Converted Shear-Wave Seismic Fracture Characterization Analysis at Pinedale Field, Wyoming

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Abstract

Multicomponent 3D surveys where downgoing compressional (P) waves convert to upgoing shear (S) waves at interfaces provide a practical means for analyzing fracture properties. This is particularly important for delineating naturally fractured reservoirs by exploiting the unique characteristics of S-wave azimuthal anisotropy induced by vertical fracturing. In the presence of fractured media, S-waves split into a fast wave that is polarized parallel to fractures and a slow wave that is polarized normal to fractures. The amount of splitting (time difference between the two S-waves) is proportional to fracture intensities. To investigate this phenomenon, we utilize a wide range of source-receiver azimuths in the processing and analyze the fast and slow S-waves to extract fracture information.

A 3D 3-component (one vertical and two horizontal geophones) survey from Wyoming is presented, acquired over the southern tip of the Pinedale field. The targets are naturally fractured gas sand reservoirs in the Lance formation. From the analysis of fast and slow S-waves a regional direction of anisotropy was observed. Layer-based analyses confirmed the presence of azimuthal anisotropy in the overburden, which required compensation during the processing to isolate S-wave splitting properties at reservoir depths. Results from the layer-stripping analysis suggested areas of increased fracturing in the overburden as well as at target levels that are associated with faults over the crest and along the limbs of the Pinedale anticline. Although FMI logs show mostly bedding planes near horizontal dip, at many levels where dip is larger, the dip direction is qualitatively in agreement with the principal S-wave directions.
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Azimuthal Anisotropy: Fractures

Fractures tend to be aligned and vertical – stress regime

They are smaller than the seismic wavelength

Measure seismic attributes to infer fracture systems

Transversely isotropic with horizontal axis of symmetry (HTI)
Quantitative Measurements of Fracturing

Fractal Properties

- Size / Length
- Clustering
- Displacement
- PD Relationship

from Mattner (2002)
Outline

- Processing and analysis highlights
- Pinedale Field case study
- Discussion and conclusions
Converted-Wave Survey Geometry

Surface

P-wave Source

CMP

CCP

3C Receiver

X

Y

Z

Reflector

Incident P-waves

Reflected P-wave

Transmitted P and S waves

Reflected Mode Converted S-waves

FAST

SLOW

SHEAR WAVE
Complexity of S-wave Splitting

Waves sourced by $S_1$

Waves sourced by $S_2$

Upper Anisotropic Rock

$S_{11}'$

$S_{12}'$

$Lag from lower level$

$S_{21}'$

$S_{22}'$

Lower Anisotropic Rock

$S_1$

$S_2$

Upper natural coordinate frame

$S_1'$ $S_2'$

Lower natural coordinate frame

$S_1$ $S_2$

Converted P to S reflection
Source to Receiver Azimuth Limitation
P$_1$-wave Direction: Prestack

SLOW (⊥ to fractures)

FAST (∥ to fractures)
$P_1$-wave Direction: Stacked

- SLOW (⊥ to fractures)
- FAST (Ⅱ to fractures)
$P_2$-wave Direction: Prestack

$P'_{2}$

$S'_{1}$

$S'_{2}$

$PS'_{11} \quad PS'_{12} \quad PS'_{21} \quad PS'_{22}$

SLOW (⊥ to fractures)

FAST (Ⅱ to fractures)
$P_2$-wave Direction: Stacked

$S'_1$, $S'_2$

$PS'_{11}$, $PS'_{12}$, $PS'_{21}$, $PS'_{22}$

$P'_1$, $P'_2$

SLOW (⊥ to fractures)

FAST (∥ to fractures)
2C\times2C \text{ Data Before Rotation to Principal Directions}

$S''_1$ $S''_2$

$P''_1$ $P''_2$

SLOW ( \perp \text{ to fractures})

FAST ( \parallel \text{ to fractures})
2Cx2C Data After Rotation to Principal Directions

\[ \theta \]

\[ S_2 \]

\[ S_1 \]

\[ P_2 \]

\[ P_1 \]

SLOW (\( \perp \) to fractures)

FAST (\( \parallel \) to fractures)
Outline

• Processing and analysis highlights
• Pinedale Field case study
• Discussion and conclusions
Pinedale Shot-Receiver Geometry
P-wave Isochron: In Lower Fort Union Formation
P-wave and PS-wave Cross line

Near Base of Fort Union

Near Base of Fort Union
Fast PS-wave Direction: N145E
Slow vs. Fast PS-wave
Azimuthal Anisotropy: Lower Fort Union
Fault and Fracture Trends

- Fractures caused by regional stress
- Fractures caused by folding
P-wave and PS-wave Inline

FMI Log Near Base of Fort Union

Near Base of Fort Union

In Lance Formation

Near Base of Fort Union

In Lance Formation
FMI Log at 7900: Near Vertical Fractures

Azimuth (Deg)

50  140  230  320

40  130  220  310

Pad 1 Azi.

N10W
N30W

Strike
FMI Log at 8500: Near Vertical Fractures

Azimuth (deg)

130  220  310  40

Strike
N20W  N20W

Pad 1
Azi.
130 deg

150 deg

8500
Azimuthal Anisotropy: Lance formation
Discussion: Borehole information for calibration

- Antelope # 15-23 on the apex of the anticline
- FMI and dipole sonic logs
  - FMI shows mostly bedding planes near horizontal
  - But at many levels dip exceeds 30° and 40° - near vertical
  - Strike direction agrees with the fast S-wave direction
- For optimal calibration with PS-wave data
  - Cross-dipole should be acquired (not available)
  - Quantitative estimates of azimuthal anisotropy
  - Orientation and magnitude of anisotropy
- Near-offset S-wave source VSPs
  - S-wave splitting at same seismic wavelengths
Conclusions

- Early estimation of principal S-wave orientation is critical for processing.
- Alford rotation analysis is a valuable tool to quantify the time variant S-wave birefringence.
- More intense azimuthal anisotropy on the crest and flanks of the Pinedale anticline suggest potential fracture sweet spots.
- Fast S-wave direction agrees with the strike of near vertical fractures on the FMI log, and appears to be sensitive to local horizontal stresses.