The effects of azimuthal anisotropy in P-wave 3-D seismic

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SUMMARY

The objective of this work is to determine optimum seismic technologies for detecting and characterizing fractures in tight gas reservoirs. The project is funded by the Dept. of Energy, Morgantown Energy Technology Center, with additional in-kind contributions from the industry partner. For testing and evaluating the seismic technologies, a gas field in the Wind River Basin in central Wyoming was selected. In the field, gas is produced from naturally fractured reservoirs from 5,000 ft to 20,000 ft depths. The target of this project is the Lower Fort Union, from 5,000 to 10,000 ft depths. Initial work has been performed on the industry partner's 3D P-wave seismic survey: P-wave azimuthal anomalies have been identified and interpreted to be associated with high fracture density with potential commercial gas pay. These anomalies will be re-surveyed using 3D-3C acquisition in order to record the mode-converted shear wave arrivals. Shear-waves have been shown to carry more diagnostic information than P-waves concerning the fracture density and fracture orientation: however, multicomponent seismic data can cost 50% to 500% more to acquire and process than P-wave (conventional) seismic data. Upon completion of the seismic investigation, the industry partner will drill to test a seismic anomaly. The project therefore aims to link properly acquired and properly processed 3D P-wave data, through the shear wave data, to fracturing associated with commercial pay. Ultimately, the industry will be better able to apply seismic technology for drilling producers.

The seismic technologies to be evaluated and ranked for cost benefit are: P-P (compressional-compressional) 3D seismic, P-S (compressional-shear) 3D seismic, and some S-S 2D reflection seismic. If a significant amount of the fracture information usually obtained through shear wave seismic can be demonstrated as obtainable from P-wave seismic, through correct acquisition and processing, then the lower cost (P-wave), more robust tool would be the tool of choice.

INTRODUCTION

The structural setting of the field is an east-west trending anticline, with the crest (7 miles by 3 miles) slivered with many faults. Production in the Lower Fort, Union is currently concentrated along the crest. Evidence that the natural fractures allow and control the gas production in the field is found in production history data, wireline data, and cores.

Four avenues Of investigation will be pursued and interlinked: 1) the seismic response (traveltimes, reflectivity, frequency, attenuation); 2) the stratigraphy, structure, and the evidence of the natural fractures, as found in wireline data, oriented core, production data, surface outcrops, and stratigraphic setting; 3) the in-situ stress field; 4) the evidence of zones of enhanced permeability and fluid flow directionality within the Lower Ft. Union, on the scale of 100s of meters, as seen in production data, DSTs, etc.

Previous publications have discussed various effects of azimuthal anisotropy in P-wave seismic data. For example, in the Silo Field P-wave 3D data, Garotta (1989) documented traveltime anomalies on the far offsets that were azimuth-dependent: parallel the fractures the P-wave traveltimes were less than on the far offsets perpendicular to the dominant fracture orientation. The dominant fracture azimuths were known from 3D S-S reflection seismic acquired in this field. A P-wave AVOA (amplitude variation with offset and azimuth) anomaly was shown in field data by Johnson (1995), and subsequent drilling by Johnson's company brought in a gas producer from a fractured gas reservoir in the early 1990s. Model data containing P-wave AVOA due to gas filled fractures was shown by Allen and Peddy (1994). Ramos et al. (1994) examined 3D P-wave data by azimuth to determine the preferential directions of azimuthal anisotropy. Lefeuvre (I 994) discussed using P wave seismic to detect the fracture effects, and pointed to 3D AVO-AVAZ (amplitude versus offset and amplitude versus azimuth) as useful. We agree with Lefeuvre (1994) that 3D AVOA is important, and that a 9C VSP is necessary to learn the nature of P and S wave propagation in the area under study. We believe that proper acquisition of the 3 P-wave survey is the most important point to consider, if re-processing of currently existing 3D P-wave surveys for fracture information is considered.

METHODS

FIELD ACQUISITION

To document the shear wave and P-wave time-depth-velocity function, in order to guide the P-S interpretation of the data, a 9C VSP was acquired in the Lower Fort Union in September, 1994, and a 9C walkaway to characterize the near surface. Feasibility tests to show type of signal and noise contained in mode-converted surface seismic were acquired in July-August, 1994, during the field operator's acquisition of a P-wave 3D surface seismic reflection survey. This 3D P-wave survey deployed circular geophone arrays, which provide the required azimuthally-isotropic array response. The feasibility tests which recorded multicomponent receivers sourced by dynamite shots revealed P-S signal in the zone of interest (2-3.5 sec, P-S time), and deeper (to 4.5 sec.s, or 15,000 ft). Twelve 3-C phones per ground station recorded are needed in this field to acquire good shear wave data. A crossed dipole shear-wave sonic log was also acquired in the VSP borehole, behind casing, in order to evaluate the shear wave birefringence (or anisotropy) at the wireline log scale and compare it to the gas kicks, lost circulation zones, and intervals of anisotropy observed in the VSP. The log documented an elevated amount of shear wave anisotropy, 15%, at the zone where at least 3000 barrels of drilling fluid had been lost. The orientation of the fast shear wave is not known, since the log was acquired behind casing.

3D PROCESSING

In order to use P-wave 3D seismic for fracture detection, two different source-receiver azimuths must be analyzed: parallel and perpendicular to the fractures. Each azimuth must contain sufficient fold and offsets to perform AVO analysis and good velocity determination. Offsets approximately equal to target depths are needed. At the field, the fractures are believed to trend east/west in the zones of interest. Seven "azimuth super-gathers" from the 3D data volume were created to display P-P common-azimuth reflection data in 18 different azimuths from N to S, each with a range of offsets from 50' to 10,000'. An azimuth super-gather is produced from a 1980' by 1980' bin in the subsurface. Each trace in the 198O'x1980' super gather is a three-to-six fold stack. These seven azimuth bins were also created using a 990 ft by 990 ft subsurface bin, in order to reduce any "smearing" due to geologic change in the 1980 ft by 1980 ft original bin. Azimuth gather #2, 99O'x990' binsize, is shown in Fig. 1. The results seen in the 990' by 990' bins are also seen in the 1980' by 1980' bins. The azimuth gather plots indicate that the N/S stacking velocities are usually slower than the E/W stacking velocities which is consistent with the presence of E/W trending fractures. Moreover, the fast shear wave is polarized E/W in the 9C VSP well, which would be consistent with a dominant E/W fracture set. The azimuth gathers indicate that to properly image the data, pre-stack, the stacking velocity must be azimuth-dependent. We expect that the migration velocities will also be azimuth-dependent.

The seven azimuth super-gathers also show that reflection coefficients, the amplitude variation with offset (AVO), and the attenuation, as well as the traveltimes, are azimuth-dependent quantities.

The dip line through azimuth gather 2 is shown in Fig. 2. Fig. 2A is the N/S seismic line stacked with the N/S (± 45 degrees) source-receiver azimuths. Fig. 2B is the seismic line stacked with the E/W (± 45 degrees) azimuths. These lines show minimal dip in azimuth bin #2. Throughout the whole survey, CDP lines were excerpted from the P-wave 3D survey, in which E/W azimuths were segregated from N/S azimuths. These stacked lines, all stacked with the same spatially-variant velocity function, picked from azimuth-blind velocity scans, also display slower N/S stacking velocities than E/W stacking velocities, and furthermore indicate that in the locations of five of the seven azimuth super-gathers, minimal dip is present. The dip-effect is present within two of the azimuth bins, in that the N/S azimuths need a faster stacking velocity than the E/W azimuths. Differences in these N/S and E/w sections are attributed to mis-stacking the data: the correct azimuth-dependent velocities must be applied before geologic meaning can be extracted.

These observations lead us to conclude that specific azimuth-dependent 3D data processing for the entire dataset and subsequent interpretation will yield a better understanding of the structure and the relative fracture density than conventional (azimuth-blind) processing.

FUTURE WORK

The current 3D seismic data will be split into two volumes, one with N/S azimuths ($\pm 45°$), and one E/W ($\pm 45°$). Each volume will be separately processed with pre-stack time migration. The prestack and poststack volumes of seismic data, and the velocity volumes, will be compared. Zones of equivalence and difference will be identified and tied to well control.

To demonstate the relationship of the P-wave azimuthal anomalies to conventional P-S and S-S azimuthal anisotropy anomalies, the latter being sensitive to relative fracture density and fracture azimuth, multicomponent seismic will also be acquired. The acquisition of 3D dynamite-sourced three-component receiver data is scheduled for fall, 1995, or spring, 1996; shear wave vibrator sources will be tested on two 2-D lines in the 3D survey.

CONCLUSIONS

Based upon the observations from the P-wave 3D data described above, we believe that azimuth-dependent processing of this 3D data volume is necessary to properly process and understand the data volume, because the earth here is azimuthally anisotropic, due to aligned vertical fractures. Moreover, azimuth-dependent processing is necessary in order to locate and identify, in space, all of the anomalies contained in the dataset. This processing will be done in March through July, 1995.

A consequence of this work and companion D.O.E. work at Bluebell-Altamont Field, Utah (Lynn et al., 1995a) is that various marine 2D-grid surveys, of different vintages, of different azimuths, which show different AVO signatures at tiepoints, can now be re-examined through careful re-processing, since the presence of gas-filled vertical aligned fractures are known to cause different AVO signatures at the tiepoints of different-azimuth lines.

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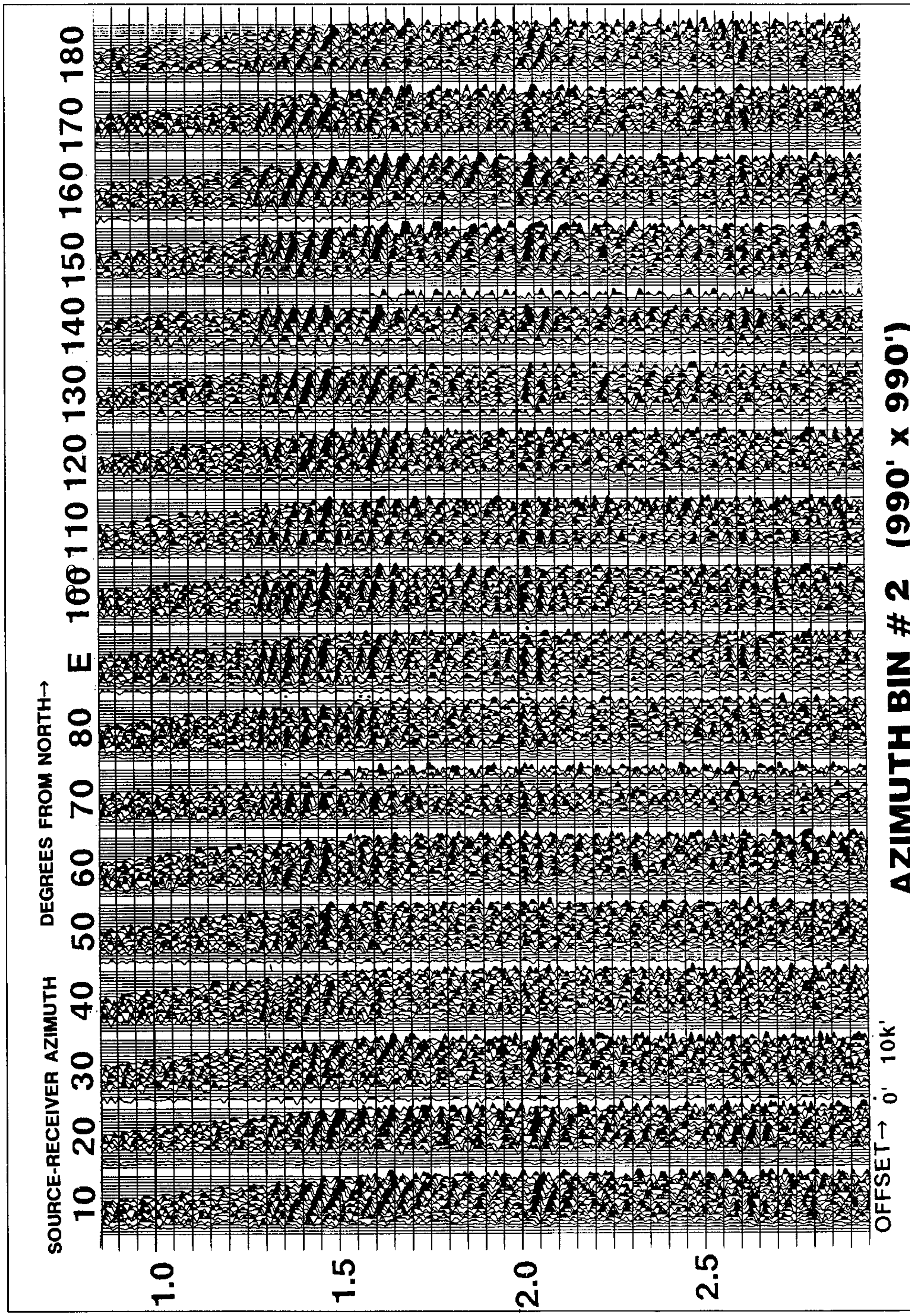

Figure 1. Azimuth Gather #2, sum of traces sorted by source-receiver azimuth in a 990' x 990' bin. N-S azimuth gathers require slower stacking vels. than E-W azimuth gathers. The same stacking velocity function was used for all of azimuth bin #2.

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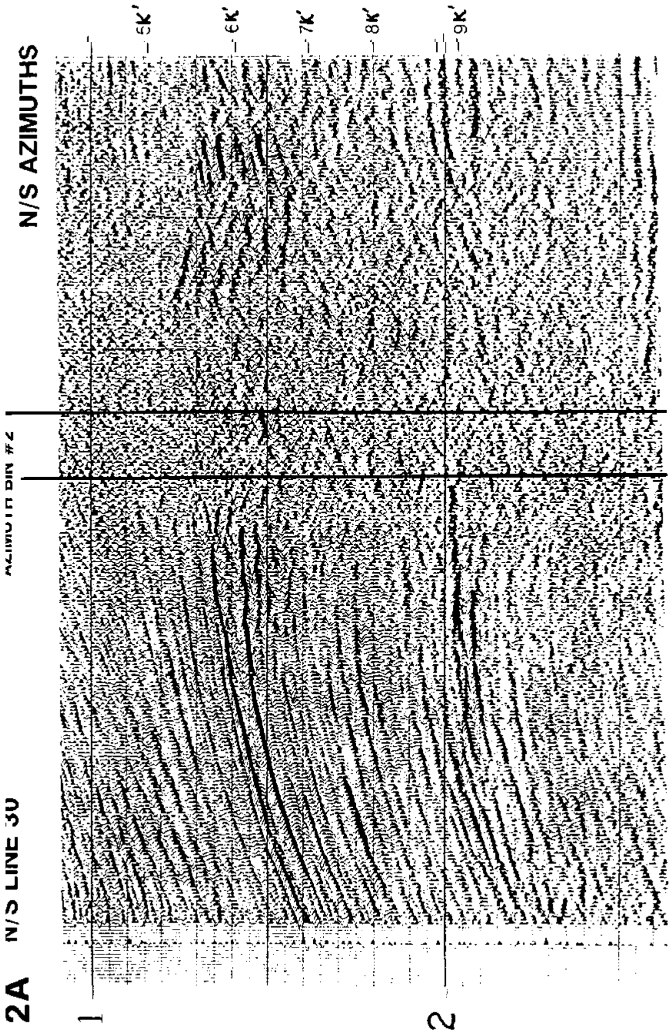
Figure 2. Dip line (N-S) through azimuth bin #2.



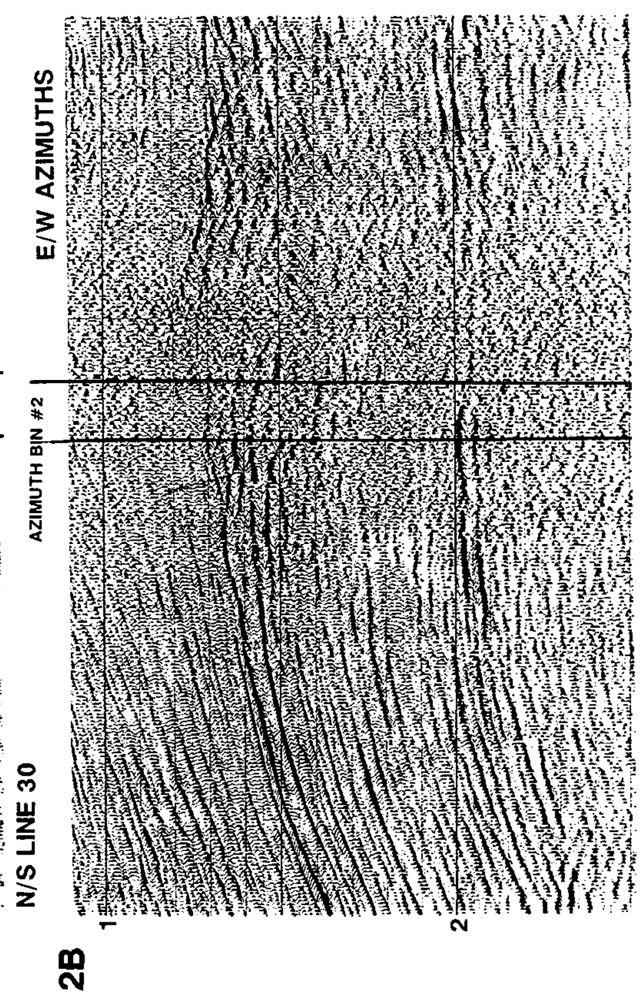


Fig. 2A. Stacked with N-S source-receiver azimuths.
Fig. 2B. Stacked with E-W source-receiver azimuths.
The same stacking velocity functions were used for both figures.