Vp/Vs character of shallow strata, Red Deer, Alberta

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SUMMARY

Acquisition of zero-offset vertical seismic profiles with both a compressional and a shear source allows a detailed examination of the velocities of shallow strata. Good correlation was found between velocity values extracted from seismic data and those extracted from cased hole well logs, with seismic traveltimes being slightly slower as a result of dispersion. Approximately 2.3% dispersion is noted in P-wave data, whereas S-wave data demonstrates approximately 6.8% dispersion. At the study site near Red Deer, Vp/Vs was found to be high (~5) in the near-surface, decreasing to approximately 2.5 at 300 m depth. This Vp/Vs profile matches well with shallow profiles recorded in other areas.

INTRODUCTION

Vertical seismic profile data were acquired at the Cygnet 9-34-38-28W4 lease, located Northwest of Red Deer, Alberta (Figure 1). Suncor Energy Inc., industry partners, and the Alberta Research Council are evaluating this site for enhanced coalbed methane recovery. Methane production and carbon dioxide sequestration are both being tested for viability within the lower Tertiary Ardley coal zone (Figure 2), one of Alberta's most prospective CBM targets.

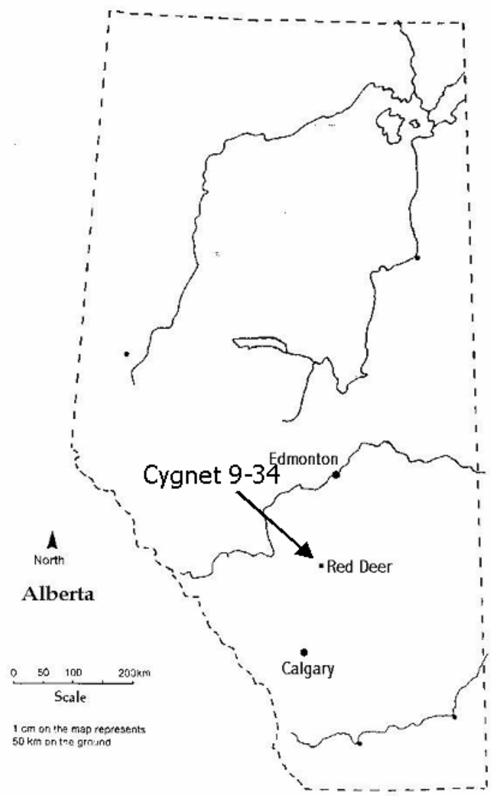

FIG. 1. Map of Alberta, showing location of Cygnet 9-34 wellbore and VSP data acquisition (Natural Resources Canada, 2002).

Ardley coal seams are overlain by the interbedded sands and shales of the Tertiary Paskapoo Formation, and underlain by Scollard and Edmonton Group strata, of similar lithology to the Paskapoo (Figure 2). The Kneehills tuff forms an important regional marker bed, as it is an easily correlatable, laterally extensive layer of volcanic ash, displaying low resistivity on well logs, and low seismic velocity (Havard et al., 1968).

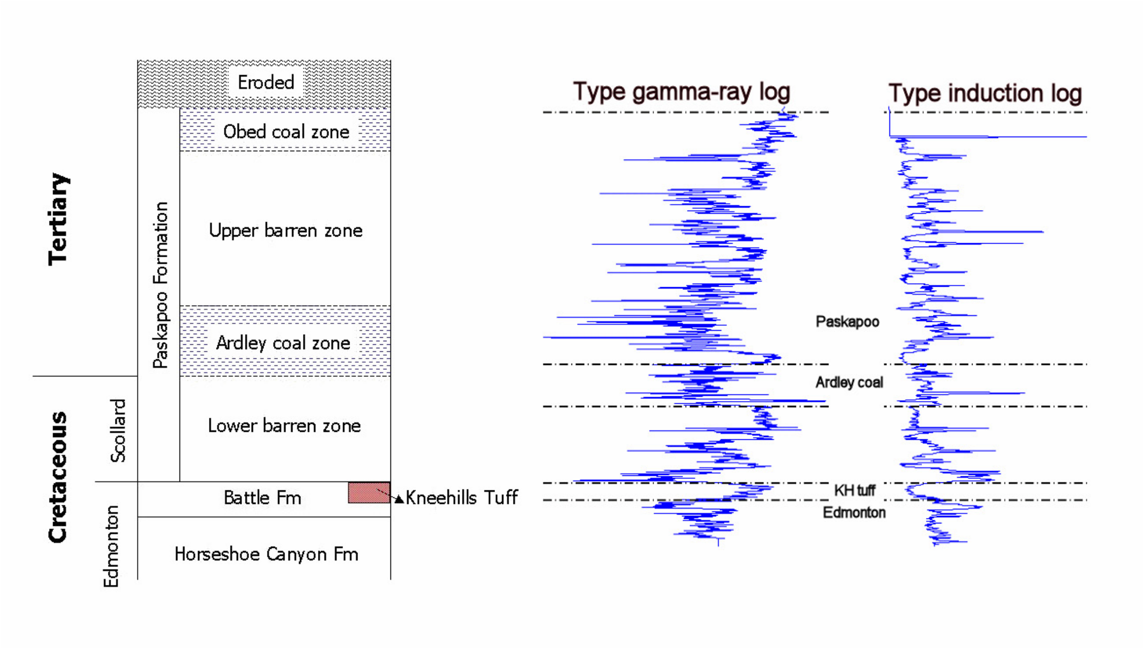

FIG. 2. Stratigraphic column showing late Cretaceous/Tertiary strata in Central Plains of Alberta (after Gibson, 1977).

Zero-offset vertical seismic profiles were acquired using both a compressional and a shear source. Both sources were truck-mounted mini-Vibroseis sources, dubbed "mini-P" and "mini-S". The mini-P source used a sweep of 8-250 Hz, whereas the mini-S source used an 8-150 Hz sweep. A five-level, three-component VSP tool with a 15 m receiver spacing was used in an interleaved manner such that receivers were spaced at 5 m intervals from TD (300 m) to surface within the wellbore. All recording was undertaken at a 1 ms sampling rate.

This complete data set, including well logs, and high-frequency seismic data recorded with two different souces allows a detailed examination of the velocity and Vp/Vs structure of the shallow strata imaged at Red Deer.

RAW DATA

Data recorded at the Red Deer test site are of excellent quality. See Richardson & Lawton, 2003, for sample raw data.

WELL LOGS

Openhole wireline logs were obtained after drilling of the Red Deer well. Compressional sonic, density, gamma-ray, and caliper logs were all run from TD to approximately 40 m KB. These logs are shown in Figure 3.

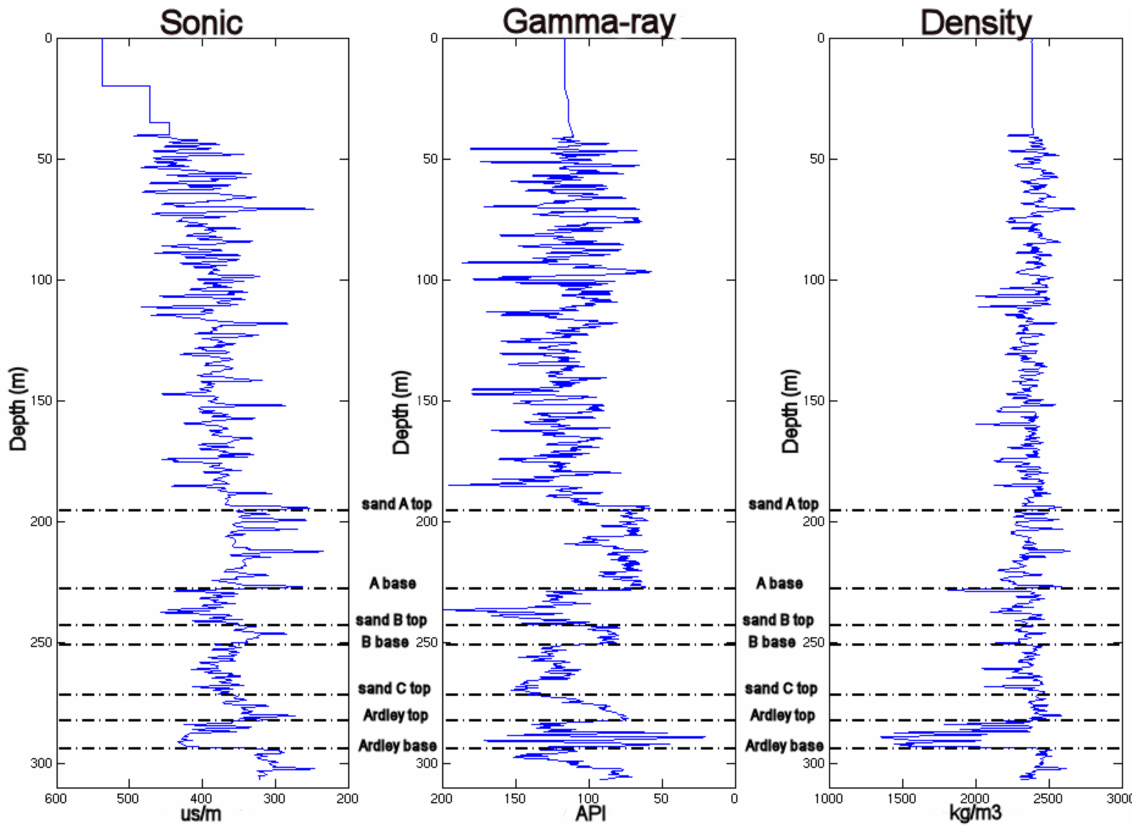

FIG. 3. Openhole wireline logs recorded in well 9-34-38-28W4. Logs were run from TD to approximately 40 m KB.

Interpretation of these logs gives information about the lithologies penetrated by the wellbore, as well as the physical condition of the strata. The caliper log shows relatively little variation in borehole width, suggesting that little wash-out of strata has occurred during drilling. This in turn suggests that all other tools were able to properly couple with the borehole wall, yielding high quality data. Sonic, density, and gamma-ray logs are used in combination to interpret the Red Deer well data. The background strata is interpreted as interbedded shales and siltstones, and three sand units were identified, as well as the Ardley coal zone, as labelled in Figure 3.

Several months following drilling and casing of the 9-34 wellbore, cased hole wireline logs were run in order to obtain a shear sonic curve. The logging suite included both a compressional and a shear sonic curve. The two sonic logs and the resultant Vp/Vs curve are shown in Figure 4.

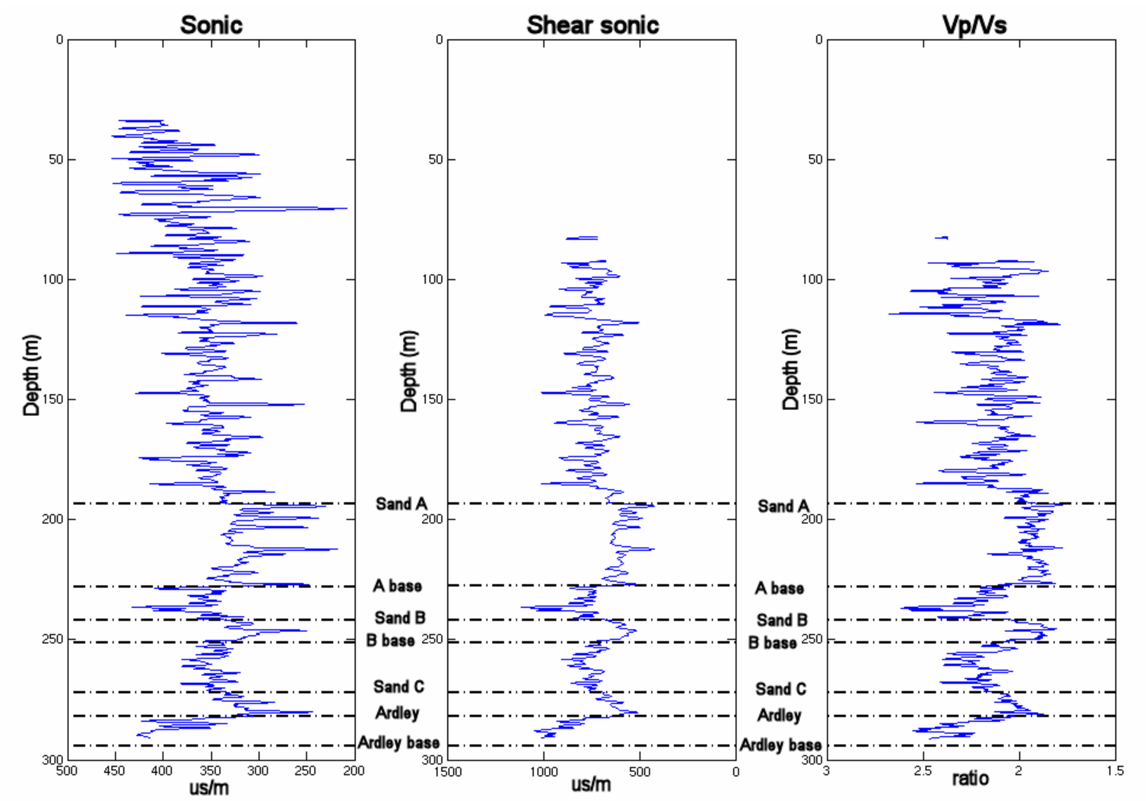

FIG. 4. Cased hole logs of 9-34-38-28W4. Because of cement in the bottom of the well, it was not possible to log the base of the Ardley coal. Poor quality logs in the upper 100 m of the wellbore (particularly the shear sonic) are likely the result of a cement integrity problem.

The cased hole compressional sonic curve shows great similarity to the open hole log, both in shape and values, indicating a reliable log run. Casing the wellbore resulted in cement in the bottom of the hole, meaning the base of the Ardley coal could not be reached by logging tools. Lower quality shear sonic readings in the upper portion of the well are likely the result of poor cement integrity.

DATA ANALYSIS

Recording of the zero-offset VSPs from TD to surface allowed a detailed examination of the seismic velocities of shallow strata in the Red Deer section. Interval and average velocities, and Vp/Vs were calculated using first arrival times for mini-P and mini-S energy at each receiver. First breaks were picked on each data set by picking the maximum of the first coherent peak, according to the Vibroseis convention used by Schlumberger. First breaks from the shallowest receiver were obscured by noise, resulting in inaccurate velocity calculations at this level. For this reason, data values from the uppermost receiver were excluded from the analysis. For simplicity, only the mini-P data were used for the P-wave velocity determinations.

Average velocities were calculated using the formula:

$$V_{avg} = \frac{t_n}{z_n}$$

where t_n is the first-break travel time at receiver n, and z_n is the distance traveled to receiver n, calculated using receiver depth and 20 m source offset, assuming straight ray-paths and a vertical wellbore.

In order to create a smoother profile, interval velocities were calculated for 15 m intervals rather than for every receiver, using the formula:

$$V_{\text{int}} = \frac{t_n - t_{n-3}}{z_n - z_{n-3}}$$

where z is calculated in the same manner as above.

Average P-wave and S-wave velocities demonstrate generally lower velocities in the near-surface, gradually increasing with depth (Figure 5). Analysis of the first arrival times from both sources demonstrates high average Vp/Vs (approximately 3.0) in the shallowest strata down to 100 m depth, decreasing to a value of slightly less than 2.5 at 300 m (Figure 6). The highest interval Vp/Vs is 4.7, at 40 m depth (Figure 7). Interval velocities are smoothed by plotting at 15 m intervals.

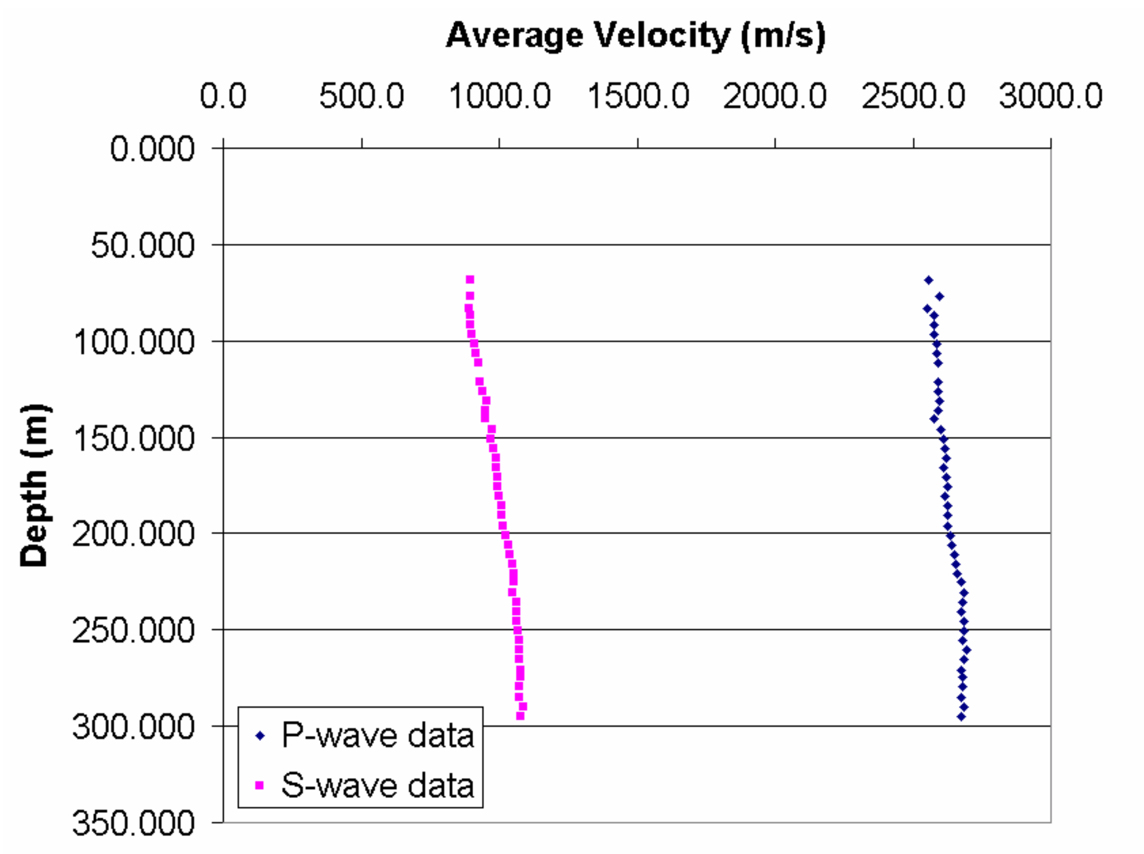

FIG. 5. Average velocity vs depth derived from zero offset mini-P and mini-S VSP data.

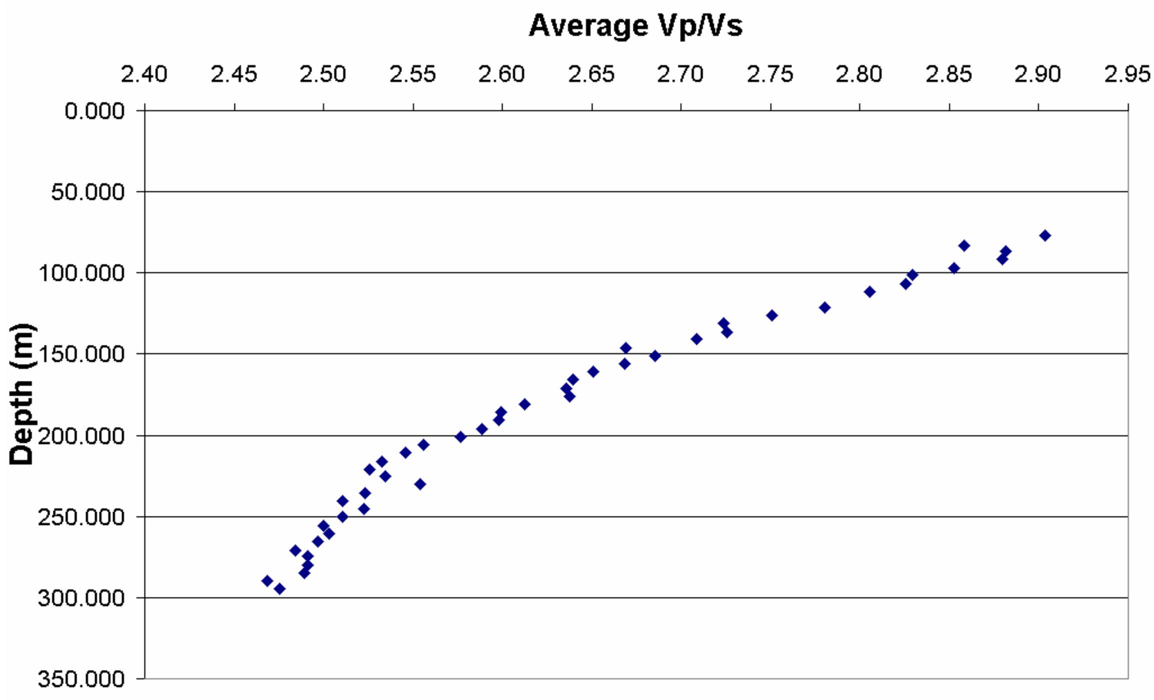

FIG. 6. Average Vp/Vs vs. depth for zero-offset VSP. High values are noted in the near-surface, decreasing gradually to less than 2.5 at the base of the well.

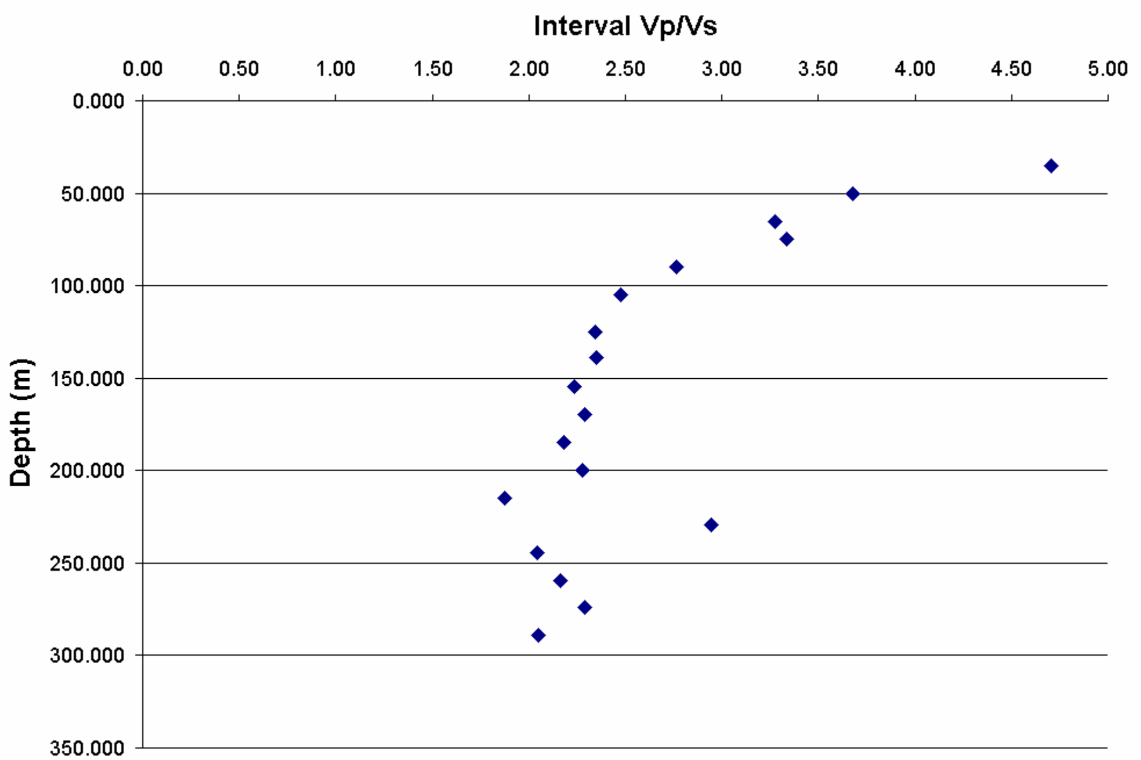

FIG. 7. Interval Vp/Vs values vs. depth for Red Deer strata, plotted in 15 m increments.

Comparing Vp/Vs determined to those determined from well log analysis shows a good correlation (Table 1). For comparison purposes, the cased hole Vp/Vs log was smoothed using a 31-sample median filter, and the instantaneous Vp/Vs found at each depth. Given the log sample interval of 0.1524 m, a 31-sample filter equals approximately 4.75 m in length. Log values are not available at depths of less than 100 m, however most recorded values match the seismic Vp/Vs values well (Figure 8). Although the log data does not contain as wide a range of values as the seismic data, the general trend of Vp/Vs is consistent between the two data sets, with most values differing very little. This suggests that either well log or seismic data may be used for numerical modelling purposes and will produce similar results.

Table 1. Comparison of cased hole log Vp/Vs with Vp/Vs derived from zero-offset VSP data. Correlation is good between the two data sets.

Depth (m)	Log Vp/Vs	VSP Vp/Vs
75	unavailable	3.33
87.5	unavailable	2.86
100	2.10	2.31
112.5	2.29	2.34
125	2.06	2.01
137.5	2.13	2.40
150	2.07	2.12
162.5	2.06	2.32
175	2.13	2.73
187.5	2.04	2.25
200	1.93	2.02
212.5	1.94	1.90
225	1.94	3.13
237.5	2.32	2.00
250	2.03	1.90
262.5	2.19	2.30
275	2.05	3.00
287.5	2.33	2.42
300	unavailable	2.80

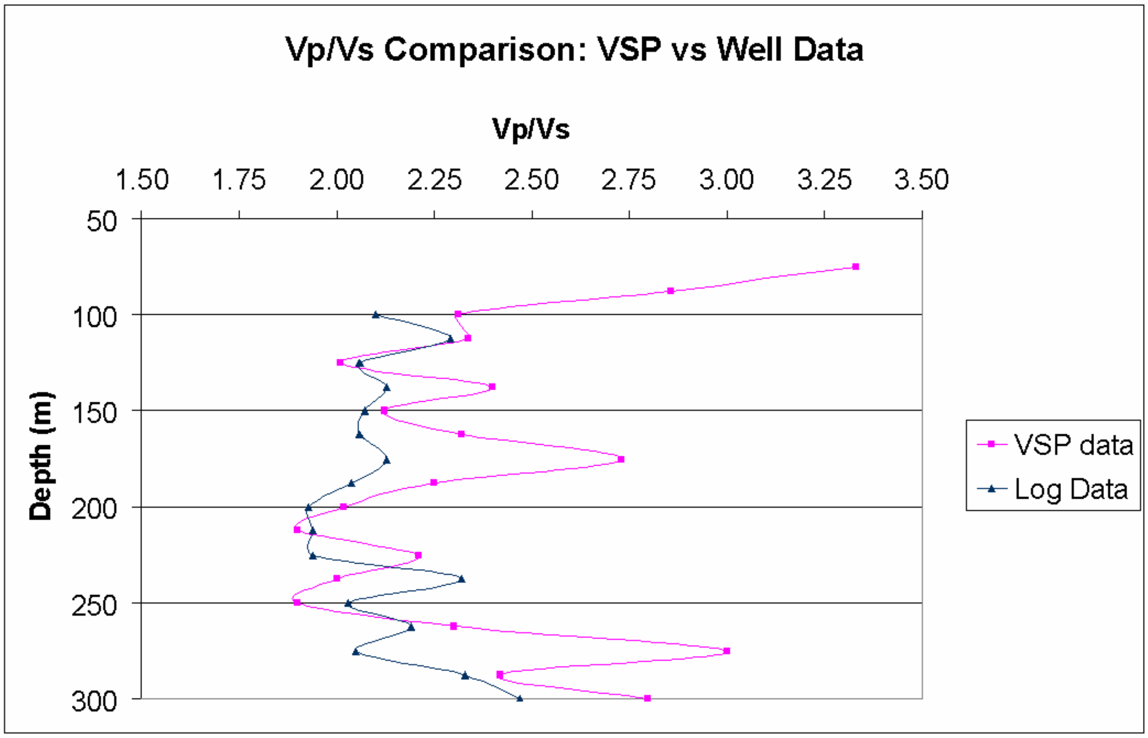

FIG.8. Comparison of Vp/Vs values derived from zero-offset VSP data with those derived from well log data.

In addition to the favourable comparison of Vp/Vs from both well log and seismic data, integration of both the P-wave and S-wave sonic logs (Figure 9) results in traveltimes that also match the seismic data well. Table 2 summarizes the 2-way traveltimes derived from integrated with those derived from VSP data. The seismic traveltimes are generally slower than those calculated from well logs (Figure 10), as a result of dispersion, determined to be approximately 2.3% for P-wave data and approximately 6.8% for S-wave data.

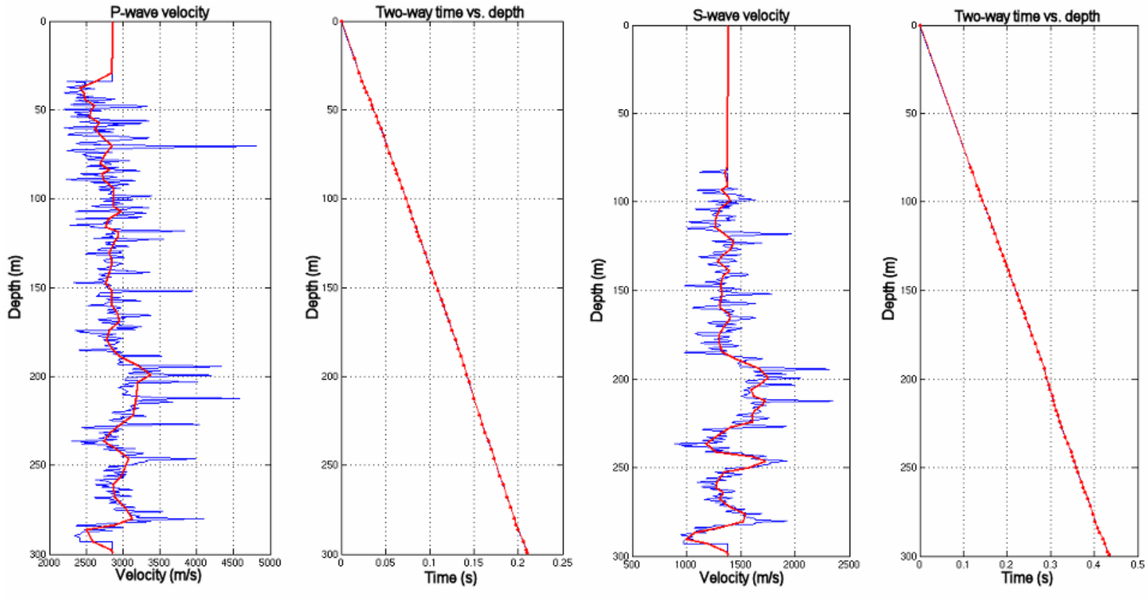

FIG.9. Integrated sonic logs and 2-way traveltime curves for both P-waves and S-waves.

Table 2. Comparison of 2-way traveltimes calculated from integrated well logs with those calculated from zero-offset VSP data.

Depth (m)	P-wave sonic 2-way traveltime	P-wave seismic 2-way traveltime	S-wave sonic 2-way traveltime	S-wave seismic 2-way traveltime
50	0.035	0.040	0.070	0.114
100	0.075	0.078	0.150	0.222
150	0.109	0.116	0.221	0.310
200	0.142	0.152	0.290	0.392
250	0.178	0.186	0.355	0.468
300	0.215	0.220	0.435	0.544

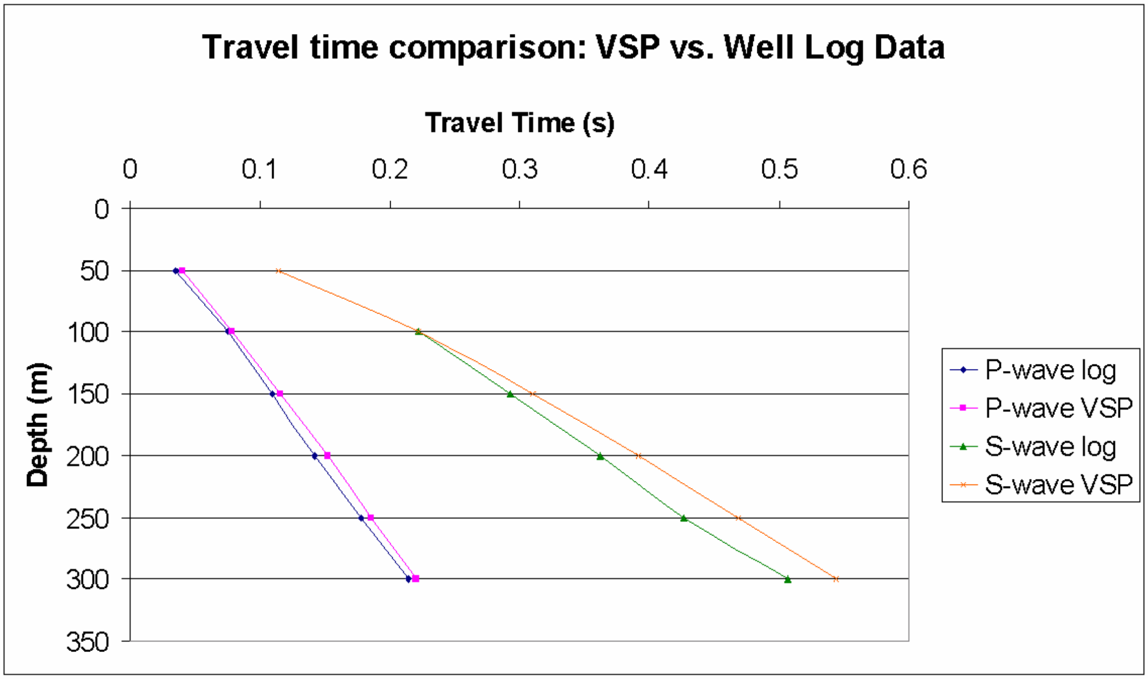

FIG. 10. Graphical comparison of 2-way traveltimes extracted from VSP and well logs data.

Vp/Vs profiles of shallow strata are rarely determined in such detail as in the Red Deer survey, as the majority of vertical seismic profiles do not include receivers in the shallow section. At Red Deer, interval Vp/Vs values are high (greater than 4.5) nearest the surface, gradually decreasing with depth to approximately 2.0. These values agree well with published data regarding near-surface velocities, summarized in Table 3.

Table 3. Comparison of shallow interval Vp/Vs in various areas. Red Deer values show a trend similar to other published data.

Depth (m)	Hamilton (1976,1979) Marine silts & turbidites	Toksöz & Stewart(1984) Dallas, TX	Lawton (1990) Calgary, AB	Osborne & Stewart (2001) Pikes Peak, SK	Hoffe & Lines (1999) Blackfoot, AB	Jaramillo & Stewart (2002) Whiterose, NL	Cieslewicz (1999) Chin Coulee, AB	Sun (1999), Cold Lake, AB	Study data (2003) Red Deer, AB
6			2.0				2.8		
12							5.1		
18			8.0				4.7		
20			8.0						
35		3.6							4.7
50	5.2			5.0				4.0	3.7
65		5.7							3.3
75									3.3
100	4.5	5.8		4.6		3.9		4.0	2.3
125									2.0
150	4.0	3.7		4.3				2.9	2.1
175									2.7
200	4.0			4.0		3.9		3.1	2.2
225									3.1
250	3.8			3.8	2.4			3.1	3.3
275									3.0
300	3.7			3.5		3.8		3.0	2.8
350				3.5	2.3				

Hamilton (1976, 1979), one of the first to predict Vp/Vs relationships in shallow strata, relied on shallow marine and land in-situ measurements, and derived empirical relationships to predict Vp/Vs with increasing depth. This prediction has proved to be reasonably accurate.

Both within Alberta and in other parts of the world, several determinations of Vp/Vs within the shallow section have found high values nearest the surface, decreasing gradually with depth. This pattern is seen in the very near surface at Chin Coulee, where Vp/Vs of approximately 5.0 was calculated using refraction methods in sediments of 6-18 m depth (Cieslewicz, 1999), and near Calgary, where a Vp/Vs of 8.0 was found using refraction methods at depths of 10-20 m (Lawton, 1990). In both of these studies, lower Vp/Vs values were found above the water table.

Vertical seismic profiles have been used to identify this pattern of decreasing Vp/Vs with depth at Pikes Peak, in Saskatchewan (Osborne & Stewart, 2001), and at a site near Dallas, Texas (Toksöz & Stewart, 1984). Compressional and shear-sonic well logs may also be used in examining Vp/Vs of shallow strata, and have been used to delineate the Vp/Vs profile at Blackfoot, Alberta (Hoffe & Lines, 1999), at Cold Lake, Alberta (Sun, 1999), and in offshore data, such as a Whiterose well, offshore Eastern Canada (Jaramillo & Stewart, 2002). In the Whiterose case, well logs started at a depth of 350 m, but the Vp/Vs relationship demonstrated a similar character to those observed in the shallow section for this study. The Whiterose trend was extrapolated to shallower depths to calculate the expected Vp/Vs behaviour.

CONCLUSIONS

Examination of the Vp/Vs character of the shallow strata at Red Deer demonstrated a profile similar to those seen in other parts of Alberta and the world. Vp/Vs values were high (nearly 5.0) in the near-surface, decreasing with depth to a Vp/Vs of approximately 2.0. Good correlation was noted between Red Deer traveltime and Vp/Vs values calculated using the zero-offset VSP data and those calculated using cased hole sonic logs. This suggests that either well log or seismic data may be used to extract velocities used in numerical modelling.

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