Analysis of converted-wave splitting in volcanic rocks: a case study from northeast China

Lifeng Wang[1,2], Xiang-Yang Li[1] and Xianyi Sun[3]

[1] *British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, UK*

[2] *School of GeoSciences, The University of Edinburgh, West Mains Road, Edinburgh EH9 3JW, UK*

[3] *PetroChina Daqing Oilfield Ltd, Henglong Jiang, China*

Summary

Converted shear-wave splitting provides a practical means for evaluating azimuthal anisotropy in hydrocarbon reservoirs that may give some insights into the internal architecture of the reservoirs. In this paper, we evaluate converted-wave seismic data acquired over volcanic gas reservoirs. The converted-wave data reveals a significant amount of shear-wave splitting over the volcanic formation, and we develop a technique to extract the shear-wave polarization and time delay from the data. The technique is particularly designed for evaluating converted-wave splitting for 2D or 3D data with a narrow-azimuth distribution. We adopt a rotation-scanning procedure that maximizes the separation of the fast and slow split shear-waves. It is interesting that the amount of splitting determined from the data can be correlated to the known gas reservoirs, revealing a potential to use shear-wave splitting to delineate gas reservoirs in volcanic rocks.

Introduction

When a P-S conversion occurs at a reflector and the medium above the reflector is azimuthally anisotropic, the converted shear wave splits into a fast and a slow shear wave, and this is referred to as converted-wave splitting. There is a wide interest from the industry to use converted-wave splitting to evaluate the internal architecture of hydrocarbon reservoirs. The splitting can be caused by the alignment of cracks, fractures, and small heterogeneities in the reservoirs. There is a vast amount of literatures on the use of converted-wave splitting to characterize fractured reservoirs (e.g. Gaiser and Van Dok 2001; Granger et al. 2001; Vetri et al. 2003; amongst others).

Shear-wave splitting in volcanic rocks has also been reported (e.g. Crampin and Lovell 1990). Volcanic rocks are known to be heterogeneous and can contain a large amount of fractures and vuggy pores, as well as other small heterogeneities. When these small-scale features are gas-charged and stress-aligned, it will introduce azimuthal anisotropy, giving rise to shear-wave splitting. Angerer et al. (2002) observed significant changes in shear-wave splitting before and after CO_2 injection in a carbonate reservoir where the presence of CO_2 kept the fractures and cracks open and increased the amount of splitting. Based on similar ideas, here we present a study of using converted-wave splitting to delineate gas reservoirs in volcanic rocks.

Analysis methods for shear-wave splitting

As we know, tensor rotation algorithms such as Alford's rotation require multi-azimuth distribution (Gaiser and Van Dok 2001). However, the converted-wave data used in this study is acquired using digital MEMS (micro-electro-mechanical-sysmtem) sensors with a 2D configuration and single-azimuth source and receiver distribution. For single-azimuth data, a rotation scanning procedure is often needed that searches for optimum solutions according to certain criteria. The common criteria include waveform similarity between the fast and slower shear-waves, or minimum spectral interference of split shear-waves (MacBeth and Crampin 1991). Here we adopt a criterion that maximizes the separation of the fast and slow shear-waves, following the approach of Yuan (2001). Once the split shear-waves are separated, we construct a time-delay spectrum between the fast and slow waves that allows the picking of time delays as a function of the vertical travel time, yielding a time-delay section for interpretation purposes.

Basic equations for rotation scanning

Figure 1 shows a map view of shear wave splitting when an up-going converted shear wave travels in a medium with a preferred distribution of heterogeneities. The principal direction of the medium forms an oblique angle θ with the survey line. The orientation of the three component geophone forms a right-handed coordinate system: radial component R, transverse component T and vertical component V, pointing to the reader. The polarization of the fast split shear wave S_1 is parallel to the principal direction and that of the slow shear wave S_2 perpendicular to it.

To process the split shear waves, it is common to use the convolution model of seismic wave propagation. Thus, in the frequency domain, the wavefield recorded by the radial and transverse components can be written as,

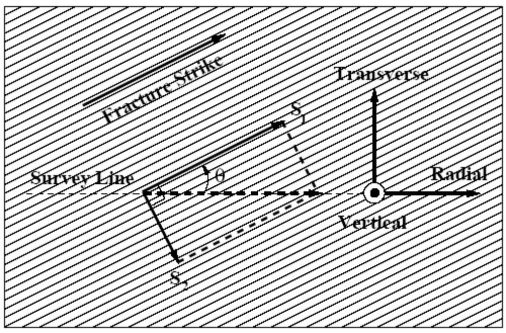


Figure1: Map view of shear wave splitting when an up-going converted shear wave travels in a vertically fracture medium.

$$\begin{bmatrix} R(\omega) \\ T(\omega) \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ \sin\theta & -\cos\theta \end{bmatrix} \begin{bmatrix} S_1(\omega) \\ S_2(\omega) \end{bmatrix} + \begin{bmatrix} N_R(\omega) \\ N_T(\omega) \end{bmatrix} \quad (1)$$

where $N_R(\omega)$ and $N_T(\omega)$ are the noise components in the radial and transverse directions. To maximize the separation between the fast and slow shear-waves, one may calculate the residual errors between the fast and slow waves as

$$E(\theta, \Delta t, \omega) = S_1(\omega) - S_2(\omega)e^{i\omega\Delta t} \quad (2)$$

where Δt is the time delay between the fast and slow waves. Substituting into equation (1) and changing into the time domain, it becomes,

$$\begin{aligned} E(\theta, \Delta t, t) &= (R(t)\cos\theta + T(t)\sin\theta) - (R(t-\Delta t)\sin\theta - T(t-\Delta t)\cos\theta) \\ &- (N_R(t)\cos\theta + N_T(t)\sin\theta) + (N_R(t-\Delta t)\sin\theta - N_T(t-\Delta t)\cos\theta) \end{aligned} \quad (3)$$

Equation (3) forms the basis for 2C vector rotation analysis. One can perform double scanning over the rotation angle θ and time delay Δt, and the objective function $F(\theta, \Delta t)$ to minimize the summed $E(\theta, \Delta t, t)$:

$$F(\theta, \Delta t) = \left(\sum_{k=0}^{n} E(\theta, \Delta t, t_k)^p\right)^{1/p} \quad (4)$$

for a time window length with n samples.

Time-delay spectra

The time-delay spectra can be constructed by scanning over vertical time using the correlation method. According to the 2C rotation analysis results, we are able to rotate the data into the fast and slow components. First we form a trace pair from traces of the fast and slow components. We then set a time window and use the correlation method to compute the correlation coefficients within the window. The time window slides downwards and therefore a time-delay spectrum is constructed.

Application results

The converted-wave data from the study area reveal a significant amount of splitting over the volcanic formations, indicated by the strong coherent energy in the transverse component (Figure 2). We use the above method and carry out a detailed analysis of the converted-wave splitting. As shown in Figure 2, we select the reservoir target as indicated by the lines for the 2C rotation analysis and Figure 3 shows the scanning results, the objective function calculated from equation (4). The average orientation angle is about 40 degrees from the inline X-direction (anticlockwise) and the average time delay is 25-30 milliseconds, indicating about 2% shear-wave splitting. The data are then rotated into the Fast/Slow components. Figure 4 shows time-delay spectra from selected CDP locations, from which a time-delay section can be obtained. Figure 5 is the interpretation results on the time-delay gradient section. As shown in Figure 5, areas of volcanic rocks with high gas accumulation show a significant amount of splitting (SS202 and SS1), whilst no-gas bearing rocks show little splitting (SS201). The splitting anomalies seem to be good indicators of gas accumulation.

Discussion and conclusions

We have presented a case study using converted-wave splitting to delineate gas reservoirs in volcanic rocks. We find that the degree of shear-wave splitting can be correlated to the known gas reservoirs. Higher values of shear-wave splitting in the presence of gas saturation is consistent with equivalent medium modelling, as in the case studied by Angerer et al. (2002). We have also presented an efficient and convenient method for analysing converted-wave splitting in single-azimuth converted-wave data. Our approach includes two key steps: rotation scanning to maximize the separation of the split shear-waves and small-window correlation to build time-delay spectra.

Acknowledgements

We thank PetroChina Daqing Oilfield Ltd. for permission to show the data. This work is funded by the Edinburgh Anisotropy Project (EAP) of the British Geological Survey, and is published by the permission of the Executive Director of the British Geological Survey (NERC) and the EAP sponsors.

References

Angerer, E., Crampin, S., Li, X.Y. and Davis, T.L., 2002, Processing, modelling and predicting time-lapse effects of overpressured fluid-injection in a fractured reservoir: Geophysical Journal International, **149**, 267-280.

Crampin, S. and Lovel, J.H., 1991, A decade of shear-wave splitting in the Earth's crust: what does it means? what use can we make of it? and what should we do next? Geophysical Journal International **107**, 387-407.

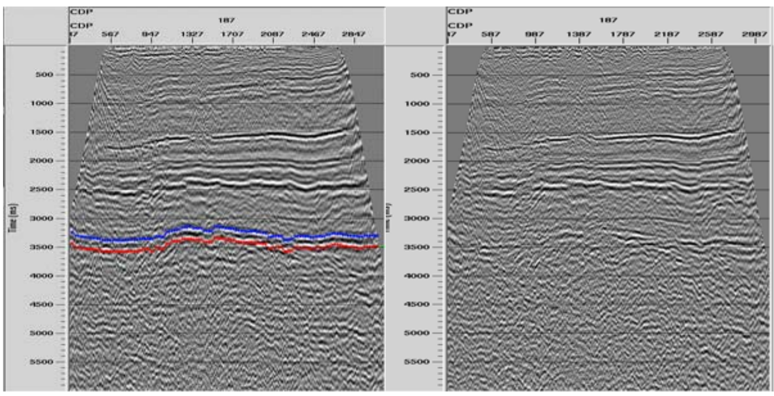
Gaiser, J. and Van Dok, R., 2001, Green River basin 3D/3C case study for fracture characterization: Analysis of PS-wave birefringence: 71st Ann. Internat. Mtg: Soc. of Expl. Geophys., 764-767.

Granger, P., Bonnot, J., Gresillaud, A. and Rollet, A., 2001, C-wave resolution enhancement through birefringence compensation at the Valhall Field: 71st Ann. Internat. Mtg: Soc. of Expl. Geophys., 772-775.

MacBeth, C. and Crampin, S., 1991, Examination of a spectral method for measuring the effects of anisotropy: Geophysical Prospecting, Eur. Assn. Geosci. Eng., **39,** 667-690.

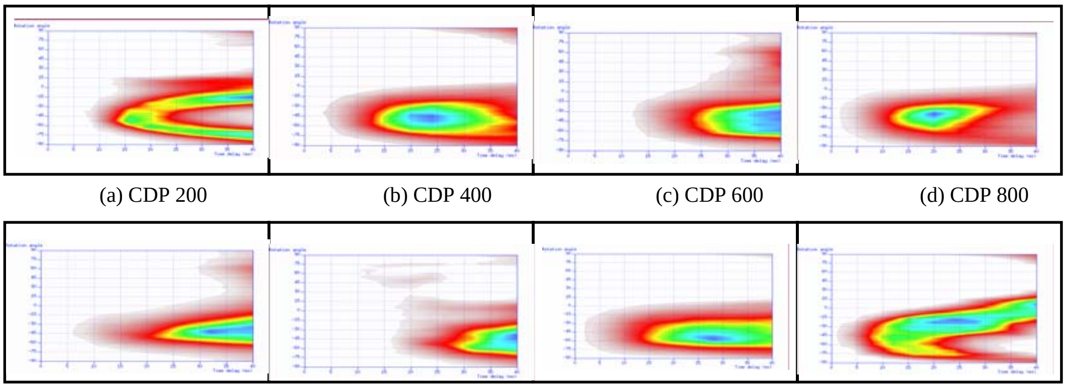
Vetri, L., Loinger, E., Gaiser, J., Grandi, A. and Lynn, H., 2003, 3D/4C Emilio: Azimuthal processing and anisotropy analysis in a fractured carbonate reservoir: The Leading Edge, **22**, 675-679.

Yuan, J., 2001, Analysis of four-component sea-floor seismic data for seismic anisotropy: PhD Thesis, University of Edinburgh.



(a) (b)

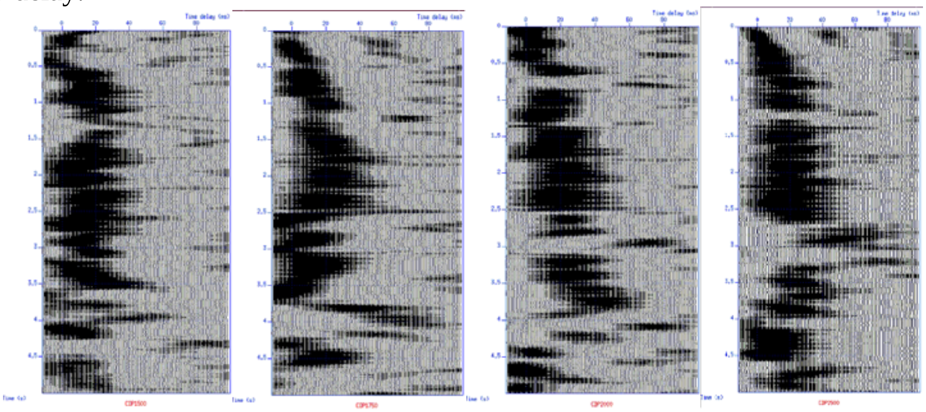
Figure 2: Input data for 2C rotation analysis. (a) is the radial component and (b) is the transverse component. The blue and red lines show the top and bottom of the target.



(a) CDP 200 (b) CDP 400 (c) CDP 600 (d) CDP 800

(e) CDP 1000 (f) CDP 1200 (g) CDP 1400 (h) CDP 1600

Figure 3: Rotation analysis for the data in Figure 2. The scanning is looking for a minimum value (in blue). The vertical axis is rotation angle, and the horizontal axis is time-delay.



(a) CDP 1500 (b) CDP 1750 (c) CDP 2000 (d) CDP 2500

Figure 4: Time-delay spectra of selected CDPs. The horizontal axis is time-delay, and vertical axis is travel time.

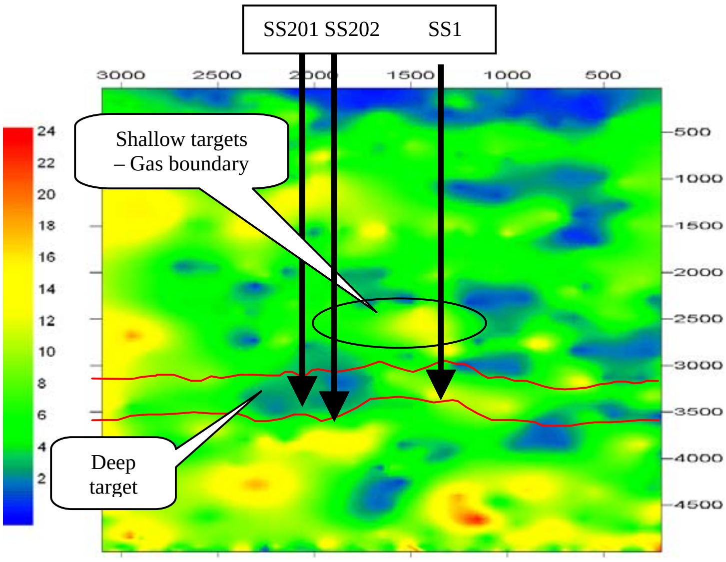


Figure 5: Interpretation results on the time-delay gradient section. SS202 and SS1 are gas-producing wells, and SS201 is a dry hole.