CANADIAN JOURNAL OF EXPLORATION GEOPHYSICS
VOL 24, NO 2 (DECEMBER 1988), P. 110-116

ELASTIC-WAVE AND RELATED PROPERTIES OF CLASTIC ROCKS FROM THE ATHABASCA BASIN, WESTERN CANADA

M.S. KING[1], M.R. STAUFFER[2], H.J.P. YANG[3] AND Z. HAJNAL[2]

ABSTRACT

Correlation of the elastic-wave velocities of drill-core specimens with mineral compositions and textures of clastic rocks at South McMahon Lake in the Athabasca basin, western Canada, suggests that these velocities might be useful for identifying large zones of high porosity or high clay content (such as some fault zones, or the clay-rich haloes surrounding known uranium ore bodies). The seismic velocities V_p and V_S, and the ratio V_p/V_S for Athabasca Group rocks are found to be influenced by changes in porosity more strongly than by changes in clay content by a factor of approximately four. For clay fractions less than 0.15, simple linear relationships appear to exist between the reciprocal velocities $1/V_p$ and $1/V_S$, and the ratio V_p/V_S, and porosity.

INTRODUCTION

In addition to conventional compressional-wave surveys, widespread use is now being made of shear-wave velocities in seismic surveys. A number of workers in recent years have described methods for obtaining such data. They have demonstrated the importance of the ratio of compressional- to shear-wave velocity (V_p/V_s) in interpreting field data in terms of lithology and texture, and as an indicator of the presence of hydrocarbons in oil exploration. Cherry and Waters (1968), Tatham and Stoffa (1976), Polškov et al. (1980) and Ensley (1984) have described field methods for obtaining shear-wave as well as compressional-wave data for these purposes in seismic surveys. Tatham (1982) has provided an extensive review of the experimental and theoretical aspects relating V_p/V_s to rock lithology and texture. Tosaya and Nur (1982) reported the effects of the presence of clays on V_p in detrital silicate rocks. Domenico (1984) studied means for determining rock lithology and porosity from V_p and V_s laboratory measurements. Wilkens et al. (1984) discussed the effect on V_p/V_s of changes in composition of siliceous limestones. Castagna et al. (1985) investigated the effect on V_p/V_s of changes in clay content in clastic silicate rocks. In other applications, V_p/V_s was used by Moos and Zoback (1983) to estimate fracture patterns from velocity data obtained in boreholes in crystalline rocks and by Hamilton (1979) to model the sea floor for underwater acoustics and foundation-engineering applications. Jain (1987) reviewed some aspects of V_p/V_s with reference to petroleum prospecting.

The variations of compressional-wave velocity with composition and texture of rocks at South McMahon Lake in the eastern part of the Athabasca basin have been reported by Hajnal et al. (1983). That study and the one described here are preludes to the development of the seismic method as a prospecting and mapping tool in this Precambrian setting. The basin is comprised of flat-lying, Middle Proterozoic, coarse clastic rocks (Athabasca Group) covering approximately 100 000 km^2 in northern Saskatchewan, Canada. Athabasca Group rocks rest unconformably on a basement of Archean to Lower Proterozoic gneiss and granite and are the host for several extremely rich uranium ore deposits located at or near the sub-Athabasca unconformity. Most of these ore deposits are surrounded by clay-rich haloes. Cores were obtained from three 200-m deep boreholes, located on a line 1 km long straddling South McMahon Lake in the vicinity of a uranium mineralized zone (Figure 1). Thin sections were studied, and measurements of V_p, V_s and porosity were made for 463 core samples representing both the Athabasca clastic rocks and the underlying basement material. Permeability measurements were made on 248 samples from two of the boreholes.

The dominant lithology in the area discussed by Hajnal et al. (1983) is slightly pebbly, moderately sorted, laminated to thin-bedded, medium-grained, quartz sandstone. Some of these features change with depth in a regular though crude manner and, as a result, the rocks can be divided into five distinctive lithologic units (Figure 2),

---

Manuscript received by the Editor February 18, 1988; revised manuscript received May 16, 1988.

[1] Department of Mineral Resources Engineering, Imperial College of Science and Technology, London SW7 2BP, United Kingdom

[2] Department of Geological Sciences, University of Saskatchewan, Saskatoon, Saskatchewan S7N 0W0

[3] College of Engineering, National Taiwan University, Taipei 107, Taiwan

This research project was supported by the Geological Survey of Canada under DSS Contract No. ISU80-00152 with the University of Saskatchewan. The authors wish to acknowledge, with thanks, the loan of drill core from Canada Wide Mines Ltd. and the assistance provided by Tanya Colbourne with the laboratory measurements.

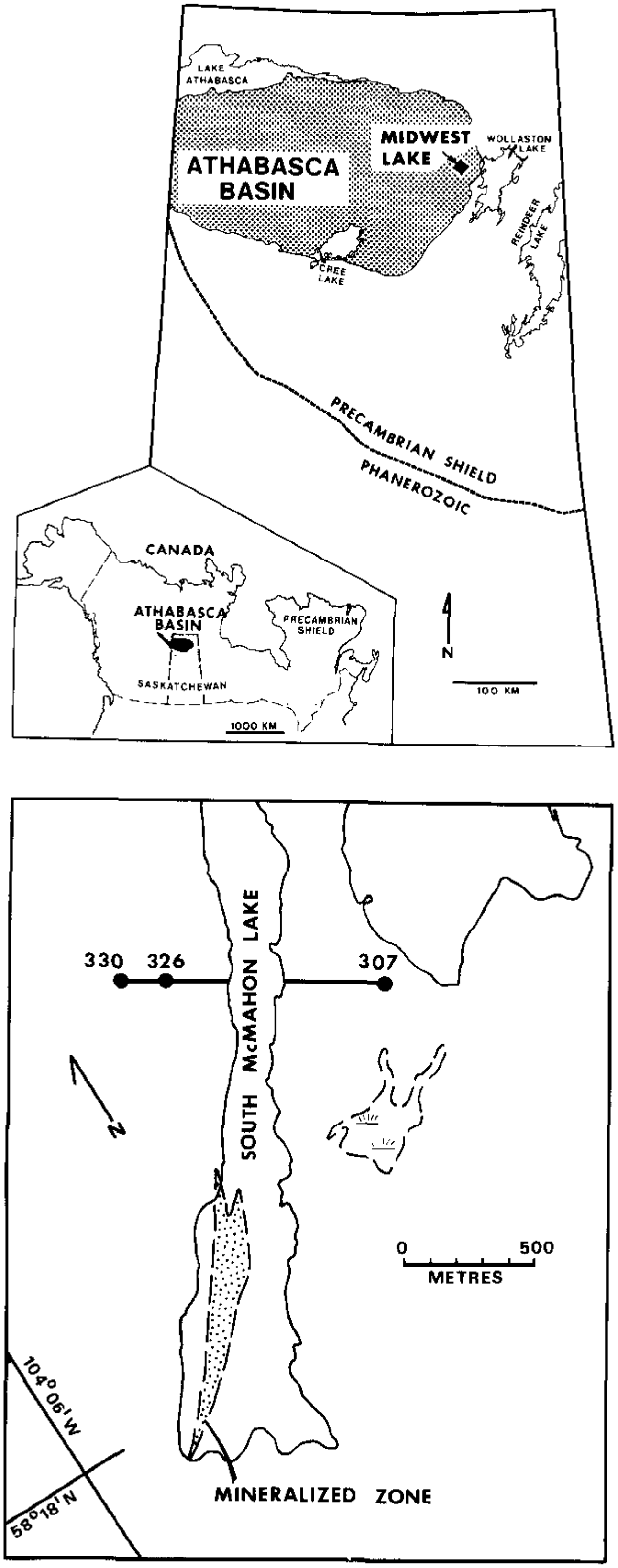

Fig. 1. (**a**) Location of South McMahon (Midwest) Lake. The uranium prospect is known as the Midwest deposit.
(**b**) Location of boreholes sampled, South McMahon Lake.

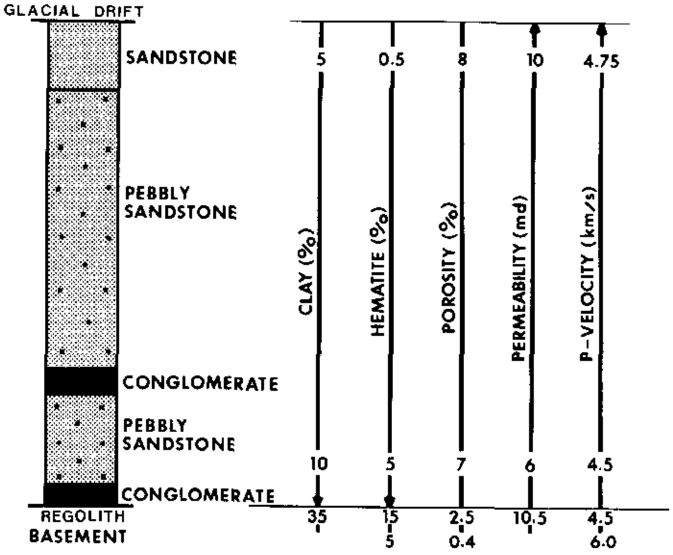

Fig. 2. Generalized stratigraphic variation of clay, hematite, porosity, permeability, and P-wave velocity: South McMahon Lake. Depth to basement is approximately 200 m. Data obtained from core samples, thin sections and laboratory measurements. More detail is given in Figures 5, 6 and 7.

forming two fining-upwards sequences, each with several metres of basal conglomerate or pebble beds. V_p, porosity and permeability also vary with rock type and with stratigraphic position, as indicated also in Figure 2.

The degrees of compaction and cementation of the Athabasca rocks were determined from the thin sections and, on this basis, the rocks were divided into four textural types (Figure 3). These textural types are largely independent of grain size but refer primarily to siltstones and sandstones or, in conglomerates, to just the sand matrix. Type 1 rocks are well compacted and have undergone considerable pressure solution. They contain little clay (less than 5 percent) or hematite (less than 1 percent), have porosities lying between 6 and 8 percent and, as Figure 3 illustrates, contain well-sorted, medium-sized grains that have smooth contacts. Type 2 rocks are the most common type present. They are moderately to poorly compacted and contain variable amounts of cement: between 6 and 20 percent clay and up to 10 percent hematite. Most of these rocks are well-sorted, medium-grained, and have porosities lying mainly between 4 and 10 percent. Type 3 rocks contain considerable amounts of clay (20 to 30 percent), locally some hematite, and most are poorly sorted. Type 4 rocks are rare and occur only in thin silt/clay seams. The clay (30 to 40 percent) forms a continuous matrix in which the silt grains are embedded; their porosity lies between 2 and 4 percent.

EXPERIMENTAL PROCEDURES

Specimen preparation

Over 450 cylindrical core specimens were used for the seismic velocity, density and porosity measurements of Athabasca rocks. These specimens were 54 mm in diameter and approximately 75 mm in length. In some cases, however, where the core was friable or contained weak

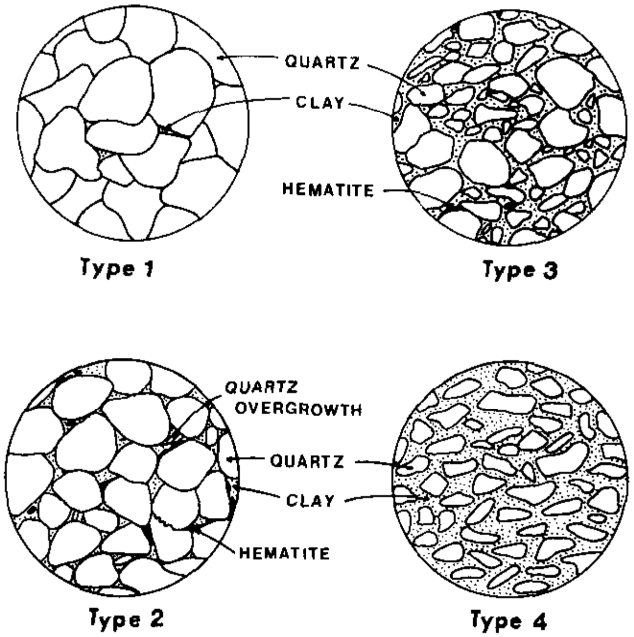

Fig. 3. Main types of textures seen in thin sections of core samples from South McMahon Lake. Each field of view has a diameter of about 2 mm.

bedding planes, the length of the specimens had to be reduced to less than 75 mm.

For permeability measurements, the test specimens were 19 mm in diameter. These were cored from some of the larger specimens referred to above, in directions parallel and perpendicular to bedding, upon conclusion of the seismic velocity and density measurements.

Measurement

The fully water-saturated specimens were weighed and their saturated bulk densities were calculated. The specimens were dried for 24 hours in a vacuum oven maintained at 80°C. They were again weighed and their dry densities calculated. The porosity of each sample was calculated from the known volume of water removed during drying. The accuracy in measuring the fractional porosity is estimated to be approximately ± 0.003.

The compressional- and shear-wave velocities were measured with an accuracy of ± 0.5 percent for V_p and ± 1.0 percent for V_s, with precisions of ± 0.3 percent and ± 0.5 percent respectively. The time-of-flight ultrasonic measuring technique used here has been described by King (1983), with the equipment shown in block form in Figure 4. Measurements were made on fully water-saturated specimens over a range of uniaxial stresses from 2 MPa to 25 MPa (specimens were placed in rubber sleeves but no confining pressure was provided; thus the axial stress is equal to differential pressure).

The permeability measurements were made on dry specimens contained in a Hassler sleeve at a confining pressure of 0.7 MPa. Nitrogen was used as the flowing fluid. In as many cases as possible, permeabilities were determined both parallel and perpendicular to the bedding plane. The accuracy in permeability measurements is estimated to range from ± 25 percent at low permeabilities (< 5mD or 5×10^{-3} μm²) to ± 5 percent at the higher values (> 15 mD or 1.5×10^{-2} μm²).

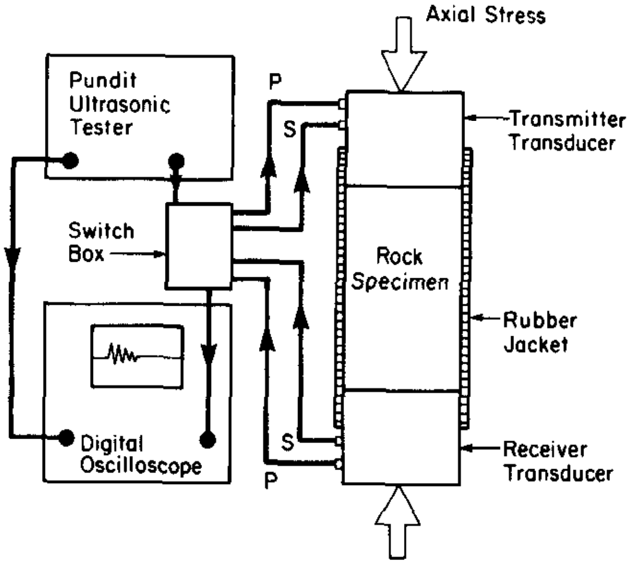

Fig. 4. Block diagram of ultrasonic velocity-test equipment for cylindrical rock specimens subjected to uniaxial stress.

Results and Discussion

Preliminary studies

The lithological factors that might be expected to affect elastic-wave velocities in rocks from the Athabasca Group — clay content, hematite content, porosity and permeability — all vary with depth, as indicated diagrammatically in Figure 2. Their detailed variations are shown in Figures 5, 6 and 7, in which laboratory measurements of porosity, density, V_p, permeability, hematite content and clay content are plotted as functions of depth for the three boreholes numbered 307, 326 and 330.

Density

The average dry and water-saturated densities of the core samples studied are 2434 and 2508 kg/m³, respectively, although there are significant local deviations from these values. In general, the values of density show no significant depth or stratigraphic variation. Changes in the hematite or clay contents also appear to have no observable effect on the values of measured density, partly because (for unknown reasons) an increase in hematite usually occurs with a concomitant increase in porosity.

Porosity

Most of the samples studied have porosities between 0.05 and 0.10. Figures 5, 6 and 7 do not reveal a significant variation of porosity with depth, nor any direct relationship

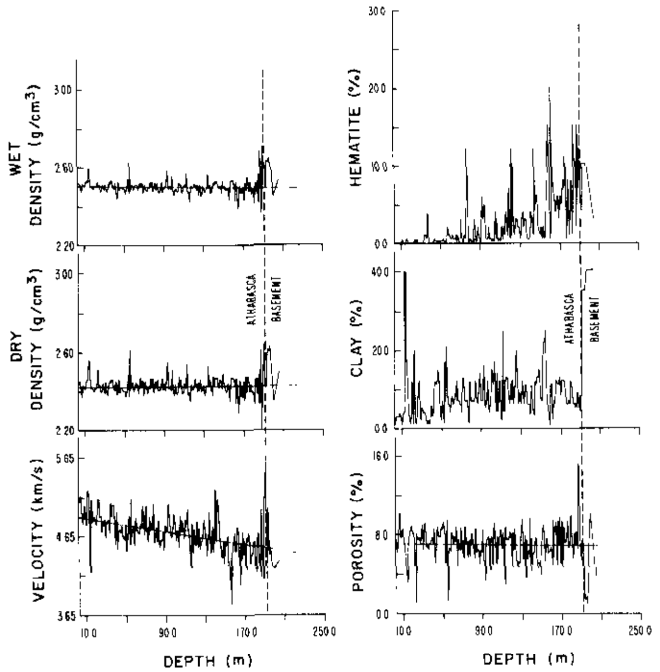

Fig. 5. *P*-wave velocity, dry and water-saturated density, porosity and clay content for core samples from borehole 307, as functions of depth. Permeabilities were not measured for this core.

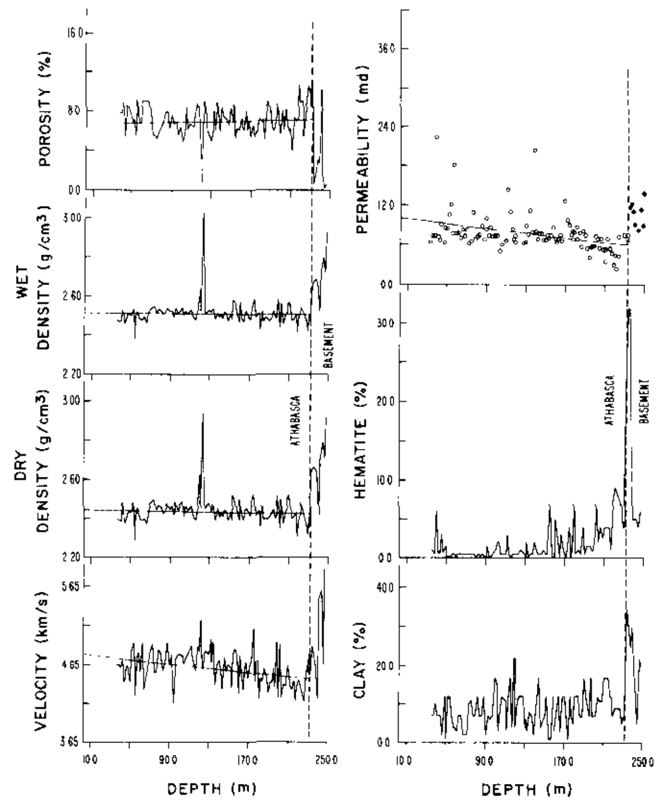

Fig. 6. *P*-wave velocity, dry and water-saturated density, porosity, clay content and permeability for core from borehole 326, as functions of depth.

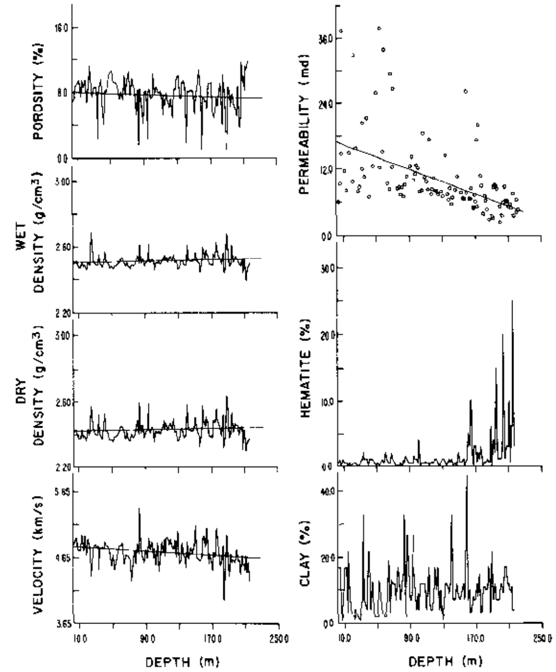

Fig. 7. *P*-wave velocity, dry and water-saturated density, porosity, clay content and permeability for core from borehole 330, as functions of depth.

between V_p and porosity. This apparent lack of correlation, however, is misleading and is due to the compositional variation among the samples, especially the clay content, as will be shown later. Figure 8 demonstrates clearly that V_p decreases as porosity increases.

Clay content

Clay fractions vary mainly between 0.05 and 0.15 but range from nearly 0 to 0.40. In general, the correlation between clay fraction and V_p demonstrates that an increase in clay content results in a marked decrease in V_p. It should be noted that as the clay fraction increases, the porosity appears to decrease by only a small amount. Figures 5, 6 and 7 indicate a general but slight increase in clay content with depth in the upper one-third of each borehole, with little overall change in the lower two-thirds.

Hematite content

Figures 5, 6 and 7 show that the hematite content is variable from bed to bed in the Athabasca rocks and that, overall, there is a pronounced increase with depth (see also Figure 2). The increase in hematite content with depth appears to coincide with the decrease in V_p with depth; however, this is misleading. Various hematite value ranges plotted on a V_p vs porosity diagram (Figure 8) show no clustering of data according to hematite content. Hematite thus appears to have about the same V_p as quartz. This may be a significant observation because no experimental data for hematite appear to have been published (despite a dedicated search of the literature by us).

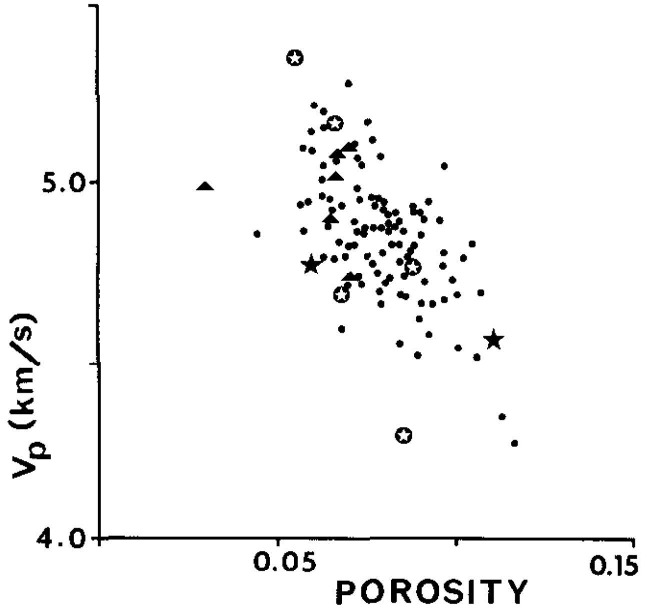

Fig. 8. V_p vs porosity vs hematite content. This plot shows the lack of effect of hematite on V_p (26 MPa uniaxial pressure). Dots represent data for hematite contents of 0 to 0.05; triangles refer to contents from 0.06 to 0.10; open stars, 0.11 to 0.15; and solid stars, 0.16 to 0.20 (symbol size varies with relative frequency of data for the various value ranges). Data from all 3 holes are plotted but only for clay contents less than 0.05 in order to reduce the clutter (this introduces no bias in interpretation).

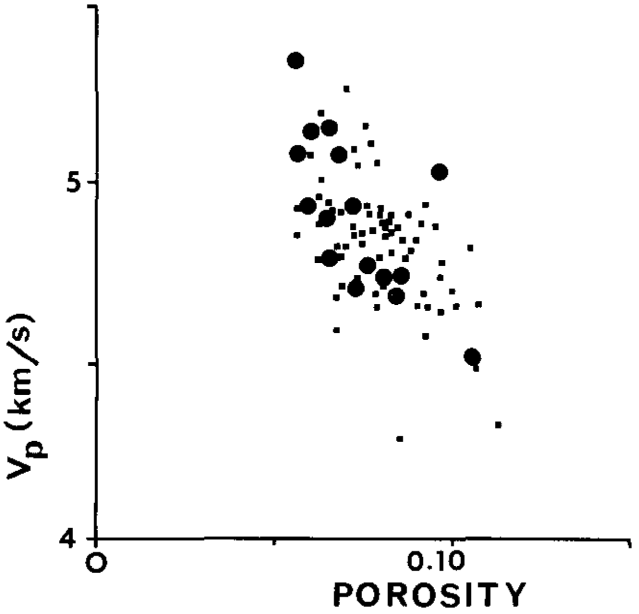

Fig. 9. V_p vs porosity vs grain size. This plot shows the lack of effect of high pebble content on V_p (25 MPa uniaxial pressure). Large dots represent data for conglomerates with 51 to 75 percent pebbles and a common pebble diameter range of 10 to 15 mm (range 2 to 30 mm); small squares represent data for sandstones, most of which contain no pebbles, although the pebble content is up to 15 percent for some samples for which the common pebble diameter range is 2 to 5 mm. Data for all 3 holes is plotted but only for clay contents less than 0.05 and for pebble contents of 0 to 15 percent and 51 to 75 percent in order to avoid clutter (this introduces no bias in interpretation).

Grain size

The various stratigraphic units at South McMahon Lake are delineated mainly by grain size (Figure 2). Figures 5, 6 and 7 do not indicate any observable difference in V_p with stratigraphic position. Also, plots of V_p vs porosity for various grain sizes do not show differential clustering (Figure 9), indicating that grain-size variation has little to no effect on V_p in the Athabasca rocks at South McMahon Lake.

Permeability

The permeability is locally highly variable but, in general, appears to decrease with depth despite the uniform porosity (Figures 6 and 7).

Linear regression analyses of the preliminary results as a function of depth for samples from each of the boreholes are shown in Table 1. It is clear from the low magnitude of the regression slopes for density, porosity and V_p that the overall changes in these parameters with depth are not dramatic. Of the various rock properties, grain size and hematite fraction have little to no effect on V_p. Porosity and clay content, however, are both important controls on the rocks' seismic velocities.

Elastic-wave velocities

V_p and V_s for typical water-saturated Athabasca Group rock specimens are plotted as functions of uniaxial stress to 25 MPa in Figure 10, for sample porosities in the range 0.03 to 0.16. The pronounced changes in slope for V_p and V_s at low axial stresses probably result from the closure of microcracks of small aspect ratios at these stresses. A statistical analysis of V_p/V_s ratios for all specimens tested indicates that in the range of axial stresses from 8 to 25 MPa there is only a small increase in V_p/V_s. This overall change (an increase of 0.07 percent) is considerably less than the ± 0.8 percent uncertainty based on the precision of the experimental results. The reason for the small change observed in V_p/V_s is discussed by Tatham (1982), who shows in his Figure 6 that once the microcracks of small aspect ratios in a porous sandstone are closed, V_p/V_s is relatively insensitive to further changes in stress (as might be caused by an increase in axial stress from 8 to 25 MPa).

The empirical time-average relationship proposed by Wyllie et al. (1956) for water-saturated porous rocks predicts a linear relationship for $1/V_p$ as a function of porosity. Geertsma (1961) used the theories of Gassman and Biot to arrive at a similar conclusion. Multiple linear regression has been employed here to determine $1/V_p$, $1/V_s$ and V_p/V_s as functions of porosity (ϕ) and clay fraction (F_c) for a total of 458 rock samples from the Athabasca Group [433 from the three boreholes studied by Hajnal et al. (1983) and 25 from other boreholes in the Athabasca basin]. The velocities used are those measured at an axial stress of 25 MPa (to avoid the effects of the presence of microcracks). The regressions determined for $1/V_p$, $1/V_s$ and V_p/V_s are shown in Table 2. The standard deviations of the regression coefficients for ϕ and F_c and multiple correlation coefficient r,

Borehole No.	Parameter y	Intercept a_0	Regression Coefficient a_1	Value at last sample or contact	
307	V_p*(km/s)	4.890	−0.0020	4.427	(contact, 192.10 m)
	Density, dry	2431	−0.02	2427	
	(kg/m^3) saturated	2504	−0.03	2497	
	Porosity (%)	7.2	−0.0010	7.0	
326	V_p*(km/s)	4.813	−0.0014	4.489	(contact, 231.35 m)
	Density, dry	2452	−0.09	2432	
	(kg/m^3) saturated	2521	−0.06	2507	
	Porosity (%)	6.9	0.0021	7.4	
	Permeability (mD)	10.1	−0.0180	5.9	
330	V_p*(km/s)	4.810	−0.0008	4.638	(last sample, 215.65 m)
	Density, dry	2419	0.13	2447	
	(kg/m^3) saturated	2501	0.08	2518	
	Porosity (%)	8.1	−0.0051	7.0	
	Permeability (mD)	17.0	−0.0575	4.6	

Table 1. Lithological features of Athabasca Group rocks that influence V_p as a function of depth.
$y = a_0 + a_1 z$; z = depth (m)
These regressions are based on data plotted in Figures 5, 6 and 7.
* V_p measured at 2 MPa axial stress
mD — millidarcies

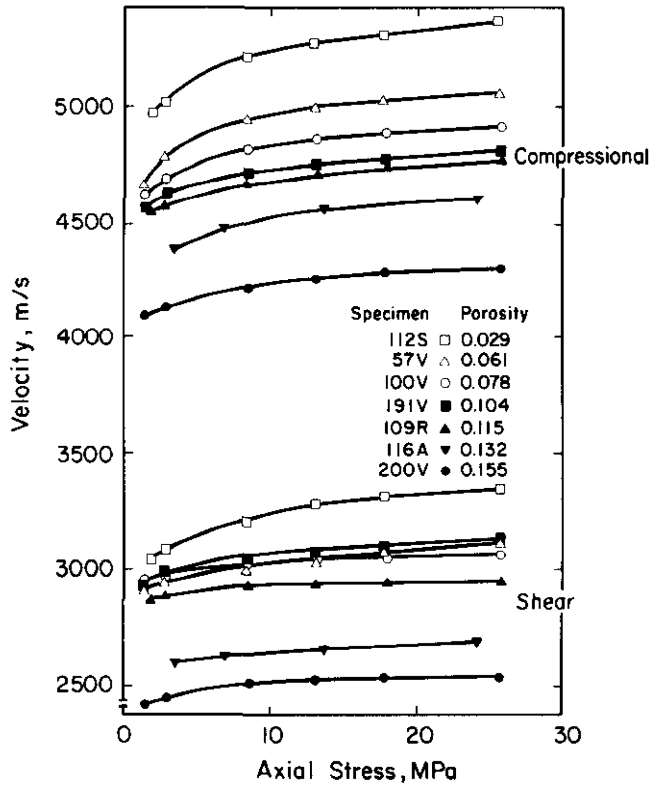

Fig. 10. P- and S-wave velocities for typical water-saturated Athabasca Group specimens as a function of uniaxial stress (no confining pressure provided).

listed in Table 2, show that the regression coefficients are significant at the 0.1 percent level and that the regression of the dependent variable in each case on ϕ and F_c accounts for a significant amount of the variation in the dependent variable.

The relationships shown in Table 2 for $1/V_p$, $1/V_s$ and V_p/V_s in the porosity range 0 to 0.15 and for clay fractions from 0 to 0.3 are similar to those reported by Tosaya and Nur (1982) and Castagna et al. (1985) for the clastic silicate rocks of their studies. *It is seen that increases in* ϕ *and* F_c result in increases in magnitude of all three parameters $1/V_p$, $1/V_s$ and V_p/V_s. It is clear also that these parameters are more sensitive to changes in porosity than to those in clay content by a factor of approximately four. This conclusion is similar to those of Tosaya and Nur (1982) and Castagna et al. (1985).

A study of the relationships for $1/V_p$, $1/V_s$ and V_p/V_s as a function of porosity and clay content for different ranges of F_c indicates that, for values less than 0.15, the influence of F_c on these parameters is not as important as at the higher values of clay content. $1/V_p$, $1/V_s$ and V_p/V_s have been plotted in Figures 11 and 12 as functions of porosity for the 404 Athabasca Group rock samples having a clay fraction less than 0.15. The velocities used are those measured at 25 MPa axial stress. The correlation coefficients shown in Figures 11 and 12 indicate that each of the regressions is significant at better than the 1 percent level. The increases in $1/V_p$, $1/V_s$ and V_p/V_s with increasing porosity are similar in magnitude to those reported by Tatham (1982) and Domenico (1984).

CONCLUSIONS

The main feature of the Athabasca stratigraphy at South McMahon Lake is variation in pebble content (Figure 2)

Parameter y	Intercept a_0	Regression Coefficients a_1	 a_2	Standard Deviations of Regression Coefficients S_{a1}	 S_{a2}	Correlation Coefficient r
$1/V_p^*$	0.1718	0.30	0.08	0.02	0.007	0.4202
$1/V_s^*$	0.2458	0.83	0.214	0.05	0.016	0.6039
V_p/V_s^*	1.4701	1.58	0.378	0.17	0.060	0.6755

Table 2. $1/V_p$, $1/V_s$ and V_p/V_s for Athabasca Group rocks as a function of porosity and clay content.
$y = a_0 + a_1\,\phi + a_2 F_c$; ϕ = porosity and F_c = clay fraction (458 samples).
$^*V_p$ and V_s measured at 25 MPa axial stress

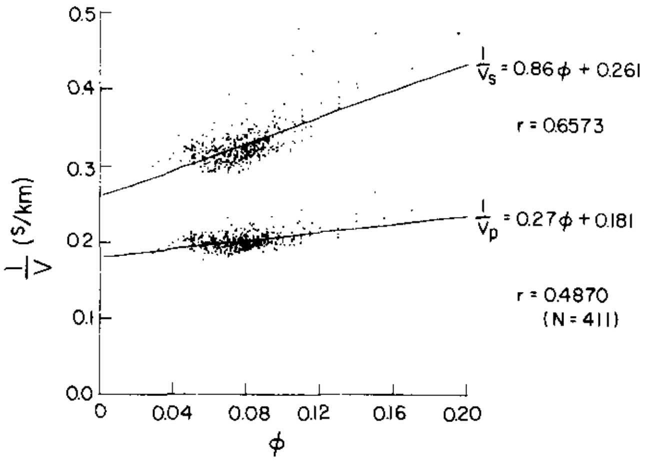

Fig. 11. Reciprocal *P*- and *S*-wave velocities ($1/V_p$ and $1/V_S$) measured at 25 MPa uniaxial pressure as a function of porosity (ϕ) for Athabasca Group samples containing less than 15 percent clay. Linear regression lines are shown and appear to fit the data reasonably well; however, the scatter patterns here and on Figure 12 make it difficult to determine whether or not linear regression is the most appropriate.

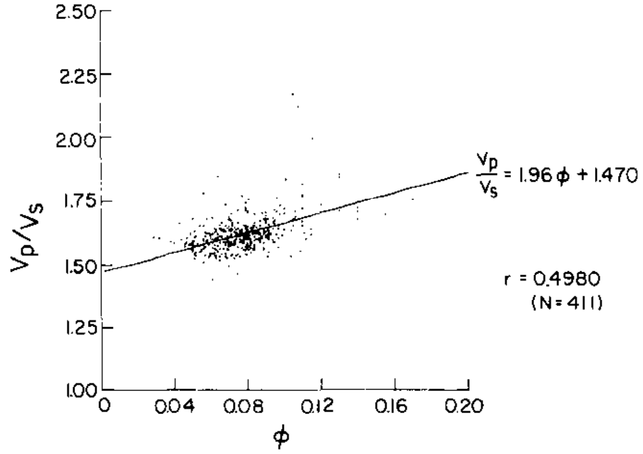

Fig. 12. Ratio V_p/V_S as a function of porosity (ϕ) for Athabasca Group samples containing less than 15 percent clay.

along with considerable variation in hematite content. However, neither of these features appears to affect seismic velocities.

Marked variations in velocities V_p and V_s and the ratio V_p/V_s for Athabasca Group rocks are functions of changes in porosity and clay content. Increases in both clay and porosity cause reductions in V_p and V_s, but clay has only about one quarter the effect of porosity in the range of porosities 0 to 0.2 and clay fraction 0 to 0.3. For clay fractions less than 0.15, simple linear relationships appear to exist between the reciprocal velocities $1/V_p$ and $1/V_s$ and the ratio V_p/V_s and porosity.

REFERENCES

Castagna, J.P., Batzle, M.L. and Eastwood, R.L., 1985, Relationships between compressional-wave and shear-wave velocities in clastic silicate rocks: Geophysics **50**, 571-581.

Cherry, J.T. and Waters, K.H., 1968, Shear-wave recording using continuous signal methods: Part I — early development: Geophysics **33**, 229-239.

Domenico, S.N., 1984, Rock lithology and porosity determination from shear and compressional wave velocity: Geophysics **49**, 1188-1195.

Ensley, R.A., 1984, Comparison of *P*- and *S*-wave seismic data: A new method for detecting gas reservoirs: Geophysics **49**, 1420-1431.

Geertsma, J., 1961, Velocity-log interpretation: The effect of rock bulk compressibility: Soc. Petr. Eng. J. **1**, 235-248.

Hajnal, Z., Stauffer, M.R. and King, M.S., 1983, Petrophysics of the Athabasca Basin near the Midwest uranium deposit, *in* Cameron, E.M., Ed., Uranium exploration in Athabasca Basin, Saskatchewan, Canada: Geol. Surv. Can., Paper 82-11, 303-310.

Hamilton, E.L., 1979, V_p/V_S and Poisson's ratios in marine sediments and rocks: J. Acoust. Soc. Am. **66**, 1093-1101.

Jain, 1987, Amplitude-vs-offset analysis: A review with reference to application in western Canada: J. Can. Soc. Expl. Geophys. **22**, 27-36.

King, M.S., 1983, Static and dynamic elastic properties of rocks from the Canadian Shield: Int. J. Rock Mech., Min. Sci., Geomech. Abstr. **29**, 237-241.

Moos, D. and Zoback, M.D., 1983, In situ studies of velocity in fractured crystalline rocks: J. Geophys. Res. **88**, 2345-2358.

Polškov, M.K., Brodov L.J., Mironova, L.V., Michon, D., Garotta, R., Layotte, P.C. and Coppens, F., 1980, Utilisation combinée des ondes longitudinales et transversales en sismique reflexion: Geophys. Prosp. **28**, 185-207.

Tatham, R.H., 1982, V_p/V_S and lithology: Geophysics **47**, 336-344.

______ and Stoffa, P.L., 1976, V_p/V_S — a potential hydrocarbon indicator: Geophysics **41**, 837-849.

Tosaya, C. and Nur, A., 1982, Effects of diagenesis and clays on compressional velocities in rocks: Geophys. Res. Lett. **9**, 5-8.

Wilkens, R., Simmons, G. and Caruso, L., 1984, The ratio V_p/V_S as a discriminant of composition for siliceous limestones: Geophysics **49**, 1850-1860.

Wyllie, M.R.J., Gregory, A.R. and Gardner, L.W., 1956, Elastic wave velocities in heterogeneous and porous media: Geophysics **21**, 41-70.