Modeling Shear-Wave Splitting in VSPs in South Casper Creek, Wyoming

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SUMMARY

Multi-component multi-offset VSPs in South Casper Creek, Wyoming are analyzed and modeled to examine the mechanism of anisotropy and to understand the characteristic of shear-wave propagation in anisotropic media.

The data set contained nine-component VSPs (three-component source and three-component receiver), and was recorded at one near-offset and two orthogonal far-offsets. The data display typical features diagnostic of anisotropy with orthorhombic symmetry forming from a combination of crack-induced and layering-induced anisotropy. These include a 10-15° change in the orientation of the polarization ellipses in one of the far offset VSPs as the depth varies, and changes in the time delays of the split shear-waves between the near-offset and the far offset VSPs. Comparison of hexagonal models containing only vertical cracks with orthorhombic models containing both vertical cracks and horizontal thin layers shows that both kinds of models can yield good fit to the shear-wave polarizations and the time delays in the near offset VSP, but only orthorhombic models can yield good fit to those in the far offset VSPs.

INTRODUCTION

In 1989, the Reservoir Characterization Project at Colorado School of Mines acquired multi-component multi-offset VSPs in the UNOCAL 10-6-3 well, South Casper Creek Field, Natrona County, Wyoming, which incorporated a three-dimensional multi-component surface seismic survey carried out in the same area in order to image zones of heterogeneities and identify shear-wave anisotropy in a structurally complex reservoir. Although the shear-wave reflection data display strong shear-wave arrivals, it is difficult to obtain good quality stack sections. Previous analysis of shear-wave splitting in the VSPs and well logging data suggested that anisotropy in the area was likely to be caused by a combination of vertical cracks and horizontal thin layers, forming orthorhombic anisotropy (Kramer 1991). Among other things, this presence of orthorhombic symmetry is likely to be one of the factors which cause difficulties in processing the surface reflection data. It is thus necessary to carry out a full wave modeling, in order to confirm the presence of anisotropy with orthorhombic symmetry and to understand the characteristics of shear-waves in such media, so that some guidelines can be established in processing the surface reflection data. As part of this attempt, here we analyze and model the multi-component and multi-offset VSP data.

OBSERVATIONS

Figure 1 (after Kramer 1991) shows the acquisition geometry of the VSP data related to the USA 10-6-3 well. Sources were located to one near offset (300ft, position 1) and two orthogonal far offsets (1092ft, positions 2 and 3). Each location has three source orientations: one vertical (P), two horizontal sources (SR and ST), and each source was recorded into three-component geophones (x, radial; y, transverse; z, vertical), forming 9-component data. The recording depth was 300ft (91m) to 2700ft (823m) for position 1, and 1975ft (602m) to 2700ft (823m) for positions 2 and 3. Here, the four horizontal shear-components are selected for study.

Good quality shear-wave arrivals were obtained (Figure 2). The polarization diagrams show typical features characterizing shear-wave splitting (Figures 3a and 4a). The direction of the fast shear-wave can be measured as about 55° clockwise from the radial direction, indicating N114°E measured from north (radial direction, N59°E). The orientations of the polarization ellipse in the near offset VSP show no change as depth varies (Figure 3a), but those in the offset VSP at position 3 show a 10-15° change (Figure 4a). This is a significant feature which diagnoses orthorhombic anisotropy as demonstrated by Bush and Crampin (1991) in the Paris Basin VSP.

ANISOTROPIC MEASUREMENTS

The linear-transform technique (Li and Crampin 1991) and the dual source independent technique (Zeng and MacBeth, personal communication) have been used to measure the polarizations and time delays of split shear-waves. Time delays of split shear-waves estimated from the near-surface geophones (between 120m and 240m) in the near-offset VSP are 10-12ms (Figure 3a), suggesting significant fracture intensity near surface. The average time delay in the near-offset VSP is about 20ms between depths of 90-810m, the average time delay in the northwest offset VSP is also about 20ms (Figures 5a and 5b). Estimating fast shear-wave polarization shows a dominant fracture set at N114°E. These measurements agree with those measured from polarization diagrams (Figures 3a and 4a) and with previous studies (Kramer 1991).

From the near offset to the northwest far offsets, the source-receiver travel distance increases by about 10%. Despite this, time delays in the northwest far offset do not increase. This suggests that either a lateral velocity variation may be present, or the ray paths from the far offset source encounter some kind of shear-wave singularities. As shown in the three-dimensional surface data, the lateral velocity changes in the azimuth from the well to source position 3 are not significant (Kramer 1991). On the other hand, shear-wave singularities are believed to be widely present in sedimentary basins (Wild and Crampin 1991). Dramatic changes in time delays of split shear-waves can be expected when ray paths are close to, or pass through shear-wave singularities.
MODELLING RESULTS

The effects of anisotropy in multi-component seismic data have been successfully modeled by crack-induced anisotropy in a number of cases (Bush and Crampin 1991; Yardley and Crampin 1990). The presence of aligned fractures in this area has been confirmed in well logging data (Kramer 1991). However substantial P-wave anisotropy in well log data is also observed. Large P-wave anisotropy in sedimentary basins is most likely to be caused by thin layer anisotropy (Postma 1985). Anisotropy caused by vertical cracks, or horizontal thin layers, has hexagonal symmetry. A combination of these two yields a kind of anisotropy with orthorhombic symmetry (Bush and Crampin 1991).

In order to discriminate the anisotropy symmetry, two models were constructed based on the above anisotropic measurements. Model 1 contains pure vertical cracks with crack density varying from 0.04 to 0.06, corresponding to 4 to 6% shear-wave anisotropy. Model 2 contains the same cracks as above but combined with thin layers with P-wave anisotropy varying from 5% to 12%, forming orthorhombic anisotropy. Both models yield good fit to shear-wave polarizations and the time delays in the near offset VSP (Figure 3a). For the far offset VSP, there is a substantial decrease of time delays in the crack model (Figure 3b), because the ray paths are probably close to the singularities. Combining cracks with thin layers shifts the singularities towards near vertical directions (Figure 6), and this increases the time delays in the far offset VSP. As a result, the orthorhombic model (Model 2) yields a better fit, particularly between depths of 620m and 700m (Figure 5b).

For the near offset VSP, the synthetic polarization diagrams given by both models (Figures 3b and 3c) match the observed ones (Figure 3a) very well. In contrast, for the far-offset VSP, the synthetic ones given by the orthorhombic model (Figure 4c) match the observed ones (Figure 4a) better. These modeling results further support the existence of anisotropy with orthorhombic symmetry in the survey area. The presence of orthorhombic symmetry, particularly, the shift of shear-wave singularities towards the vertical direction (Figure 6) distorts the reflected shear-waves in the surface observation, which coincides with the difficulties encountered in processing the reflection data.

CONCLUSIONS

We have showed that the effects of anisotropy can be modeled by stress-aligned cracks or fractures. To discriminate the anisotropic symmetry by VSPs, at least one far offset VSP is required in addition to a near-offset VSP. In conclusion, in the survey area, both the near surface and the reservoir zone are substantially fractured with fracture density from 0.04 to 0.06. Anisotropy with orthorhombic symmetry is present with P-wave anisotropy from 5% to 12%. The presence of orthorhombic anisotropy shifts the shear-wave singularities towards the vertical direction, and this is likely to be one of the factors which cause difficulties in the processing of the surface reflection data.

ACKNOWLEDGEMENTS

We thank the Reservoir Characterization Project and its sponsors for permission to publish the VSP data. We thank John Lovell for his comments. The synthetic seismograms were calculated with the ANSEIS software package of Macro Ltd and Applied Geophysical Software Inc. This work was supported by the Edinburgh Anisotropy Project and the Natural Environment Research Council, and is published with the approval of the Sponsors of the Edinburgh Anisotropy Project and the Director of the British Geological Survey (NERC).

REFERENCES


Figure 1. Acquisition geometry (after Kramer 1991).
Figure 2. The four horizontal components of the northwest far offset VSP at position 3 in Figure 1. Nomenclature for the data is first the source type (P, SR, or ST) then the offset position (1, 2, or 3) and finally the recording axis (x, y, or z). Here SR3X is the radial shear-wave source from the third offset position recorded on the transverse component.

Figure 3. Comparison of observed and modelled polarization diagrams (PDS) from the shear-transverse source (ST) for the near offset VSP at position 1. (a) Observed PDS; (b) corresponding synthetic ones produced by Model 1 (the crack model); (c) those by Model 2 (the orthorhombic model).

Figure 4. Same as Figure 3 but for the northwest far offset VSP at position 3. (a) Observed PDS; (b) PDS produced by Model 1; (c) those by Model 2.
Figure 5. Comparison of time delays between the observed and modelled. The triangles are the observed time delays, the dotted line corresponds to the pure crack model (Model 1), and the solid line to the orthorhombic model (Model 2). (a) the near-offset VSP; (b) the far offset VSP at position 3.

Figure 6. Phase velocities of the two quasi-shear waves against incidence angle measured from the vertical direction. (a) The crack model (Model 1); and (b) the orthorhombic model (Model 2). The black dots mark the singularities. Note that the singularities in the orthorhombic model shift about 10° towards the vertical direction, comparing with those in the crack model.