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Anisotropy Parameter Estimation Using Semblance Based Rational Interpolation Technique

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Abstract: The presence of anisotropy influences many aspects of seismic wave propagation and therefore has profound implications for conventional data processing schemes in exploration seismics. Here, we have studied the lateral variation of the anellipticity parameter (η), the horizontal velocity (v_{hor}) and normal moveout velocity (v_{nmo}) using 2D surface seismic data acquired in the Gulf of Mexico. Data processing included application of a bandpass filter to remove frequencies outside of the useful signal bandwidth; formation of supergathers by vertically stacking nine consecutive common midpoint (CMP) gathers to enhance signal-to-noise ratio and frequency-wavenumber (F-K) filtering to suppress coherent noise. Frequency-offset (F-X) deconvolution and coherency filtering to further suppress residual random noise and enhance signal continuity. Moveout curves for three reflection events of interest were obtained by application of a rational interpolation procedure to tau-p derived travel times and offsets. Semblance analysis carried out on each of the moveout curves yielded η, v_{hor} and v_{nmo}. The results show that the effective and interval values of η varies mainly between 0.03-0.16±0.01 and 0.03-0.2±0.03, respectively. Effective values of v_{nmo} and v_{hor} vary between 1850-2250±111 and 1975-2475±122 m sec^{-1}, respectively. Interval values of v_{nmo} and v_{hor} vary between 1750-2650±120 and 2100-3100±122 m sec^{-1}, respectively. The results suggests that in ensembles 1-4 and 7-9, layer 2 is a shaly formation while layers 1 and 3 are sandy formations characterised by considerably reduced anellipticity.

Key words: Anisotropy, normal moveout, filtering, semblance, Gulf of Mexico

INTRODUCTION

Sedimentary rocks especially shales show anisotropy if seismic waves pass through them at different directions. The presence of anisotropy has considerable influence on many aspects of seismic wave propagation and therefore has profound implications for both conventional processing schemes and interpretation. When the subsurface is anisotropic, the moveout of P-waves in horizontally layered media as observed in common midpoint gathers, deviates from being hyperbolic at far offsets. Thus the nonhyperbolic component of the moveout is routinely used for estimating relevant seismic parameters describing such anisotropy (Grechka and Tsvankin, 1998). For P-waves in Vertical Transverse Isotropic (VTI) media, these parameters are the anellipticity parameter (η) and the normal moveout velocity (V_{nmo}). Quantitative measurement of seismic anisotropy provides a valuable clue to lithology and degree of stratification, a tool for imaging and can as well provide important quantitative information about depth discrepancies observed from depths determined from seismic and well log data (Van der Baan and Kendall, 2002).

Anisotropic properties are estimated using a variety of ways. Laboratory tests are the main techniques used in measuring anisotropic properties. Vertical Seismic Profiling (VSP) and surface seismic data are the *in situ* techniques used to determine anisotropic parameters (Li, 2006). Using surface seismic data, the most popular approach is using modified Taylor series expressions (Alkhalifah, 1997) or tau-p (τ-ρ) based methods (Van der Baan and Kendall, 2002). Recently, Douma and Calvert (2006) used a semblance based rational interpolation method to analyse non-hyperbolic moveout in the time-offset (t-x) domain to estimate anisotropy parameters and moveout velocity. These workers pointed out that the picking of traveltimes in the t-x domain which is often laborious and prone to error in the τ-ρ technique of Van der Baan and Kendall (2002) is a practical disadvantage. To overcome this caveat, Douma and Van der Baan (2006) combined the τ-ρ technique of

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Van der Baan and Kendall (2002) and the rational interpolation method of Douma and Calvert (2006) to estimate anisotropy parameters.

In this study, we use the approach of Douma and Van der Baan (2006) to determine the lateral variations of both effective and interval values of the anellipticity parameter (η), the NMO (v_{nmo}) and horizontal (v_{hor}) velocities at selected CDP locations in a marine 2D seismic dataset acquired in the Gulf of Mexico.

THEORETICAL BACKGROUND

The τ-p transform relates traveltime t and offset x to intercept time τ and horizontal slowness p by:

$$t = p_x x + \tau \quad (1)$$

Hake (1986) observed that the total intercept time τ for p-wave reflections in horizontally layered transverse isotropy with vertical axis of symmetry (VTI) media is a summation of the products of layer interval zero-offset time ($\Delta t_{0,i}$), the vertical P-wave velocity ($v_{0,i}$) and the vertical slowness (q_i) expressed as:

$$\tau = \sum_i \Delta t_{0,i}\, v_{0,i}\, q_i \quad (2)$$

Alkhalifah (1998) expressed the vertical slowness q_i in terms of v_{nmo} and the anellipticity parameter η by assuming that the interval shear-wave phase velocity V_{so} has negligible influence on the traveltimes of P-waves in VTI media. Alkhalifah's equation is expressed as:

$$V_{p0}^2 q^2 = 1 - \frac{1 - p^2 V_{nmo}^2}{1 - 2\eta p^2 V_{nmo}^2} \quad (3)$$

Where:
p = The horizontal component of the slowness vector

Grechka and Tsvankin (1998) however demonstrated that the horizontal velocity expressed as $V_{hor} = V_{nmo}\,[1+2\eta]^{1/2}$ is better suited for semblance-based moveout analysis than η as used in Alkhalifah's equation. Thus, expressing Eq. 3 in terms of V_{hor} and V_{nmo} and substituting into 2, gives:

$$\tau = \sum_i \Delta t_{0,i} \left[\frac{1 - p^2 (V_{hor,i})^2}{1 - p^2 \left\{ (V_{hor,i})^2 - (V_{nmo,i})^2 \right\}} \right]^{1/2} \quad (4)$$

Where:
$V_{hor,i}$ = Horizontal velocity in layer i
V_{nmo} = NMO velocity in layer i

For semblance analysis to be carried out in the t-x domain requires the traveltime for each recorded offset. From Eq. 1,

$$x = -\frac{\partial \tau}{\partial p} \quad (5)$$

Substituting Eq. 4 into 5 and simplifying, gives:

$$x = \sum_i \Delta t_{0,i} \left[\frac{p (V_{nmo,i})^2 / \left\{ 1 - p^2 (V_{hor,i})^2 \right\}^{1/2}}{\left\{ 1 - p^2 \left[(V_{hor,i})^2 - (V_{nmo,i})^2 \right] \right\}^{3/2}} \right] \quad (6)$$

The traveltime associated with this offset was obtained by combining Eq. 1, 2 and 6 giving:

$$t = \sum_i \Delta t_{0,i} \left(\frac{p^2 (V_{nmo,i})^2 / \left\{ 1 - p^2 \left[(V_{hor,i})^2 - (V_{nmo,i})^2 \right] \right\} + \left[1 - p^2 (V_{hor,i})^2 \right]}{\left(\left[1 - p^2 (V_{hor,i})^2 \right] \left\{ 1 - p^2 \left[(V_{hor,i})^2 - (V_{nmo,i})^2 \right] \right\} \right)^{1/2}} \right) \quad (7)$$

NONHYPERBOLIC MOVEOUT ANALYSIS USING RATIONAL INTERPOLATION

A rational approximation to a function T(x) is generally written as Stoer and Bulirsch (1993)

$$T(x) \approx \frac{N_L(x)}{D_M(x)} \quad (8)$$

where, $N_L(x)$ and $D_M(x)$ are polynomials of degree L and M. Such a rational approximation can be written as [L/M]. For a polynomial of degree 2, L = M = 2. Thus, Eq. 8 can be rewritten as:

$$T(x) \approx \frac{N_2(x)}{D_2(x)} \quad (9)$$

For a [2/2] rational interpolation for a single horizontal VTI layer, Douma and Calvert (2006) derived the squared traveltimes T as a function of squared offset X as:

$$T(X) \approx \frac{T_0 + n_1 X + n_2 X^2}{1 + d_1 X + d_2 X^2} \quad (10)$$

where, $T_0 = t_0^2$ is the squared zero-offset two-way traveltime and n_1, n_1, d_1 and d_2 are the coefficients of the numerator and denominator of the rational approximant. To determine the unknowns, four traveltimes (t_i) and four associated offsets (x_i) are required. The traveltimes (t_i) and the associated offset (x_i) are determined using Eq. 7 and 11, respectively.

$$x_i = \frac{V_{NMO} t_0 k_i}{2} \qquad (11)$$

Where:
k_i = The offset-to-depth ratios.

The interpolation traveltimes (t_i) and (x_i) are used in determining the coefficients of Eq. 10. When once the coefficients of Eq. 10 are known, the traveltimes (t) for offset (x) can be evaluated. Douma and Van der Baan (2006) extended this approach to horizontally layered VTI media.

DATA PROCESSING

The data used in this study is a 2D marine seismic P-wave data set acquired in the Gulf of Mexico. The data was processed by applying a bandpass filter of frequency range 1-5-35-70 Hz to remove frequencies outside of the useful signal bandwidth. Common Midpoint gathers were then collected into groups of nine and stacked (vertically) to form supergathers. Frequency-wavenumber (F-K) filtering was then applied to each supergather to suppress coherent noise and semblance analysis performed in order to obtain stacking velocities for use in normal moveout (NMO) correction. Common noise observed after F-K filtering is random noise. To reduce the random noise further, frequency-offset (F-X) deconvolution (Canales, 1984) was applied. Finally, a coherency filter was applied to improve signal character and continuity within the frequency range of the data.

ANISOTROPY PARAMETER ESTIMATION

Ten supergathers (38559-38640) between CDPs 37999 and 38941 were chosen for parameter estimation. These ten supergathers hereinafter are referred to as ensembles 1-10. This zone was chosen because the stack section shows horizons that are relatively flat. Thus, it was assumed that the presence of any nonhyperbolic moveout will be due to anisotropy. In each supergather, three events were chosen for analysis, these events occur at 1.14, 1.44 and 2.4 sec (Fig. 1). The algorithm SUVEL2DF used in this study determines values of the effective and interval anellipticity parameter (η), horizontal velocity (v_{hmax}) and NMO velocity (v_{max}) through semblance analysis. Semblance analysis using SUVEL2DF requires the computation of the traveltimes for each offset acquired in the field for a specific combination of zero-offset time (t_0), NMO (v_{nmo}) and horizontal (v_{hor}) velocities.

The most important input parameters are the zero-offset time (t_0) of the layer of interest determined from the supergather gather and user specified effective NMO (v_{nmo}), horizontal (v_{hor}) velocities and four offset-to-depth ratios ranging from 1-4. For each particular v_{hor} and v_{nmo}

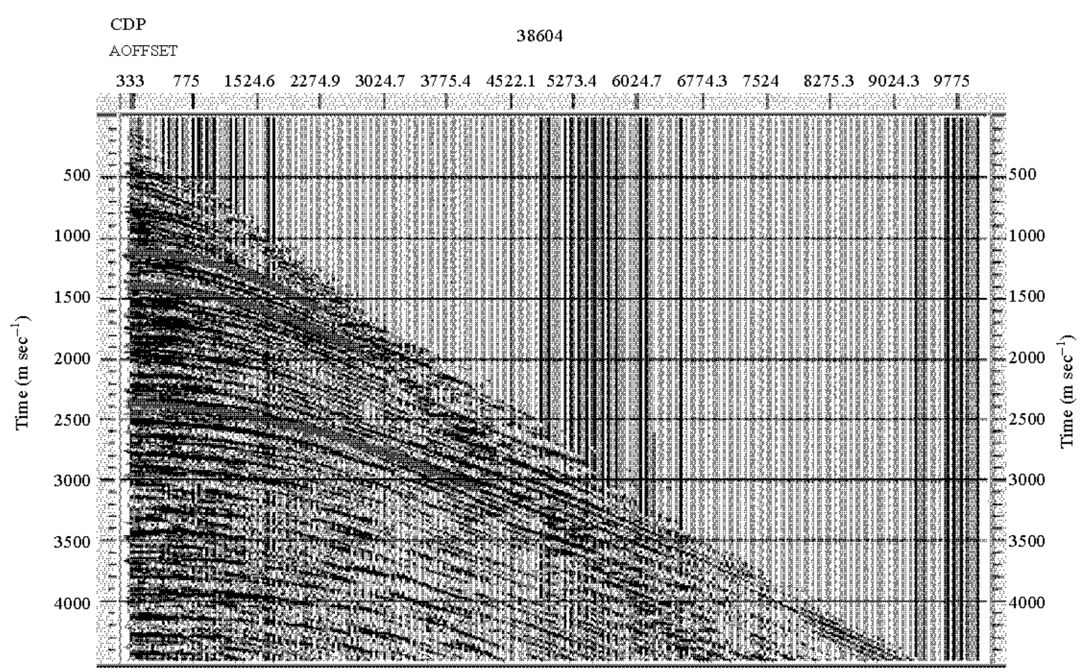

Fig. 1: Ensemble 38604 showing reflection events chosen for parameter estimation in each supergather

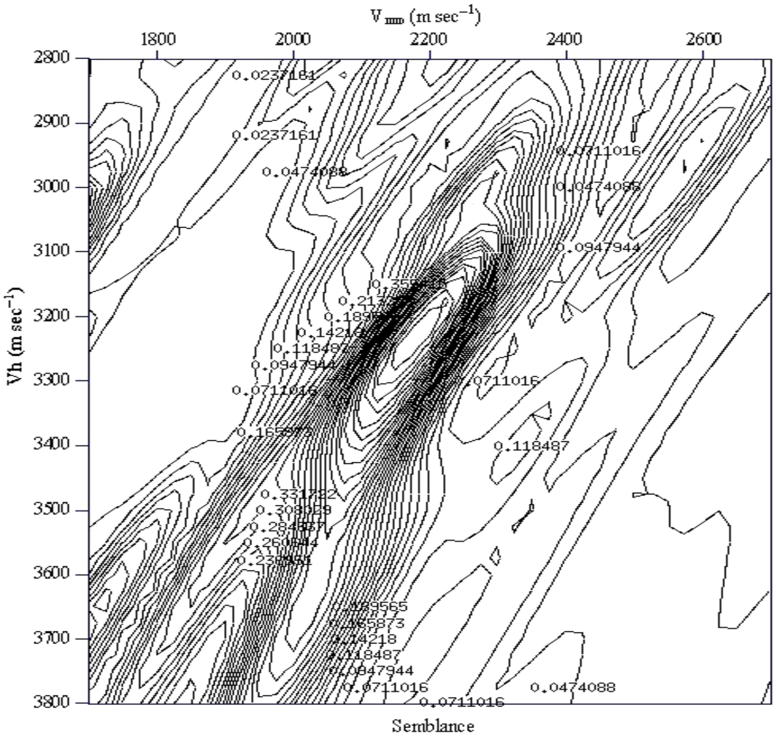

Fig. 2: Semblance scan for layer 1 (ensemble 6) showing optimal semblance response

input into the algorithm, the four offset-to-depth ratios are converted to target offsets (x_j) using Eq. 11. The algorithm also computes the appropriate horizontal slowness (p_j) to target offsets (x_j) using Eq. 6 and subsequently determine the corresponding traveltimes (t_j) by the use of Eq. 7. The four values of the target offsets (x_j) and traveltimes (t_j) constitute the support points for the [2/2] rational interpolation. The algorithm then determines the desired traveltimes t(x) at any offset x using the rational approximant (Eq. 10). The resulting t-x curves are then used for the semblance analysis.

We determined both effective and interval values of η, ν_{hor} and ν_{nmo}. In determining effective values, we treated the overburden of the reflection event of interest as a single horizontal homogeneous VTI layer. As result, the effective values are average values. Interval values were obtained using a layer-stripping approach. The accuracy of the inversion was confirmed by the high semblance maxima (S_{max}= 0.8-1.0) which coincided with the semblance contours nicely centred in the respective semblance scans (Fig. 2).

RESULTS AND DISCUSSION

Effective values of ν_{nmo} and ν_{hor} range between 1850-2250±111 and 1975-2475±122 m sec^{-1} while interval values of ν_{nmo} and ν_{hor} range between 1750-2650±120 and 2100-3100±126 m sec^{-1}, respectively. Values of the anellipticity parameter (η) as a function of ensemble number are shown in Fig. 3 and 4, respectively. The effective values are mainly between 0.03-0.16 ±0.01 in all the three layers investigated. Interval values range mainly between 0.03-0.2±0.03. Variation in anellipticity is observed in both effective and interval values suggesting lateral variation in anisotropy along the seismic line presumably due to varying shale content since the presence of shale is widely accepted as the cause of anisotropy (Wang, 2002; Li, 2006). The recovered values of ν_{hor} and ν_{nmo} exhibit a similar behaviour. In layer 2 in Fig. 3 (ensemble 1) and layer 2 in Fig. 4 (ensembles 4 and 8), we observe an abrupt increase in anellipticity values where the anellipticity is as high as 0.3 and 0.4, respectively. These values of η are high compared to values typically reported from nonhyperbolic moveout analysis (Toldi *et al*., 1999).

Without detailed geologic information, we can only speculate as to the cause of these localised extreme values. The relatively high η values might reflect some internal property of the medium, presumably increased shale content or that these are inaccurate values due to the inability to obtain optimal semblance response occasioned by the use of inaccurate input model parameters. If the first assumption was correct, the nonhyperbolic moveout in the input CDP gathers in these

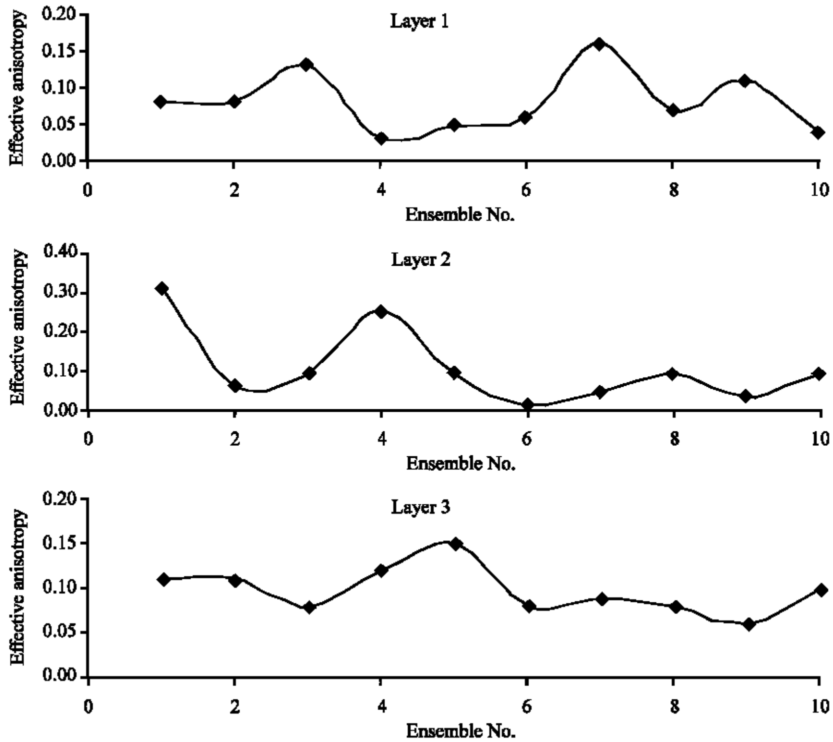

Fig. 3: Effective anellipticity parameter (η) against ensemble number for all three layers showing lateral the lateral variation of anisotropy at ensemble locations

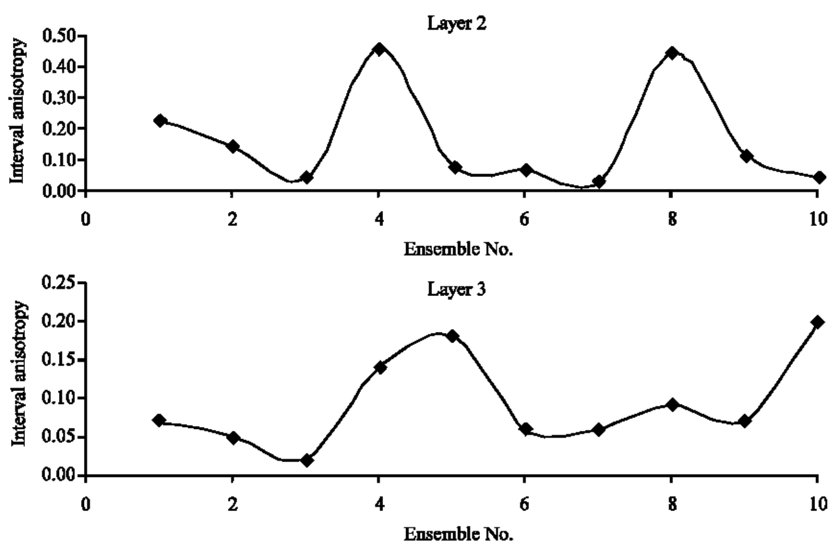

Fig. 4: Interval anellipticity parameter (η) against ensemble number. Layer 1 is not shown because in layer 1, effective and interval values are the same

events should have been substantial. We observe that the nonhyperbolic moveout in these events was rather small and therefore might not be able to cause such a high level of anellipticity, since the strength of the anisotropy determines the amount of non-hyperbolic moveout (Wookey *et al*., 2002). On the other hand, a careful look at the semblance scans of these events show more than one semblance contour making it difficult to obtain optimum semblance response. Since correct anellipticity values are only obtained at optimum semblance response, we are convinced that the anellipticity values of 0.3 observed in ensemble 1, layer 2 (Fig. 3) and ~0.4 in ensembles 4 and 8, layer 2 (Fig. 4) are not correct and do not represent the actual subsurface anellipticity level at these ensemble locations. The presence of more than one semblance contour might be due to the presence of multiples.

CONCLUSION

Results from this study show that the three layers investigated have considerable variations in lithology. The effective and interval values of the anellipticity parameter vary mainly between 0.03-0.2±0.01. Effective and interval values of ν_{nmo} and ν_{hor} range between 1975-2825±111 and 1750-2650±126 m sec^{-1}, respectively. We attribute the variation in anisotropy to varying shale content. These results can be employed as new constraints in processing algorithms that include anisotropy so as to improve the imaging of dipping reflectors, such as fault planes in the study area.

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