More Powerful Fracture Detection: Integrating P-wave, Converted-wave, FMI and Everything

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Abstract

Knowledge of the orientation and distribution of fractures can be critical to exploration success; the advantage of *seismically* driven fractured reservoir characterization is accurate estimation of the fracture distribution *between* wells. The key to using seismic to characterize fracturing is to measure and understand anisotropy. Measuring and understanding this anisotropy – which is encrypted in various types of seismic data - will lead us to more reliable descriptions of fracture density, orientation connectivity, and permeability pathways in fractured reservoirs.

The study presented here shows how to use PP and PS data to identify and delineate zones with the highest probability of being naturally fractured. The results are verified with FMI and production information.The objective is not to identify any single seismic attribute to provide the definitive answer for the distribution of fracture density and orientation, but to integrate information available from wide-azimuth long-offset 3D data, azimuthal differences in AVO gradient, azimuthal variations in travel time, azimuthal variations in converted wave travel time, and well performance and FMI data. These independent data are brought together to build an integrated characterization of a gas-bearing fractured dolomite reservoir.

The reservoir

The exploration area is a natural gas play, onshore USA. The formation of interest was initially deposited as a broad limestone shelf during the middle Ordovician period. Fractures were formed in these limestones as a result of tectonic forces. High temperature fluids subsequently moved into these fractures, locally dolomitizing the limestone.

Porosity in the play depends on this hydrothermal dolomite formed in the reactivated faults and associated fractures. Porosity in the fractured parts of the reservoirs ranges up to 15%, with a matrix porosity of about 3%. Permeability is similarly high in fractures and low in the matrix, which contains limited micro-fractures. These dolomite pockets act as the reservoir for large accumulations of natural gas. The thickness of the effective reservoir is well over 100 feet and no clear regional gas-water contact has been established. Today these reservoirs produce from depths approaching 10,000 feet.

FMI and well production data

Wells must intersect the natural fractures in this gas bearing formation to be productive. Horizontal drilling increases this probability. Determination of the intensity, orientation and distribution of the fractures is necessary to guide optimal positioning of the horizontal wells. Some wells are producing at over 20 mmcf/day. Regional cumulative gas production to date is greater than 80 Bcf. Available log information, including FMI logs, provides valuable information about the major fracture orientations at the well locations. The most productive fracture trend orientation is essentially ENE-WSW (but ranges from E-W to NE-SW). A NNE-SSW trend is from late stage faulting which to date has been unproductive.

The interpretation of the FMI log from a horizontal well indicates that this area is naturally fractured. This horizontal well was drilled in NNW direction. An analysis of fractures in FMI images shows dominant fracture orientation at this well location to be ENE-WSW. These measurements confirm seismic analysis. The bed dips are all reasonably flat (validating the assumptions in the azimuthal velocity analysis).

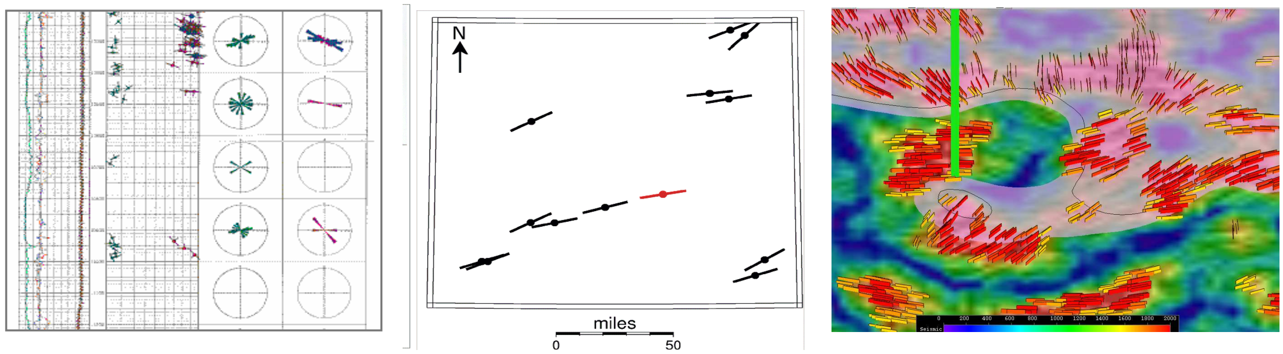

Figure 1: FMI log interpretation (left); regional stress map - WSM (middle); fracture density and direction (right) estimated from the AVAZ analysis around the location of one of the most prolific wells in the field (6 mmcf/day). Note the horizontal well path direction, a consistent E-W fracture direction is observed, and this is in agreement with FMI interpretation at the well location and the regional stress trend (Reinecker et al.).

PP and PS anisotropy analysis

We used PP (full azimuth, long offset) and PS 3D pre-stack surface seismic data to map the fracturing pattern away from the well control. The seismic data quality was very good and the main zone of interest has flat to gentle dips.

Azimuthal amplitude variation

Amplitude Variations with Offset and Azimuth (AVAZ) - is a technique to derive fracture density and orientation from wide-azimuth long-offset PP data. Vertically aligned fractures, cracks or micro-cracks are known causes of Horizontal Transverse Isotropy (HTI). It is widely recognized (Hall et al, 2000; Gray et al, 2002, for example) that HTI anisotropy has a strong effect on the seismic amplitude. Seismic waves experience the rock differently depending on whether they cross or are parallel to the fractures. This can be measured by fitting the parameters of the P-wave Amplitude Versus Angle and Azimuth (AVAZ) equation of Rüger (1996) to seismic amplitudes. The anisotropic gradient describes the variations of the AVO gradient with azimuth and is related to the crack density (Lynn et al, 1996), that is, to the magnitude of the differential horizontal permeability. To the extent that a reservoir with vertical open fractures represents an HTI medium, the azimuth of the anisotropic gradient - the orientation of the symmetry axis - indicates the orientation of the fractures. The AVAZ analysis was done on seismic data gathers flattened by moveout and static corrections. The identified fracture intensity and fracture orientation show an excellent correlation with known production (Figure 3) and with fractures from FMI and WSM data (Figure 1).

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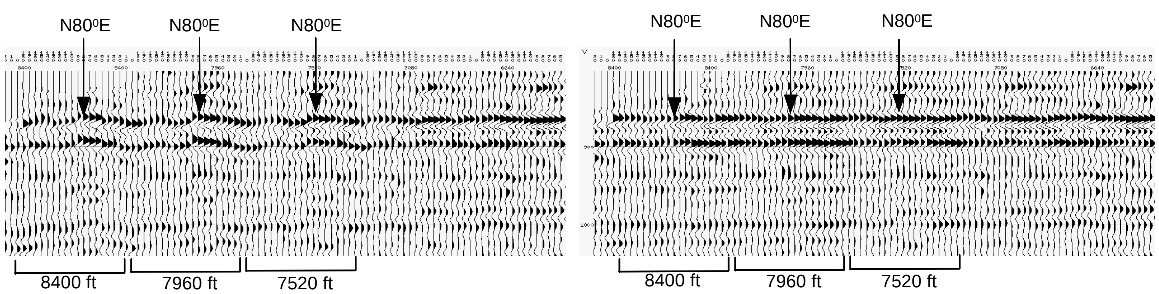


Figure 2. Azimuth-offset sorted NMO super-gather centered on the well location. Right: Note the variable travel time: minimum travel observed at N80^{0}E orientation. Left: The same gather flattened. Note the larger amplitudes at the same direction. This is in agreement with AVAZ, FMI (at the well location) and WSM data that show the regional trend (Figure1).

Azimuthal Moveout Analysis

Anisotropic Moveout Analysis (AMA) provides an independent comparison to the PP AVAZ results. Fracture-induced HTI causes azimuthal variations in the P-wave NMO velocity. Unlike VTI, which only manifests itself in long offset moveout, the effect of HTI is apparent on short offset moveout measured along different azimuthal directions. The theoretical basis for this is discussed by Tsvankin (1997). Near vertical incidence, traveltimes are characterized by an NMO velocity that varies with azimuth; this azimuthal variation in velocity can be described as an ellipse. The parameters of the ellipse are the fast and slow velocities, V_f and V_s, and the azimuth of the fast velocity. A measure of the intensity of the anisotropy is given by the normalized difference between the fast and slow velocities, $(V_f - V_s)/V_f$. Larger velocity difference values (larger anisotropy) occur in the southern part of the survey, and show good correlation with overlain semblance data (the white features in Figure 3).

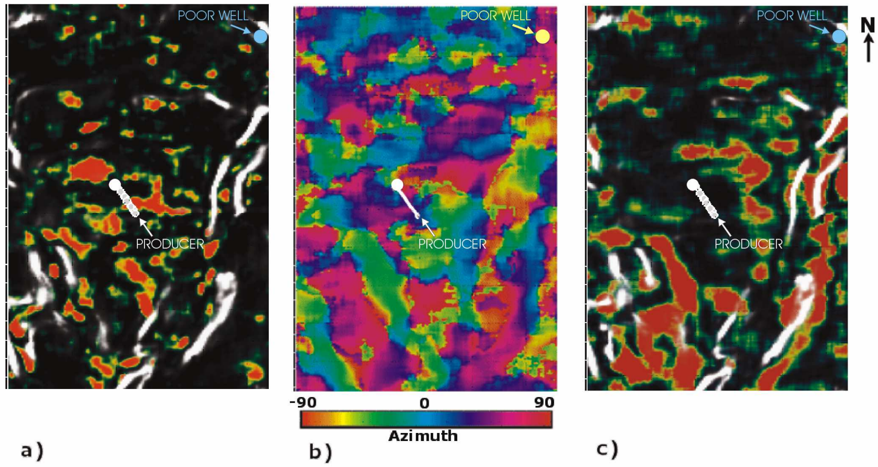


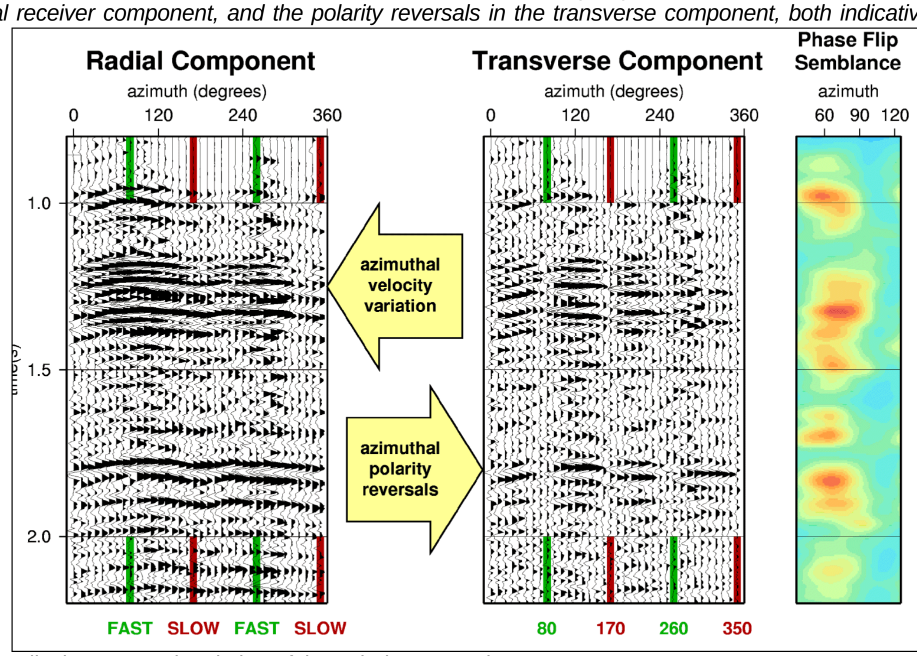
Figure 3: time slices through volumes of: a) fracture density (red=high) identified by AVAZ; b) azimuth of the fact velocity, V_f; c) velocity anisotropy at the reservoir level. White line shows a path of producing horizontal well. Pink circles represent surface locations of two poor wells. The well in the upper right corner was initially a vertical well. It was given a short kick SE and then suspended. Last year, prior to this analysis, the well was re-entered and drilled horizontally to the SW. None of these drill paths encountered significant gas.

There are some important differences between AVAZ and AMA. Generally, the AVAZ method is a local method that is sensitive to rapid vertical changes of HTI, while the Azimuthal Moveout Analysis is a global method that measures the cumulative effect on moveout from the surface to depth. This makes it quite stable, though less able to detect local anomalies. This lack of sensitivity may explain why AMA did not detect velocity anisotropy at the producing well location.

Azimuthal Variations in Converted Waves Traveltime

The converted-wave data illustrate the general characteristics of converted waves in azimuthally anisotropic media as described by Li (1998).The azimuth stacks of Figure 4 are constructed from an isotropically-processed NMO-corrected super-gather which is sorted into 100 azimuth sectors before stacking.

Figure 4: 10° azimuth-sectored stacks of the conver ted-wave data within a super-gather centered on the well location. Note the variable traveltime in the radial receiver component, and the polarity reversals in the transverse component, both indicative of azimuthal anisotropy.



The semblance plot details the temporal variation of the polarity reversals.

The amplitude nulls observed between polarity reversals in the transverse component define the orientation of the symmetry-axis and isotropy planes, with a 90° ambiguity. This ambiguity is resolved by traveltime variations of the radial component because the orientation of the isotropy plane - which is parallel to maximum horizontal stress - is determined by the fast shear arrival. Note that the traveltime minima and maxima of the radial component coincide with the amplitude nulls of the transverse component, as would be expected for azimuthal anisotropy. Cumulative anisotropy analysis of the converted-wave data centered at the well location supports the estimated N80°E fracture orientation agrees well with AVAZ from the PP data and FMI. In this case AMA was inconclusive and layer striping is recommended to yield to more local information.

Analysis of azimuthal amplitude variations with offset is well-suited for fracture characterization because it yields local information of the anisotropy at the target reservoir interface. In comparison, the velocity information at the target interface may include the footprint of overburden layers. Converted-wave data express a combination of local (reflectivity) and global (transmission) effects. Shear wave polarization and traveltime splitting into fast and slow components occurs locally at the fractured reservoir, but may also be affected by transmission through the overburden. The value of integrating these various analyses is that each measure anisotropy effects independently, and so collectively provides more confidence in the seismic fracture detection.

Conclusions

The study presented here aims to obtain an image of the zones most likely to be naturally fractured through the use of seismically driven fractured reservoir characterization. This method of integrating information extracted from various seismic analyses with well information has been tested on a fractured hydrothermal dolomite reservoir and has proven successful at identifying both the intensity of producing fractures and their orientation. Results from the various independent data used - AVAZ, AMA, converted wave seismic analysis, production data, and FMI logs - are generally consistent with each other, increasing confidence in the fracture estimations and thereby reducing drilling risk. In particular, analysis of PS data helps to reduce fracture orientation ambiguity contained in both AVAZ and AMA from the PP data (Zheng et al., 2004). Estimating fracture orientation from AVAZ, AMA and PS analyses is more consistent than from velocities alone.

The use of the information gleaned from the detected anisotropy has resulted in an increase in production from 40mmcf/day to 100 mmcf/day from this reservoir. Based on the results shown here, the selection of future drilling locations will incorporate the use of seismic anisotropy and it is expected that substantial new reserves will be identified.

Acknowledgments

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