Azimuthal Anisotropy Characterization with Multicomponent Virtual Shear Sources at Rulison Field, Colorado

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Summary

We apply a new method for birefringence analysis at depth to a tight gas reservoir in Rulison Field, Colorado. The new method is based on a multicomponent version of the virtual source method in which VSP receivers are turned into virtual shear sources in the zone of interest. This allows accurate detection of even small amounts of azimuthal anisotropy under complex overburden where traditional methods fail. We used the new method to measure shear wave splitting of less than 1% in a reservoir under significantly anisotropic overburden. That was enough to infer fracture orientation, which turned out to be close to the orientation interpreted from FMI logs.

Introduction

Rulison field in the Piceance basin, Colorado (Figure 1), produces gas from a low-permeability interbedded sequence of sand and shales in the Williams Fork formation of the Mesaverde group. Production is thought to be controlled by interconnected natural vertical fractures (Lynn, 1999). Hence, to optimize field development, it is necessary to map fracture distribution and azimuth. This can be facilitated by measuring azimuthal anisotropy in the reservoir from VSP data in key wells. In particular, we would like to study shear wave splitting and polarization in the reservoir because these quantities can be related to fracture density and orientation. The problem is that the overburden at Rulison is complex and exhibits azimuthal anisotropy stronger than that in the reservoir. Its influence on shear waves would need to be removed before studying the reservoir. Traditionally that would be done through layer-stripping of 2C x 2C VSP data (Winterstein and Meadows, 1991; Thomsen et al., 1999). However, if the overburden symmetry axes vary with depth, as they presumably do at Rulison, we would need to instrument the well all the way from the surface to the reservoir for proper layer stripping. Given that the reservoir is at more than 4500 ft depth, that is unfeasible.

To circumvent this problem, a new approach to studying shear wave splitting at depth was proposed by Bakulin and Mateeva (2008). It involves turning the horizontal components of VSP receivers into orthogonal shear virtual sources in the borehole – or, essentially, redatuming the 2C x 2C VSP to a 2C x 2C virtual data set with sources and receivers in the borehole. Then, signals from these new shear sources recorded at the horizontal components of other receivers can be used to study shear wave splitting in the medium between and below the receivers. The most remarkable feature of this method is that we do not need to know anything about the overburden to create virtual sources in the borehole. Therefore, we can use it to probe a layer of interest below any heterogeneous and anisotropic overburden, or in this case, to probe the Williams Fork formation with fast and slow shear waves without characterizing the overburden first. The procedure is described below.

Creating Fast and Slow Shear Virtual Sources

Let us start by a brief explanation of how multicomponent virtual shear sources are created in the borehole. For more on the fundamentals of the virtual source method see Bakulin and Calvert (2004, 2005), and for more details on this particular application see Bakulin and Mateeva (2008) or their companion abstract in this book.

Consider a vertical well in which a 2C x 2C VSP was acquired – i.e., signals from two orthogonal shear vibrators acting along X and Y directions on the surface were recorded by the horizontal components, X and Y, of downhole receivers. In most general terms, cross-correlating the responses at two receiver levels allows us to construct new data as if the first receiver acted as a virtual source (VS). With two types of surface sources (X and Y) and two receiver components (X and Y) there are eight possible cross-correlations that could be made between traces from a common surface source to two depth stations: XX_1*XX_2, YX_1*YX_2, XY_1*XY_2, YY_1*YY_2, XX_1*XY_2, YX_1*YY_2, XY_1*XX_2, YY_1*YX_2, where the first letter denotes source polarization, the second letter denotes receiver component, and the subscript identifies the receiver location (1 or 2). To create a 2C x 2C virtual dataset between receiver locations 1 and 2, the above entities need to be combined as follows (Bakulin and Mateeva, 2008):

$$\begin{aligned} XX_{VS} &= \Sigma\,(XX_1*XX_2 + YX_1*YX_2)\\ YY_{VS} &= \Sigma\,(XY_1*XY_2 + YY_1*YY_2)\\ XY_{VS} &= \Sigma\,(XX_1*XY_2 + YX_1*YY_2)\\ YX_{VS} &= \Sigma\,(XY_1*XX_2 + YY_1*YX_2) \end{aligned} \qquad (1)$$

where the summation is over shot locations along the surface. The so obtained virtual source dataset has correct ratios between amplitudes and can be diagonalized by Alford rotation (Alford, 1986) so that the fast- and slow-shear modes propagating between the receivers are isolated on the XX_{VS} and YY_{VS} components.

It is important to note that the orthogonal shear sources on the surface should have equal strengths to create proper 2C x 2C virtual data.

VSP Acquisition at Rulison

As part of a comprehensive study of Rulison field conducted by The Reservoir Characterization Project at Colorado School of Mines (Davis, 2007), a 3D multicomponent VSP was acquired in 2006. The VSP well was vertical and instrumented with a 60-level tool of 3C geophones (one vertical and two horizontal components). The shallowest 3C receiver was located at the top of the Williams Fork formation, at ~4500 ft, and the deepest receiver was within the underlying Cameo Coal, at ~7500 ft (Figure-2). The receiver spacing was 50 ft. Two horizontal vibrators operating in mutually orthogonal directions were used as seismic sources at 700 shot-points on a grid around the well. The data from these horizontal vibrators was used to create shear virtual sources. In addition, a vertical vibrator was operated at ~300 far-offset shot points. The P-wave first arrivals from the vertical vibrator were used to orient the horizontal receiver components at all depth stations to a common direction – a standard procedure for wireline VSP. The orientation was based on the usual assumption of in-plane propagation and was therefore approximate.

Overburden Issues

In the receiver rotation procedure mentioned above, the horizontal receiver orientations were chosen to coincide with the shear vibrator directions. In isotropic media, such an arrangement would result in a diagonal 2C x 2C data set; i.e., shear waves from each horizontal vibrator would be recorded only on the receiver pointing in the same direction and would arrive at the same time on either component. That was not the case at Rulison. To get an idea about the shear wave splitting in the overburden, we applied Alford rotation to the VSP data. Figure 3 shows the VSP data after Alford rotation for a near-offset shot. It exhibits a rather prominent time difference, ~25 ms, between the first arrivals on the XX and YY components at the top receiver station. This translates into shear-wave splitting γ~3% in the overburden where $\gamma = (V_s^{fast} - V_s^{slow}) / V_s^{slow}$. This number may not seem large but since the overburden is thick, it becomes significant. Moreover, as the non-zero off-diagonal components in Figure 3 suggest, the symmetry axes in the overburden vary with depth, and thus, birefringence accumulated there cannot be undone by a single Alford rotation. This is a case in which, if we were to do traditional layer stripping, we would need receivers throughout the overburden.

Instead, we render overburden effects irrelevant by creating virtual sources in the reservoir.

Multicomponent Virtual Shear Sources at Rulison

In preparation for virtual source creation we took two steps. First, we made sure the two horizontal vibrators at each shot point had equal strength, based on total trace energy.

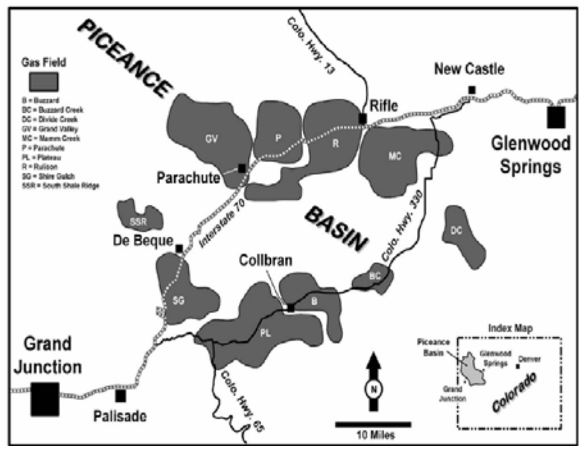

Figure 1: Map of gas producing fields in Piceance Basin, Colorado

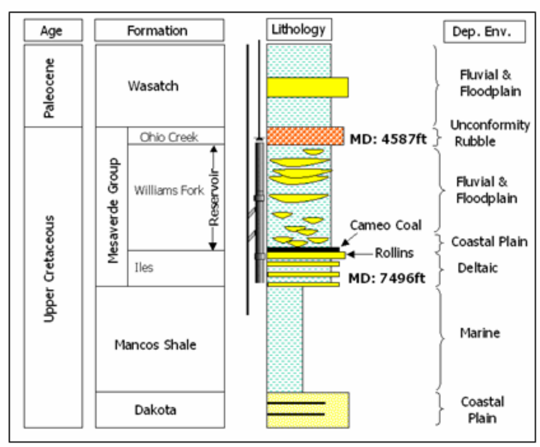

Figure 2: Schematic representation of VSP tool layout and the stratigraphy in Rulison field, CO

Second, we muted the first arrivals (P waves) generated by the horizontal vibrators. This step is standard in shear virtual source creation (e.g., Bakulin *et al*., 2007) – it ensures that the virtual sources emit mainly shear waves and not P-waves.

Using equations (1), we created virtual shear sources at every receiver station in the well. This provided redundancy of shot-receiver pairs for studying the reservoir interval. We aimed at assessing anisotropy in the reservoir as a whole and did not subdivide it into smaller intervals because the average thickness of individual sand bodies in it is only about 3 m – well below seismic resolution. It

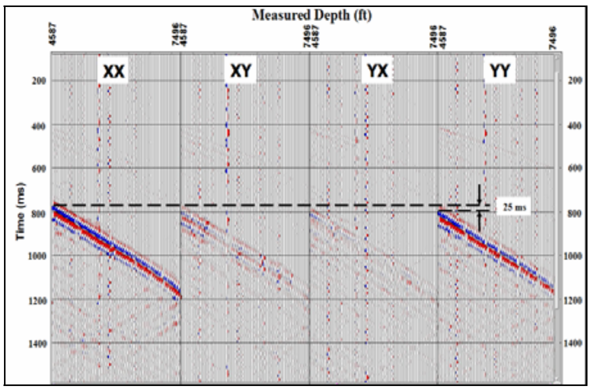

Figure 3: VSP data from a near-offset shot after Alford rotation. Note the shear wave splitting in the overburden visible at the topmost geophone.

makes sense to characterize the interval as an effective medium.

With this on mind, we subjected the entire virtual dataset to Alford rotation with trial angles in search for the principle directions in the reservoir; i.e., for the angle that provides best diagonalization of the virtual data. To automate the search process, we used the following measure of diagonalization:

$$R(\phi) = \frac{RMS[XX_{VS}(\phi)] + RMS[YY_{VS}(\phi)]}{RMS[XY_{VS}(\phi)] + RMS[YX_{VS}(\phi)]} \qquad (2)$$

where each of the terms on right hand side is the root mean square of the amplitudes in a time window on the direct shear wave (first arrival) from a virtual source to receivers below. The value of R(ϕ) reaches a maximum when the diagonal components of the virtual dataset are maximal and the cross-diagonal elements are minimal, and the angle at which this occurs indicates the principal directions in the reservoir. Figure 4 shows R as a function of the rotation angle ϕ. The maximum occurs at about 65° East of North which is very close to the fracture direction interpreted from Formation Micro Imager (FMI) data in the same well (Figure-4 insert). FMI sees fractures intersected by the borehole and hence its depth of investigation is much less than that of shear waves at seismic frequencies. The FMI shows that the predominant fracture orientation in the reservoir is 75°-85° East of North. The ~10° difference between the fracture directions estimated from virtual source and FMI interpretations is reasonable keeping in mind that our estimates are affected by uncertainty in the horizontal receiver orientations as well.

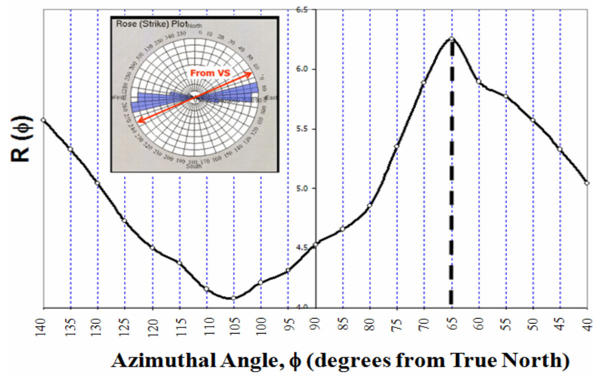

Figure 4: RMS amplitude ratio, R, between diagonal and off-diagonal components of the virtual source data after Alford rotation with trial angles ϕ. Insert: comparison between fracture orientation deduced from this graph and that interpreted from FMI log in the reservoir interval.

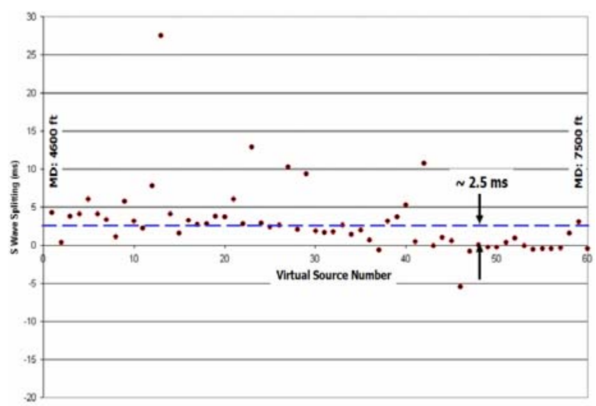

Figure 5: Shear wave splitting accumulated over the reservoir interval as measured from direct arrivals from virtual sources at various depths

Next we study the amount of shear wave splitting in the reservoir. One simple measure of it is the difference in total traveltime accumulated from the top to the bottom of the reservoir as measured from the XX and YY components of the virtual source data after Alford rotation. Figure 5 shows that difference estimated from data from different virtual source locations along the receiver tool. It averages ~2.5 ms over a 3000 ft interval and corresponds to $\gamma < 1\%$. This is a tiny amount of splitting that would have been very difficult to pick directly from the VSP given the significant birefringence in the overburden.

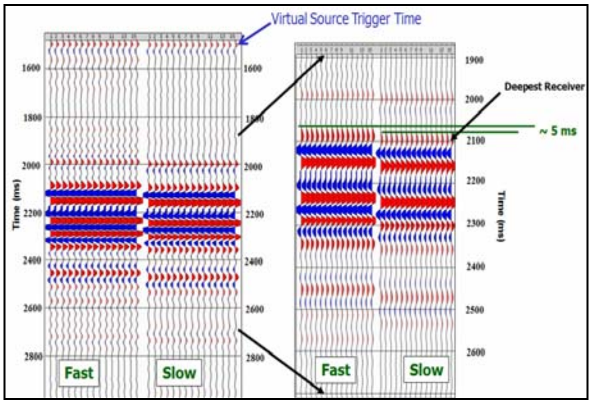

Figure 6: Corridor stacks of fast and slow shear waves from virtual sources

To verify this estimate we also look at reflection images in terms of fast and slow shear waves. Since reflector dips at Rulison are small and the well is vertical, we can process each virtual source gather to a corridor stack much in the same way one would process a 1D VSP. The processing included picking the first arrival (fast or slow shear wave) on the XX and YY components, separating up-going from down-going waves by dip median filtering, aligning the up-going field based on first arrival moveout, and forming a corridor stack. Since we had created a pair of virtual sources at every receiver station, we had a redundancy of images of the same reflectors for each wave mode (fast and slow). We averaged corridor stacks from different virtual source locations to increase the signal-to-noise ratio. The final images obtained from the XX and YY components are shown in Figure 6 labeled “fast” and “slow” respectively. The images are in two way time with respect to the top receiver (its time was set arbitrarily to 1500 ms). The strongest events visible correspond to the Cameo Coals below the reservoir. The deepest receiver is just below the top coal. Inspecting the zoom on the right in Figure 6, we notice that the top coal reflection on the slow shear wave section arrives about 5 ms later than that on the fast shear wave section. That represents shear wave splitting accumulated during two-way propagation through the reservoir and is in excellent agreement with the one-way traveltime difference of 2.5 ms between direct arrivals measured from XX and YY virtual source gathers.

Conclusion

Shear wave splitting in the Rulison reservoir is very small but measuring it is still important because it provides hints about the fracture system and thus can help optimize field development. Using multicomponent virtual shear sources created from a multicomponent 3D VSP we found splitting of less than 1% in the reservoir. Albeit weak, this anisotropy effect was enough to suggest that the predominant fracture orientation is ~N65°E at this location. Fracture orientations are expected to change across Rulison field, and therefore, similar measurements at other wells would be needed to map variations from VSP data.

The tiny amount of shear wave splitting in this reservoir would have been extremely hard to measure with traditional methods such as VSP layer stripping given the strong and complex birefringence in the overburden. The new method utilized here bypasses the overburden entirely by turning VSP receivers into multicomponent shear virtual sources. It is rather easy to implement given a 3D 2C x 2C VSP.

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EDITED REFERENCES

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