S-wave splitting analysis of 4-C VSP in Altamont-Bluebell field

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ABSTRACT

The 4-C VSP was acquired within Bluebell Field, the eastern portion of Altamont-Bluebell field in northeastern Utah. Altamont-Bluebell field is within the Uinta Basin, and is considered an unconventional reservoir in the sense that natural fractures act as fluid storage and conduits in the tight sandstones and carbonates. Information related to fracture orientation and intensity is vital for the development of such reservoirs. S-wave splitting can be useful for fracture-induced anisotropy. Therefore, this paper utilizes S-wave splitting to estimate the direction and intensity of fractured-induced anisotropy within the three main reservoirs using 4-C VSP data.

S-wave analysis is carried using Alford (1986) 4-C rotation to separate fast and slow modes. This method assumes that the symmetry axis is vertically invariant. In order to overcome this assumption, a layer stripping technique was applied using Winterstien and Meadows (1991).

INTRODUCTION

Bluebell-Altamont field is located in northeastern Utah in the Uinta basin. The Uinta basin is an asymmetric east-west trending basin with a south flank that slopes gently. The north flank is bounded by east-west trending Uinta Mountains. The Bluebell-Altamont field is located in the northern-central part of the basin (Figure 1). Production is from Tertiary sandstones, shales and carbonates. There are three main targets in the field: Upper Green River, Lower Green River, and Wasatch/Colton (Lynn et. al, 1995).

The strata were deposited in lacustrine and alluvial environments. The Upper Green River formation was deposited in open-lacustrine and most of the kerogen is immature. Gas may be migrated from deeper formations. The Lower Green River formation was deposited in marginal and open lacustrine. The kerogen-rich shale and marlstone are the sources of oil. Lastly, Wasatch/Colton formation is alluvial and its source of oil is the Kerogen-rich shale. It is a highly overpressured reservoir as a result of hydrocarbon generation. The hydrocarbon generation in the deep Colton formation is the main cause for natural fractures. Natural fractures in the shallower Green River reservoirs are tectonically induced (Morgan et. al., 2003).

Bluebell-Altamont field is unconventional in the sense that natural fractures act as storage and conduits in the tight sandstones and carbonates. Bluebell field is the eastern portion of the Bluebell-Altamont field. Its cumulative production is 336 MMBO, 588 BCFG, and 701 MMBW. The objective of this study is to identify density and direction of fractures to help in determining well spacing to existing wells needed to effectively drain the remaining hydrocarbon reserves in the Bluebell field, and to identify new drilling opportunities (Adams et. al, 2014).

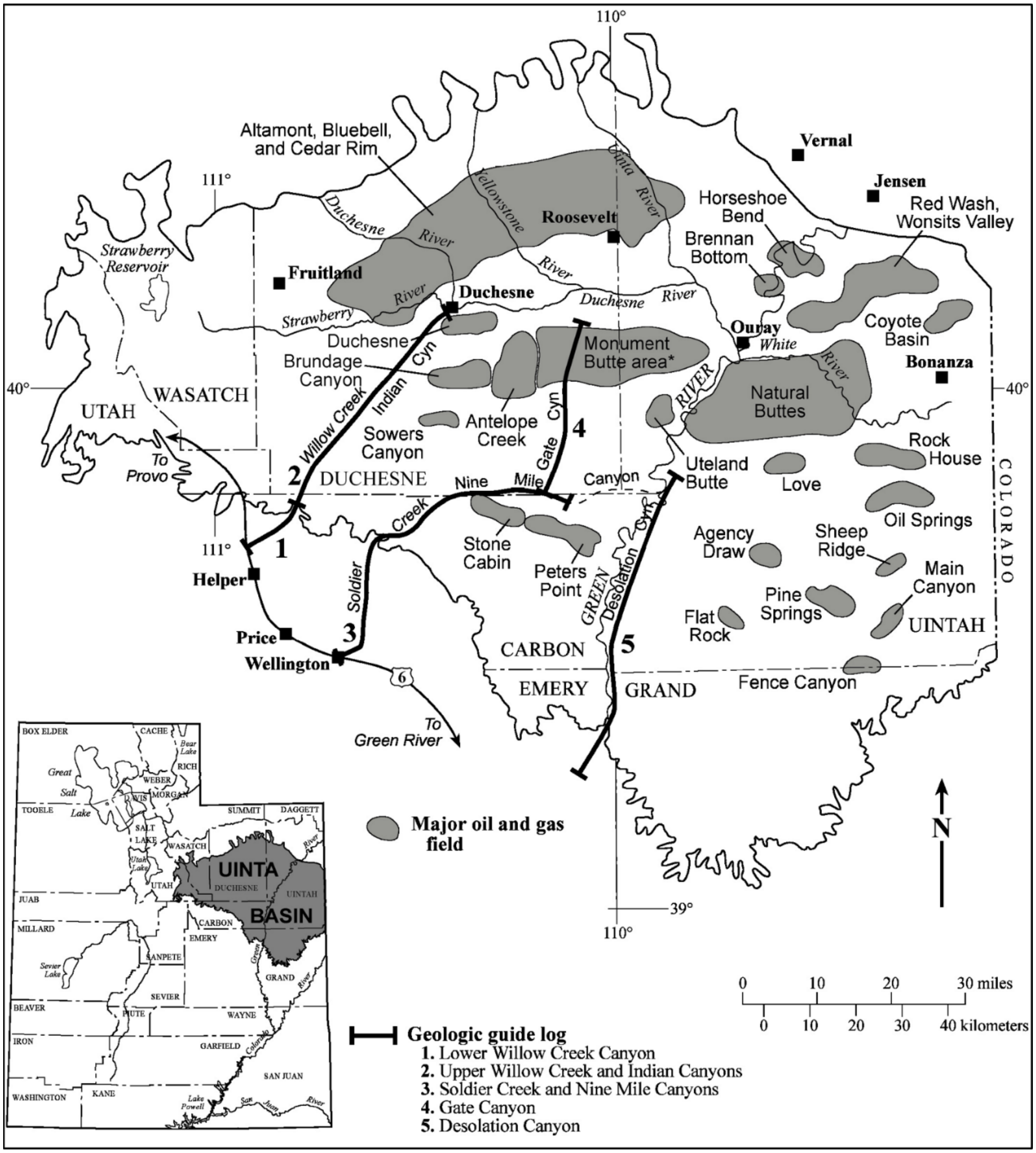

Fig. 1. Location of Uinta basin, Utah (bottom left) and major oil and gas fields within Uinta basin (after Morgan, 2003).

A 4-C VSP was acquired within Altamont-Bluebell field. The objective of the 4-C VSP is to analysis S-wave splitting, a phenomena related to anisotropic media. Common techniques for analyzing S-wave splitting are tensor rotation (Alford, 1986) and vector rotation (Thomsen, 1988) of 4-C S-wave data. However, these techniques require that the principle direction of azimuthal anisotropy do not vary with depth; a condition that can be rarely applicable to Earth. Winterstein and Meadows (1991) showed how to extend 4-C rotation of S-wave VSP data to the case of vertically variable stress principible direction by a layer-stripping technique. That technique is utilized for Altamont-Bluebell data in this report.

VSP DATA ACQUISTION

A 4-C VSP was acquired using an S-wave source on surface and a 2-level tool of 3-C geophones in the borehole. The natural frequency of the geophones is 15 Hz, and the vibroseis sweep is 4-48 Hz~ half the sweep used for P-wave VSP (4-69 Hz). The total depth (TD) is 14240'. The VSP was acquired into two runs. The first run was acquired over depths from 480' to 3580, and the source was 385' away from borehole at azimuth of 155°. The second run was acquired over depths from 3300' to 14050', and the source was 672' away from borehole at azimuth of 164°. In this report, only the second run is used because the first run is not within any of the three reservoirs. However, the first run can be useful for near-surface analysis. The surface elevation of the borehole is 5254' above mean sea left (MSL), while the Kelly Bushing (KB) elevation is 5288' above MSL.

While being in the borehole, the tool rotates and the oriention of N-S component and E-W compenent of the geophone will be hard to determine without a vertical source. Luckily, there were other 3-C VSPs acquired while the tool was fixed. We have used one of those VSPs to preform a conventional 2-C rotaion to calculate the angle required to orient the 2 components to the vertical source, and later to N-S and E-W. Figure 2 shows 4-C VSP before rotation with N-S shot components being on top, E-W shot components being on bottom, N-S receiver componets being on left, and E-W receiver components being on right.

S-WAVE SPLITTING: ALFORD ROTATION & LAYER STRIPPING

In the HTI media, the P wave is fastest along the fracture planes, slowest perpendicular to fracture planes, somewhere in between in other directions. On the other hand, S wave has to split into two phases; a phenomena known as S-wave splitting, S-wave birefringence, or S-wave double-refraction. Polarizations of the two S waves are determined by anisotropy axis of symmetry. The fast S is polarized along the fracture planes and slow S is perpendicular to the fracture planes. Beside the anisotropy axis of symmetry, the velocity of S wave is controlled also by the angle of incidence and the azimuth of propagation. The two S waves travel at different velocities and are recorded at different times. The delay in time is proportionally related to the degree of S-wave anisotropy and thickness of the anisotropic medium (Crampin, 1981).

An Alford 4-component rotation (Alford, 1986) can be used to statistically rotate horizontal components (***V***) recorded in acquisition recorded system into anisotropy natural coordinate system (***U***) using rotation matrix ($\boldsymbol{R}(\theta)$):

$$V = \begin{bmatrix} v_{11} & v_{12} \\ v_{21} & v_{22} \end{bmatrix}, \tag{1}$$

$$U = \begin{bmatrix} u_{11} & u_{12} \\ u_{21} & u_{22} \end{bmatrix}, \tag{2}$$

and

$$R(\theta) = \begin{bmatrix} \cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \tag{3}$$

The rotation matrix, $\boldsymbol{R}(\theta)$ is an orthogonal matrix that gives the identity matrix when multiplied by its transpose or its inverse. To find a new basis of the natural coordinate system, the counterclockwise rotation by angle (θ) is

$$U = R(\theta)\; V\; R^T(\theta). \tag{4}$$

Substituting equations (1), (2), and (3) into equation (4):

$$\begin{bmatrix} u_{11} & u_{12} \\ u_{21} & u_{22} \end{bmatrix} =$$

$$\begin{bmatrix} \cos^2\theta\, v_{11} + \sin^2\theta\, v_{22} + 0.5\sin 2\theta\,(v_{21} + v_{12}) & \cos^2\theta\, v_{12} - \sin^2\theta\, v_{21} + 0.5\sin 2\theta\,(v_{22} - v_{11}) \\ \cos^2\theta\, v_{21} - \sin^2\theta\, v_{12} + 0.5\sin 2\theta\,(v_{22} - v_{11}) & \cos^2\theta\, v_{22} + \sin^2\theta\, v_{11} - 0.5\sin 2\theta\,(v_{21} - v_{12}) \end{bmatrix}. \tag{5}$$

Equation (10) transforms $\boldsymbol{V}$, horizontal components in acquisition coordinate system into the natural coordinate system (Alford, 1986).

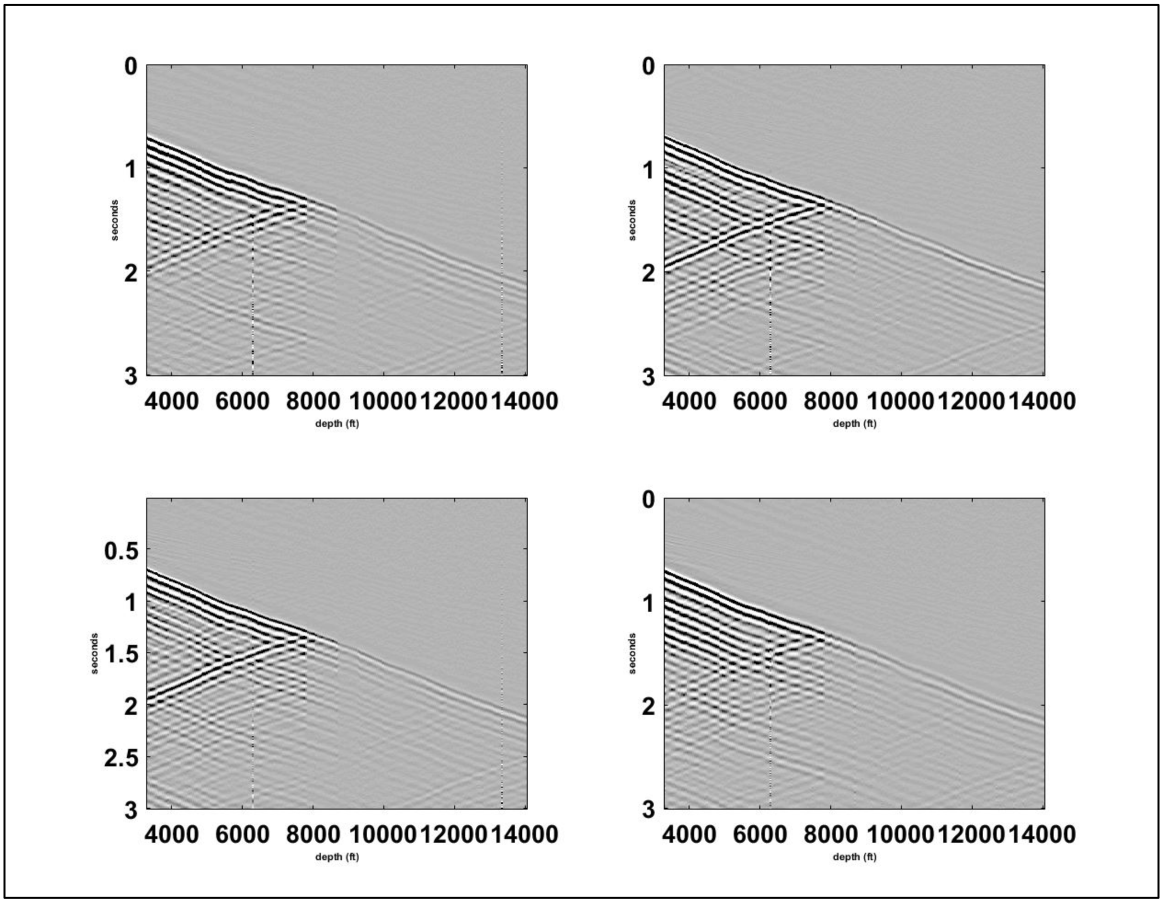

FIG. 2. 4-C VSP before rotation: N-S shot components (top), E-W shot components (bottom), N-S receiver componets (left), and E-W receiver components (right).

The rotation angle (θ) is found by scanning different angle values, and then selecting the angle that minimizes u12 and/or u21. Angles were scanned within a time window selected around fist S-wave arrivals to determine the rotation angle (θ). For layer stripping, all data below the depth at which S-wave polarization change is rotated with the rotation angle. Then, a static time shift is applied to remove the lag between fast and slow S waves at that depth. This technique simulates placing a source at the depth where S-wave polarization changes.

We applied layer-stripping technique (Winterstien and Meadows,1991) for 3 layers: overburden, Upper Green River formation, Lower Green River formation. For the last layer which is Wasatch formation, Alford rotation was also applied. Figure 3 shows 4-C VSP after rotation with N-S shot components being on top, E-W shot components being on bottom, N-S receiver components being on left, and E-W receiver components being on right. Fast S-wave is on top left, while slow S-wave is on bottom right. Figure 4 shows an overlay of fast S-wave in blue traces and slow S-wave in red traces.

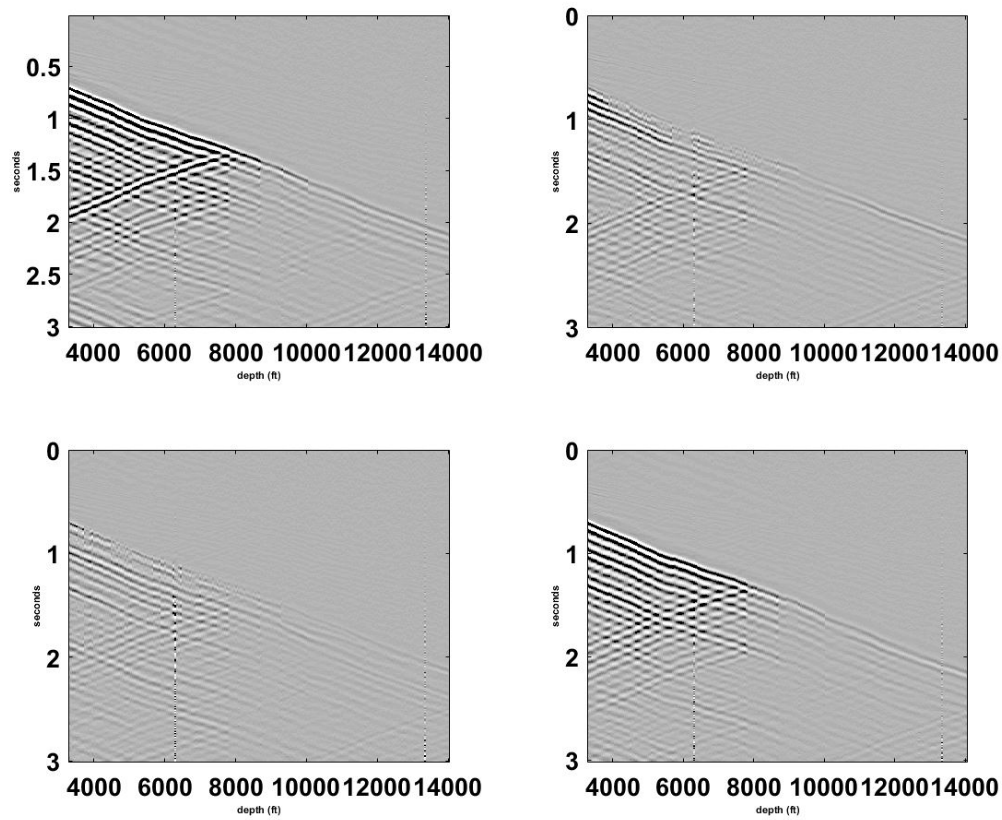

FIG. 3. 4-C VSP after rotation and layer stripping: N-S shot components (top), E-W shot components (bottom), N-S receiver componets (left), and E-W receiver components (bottom).

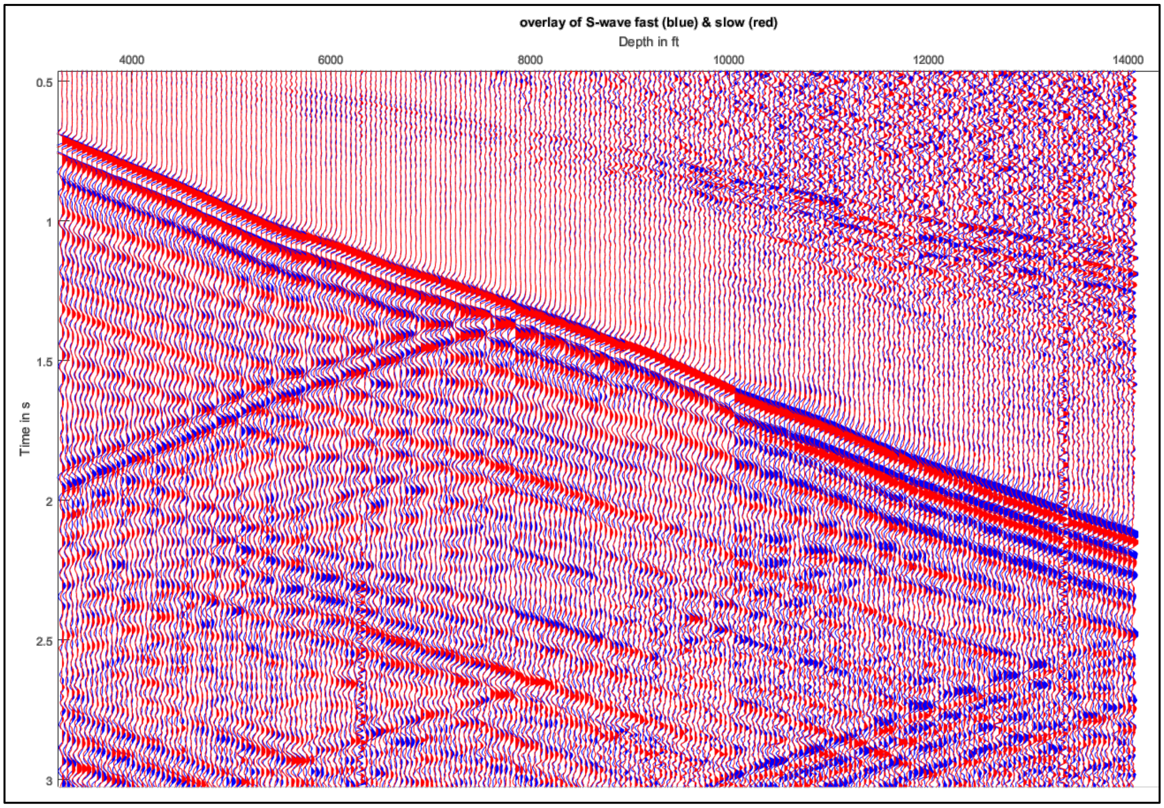

FIG. 4. S-wave data after rotation and layer stripping of 4-C VSP. The S-wave fast is indicated by blue traces, while slow is indicated by red traces.

RESULTS

The plot of cross energy against rotation angle is shown in Figure 5 for the 4 layers analyzed. The rotation angles of overburden, Upper Green River formation, Lower Green River formation, and Wasatch formation were found to be 42^o, 178^o, 161^o, and 35^o respectively. The Upper and Lower green river formation have anisotropy orientation of NW-SE, while the overburden and Wasatch formation have anisotropy orientation of NE-SW. The fast S-wave and slow S-waves were picked on rotated data. The picks are shown in Figure 6 with blue picks being fast S-wave and red picks being slow S-waves. From, the lag between the two modes of S-wave anisotropy intensity log is calculated in Figure 7. At the borehole location, Wastach formation has the most anisotropy intensity.

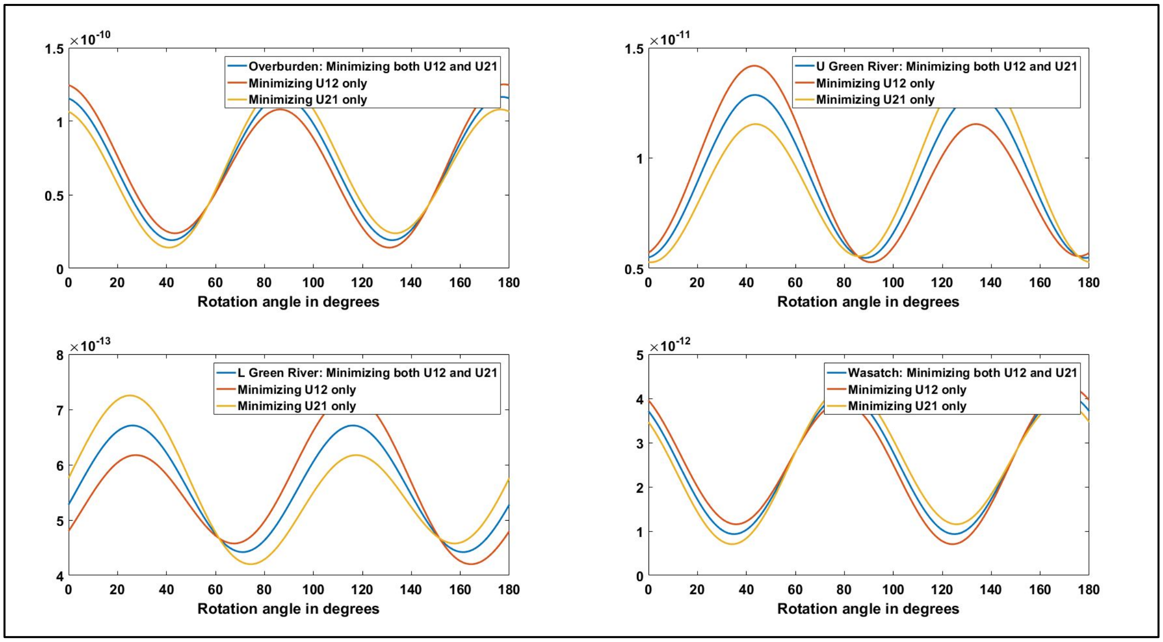

FIG. 5. 4-C VSP cross energy vs. rotation angle of: overburden, Upper Green River, Lower Green River, and Wasatch.

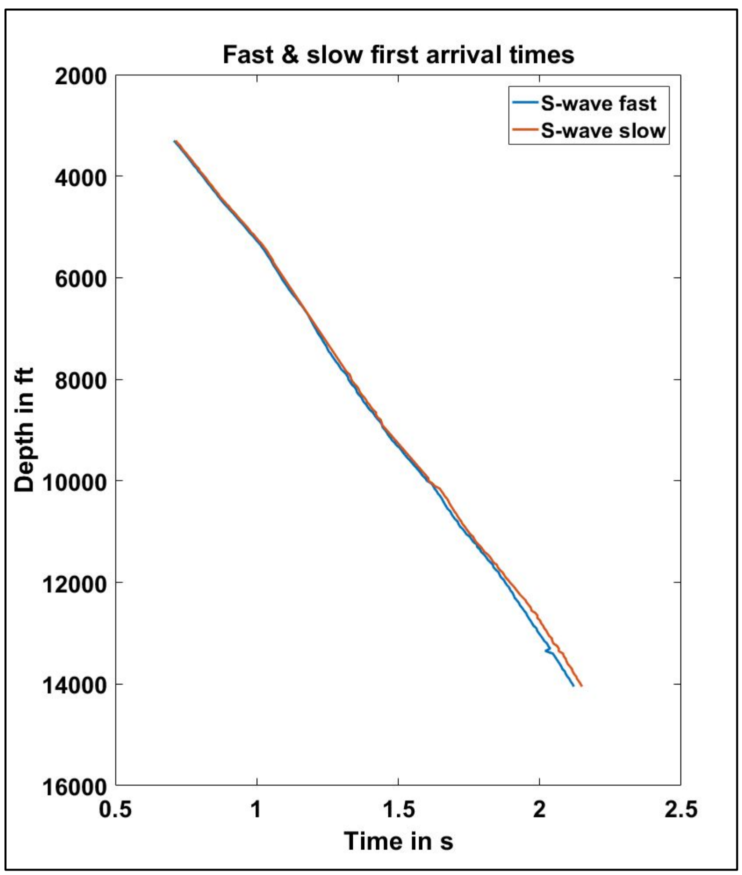

FIG. 6. Fast S-wave first arrival times indicated by blue, and slow S-wave indicated by red.

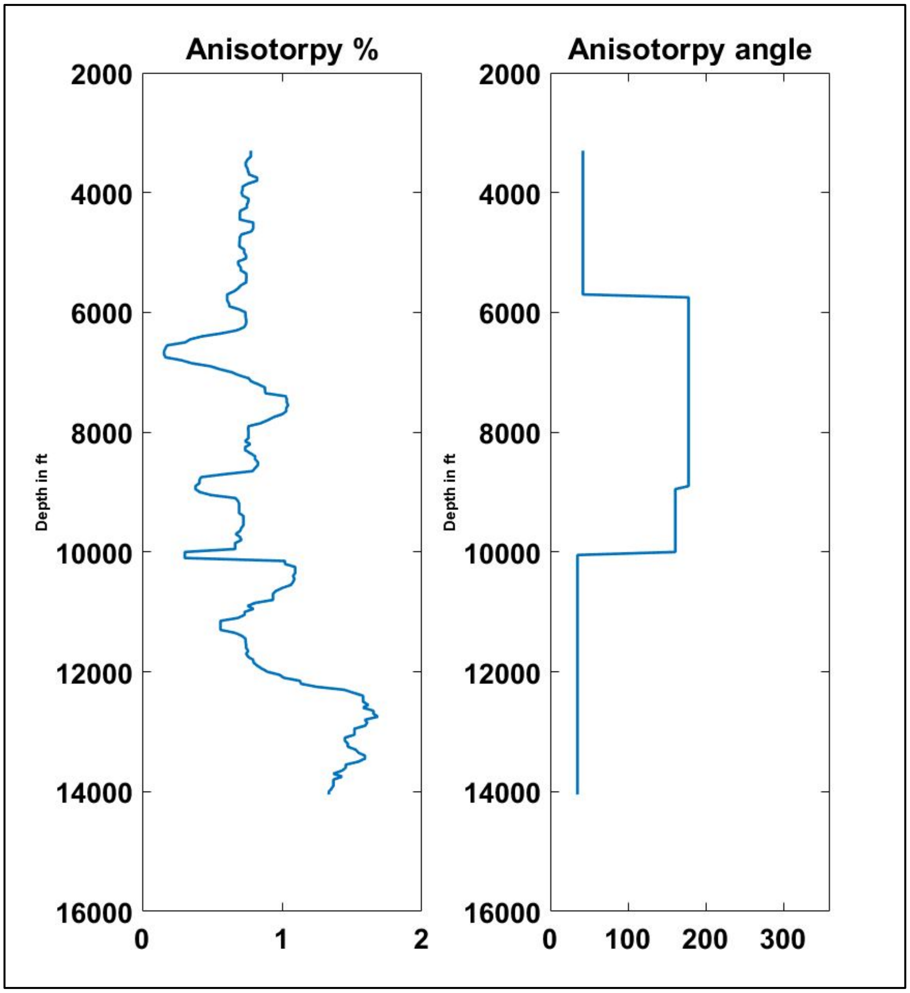

FIG. 7. S-wave analyis: anisotorpy intensity (left) and direction (right).

CONCLUSIONS

Beside other seismic data that was acquired within Altamont-Bluebell field, 4-C VSP is useful to estimate azimuthal anisotropy via S-wave splitting analysis. Most S-wave splitting methods assume that the principle direction of azimuthal anisotropy do not vary with depth; a condition that can be rarely applicable to Earth. In order to overcome this assumption, a layer stripping technique was applied using Winterstien and Meadows (1991).

From S-wave splitting analysis, the Upper and Lower green river formation were found to have an anisotropy orientation of NW-SE, while the overburden and Wasatch formation have anisotropy orientation of NE-SW. Also, the Wasatch formation was found to have the highest anisotropy intensity.

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