Analysis of Array-sonic logs from the Medicine River field, Alberta

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ABSTRACT

Array-sonic logs from four wells in the Medicine River field of Alberta are analyzed for relationships between Vp (compressional-wave velocity), Vs (shear-wave velocity), Vp/Vs, lithology, shaliness and porosity. Vp/Vs in conjunction with Vp effectively discriminates between sandstone, limestone and shale lithologies in the sampled intervals. Vp appears to increase linearly with Vs in sandstones, limestones, and mixtures of clastics and carbonates. The average Vp/Vs value of 1.61 for sandstone agrees with the literature values of 1.6 - 1.7 obtained from core analysis. The average Vp/Vs value for the limestone is 1.86 which falls between the literature values of 1.8 for dolomite and 1.9 for limestone. This is attributed to the slightly dolomitic nature of the limestone formation from which the data are taken. Mixed lithologies have Vp/Vs ratios which fall between values for their component lithologies. Vp/Vs has been found to vary in the Basal Quartz formation between two adjacent wells. A drop in Vp/Vs may be due to an increase in porosity, a decrease in shaliness, a change in pore fluid or some combination thereof.

Both Vp and Vs decrease as porosity increases in the sandstones and in the Nordegg, Shunda, and Detrital formations, which are carbonate/clastic mixtures. With the exception of the Nordegg, Vp is more sensitive to porosity than Vs which results in an overall decrease in Vp/Vs with increasing porosity. This is the opposite trend to that which is reported by several other investigators. The Nordegg does not exhibit any Vp/Vs trend with changing porosity. In the limestone there are no trends for Vp, Vs or Vp/Vs with respect to porosity.

INTRODUCTION

Shear-wave techniques have important implications both for well logging and for seismic exploration (Nations, 1974; Gregory, 1977; Tatham, 1982; Robertson, 1987). It is the objective of this study to analyze full-waveform sonic logs in the Western Canadian basin and search for trends which provide information on lithology, porosity and pore fluid. Information obtained from the study of well logs can then be applied to the interpretation of multicomponent seismic data.

Extensive laboratory research suggests that shear-wave data in conjunction with compressional-wave data can provide additional rock information on lithology, porosity, pore fluid, pore shape, clay content and fracture orientation. Most of this work has concentrated on the use of the ratio of compressional-wave velocity (Vp) to shear-wave velocity (Vs). Pickett (1963) demonstrated the potential of Vp/Vs as a lithology indicator and his laboratory research determined values of 1.9 for limestone, 1.8 for dolomite and 1.6-1.7 for sandstone. The relationship between Vp/Vs and porosity has been examined by many other researchers (Nations, 1974; Tatham, 1982; Eastwood and Castagna, 1983; Han et al., 1986; King et al., 1988). Observations by Domenico (1984), Han et al., (1986) and King et al., (1988) indicate that Vs in sandstone is much more sensitive to variations in porosity than Vs in limestone or Vp in either lithology. Tatham (1982) suggested that pore geometry has a stronger effect on Vp/Vs than matrix composition. Robertson (1987) used modeling and field studies to demonstrate that Vp/Vs is sensitive to limestone porosity when the pore shape is elongate. Wilkens et al., (1984) concluded that Vp/Vs response is dominated by carbonate content with a lesser influence from porosity and aspect ratio. The effect of clay content in sandstones was studied by Castagna et al. (1985), Han et al. (1986), Eberhart-Phillips et al., (1989) and King et al., (1988). Vp/Vs was observed to be more sensitive to porosity than clay content, but the latter may be more significant due to the wide range of variation in real rock. Gregory (1977) observed a sharp reduction in Vp/Vs in the presence of even small amounts of gas.

In general, literature results to date suggest the following:

(i) Vp/Vs is an effective discriminator between sandstone, limestone and dolomite lithologies;

(ii) Vp/Vs increases as porosity increases in a water-filled sandstone;

(iii) Vp/Vs increases as clay content increases in a water-filled sandstone;

(iv) Vp/Vs response to porosity in limestones is questionable, but may increase as porosity increases if pore shape is elongate and remain constant if pore shape is spheroid;

(v) Vp/Vs decreases if gas is present in the pore spaces.

The fact that Vp/Vs is affected by various factors causes difficulties in interpretation. Ikwuakor (1988) stressed the problem of non-uniqueness and also suggested that researchers have erred in their emphasis on the velocity ratio. He concluded that porosity is actually linearly related to the difference between the shear wave transit time (Δts) and the compressional wave transit time (Δts).

Results obtained in the laboratory are useful to the explorationist if they can be applied to interpretation of field data. Shear-wave well logs are critical in tying observed elastic response to known geology and guiding the interpretation of shear seismic sections.

This paper deals with four wells in the Medicine River oil field. The approach has been to examine several of those parameters which have been studied in the laboratory and determine if similar trends are present in the field data.

METHODOLOGY

The Medicine River field is an oil field in central Alberta which was discovered in 1956. Production occurs from a number of zones in the Cretaceous, the Jurassic and the Missisippian. Hydrocarbon trapping is either stratigraphic or of the subunconformity type. The wells examined in this paper are 9-5-39-3W5, 9-7-39-3W5, 15-18-39-3W5, and 9-13-39-4W5. These are development wells drilled by Suncor Inc. between 1987 and 1989. 9-7-39-3W5 and 9-13-39-4W5 produce oil out of the Nordegg formation and 9-5-39-3W5 produces from the Basal Quartz (Ellerslie) unit. Data from Suncor Inc. consists of a full suite of wireline logs, a lithology log and a computer processed elemental analysis log for each well.

Each of the wells was examined for zones with relatively pure litholgies as determined by the lithology log and the gamma ray curve. Several mixed lithologies were also chosen for analysis. Compressional slowness, shear slowness and gamma ray curves were digitized, with readings recorded every metre.

Transit times were used to calculate Vp, Vs and Vp/Vs. Vp and Vs are directly used in seismic processing and conventional rock characterization: thus I prefer to use Vp/Vs instead of introducing the new value of Poisson's ratio (σ). The two are related by:

$$\sigma = \frac{.5(Vp/Vs)^2 - 1}{(Vp/Vs)^2 - 1}$$

Gamma ray response was converted to percentage shale by the relationship:

$$\% \text{ shale} = \frac{GR_{log} - GR_{sand}}{GR_{shale} - GR_{sand}} \text{ X } 100 \, ,$$

where GR is the gamma ray response in GAPI units and GR_{sand} and GR_{shale} values are based on the interpreted sand and shale lines.

This assumes a linear relationship between shale content and gamma ray deflection which may not be completely accurate. Shale determination is highly complex and is also geographically and stratigraphically dependent (Minear, 1982; Heslop, 1974). This simple relationship has been used, not in an effort to accurately evaluate shale content, but in order to test for general correlations between Vp/Vs response and shaliness.

Porosities were obtained from Compensated Neutron-Litho-Density logs when possible. When density porosity and neutron porosity curves did not agree the values were taken from the Elemental Analysis Log, a computer-processed interpretation which uses multiple curves to determine lithology, porosity, hydrocarbon saturation and permeability. Again, absolute values may not be completely accurate, but we should be able to observe any trends due to relative variations in porosity. Porosity values were not taken in shales due to the difficulty of obtaining meaningful values in this lithology.

Lithologies were obtained from the lithology log (which is based on the chippings observed by the wellsite geologist). These are in general agreement with the elemental analysis with two exceptions which will be noted.

Analysis involved making a number of crossplots of velocities, velocity ratios, porosity and percentage shale for each of the selected units in each of the four wells. These were then examined for trends. Comparisons were made between different formations and lithologies within each well and between wells. The overall response of the formations and the general lithologies from all four wells were also examined.

The full-waveform sonic logs analyzed in this study are Schlumberger Array-sonics. They do not extend over the entire well but rather over several hundred meters through the zones of interest. The Array-sonic tool is not borehole compensated so that transit times in regions of borehole washout are suspect. The shear-wave curve cannot be used in formations in which the shear-wave velocity is slower than the compressional-wave velocity of the mud as there will be no shear-wave refraction. In these wells this occurs in some shales and in all coals and is indicated by warning flags on the log and either off-scale or staight line shear-wave transit times.

Lithology log depths were not the same as wireline log depths and required adjustment using a suitable marker for reference. All depths referred to in this paper are Array-sonic log depths.

RESULTS AND ANALYSIS

Examining all four wells as a whole provides the widest variety of lithologies and a greater number of values to elucidate trends and variations.

To first test whether Vp/Vs is an effective lithology discriminator, only relatively pure examples of rock type are used. For sandstone, this includes the Basal Quartz sandstone (two wells), the Ostracod sandstone (two wells) and the Glauconitic sandstone (all four wells). The Basal Quartz is a very fine to fine grained, well sorted, subangular, quartzitic clean sandstone. The Glauconitic is a fine grained, well sorted, angular to subangular, quartzose sandstone with siliceous cementation (Watkins, 1966). The

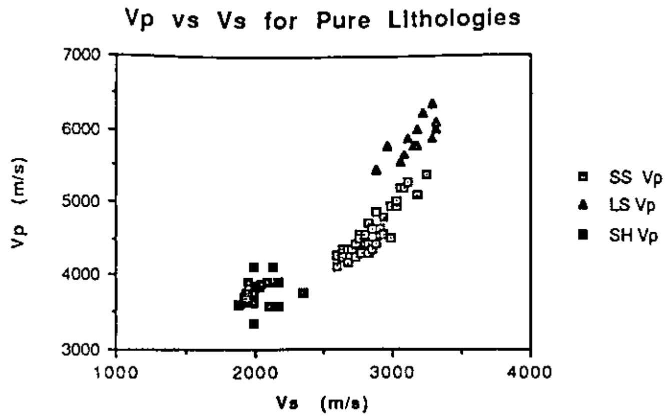


FIG. 1

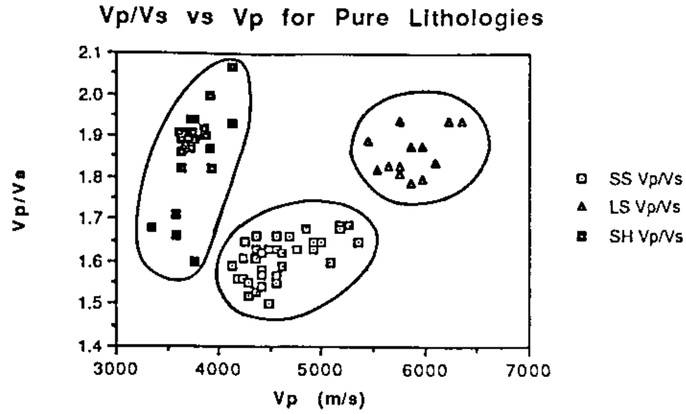


FIG. 2

FIG. 1. Pure sandstone (SS), limestone (LS) and shale (SH) are distinguished by differences in both compressional and shear-wave velocities.

FIG. 2. Replot of data in figure 1 as Vp/Vs vs. Vp shows a clear separation of lithologies.

Ostracod zone consists of medium quartz sand and shell fragments with calcareous cement (Ter Berg, 1966).

The only limestone is the Pekisko with data from two wells. The shale points are from the Fernie shale only, with data from three wells.

Figure 1 is a plot of Vp vs. Vs for each of these lithologies and demonstrates that the use of both velocities separates lithology better than compressional velocity alone as it separates data points in both the x and the y direction. Clearer differentiation is provided by a plot of Vp/Vs vs. Vp (Figure 2) which shows each lithology occupying a unique space.

Several mixed lithologies are also examined. The Shunda is sampled in one well and consists of interbedded limestone and shale according to the lithology log. The Nordegg formation is of Lower Jurassic age and is described by Ter Berg (1966) as a sandstone consisting of medium sorted, fine to medium grained quartz and chert which is cemented by dolomitic limestone. It is sampled in two wells. The Detrital is a mixture of lithologies, as its name suggests, but consists chiefly of dolomite in the one well from which the data is taken. The Upper Manville refers to a section of shaley sandstone taken from one well which has a fairly constant gamma response corresponding to about 25% shale.

A plot of Vp/Vs vs. Vp shows that the mixed lithologies fall in between and overlap with the pure lithologies of limestone, sandstone and shale (Figure 3). The Nordegg, Shunda and Detrital are mixtures of carbonates and clastics and plot between the sandstone and limestone data points. The Upper Manville plots close to the shale although it is 75% sandstone and 25% shale. This illustrates the strong influence of shale.

The average Vp/Vs for the sandstone units is 1.61, which falls within the literature value of 1.6-1.7. For the Limestone, the average is 1.86, lower than the literature value of 1.9. The Pekisko is somewhat dolomitic and not actually a pure limestone. Dolomite has a literature Vp/Vs of 1.8 which may explain the Pekisko value. As laboratory testing of shales is notoriously difficult and as shales are of less commercial interest, there are no values for the Vp/Vs of shale in the studies referenced. However, the average shale Vp/Vs of 1.86 is in agreement with preliminary work (Gittins, 1989) which quotes shale Vp/Vs averages ranging from 1.81-1.87 in other wells in Alberta.

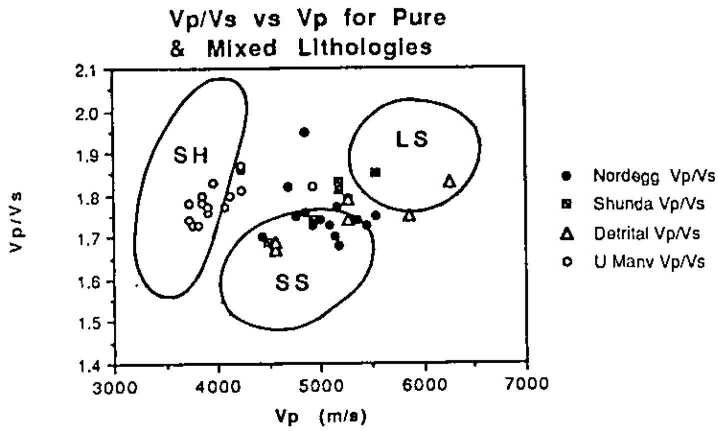


FIG. 3

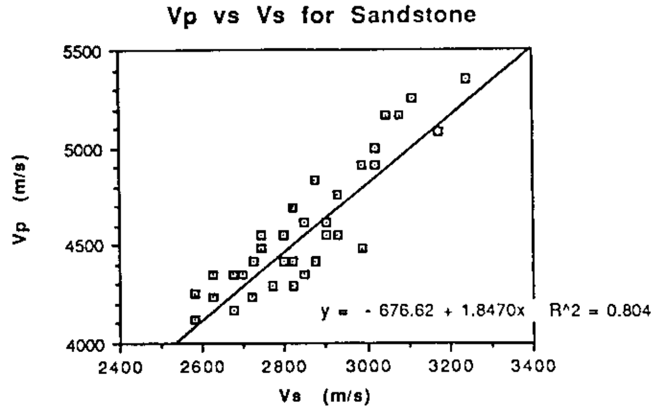


FIG. 4

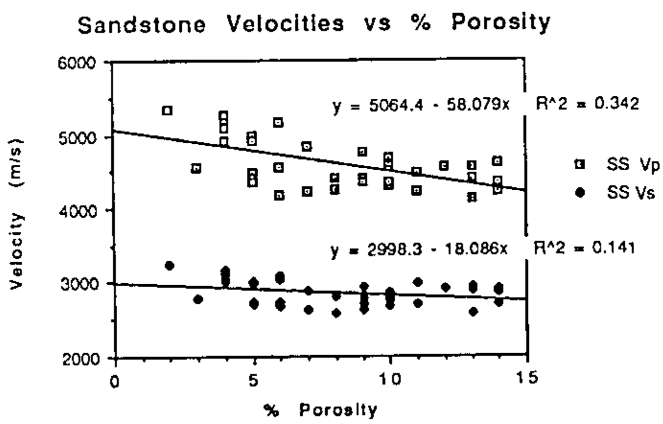


FIG. 5

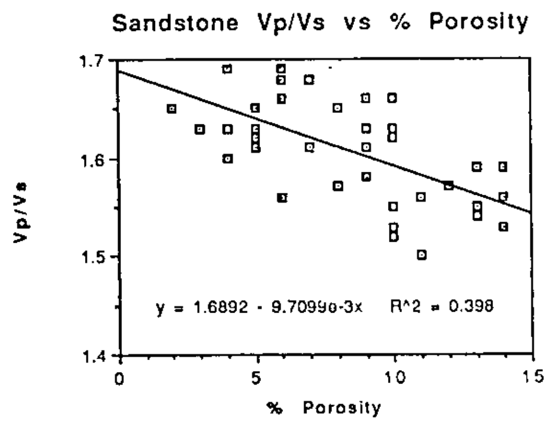


FIG. 6

FIG. 3. The Nordegg, Shunda, Detrital and Upper Manville units consist of mixed lithologies and have a Vp/Vs response which plots between their component lithologies.

FIG. 4. Shear-wave velocity appears to increase linearly with compressional-wave velocity for the sandstone samples.

FIG. 5. Both shear-wave and compressional-wave velocity decrease as porosity increases in the sandstones, but Vp is more sensitive.

FIG. 6. The velocity ratio decreases as porosity increases in sandstone due to the greater sensitivity of Vp.

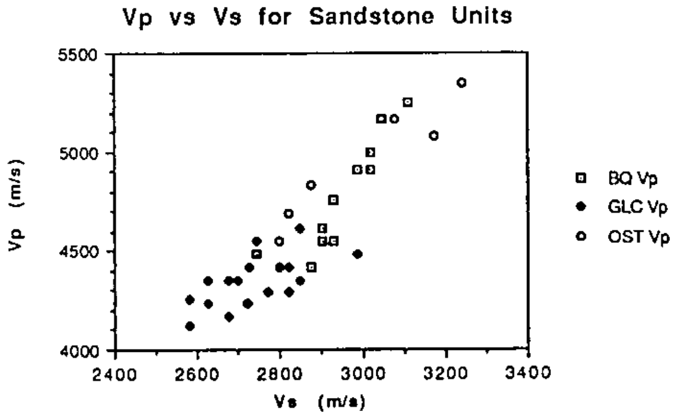


FIG. 7

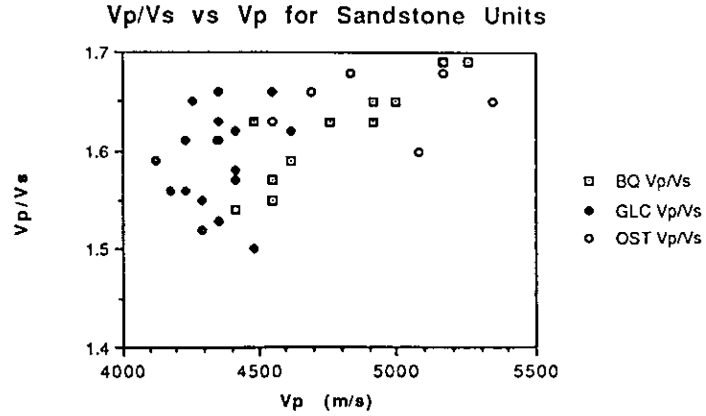


FIG. 8

FIG. 7. Shear-wave and compressional-wave velocities vary among the three sandstone units used to evaluate sandstone response.

FIG. 8. Vp/Vs values are scattered over a wide range for both the Basal Quartz and the Glauconitic units. There is considerable overlap in Vp/Vs for all three units.

The average Vp/Vs for the Detrital is 1.75, placing it between sandstone and dolomite. This is reasonable as the unit appears to be a dolomite with some sandstone, limestone and shale present. The Nordegg has an average Vp/Vs of 1.75; the presence of limestone appears to have raised the ratio above what we expect for a sandstone. The Shunda, a limestone with shale interbeds, has a Vp/Vs of 1.79, lower than the 1.9 value for pure limestone. In fact, as 1.8 is the expected value for dolomite, this could lead to a mistaken lithological identification of the Shunda. Interestingly, the elemental analysis logs, based on data from five well logs, mistakenly identify both the Shunda and the Nordegg as pure dolomites.

The Manville, with an average Vp/Vs of 1.79, falls above the high end of the sandstone range and is approaching the shale values. There is no danger of identifying the Manville unit as a dolomite since the Vp is dramatically lower and places it in an entirely different area of the Vp/Vs vs. Vp crossplot.

The functional relationship between Vp and Vs is still open to question. Figure 4 illustrates the quasi-linear relationship between Vp and Vs for the sandstone samples. The significance of the slope and intercept values and how they relate to physical rock properties is a subject for further investigation.

The sandstone velocity values used for the pure lithology crossplots are also plotted against porosity (Figure 5). Both Vp and Vs decrease as porosity increases but Vp decreases more rapidly, resulting in an overall decrease in Vp/Vs (Figure 6).

Sandstone data points are from three different rock units: the Basal Quartz, the Glauconitic and the Ostracod. These units are plotted individually in order to see if there is a difference in elastic response (Figure 7). There is in fact some clumping of the sandstone units with the Ostracod and Basal Quartz tending toward higher Vp and higher Vs than the Glauconitic. The Vp/Vs ratios are scattered over roughly the same range of 1.5 to 1.7 (Figure 8). The average Vp/Vs ratios are: 1.62 for the Basal Quartz, 1.60 for the Glauconitic and 1.66 for the Ostracod. Although there are too few data points to be conclusive, the units appear to have slightly different responses. Porosity, clay content and cementation could all contribute to these differences.

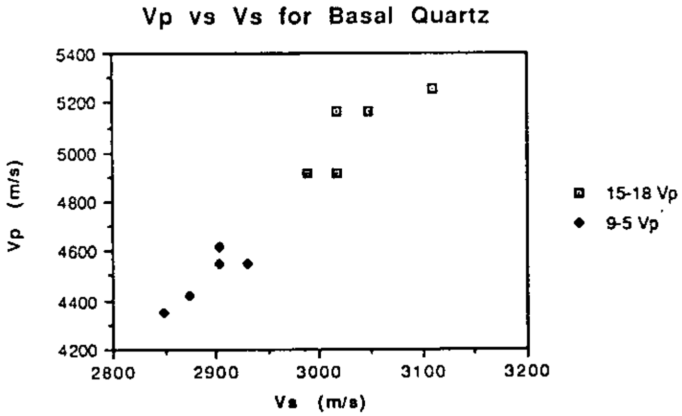


FIG. 9

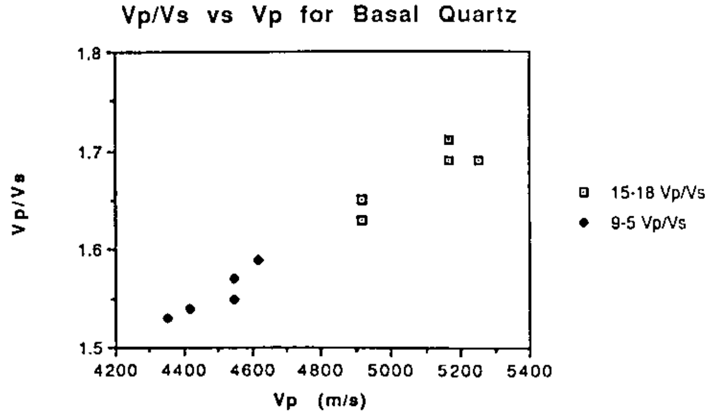


FIG. 10

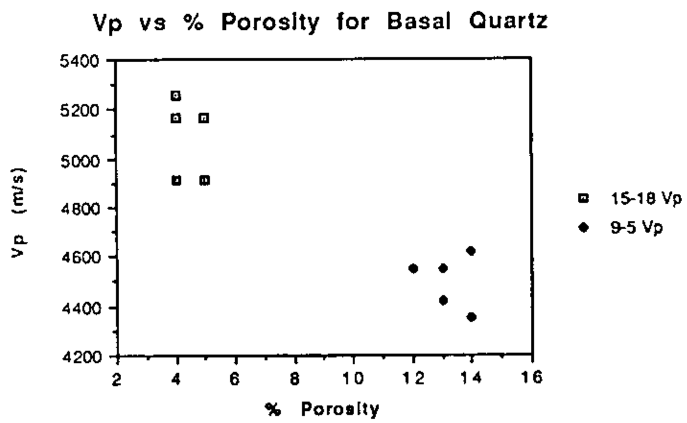


FIG. 11

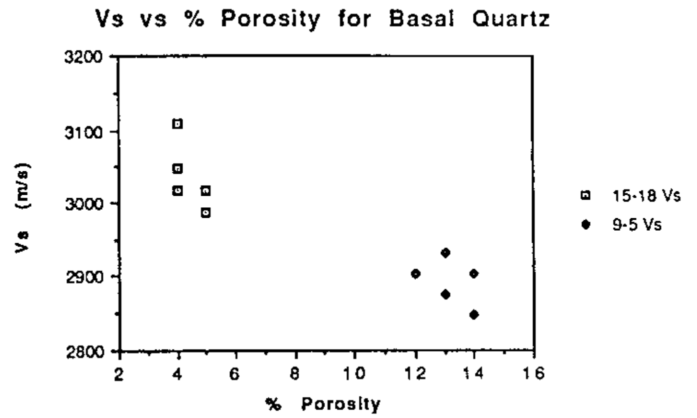


FIG. 12

FIG. 9. When the two wells from which the Basal Quartz data points are taken are compared, the 9-5 well exhibits substantially lower velocities than the 15-18 well.

FIG. 10. The velocity ratio for the 9-5 well (which produces oil out of the Basal Quartz) is lower than for the 15-18 well (in which this portion of the Basal Quartz is wet).

FIG. 11. Compressional-wave velocity is lower in the 9-5 well, which has greater porosity than the 15-18 well.

FIG. 12. The shear-wave velocity is lower in the more porous 9-5 well.

The data are also analyzed for the response of a particular formation from well to well. Variations in Vp/Vs response should be attributable to changes in porosity, pore fluid, or a facies change such as increasing shaliness. In cases where there are too few data points to establish any trends or draw any conclusions the analysis has been omitted from this paper.

The Basal Quartz sandstone is sampled from 9-5-39-3w5 (2144 - 2148 m) and 15-18-39-3w5 (2170 - 2174 m). The portion of the Basal Quartz sampled in the 9-5 well is clean, porous and oil-saturated sandstone. In 15-18, the Lower Basal Quartz section which is sampled has lower porosity, higher shale content and is water-saturated. These two wells separate quite distinctly on the velocity crossplots (Figures 9 & 10). This separation may be due to a differences in porosity, shale, pore fluid or some combination thereof. Figures 11 and 12 show that both Vp and Vs decrease as porosity increases in moving from 15-18-39-3w5 to 9-5-39-3w5. Again, Vp is more sensitive to the variation so that Vp/Vs decreases overall (Figure 13). This increase in porosity also corresponds to a decrease in shaliness (Figure 14). Both Vp and Vs increase with shaliness (Figures 15 & 16) but a more rapid rise in Vs results in an overall increase in Vp/Vs (Figure 17).

The shale data points are obtained exclusively from the Fernie shale and were taken from three wells: 9-7-39-3w5, 15-18-39-3w5 and 9-13-39-3w5. No clear trends are apparent on the crossplots for individual wells and no clumping of data points from individual wells was evident on the velocity crossplots.

The limestone data points are from the Pekisko formation and are taken from 9-5-39-3w5 and 15-18-39-3w5. The data points from each of the wells overlap on the velocity plot and appear to be in general agreement although there is considerable scatter (Figure 18). Plots of velocities against porosity indicate that Vp and Vs are not dependent on porosity (Figure 19).

The data from the Nordegg formation are from the 9-7-39-3w5 and the 9-13-39-4w5 wells. The velocity plot shows that the data from each of the wells overlap and are in good agreement with an apparent linear correlation between Vp and Vs (Figure 20). Porosity crossplots show Vp and Vs decreasing sharply in both wells as porosity increases (Figure 21). Vp/Vs is scattered but remains relatively constant (Figure 22). The crossplots of velocity vs. shale for the Nordegg do not show any clear trends for Vp or Vs. The Vp/Vs is relatively constant over a range of shale values from 0% to 35%.

Although the Shunda and the Detrital are distinct lithologies according to the lithology log, they resemble each other in Vp/Vs response. This point is graphically illustrated by plotting both formations together. Both formations appear to have a linear relationship between Vp and Vs (Figure 23). Velocity responses to porosity are similar with a more rapid decrease in Vp than in Vs resulting in an overall decrease in Vp/Vs (Figures 24, 25, & 26). Vp/Vs shows no trend with increasing shale content in the Shunda; gamma readings are not available for the Detrital.

DISCUSSION

The most unusual result of this analysis is the consistent drop in Vp/Vs as porosity increases. This was observed in the pure sandstone lithology, and the Shunda, Basal Quartz and Detrital formations. This trend differs from the results of Domenico (1984), Han et al., (1986) and King et al., (1988), in which Vp/Vs increases with increasing porosity except in the presence of gas.

The Basal Quartz sandstone wells illustrate the difficulty in interpreting variations in Vp/Vs. The 9-5 well produces oil out of this zone and exhibits higher porosities and lower shale content than 15-18, which is wet. The decrease in Vp and in Vs in 9-5 is expected because the rock is more porous. The decrease in Vp/Vs is surprising because it indicates that Vp is more sensitive to porosity as noted previously.

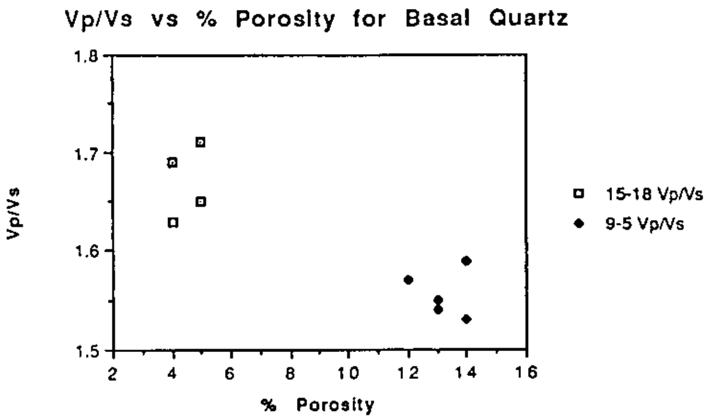


FIG. 13

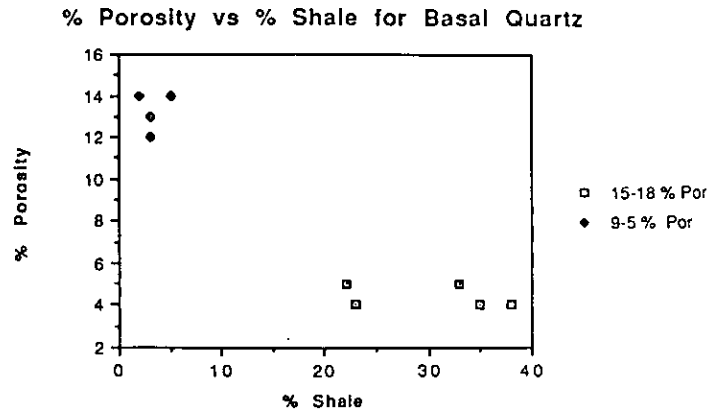
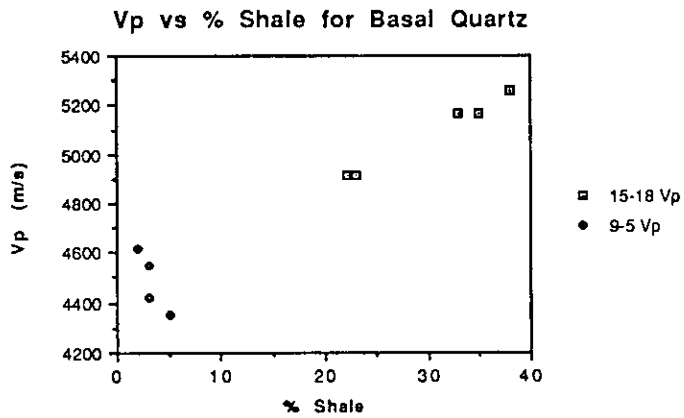


FIG. 14



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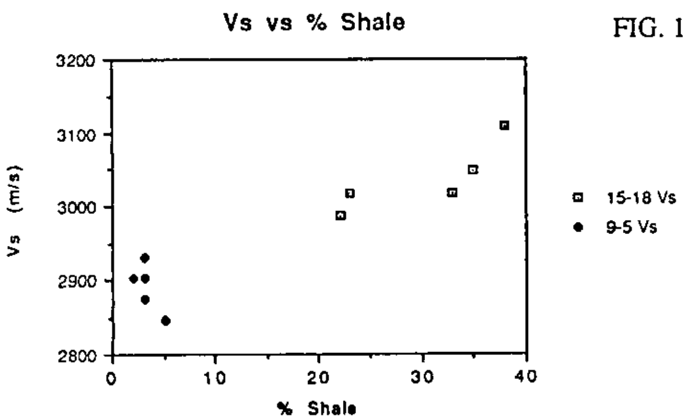

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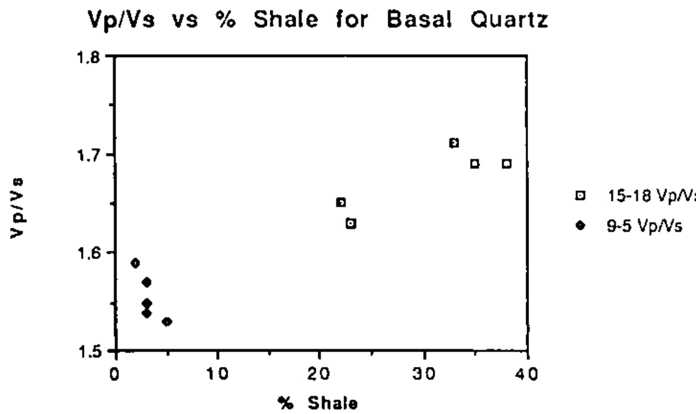

FIG. 17

FIG. 13. A lower Vp/Vs in the 9-5 well suggests that the velocity ratio decreases as porosity increases due to the greater sensitivity of Vp.

FIG. 14. The decrease in porosity as we move from the 9-5 well to the 15-18 well is accompanied by an increase in shaliness. This makes the cause of Vp/Vs variations difficult to pinpoint.

FIG. 15. Compressional-wave velocity is higher in the 15-18 well, which has greater shale content.

FIG. 16. Shear-wave velocity is greater in the 15-18 well.

FIG. 17. The Vp/Vs ratio is higher in the 15-18 well, which is more shaley, less porous and is wet rather than oil-saturated.

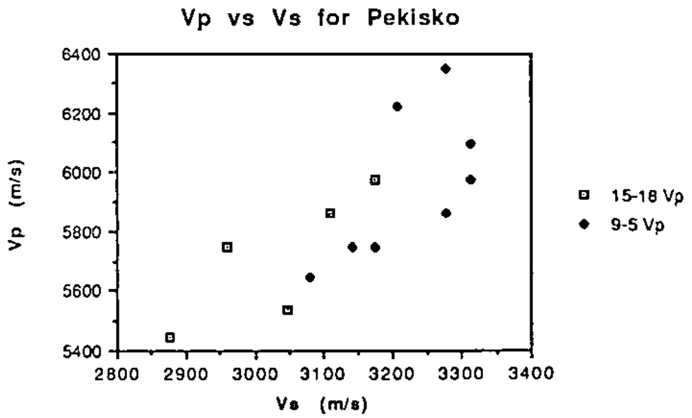

FIG. 18

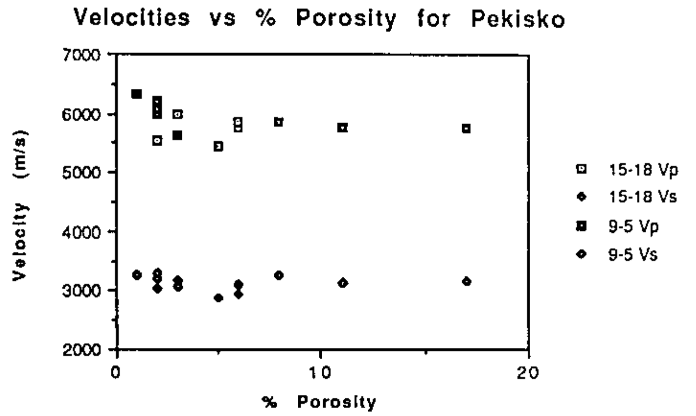

FIG. 19

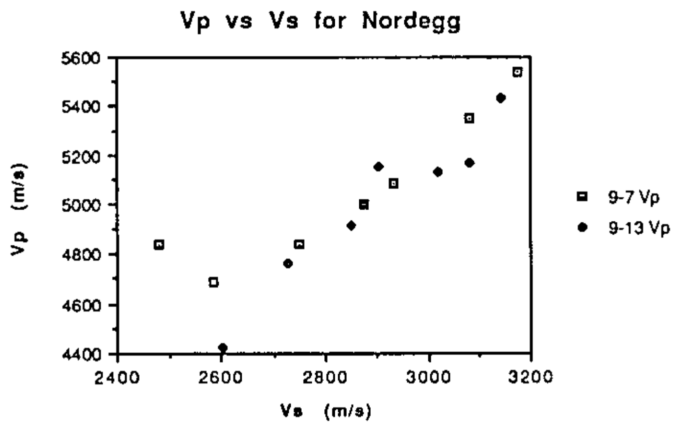

FIG. 20

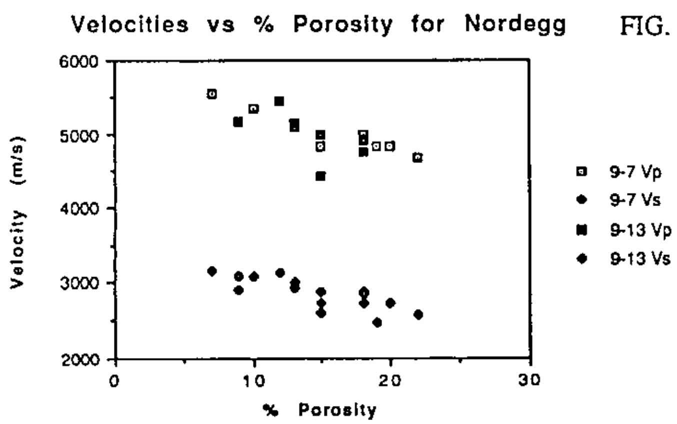

FIG. 21

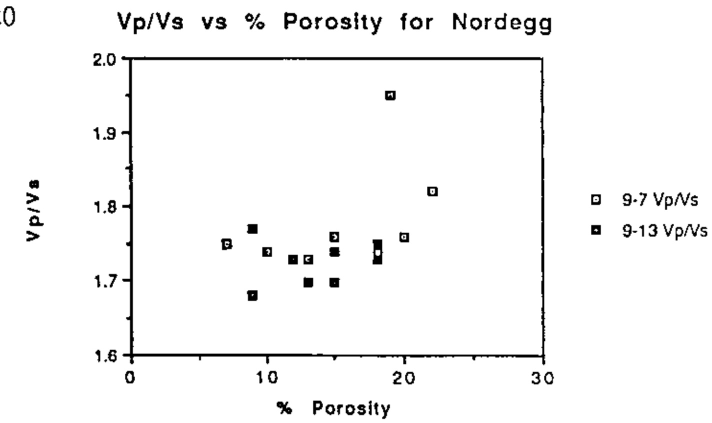

FIG. 22

FIG. 18. Both wells from which the samples for the Pekisko limestone are taken show Vp increasing with Vs, but the data are scattered.

FIG. 19. The limestone samples do not display any consistent velocity trends with changing porosity for either mode in either well.

FIG. 20. Vp increases linearly with Vs in both wells from which the Nordegg unit is sampled. The amount of overlap indicates a consistent response between wells.

FIG. 21. In both wells compressional-wave and shear-wave velocities decrease as porosity increases in the Nordegg.

FIG. 22. The Vp/Vs ratio does not display a clear response to porosity variation in either of the Nordegg units.

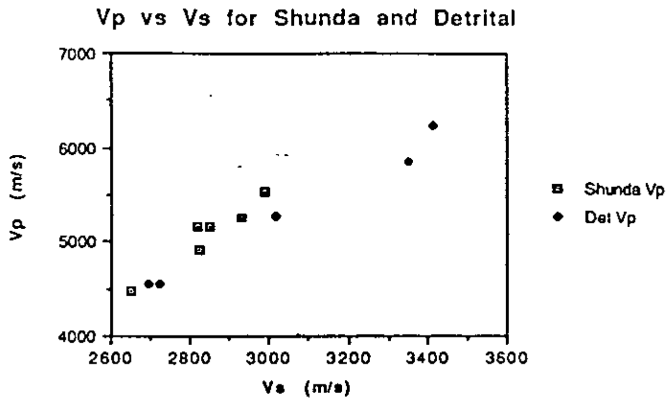

FIG. 23

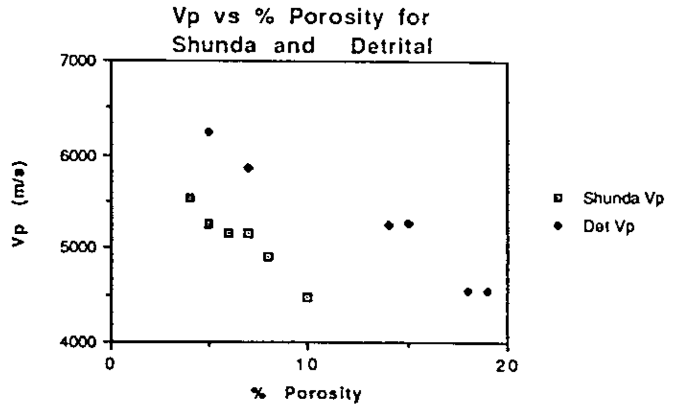

FIG. 24

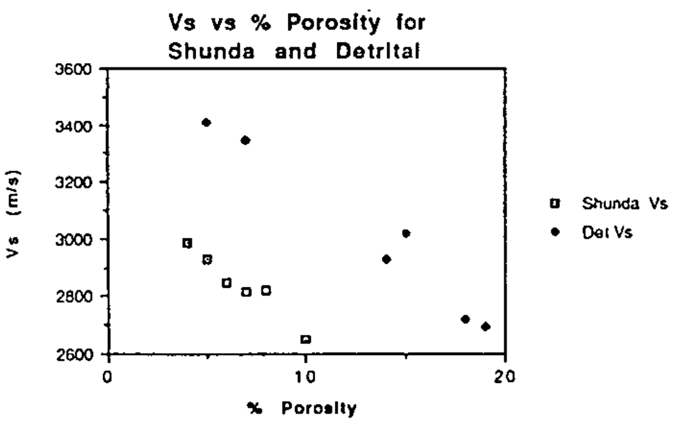

FIG. 25

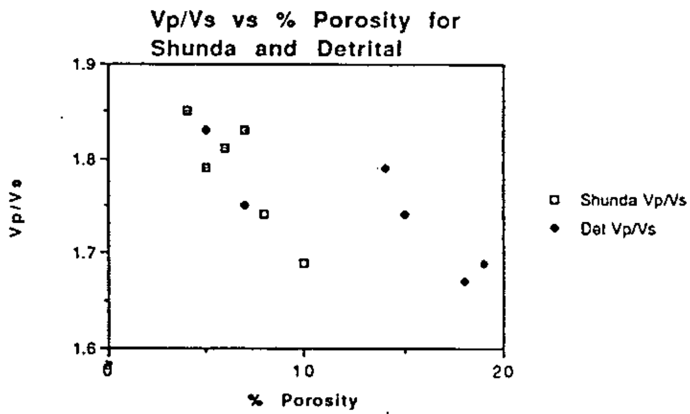

FIG. 26

FIG. 23. Both the Shunda and the Detrital (Det) units exhibit an increase in Vp with Vs.

FIG. 24. Compressional-wave velocity decreases as porosity increases in both units.

FIG. 25. Shear-wave velocity decreases with rising porosity in both units, but at a slower rate than Vp.

FIG. 26. Both the Shunda and the Detrital exhibit an overall decrease in Vp/Vs with a rise in porosity.

Comparison between wells for this unit also shows a rise in Vp/Vs as shaliness increases. This result is in agreement with published data (Castagna et al., 1985; Han et al., 1986; King et al., 1988). The theory behind this observation is simply that saturated shales tend to soften the rock matrix and thus reduce the shear modulus, while not appreciably altering the bulk modulus. Both velocities are expected to decrease, but shear velocity will be more severly affected and the Vp/Vs will increase.

Another unexpected trend in the Basal Quartz is the increase in both Vp and Vs with increased shaliness - a result that does not appear reasonable in light of the decreasing shear strength of the rock. The velocity increase may actually be due to the decrease in porosity which occurs simultaneously. This example illustrates the problem of non-uniqueness associated with Vp/Vs ratios. Literature would suggest that, since Vp/Vs is expected to increase as porosity increases, the increase is due to the shale effect. Although porosity has a stronger influence on Vp/Vs than clay content, this may be a case where the shale effect overpowers the porosity effect due to its greater range of values. Pore fluid is another consideration in this case. Oil has a slightly lower Vp than water and may cause a reduction in Vp/Vs. Although this is an oil well, small amounts of gas can cause large reductions in Vp/Vs and may account for the result. The other formations in which Vp/Vs decreased with increased porosity did not exhibit any particular trends related to shaliness.

Understanding the relationship between Vp, Vs and porosity is critical if the velocity ratio is going to be of full use in hydrocarbon exploration. Investigation of the anomalous porosity results observed in this study is ongoing.

From previous results, an increase in Vp/Vs may indicate a rise in porosity - prospective - or a rise in shale content - not prospective. In the Basal Quartz, a decrease in Vp/Vs accompanied a rise in porosity and a decline in shaliness - both indications of a prospective location. A decrease in Vp/Vs is also indicative of gas, again a potential well location. If the decrease in Vp/Vs with increased porosity is a genuine trend this would be good news for the explorationist, who could interpret all Vp/Vs reductions within a known lithology as good indications for a prospect.

CONCLUSIONS

This study found that the Vp/Vs ratios derived from full-waveform sonic logs reliably discriminate between sandstone, limestone and shale lithologies in the wells considered. This result is in agreement with published theoretical and laboratory work. Crossplots of Vp/Vs and Vp are particularly effective in separating these lithologies.

Formations which consist of mixed lithologies have Vp/Vs ratios which fall between and may overlap with those of pure lithologies. This does not cause confusion in the case of a shaley sandstone but does in the case of a shaley limestone, which has a response similar to dolomite.

Vp/Vs ratios have complex dependencies on porosity, shale content and pore fluid which are difficult to unravel. Several horizons in these wells exhibited a Vp/Vs decrease as porosity increased, a result which does not conform to previous published studies. This trend was also observed in previous unpublished studies at the University of Calgary. Further study is required in order to better understand these results and to differentiate between the various factors which affect seismic velocities.

The limestone data base is quite small and not taken from a pure limestone, but no correlations between velocity ratio and porosity were observed. This has also been the general experience of other researchers.

The only conclusive statement about the shale is that it separates clearly from other lithologies on velocity crossplots.

FUTURE DIRECTIONS

The CREWES project has received full-waveform sonic logs from a number of oil companies. The analysis of these logs will allow CREWES to establish a data base for full-waveform well log data in the Western Canadian basin. We hope to determine if there are consistent trends for particular horizons or for particular areas. Such knowledge will assist both in well-log analysis and in multicomponent seismic interpretation.

ACKNOWLEDGMENTS

I would like to thank Suncor Inc., in particular David Byler, Manager of Technical Services, for the donation of well log and lithology information for this study.

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