

## **Estimation of Thomsen's anisotropy parameter, delta, using CSP gathers.**

Pavan Elapavuluri and John C. Bancroft

### **ABSTRACT**

In order to extend the seismic processing techniques to anisotropic media, a measure of the different parameters of anisotropy is required. The purpose of this study is to estimate the Thomsen's parameter,  $\delta$  (delta), for transversely isotropic (TI) media. Thomsen's anisotropic normal moveout equation (NMO) is used to determine  $\delta$  (delta). It is also shown that  $\delta$  estimated using common Scatter Point (CSP) gathers is more accurate than those estimated from common mid point (CMP) gathers.

### **INTRODUCTION**

Earth is fundamentally anisotropic but most of the processing algorithms assume the ideal condition of isotropy, this faulty assumption leads to erroneous imaging and thus faulty interpretations. Backus (1962) stated that if the layered earth is probed with an elastic wave of wavelength much longer than the typical layer thickness the wave propagates through this medium as it were in a homogenous and anisotropic medium. Alkalifah and Tsvankin (1994) used an inversion scheme over the non-hyperbolic equation to estimate Thomsen's anisotropic parameters.

Haase(1998) showed that the non hyperbolic moveout observed with the flat reflectors in the plains data is due to the transverse isotropy(even though the individual layers are isotropic). He also estimated Thomsen's anisotropy parameters in the plains data. In this study we estimate Thomsen's parameter  $\delta$  using the Thomsen's anisotropic NMO equation, with the assumption of weak anisotropy. The main idea is to use velocities estimated from the common scatter point (CSP) gather and the velocities from the sonic log run in a well, nearest to the seismic line to estimate the value of  $\delta$ .

### **THEORY**

The most common measure of P wave anisotropy is the ratio between the horizontal and vertical P wave velocities, typically between 1.05 to 1.1 and is often as large as 1.2 (Sheriff 1991).

Thomsen (1986) introduced a more effective and a scientific measure of anisotropy. He introduced the constants  $\epsilon$ ,  $\gamma$ , and  $\delta$  as effective parameters of measure of anisotropy. According to Thomsen,  $\delta$  is the most critical measure of anisotropy and it doesn't involve the horizontal velocity at all in its definition. Therefore measuring  $\delta$  is very important for processes like depth imaging. According to Toldi et.al (1999) "The depth effects are carried by the parameter  $\delta$  which must therefore be measured with help of well control."

Using weak anisotropy approximation and Thomsen's parameters, the phase velocity,  $V$  can be written as equation 1. It is a function of phase angle  $\theta$ .

$$V(\theta) = V_0 (1 + \delta \sin^2 \theta \cos^2 \theta + \varepsilon \sin^4 \theta) \quad (1)$$

(Thomsen, 1986).

Under the short spread assumption (the half offset is smaller than the depth of the reflector, typically the moveout is hyperbolic in hyperbolic even in anisotropic media at shorter offsets), the NMO velocity is controlled by only the Thomsen's parameter  $\delta$ . (Thomsen, 1986).

This is shown in equation 2 (Thomsen, 1986)

$$V_{nmo}(p) = V_0(p) \sqrt{1 + 2\delta} \quad (2)$$

### **Common Shot Point (CSP) gathers**

A common scatter point gather is a pre-stack migration gather that collects all the input traces that contain energy from a vertical array of scatter points.

The distance from the surface location of the scatter point to the source and receiver defines the offsets in a CSP gather, but not the source receiver offset. The CSP gather is similar in appearance to a common mid point (CMP) gather. They both define a subsurface location, and are sorted by offsets. Hence all the traces in the prestack migration aperture, regardless of the source or receiver position, may be used to form a CSP gather.

The offsets in a CSP gather are defined as given by equation 3 (Bancroft, et.al, 1998)

$$h_e = x^2 + h^2 - \frac{4x^2h^2}{t^2v_{rms}^2} \quad (3)$$

Where  $x$  is distance between CMP and the CSP gathers location and  $h$  is half the source receiver offset,  $v_{rms}$  is the RMS velocity.

### *Advantages of CSP gather*

A CSP gather is characterized by its very high fold, increasing the SNR, which makes velocity picking more accurate. Generally CSP gathers have larger offsets when compared to CMP gathers.

The semblance plot of the CSP gather shows tighter clustering of energy, which enables (and requires) more accurate picking of velocities. It has been shown by Bancroft (1996) that NMO velocities estimated using a CSP gather are more accurate than velocities estimated over a CMP gather.

## METHOD

### Calculation of $V_{nmo}^i$

$V_{nmo}^i$  is the interval NMO velocity estimated from the semblance analysis using the procedure described below.

The short spread normal moveout(NMO) of an N layered transverse isotropic (TI) medium as given by Alkhalifah and Tsvankin in 1995 can be written as equation (4)

$$V_{nmo}^2(p) = \frac{1}{\tau} \sum_{i=1}^N [V_{nmo}^i(p)]^2 t_0^i \quad (4)$$

where  $\tau$  is the 2-way zero-offset travelttime to the bottom of the  $N^{\text{th}}$  layer,  $t_0$  is the 2 way zero offset travelttime for an individual layer and "...  $V_{nmo}(p)$  is the root-mean-square velocity of the NMO velocity in each layer taken at the ray parameter ' $p$ '" (Alkhalifah and Tsvankin, 1995).

In the case of a flat layered earth the equation (4) reduces to the Dix equation. "In order to obtain the NMO velocity in any layer ' $i$ ' (including the one immediately above the reflector), we need to apply the Dix formula (Dix, 1955) to the NMO velocities from the top  $V_{nmo}(i-1)$  and the bottom  $V_{nmo}(i)$  of the layer" (Alkhalifah and Tsvankin, 1995).

$$[V_{nmo}^i] = \frac{t_0(i)V_{nmo}^2(i) - t_0(i-1)V_{nmo}^2(i-1)}{t_0(i) - t_0(i-1)} \quad (5)$$

$t_0$  is the 2 way zero offset travelttime for an individual layer.

$V_{nmo}(i)$  is estimated from the velocity analysis over the CSP/CDP gathers formed at the CDP point, which is closest to the well location.

### Calculation of $V_0^i$

$V_0^i$  is the interval vertical velocity. This can be estimated from well logs or VSP measurements. In this study Velocities were estimated from the sonic log recorded at the well located nearest to the seismic line.

### Calculation of $\delta^i$

Using both of the velocities  $V_{nmo}^i$  and  $V_0^i$  the value of  $\delta^i$  can be estimated at each time step using equation (2), which can be written as equation (6).

$$\delta^i = \frac{1}{2} \left( \frac{(V_{nmo}^i)^2}{(V_0^i)^2} - 1 \right) \quad (6)$$

where  $V_{nmo}^i$  is the 'interval nmo' velocity and  $V_0^i$  is the vertical velocity.

### CASE STUDY

This technique will now be tested over a synthetic anisotropic data generated using NORSAR2D software. Norsar 2D is ray tracing program based on the ray theory by (Cerveny, 1985).

A layered geologic model (figure 1) was built with 9 flat layers in it. The model is built in the depth domain and is 6kms deep. The thinnest layer is of thickness 0.5 km and its velocity is 1000m/s. A 40hz zero-phase Ricker wavelet was used for the generation of seismograms without violating the raytracing assumptions. There are 101 shots in total and 300 receivers per shot. The shot spacing was 40m and receiver spacing was 20m.

Figure 1 shows the layered model with table (1) showing the values of the material properties viz.

- P-wave velocity
- S-wave velocity
- Density
- $\epsilon$  and
- $\delta$

Interface	P-velocity	S velocity	Density	$\epsilon$	$\delta$
1	1000	500	1.1	0	0.2
2	1200	600	1.2	0.05	0.25
3	1500	750	1.3	0.1	0.3
4	2000	1000	1.5	0.15	0.1
5	2500	1250	1.7	0.2	0.15
6	3000	1500	1.9	0.25	0.2
7	4000	2000	2.2	0.3	0.25
8	5000	2500	2.4	0.2	0.3

Table 1. Material properties of the model used.

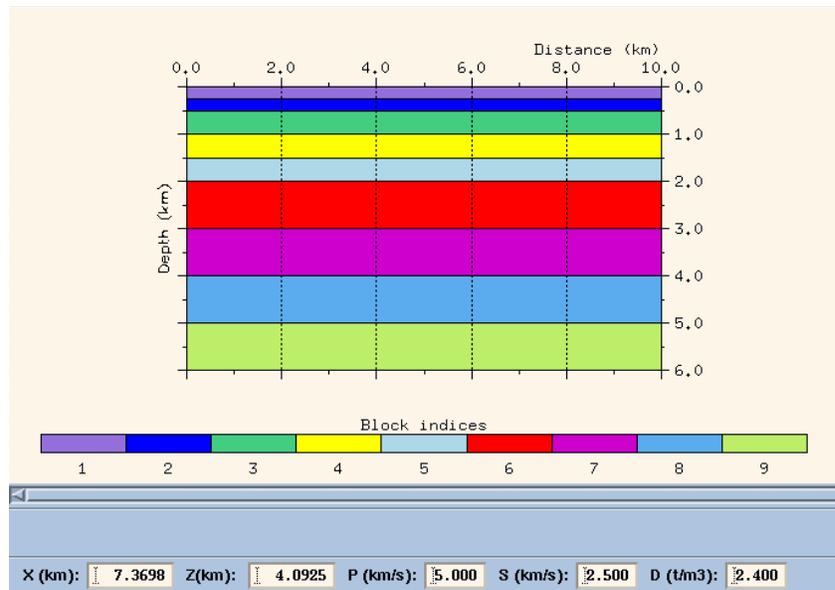


FIG. 1. The Geological model.

This model data was used to test the above method. The algorithm can be described as follows:

- Perform semblance analysis on the gathers to yield  $V_{nmo}$ .
- Use equation (5) to estimate the ‘interval NMO velocities’
- Determine the value of  $V_0$ , the vertical velocity, from the VSP data/sonic logs.
- Use equation (6) to calculate  $\delta$ .

Semblance analysis was performed on both common mid point (CMP) and common scatter point (CSP) gathers (Figures 2 & 3). The values of  $\delta$  were calculated using the NMO velocities from both the CMP and CSP gathers. Tables (2 and 3) show the values of  $\delta$  calculated using CMP and CSP gathers respectively.

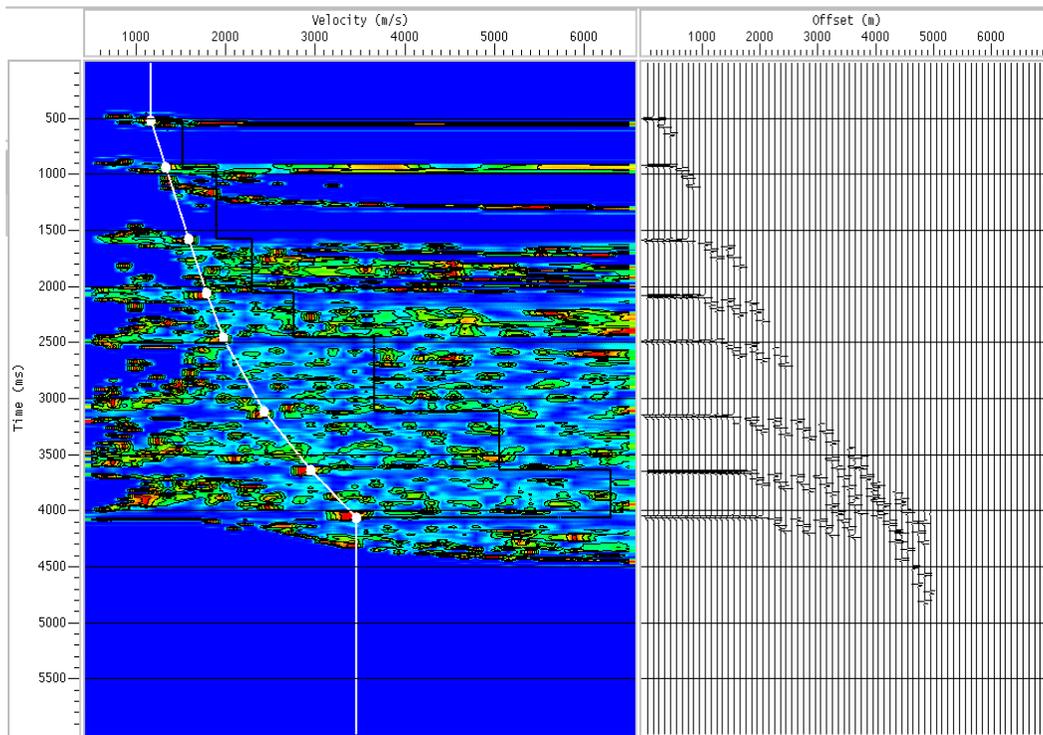


FIG. 2. The semblance plot over a CDP gather.

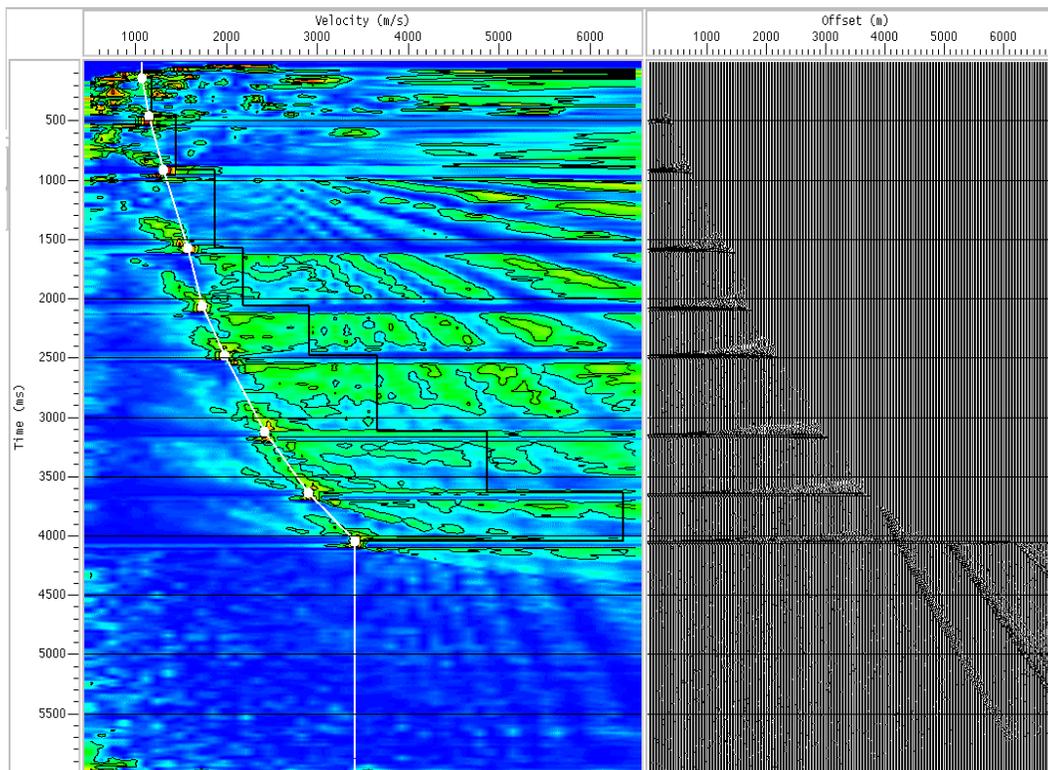


FIG. 3. The semblance plot over a CSP gather.

$V_{nmo}$ (CMP)	$V_{0,i}$	$\delta$	$\delta$
		(model)	(estimated)
1237	1000	0.20	0.26
1336	1200	0.25	0.11
1828	1500	0.30	0.24
2290	2000	0.10	0.15
2908	2500	0.15	0.17
3655	3000	0.20	0.24
5059	4000	0.25	0.29
6259	5000	0.30	0.28

Table 2.  $\delta$ 's calculated using CMP gathers.

$V_{nmo}$ (CSP)	$V_{0,i}$	$\delta$	$\delta$
		(model)	(estimated)
1176	1000	0.20	0.19
1445	1200	0.25	0.22
1876	1500	0.30	0.28
2187	2000	0.10	0.09
2907	2500	0.15	0.17
3556	3000	0.20	0.20
4873	4000	0.25	0.24
6366	5000	0.30	0.31

Table 3.  $\delta$ 's calculated using CSP gathers.

It is evident from the tables (2 and 3) that the values of  $\delta$  estimated using CSP gathers are much more accurate than those calculated using CMP gathers.

## Error analysis

The values of  $\delta$  estimated are heavily dependent on the velocities estimated from the semblance analysis. We did a simple error analysis by introducing an error into the NMO velocities estimated from the CSP gather. The results are shown in the Figure 4. For a 0-10% error in velocities we encountered around 10-150% error in the values of  $\delta$  estimated. As the velocities estimated from a CSP gather are more accurate,  $\delta$ 's can be estimated with better confidence using the CSP velocities.

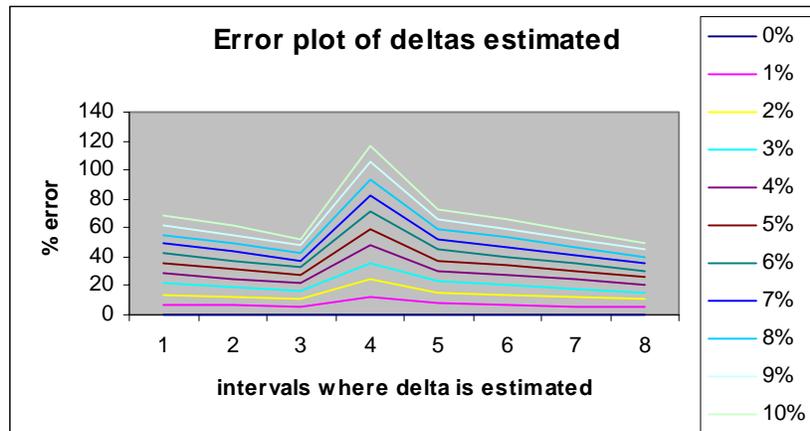


FIG. 4. The error plot.

## Field data

This method was applied over the seismic data collected over the Blackfoot field. Blackfoot field is near Strathmore, Alberta and is operated by PanCanadian petroleum. A 3C 3D data was acquired by CREWES in 1997.

The Blackfoot Field is located in Township 23, Range 23, West of 4<sup>th</sup> meridian, in south central Alberta.

## Geology

The geology of Blackfoot field has been discussed in detail by Miller et. al (1995). This is a very brief review of the lithology of the formations of interest to this work. The reservoir rocks in this field are Glauconitic incised valleys in Lower Manville group of lower Cretaceous. Coals, Viking formation and Base of fish scales shales overlie these reservoir rocks.

A line numbered '20M vertical' that has a well (#09-08) located very near to it was chosen to test this method. The figure 5 shows the position of the well on the CDP plot. Figure 6 shows the position of the well on the stacked section. CMP and CSP gathers are the formed at CDP 149, which is nearest to the well location. Semblance analysis was performed on both CSP and CDP gathers formed at this location. The velocities estimated were used in the algorithm discussed above to estimate the values of  $\delta$ .

The position of the well



FIG. 5 Position of the well 09-08 on the CDP plot.

The position of the well

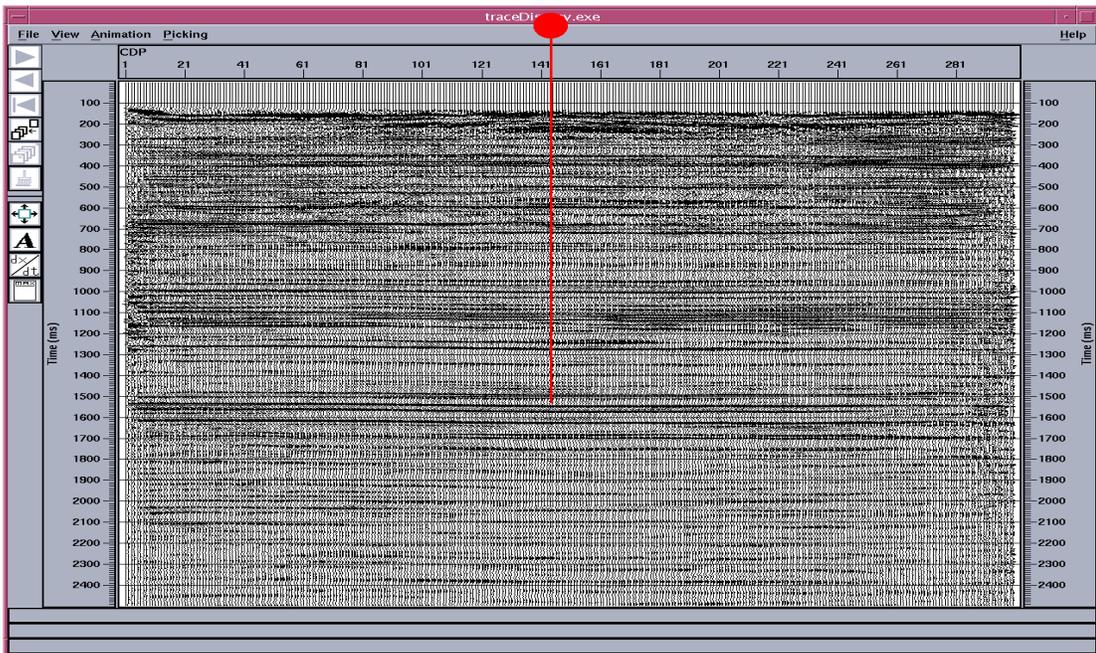


FIG. 6 Position of the well 09-08 on the stacked section.

The following figures (7 and 8) show the semblances plots of CDP and CSP gathers at CDP 149 respectively.

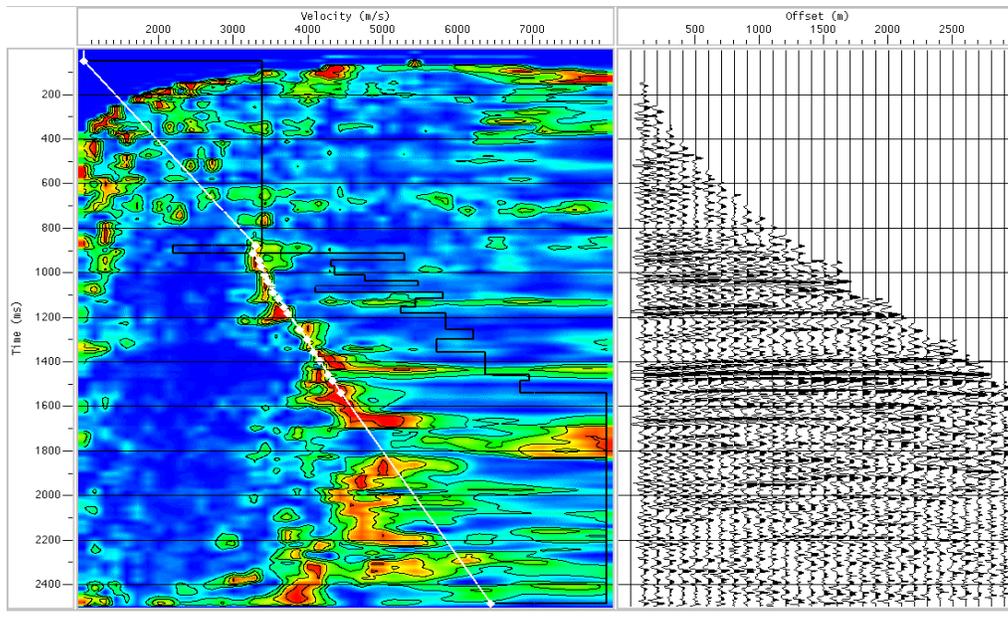


FIG. 7 Semblance plot over a CDP gather.

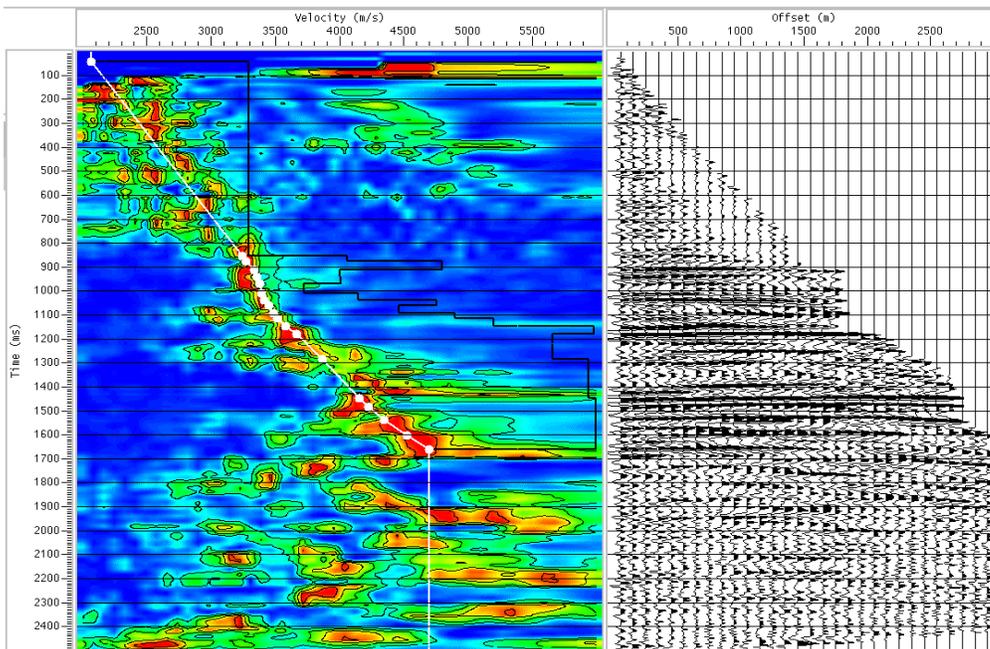


FIG. 8 Semblance plot over a CSP gather.

The velocities estimated from the semblance analysis over CMP and CSP gathers were used to estimate the values of  $\delta$  for the formations of interest. Table 4 shows the formation naming convention used here. Tables 5 and 6 show the values of  $\delta$  estimated from CMP and CSP gathers respectively.

Abbreviation	Unit Name
BFS	Base of Fish Scales Zone
MANN	Blairmore- Upper Mannville
COAL	Coal Layer
GLCTOP	Glaucconitic Channel porous Sandstone unit
MISS	Shunda Mississippian

Table 4. Formation naming conventions.

Formation	$V_{nmo}$ (CMP)	$V_{0,i}$	$\delta$
			(estimated)
BFS	4002	3300	0.23
MANN	4148	3990	0.04
COAL	4755	3900	0.24
GLCTOP	4460	3860	0.16
MISS	5998	6000	0.00

Table 5.  $\delta$ 's calculated using CMP gathers.

Formation	$V_{nmo}$ (CSP)	$V_{0,i}$	$\delta$
			(estimated)
BFS	3990	3300	0.23
MANN	3993	3990	0.00
COAL	4554	3900	0.18
GLCTOP	4200	3860	0.09
MISS	5930	6000	-0.01

Table 6.  $\delta$ 's calculated using CSP gathers.

## DISCUSSION AND CONCLUSIONS

Estimation of anisotropy parameters is an important aspect in seismic analysis. Thomsen's anisotropic parameter  $\delta$  has an effect on the depth calculations. The  $\delta$  estimation is highly dependent on the estimation NMO velocity. The error analysis of  $\delta$ 's estimated proves how important is estimation of accurate NMO velocities is. It has also been showed that  $\delta$  estimated using CSP gathers are more accurate than that of those estimated from CMP gathers.

Extending this analysis to the real field data, we found that the shales and coals show very significant anisotropy. The vertical velocities estimated from a sonic log were used in this study. The velocities from sonic log are greater than the seismic velocities. Vertical interval velocities estimated from VSP data would give more accurate estimates in this area.

## ACKNOWLEDGEMENTS

We acknowledge the CREWES sponsors for their continued support. We thank Ian Watson for helping with the interpretation of Blackfoot data.

## REFERENCES

- Alkhalifah, T. and Tsvankin, I., 1995, Velocity analysis for transversely isotropic media: Geophysics, Soc. Of Expl. Geophys., **60**, 1550-1566.
- Backus, G. E., 1962, Long-wave elastic anisotropy produced by horizontal layering: J.Geophys Res., **70**, 3429.
- Bancroft, J.C., 1996, Velocity sensitivity for equivalent offset prestack migration , Ann. Mtg: Can. Soc. Of Expl Geophys.
- Bancroft, J.C., Geiger, H.D. and Margrave, G.F., 1998, The equivalent offset method of prestack time migration: Geophysics, Soc. Of Expl. Geophys., **63**, 2041-2053.
- Cerveny, V., 1985. The application of numerical modelling of seismic wavefields in complex structure. *Seismic shear waves*, Part A: Theory (ed. G Dhor). Pp. 1-124. Geophysical press, London.
- Dix, C.H., 1955, Seismic velocities from surface measurements: Geophysics, Soc. Of Expl. Geophys., **20**, 68-86.
- Haase, Armin. B., 1998, Non hyperbolic moveout in plains data and the anisotropy question: Recorder, Can. Soc. of Expl Geophys. Nov, 1998, 21-33.
- Miller, S.L.M., Aydemir, E.O. and Margrave, G.F., 1995, Preliminary interpretation of P-P and P-S seismic data from Blackfoot broad-band survey: Crewes Research Report 1995, Ch 42.
- Sheriff, R. E., 1991, Encyclopedic Dictionary of Exploration Geophysics, Encyclopedic dictionary of exploration geophysics: Soc. of Expl. Geophys., 384.
- Thomsen, L., 1986, Weak elastic anisotropy: Geophysics, Soc. Of Expl. Geophys., **51**, 1954-1966.
- Toldi, J., Alkhalifah, T., Berthet, P., Arnaud, J., Williamson, P. and Conche, B., 1999, Case study of estimation of anisotropy: The Leading Edge, **18**, no. 5, 588-593.