Fracture mapping using Offset Vector Tile Technology

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Summary

Wide Azimuth Acquisition paired with new processing techniques, have made possible the imaging and analysis of fractured reservoirs. With the use of Offset Vector Tiles (OVT) and especially designed azimuthally preserving Migrations, capable of producing Azimuthal Common Image Gathers (ACIG), we study a particular reservoir and determine the density and orientation of fractures in the formation. Use of a 3D surface fitting algorithm allows us to determine the fracture intensity and orientation, culminating in the production of fracture maps.

Introduction

The need to better understand the fractured nature of reservoirs has encouraged the acquisition of wide azimuth data. Many 3D land surveys are being designed to have enough fold, azimuth and offset coverage for a proper azimuthal processing sequence, allowing for the estimation of subsurface stress direction and intensity as well as other attributes (Roende et al 2008)

The use of different attributes, including curvature and rock property inversions and the subsequent construction of petrophysical moduli has been successful in determining the existence of fractured in a given formation (Chopra & Marfurt 2009). Until recently the entire set of “fracture indicators” where volumetric in nature, and only able to prove the existence of the fractures, but not their direction or intensity. This information came from regional stress analysis or perhaps well log information.

In an effort to elucidate more about the subsurface, many in the industry have looked in the realm of converted waves and their application or fracture detection in a deep tight-gas reservoir (Jianming et. al., 2009). Even tough, converted waves are useful; they are by no means the only way to detect fracture orientation. We will argue and proof that if the acquisition geometry is such that sufficient offset and azimuthal coverage is achieved, then it is possible to obtain enough velocity and anisotropy information from conventional P-wave seismic to detect fracture orientation.

We will present a way of processing seismic such that it preserves azimuthal information that can be used to construct fracture maps. It is based on the use of Offset Vector Tiles, Azimuthally preserving Migration and Migrated Offset Gathers.

The right Data Set

The data set we will use to demonstrate the technology comes from North America, the exact location being unimportant. Of importance is that the acquisition geometry is well suited for azimuthal processing as can been seen from the rose diagram (figure 1) computed from this aforementioned geometry. The diagram shows that the data should be well populated in all direction up to an offset of about 15,000 feet.

Hybrid Gathers and Offset Vector Tiles

Hybrid gathers are single-fold 3D cubes of data formed by collecting data into a cross-spread centered at the intersection point of the source-receiver lines. The sizes and shape of these subsets are defined by the size of the recording patch. Processing in this domain is well understood and it has been performed for many years. It offers many advantages, primarily for 3D pre-stack noise elimination (Stein & Langston 2007).

Offset Vector Tiles (OVT’s) are a natural extension of hybrid gathers and are very thoroughly described by Vermeer (2002, 2003 & 2007). The best way to think about an OVT is as a set of data with a limited offset and azimuthal range that has good enough Signal-to-Noise ratio and coverage to be migrated and produce a 3D interpretable volume, i.e., it forms a minimal data set (Padhi and Holley 1997). Of course the migration of these OVT requires the determination of “many velocities” or better said of all components of the velocity vector field in different directions.

OVT Migrations and Offset Vector Gathers

OVT-gathers are minimal data sets with limited offset and azimuth ranges, they can be migrated with a Kirchhoff algorithm that has been modified to account for the limited azimuthal range. By binning the migration output into azimuthal ranges, it is possible to construct Azimuthal Common Image Gathers (ACIG). See Figure 2 for a workflow used and figure 3 a depiction of the migration algorithm and the construction of ACIG (Stein *et al* 2010)

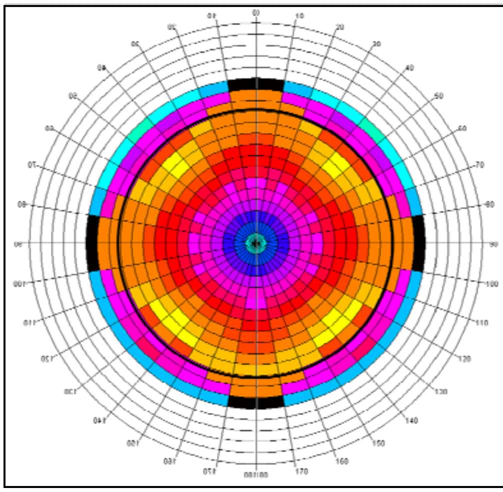

Figure 1: Rose diagram showing good azimuthal coverage to at least 15 000 ft (black circle).

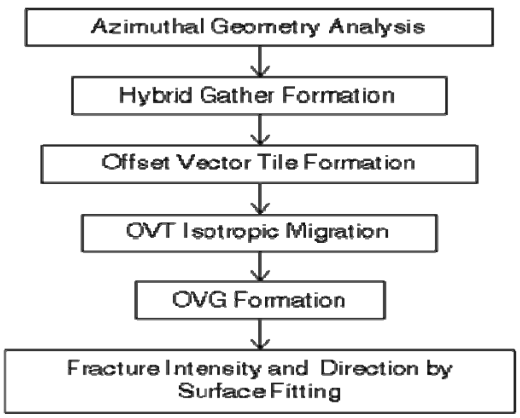

Figure 2: OVT Workflow needed for the construction of FracMaps

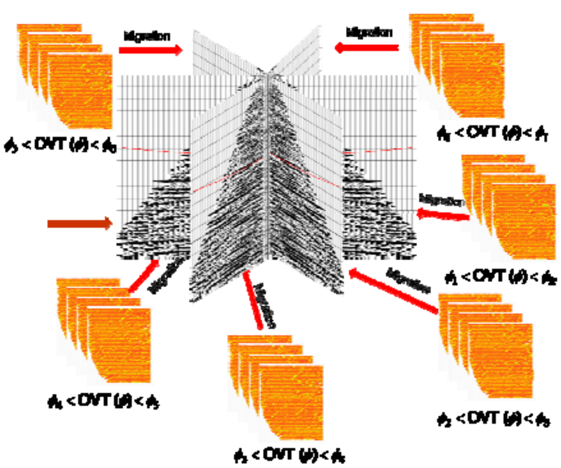

Figure 3: Each group of OVT is migrated and summed into an output offset/azimuth bin to form an ACIG.

A selection of ACIG is shown in Figure 4. Note the *hockey stick* moveout in the far offset traces indicating the presence of Vertical anisotropy (VTI). This gathers can be “flatten” by performing an anisotropic migration. It is not the goals of this paper to discuss how this is accomplish and we will instead refer the reader to another publication that explain it (Stein 2010 SEG). Figure 5 shows the results of stacking these gathers and producing six azimuthal stacks. Clearly both the structure and the amplitudes change from section to section

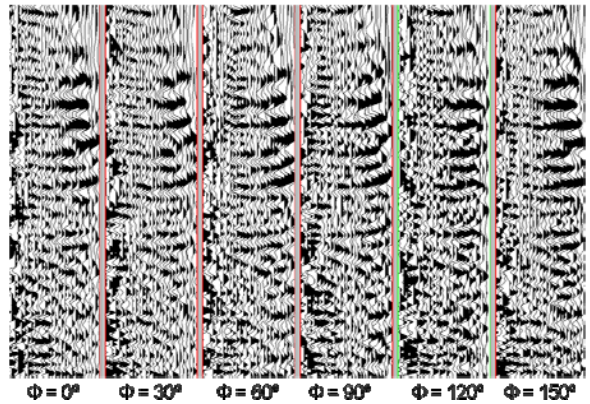

Figure 4: Migrated ACIG for all six azimuths.

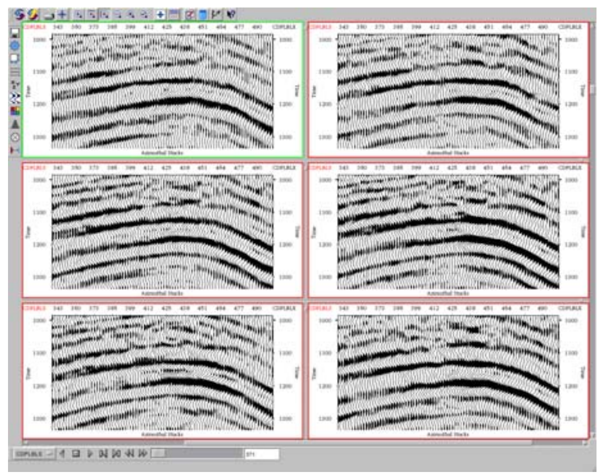

Figure 5: Section produce by stacking the migrated gathers above

What it is the goal of this paper is to explain how this anisotropic moveout is measured and used to determine the fractured nature and fractured orientation of the reservoir? Following the standard methodology for measuring anisotropic parameters in seismic the process starts by performing an isotropic migration. When the ACIG are sorted into (azimuth, offset) the non-flatness indicated the existence of a VTI effect. Moreover, when the ACIG are sorted into (offset, azimuth) then a different kind of moveout is observed (see figure 6). This azimuthal moveout has a sinusoidal behavior and is indicative of horizontal anisotropy or HTI (Jenner et al 2001)

By properly accounting for the vertical (VTI) and Horizontal (HTI) anisotropy, the migrated gathers in the offset domain can be made flat and a final section, ready for interpretation produced. The methodology used to achieve this orthorhombic migration has been described in a separate publication (Stein 2010 SEG). Our focus will be on how to derive the anisotropic parameters needed for the migration and exploit the richness of information contain within them to help characterize the reservoir.

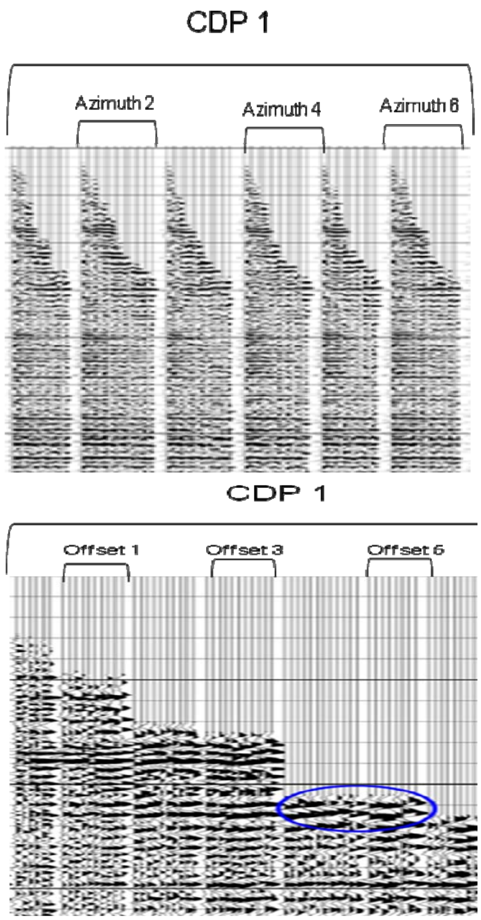

Figure 6: ACIG sorted into Azimuth and Offset (top) display VTI anisotropy for every azimuth, while when sorted into Offset and Azimuth (bottom) display HTI anisotropy

FracMap Construction.

Looking in more detail at the azimuthal moveout (figure 7) it is easy to understand that the variable to measured are a difference in travel time Δt as function of direction and a direction φ along which the travel times are minimal (or maximal).

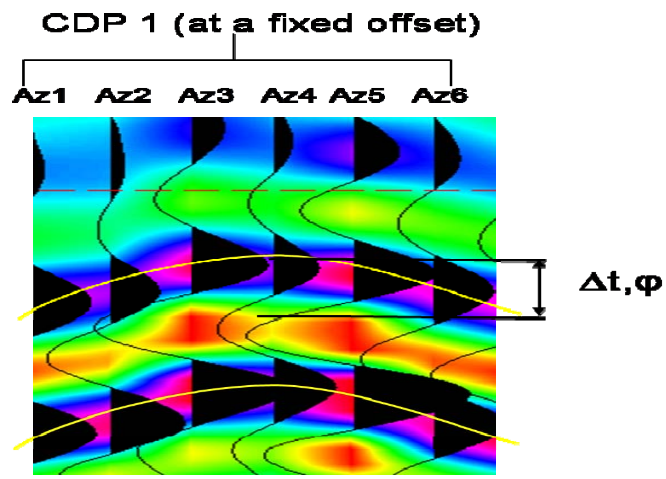

Figure 7: Computation of fracture intensity and orientation

In general there is a VTI and an HTI moveout occurring simultaneously and they need to be dealt together (Stein 2010 SEG), however, if we assume that the vertical anisotropy is small (as in the example shown) then the horizontal anisotropy can be treated separately.

By utilizing a surface fitting algorithm that fits a velocity ellipse w semi-major and semi-minor axis are the two components of the horizontal velocity it is possible to extract, for all offsets and all times, a pair of values (Δt, φ).

We have noticed that in this and other examples the effect is highly localized to what appears to be flat layers. This is the reason we identify the affect with a fractured reservoir. And the different travel times simply being the effect of waves propagating along or against the fractures orientation

The azimuth in question will represent the orientation of the fractures (or anisotropy) as well as the direction of the fast propagation velocity. The physical explanation of this effect is straightforward (Bacharach 2009). The ACIG represent the migrated image at a common reflection point, as seen from different directions.

The azimuthal moveout comes from the fact that waves traveling along the anisotropy direction (fracture orientation) are not affected by it but the waves traveling perpendicular to it are slowed down and hence their traveltimes are longer. This effect provides the key to detecting the fractures. The difference in travel time Δt and the azimuth φ at which the shortest travel time is observed will determine the fracture intensity and orientation (Figure 8). These quantities can also be used to derive a velocity ellipse whose axes represent the fastest and slowest propagation velocity.

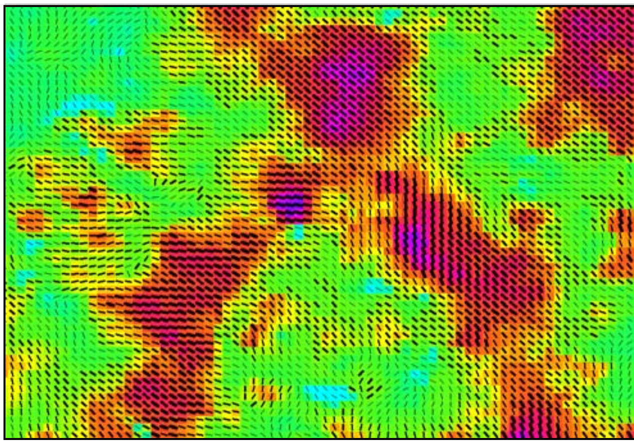

Figure 8: Note that faulting and fracturing are not always aligned

This delay time Δt and the azimuth φ describe a vector field indicating the fracture density and orientation. After processing the entire 3D volume in this fashion we can display the effect on a time/depth slice where the faulting and fracturing can be seen simultaneously. Note in figure 8 the interesting fact that the fault direction is sometimes parallel to the fractures and sometimes perpendicular to it. The proper understanding of this phenomena calls for a better understanding of the depositional history of the play as well as the geomechanics on rock fractures (Settari & Sen 2007).

Dynamics Considerations: Azimuthal AVO.

The above calculations are mostly concern with kinematical effects, relaying mostly on arrival times as an indicator of anisotropy and fractures. There is a dynamical aspect to the problem that is mostly concern with the amplitude response to anisotropy.

Reflectivity changes with both the reflection angle θ and the azimuthal angle φ. To first order in angle the formula to compute the pp reflectivity is given by (Ruger 1997)

$$R_{pp}(\theta,\varphi) = A + B(\varphi)\sin^2\theta \qquad (1)$$

$$\hat{B}(\varphi) = B_{iso} + B_{ani}\cos^2(\varphi - \varphi_{frac}) \qquad (2)$$

Where A represents the standard (angularly independent) intercept and B(φ) is the gradient. Note that the gradient term is made out of two contributions, an isotropic piece Biso that accounts for the standard AVO effect in the absence of HTI and Bani accounting for the presence of fractures oriented in a given direction. Clearly from equation (1) we can see that B(φ) is minimal when φ = φfrac + π/2 or moving perpendicular to the fractures. An inversion was performed on a small data set and the results are shown in figure 9. From the we can clearly see that the DC component of the signal representing the isotropic component is present, while the anisotropic one closely resembles a cosine-square function showing a minimum/maximum value along a certain direction consistent with the kinematical (i.e. anisotropic) prediction

Conclusions

We have presented a methodology using Offset Vector Tiles (OVT) and Vector ACIG that preserved the azimuthal information after a time or depth migration. Kinematic analysis, i.e. migration and velocity analysis provide an estimate of the directionality of the fracture. Azimuthal AVO provide a dynamical i.e. amplitudes and phases, analysis of the same data and to first order an estimate of the same fracture orientation. It is easy to verify that the predictions coming from the anisotropic analysis is the same as that from AVO.

OVT, although not the only way to process azimuthally complete data, it certainly presents the most efficient and geophysical accurate domain to do basic data processing including noise attenuation, interpolation, regularization, imaging, velocity determination, AVO and rock property inversion while preserving the azimuthal information.

The final note reminds the reader that all the results presented here came from compressional (PP) waves and there was no need to introduce converted waves. We do not mean to imply that shear wave are not be important, but it would appear that good acquisition geometry can provide enough information to determine anisotropy and fracture properties without the need for shear waves.

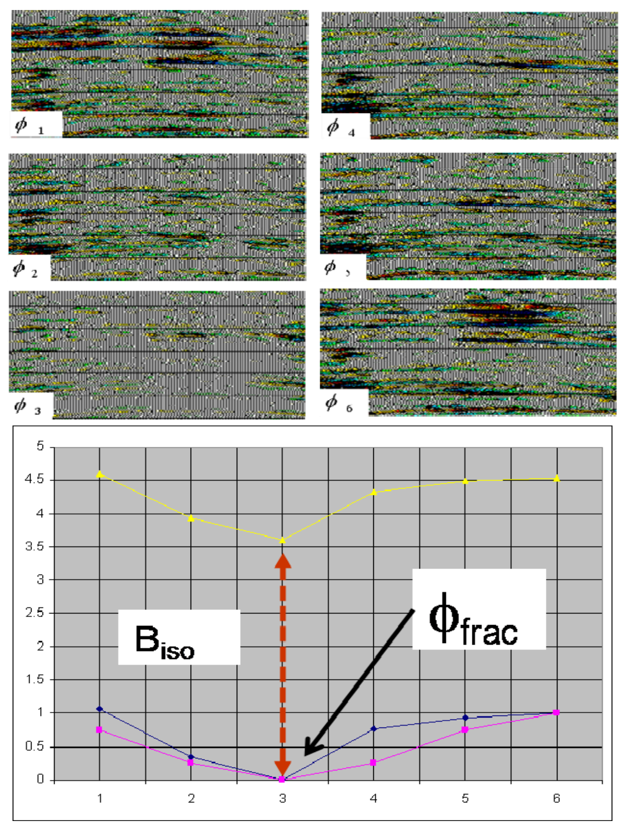

Figure 9: Gradient along different azimuthal directions, Anisotropic Gradient Extraction predicting the principal direction.

Acknowledgements

We would like to Geotrace for permission to publish

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