Seismic characterization of multiple fracture sets at Rulison Field, Colorado

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Summary

Conventional fracture-characterization methods assume the presence of a single set of aligned, vertical cracks in the subsurface. We relax this assumption and demonstrate the feasibility of seismic characterization of *multiple* fracture sets. Our technique relies on recent numerical findings indicating that multiple, differently oriented, possibly intersecting planar cracks embedded in an otherwise isotropic host rock result in nearly orthorhombic effective media. We estimate the governing parameters of crack-induced orthotropy from 3D, wide-azimuth, multicomponent seismic reflection data acquired over the tight-gas Rulison Field in Colorado.

Our inversion procedure identifies a set of cracks more or less aligned in the WNW-ESE direction in the western part of the study area and multiple, likely intersecting fractures in its eastern part. We validate both our underlying theoretical model and the obtained estimates by a number of independent measurements: (i) the estimated fluid-infill parameter indicates dry cracks as expected for the gas-producing sandstones at Rulison; (ii) our model predicts almost elliptical anisotropy and, indeed, the long-spread P-wave data exhibit no nonhyperbolic moveout; (iii) the obtained crack orientations are supported by well observations. As a by-product of fracture characterization, we build an *orthorhombic* velocity model of the Rulison reservoir which, we believe, is the first velocity field of such a low symmetry ever constructed from seismic reflection data.

Introduction

Naturally fractured rocks are widely recognized as potential hydrocarbon-bearing formations. Perhaps this is why the 2004 Summer Research Workshop of the SEG and the EAGE was held to determine the state of the art of seismic characterization of fractured reservoirs. The workshop demonstrated that current industry capabilities are limited to a single set of parallel, vertical cracks in an otherwise isotropic host rock. This arrangement leads to the effective horizontal transverse isotropy that allows estimation of the fracture parameters from a variety of seismic signatures including the normal-moveout velocities, amplitude-versus-offset variations, and shear-wave splitting coefficients.

The existing techniques are inherently based on measuring the magnitude of azimuthal anisotropy in a selected seismic signature and interpreting it in terms of parameters of a single set of cracks. Being such, these methods are bound to produce misleading results in the presence of differently oriented fractures which are usually identified in the borehole televiewer data and observed at numerous outcrops throughout the globe. To characterize multiple fracture sets, one has to translate their microstructural complexity into a few parameter combinations that control propagation of long (compared to the sizes of fractures) seismic waves. We accomplish this parameter reduction by applying the effective media theory developed by Kachanov (1980) and recently confirmed by extensive numerical studies on the so-called digital rocks (Grechka and Kachanov, 2005; Grechka et al., 2006). The most important conclusion of Kachanov's theory is that arbitrarily oriented vertical fractures embedded in isotropic host rock cause nearly orthorhombic effective symmetry and, therefore, can be approximated by *two* equivalent (or principal) sets. Furthermore, such effective media are fully described by five governing parameters that can be estimated in a unique fashion from 3D, multiazimuth, multicomponent seismic reflection data (Grechka and Kachanov, 2005).

Here we apply this fracture-characterization technique to a 3D, 9C, wide-azimuth data set acquired over the tight-gas Rulison Field located in Colorado. We invert the interval NMO ellipses of P, S_1 (fast shear), and S_2 (slow shear) waves for the two principal crack densities, fracture azimuths, and fluid factors and compare our parameter-estimation results with other data.

Theoretical background

Multiple, differently oriented, open or partially closed, intersecting or non-intersecting, circular or irregularly-shaped vertical fractures embedded in an otherwise isotropic background rock can be replaced by *two orthogonal* vertical sets as far as propagation of long seismic waves is concerned. These two (the so-called principal) sets result in effective media that have orthorhombic symmetry (Kachanov, 1980, for the theory; Grechka and Kachanov, 2005, and Grechka et al., 2006, for numerical confirmation). The effective elastic properties of such media are described by the parameter vector

$$\boldsymbol{M} = \{\lambda_b,\, \mu_b,\, e_1,\, e_2,\, \varsigma\}\,, \tag{1}$$

where λ_b and μ_b are the density-normalized Lamé constants of the host rock, e_1 and e_2 are the densities of the two principal vertical fracture sets, and $0 \le \varsigma \le 1$ is the fluid factor ($\varsigma \approx 0$ for dry cracks, $\varsigma \approx 1$ for liquid-filled ones).

Grechka and Kachanov (2005) demonstrated that 3D, multiazimuth, multicomponent seismic reflection data constrain vector $\boldsymbol{M}$. Specifically, $\boldsymbol{M}$ can be unambiguously inverted from the data

$$\boldsymbol{D}(\boldsymbol{M}) = \left\{ \frac{V_{S1}}{V_{P0}},\, \frac{V_{S2}}{V_{P0}},\, \boldsymbol{W}^P,\, \boldsymbol{W}^{S1},\, \boldsymbol{W}^{S2} \right\}, \tag{2}$$

where V_{P0}, V_{S1}, and V_{S2} are the velocities of vertically propagating P- and two split shear-waves (fast

S_1 and slow S_2). The velocity ratios entering $\boldsymbol{D}$ are computed from the zero-offset times after establishing the P-to-S event correspondence. The 2×2 matrices $\boldsymbol{W}$ in equation (2) are the normal-moveout (NMO) ellipses of pure modes reflected from a horizontal interface (Grechka and Tsvankin, 1998).

In practice, we estimate data (2) from wide-azimuth P, S_1, and S_2 common-midpoint (CMP) gathers. 3D semblance analysis yields the effective NMO ellipses. Then the Dix-type differentiation is applied to calculate the interval NMO ellipses $\boldsymbol{W}^{P}_{\rm int}$, $\boldsymbol{W}^{S1}_{\rm int}$, and $\boldsymbol{W}^{S2}_{\rm int}$ that enter the interval data vector $\boldsymbol{D}_{\rm int}$. We use these ellipses to estimate parameter vector $\boldsymbol{M}$ at each CMP location though the nonlinear minimization,

$$\mathcal{F} = \min_{(\boldsymbol{M})} ||\boldsymbol{D}_{\rm int} - \boldsymbol{D}(\boldsymbol{M})|| \,. \qquad (3)$$

Rulison field data

Brief overview of the field

Rulison Field, located in the South Piceance Basin, Garfield county, Colorado (Figure 1), produces gas from a 1,200 ft pay section of channel sand lenses stacked within the Cretaceous Mesaverde sandstone. Porosities (from 1% to 10%) and permeabilities (from 1 μD to 60 μD) of these sand bodies characterize the formation as a tight gas reservoir. Because of such a low matrix permeability, it is believed that gas production is controlled by open natural fractures. Fracture orientations vary over the field, and their intersections are thought to be important for the reservoir production. The thickness of sand lenses of about 10 ft makes them impossible to image with surface seismics. Since neither sand bodies nor fracture zones can be individually isolated on seismic images, it is necessary to characterize the fractures collectively as an effective medium. Reflector dips at Rulison are small and can be neglected for the purposes of seismic data processing.

Data acquisition and processing

Wide-azimuth, 3D, 9C seismic data set covering 5.5 km^2 over the Rulison Field was acquired by the Reservoir Characterization Project (Colorado School of Mines). The data were pre-processed (deconvolved for the source signature and corrected for the source-receiver statics) by Veritas. After removing the ground roll in shot and receiver cross-spreads with a specially designed f-k_x-k_y filter, we created the 440×440 ft superbins and estimated the P-, S_1- and S_2-wave NMO ellipses.

We obtain the P-waves NMO ellipses over the entire survey area (the corresponding semblance values range between 0.55 and 0.65). As the shear data are noisier, the S-wave NMO ellipses have been estimated for only about one third of the survey. In these higher-quality data areas, the azimuthal traveltime variations are clearly seen on the gathers corrected with an azimuthally-constant NMO velocity (Figure 2). Next, we proceed with the Dix-type differentiation that yields the interval ellipses $\boldsymbol{W}^{P}_{\rm int}$, $\boldsymbol{W}^{S1}_{\rm int}$, and $\boldsymbol{W}^{S2}_{\rm int}$. Finally, minimizing the objective function (3), we invert $\boldsymbol{W}^{P}_{\rm int}$, $\boldsymbol{W}^{S1}_{\rm int}$, $\boldsymbol{W}^{S2}_{\rm int}$, and the interval zero-offset time ratios of P- and S-waves for the fracture parameters.

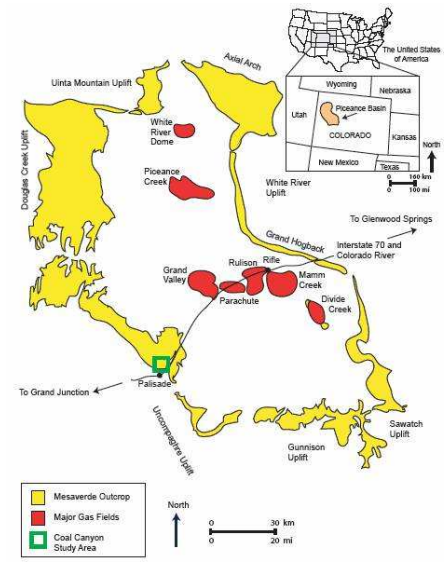

Fig. 1: Map of gas-producing fields in Piceance Basin, Colorado (after Ellison, 2004).

Fracture characterization

Figure 3 displays the estimated background velocity fields $V_{P,b}$ and $V_{S,b}$ and the principal crack densities e_1 and e_2 (by definition, $e_1 \geq e_2$). Clearly, the crack densities in Figure 3c are considerably greater than those in Figure 3d suggesting that the fracturing is dominated by the cracks trending in the WNW-ESE direction. Our results indicate that the western part of the area is mainly controlled by a single fracture set that has density e_1, while the eastern part exhibits a non-negligible contribution of other fractures that translate themselves into the set with density e_2 (Figures 3c and 3d). We also see that the areas of the highest crack densities do not necessarily coincide with the largest P-wave NMO ellipse eccentricities. The fluid factors ς have been estimated also but we do not display them because all $\varsigma < 0.01$. These estimates are consistent with the fact that Rulison Field produces only gas.

Orthorhombic model of the reservoir

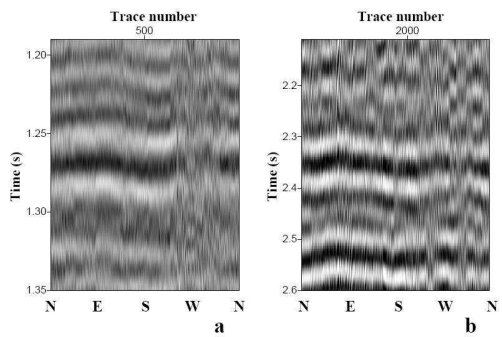

Fig. 2: P- (a) and S_1-wave (b) gathers after azimuthally-constant NMO correction. The traces are sorted by azimuth. The apparent cosine-type dependence of the residual moveout is indicative of azimuthal anisotropy. The reflection events at approximately at 1.27 s in (a) and at 2.35 s in (b) correspond to the reservoir bottom. The offset-to-depth ratios are between 0.8 and 1.0.

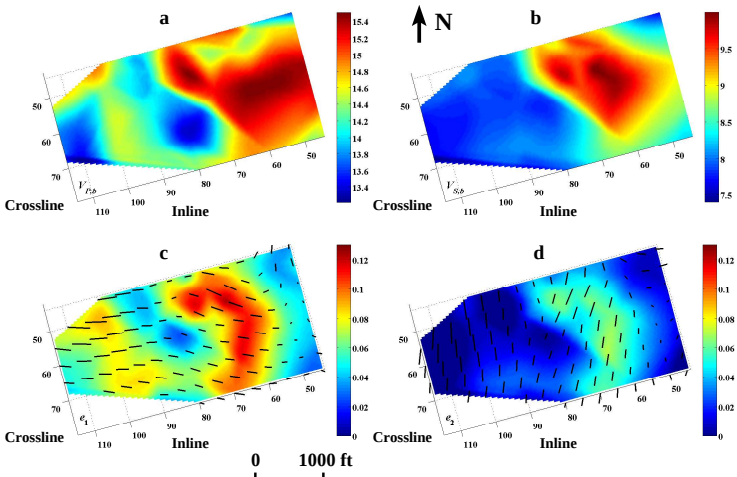

Fig. 3: Output of fracture characterization: background velocities $V_{P,b}$ and $V_{S,b}$ (in kft/s) of P- (a) and S-waves (b), and principal crack densities e_1 (c) and e_2 (d). The directions of the principal fracture sets are shown with ticks. Their lengths are proportional to the eccentricities of the interval P-wave NMO ellipses (shown in Figure 4c).

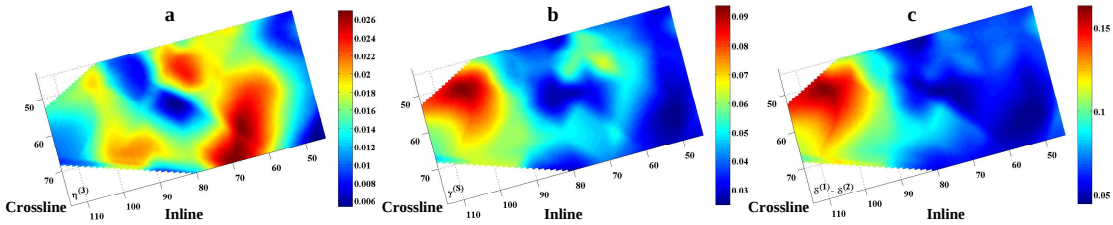

Fig. 4: The anellipticity coefficient $\eta^{(3)}$ (a), shear-wave splitting coefficient $\gamma^{(S)}$ (b), and the eccentricity of the P-wave NMO ellipses $\delta^{(1)} - \delta^{(2)}$ (c) at Rulison reservoir (approximately between 4,000 ft and 7,500 ft depth).

The obtained background velocities and crack densities (along with the fluid factors $\varsigma \approx 0$) are sufficient for building an *orthorhombic depth model* of the reservoir. We have computed the vertical velocities, V_{P0} and V_{S0}, and all seven anisotropic coefficients. Figure 4a displays the anellipticity coefficient $\eta^{(3)}$, whose magnitude is greater than those of $\eta^{(1)}$ and $\eta^{(2)}$. Clearly, the predicted anisotropy is elliptical by seismic standards.

It is instructive to point out that our orthorhombic velocity field was constructed solely from seismic reflection data. It became possible because we explicitly targeted the *crack-induced* rather than general orthotropy. Rulison reservoir turned out to be noticeable anisotropic: the magnitudes of anisotropic coefficients $\epsilon^{(2)}$ and $\delta^{(2)}$ reach 0.2 (not shown) at places with the highest total crack density $e = e_1 + e_2 = 0.17$ (Figures 3c and 3d).

Conventional approaches to fracture characterization

Having estimated the reservoir parameters from both P- and S-wave data, we can predict what would happen if we relied either on S- or P-waves alone for fracture characterization. In a typical pure shear-wave survey, one would measure the shear-wave splitting coefficient, $\gamma^{(S)} \approx \gamma^{(1)} - \gamma^{(2)}$, and interpret it as the crack density of a single fracture set. The result of this interpretation (Figure 4b) suggests that the western part of the study area is more fractured than the eastern one, quite opposite to the conclusion drawn from Figures 3c and 3d. If only P-wave data were used, one would obtain the eccentricity of the P-wave NMO ellipses, which is quantified by the difference of two δ coefficients, $\delta^{(1)} - \delta^{(2)}$. This difference, shown in Figure 4c, leads to a similar conclusion that the western part of the area is apparently more fractured than the eastern part.

These mutually contradictory results originate from the fact that both quantities $\gamma^{(S)}$ and $\delta^{(1)} - \delta^{(2)}$ are governed by the difference $e_1 - e_2$ between the crack densities of two principal fracture sets. Therefore, conventional techniques that rely on $\gamma^{(S)}$ or $\delta^{(1)} - \delta^{(2)}$ for fracture characterization can be used only when one set of cracks dominates the others.

Verification of results

Assessing the errors in the estimated quantities was an important part of our study. We estimated the data variances associated with uncertainties in travel-time and NMO-velocity picking and propagated them into the quantities shown in Figure 3. This yields errors of about 7% in the velocities $V_{P,b}$ and $V_{S,b}$ and 0.01 in the principal crack densities e_1 and e_2 within the 90% confidence interval. We also analyzed the misalignments in the orientations of the interval NMO ellipses for different wave modes. While no misalignments was observed at many CMP locations, the average differences in the ellipse orientations of P- and S_1-waves and P- and S_2-waves turned out to be 12° and 17°, respectively. As significant part of these misalignments can be attributed to interaction

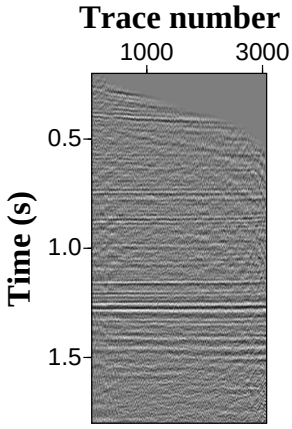

Fig. 5: Typical long-spread P-wave gather after hyperbolic moveout correction. The offsets are irregularly sampled. Maximum offset-to-depth ratio is 2.0.

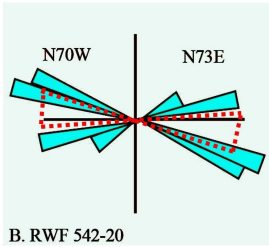

Fig. 6: Fracture count (blue) in well B. RWF 542-20 located at Inline 92, Crossline 76 and the 90% confidence interval (dashed red) corresponding to the azimuth of the fracture set with density e_1 estimated from seismic data.

of the closely spaced cracks (Grechka and Kachanov, 2005), we conclude that orientations of the NMO ellipses are consistent with our fracture model over most of the survey area.

Nonhyperbolic moveout

Small values of the anellipticity coefficients in the reservoir (Figure 4a) and nearly isotropic overburden imply the absence of nonhyperbolic moveout. Figure 5, which displays a typical long-spread P-wave gather, supports this model conclusion. Indeed, no 'hockey-sticks' indicative of the nonhyperbolic moveout are observed at Rulison.

Borehole measurements

The survey area contains well B. RWF 542-20 (located at Inline 92, Crossline 76), where an FMI log was run and fractures in the entire reservoir were counted. Figure 6 compares the borehole fracture count with our estimate of the crack orientation. As a dominant set of cracks has been identified at Inline 92, Crossline 76 (Figures 3c and 3d), we do not display the second set in Figure 6 because it has nearly zero crack density. The fractures observed in FMI are not orthogonal to each other, and yet, their influence on propagation of long (compared to the fracture sizes) seismic waves is equivalent to that of two orthogonal sets. The dashed red line in Figure 6 shows the azimuth of the dominant set estimated from seismics, thus, confirming that our fracture-characterization results are consistent with the available FMI log.

Conclusions

We have discussed seismic characterization of fractures at Rulison Field, Colorado. To the best of our knowledge, Rulison is the first case study described in the geophysical literature, where parameters of *multiple* fracture sets, that is, their orientations, crack densities, and the type of infill, have been estimated from multicomponent seismic reflection data. The key of our parameter-estimation methodology is the understanding that differently oriented, multiple vertical sets of cracks in isotropic background appear as two orthogonal sets for long seismic waves. Following this notion, we have targeted the parameters of those two orthogonal (or principal) sets in our inversion. The obtained results point to the presence of fractures aligned in approximately WNW-ESE direction in the western part of the study area. In contrast, two or more sets of cracks exist in its eastern part. Their principal crack densities reach $e_1 = 0.11$ and $e_2 = 0.06$ indicating that these fractures are likely to form an interconnected network.

As a by-product of our fracture-characterization procedure, we have built an *orthorhombic depth model* of the Rulison reservoir. The reconstructed orthorhombic velocity field explicitly attributes the observed anisotropy to the presence of fractures. This rock-physics constraint reduces the number of independent quantities to be estimated and obviously improves stability of the inversion. In particular, it allows the vertical P- and S-wave velocities and all anisotropic coefficients to be uniquely determined solely from 3D, multiazimuth, multicomponent seismic reflection data. We believe that Rulison is the first example of building a subsurface velocity model that has orthorhombic symmetry.

We paid special attention to verifying our fracture-characterization results. They are supported by long-spread seismic data that were not used in the inversion, by direct borehole measurements, and by the fact that Rulison Field produces dry gas.

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