Hydraulic fracture quality from time lapse VSP and microseismic data

M.E. Willis, K.M. Willis, D.R. Burns
Earth Resources Laboratory
Dept. of Earth, Atmospheric, and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, MA 02139

N.J. House
EnCana Corporation, Denver CO

J. Shemeta
Pinnacle Technology, Denver CO

Abstract

The ability to produce from low permeability, tight gas reservoirs is directly tied to the ability to repetitively perform successful hydraulic fracturing in a series of closely spaced wells. The key question is whether the induced fractures remain open and permeable, which is in part a function of the stress field and the emplacement of proppant. We study the ability to detect and characterize hydraulic fractures from scattered seismic energy. A 3D VSP forms the reference for seismic reflectivity before hydraulic fracturing. During the hydraulic fracturing the microseismic events are recorded and then the arrival times picked and the events located. Another 3D VSP survey is recorded after the fracture treatment. The difference between the VSP surveys yields a 3D time lapse VSP dataset which contains the changes in the reflected wave field and the addition of scattered energy. The microseismic moveout times can be used to extract from the time lapse VSP data the seismic energy scattered from the induced fracture planes. We show the encouraging results from both model and field data.

1 Introduction

There is great potential for hydrocarbon production from tight gas reservoirs, which are large, untapped fields, frequently over 1000 ft (330 m) thick. Estimates show that over 21% of the recoverable remaining natural gas reserves in the United States may come from these formations (National Petroleum Council Report, 2003). Due to low (less than 0.1 millidarcy) permeability, tight gas fields require extensive hydraulic fracturing in order to produce economic quantities of hydrocarbons. Since the yield of each well is typically low and short lived, the goal is to invest only as much technology as needed. Thus it is very important to be able to judge the effectiveness of a hydraulic stimulation program.

One measure of the effectiveness of hydraulic fracturing operations can be determined by processing
the three component seismic recordings made in an observation well of the microseismic events. Typically the arrival times of these events are picked and the location of the fracturing is determined using standard earthquake location technologies. These events can then be co-rendered with a 3D seismic volume so that the lateral and vertical extent of fracturing is kept to be within the desired reservoir unit.

Hydraulically induced microseisms are frequently located in bands aligned with the maximum horizontal stress direction and reactivated pre-existing fractures. In this paper, we advance the work by Willis et al. (2007) which presented a model study of scattered energy from a single hydraulic fracture plane. Meadows and Winterstein (1994) have demonstrated on field data that it is possible to detect VSP energy scattered from a hydraulic fracture plane. They also show that scattered energy decreases in amplitude as the fracture closes when the pressure is leaked off. Liu et al. (1997) modelled the scattered energy in this field data with Kirchhoff integral methods showing the azimuthal scattering characteristics of a fracture plane.

It is an active research topic to determine effective methods to characterize and model fractures in the subsurface (e.g. Worthington, 2007; Pyra-Nolte, 2007; Nehei, et al, 2002). Because the seismic wavelength and fracture features are roughly the same dimensions, simple ray concepts breakdown and more complicated interactions occur. The point of this paper is not to advance the methods of modelling fractures themselves. Rather it is to test the idea of whether it is possible to systematically extract and characterize scattered seismic energy from induced fracture planes utilizing time lapse VSP and microseismic data sets.

2 Methodology

As discussed in Willis et al. (2007), our methodology is as follows:

1. Collect a reference (limited) 3D VSP around the treatment well, as observed in a monitor well.
2. Perform the hydraulic fracture treatment while recording the microseismic events in the monitor well.
3. Collect a second (limited) 3D VSP after the hydraulic fracture treatment is finished.
4. Pick the arrival times of the microseismic events and locate them within the reservoir.
5. Create the time lapse VSP records which are generated from the difference between the after treatment VSP and the before treatment VSP.
6. Extract the scattered energy from the induced fracture planes by using the arrival times of the microseismic events as stacking operators in the time lapse VSP volume.
7. Characterize the scattered energy as a function of illumination azimuth for locations along the induced fractures planes, noting that large amounts of scattering is correlated with open, communicating fractures.

We use a two fracture plane model to demonstrate the concept. Figures 1 and 2 show the geometry of a layer cake, 3D elastic model in which two hydraulic fracture planes will be modeled. A nine source-point, 3D VSP survey is simulated with an elastic finite difference modeling algorithm which is recorded in the monitor well. Then a microseismic event is simulated by a single impulsive source at the location of each fracture plane which is recorded in the monitor well. Then a repeat 3D VSP is simulated but this time two discrete, fracture planes are included in the finite difference grid. The fractures are simulated with discrete grid cells containing an equivalent medium representing a zone with fractures (Coates and Schoenberg, 1995).
The blue lines coming from the lower fracture plane in Figure 1 depict the ray paths of microseismic events coming from the fracture plane and traveling to the monitor well. The red line coming from the surface source (red star) depicts the VSP energy illuminating the lower fracture plane. The blue lines coming from the fault plane also indicate the ray paths of the scattered seismic energy coming from the lower fault plane into the monitor well. It is clear that the (blue) ray paths coming from the fault plane are the same for both the microseismic energy and the scattered VSP energy. Figure 2 shows the equivalent ray paths for the upper fracture.

Figure 1: Model geometry of VSP sources (red stars), monitor well (vertical blue line), fracture planes (black squares), and horizontal layering. The blue lines from the fracture show the ray paths for the microseismic energy. The red and blue lines show the total ray paths for scattered seismic energy from the VSP source to the lower fracture plane and then to the monitor well.

We show in Figure 3 the time lapse VSP records for a model with just the lower fracture (bottom panel) and another with both fractures (top panel). We can see that the location of the fracture plane will control the arrival time and depth that the scattered energy appears. The upper fracture creates scattered energy with an apex at about 450m depth while the lower fracture creates an apex at about 1000m depth. The relative arrival times will change for each VSP source location giving another way to extract the scattered energy from the time lapse VSP record.
We show in Figure 4 a very simple modeling of a microseismic event on the lower fracture plane. We used a simple impulsive seismic source, not to get an accurate dynamic record, but only to create the kinematic travel times from a microseismic event. Clearly seen is the P wave arrival and the secondary, S wave arrival.

We pick the arrival times of the P and S waves on the microseismic event to use as moveout operators on the time lapse VSP data. Figure 5 shows the effect of applying the picked S wave arrivals from the microseismic event on the lower fracture plane as moveout operators on both time lapse VSP records. The scattered energy from the upper fracture plane is greatly distorted (top panel of Fig. 5) while the energy from the lower fracture plane is aligned.

Figure 3. Time lapse VSP single (top) and double (bottom) fracture scattered seismic energy. The single fracture refers to only the lower fracture in figures 1 and 2. The double fracture refers to both fractures in figures 1 and 2.

Figure 4. Modeled microseismic event on the lower fracture plane of Figures 1 and 2.

Figure 5. Modeled time lapse VSP records from Figure 4 which have been aligned using the S wave moveout picked from the microseismic event. The bottom record is from the single fracture model while the top record is from the two fracture model.

Figure 6. Microseismic event locations for 10 stages of hydraulic fracturing in 5 closely spaced wells in the Jonah field.
The generation of the time lapse volume of data requires several steps. First is the defining and implementing a of common frequency bandwidth. The reference 3D VSP survey contains significant amounts of broad band noise. This requires the band pass filtering of the data to eliminate for example the extraneous 150 Hz high frequencies possibly from field operations. The second step is eliminating the traces from geophones which were not adequately clamped to the borehole wall.

Another step is the matching of the source and receiver characteristics between the two VSP surveys. We perform a “surface consistent” inversion process to remove the common source difference between the surveys. We create a filter which is applied to the after treatment survey which attempts to make it look like the reference survey. We then create individual receiver terms which attempt to correct small changes in the receiver couplings between surveys. These filters are created by spectral matching of the first arrivals from each survey.

Figure 8 shows the results of match processing for the VSP record form the surface location shown in Figure 7. The upper record is the reference VSP and the middle record is the after treatment survey which has been matched to the reference survey. The bottom record is the time lapse record which is created by subtracting the reference record from the matched after treatment record. The common events in each record are eliminated, as demonstrated by the removal of the first arrivals.

Figure 7. 3D VSP survey layout for Jonah Field. Red dots are surface source locations, blue dots are down hole geophones and the green dot is the location of the source for the VSP records shown in Figure 8.
Figure 8. Matched processing for an example VSP record before (top) and after (middle) hydraulic fracturing. The time lapse VSP record (bottom) is the difference of the “after” and “before” records which shows scattered energy after the first arrival times. The vertical and horizontal axes show depth (ft) and time (s), respectively.

3 Discussion

The method we advance uses picked microseismic arrival times to form imaging operators to extract scattered energy from the induced fractures recorded in a time lapse VSP. An alternative method to this one, is to simply apply prestack (depth) migration to the time lapse VSP records. This would create a 3D image volume which back propagates and collapses the scattered wave field onto the induced fracture planes. The advantage of using prestack migration would be that it does not require any microseismic monitoring and picking of microseismic events. In fact, if the scattered field were large enough in amplitude, only a post fracturing 3D VSP would need to be collected and used to image the fracture plane. However, it is our expectation that the scattered wave field will be small. To be able to pull out the scattered wave field from only the post fracturing 3D VSP and form an interpretable image is quite desirable, but probably unlikely. In addition, we would need a very accurate velocity model so that the migration operator can stack the weak scattered signal whether in the time lapse VSP records or the post fracturing VSP records. The advantage of using the microseismic moveouts as operators is that they are the exact times which stack the scattered wave field. Thus if we are successful at using the microseismic operators to characterize the hydraulic fractures, then we will investigate using prestack depth migration.

On field data from the Jonah Field, there are about 50 induced fracture systems that can be characterized by the microseismic events. We have demonstrated that it is possible to identify scattered energy from the time lapse VSP data. Additional effort will be applied to create optimal differences between the reference and after treatment VSP surveys. With over 350 surface shots we expect that, while challenging, it will be possible to extract and characterize the scattered energy from most of these fracture systems.
4 Acknowledgements

We wish to thank Rongrong Lu (ExxonMobil) for generating the single fracture data sets, Yang Zhang for generating the two fracture data sets, and helpful conversations with M. Nafi Toksoz, Sean Maxwell and Norm Warpinski (Pinnacle Technologies), and Enru Liu ExxonMobil. We wish to thank EnCana USA for releasing the field data set to us. This work was supported by DOE grant 06NT42956 and the ERL Founding Member Consortium.

5 References


