tensile microseismic events.

During a hydraulic fracture, the mechanical properties of the rupture and the source characteristics of the events reflect dynamic changes in the reservoir. The focal sphere represents a combination of the rock matrix properties and content of fracture which is a combination of fluid, proppant and hydrocarbon. As the fracturing proceeds, we expect that the strength of the rock will decrease. However, increases in pore pressure, the presence of proppant and fluid will alter the apparent strength of the rock and will result in an apparent change in the Vp/Vs ratio. The introduction of proppant during the hydraulic fracture stage could also alter the rupture process, which could change the seismic efficiency.

We are interested in tracking the dynamic changes in the rock properties and investigating the physical mechanisms responsible for these changes and how these evolve with the treatment program and proppant injection.

Example

To study the dynamic changes in the apparent Vp/Vs ratio, we use a database of microseismic events recorded in the Horn River Basin during a multi-stage hydraulic fracture program. We focus on 4 stages from one Otter Park treatment well and compare the Vp/Vs of the focal sphere region, the apparent Vp/Vs and the seismic efficiency of these effects to track the influence of fluid and proppant in the focal sphere. We select a subset of over 2900 microseismic events within the Otter Park formation which correspond with shear/tensile crack opening or shear/tensile closures on faults with near vertical dips. Robust estimation of dynamic Vp/Vs is accomplished though clustering events in space and time and obtaining a single value for that ratio.

Figure 1 (left) shows the results from the four stages, coloured by the median seismic efficiency of the group. These results are plotted with the bottom-hole proppant concentration for the four stages studied. Apparent Vp/Vs estimates from events early in the stage have higher Vp/Vs values and more scatter, while later events have lower Vp/Vs values. To test the likelihood that the two groups of samples were drawn from the same statistical distribution a two-sample Kolmogorov-Smirnoff test was used. The results of this test suggest that estimates of apparent Vp/Vs from the first 50 minutes within these four fracture stages are likely to be statistically different than the estimates from events generated anytime afterwards.

Using estimates from an AVO survey conducted prior to driling to correct for the heterogenity in rock properties within the reservoir, we examine the difference between the apparent Vp/Vs and the Vp/Vs prior to driling, shown on the right in Figure 1. Early in the fracture stage, some clusters of events with higher seismic efficiency- more radiated energy and a smaller influence of fluid - are associated regions with higher estimates of apparent Vp/Vs (shown in left panel of Figure 2). However, after proppant injection, higher estimates of apparent Vp/Vs, have lower sesimic efficiency and are therefore easier to rupture (shown in right panel of Figure 2). The anti-correlation between seismic efficiency and Vp/Vs after proppant has been in jected during these four stages suggests that the estimates of apparent Vp/Vs are sensitive to proppant in the focal sphere.

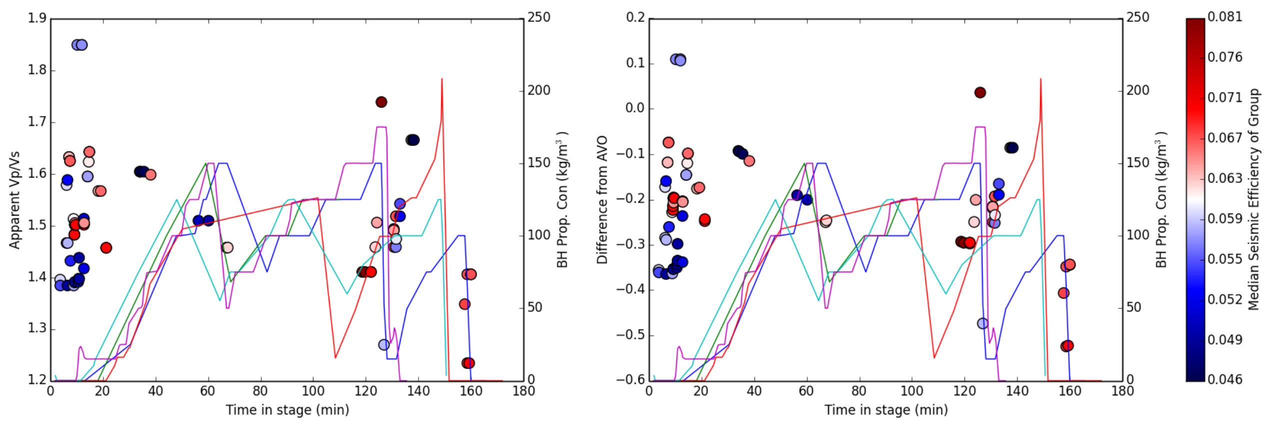

Figure 1 (Left): Shows the apparent Vp/Vs estimates for different event clusters plotted by time within the stage, from four hydraulic fracture stages, with the colour representing the median seismic efficiency of the cluster. A time series of the bottom-hole proppant concentration for the 4 stage is also shown. **(Center):** The difference between apparent Vp/Vs and the average Vp/Vs, from AVO of the 5 events in the group, coloured by the median seismic efficiency of the cluster and shown against bottom-hole proppant concentration for time within the stage. **(Right):** Colourbar for both plot

Conclusions

Our technique estimates dynamic variations in the apparent strength of the focal sphere region as the fracturing proceeds. Shortly after the proppant injection, there is an anti-correlation between the median seismic effciency of the group and the Vp/Vs ratio. This suggests that the influence of proppant and fluid is resulting in variations in the apparent strength of the focal sphere region. In order to resolve the exact impact of fluid and proppant, futher study involving more characteristics of the source is needed. Once we can predict the expected changes due to proppant, this method can pinpoint times and regions within the reservoir with proppant and fluid and allow for far more accurate determination of the stimulated reservoir volume and the extent of proppant penetration as the treatment progresses.

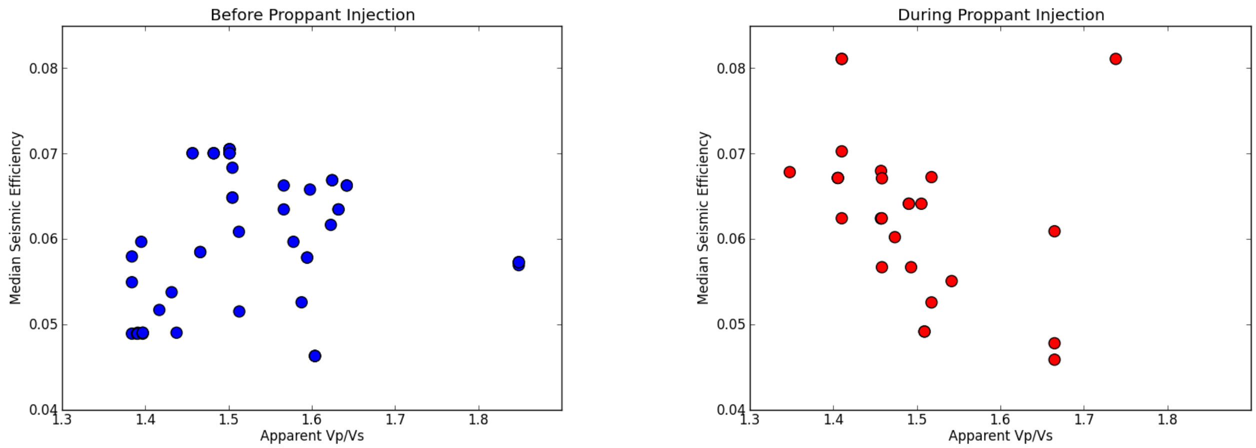

Figure 2 (Left): Shows median seismic efficiency of the cluster against apparent Vp/Vs for events within the first 50 minutes of a stage. **(Right):** Median seismic efficiency versus the apparent Vp/Vs for events after the first 50 minutes of a stage, when the proppant has been injected.

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