DETECTION OF FRACTURE ORIENTATION USING AZIMUTHAL VARIATION OF P-WAVE AVO RESPONSES

Maria Auxiliadora Pérez and Richard L. Gibson, Jr.

Earth Resources Laboratory
Department of Earth, Atmospheric, and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, MA 02139

ABSTRACT

Azimuthally-dependent P-wave AVO (amplitude variation with offset) responses can be related to open fracture orientation and have been suggested as a geophysical tool to identify fracture orientation in fractured oil and gas reservoirs. A field experiment recently conducted over a fractured reservoir in the Barinas Basin (Venezuela) provides data for an excellent test of this approach. Three lines of data were collected in three different azimuths, and three component receivers were used. The distribution of fractures in this reservoir was previously obtained using measurements of shear wave splitting from P-S converted waves from the same dataset (Ata and Michelena, 1995). In this work, we use P-wave data to see if the data can yield the same information using azimuthal variation of P-wave AVO responses. Results obtained from the azimuthal P-wave AVO analysis corroborate the results previously obtained using P-S converted waves. This analysis with field data is an example of the high potential of P-waves to detect fracture effects on seismic wave propagation.

INTRODUCTION

The detection of fractured zones and determining their orientation is an important part of reservoir development and enhanced oil recovery (EOR) projects. S-waves have been shown to be very effective in detecting azimuthal anisotropy and, more precisely, of fracture induced anisotropy. They are considered more reliable than P-waves for two main reasons. First, an anisotropic medium allows propagation of two quasi-shear waves with different polarizations. Measurements of travel times of these waves in a single propagation direction (vertical, for example) allow a definitive identification of anisotropy. In contrast, a single quasi-compressional wave exists. Its velocity can be affected by heterogeneity as well as anisotropy, and its travel time must be examined in many directions. Second, the polarization of the two quasi-shear waves in a fractured reservoir is related to fracture orientation, one perpendicular to cracks, and the other polarized parallel to the cracks. Therefore, crack orientation, as well as anisotropy, can be determined with a shear wave experiment. However, the aquisition and processing of S-waves is very expensive compared to conventional P-wave data. Therefore, the characterization of fractured reservoirs using P-waves instead of S-waves is an important exploration problem that has attracted much attention from exploration geophysicists and reservoir engineers interested in fracture detection and analysis. Some theoretical works show that P-waves are sensitive to fractures or cracks (Crampin, 1980). In particular, P-wave reflection AVO has been suggested as an indicator of azimuthal anisotropy (Mallick and Frazer, 1991; Rüger and Tsvankin, 1995; Strahilevitz and Gardner, 1995; Sayer and Rickett, 1997). There are also some field studies of azimuthally-dependent P-wave AVO responses related to fractured reservoirs (Lefeuvre, 1994; Lynn *et al.*, 1995).

Amplitude Variation with Offset (AVO) analysis is based on the variation of reflection and transmission coefficients with incident angle and the corresponding increasing offset (Castagna, 1993a). Different equations have been presented in the literature for the reflection coefficients (Knott, 1899; Zoeppritz, 1919; Aki and Richards, 1980; Waters, 1981). These equations are very complex. A simplified approximation of the reflection coefficient for isotropic media was presented by Shuey (1985); for restricted angles of incidence, the equation is

$$R_{pp}(\theta) = R_p + B\sin^2(\theta) \tag{1}$$

where $R_{pp}(\theta)$ is the reflection coefficient at angle θ, R_p is the reflection coefficient at normal incidence (also called the AVO intercept), and B is called the AVO gradient which is mainly influenced by variation in Poisson's ratio (σ). Therefore, R_p dominates the reflection coefficient at small angles, whereas $\Delta\sigma$ and consequently V_p/V_s contrast dominates at larger angles. However, the term B in Shuey's equation 1 is still complicated. Thomsen (1990) suggests that Wright's (1986) reflection coefficient equation has a simpler expression for the term B (AVO gradient)

$$B = (1/2) * ((\Delta V_p/V_{pa}) - ((2 * V_{sa}/V_{pa})^2 * (\Delta\mu/\mu_a))). \tag{2}$$

Therefore, the equation for the reflection coefficient in this case is given by

$$R_{pp}(\theta) = R_p + (1/2) * ((\Delta V_p/V_{pa}) - ((2 * V_{sa}/V_{pa})^2 * (\Delta\mu/\mu_a))) * \sin^2(\theta). \tag{3}$$

It can be observed in equation 3 that any change in V_p clearly affects the resulting reflection coefficient.

Gassmann's (1951) equations predict a large drop in P-wave velocity and a small increase in S-wave velocity when even a small amount of gas is introduced into the pore space of a compressible brine-saturated sand. This drop causes a drop in V_p/V_s

resulting in AVO anomalies. Oil and water are often assumed to have similar acoustic properties, and to be indistinguishable using seismic methods. However, gas or light hydrocarbons can go into solution in crude oils, and can dramatically alter the velocities (Castagna, 1993b). Therefore, depending on the gas-oil-ratio (GOR), the ratio V_p/V_s can be strongly affected, likewise the AVO response.

We analyze the fracture reservoir data with the following conceptual model. If the experiment is conducted parallel to fracture orientation, the fractures should have minimal influence on the reflection properties, regardless of the angle of incidence. This is because the P-wave particle motion will always be parallel to the thin cracks. However, if the line is oriented more perpendicular to the fractures, at large angles of incidence, the reflection coefficients will be affected strongly (Lynn *et al.*, 1995). At large angles of incidence, the P-wave velocity is expected to be affected by the acoustic properties of the fluid filling the fractures when the wave propagation is perpendicular to the fractures, while it is less affected when the wave propagation is parallel to the fractures.

If no azimuthal anisotropy exists, the AVO response will be the same in all directions, while in the presence of anisotropy, the AVO response will vary depending on the source-receiver azimuth. In our work, we will apply AVO analysis to a known fractured reservoir, which has azimuthal anisotropy associated with the aligned, vertical fractures. In this case, Wright's (1986) equation will not be directly applicable for the study of P-wave reflections because it assumes isotropic formations. However, for P-wave AVO, the reflection coefficient at normal incidence (AVO intercept) is independent of azimuth. We therefore assume that the reflection coefficient at small angles of incidence will still have the same form as equation 3, but that the precise, explicit form of the AVO gradient term B will depend on the experimental azimuth. Some initial theoretical results for P-wave reflection coefficients for symmetry planes and AVO attributes in azimuthally anisotropic media (Rüger, 1996) confirm this hypothesis. For incident angle θ and azimuthal angle ϕ the reflection coefficient is given by

$$\begin{aligned} R_{pp}(\theta,\phi) = R_p \quad &+ \quad (1/2) * ((\Delta V_p/V_{pa}) - ((2 * V_{sa}/V_{pa})^2 * (\Delta\mu/\mu_a)) \\ &+ \quad (\Delta\delta + 2 * (2 * V_{sa}/V_{pa}) * \Delta\omega) * \cos^2(\phi)) * \sin^2(\theta). \end{aligned} \tag{4}$$

For the particular case perpendicular to the symmetry axis $\phi = 90$ (parallel to the fracture orientation), equation 4 reduces to the approximation given by equation 3 for the isotropic case, and for any other case, any change in V_p will also affect the reflection coefficient.

In a previous work, Ata and Michelena (1995) estimated the fracture orientation in a fracture reservoir using splitting measurements from the P-S converted data. The purpose of our study is to attempt to identify azimuthal P-wave AVO over the same fractured oil reservoir and compare it to previous independent results obtained using P-S converted waves to see if we can obtain similar results to identify fracture orientation.

GEOLOGICAL SETTING

The Maporal field is located in the north-central part of the Barinas-Apure Basin. Structurally, the Maporal field is a dome slightly extended in the NE direction. The geological setting is composed mainly of nearly flat-lying sediments. Two fault systems are present in the area. One runs southeast-northwest and the other northeast-southwest. A brief description of the main formations present in the zone is shown in Figure 1. The target zone is the member 'O' of the 'Escandalosa' formation. It is a fractured limestone at a depth of approximately 3000 m (2.32 s). The fractures in the reservoir are filled with crude oil of approximately 28 API number. There is also evidence that some production comes from the 'P' and 'S' members of the stratigraphic section. These are composed mainly of sandstones; fractures also exist in these two members.

A number of wells exist in the field, which provide good background information on reservoir and fracture properties in the area, and which can be used for correlation studies. The well data includes sonic, dipole (shear), caliper, resistivity, gamma ray and other logs.

Knowing the orientation of the maximum horizontal stress in the field is important to determine the fractures that are more likely to be open or to be closed. Figure 2 shows a map with the maximum horizontal stress and fracture strike in the area at the reservoir level. The maximum horizontal stress in the field has been estimated using borehole ellipticity measurements. Besides, the fracture strike has been obtained using televiewer well logs. The maximum horizontal stress runs southeast-northwest and different fracture systems have been identified. Based on the theory that open fractures tend to align along the direction of maximum regional stress, and consequently that perpendicular fractures may be closed, the fracture system of interest should be oriented southeast-northwest.

As we can see, the Maporal field is well suited for this study. The existence of fracturing is confirmed from in situ borehole observations, and we also have a preliminary estimate of orientation.

DATA ACQUISITION

Three 10 km three-component seismic lines were recorded over the area of interest along three different azimuths. The lines have a single intersection point. As was mentioned above, two systems of normal faults are present in the area. The azimuths of two lines (lines 1 and 3) were almost parallel to the fault systems, and the third line (line 2) almost bisected them and formed an angle of approximately 40 degrees with line 1. Figure 2 is an illustration of survey geometry with respect to the fault systems. A charge of one kilogram explosives at 10 m depth was used for the source. The source interval was set at 51 m and the geophone group interval at 17 m with a linear array between stations. The near offset trace was set at 17 m and the far offset extended to 3600 m, which satisfies the suggested minimum offset for an azimuthal AVO study (at least the same as the depth of the target zone). With this geometry we can expect a maximum incident angle of approximately 32 degrees for the target zone.

PREVIOUS STUDIES

A study of S-wave birenfringence, or splitting, was previously conducted using this dataset by Ata and Michelena (1995). Due to the simple structure of the area, they used the asymptotic approximation (Tessmer and Behle, 1988; Tessmer *et al.,* 1990) to calculate the Common Conversion Point (CCP). Then, they applied rotation analysis to align observed data to the principal axes of symmetry and therefore to estimate the fracture orientation. They also made travel time studies (S_1 and S_2 modes) to estimate the fracture density. As a result of this study a map showing the fracture orientation at the reservoir level was generated and is shown in Figure 3. Ata and Michelena (1995) concluded that lines 1 and 2 are nearly-perpendicular to fracture orientation, and line 3 is nearly-parallel to fracture orientation. We compare these results to our analysis.

AVO STUDY

The first goal of our work is to perform AVO analysis of the P-wave data. Specifically, we focuse on the intersection point of the three seismic lines. At this point, all lines should be looking at the same point in the subsurface and we compare the differences in the azimuthal response.

Data Processing

The basic objective of the data processing for AVO analysis is to preserve relative amplitude for all offsets at all times for any CDP gather. Additionally, relative amplitudes among all depth points need to be preserved. In the case of stacked data, the process of CDP stacking cancels many types of noise. However, in the prestack domain the processor cannot count on this tool.

The same data processing sequence was applied to all lines using a basic but robust scheme in order to conserve the reflectivity variation with offset. A subset of the data was extracted from the original one to consider the area of the reservoir near the intersection point. The number of shots selected guaranteed maximum fold over the cross point (36 traces). Special emphasis in the processing was made around the cross point of the lines, at approximately CDP 224 of the reduced dataset. The processing sequence applied to all lines was:

1. Spherical divergence correction.
2. Coherent noise suppression (f-k filtering).
3. Velocity analysis and statics iterations.

4. NMO correction.

5. AVO analysis.

6. Stacking.

In addition, we made a spectral analysis over the data; the center frequency was found to be around 25 Hz.

It is known that the NMO stretch decreases frequency at far offsets, which affects the amplitudes. However, this distortion is significant at shallow depths and at a large offset. The target zone in our study is relatively deep and the stretch problem does not significantly affect the results. NMO-corrected gathers around the intersection point for the three lines are presented in Figures 4a, 4b, and 4c. As it is also known, deconvolution is a process that improves the temporal resolution by compressing the seismic wavelet. It is often used to isolate seismic events, which is important for AVO analysis. However, we did not use deconvolution in order to conserve amplitude information.

It is important to note the consistency of the processing among all lines, which is supported by the good tie between the three lines (see Figure 5). The top of the fractured reservoir is located at 2320 ms and the base at 2370 ms. A higher frequency can be observed at the reservoir level for the line parallel to fracture orientation (line 3). However, these results are consistent with the ones obtained by Lynn *et al.* (1996), where the frequency content is related to source-receiver azimuth relative to fracture strike.

Azimuthal AVO Analysis

AVO analysis was made for each line and the AVO gradient and intercept were obtained. An AVO anomaly with a large positive gradient was found for the base of the Escandalosa formation in lines 1 and 2, perpendicular to fracture orientation (see Figures 6a and 6b). This AVO anomaly is not present in line 3, parallel to fracture orientation (see Figure 6c). The AVO gradient versus AVO intercept graph for CDP gathers of each line around the cross point shows the high positive gradients for the lines perpendicular to the fracture, while they are smaller for the line parallel to the fracture (see Figure 7).

The AVO intercept for the bottom of the reservoir is very small for all lines. Theoretically, it should be the same for all lines no matter the source-receiver azimuth relative to fracture strike. However, some small differences were observed that could be caused by some noise in the data.

A detailed example of the behavior of the amplitudes for the cross point CDP gather for each line is shown in Figures 8a, 8b and 8c. These figures also show that an increase of the amplitude with the offset is larger for the lines perpendicular to the orientation of the fractures (lines 1 and 2) than for the line parallel to the orientation of the fractures (line 3).

DISCUSSION

To start the discussion of the obtained AVO response, we present two of the five rules empirically established by Koefoed (1955) about the effects of Poisson's ratio on the reflection coefficients of plane waves:

1. "When the underlying medium has the greater longitudinal P-wave velocity and the other relevant properties of the two strata are equal to each other, an increase of Poisson's ratio for the underlying medium causes an increase of the reflection coefficient at the larger angles of incidence." Shuey (1985) points out that the qualifications concerning the medium properties are not necessary for this and the next rule.

2. "When, in the above case, Poisson's ratio for the incident medium is increased, the reflection coefficient at the larger angles of incidence is thereby decreased."

The azimuthal difference in AVO gradients can be explained by a low Vp/Vs ratio for the lines perpendicular to the fracture due the inluence of the fluid filling the fractures, resulting in a large positive contrast in Poisson's ratio with the lower layer, and a very positive AVO gradient anomaly. For the line parallel to the fracture, the Vp/Vs ratio is less affected by the fluid filling the fractures and is greater than the previous case. This corresponds to rule number 2 and therefore the AVO anomaly is not present.

Until this point, we have been analyzing the results with the isotropic idea in mind. As we mentioned before, it has been shown that the reflection coefficient response depends on the source-receiver azimuth related to fracture orientation. However, there are only a few studies (e.g., Rüger, 1996) that relate AVO attributes to crack parameters. What seems to be clear is that the P-wave AVO gradient is affected by fracture-induced azimuthal anisotropy. In order to analyze our results using azimuthal differences in the reflection coefficients due to source-receiver azimuths, we calculate some reflection coefficients curves in two azimuths (one parallel and the other perpendicular to fracture orientation), and compare them to our results. We use information about the velocities (V_p and V_s) and densities around the reservoir from nearby well logs to build our two-layer model. Layer 1 is a fractured layer and layer 2 is an isotropic one. We use Hudson's (1981) theory to estimate the elastic constants, using a fracture density of 0.1, and a bulk modulus for fluid filling the fractures that approximates an oil of 28 API (Batzle and Wang, 1992), as the one we have in the reservoir. Thomsen's (1986) anisotropic coefficients for the fractured layer are shown in Table 1. Different results were obtained changing only V_s, and consequently the relation of the V_p/V_s ratio between the two layers (see Figures 9 10, and 11). Model 1 corresponds very well to the results obtained from our data where the AVO gradient is bigger for the lines perpendicular to fractures (lines 1 and 2) than for the line parallel to the fractures (line 3).

No azimuthal AVO anomaly is apparently observed at the top of the fractured reservoir. We calculate the reflection coefficient for this interface (see Figure 12), using data from well logs. Thomsen's anisotropic coefficient for the fractured layer in this model, are presented in Table 2. We can observe a difference between the two lines (perpendicular and parallel to fractures), however it is smaller than for the bottom of the reservoir, and could also be reduced for some tuning effects. We do not get the anomaly we expect from the top of the reservoir from our field data. However, this correspond to the observation presented by Sayers and Rickett (1997), where they point out that at conventional angles the variation in reflection amplitude with azimuth from the base of the fractured reservoir is much greater than for the reflections at the top.

CONCLUSIONS

From the azimuthal-dependent AVO analysis at the crosspoint of three 2D seismic lines, over a fractured reservoir, the following conclusions can be made:

1. In the presence of fracture induced azimuthal anisotropy, the P-wave AVO response may depend upon azimuth.
2. The results obtained using azimuthal-dependent P-wave AVO analysis are consistent with the results obtained in a previous study with the same field data using P-S converted waves.
3. Azimuthal P-wave AVO analysis can aid in detecting azimuthal anisotropy and fracture orientation.

One limitation in this work was that 2D data allowed the analysis of only one surface location (intersection point of the three seismic lines). There is a 3D survey over the same area, and in the future we will do azimuth-dependent AVO analysis using this dataset to confirm the results obtained in the present work.

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REFERENCES

Aki, K., and Richards, P. G., 1980, *Quantitative Seismology: Theory and Methods*: W. H. Freeman & Co.

Ata, E., and Michelena, R. J., 1995, Mapping distribution of fractures in a reservoir with P-S converted waves: *The Leading Edge, 12*, 664–676.

Batzle, M., and Wang, Z., 1992, Seismic properties of pore fluids: *Geophysics, 57*, 1396–1408.

Castagna, J. P., 1993a, Avo analysis—tutorial and review: in *Offset-Dependent Reflectivity-Theory and Practice of AVO Analysis*, pp. 8–36.

Castagna, J. P., 1993b, Rock physics—the link between rock properties and avo response: *Offset-Dependent Reflectivity—Theory and Practice of AVO Analysis*, pp. 135–171.

Castagna, J. P., and Backus, M., 1993, Offset-Dependent Reflectivity—Theory and Practice of AVO Analysis: *Soc. Expl. Geophys., Investigations in Geophysics Series.*

Crampin, S., McGonigle, R., and Bamford, D., 1980, Estimating crack parameters from observations of P- wave velocity anisotropy: *Geophysics, 46*, 345–360.

Gassman, F., 1951, Elastic waves through a packing of spheres: *Geophysics, 16*, 673–685.

Hudson, J. A., 1981, Wave speeds and attenuation of elastic waves in material containing cracks: *Geophys. J. Roy. Astr. Soc., 64*, 133–150.

Knott, C. G., 1899, Reflection and refraction of elastic waves with seismological applications: *Phil. Mag., 48*, 64–97.

Koefoed, O., 1955, On the effect of Poisson's ratios of rock strata on the reflection coefficients of plane waves: *Geophys. Prosp., 3*, 381–387.

Lefeuvre, F., 1994, Fracture related anisotropy detection and analysis: "And if the P-waves were enough?": *64th Annual International Meeting, Soc. Expl. Geophys., Expanded Abstracts*, 942–944.

Lynn, H., Simon, K. M., Layman, M., Schneider, R., Bates, C. R., and Jones, M., 1995, Use of anisotropy in P-wave and S-wave data for fracture characterization in a naturally fractured gas reservoir: *The Leading Edge, 14*, 887–893.

Lynn, H., Simon, K. M., Bates, C. R., and Van Dok, R., 1996, Azimuthal anisotropy in P-wave 3-D (multiazimuth) data: *The Leading Edge, 15*, 923–928.

Mallick, S., and Frazer, L. N., 1991, Reflection/transmission coefficients and azimuthal anisotropy in marine seismic studies: *Geophys. J. Internat., 105*, 241–252.

Rüger, A., and Tsvankin, I., 1995, Azimuthal variation of AVO response for fractured reservoirs: *65th Annual International Meeting, Soc. Expl. Geophys., Expanded Abstracts*, 1103–1106.

Rüger, A., 1996, Variation of P-wave reflectivity with offset and azimuth in anisotropic media: *66th Annual International Meeting, Soc. Expl. Geophys., Expanded Abstracts,* 1810–1813.

Sayers, C. M., and Rickett, J. E., 1997, Azimuthal variation in AVO response for fractured gas sands: *Geophys. Prosp., 45*, 165–182.

Shuey, R. T., 1985, A simplification of the Zoeppritz equations: *Geophysics, 50*, 609–614.

Strahilevitz, R., and Gardner, G. H. F., 1995, Fracture detection using P-wave AVO: *65th Annual International Meeting, Soc. Expl. Geophys., Expanded Abstracts,* 723–724.

Tessmer, G., and Behle, A., 1988, Common reflection point data stacking technique for converted waves: *Geophys. Prosp., 36*, 671–688.

Tessmer, G., Krajewski, P., Fertig, J., and Behle, A., 1990, Processing of PS-reflection data applying a common conversion point stacking technique: *Geophys. Prosp., 38*, 267–286.

Thomsen, L., 1986, Weak elastic anisotropy: *Geophysics, 51*, 1954–1966.

Thomsen, L., 1990, Poisson was not a geophysicist!: *The Leading Edge,* 27–29.

Waters, K. H., 1981, *Reflection Seismology: A Tool for Energy Resource Exploration*: John Wiley and Sons, Inc.

Wright, J., 1986, Reflection coefficients at pore-fluid contacts as a function of offset: *Geophysics, 51*, 1858–1860.

Zoeppritz, K., 1919, On the reflection and propagation of seismic waves: *Gottinger Nachrichten, 1*, 66–84.

Table 1: Thomsen's anisotropic coefficients for the fractured layer in models 1, 2, and 3.

ε	0.3035
γ	-0.1
δ	-0.0062

Table 2: Thomsen's anisotropic coefficients for the fractured layer in model 4.

ε	0.28
γ	-0.09
δ	-0.003

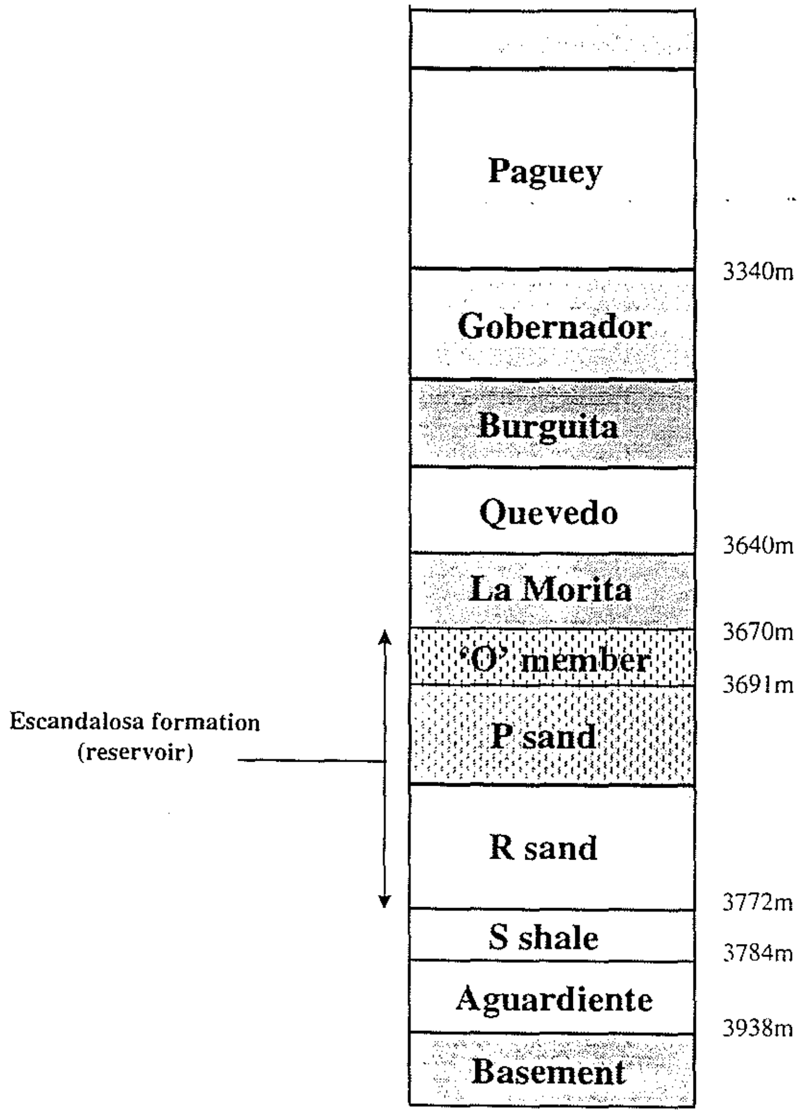

Figure 1: Lithology of the reservoir.

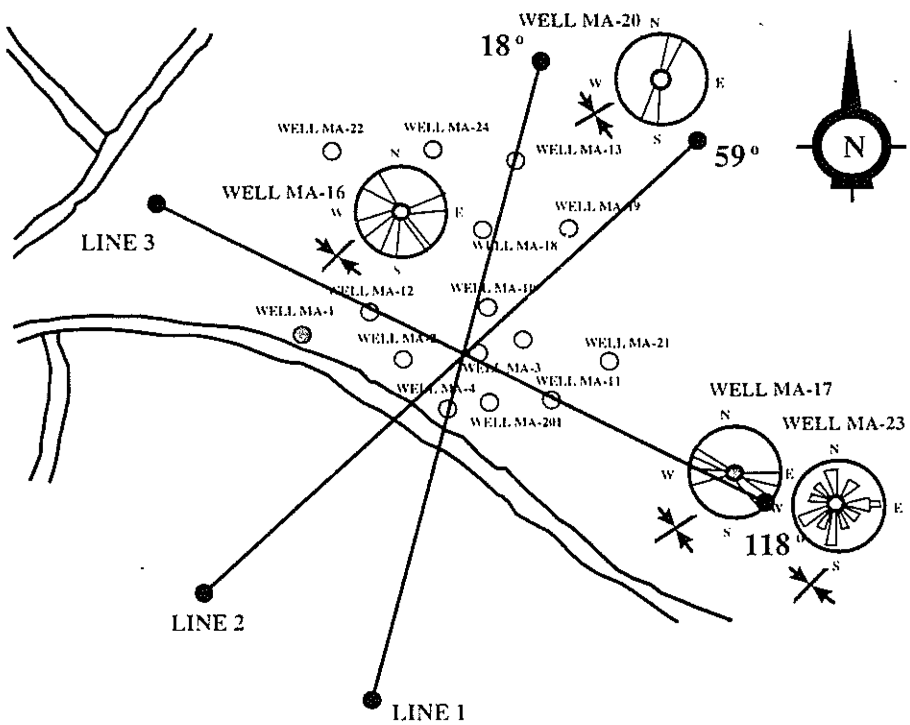

Figure 2: Maximum horizontal stress and fracture strike at the reservoir level. Fracture strike was obtained using televiewer logs. Maximum horizontal stress was estimated from borehole ellipticity. Arrows indicate the estimated direction of the maximum horizontal stress field.

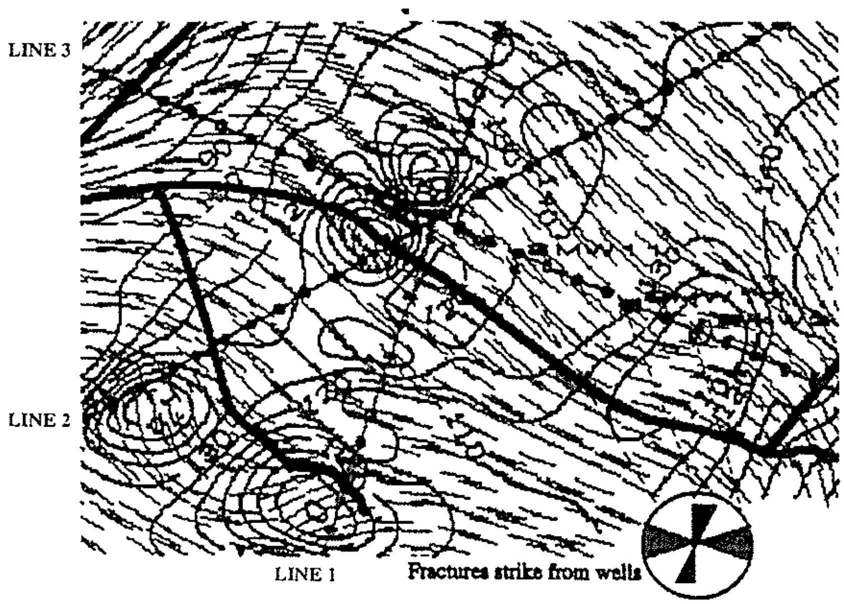

Figure 3: Map view of fracture orientation at reservoir level, obtained from rotation analysis of the three lines (Ata and Michelena, 1995). The orientation is in general quasi-parallel to line 3 and quasi-perpendicular to lines 1 and 2.

(a)

(b)

(c)

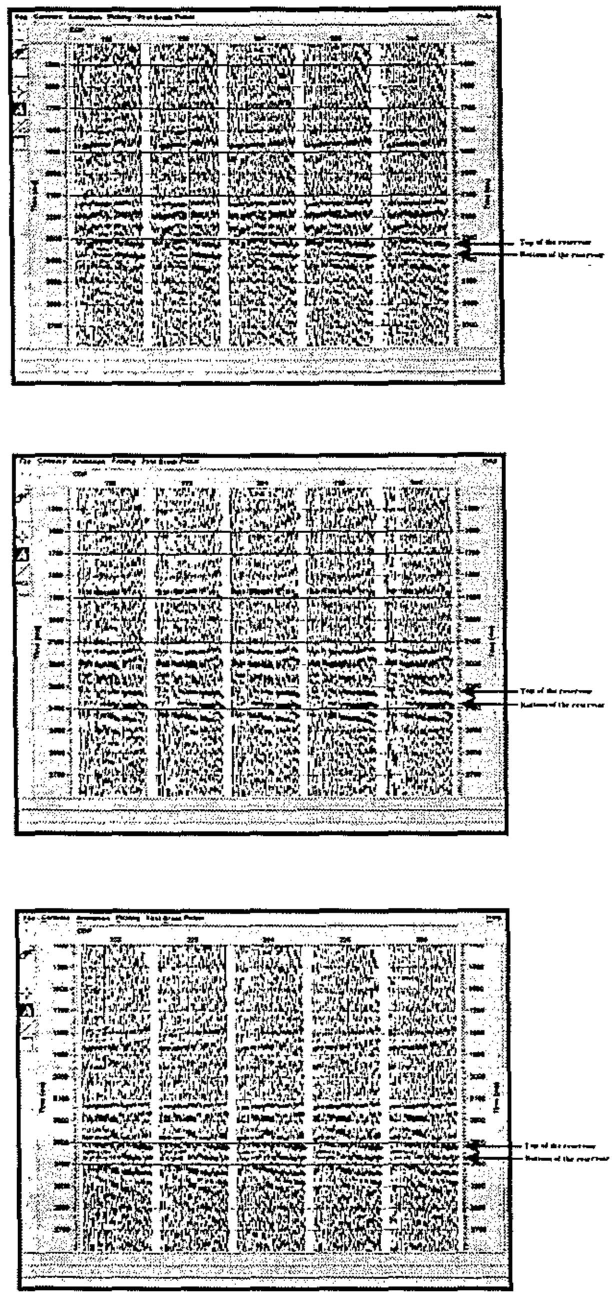

Figure 4: NMO corrected gathers around the cross point (a) for line 1 (b) for line 2 (c) for line3.

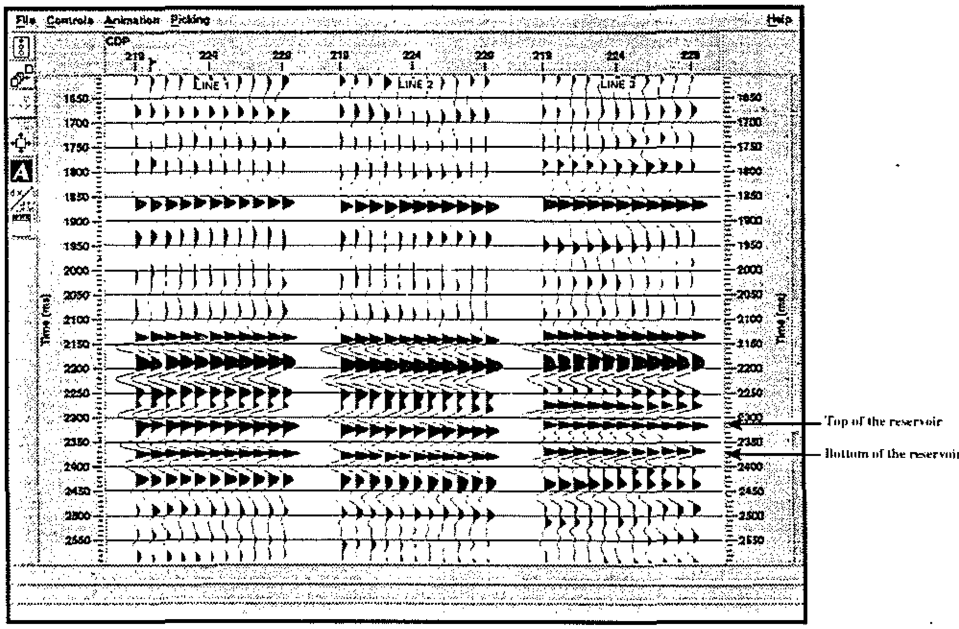

Figure 5: The consistency of the processing among all three lines is supported by the good tie between all of them at the cross point.

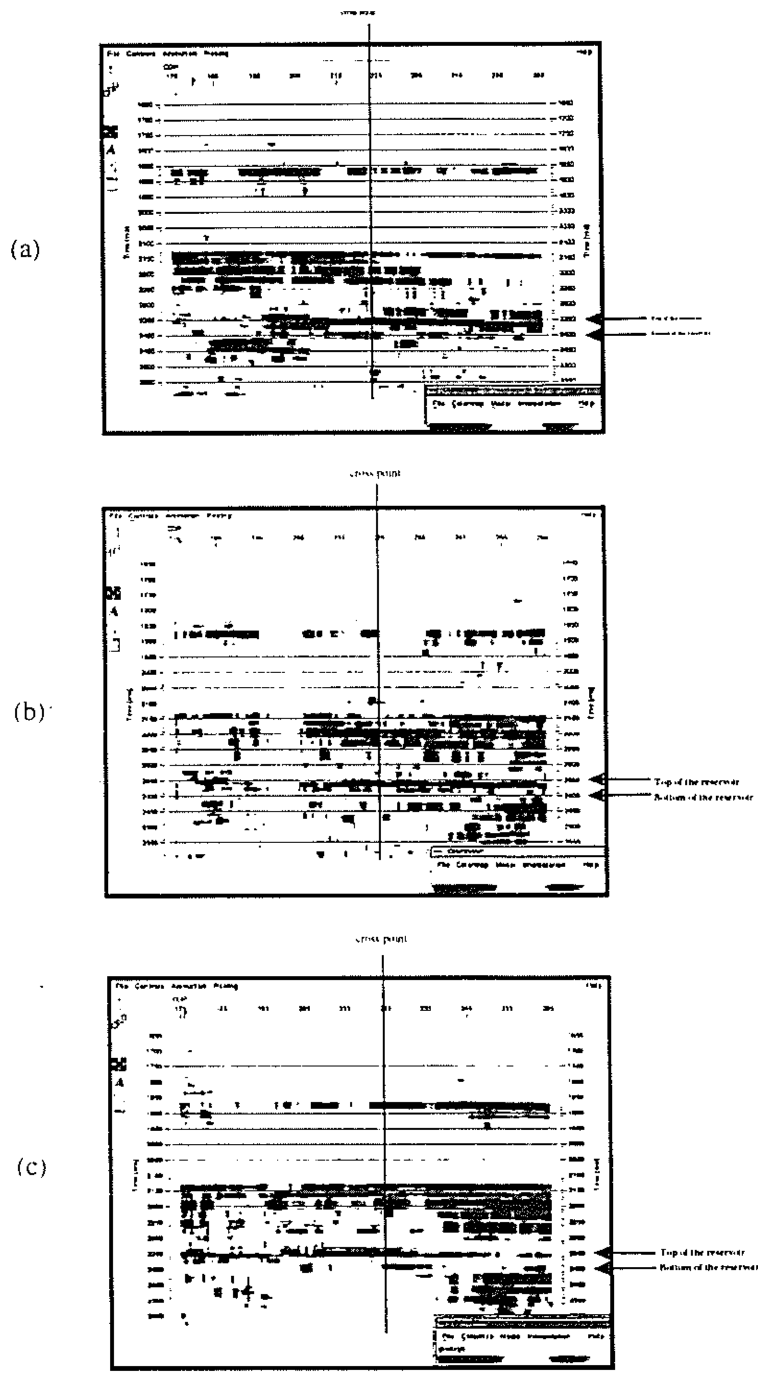

Figure 6: AVO gradient (a) for line 1 (quasi-perpendicular to fracture orientation) (b) for line 2 (quasi-perpendicular to fracture orientation) (c) for line 3 (quasi-parallel to fracture orientation).

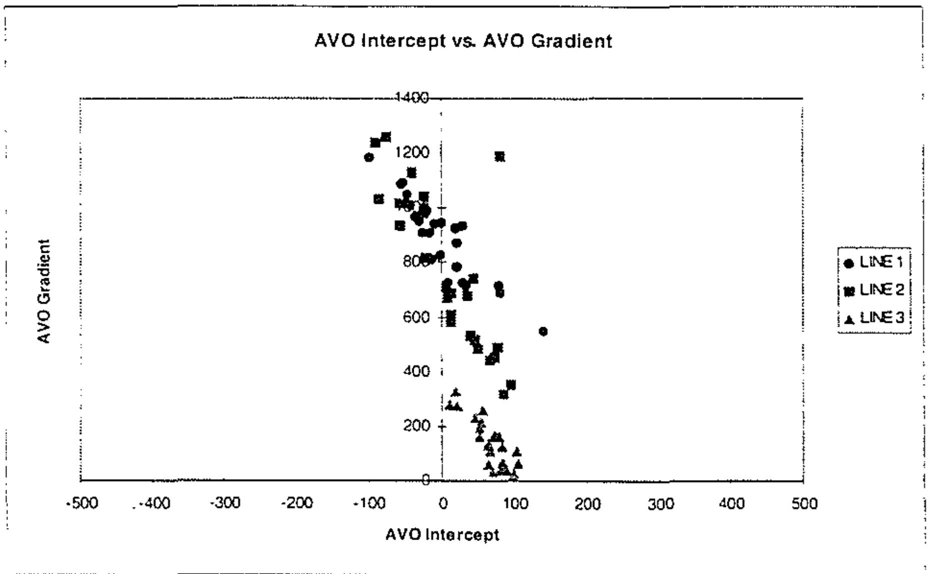

Figure 7: AVO intercept vs. AVO gradient for lines 1, 2 and 3.

a)

b)

c)

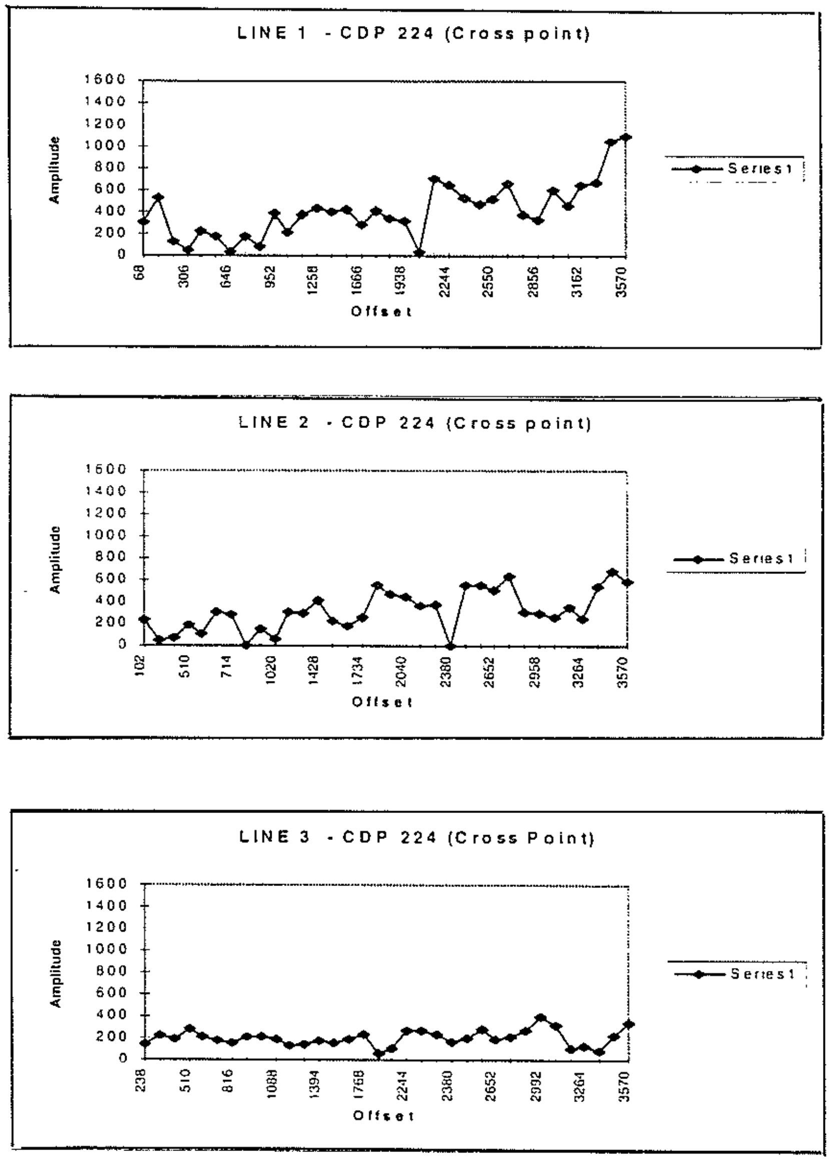

Figure 8: Amplitudes vs. offset for the CDP at the cross point. (a) Line 1, perpendicular to fracture orientation. (b) Line 2, perpendicular to fracture orientation. (c) Line 3, parallel to fracture orientation.

Layer 1 : Fractured layer
$Vp = 4.99$ Km/s
$Vs = 2.78$ Km/s
$\rho = 2.5$ g/cm^3
Layer 2: Isotropic layer
$Vp = 4.75$ Km/s
$Vs = 3.345$ Km/s
$\rho = 2.2$ g/cm^3

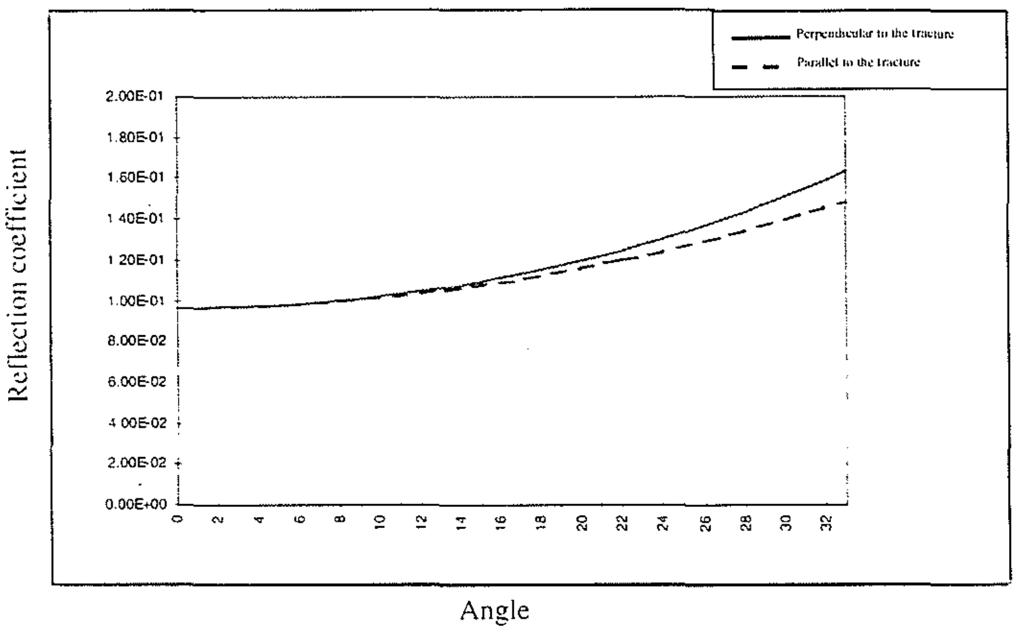

Figure 9: Reflection coefficients vs. angle at the bottom of the reservoir (Model 1).

Layer 1 : Fractured layer
Vp = 4.99 Km/s
Vs = 2.78 Km/s
ρ = 2.5 g/cm^3
Layer 2: Isotropic layer
Vp = 4.75 Km/s
Vs = 2.845 Km/s
ρ = 2.2 g/cm^3

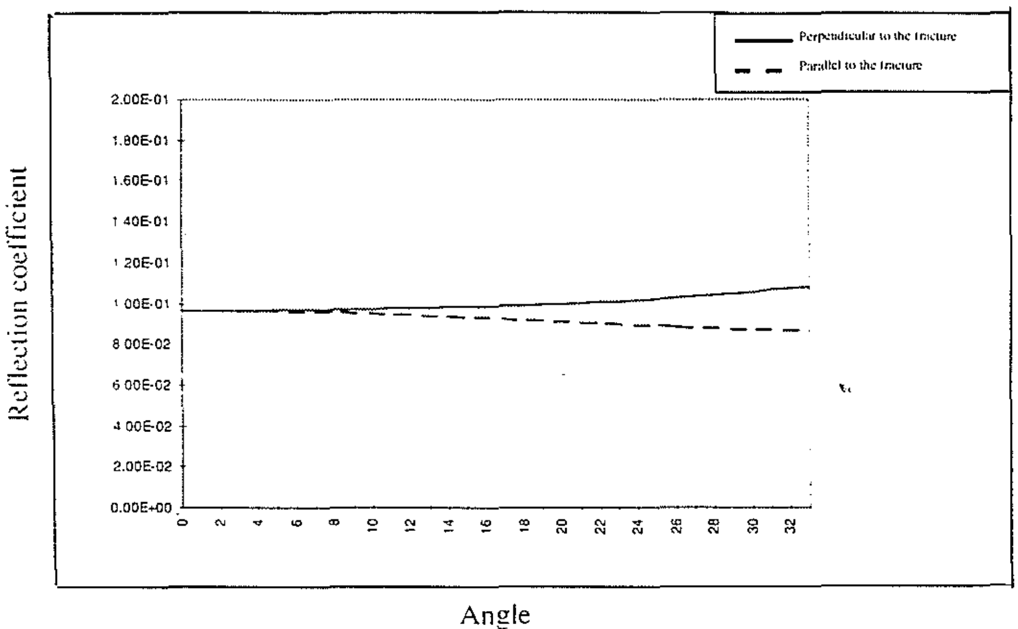

Figure 10: Reflection coefficients vs. angle at the bottom of the reservoir (Model 2).

Layer 1 : Fractured layer
Vp = 4.99 Km/s
Vs = 2.78 Km/s
ρ = 2.5 g/cm^3
Layer 2: Isotropic layer
Vp = 4.75 Km/s
Vs = 2.345 Km/s
ρ = 2.2 g/cm^3

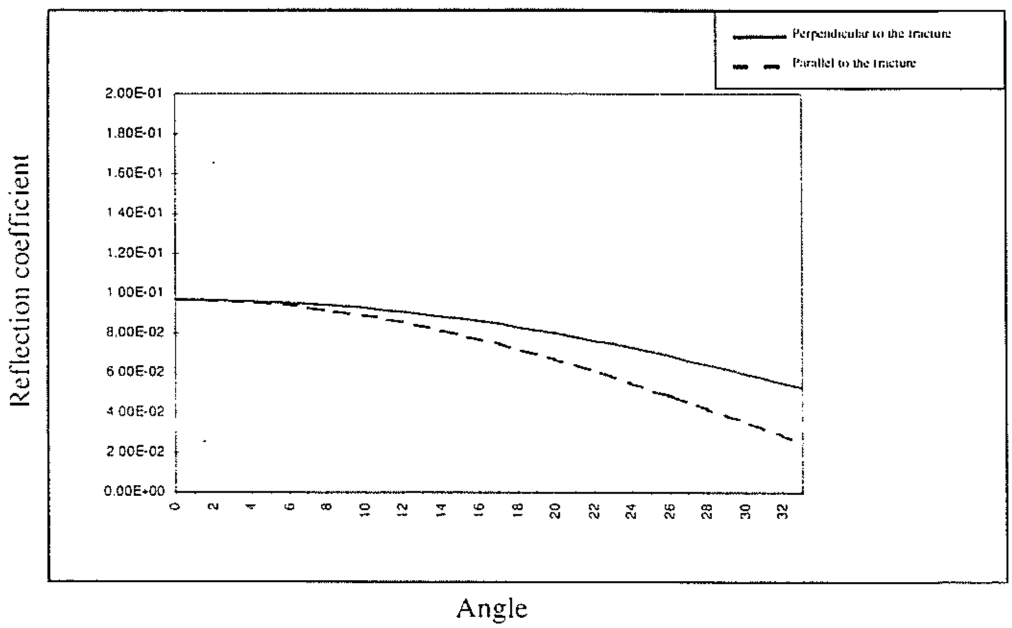

Figure 11: Reflection coefficients vs. angle at the bottom of the reservoir (Model 3).

Layer 1 : Isotropic layer

$Vp = 3.345$ Km/s

$Vs = 1.580$ Km/s

$\rho = 2.4$ g/cm^3

Layer 2: Fractured layer

$Vp = 4.99$ Km/s

$Vs = 2.78$ Km/s

$\rho = 2.5$ g/cm^3

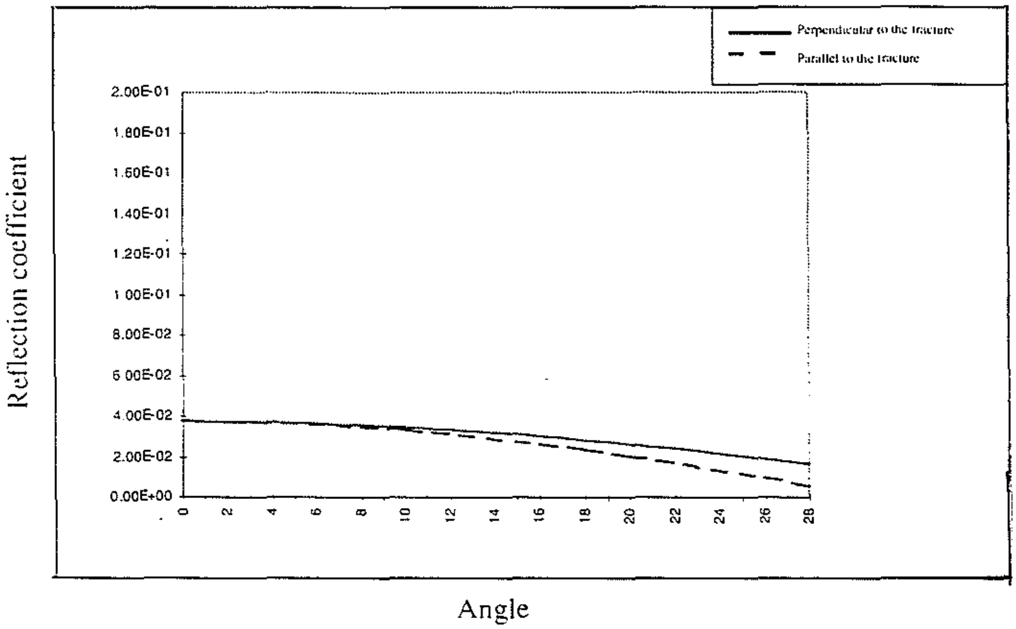

Figure 12: Reflection coefficients vs. angle at the top of the reservoir (Model 4).