Estimating TIV Anisotropy Parameters in the Jeanne d'Arc Basin at White Rose H-20 Well

Emery, David J., Brown, R. Jim, and Enachescu, Michael E.

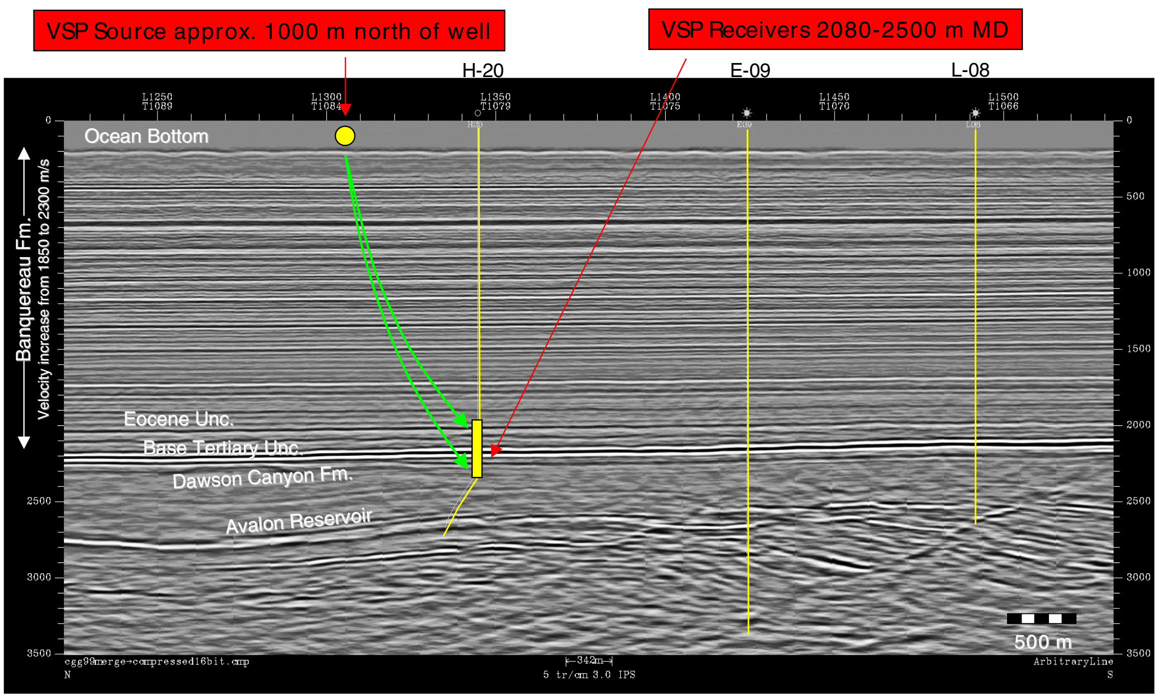
Summary

In the summer of 1999 three delineation wells (L-08, A-17 and N-30) were drilled in the White Rose field of the Jeanne d'Arc Basin. Interpretation of the VSP and log information indicates that the seismic velocities increase reasonably linearly with depth within the Tertiary section followed by an abrupt velocity increase in the penetrated Cretaceous. Evaluation of anisotropy parameters using check shots and stacking velocities indicates a ~6% difference between $v(0°)$ and $v(90°)$ (Hedlin, 1999).

During the summer of 2000, a single delineation well, H-20, was drilled into the northern part of the White Rose South Avalon Pool (figure 1). The H-20 well was targeted to penetrate the hydrocarbon bearing Avalon Formation through a small intra-reservoir fault with a throw of approximately 25 m. Due to the deviated nature of the H-20 well the VSP program was designed with a walkabove configuration. Rig time and equipment availability provided the opportunity to also acquire a single offset over a limited depth range.

This paper deals with the evaluation of this limited VSP information for anisotropy parameters. The H-20 direct-arrival for the offset VSP indicates that the Tertiary age Banquereau Formation of Tertiary age is weakly anisotropic ($\delta = 0.03$ $\varepsilon = 0.07$). Evaluation of the interval velocities derived from VSP shows a direct relationship between shale compaction and degree of anisotropy. The VSP interval velocity information also indicates that the Santonian age Dawson Canyon shales are highly anisotropic ($\delta = 0.40$ $\varepsilon = 0.80$).

Figure 1: White Rose H-20 Offset VSP located on a N-S 3-D seismic line



Theory

The evaluation of the White Rose H-20 VSP for rock anisotropy was performed using Thomsen's (1986) equations for weak elastic anisotropy. The velocity of P-waves in such media is defined as:

$$v(\theta) = v_0 (1 + \delta \sin^2\theta \cos^2\theta + \varepsilon \sin^4\theta) \qquad (1)$$

where $v(\theta)$, the P-wave velocity for a phase angle θ, is determined by the vertical velocity (v_0) and the two anisotropy parameters δ and ε (Thomsen, 1986, equation 16a).

A short-spread assumption is appropriate for both surface reflection seismic, where the effective offset is less than the depth of investigation, and for VSP data, where the offset is less than half the depth of investigation. Using Thomsen's (1986) equation for a short-spread the δ parameter can be estimated using the NMO velocity:

$$\delta = ½[(\upsilon_{NMO}/\upsilon_0)^2 - 1] \qquad (2)$$

To estimate a range for ε, a least-squares solution was determined for a varying set of ε and δ values. The least-squares solution attempts to minimize the traveltime and NMO velocity differences using the straight-ray angle for the average phase angle and the isotropic ray length for raypath distance.

Assuming that the majority of the anisotropy effects on the direct arrivals occur in the 2050 m interval above the shallowest geophone location in the offset VSP, the least-squares solution should represent the average anisotropy parameters for the Banquereau Formation.

Two different assumptions were used to estimate the range of interval anisotropic parameters for the 420 m span in the offset VSP. The first approximation was for elliptical anisotropy ($\delta = \varepsilon$) discussed by Daley & Hron (1977), because of its algebraic simplicity. Substituting ω for δ and ε in Thomsen's equation results in:

$$\omega = [(v(\theta) \ / \ v_0) - 1] \ / \ \sin^2\theta \qquad (3)$$

The second estimation was for intrinsic anisotropy where $\varepsilon > \delta$ as proposed by Berryman (1979) and Thomsen (1986). Using a ratio of $2\delta = \varepsilon$, Thomsen equation can be modified by letting $\tau = \delta = \varepsilon/2$ resulting in:

$$\tau = ((v(\theta) \ / \ v_0) - 1) \ / \ (\sin^2\theta + \sin^4\theta) \qquad (4)$$

Results

The White Rose H-20 VSP values for δ, vary from 0.029 to 0.048, with the Tertiary section (above 2230 m) having the lowest values (table 1). The stacking velocities from the 3-D surface seismic compares with the observed moveout velocity from the VSP. The corresponding log derived formation velocities are overestimated by 4-6%.

Since v_{NMO} is derived from the lithology above each sample point, and since there is no significant change in δ until a depth of 2230 is reached, it would be reasonable to assume that the Tertiary is only slightly anisotropic. The deviation in δ below 2230 m would indicate a sharp change in properties below this point and a significant increase in anisotropic parameters.

The best fit for a least-squares error between the calculated and observed moveout velocities occurs at $\varepsilon = -0.46$ with a $\delta = +0.21$. This solution falls far outside the expected anisotropy parameter range for the White Rose area. The solution for elliptical anisotropy ($\omega = \delta = \varepsilon = 0.04$) is closer to the expected range and is situated at a local minimum. Around this solution is a group of solutions from $\delta = 0.02$ $\varepsilon = 0.10$ to $\delta = 0.04$ $\varepsilon = 0.03$ with approximately the same degree of error. The answer of $\delta \cong .03$ $\varepsilon \cong .07$ falls at the center point of this cluster of solutions and represent the average anisotropy parameters in the Banquereau Formation.

Table 1: H-20 VSP summary

	Interval	Average Velocity	Average v(NMO)	Average v(NMO)^	Minimum δ	Maximum δ	Group Angle
Tertiary Shale	2050 to 2220	2168	2179	2236	0.028	0.036	25.11
Shale 1	2050 to 2120	2158	2171	2228	0.029	0.036	25.57
Shale 2	2130 to 2220	2176	2187	2242	0.028	0.034	24.69
Eocene Peak	2230 to 2250	2188	2200	2259	0.029	0.036	23.54
Paleocene	2260 to 2370	2208	2219	2282	0.032	0.038	23.32
Dawson Canyon	2400 to 2460	2243	2257	2341	0.042	0.048	22.33

^ NMO velocity estimated using raypath length from isotropic GXII model

	Interval Velocity	Offset Velocity	Phase Angle	Elliptical $\varepsilon=\delta$	Intrinsic $2\delta = \varepsilon$ δ	ε	Estimate Error*
Tertiary Shale	2694	2800	31.18	0.147	0.116	0.232	0.06
Shale 1	2632	2684	31.60	0.072	0.056	0.113	0.14
Shale 2	2745	2845	30.80	0.139	0.110	0.220	0.12
Eocene Peak	2846	3686	29.13	1.246	1.007	2.015	0.69
Paleocene	2994	3163	29.32	0.235	0.190	0.380	0.11
Dawson Canyon	3726	4485	37.00	0.562	0.413	0.826	0.24
D Canyon (GXII)	3726	6376	37.28	1.938	1.418	2.836	0.24

** Estimated Error represents a 1ms time shift and the effects on the calculated Elliptical parameters*

Evaluating the interval velocity behavior provides insights into the discrete anisotropy parameter of individual geological layers. The velocity in the Tertiary sequences is relatively linear with crossover in the velocity display (figure 2). This may indicate that the Tertiary is predominately isotropic with the net anisotropic effect occurring because of the intrinsic layering. Assuming elliptical anisotropy the Tertiary would have a $\omega = 0.15$ which is higher than the δ determined from v_{NMO} values. Using the anisotropy relationship $2\delta = \varepsilon$ the results for the Tertiary would be $\varepsilon = 0.23$ with a δ of 0.11 or higher than the values determined from the average velocities.

The high velocity anomaly from 2230 to 2260 m feature a sharp increase in anisotropy parameters to $\omega = 1.2$ or $\varepsilon = 2.0$ and $\delta = 1.0$. The anisotropy parameters are unexpectcally high. The sonic and density logs indicate only a small incremental change in rock properties where the surface seismic indicates a relatively strong impedance response. While, geologically this interval corresponds with the Eocene unconformity, the high velocity obtained for the interval is most likely the effect of time sampling errors (figure 2).

The Paleocene shales (2260 to 2370) are just slightly deformed and have undergone significant compaction with a $v(0) = 2994$ m/s and $\omega = 0.23$ or $\varepsilon = 0.38$ and $\delta = 0.19$. The Paleocene shale interval has a consistent velocity shift and an constant set of anisotropy parameters. This interval appears to be moderately anisotropy.

At 2380 m there is a pronounced shift in the interval velocities and calculated anisotropy parameters. This shift correlates with the Base Tertiary unconformity and marks the change from parallel layering to moderately faulted and folded geometry. The underlying Dawson Canyon Formation is made up of compacted Cretaceous shale and limestones with dips varying from 3° to 10°. The GXII raypath-model solution indicates a substantial offset velocity (7450 m/s) and an unrealistic anisotropy effect $\omega = 1.9$. While the ray-traced data may need checking, the straight-ray approximation still demonstrates a significant anisotropy effect $\omega = 0.56$ or $\varepsilon = 0.83$ and $\delta = 0.41$. While the investigated Dawson Canyon interval is limited on the offset VSP, it would be reasonable to conclude that these Senonian shales are strongly anisotropic ($\varepsilon > 0.4$).

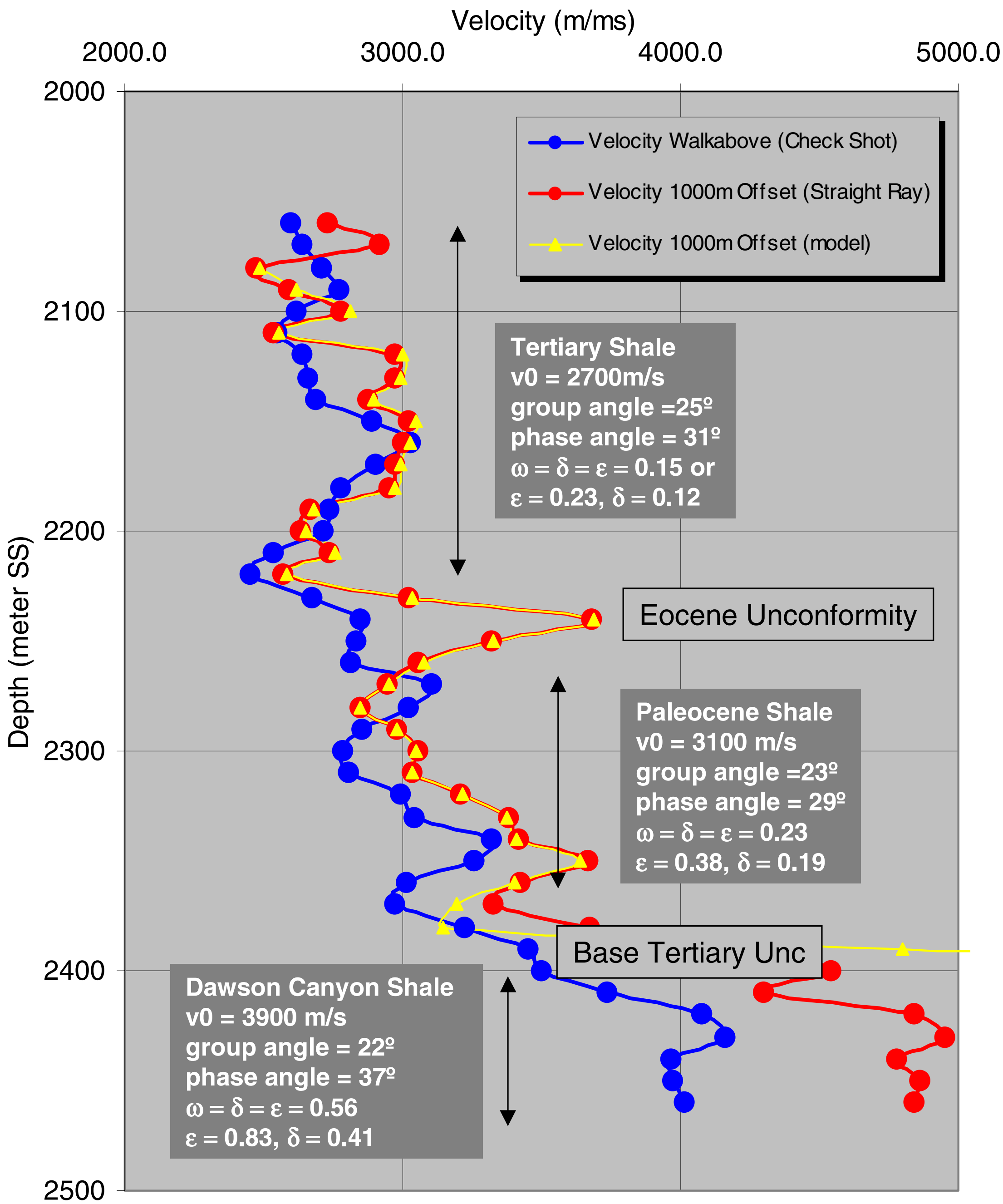


Figure 2: White Rose H-20 Interval Velocity Profile - The blue line represents the velocities for the zero offset VSP, the red line for the 1000-m offset VSP using a straight line geometry and yellow using the raypath length from the GXII model.

Conclusions

Previous work done by Hedlin (1999) indicated that the Banquereau Formation Tertiary shales are slightly anisotropic with an approximate 6% difference between $V(0°)$ and $V(90°)$. The offset VSP average velocities agree with this observation and gives a range of anisotropy parameters from $\delta = 0.02$ and $\varepsilon = 0.10$ to $\delta = 0.04$ and $\varepsilon = 0.03$.

Since the White Rose VSP represents a short spread geometry, the dominant Thomsen (1986) parameter should be δ because of its control on wavefront shape from 0° to 30°. This is reflected in the limited anisotropy parameter range estimated from the VSP ($\delta = 0.029$ to 0.048). The least square solution of $\varepsilon = 0.07$ with a $\delta = 0.03$ would be consistent with the both surface 3-D seismic and VSP data.

The interval velocities indicate that the shales in the White Rose area have varying degrees of anisotropy parameters. The accuracy of measuring the anisotropy parameters of these shales at White Rose, is unfortunately limited, since only a single offset was used. The interval anisotropy parameters indicate that the lower portion of Banquereau Formation is weakly anisotropic ($\omega = 0.15$ or $\varepsilon = 0.23$ with $\delta = 0.11$), the Paleocene shales are moderately anisotropic ($\omega = 0.23$ or $\varepsilon = 0.40$ and $\delta = 0.19$) and the Dawson Canyon Formation is strongly anisotropic ($\varepsilon > 0.4$).

Acknowledgments

Special thanks to Larry Mewhort and Ken Hedlin for their technical evaluation and application assistance, Larry Mayo for design and acquisition of the VSP.

References

Berryman, J.G., 1979, Long-wave elastic anisotropy in transversely isotropic media: Geophysics, 44, 896-917.

Brown, R.J., Lamoureux, M.P., Slawinski, M.A. and Slawinski, R.A., 2000, Direct traveltime inversion of VSP data for elliptical anisotropy in layered media: CREWES Research Report, 12, 19-34.

Daley, P.F. and Hron, F., 1977, Reflection and transmission coefficients for transversely isotropic media: Bull. Seis. Soc. Am. Vol 67, 661-675.

Enachescu, M.E., 1987, Tectonic and structural framework of the northeast Newfoundland continental margin in Beaumont, C. and Tankard, A. J., Eds., Sedimentary basins and basin-forming mechanisms: Can. Soc. Petr. Geol., Mem. 12, 117-146.

Enachescu, M.E., 1988, Extended basement beneath the intracratonic rifted basins of the Grand Banks of Newfoundland: Can. J. Expl. Geophys., 24, No. 1, 48-65.

Grant, A.C. and McAlpine, K.D., 1990, The continental margin around Newfoundland in Keen, M.j. and Williams, G.L., Eds., Geology of the Continental Margin of East Canada: Geol. Surv. Can., Geology of Canada, No. 2, 239-292.

Hedlin, K., 1999, White Rose time-depth analysis: Husky Oil Operation Ltd, internal report.

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

Schlumberger, 2000, White Rose H-20 VSP report: Husky Energy, internal report.