Estimation of Dip of Oblique Fractures Using AVOA Analysis

Ranjit K. Shaw[1], Mrinal K Sen[2], Ankur B. Chatterjee[1]
[1]Department of Applied Geophysics, Indian School of Mines, Dhanbad
[2]Institute for Geophysics, John A. and Katherine G. Jackson School of Geosciences, University of Texas at Austin, USA.
[3]Gas Authority of India Limited, New Delhi

Summary

Presence of obliquely dipping fractures in an otherwise isotropic medium reduces the symmetry of the elastic coefficient tensor, with the resulting medium behaving as transversely isotropic with a tilted axis of symmetry. The amplitude variation with offset and azimuth (AVOA) response exhibits sinusoidal variation with respect to the azimuth with peak/ trough oriented along the fracture strike direction, except for near vertical incidences. We have developed a scheme to estimate the dip of arbitrarily dipping fractures from the analysis of AVO along and perpendicular to the strike of the dipping fractures. Results from simulated examples show that the present method yields satisfactory values of the dip estimates for dilute fractures either fully or partially saturated with gas.

Introduction

Hydrocarbon reservoirs, in general, contain one or more sets of parallel natural fractures which are collections of cracks with dimensions varying from less than a micron to few millimeters. The aperture, shape and density of fractures are determined by the elastic properties of the rocks hosting the fractures as well as the in situ stress distribution. The stress regime plays a major role in determining the geometry of the fractures, viz., the orientation (strike), dip as well as the micro-structural properties, i.e., fracture density, shape etc. For example, the compressive stress acting normal to the plane of the cracks tend to reduce the crack aperture unless these are propped by mineralization. Besides providing space for storage, fractures in a hydrocarbon reservoir act as vents for flow of hydrocarbon thereby increasing the permeability of the reservoir in a preferred direction. This information on permeability anisotropy helps reservoir engineers plan drilling strategies for enhanced recovery of hydrocarbon.

Over the last decade, there has been significant progress in understanding the effects of fractures on seismic data observed on surface as well as in boreholes, i.e., vertical seismic profiles. Conventional methods of fracture characterization, viz. determining the strike and the dip of incipient fractures, estimating fracture density and fluid infill which involve analyses of cores, drill cuttings, down hole images, well logs etc. can provide information on fracture properties at local scale only. On the other hand, the fracture aperture is far smaller than the wavelength of seismic waves (~10-100m) in a common seismic experiment and as such the micro-structural parameters of fractures are not resolved in surface seismic data. Nevertheless, as the fractures are more compliant to stress than the background rock matrix hosting the fractures, the elastic properties of fractured rocks are different from the otherwise isotropic rock in which these are embedded. As a result, certain attributes of the seismic reflection- e.g., the normal move out velocity (NMO), amplitude variation with offset (AVO) etc.- exhibit variations with azimuth of the seismic line with respect to the symmetry axis of the fracture set. Moreover, the shear waves with polarizations parallel and perpendicular to the fracture strike travel with different velocities resulting in the 'shear wave splitting'. Effects of micro structural parameters of incipient fractures, viz. fracture density, fluid infill, fracture shape and roughness combined together give rise to observable velocity anisotropy and amplitude variations with offset and azimuth in seismic reflection data.

Most of the investigations on seismic wave propagation in fractured media consider vertical or steeply dipping fractures. The presence of obliquely dipping fractures in an otherwise isotropic host medium results in a transversely isotropic medium with a tilted axis of symmetry (TTI). Angerer (2002) reported on the existence of obliquely dipping fractures in hydrocarbon reservoirs. Grechka and Tsvankin (2004) developed a method for quantitative characterization of obliquely dipping fractures using travel time data. Shaw and Sen (2004) used Born formulation to write an approximation of linearized PP-reflection coefficients over a TTI medium in terms of weak anisotropic parameters.

The variation of seismic amplitudes with azimuth provides information on the strike of the fractures. However, the dip of the fractures cannot be estimated easily. The presence of obliquely dipping fractures can be inferred from the following observations on single/ multi component seismic data.

(i) asymmetry of travel times in mode converted PS-waves (Angerer et al, 2002) reflected from a horizontal reflector.

(ii) a significant horizontal component of P-wave as well as vertical component of slow S-wave, for near vertical incidence (Grechka and Tsvankin, 2004).

In this work, we investigate the effect of fluid infill on the AVOA over obliquely dipping fractures. We developed a method to estimate the dip of the obliquely dipping fractures from analysis of AVO data along and perpendicular to the strike of the fractures. Our results on synthetic data show that the reflection coefficients over a fractured reservoir with obliquely dipping fractures exhibit sinusoidal variation with azimuth of the observation line with respect to the axis of symmetry. For oblique fractures either fully or partially saturated with gas , the dip can be determined accurately provided the elastic properties of an isotropic background medium can be derived from conventional methods.

Theory

We follow, Grechka and Tsvankin (2004) to obtain the elastic stiffness parameters over obliquely dipping fractures. We consider an isotropic background with density ρ and elastic parameters λ and μ in which are embedded a set of rotationally invariant fractures with strike along x_2 direction (Figure 1) with dip of symmetry axis θ. Representing the normal and shear fracture weaknesses of the fracture system by ΔN and ΔT respectively, the stiffness of the fractured media is given by (Schoenberg and Sayers, 1995)

$$C = (\lambda + 2\mu)\left[C^b - C^f\right] \qquad (1)$$

with

$$C^b = \begin{bmatrix} 1 & 1-2g & 1-2g & 0 & 0 & 0 \\ & 1 & 1-2g & 0 & 0 & 0 \\ & & 1 & 0 & 0 & 0 \\ & & & g & 0 & 0 \\ & & & & g & 0 \\ & & & & & g \end{bmatrix}$$

and

$$C^f = \begin{bmatrix} c_{11} & c_{12} & c_{13} & 0 & c_{15} & 0 \\ & c_{22} & c_{23} & 0 & c_{25} & 0 \\ & & c_{33} & 0 & c_{35} & 0 \\ & & & c_{44} & 0 & c_{46} \\ & & & & c_{55} & 0 \\ & & & & & c_{66} \end{bmatrix},$$

where, $g = \mu/(\lambda + 2\mu)$ is the ratio of the squares of S- and P-wave velocities in the isotropic background medium. Equation (1) shows that the presence of obliquely dipping fracture reduces the symmetry of the elastic coefficient tensor and that the fractured medium exhibits monoclinic symmetry.

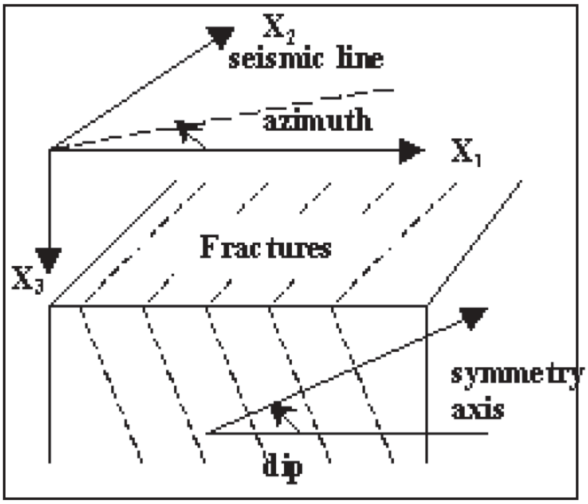

Fig. 1: Geometry of obliquely dipping fractures. Fractures are striking along Xa_2 direction.

Following Grechka and Tsvankin (2004),we write the explicit expressions for the coefficients of the (symmetric) stiffness matrix C^f

$$c_{11} = \Delta N\left[(1 - 2g + \frac{3}{2}g^2) + 2g(1-g)\cos 2\theta + \frac{g^2}{2}\cos 4\theta\right] + \Delta T\frac{g}{2}\left[1 + \cos 4\theta\right]$$

$$c_{12} = \Delta N\left[(1 - 3g + 2g^2) + g(1-2g)\cos 2\theta\right]$$

$$c_{13} = \Delta N\left[(1 - 2g + \frac{1}{2}g^2) - \frac{g^2}{2}\cos 4\theta\right] - \Delta T\frac{g}{2}\left[1 - \cos 4\theta\right]$$

$$c_{15} = -\Delta N g \sin 2\theta\left[(1-g) + g\cos 2\theta\right] + \Delta T\frac{g}{2}\sin 4\theta$$

$$c_{22} = \Delta N(1 - 2g)^2$$

$$c_{23} = \Delta N(1 - 2g)\left[(1-g) - g\cos 2\theta\right]$$

$$c_{25} = g\Delta N(1-2g)\sin 2\theta$$

$$c_{33} = \Delta N\left[(1-2g+\frac{3}{2}g^2)-2g(1-g)\cos 2\theta+\frac{g^2}{2}\cos 4\theta\right]+$$

$$\Delta T\frac{g}{2}[1+\cos 4\theta]$$

$$c_{35} = -c_{15} \qquad \ldots (2)$$

$$c_{44} = g\Delta T\sin^2\theta$$

$$c_{46} = g\Delta T\sin\theta\cos\theta$$

$$c_{55} = \Delta N\frac{g^2}{2}(1-\cos 4\theta)+\Delta T\frac{g}{2}(1+\cos 4\theta)$$

$$c_{66} = g\Delta T\cos^2\theta$$

with all other coefficients identically equal to zero.

It is interesting to note that the factor $g\frac{\Delta N}{\Delta T}$ is a quantitative measure of fluid saturation with its value approaching unity for gas saturated fractures and tending to zero for fluid saturated fractures (Schoenberg and Sayers, 1995).

We used the reflectivity method (Fryer and Frazer, 1984) to compute the AVO responses over a fractured reservoir with obliquely dipping fractures.

G

Dip Estimation

Follwing Shaw and Sen (2004), we write the expression for linearized reflection coefficient over a fractured reservoir with obliquely dipping fractures as

$$R_{PP}^{frac}(i,\phi) = R_{PP}^{iso}(i) + R_{PP}^{ani}(i,\phi) \qquad \ldots(3)$$

with

$$R_{PP}^{iso} = \frac{1}{2}\frac{\Delta Z}{\overline{Z}} + \frac{1}{2}\left\{\frac{\Delta\alpha}{\overline{\alpha}} - 4g\frac{\Delta G}{\overline{G}}\right\}\sin^2 i + \frac{1}{2}\frac{\Delta\alpha}{\overline{\alpha}}\sin^2 i\tan^2 i$$

and

$$R_{PP}^{ani}(i,\phi) =$$

$$\left\{\frac{\delta}{2}(\cos^2\psi-\sin^2\theta)-(\varepsilon-\delta)(\cos^2\psi+\sin^2\theta)\sin^2\theta+4g\gamma\cos^2\psi\right\}\sin^2 i$$

$$+\frac{1}{2}\left\{\delta(\cos^2\psi-\sin^2\theta)+(\varepsilon-\delta)(\cos^4\psi+\sin^4\theta)\right\}\sin^2 i\tan^2 i$$

representing the isotropic and anisotropic part of the linearized reflection coefficient respectively.

Here, $\cos\psi = \cos\theta\cos\phi$ with ϕ representing the azimuth of the observation line with respect to the symmetry axis of the obliquely dipping fractures. The symbols Z, α and represent the P-wave acoustic impedance, P-wave velocity and shear modulus respectively with the over bar representing the isotropic background medium properties and the prefix Δ indicating weak contrasts in respective properties across the interface separating the fractured reservoir from the isotropic background. The Thomsen parameters ε, γ and δ (Thomsen, 1986) relate to the elastic coefficients of the fractured medium (eq. 2) as

$$\varepsilon = \frac{c_{11}-c_{33}}{2c_{33}} \approx 2g(1-g)\Delta N,$$

$$\delta = \frac{c_{13}-c_{33}+2c_{55}}{c_{33}} \approx 2g(\Delta N-\Delta T) \qquad \ldots(4)$$

and

$$\gamma = \frac{c_{44}-c_{55}}{2c_{55}} \approx \frac{\Delta T}{2}.$$

It is obvious from equation (3) that the dip of obliquely dipping fractures relates to AVOA in a complicated way. Assuming that a proper background medium could be appropriately derived from conventional methods, we focus on the anisotropic part of the reflection coefficient and express this as

$$R_{PP}^{ani}(i,\phi) = \left[A(\phi) + B(\phi)\tan^2 i\right]\sin^2 i \qquad \ldots(5)$$

where the constants $A(\phi)$ and $B(\phi)$ are AVO-intercept and AVO-gradient attributes respectively for the azimuth ϕ. These attributes are functions of Thomsen parameters besides the dip of the fractures and can be determined from the observed AVOA data. We considered and along the dip ($\phi = 0^0$) and strike ($\phi = 90^0$) directions of the fractures to eliminate the Thomsen parameters from the system of equations (5). This results in the following bi-quadratic equations in (Chatterjee, 2005),

$$a\sin^4\theta + b\sin^2\theta + c = 0 \qquad \ldots(6)$$

with

$$a = 2A_s - 4B_s + B_d \quad ,$$

$$b = 4B_s - 3A_2 \quad \text{and}$$

$$c = A_s - B_s$$

where the suffices s and d represent the strike and dip directions respectively.

One of the real solutions of equation (6) yields the dip of the fractures.

Results and Discussions

We investigated the effects of fluid infill on P-wave AVOA over an interface separating an isotropic medium from a fractured medium with the physical properties of the media given in Table 1.

Table 1: Physical properties of background medium and fractures.

Medium	**P-wave velocity, m/s**	**S-wave velocity m/s**	**Density, kg/m^3**	**ΔN**	**ΔT**
Isotropic	2000	1000	2000	0.00	0.00
Fractured (partially saturated)	2000	1000	2000	0.15	0.10

First, we investigated the variation of reflection coefficient with azimuth. With this objective,, we selected an incidence angle of 30^{o} and computed the PP-reflection coefficient for azimuth varying between 0^{o} and 180^{o} at an interval of 10^{o} with dip of the symmetry axis kept fixed at 30^{o}, 45^{o} and 60^{o}. The results (Figure 2) show that AVOA for obliquely dipping fractures exhibit similar behavior as that over vertical fractures (Ruger, 1998). Thus, the strike direction of obliquely fractures can be determined from the azimuthal variation of reflection amplitudes, to an ambiguity of 90^{o}.

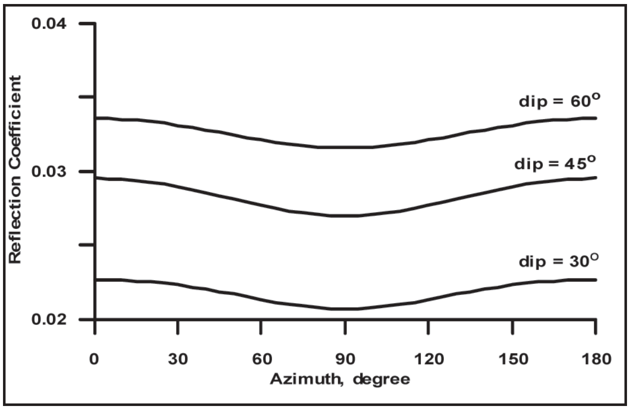

Fig.2 : AVOA over partially gas saturated obliquely dipping fractured reservoir at incidence angle 30^{o}.

Further, we selected a set of parallel fractures with the dip of the symmetry axis as 0^{o} (vertical fractures), 30^{o}, 45^{o}, 60^{o} and 90^{o} (horizontal fractures, VTI medium). For each dip of the fractures, we computed the exact PP-reflection coefficients along and perpendicular to the fracture strike for incidence angles varying between 0^{o} and 40^{o} at an interval of 2^{o}. Figure 3 shows that appreciable azimuthal variation could be observed for angles of incidence above 15^{o}.

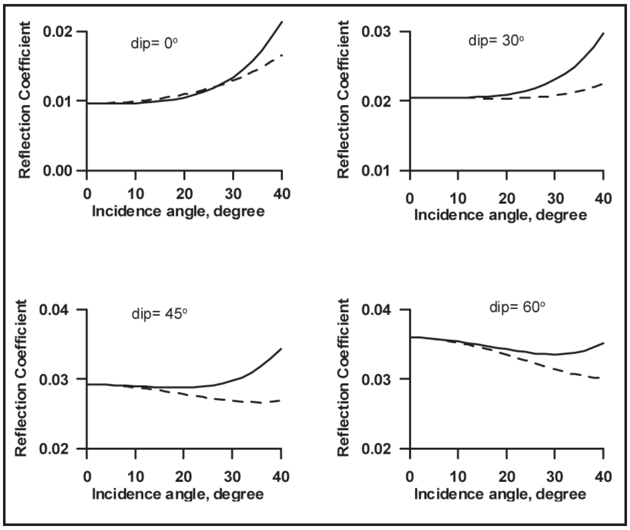

Fig. 3: AVO over a fractured reservoir with obliquely dipping fractures partially saturated with gas. Solid and dotted lines represent AVO along and perpendicular to the fracture strike directions respectively.

In order to evaluate to efficacy of our method to estimate dip of obliquely dipping fractures, we selected a fractured chalk reservoir underlying an isotropic shale with the properties of the solid rock and the fracture described in Table 2.

Table 2: Physical properties of a fractured chalk reservoir underlying an isotropic shale

Medium	**P-wave velocity, m/s**	**S-wave velocity m/s**	**Density, kg/m^3**	**ΔN**	**ΔT**
Shale	2460	1230	2300	0.00	0.00
Chalk (Gas saturated)	3620	1810	2420	0.20	0.05
Chalk (partially saturated)	3620	1810	2420	0.10	0.05

We varied the dip of the fractures from 0° to 75° at an interval of 15° and simulated the AVO responses along and perpendicular to the strike direction using the reflectivity method mentioned earlier. In view of the fact that the azimuthal variation of amplitudes become prominent at incidence angles above 15°, we selected a range of incidence angles between 20° and 40° to compute A_d, B_d, A_s and B_s through equation (5). We used equation (6) to estimate the dip of the fractures. The results (Table 3) show that the dip of the oblique fractures can be estimated with reasonable accuracy in both situations investigated, viz. fully or partially saturated with gas.

Table 3: Estimation of dip of the symmetry axis of the obliquely dipping fractures.

Assumed dip (degrees)	**Estimated dip (degrees)**	
	Fully saturated with gas	**Partially saturated with gas**
0	0.0	0.0
15	23.1	28.3
30	35.1	34.3
45	50.6	45.1
60	60.6	80.1
75	81.8	90.0

Conclusions

Following Grechka and Tsvankin's (2004) representation of elastic stiffness coefficients over obliquely dipping fractured medium in terms of normal and tangential weaknesses of the fracture system, we studied the effects of fluid infill on the AVOA. We observed that the pattern of variation of AVOA over obliquely dipping fractures is similar to that over vertical fractures, so that the strike of the obliquely dipping fractures can be determined from the peak/ troughs of sinusoidal variation of the amplitudes, to an ambiguity of 90°. The effects of fractures on AVOA become appreciable for angles of incidence above 15^0. Our method for dip estimation from AVOA analysis yields satisfactory dip over oblique fractures either fully or partially saturated with gas.

Acknowledgment

RKS acknowledges the financial support from the Department of Science and Technology, New Delhi under grant No. ESS/16/203/2004.

Scholarship awarded to ABC under Schlumberger Indian University Handshake Programme for the academic session 2004-2005 is gratefully acknowledged.

References

Angerer, E., Horne, S. A., Gaiser, J. E., Walters, R., and Vetri, L, 2002, Characterization of dipping fractures using PS mode converted data; Expanded Abstracts, 72nd SEG meeting, 1010-1013.

Chatterjee, A. B., 2005, Inversion of azimuth dependent seismic velocities and amplitudes to characterize fracture geometry and fluid infill; Unpublished M.Sc. Tech. dissertation, Indian School of Mines, Dhanbad.

Fryer, G. J. and Frazer, L. N., 1984, Seismic waves in stratified media; Geophysical Journal of Royal Astronomical Society, 78, 691-710.

Grechka, V., and Tsvankin, I., 2004, Characterization of dipping fractures in a transversely isotropic background; Geophysical Prospecting, 52, 1-10.

Ruger, A., 1998, Variation of P-wave reflecivity with offset and azimuth in anisotropic media; Geophysics, 63, 935-947.

Schoenberg, M., and C. Sayers, 1995, Seismic anisotropy of fractured rock; Geophysics, 60, 204-211.

Shaw, R. K., and Sen, M. K., 2004, Born integral, stationary phase and linearlized reflction coefficients in weak anisotropic media; Geophysical Journal International, 158, 225-238.

Thomsen, L., 1986, Weak elastic anisotropy; Geophysics, 51, 1954-1966.