Well log analysis of Vp and Vs in carbonates

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ABSTRACT

Well log data from three carbonate formations in Alberta were analyzed for relationships among Vp, Vs, porosity, density, and lithology. A review of the literature suggests that these relationships are highly variable among carbonates, and thus each geological setting should be characterized individually. In this well, Vp and Vs were inversely correlated with porosity in the Leduc formation. Velocity-porosity correlations were weak for the Pekisko and Wabamun carbonates. Vp/Vs did not appear to be correlated to porosity in any of the formations. Densities calculated from Gardner's relation were compared to measured well log densities. Calculated densities were close to measured densities in pure carbonates, but were underestimated in zones where anhydrite was present. Vs generally increased with density in pure carbonates, but samples with high anhydrite content had anomalously low velocities. Vp and Vs were linearly correlated in all the formations. The presence of anhydrite tended to raise the Vp/Vs ratio in the dolomites, and cause an overlap with the limestone Vp/Vs values. The Vp/Vs curve closely tracked the dolomite/anhydrite layers indicated by the photoelectron cross section index (PEF) log and the anhydrite fraction curve. The Vp/Vs curve also tracked the PEF and the limestone fraction curve across the boundary between the dolomite/anhydrite facies and a limestone formation. In the carbonates studied here, Vp/Vs appears to be a good lithology indicator which is independent of porosity effects.

INTRODUCTION

Identifying correlations between elastic wave velocities and other rock parameters is an important step in extracting petrophysical information from seismic data. Well logs provide a variety of measurements with which to characterize the rock and look for these correlations. With the advent of full-waveform logging tools we have been able to obtain shear-wave information as well as the conventional compressional-wave data.

Numerous studies have shown that the ratio of compressional-wave velocity (Vp) to shear-wave velocity (Vs), or Vp/Vs, is indicative of lithology. Pickett introduced this idea in 1963 when he used core measurements to establish Vp/Vs values of 1.9 for limestone, 1.8 for dolomite and 1.6 for sandstone. These values have generally been confirmed by subsequent research, which also suggests that mixed lithologies have Vp/Vs values which range between those of the end members (Nations, 1974; Kithas, 1976; Eastwood and Castagna, 1983; Domenico, 1984; Miller and Stewart, 1990).

Tatham (1982) attributed the association between Vp/Vs and lithology to pore geometry. Wilkens et al. (1984) concluded from core data that silica content in carbonates has a greater effect on Vp/Vs than pore shape.

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A number of workers have examined the relationship between rock velocities and petrophysical parameters. Wyllie et al. (1956) proposed a relationship between Vp and porosity, and Raymer et al. (1980) sought to improve upon this relationship. Kuiper et al. (1959) did laboratory analyses of chemically pure limestones and found a strong positive correlation between Vp and density, and a tendency for Poisson's ratio to increase with increasing density. Domenico (1984), using Pickett's data, concluded that velocity is less sensitive to porosity in limestones than in sandstones, and that, in limestone, Vp is less sensitive than Vs.

Rafavich et al. (1984) did a detailed laboratory study of velocity relationships with petrographic character in carbonates. They concluded that the primary influences on Vp and Vs are porosity and density, with lithology exerting only a small influence. Neither pore shape nor pore fluid were significant factors. The Vp/Vs ratio successfully differentiated limestones and dolomites, but anhydrites were more difficult to identify. Anhydrite Vp/Vs values ranged from about 1.72 to 1.85. Porosity-velocity trends were well described by the Wyllie time-average equation, provided the correct matrix velocities were used. The results of the laboratory analysis were used to interpret porosity and lithology variations in seismic data from a carbonate sequence. The interpretation agreed with well log data.

Robertson (1987) interpreted porosity from seismic data by correlating an increase in porosity with an increase in Vp/Vs. He based his interpretation on the model of Kuster and Toksöz, which incorporates pore aspect ratio as a factor in velocity response. According to this model, Vp/Vs will rise as porosity increases in a brine-saturated limestone with flat pores, but will decrease slightly if the pores tend to have a higher aspect ratio (are rounder). If the limestone is gas saturated, Vp/Vs will drop sharply as porosity increases if pores are flat, and drop slightly if pores are rounder.

Georgi et al. (1989) did not observe a reduction in Vp/Vs due to gas in their study of Alberta carbonates. They concluded that this may have been because the pores in the formations studied were primarily round in shape. Both compressional and shear transit times were useful for computing porosity from the Raymer-Hunt-Gardner transform (1980), which was modified to accommodate shear-wave transit times.

Eastwood and Castagna (1983) studied full-waveform sonic logs in the Appalachian limestone and observed constant Vp/Vs with increasing porosity. This confirmed the results they calculated using the model of Kuster and Toksöz. Goldberg and Gant (1988) studied full-waveform sonic log data in a limestone/shale sequence and found the Vp/Vs ratio effective at identifying limestone/shale boundaries, but ineffective at identifying fracturing in the limestone. They concluded that shear-wave amplitude attenuation is more useful for detecting fractures. Shear-wave amplitude was also attenuated in the shale zones, and thus could also be used for lithology identification in this case. Well log data from the Pekisko limestone of Alberta was analyzed by Miller and Stewart (1990). They observed a decrease in both Vp and Vs as porosity increased, but did not observe a correlation between Vp/Vs and porosity.

Even this incomplete literature review reveals a number of differing results and conclusions regarding velocity-rock property relationships, especially in carbonates. There are a number of factors which affect rock velocities, and past research does not concur on the relative significance of these factors. This disparity underscores the need to examine each geological setting individually. The observations in this study relate to the Paleozoic carbonates of Alberta, which are a rich source of hydrocarbons.

METHODS

The data in this paper are from one well, Mobil Davey (3-13-34-29W4), from the Davey field in central Alberta. The well was abandoned after a DST in the Wabamun indicated low permeability. The well logging suite consisted of array sonic, compensated neutron litho-density, and spherically-focused phasor induction logs. The geological summary of well cuttings and a core report were also available, and were used to corroborate mineralogy and porosity values. Although the entire well was logged with the array sonic, not all of the data were usable. Shear-wave measurements were not available in slow formations, and both compressional and shear-wave transit times were considered unreliable through poor borehole zones, as the tool is not borehole compensated. The data in this paper were from competent carbonates with high velocities and good borehole conditions (as indicated by the caliper curve). Amplitude data was not available, so only transit times were used for this analysis.

Curves were digitized at a 0.5 metre sample rate and analyzed using petrophysical analysis software. Input curves were the neutron and density porosity, bulk density, compressional and shear transit time, PEF (photo electron), and deep resistivity. A multimineral analysis calculated volumes of limestone, dolomite, and anhydrite. Although this three-mineral determination is undoubtedly a simplification of the true lithology, it is useful for observing trends relating to compositional variations. This analysis also computed an effective porosity curve, using the bulk density curve and the matrix densities from the mineralogical analysis. Of the many porosity curves available, this was judged the most reliable for the mixed lithologies in this well. It was also the closest match to the core porosities from the Leduc. All calculated curves were corrected for clay volume, as determined from the gamma-ray curve.

The formations examined in this paper are the Pekisko (2167-2176 m.), Wabamun (2360-2567 m.) and Leduc (2640-2737 m.). The Pekisko is a Mississippian limestone, and the Wabamun and Leduc are Devonian dolomites. All of these formations are potential hydrocarbon reservoirs. The dolomites were anhydritic in some zones, and were also streaked with anhydrite. Clay content in all formations was negligible. Porosities were low, averaging 5 -10% in porous zones. There were no crossovers on the neutron-density curves, and it was assumed that no gas was present. Table 1 lists standard values for the dominant minerals in the lithologies studied here.

Table 1. Mineral parameters. (Limited data was available for Vp/Vs in anhydrite.)

Mineral	Density (g/cm^3)	Vp (m/s)	Vs (m/s)	Vp/Vs (empirical)	PEF (barns/e)
Calcite	2.710	6530	3360	1.9	5.08
Dolomite	2.870	6960	3980	1.8	3.14
Anhydrite	2.960	6050	3030	1.75-1.85?	5.05

OBSERVATIONS

Velocity-Porosity Relationships

In the Pekisko limestone, Vp decreased slightly as porosity increased. Vs did not vary appreciably with porosity, which ranged from 1% to 8%. (Figure 1). The data did not deviate significantly from the best fit lines, although there was somewhat more scatter in Vp. The correlation between Vp/Vs and porosity was weak with considerable scatter in the data (Figure 2).

The Wabamun formation is primarily dolomite with streaks and interbeds of anhydrite. Velocities were cross plotted with porosity in Figure 3. The data did not appear to be correlated up to about 5% porosity for either Vp or Vs, and the Vp data showed considerable scatter at low porosities. The Vp and Vs values were noticeably lower in samples with porosities in the 6 to 13% range. Although there were not enough data points in this porosity range to be statistically significant, it is possible that the higher porosities were affecting both Vp and Vs. There did not appear to be a correlation between Vp/Vs and porosity in this formation (Figure 4). There is a large range of Vp/Vs values at zero porosity, perhaps due to anhydrite and other minerals in the formation.

The Leduc is also a dolomite with some anhydrite streaks. Both Vp and Vs showed an inverse linear correlation with porosity (Figure 5). Vs had a stronger correlation than Vp and was less scattered. Vp/Vs did not appear to be correlated with porosity in the Leduc (Figure 6).

Velocity-Density Relationships

Gardner's relation (Gardner et al., 1974) is frequently used to derive density values from Vp when measured densities are unavailable. Density was calculated from Vp using Gardner's relation and compared to the measured bulk density from the logging tool. Figure 7 demonstrates that the agreement between the calculated and measured values was good in the limestone and clean dolomite zones. The equation overestimated the density in the porous zone (2360-2365 m.) and underestimated the density in anhydritic zones. This confirms Gardner et al.'s results, which indicated that anhydrite did not conform to the equation.

Anhydrite has a high density and low elastic velocities relative to other common sedimentary rocks (see Table 1). We observe this effect in the relationship between Vs and bulk density, shown in Figure 8. There was a scattered yet evident trend for Vs to increase with density for pure carbonates. However, as the anhydrite fraction increased, the trend reversed and velocity values decreased.

Velocity-Lithology Relationships

Figure 9 illustrates the linear relationship between Vp and Vs. There is substantial overlap in the Vp/Vs ratio of the limestone and dolomite formations. The presence of anhydrite appears to raise the Vp/Vs of dolomite (1.8) towards that of limestone (1.9). This effect is clearly observed in Figure 10, which shows the Vp/Vs, PEF, and anhydrite volume curves all tracking each other through a section of the Wabamun where the dolomite is interbedded with anhydrite streaks. All three logs track closely. The PEF is a lithology curve which clearly distinguishes between dolomite and anhydrite (see Table 1).

Both the PEF curve and the Vp/Vs curve detect the dolomite/limestone boundary at 2770 metres (Figure 11). Vp/Vs in the Leduc is higher than in a pure

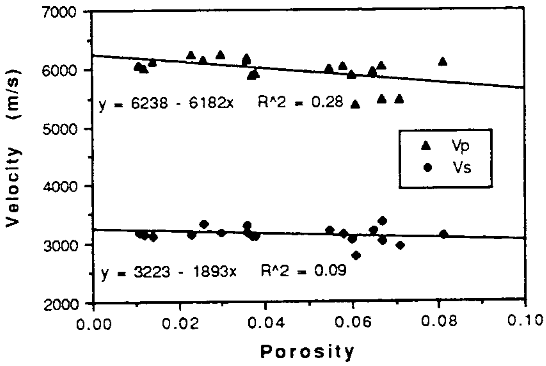

FIG. 1. Pekisko limestone: Vp decreases slightly as porosity increases; Vs does not appear to be sensitive to porosity variations.

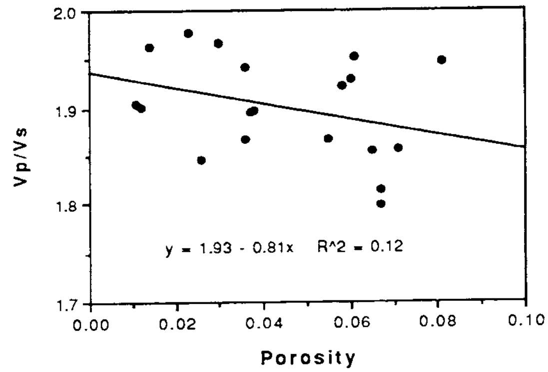

FIG. 2. Pekisko limestone: the data are too few and too scattered to depict any trend.

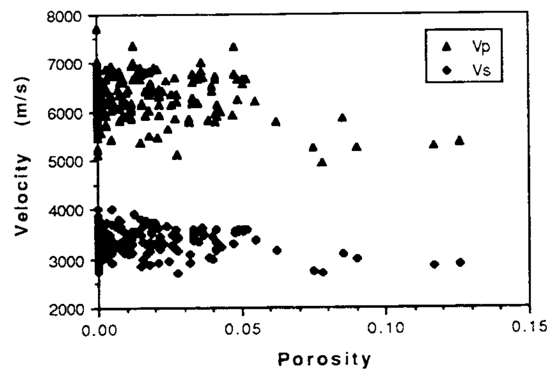

FIG. 3. Wabamun dolomite: there is no apparent correlation at low porosities, but the few samples with more than 5% porosity have lower Vp and Vs.

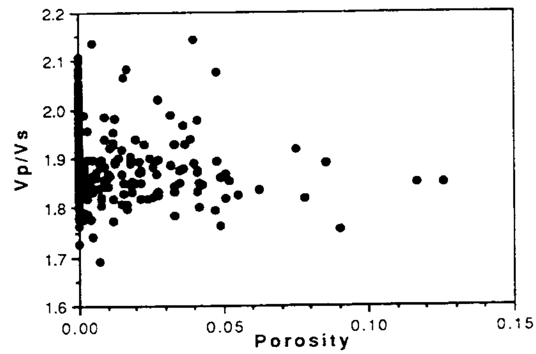

FIG. 4. Wabamun dolomite: the large range of Vp/Vs values at zero porosity may be due to compositional variation, such as the presence of anhydrite.

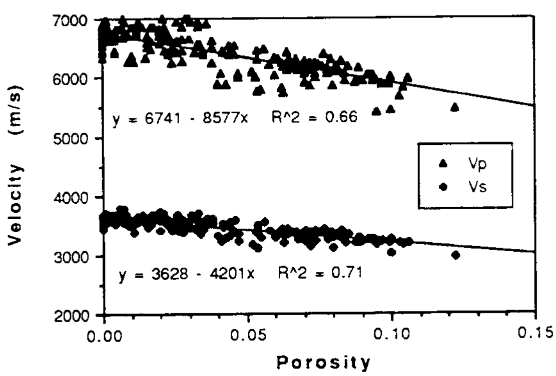

FIG. 5. Leduc dolomite: both Vp and Vs are inversely correlated with porosity. Vs has a higher correlation and less scatter.

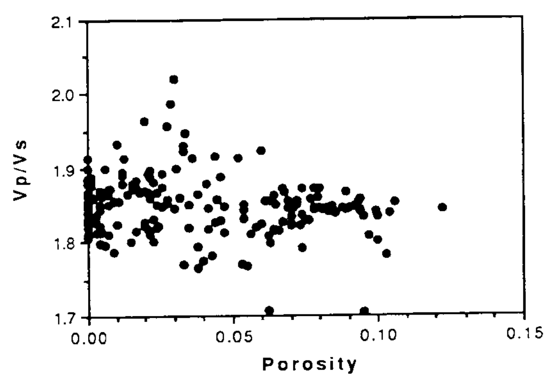

FIG. 6. Leduc dolomite: no correlation is evident between Vp/Vs and porosity.

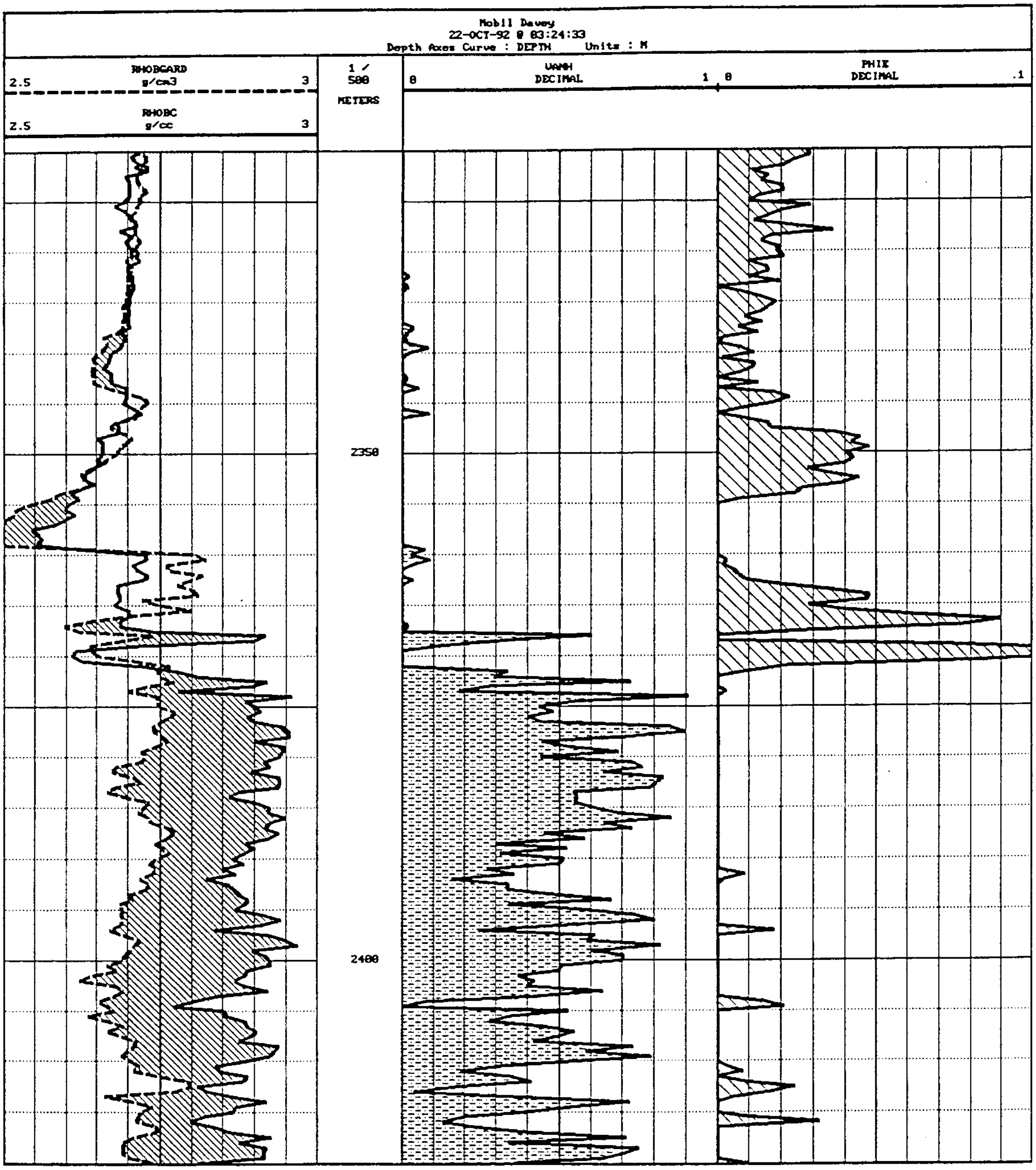

FIG. 7. Comparison of measured bulk density (RHOB) and density calculated from Gardner's equation (RHOBGARD). The second track is anhydrite fraction (VANH), and the third track is the effective porosity (PHIE). Agreement between the measured and calculated densities is very good in the clean limestone, up to about 2355 m. The Exshaw shale is from 2355-2360 metres. Gardner's relation overestimates the density in the upper porous zone of the Wabamun (2360-2365 m.) and underestimates density in anhydritic zones, starting at about 2372 m.

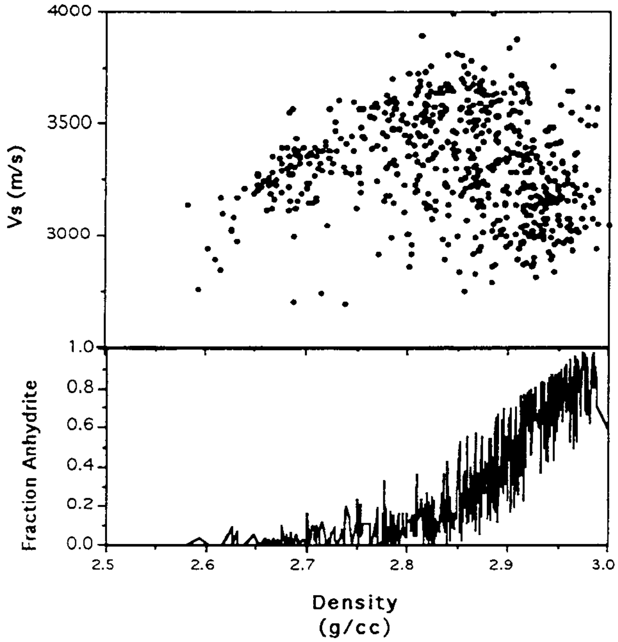

FIG. 8. Vs is plotted against density for all three formations. For samples with low anhydrite content, Vs increases with density. As the volume of anhydrite increases, Vs begins to drop off.

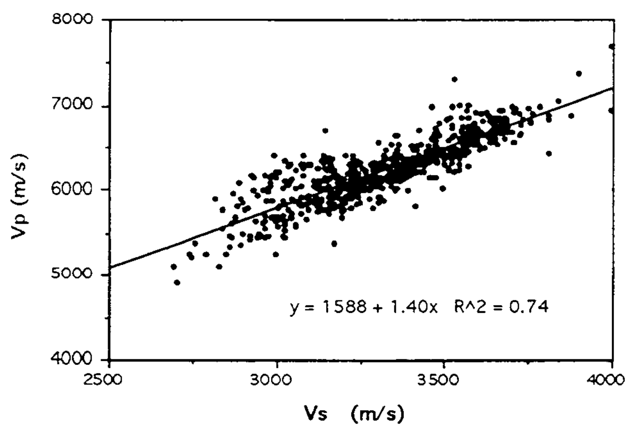

FIG. 9. Vp is linearly correlated with Vs for all three formations. The formations are not shown individually here, but dolomite and limestone could not be differentiated on this type of plot. There are very few limestone data, and velocities in the Wabamun and Leduc are affected by anhydrite streaks. Anhydrite has lower Vp and Vs than dolomite, and, according to these data, higher Vp/Vs.

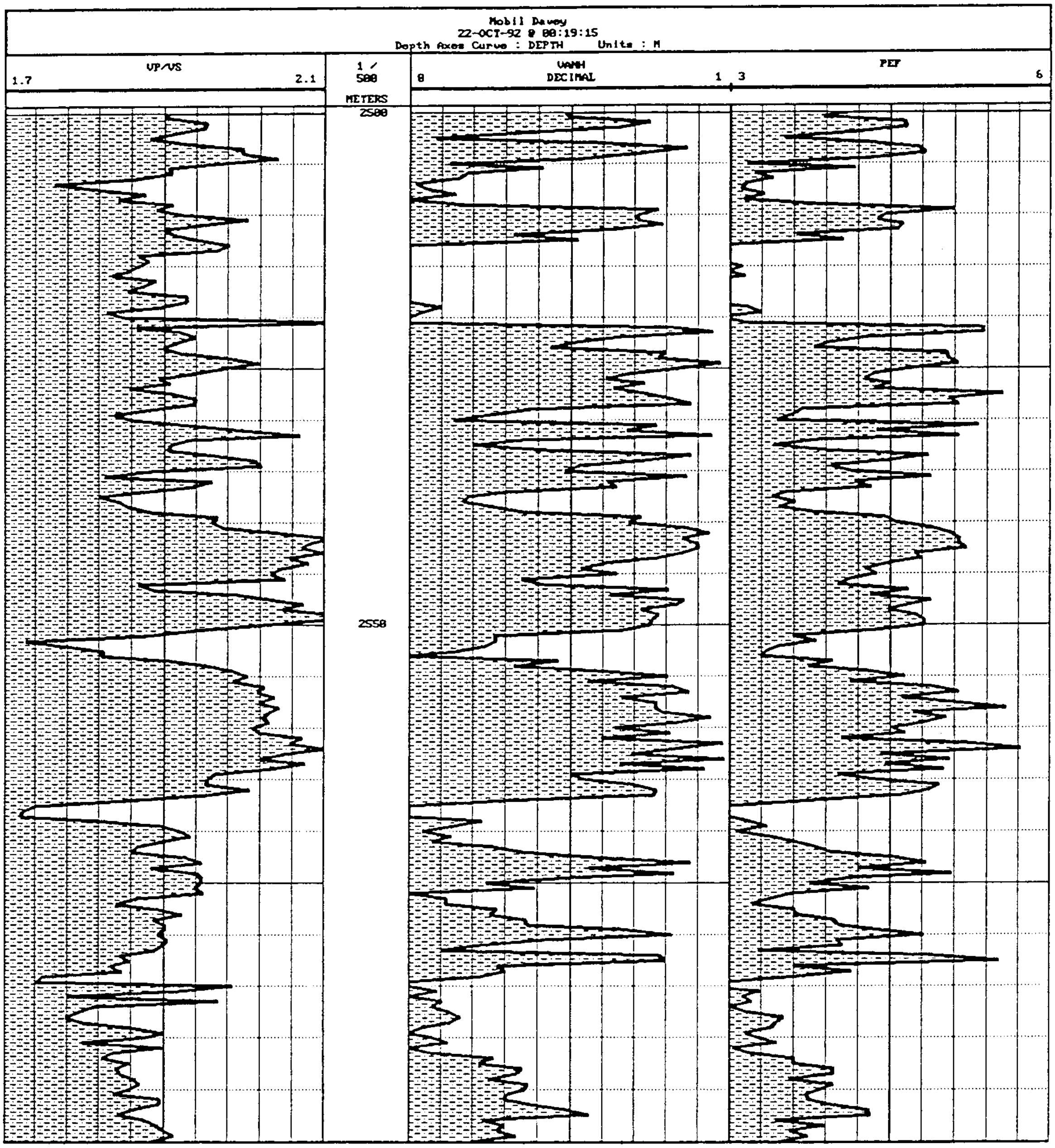

FIG. 10. The three curves are Vp/Vs, calculated from the array sonic curves, the anhydrite fraction (VANH), and the photoelectric cross section index curve (PEF). The PEF curve is a lithology indicator and is one of the curves used to calculate the volume of anhydrite, so they track very closely. Vp/Vs also tracks closely, though with less resloution. Vp/Vs increases as the volume of anhydrite increases. The sequence is dolomite and anhydrite in the Wabamun.

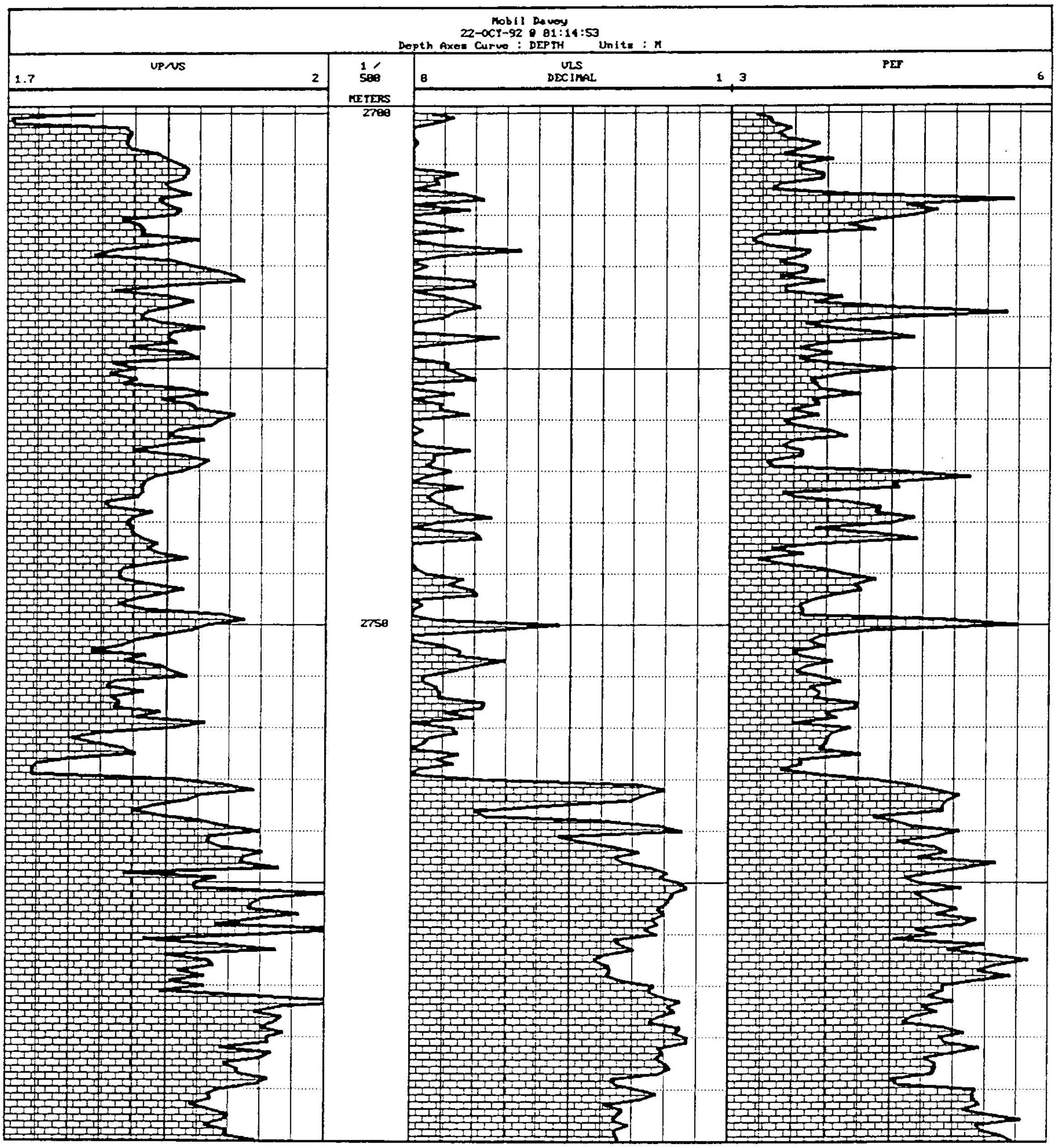

FIG. 11. The three curves are Vp/Vs, calculated from the array sonic curves, the limestone fraction (VLS), and the photoelectric cross section index curve (PEF). The dolomite/limestone boundary is clearly evident on all three curves at 2765 metres. The PEF increases from about 3.5 to 5.0 and the Vp/Vs increases from about 1.80 - 1.85 in the dolomite/anhydrite facies to about 1.90 - 1.95 in the limestone.

dolomite because of the anhydrite, but it still shows a sharp increase passing into the limestones of the Duverney.

DISCUSSION

The variation in the results from carbonates in one well confirms that it is difficult to generalize velocity-porosity relationships in carbonates. One of the reasons for this is the wide variety of other factors can affect elastic-wave velocities, including pore geometry, pore fluid, and mineralogy.

In this study both Vp and Vs showed strong correlations with porosity in the Leduc. Although the Wabamun has a similar lithological makeup, the relationship in the Wabamun was less clear. This may simply be due to the smaller range of porosities in the Wabamun. A careful look at Figure 5 reveals that for porosities less than 4%, the correlation between Vp and porosity in the Leduc is not clear. The trend for Vp does not become established until porosities exceed 5%.

Variations in velocity response may be due to factors which are difficult to assess from the available data, such as pore geometry. For example, fractures, which have low aspect ratios, may also induce velocity anisotropy. Random mineral inclusions could affect velocities in a manner which is difficult to evaluate or predict.

One of the recurring factors in this analysis was the influence of anhydrite streaks. Gardner's relation is inaccurate in intervals where anhydrite is prevalent. Vp/Vs accurately identified anhydrite interbeds in dolomites and the lithologic boundary between the dolomite/anhydrite sequence and the underlying limestone. Vp/Vs appeared to be independent from porosity in these data. This reduces the degree of ambiguity involved, and gives us more confidence in attributing Vp/Vs variations to compositional changes. This study suggests the possibility that Vp/Vs might be useful in tracking limestone/dolomite ratios or dolomite/anhydrite ratios on seismic data. The same principal has been used to track sandstone/shale ratios from seismic data (McCormack et al., 1984; Garotta et al., 1985),

CONCLUSIONS

Relationships between elastic velocities and rock properties in carbonates are complex. The disparity among results from the literature suggests that it is useful to examine formations of interest individually. This study consisted of well log data from three Paleozoic carbonates: the Pekisko, Wabamun and Leduc. Vp and Vs were inversely correlated with porosity in the Leduc formation. Vs was more sensitive to porosity and showed less scatter than Vp. In the Pekisko limestone, there was a slight decrease in Vp with increased porosity, but no apparent Vs response. Velocity-porosity correlations were weak in the Wabamun, but the very low porosities in this formation may limit the usefulness of this observation. Vp/Vs did not appear to be correlated to porosity in any of the formations.

Densities calculated from Gardner et al.'s relation were close to measured densities in pure carbonates, but were underestimated in zones where anhydrite was present. Vs generally increased with density in pure carbonates, but decreased in samples which had a high anhydrite content.

Vp and Vs were linearly correlated in all the formations. The presence of anhydrite tended to raise the Vp/Vs ratio in the dolomites, and cause an overlap with the limestone Vp/Vs values. The Vp/Vs curve closely tracked the dolomite/anhydrite layers indicated by the PEF lithology log and the anhydrite fraction curve. The Vp/Vs curve also tracked the PEF across the boundary between the dolomite/anhydrite facies and a limestone. In the carbonates studied here, Vp/Vs appeared to be a good lithology indicator. Vp/Vs also appeared to be independent of porosity in these formations, which reduces the ambiguity involved in interpretation. It may be feasible to use the Vp/Vs ratio to monitor variations in dolomite/anhydrite or dolomite/limestone concentrations.

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