

**Fracture quality images from 4D VSP
and microseismic data at Jonah Field, WY.**

*Mark E. Willis, Kent M. Willis, Daniel R. Burns, MIT Earth Resources Lab, Julie Shemeta,
Pinnacle Technologies, and Nancy J. House, EnCana Oil and Gas (USA) Inc.*

Abstract

Natural and induced fractures provide the only means of production in tight gas sand reservoirs. The objective of this work is to locate and characterize natural and induced fractures from the analysis of scattered waves recorded on 4-D (time lapse) VSP data in order to optimize well placement and well spacing in these gas reservoirs. Using synthetic seismic data, we have previously shown that it is possible to characterize the quality of fracturing based upon the amount of scattering of seismic energy from hydraulic fractures. We show this concept applied to a field dataset from the Jonah Field in Wyoming. The time lapse (4D) VSP data from this field are imaged with a migration algorithm using shot travel time tables derived from the first breaks of the 3D VSPs and receiver travel time tables based on the microseismic and perf shot arrival times. We create images of the fracture planes through two of the hydraulically fractured wells in the field. The scattered energy shows correlation with the locations of the microseismic events and azimuthal scattering which is different from the azimuthal reflectivity of the reservoir. This gives us more confidence that we have separated the scattered signal from simple formation reflectivity. Variations of the scattered energy along the image planes suggest differences in the quality of the fractures in three distinct zones.

Introduction

In order to determine the extent of hydraulic fracturing away from the injection well, recordings of the micro-earthquakes during the fracture stimulation are sometimes recorded in a nearby observation well equipped with multiple levels of three component, clamped seismometers. The P and S wave arrival times of these events are picked and the event location is determined using standard earthquake location techniques. The effectiveness or quality of the fracturing is then measured by actual flow back tests into the well bore, usually with all fractured levels commingled in a single stream to conserve costs. Production spinner tests can identify the quality of individual perforated and fractured zones, but even if these are run, it is currently not possible to determine how far away from the borehole and what specific portions of fractured rock volume are productive. The purpose of our research is to investigate whether these induced fracture systems scatter seismic energy that can be observed in a 3D, time-lapse VSP survey and

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analyzed to provide diagnostic information about the effectiveness of the fractures. In Willis et al. (2007, 2008 and 2009) we described a model study mimicking a field data acquisition in the tight gas Jonah field. Time lapse VSP and microseismic recordings of a hydraulic fracturing treatment were simulated. The microseismic events are at the locations of the fractures within the VSP imaged volume, and the relative amplitudes of the P and S wave scattering in the VSP data provide an indication of the fracture properties. In this paper we present the results of this methodology on the Jonah Field data set.

A 3D VSP collected before the hydraulic fracture treatment contains the reference, or background, reflectivity. After the hydraulic fracture treatment, multiple sets of fractures have been introduced into the formation at specific, controlled depth levels. The microseismic events associated with the hydraulic fracturing reveal the location of the fractures. Because the new fractures are expected to be roughly planar, and generally follow the maximum stress orientation, the gross volume properties of the formation are not expected to change significantly. This means that the formation velocity stays relatively the same and it is possible to subtract the reference VSP from the after treatment VSP survey. This difference is called the time lapse survey.

Proppant is pumped into the formation at specific times along with the fracturing fluid. In the locations where the proppant is successfully deposited, the hydraulic fracture will remain open after the high pressure fluid is released and ultimately removed through production. Therefore the compliance of the propped open hydraulic fracture plane will be larger than the background formation compliance. In other areas without proppant, the fracture is likely to be closed and the difference between the formation and fracture compliances will be negligible. This means that in areas where the proppant was deposited, the fracture planes are open will likely scatter the seismic energy which will be recorded in the after treatment VSP. The scattered VSP energy from the location of a microseismic event follows the same travel path from the fractures to the monitor borehole that the microseismic energy follows. Thus the picked arrival times of both the P and S waves of the microseismic events provide stacking operators we can use on the time lapse VSP data to extract, image, and characterize the scattered seismic energy from the fracture planes.

Field Experiment

The Jonah Field is a tight gas field located in Sublette County, Wyoming. The field is defined by a wedge shaped structural block created from the intersection of two subvertical shear fault zones. The reservoir is comprised of the sandstones of the Lance Formation, which are meandering stream channels intercalated with overbank siltstones and mudstones (DuBois *et al.*, 2004). The gross thickness of the reservoir can be in excess of 900 m. Despite high reservoir

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pressures, production is difficult due to low permeability which requires extensive, multi-stage hydraulic fracturing to produce economic quantities of hydrocarbons.

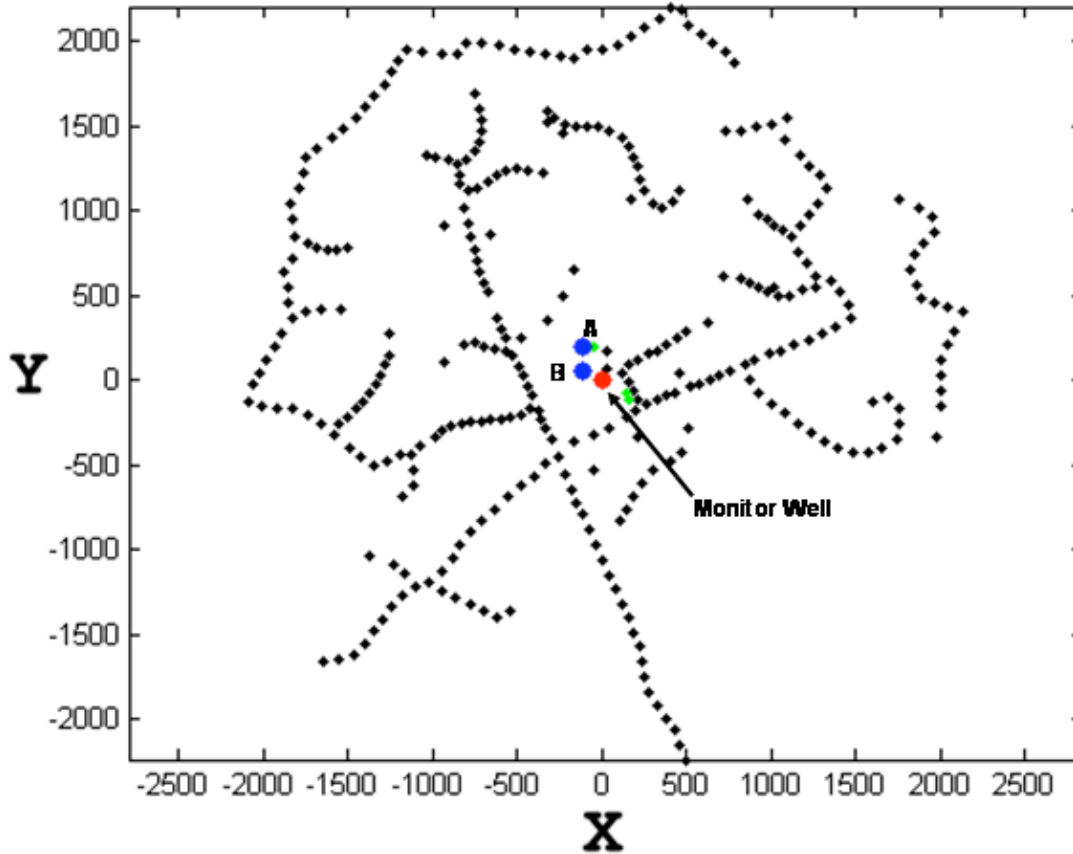


Figure 1. Map of test area in Jonah Field showing the shot locations with dots. The red dot at (0,0) is the location of the monitor well. The two blue dots show the bottom hole locations for the two hydraulically fractured wells studied in this paper. The axes are scaled meters.

A map of the 3D VSP survey area is shown in Figure 1. The black dots show the layout of the surface seismic sources used in the time lapse survey. The red circle shows the location of the monitor well which was instrumented with clamped geophones. Hydraulic fracturing was performed in five wells during this treatment program. The two blue circles show the bottom-hole locations of the two wells used in this study. The three green circles show the bottom-hole locations for three additional wells which were also fractured during the treatment program.

Before the treatment program began, a 3D reference VSP survey was recorded over the field using 338 surface shot locations. A multi-level Oyo 3C geophone tool string was progressively

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moved up the monitor borehole to record a total of 140 VSP depth levels. Then the hydraulic fracturing was performed. Microseismic events were monitored in as many as twelve stages of fracturing in each well. About a month after the original 3D reference VSP survey was collected, and after the hydraulic fracturing was completed, a second 3D VSP survey was collected over the field using the same geometry as the first VSP.

VSP Time Lapse Processing

All 676 VSP records were examined and noisy shots and traces were manually edited out. Then we applied amplitude and phase matching between the surveys using source deconvolution applied separately to each shot record of each survey. The final time lapse volume was created using an adaptive, optimized subtraction of the two VSP surveys. Figure 2 shows an example processed VSP common shot gather.

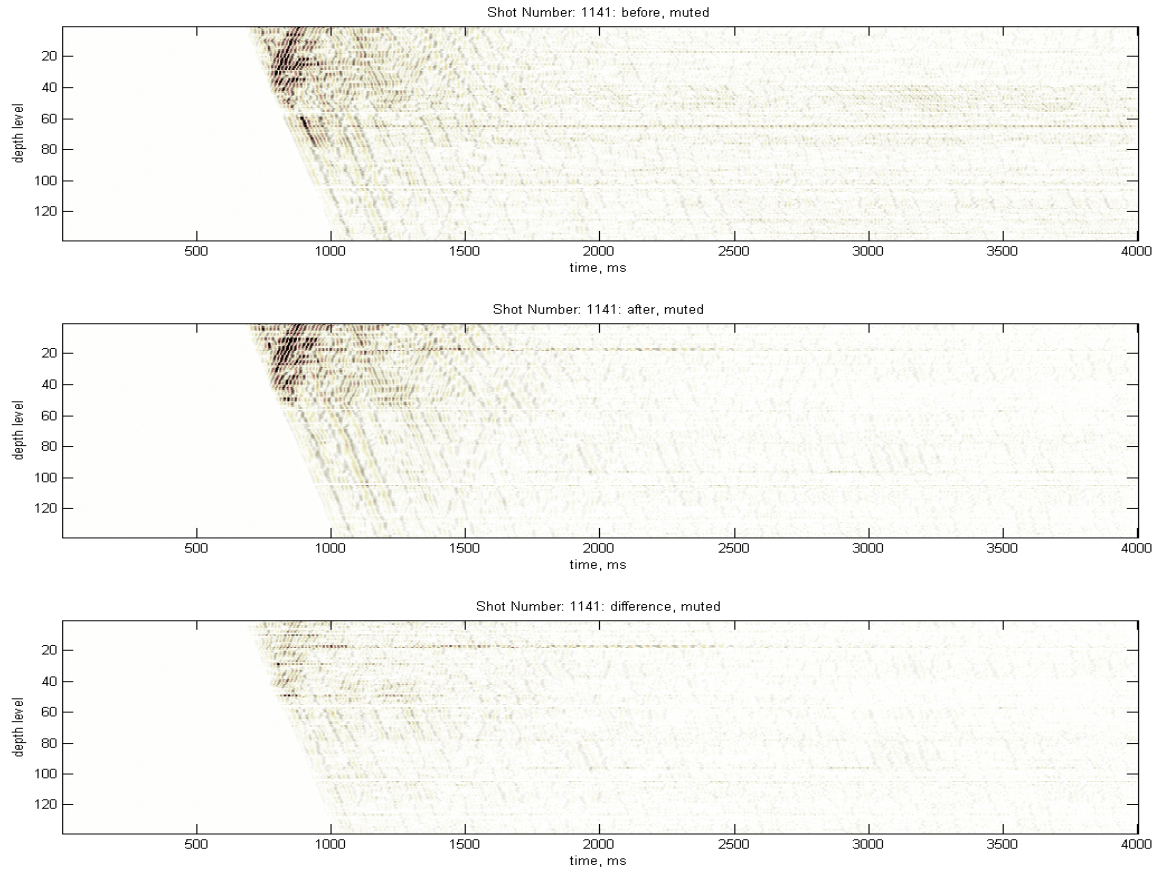
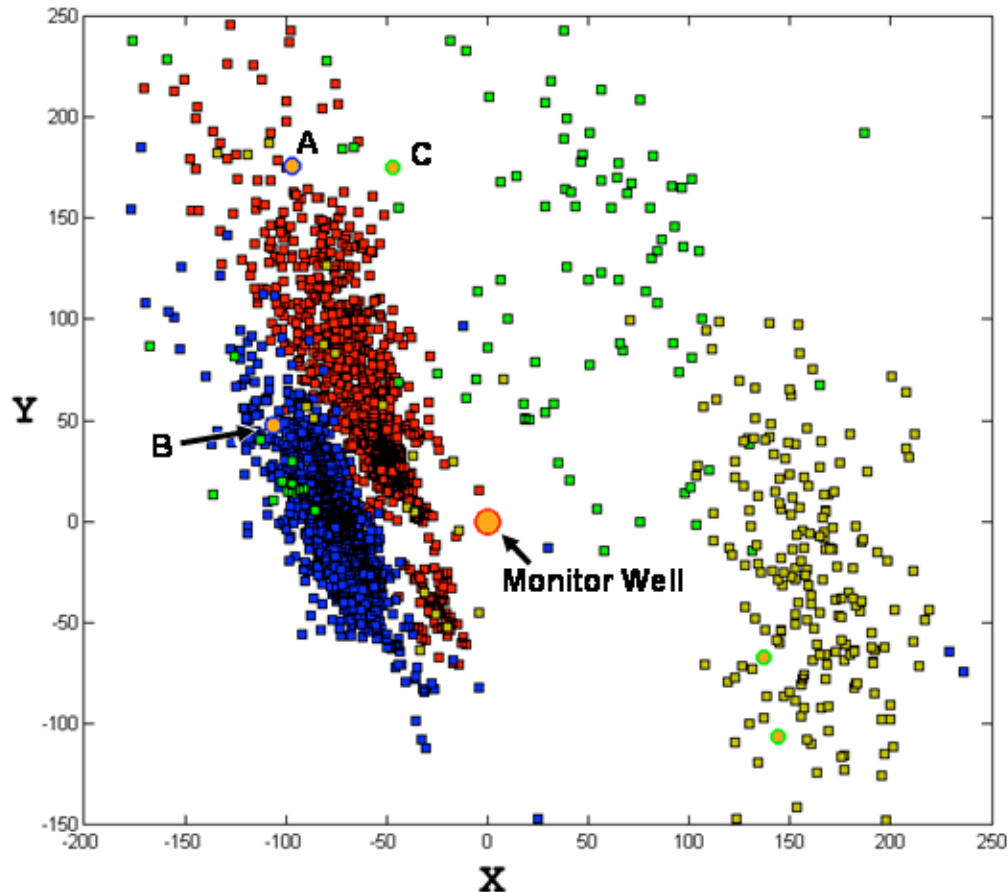


Figure 2: Example VSP records after source deconvolution and a mute to eliminate the first breaks. a) Before fracturing, b) after fracturing, and c) the optimal difference. The vertical axis is trace number from shallow (top) to deep (bottom). The horizontal axis is time (ms).

Microseismic Data

The microseismic events for each fracture stage were recorded and analyzed for location by Pinnacle Technologies. The perforation shots were recorded for each of the wells to provide velocity calibration for the event location process. A different constant velocity was used for each fracturing stage which was derived by analysis of the perforation shot data. These velocities were typically 10 to 20% faster than the log and VSP derived velocities. The event locations for all of the fracture stages in four of the five wells are shown in Figure 3. Due to the proximity of the monitor well and the orientation of the fractures, the most reliable microseismic events appear to be obtained for wells A and B, which are shown as the blue dots in Figure 1.



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Figure 3: The event locations for four wells. The events for all twelve fracture stages of Well A are shown with red dots. The events for the nine fracture stages for Well B are shown with blue dots. The axes show scaled distances. The orange circles show the bottom hole locations of each well. The monitor (observation) well is shown

Fracture Imaging

The first break VSP times were picked for over 200 surface shot locations. These picks were interpolated to provide the shot travel time tables for VSP migration, in a similar fashion to the way Brandsberg-Dahl et al. (2007) used them for surface seismic migration. The travel times were sorted into quadrants around the monitor well which provided four independently derived travel time tables, one for each quadrant of sources. This allowed the preservation of any local anisotropy, and provided “exact” one-way travel times from the shot to the fracture image planes. The velocities derived from the perf shots were used for the migration receiver travel time tables. These times were significantly (10 to 20%) faster than the VSP derived times and created better images.

Migrated images were created through the microseismic clouds for two wells, A and B. The image through Well A is shown in Figure 4a. The migrated time lapse images show generally higher amplitudes near the treatment well and near the zones with higher numbers of microseismic events. Changing the migration velocity makes significant changes in the images, thus it is very important to determine the appropriate velocities to tie the microseismic events to the time lapse images. The best quality images for Well A appear to be from using constant velocities for the receiver tables derived from the perf shots which were used to locate the microseismic events. The apparent insensitivity to some aspects of the acquisition geometry is shown in Figure 4b, where we drop all shots less than 1300 m from the monitor well. We then decimate those far offset shots by a factor of about two and the migrated image is shown in Figure 4c.

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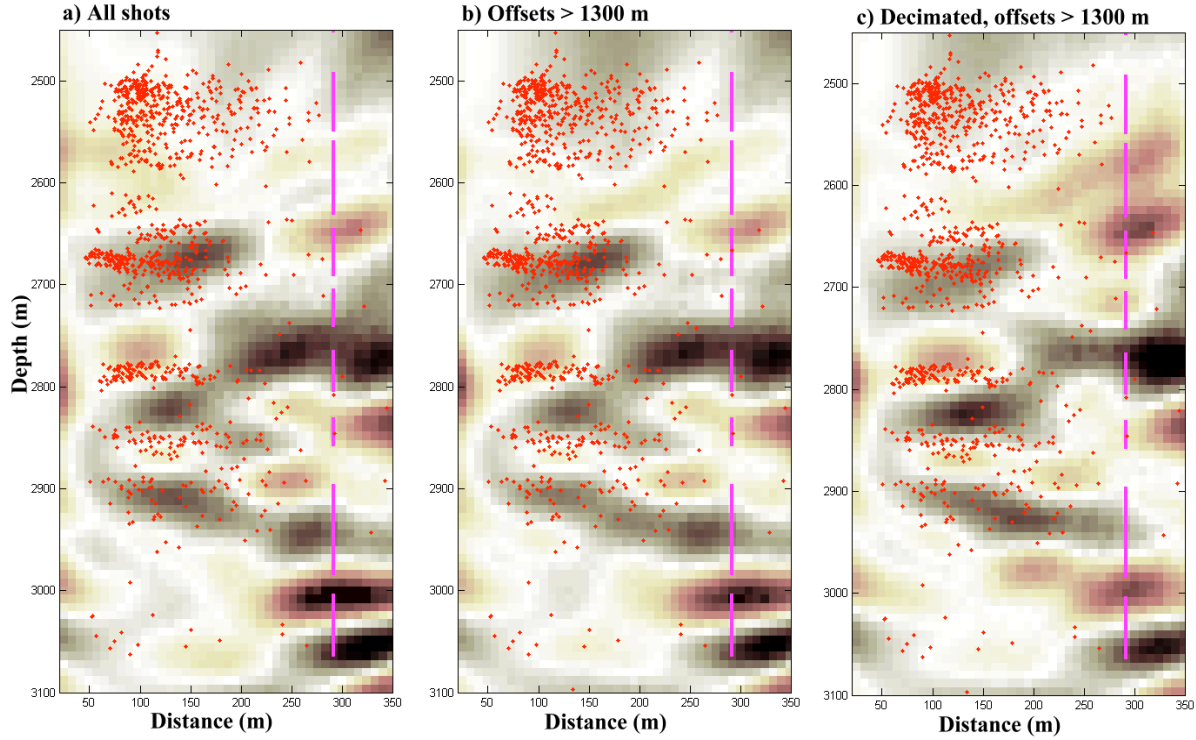


Figure 4. Migrated images using a) all good shots, b) all good shots with offsets greater than 1300 m, and c) every other good shot with offsets greater than 1300 m. The microseismic events from each well are plotted as red dots. The vertical pink lines denote the well track locations of the perforated intervals in the hydraulic fracture well. The view is looking towards the south west so that the left side of each image is toward the south east and the right side is toward the north west.

Conclusions

The proper time lapse VSP migration velocity is critical to the success of aligning the microseismic events with the imaged fracture planes. A 2D line or 3D areal VSP can provide data derived travel time tables for the shot portion of the VSP migration algorithm. The microseismic events can provide the velocity and/or moveout functions for the receiver travel time tables of the migration algorithm. We used the constant horizontal velocities derived from the perf shots for the receiver tables which were greater than 10% faster than the derived vertical VSP velocities. Since the shot travel time tables measure essentially the horizontal travel paths through the subsurface, a good estimate of the reservoir level anisotropy must be incorporated in these tables.

Our fracture plane images generally follow the trends of the microseismic events. Variations on these fracture plane images may reveal the changes in fracture quality. Three zones were

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observed: 1) the deepest zone showed good scattering within 50 m of the borehole, 2) the intermediate depth zone shows good and moderate scattering out to about 300m, and 3) the shallowest zone showed limited scattering. We don't have access to the production data, but we are tempted to imply that the deep zone has very good fracturing but only near the well bore, the intermediate zone has medium quality fractures out to about 300m, and the shallower zone has poor quality fractures.

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