GEOPHYSICS, VOL. 51, NO. 11 (NOVEMBER 1986); P. 2093–2107, 13 FIGS., 2 TABLES.

Effects of porosity and clay content on wave velocities in sandstones

De-hua Han*, A. Nur*, and Dale Morgan‡

ABSTRACT

The ultrasonic compressional (V_p) and shear (V_s) velocities and first-arrival peak amplitude (A_p) were measured as functions of differential pressure to 50 MPa and to a state of saturation on 75 different sandstone samples, with porosities ϕ ranging from 2 to 30 percent and volume clay content C ranging from 0 to 50 percent, respectively. Both V_p and V_s were found to correlate linearly with porosity and clay content in shaly sandstones. At confining pressure of 40 MPa and pore pressure of 1.0 MPa, the best least-squares fits to the velocity data are

$$V_p\ (\text{km/s}) = 5.59 - 6.93\phi - 2.18C$$

and

$$V_s\ (\text{km/s}) = 3.52 - 4.91\phi - 1.89C.$$

Deviations from these equations are less than 3 percent and 5 percent for V_p and V_s, respectively.

The velocities of clean sandstones are significantly higher than those predicted by the above linear fits (about 7 percent for V_p and 11 percent for V_s), which indicates that a very small amount of clay (1 or a few percent of volume fraction) significantly reduces the elastic moduli of sandstones.

For shaly sandstones we conclude that, to first order, more sensitive to the porosity and clay content than is V_p. Consequently, velocity ratios V_p/V_s and their differences between fully saturated (s) and dry (d) samples also show clear correlation with the clay content and porosity.

For shaly sandstones we conclude that, to first order, clay content is the next most important parameter to porosity in reducing velocities, with an effect which is about 0.31 for V_p to 0.38 for V_s that of the effect of porosity.

INTRODUCTION

Shaly sandstones and shales comprise a major component of sedimentary basins and are of foremost relevance to hydrocarbon reservoirs. The acoustic properties of shaly sandstones and shales are thus of great interest in seismic and well log interpretation.

For years, the time-average equation of Wyllie et al. (1956, 1958) has been used to obtain porosities from acoustic velocity logs. The equation for P-wave velocity V_p in water-saturated rock is

$$\frac{1}{V_p} = \frac{(1-\phi)}{V_m} + \frac{\phi}{V_f}, \tag{1}$$

where V_m is the P-wave velocity of the rock matrix and V_f is the velocity of the pore fluid. When both V_m and V_f are fixed, the only variable in the equation is porosity. To first order, this simple equation appears adequate for clean sandstones in the middle range of porosity (10 percent $< \phi <$ 25 percent). However, it is well-known that acoustic velocities of sandstones are also related to mineralogy, pore geometry, degree of consolidation, cementation, confining pressure, pore fluid, pore pressure, and temperature. Consequently, the shortcomings of the time-average equation have been extensively discussed (Geertsma, 1961; Geertsma and Smit, 1961; Raymer et al., 1980; Kevin, 1981). A newer, empirical equation based on well log data was obtained by Raymer et al. (1980):

$$V_p = (1-\phi)^2 V_m + \phi V_f. \tag{2}$$

Equation (2) was proposed as an alternative to the time-

Manuscript received by the Editor October 18, 1985; revised manuscript received May 5, 1986.
*Stanford Rock Physics Project, Department of Geophysics, Stanford University, Stanford, CA 94305.
‡Formerly Stanford Rock Physics Project, Stanford University; presently Department of Geophysics, Texas A&M University, College Station, TX.

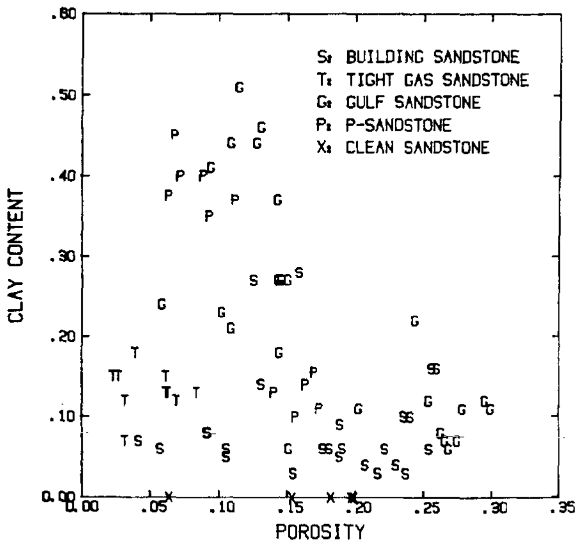

FIG. 1. The ranges of clay content and porosity for the 75 shaly sandstones of this study. Porosity ranges from 2 to 30 percent, and clay content ranges from 0 to about 50 percent. The data indicate that sandstones with high clay content tend to have low porosities.

average equation for interpretation of acoustic logs. Because the porosity is the only parameter in this equation, it is not very different from the time-average equation [equation (1)].

Neither equation (1) nor equation (2) can be directly applied to shaly sandstones. From the results presented here, as well as from earlier work by De Martini et al. (1976), Tosaya and Nur (1982a), and Kowallis et al. (1984), in shaly sandstones and shales the time-average equation significantly overestimates velocities, as does Raymer's model. The question then is how can the effect of clay best be represented in the velocity equation for shaly sandstones?

Although there are many theoretical models for the effects of porosity, pore shape, fluid, and matrix moduli on the elastic properties of rocks (Gassmann, 1951; Biot, 1956; Geertsma, 1961; Kuster and Toksöz, 1974; O'Connell and Budiansky, 1974; Mavko and Nur, 1978; Walsh and Grosenbaugh, 1979), none of them includes the effect of clays on velocities in sandstones. Minear (1982) applied the Kuster and Toksöz (1974) model to simulate the effects of clays on velocities of sandstones. His results suggest that clay minerals may significantly reduce elastic moduli and velocities of sandstones. However, the magnitude of these effects of clays remains far from clear. In contrast with theory, some experimental and petrographic work has been published on the effects of clay minerals (De Martini et al., 1976; Tosaya and Nur, 1982a; Kowallis et al., 1984). Although each of the above studies was limited to a few samples, all results have alluded to a general trend—that increasing clay content in sandstones systematically decreases acoustic velocities in both well-consolidated and poorly consolidated sandstones. Costagna et al. (1985) obtained field results which suggest a linear dependence on the porosity and clay content for both V_p and V_s, inferred from sonic log data from the Frio formation. Thus, because of the paucity of data, the main goal of this study is to investigate systematically, under laboratory conditions using a large number of samples

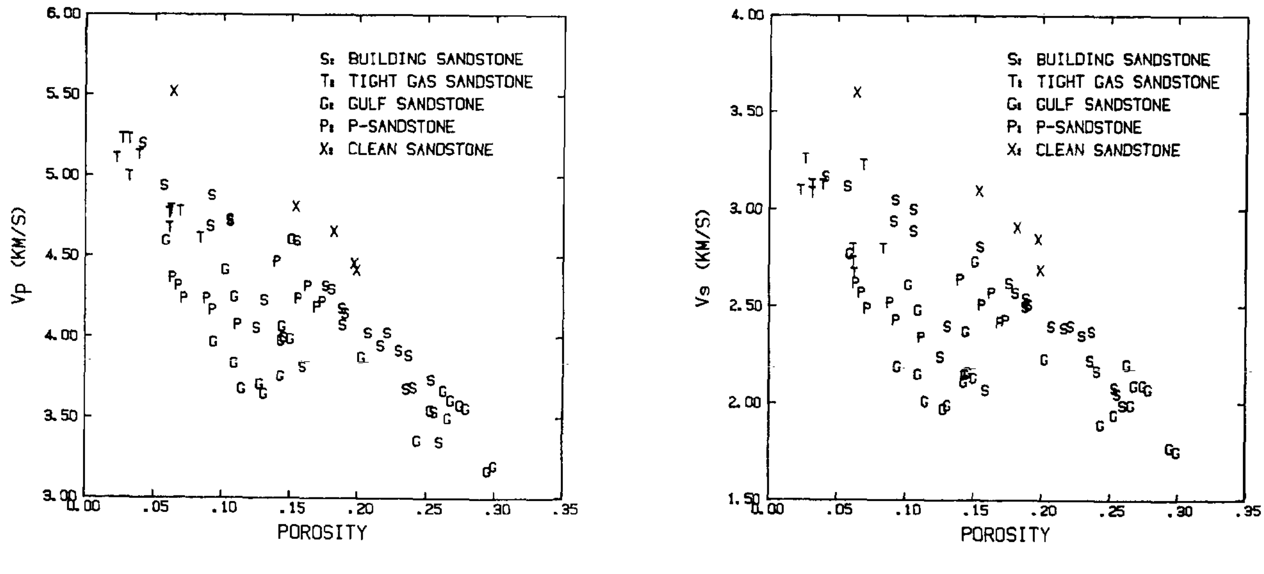

FIG. 2. Measured (a) compressional and (b) shear velocities versus porosity for 75 sandstone samples at $P_c = 40$ MPa and $P_p = 1.0$ MPa.

covering a wide range of porosities and clay contents, the effect of clay content versus porosity on the acoustic velocities in sandstones.

Because shear wave velocities are now available from well logs and seismic reflection measurements, it is of particular interest to explain the relation between shear velocity and porosity. An empirical relation between shear velocity and porosity has been proposed in a modification of the time-average equation (e.g., Domenico, 1984). However, as we show later, this equation cannot be used very well to interpret shear velocity values in shaly sandstones. A systematic investigation of the effects of clay content and porosity on shear velocity V_s is consequently of great interest.

We measured compressional velocity V_p and shear velocity V_s as functions of pressure in 75 sandstone samples with varying clay contents and porosities. All the data are tabulated in Appendix A. We also investigated the relations among changes in relative attenuation of waves with varying rock porosity and clay content. The relations among the velocity ratio V_p/V_s, water saturation, elastic moduli, porosity, and clay content are also examined.

Finally, Gassmann's equation (Gassmann, 1951) was used to explore the frequency dependence of rock elasticity as proposed by Winkler (1985).

EXPERIMENTAL PROCEDURES

Sample description

The 75 sandstone samples used in this study come from either well cores or quarries. The porosities of the samples range from 2 to 30 percent, and the clay contents by volume fraction range from 0 to 50 percent (Figure 1). Ten samples are tight gas sandstones (T) with very low porosities. Twenty-four samples (G) come from a few offshore wells in the Gulf of Mexico; some of these are poorly consolidated. Eleven samples (P) are also borehole cores which are well-consolidated. Thirty well-consolidated samples (S) are from quarries, of which five (X) are clean sandstones with less than 1 percent clay content. Figure 1 shows clay content versus porosity for all samples. It is noteworthy that samples with more than 20

Table 1. Model fitting to the experimental velocity data.

WITHOUT CLAY TERM (70 samples)		
$\frac{1}{V_p} = 0.194 + 0.328\phi$	R: 0.844	rms: 6.6%
$\frac{1}{V_s} = 0.322 + 0.628\phi$	R: 0.750	rms: 10.3%
$V_p = 5.02 - 5.63\phi$	R: 0.840	rms: 6.8%
$V_s = 3.03 - 3.78\phi$	R: 0.754	rms: 10.8%
WITH A CLAY CONTENT TERM		
1. LINEAR EQUATION		
$V_p = 5.59 - 6.93\phi - 2.18C$	R: 0.985	rms: 2.1%
$V_s = 3.52 - 4.91\phi - 1.89C$	R: 0.959	rms: 4.3%
2. TRAVELTIME AVERAGE EQUATION		
$\frac{1}{V_p} = 0.163 + 0.399\phi + 0.119C$	R: 0.972	rms: 2.8%
$\frac{1}{V_s} = 0.242 + 0.812\phi + 0.307C$	R: 0.945	rms: 5.1%

R: CORRELATION COEFFICIENT

RMS: RELATIVE rms DEVIATION WITH 68.3% CONFIDENCE.

percent clay content tend to have lower porosities, ranging from 5 to 15 percent.

Acoustic measurement

Wave velocities V_p and V_s and the associated compressional first-arrival peak amplitude A_p are measured as functions of pressure and the state of water saturation. Confining pressure P_c and pore pressure P_p are controlled separately. With differential pressure P_d limited to 50 MPa and pore pressure limited to 1.0 MPa, the system can thus simulate pressure conditions to depths of over 2 000 m.

The velocities are measured at ultrasonic frequencies using the pulse transmission technique (Birch, 1960). The central frequencies of the transducers used for P- and S-waves are 1.0 and 0.6 MHz, respectively. The wavelengths for P- and S-waves are greater than 5 mm and at least five times greater than a mean grain size for our samples. On each sample the measurements were first performed in a vacuum dry state (vacuum pressure less than 0.01 Torr), then at full saturation with water. In some samples with high clay content, brine is used as the pore fluid. No velocity differences are found between saturation with brine and saturation with plain water.

Samples are 5.0 cm in diameter and 2.0 to 5.0 cm in length, or more than 100 times the average grain size. Both sample dimensions are measured to within 0.05 mm. The two end surfaces of each sample are ground parallel to within 0.05 mm.

P-wave arrival times are picked to within 0.03 μs, which leads to less than 1 percent absolute error in the measurement of V_p. The error in the V_s measurement is less than 2 percent, except for poorly consolidated sandstones at low differential pressure ($P_d < 10$ MPa), where errors may be up to 3 percent due to poor signal.

The velocities are measured during loading and unloading pressure cycles. Generally, hysteresis is observed, but its magnitude is typically small. After the first pressure cycle, velocities measured during unloading cycles are repeatable, with hysteresis in the well-consolidated samples of less than 1 percent and in the poorly consolidated samples of less than 2 percent. The first peak amplitudes A_p were measured using the method of Tosaya (1982b).

Unless otherwise mentioned, data shown in the figures are for confining pressure of 40 MPa and pore pressure of 10 MPa. The detailed results are given in Appendix A.

Density and porosity measurements

Samples are vacuum oven-dried at less than 50°C for two to eight weeks, and weighed to within 0.01 g so that the density of a dry sample ρ_d can be determined to within 0.3 percent. The density of the wet sample ρ_w is then calculated by the relation

$$\rho_w = \rho_d + \phi \rho_f, \tag{3}$$

where ρ_f is the pore fluid density and ϕ is the porosity of the sample. The porosity of each sample at room pressure is measured with a helium porosimeter, repeatably within 1 percent of total bulk volume. This value of porosity is considered equal to the porosity at differential pressure P_d of 1.0 MPa.

Although the bulk volume of each sample decreases with increasing differential pressure, in the pressure range used the change in volume of the grains is very small, so that the variation of bulk volume with pressure can be considered equal to the change of the pore volume only. The variations of the pore volume are monitored with a pore-pressure intensifier while the pore pressure is kept constant. The ambient temperature is 22°C ± 1°C.

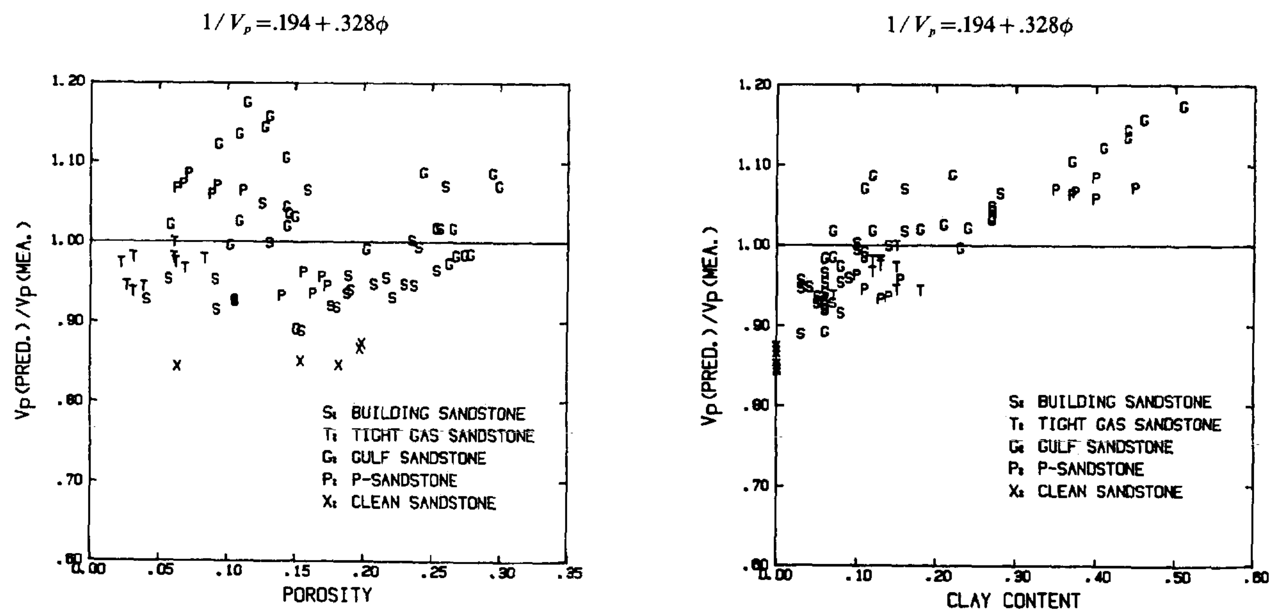

FIG. 3. Compressional velocity V_p data at $P_c = 40$ MPa and $P_p = 1.0$ MPa fitted by the time-average equation. (a) Relative deviations versus porosity showing large scatter. (b) Relative deviations show a clear correlation with clay contents.

Petrographic measurement

The clay content of each sample is obtained by point counting on thin sections. Most results are based on 300 point counts per section, with a few earlier results based on only 100 point counts. Minerals with flaky textures, such as hematite and other iron oxides, are counted as part of the clays. Usually two thin sections are taken, from the top and bottom of the sample, respectively. For some samples the clay contents from these two sections differ by as much as 20 percent, due mainly to heterogeneity in the sample.

THE EFFECTS OF POROSITY AND CLAY CONTENT ON VELOCITIES

Based on the combination of acoustic and petrographic data, the effects of confining pressure P_c, pore pressure P_p, and fluid saturation on acoustic P- and S-wave velocities and amplitude are studied.

Compressional velocity V_p and shear velocity V_s versus porosity ϕ for all samples are shown in Figures 2a and 2b. Despite significant scatter, clear trends indicate that both V_p and V_s decrease with increasing porosity. As a first trial, the

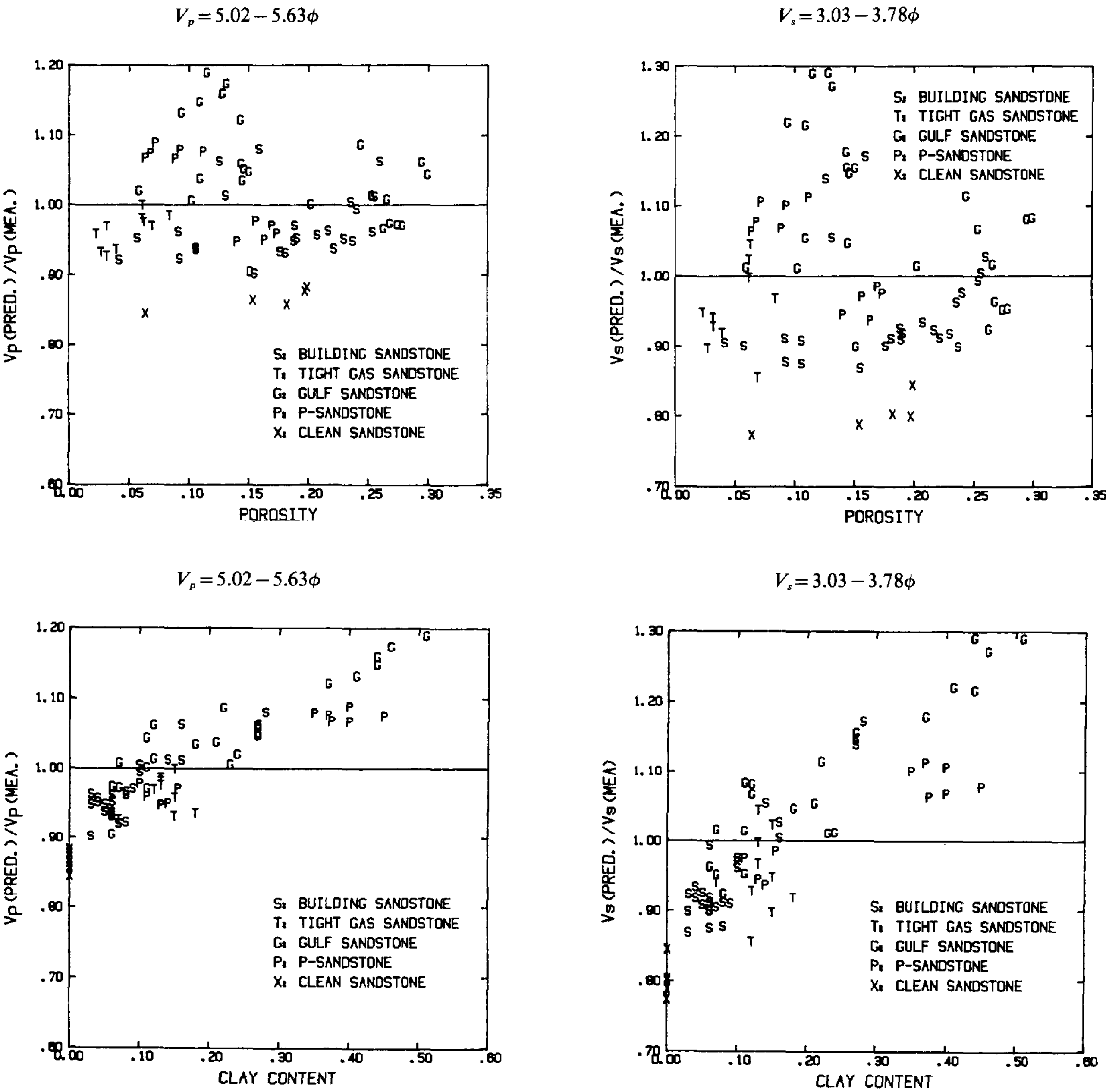

FIG. 4. Compressional V_p and shear V_s velocities fitted by the model $V = A_0 - A_1\phi$. (a) Relative deviations of V_p versus porosity, showing large scatter. (b) Relative deviations of V_p versus clay content. (c) Relative deviations of V_s versus porosity, showing large scatter. (d) Relative deviations of V_s versus clay content.

modified time-average equation $1/V_p = B_0 + B_1\phi$ is fitted to the data. By least-squares regression, the fitted results (Table 1) are presented in the form of relative deviations versus porosities, as shown in Figure 3a. The matrix P wave velocity computed from the fit is $V_m = 1/B_0 = 5.15$ km/s, which is much lower than the value for nonporous quartz aggregates, $V_p = 6.05$ km/s (Robert, 1982). The relative deviations of the data from the values predicted by the equation are quite large (Figure 3a). However, these deviations clearly depend upon the clay content (as in Figure 3b), which indicates that clay content systematically affects velocity.

We also use the empirical linear model $V = A_0 - A_1\phi$ to fit both V_p and V_s data. Again, the relative deviations of the data from the values predicted by the equation are quite large (Figures 4a and 4c) and clearly depend upon the clay content (Figures 4b and 4d).

As shown in Figures 3a, 4a, and 4c, velocities of clean sandstones are systematically higher than predicted from the fit. To emphasize the effects of clay content, the data used to fit the model excluded the totally clay-free sandstones.

Based on the above results, we conclude that any model used to fit both V_p and V_s data in shaly sandstones must account for clay content. Two simple equations that include clay-content terms are used to describe the data by least-squares regression; namely,

$$V = A_0 - A_1\phi - A_2 C, \tag{4}$$

and

$$1/V = B_0 - B_1\phi - B_2 C. \tag{5}$$

Equation (5) is actually the time-average equation modified to include a linear term for clay content. The coefficients B_0, B_1, and B_2 may be interpreted as follows:

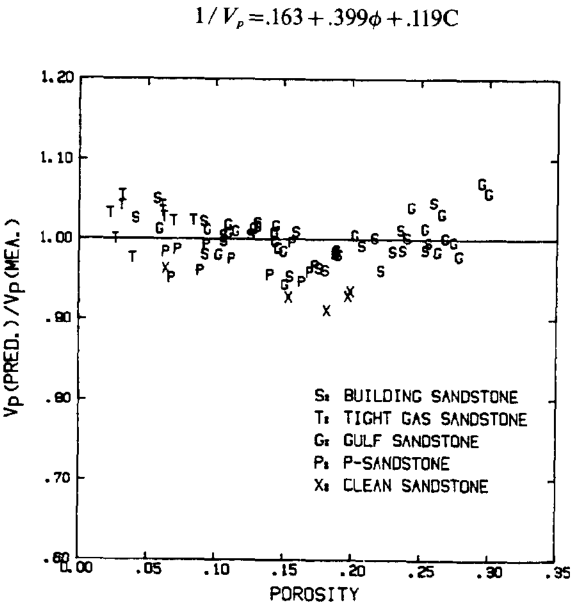

FIG. 5. Compressional velocity data fitted by the modified time-average equation with a clay-content term. Relative deviations versus porosity indicate that the model overestimates V_p at porosities lower than 7 percent or higher than 25 percent, and underestimates V_p at intermediate porosities.

$$B_0 = 1/V_m;$$
$$B_1 = (1/V_f - 1/V_m); \tag{6}$$
$$B_2 = (1/V_c - 1/V_m),$$

where V_m is matrix velocity, V_f is fluid velocity, and V_c is clay velocity.

Results of the fits of these equations to the velocity data are listed in Table 1. Both equations show similar correlation coefficients and relative rms deviations from the data. However, the time-average equation is obviously meaningless for shear waves. Furthermore, the velocities computed from this equation are systematically higher than measured ones in the low range of porosity ($\phi < 7$ percent) and high range of porosity ($\phi > 25$ percent), in contrast with the porosity in the middle range (Figure 5). On the other hand, the deviations of the data from linearity are randomly distributed. Furthermore, the linear equation (4) fits both V_p and V_s data slightly better. Consequently, we choose the linear equation (4) to describe the dependencies of velocities on the porosity and clay content in sandstones. The equations are similar to those proposed by Tosaya and Nur (1982a), Kowalis et al. (1984), and Costagna et al. (1985).

The following best fits to the data at the confining pressure 40 MPa and pore pressure 1.0 MPa are obtained by least-squares regression. For the compressional velocity,

$$V_p\,(\text{km/s}) = 5.59 - 6.93\phi - 2.18C, \tag{7}$$

and for the shear velocity,

$$V_s\,(\text{km/s}) = 3.52 - 4.91\phi - 1.89C. \tag{8}$$

Velocity deviations from fits versus porosites and clay content, respectively, are shown in Figures 6a and 6b for V_p, in Figures 6c and 6d for V_s. The correlation coefficient is 0.985 and the relative rms deviation is 0.021 for V_p; the corresponding values are 0.959 and 0.043 for V_s. These values show greatly improved fit in comparison with the results using porosity alone.

In the very clean sandstones (St. Peter, Beaver, and Fontainebleau), the measured velocities are higher than those predicted by equations (7) and (8), by about 7 percent for V_p and 11 percent for V_s (Figures 6a and 6b). This distinct difference between the clean and shaly sandstones implies that even small amounts of clay in sandstones tend to soften grain contacts significantly. Such softening is most likely related to clay particles situated between grain boundaries. Because the grain size of the clay particles is so small and their surface area is so large, even a small volume fraction of clays can cover the entire pore surface area throughout the rock, including the grain contacts. We believe that the contact clay is responsible for the decrease of velocity from clean sandstones to shaly ones.

The good fit of shaly sandstone velocities [represented by equations (7) and (8)] suggests that the velocities are nearly independent of the type of clay or the location of clay particles within the rock matrix. Minear (1982) has investigated models of sandstone with (1) structural, (2) laminal, and (3) clay suspended in the pores. His model results show that the suspended clay has only a small effect on velocities, whereas both structural and laminal clays have significant and similar effects on velocities. Both arrangements predict a nearly linear relation between velocities and clay content for clay content below 50 percent. Because the exact arrangement of clays within sandstones is not known, we can only suggest that something like Minear's (1982) structural or laminal arrangement is typical.

The coefficients of the linear fits in equations (7) and (8) for both V_p and V_s are fairly constant with differential pressure over 10 MPa (Table 2). These results suggest that the effects of porosity and clay content are fairly independent of differential pressure, which can be extrapolated to a higher P_d range. For data with P_d below 10 MPa, the fit is somewhat worse.

Finally, the coefficients in equations (7) and (8) indicate that the influence of clay content (by volume) is about 1/3.2 that of the influences of porosity for V_p and 1/2.6 for V_s. These ratios are also fairly independent of pressure (Table 2).

In summary, it appears that the volume of clay in consolidated shaly sandstones is an important parameter when accurate porosity evaluations from seismic or acoustic data (e.g., well logs) are required. Other parameters, including pore geometry, grain size, grain contacts, cementation, type of clay,

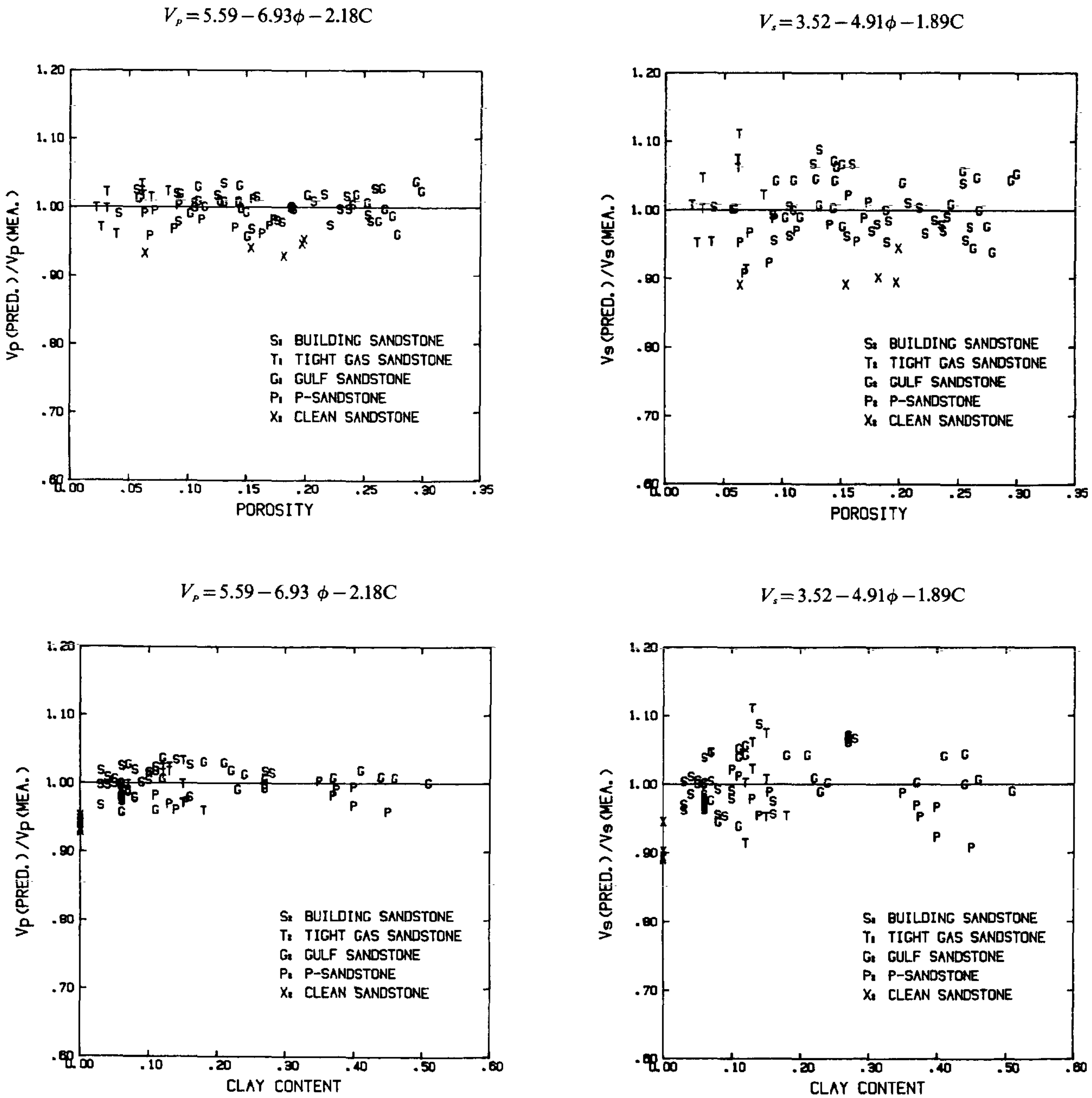

FIG. 6. Linear fit between velocity and porosity and clay content: (a) V_p relative to porosity, (b) V_p relative to clay content; (c) V_s relative to porosity; (d) V_s relative to clay content, all at $P_c = 40$ MPa and $P_p = 1.0$ MPa.

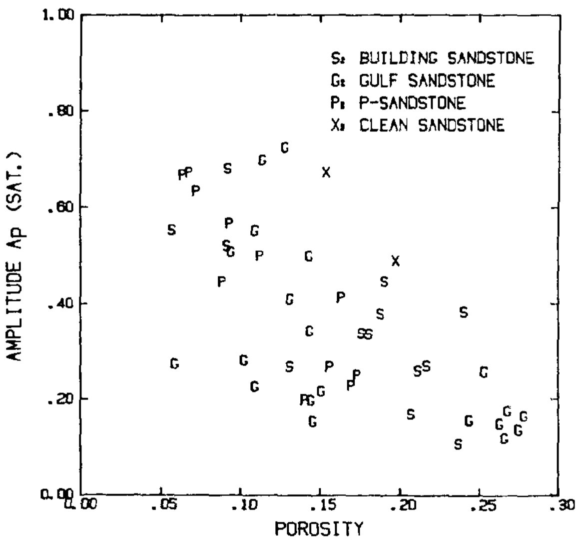

FIG. 7. Normalized amplitude A_p versus porosity for 46 sandstone samples at $P_c = 40$ MPa and $P_p = 1.0$ MPa. The results indicate that A_p tends to decrease with porosity.

distribution of clays, and mineralogy, have much smaller influences on velocities at high differential pressure for shaly, water-saturated sandstones.

EFFECTS ON WAVE AMPLITUDES

We have also studied the dependence of wave amplitude on porosity and clay content, using a comparative method as described by Tosaya (1982b). All the amplitude data were corrected and normalized by that of an aluminum sample with the same length. For P-waves, we find that the amplitude A_p increases with decreasing porosity (Figure 7), although the scatter is quite substantial. For 46 water-saturated samples, the best fit by linear regression of the amplitudes as functions of the porosity and clay content is

$$A_p = 0.58 - 1.57\phi + 0.23C, \tag{9}$$

with a correlation coefficient of 0.68. The results show that the amplitude depends strongly on the porosity and only weakly on clay content. We conclude that parameters other than clay content are probably important. No clear relations are observed between shear amplitude A_s and porosity, probably

Table 2. The pressure dependence of the coefficients in the linear velocity-porosity clay model.

VELOCITY EQUATION

$V = A_0 - A_1\phi - A_2C$

(bars)	(km/s)	(km/s)	(km/s)		(km/s)	(%)
400	5.59	6.93	2.18	0.985	0.09	2.1
300	5.55	6.96	2.18	0.985	0.09	2.1
200	5.49	6.94	2.17	0.981	0.10	2.4
100	5.39	7.08	2.13	0.978	0.11	2.8
50	5.26	7.08	2.02	0.969	0.14	3.4
300	3.47	4.84	1.87	0.957	0.11	4.5
200	3.39	4.73	1.81	0.951	0.12	4.9
100	3.29	4.73	1.74	0.937	0.14	5.8
5(						

R:

Sd: STANDARD DEVIATION

RMS: RELATIVE rms DEVIATION WITH 68.3% CONFIDENCE.

because the shear signal is often distorted in a sample with high clay content, so that A_s cannot be measured accurately.

THE EFFECT OF CLAY CONTENT ON THE ELASTIC MODULI

The effective elastic moduli for our samples are computed from the velocities by the expressions

$$K = \rho(V_p^2 - 4V_s^2/3)$$

and (10)

$$G = \rho V_s^2,$$

where ρ is the density of the sample. Clearly, elastic moduli relate to porosity and clay content in a manner similar to the velocities, as shown for bulk and shear moduli versus porosity in Figures 8a and 8b. For shaly sandstones, clay content affects the shear modulus more than the bulk modulus. Moreover, as seen in Figure 8b, clean sandstones have much higher shear moduli than do shaly sandstones with the same porosities, suggesting that grain boundary clays significantly reduce the shear modulus but have only little influence on the bulk modulus. Consequently, the effects of clay content on V_p and V_s [equations (7) and (8)] are more due to the fact that clays reduce the shear modulus of sandstones.

The effects of porosity on the shear modulus are also larger than effects on bulk modulus, as indicated by equations (7) and (8).

THE EFFECTS OF CLAY CONTENT ON VELOCITY RATIO

Because more shear velocity data are becoming available in seismic exploration and well logging, the velocity ratio V_p/V_s is becoming a useful parameter in the determination of rock properties. Previous laboratory and well-logging studies have suggested correlations between lithology, porosity, and V_p/V_s values (Pickett, 1963; Gregory, 1977; Benzing, 1978; Johnson, 1978; Tatham, 1982; Eastwood, 1983; Domenico, 1984; Rafavich et al., 1984; Costagna et al., 1985). Our data show that the velocity ratio for water-saturated shaly sandstones depends upon both porosity and clay content. By least-squares regression, this dependence is found to be

$$V_p/V_s = 1.55 + 0.56\phi + 0.43C, \tag{11}$$

with a correlation coefficient of 0.70. The results show that increasing porosity or clay content (Figure 9) increases V_p/V_s and that the velocity ratio is more sensitive to porosity changes, in agreement with the results of Costagna et al. (1985).

Sandstones with high clay content have velocity ratios and Poisson's ratios similar to carbonate rocks. The resulting ambiguity in the interpretation of velocity data may be resolved by the combined use of the velocity and the velocity ratio, providing a useful tool for reliable lithology discrimination.

Costagna et al. (1985) found that shear velocity is nearly linearly related to compressional velocity for water-saturated clastic silicate sedimentary rocks; the relation is

$$V_p(\text{km/s}) = 1.16V_s + 1.36. \tag{12}$$

Our data also show that V_s is nearly linearly related to V_p, with somewhat different coefficients than in equation (12). For 75 samples, the best linear least-squares fit yields

$$V_p\ (\text{km/s}) = 1.26V_s + 1.07, \tag{13}$$

with a correlation coefficient of 0.97.

THE EFFECTS OF WATER SATURATION

The data shown so far are all for water-saturated samples. In contrast, data for dry samples show much more scatter in the relations among velocities, porosity, and clay content, with large deviations appearing when fitting linear equations to the

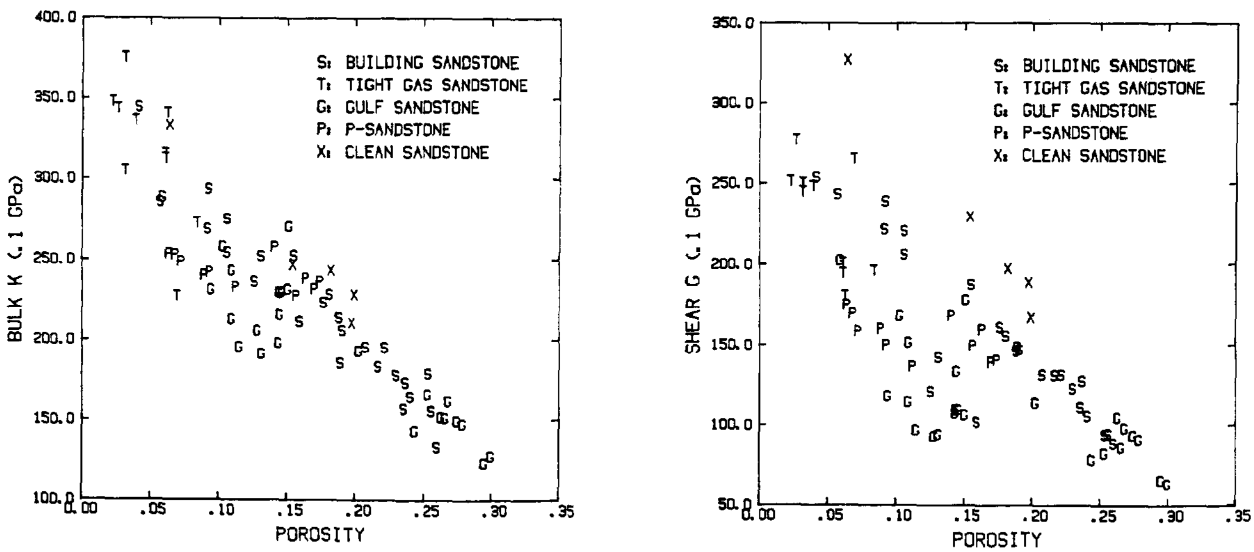

FIG. 8. (a) Bulk and (b) shear moduli versus porosity at P_c = 40 MPa and P_p = 1 MPa. Relative decrease of the shear modulus is more than the bulk modulus with increasing porosity. Scatter of the shear modulus, caused by the clays, is larger than corresponding scatter of bulk modulus data.

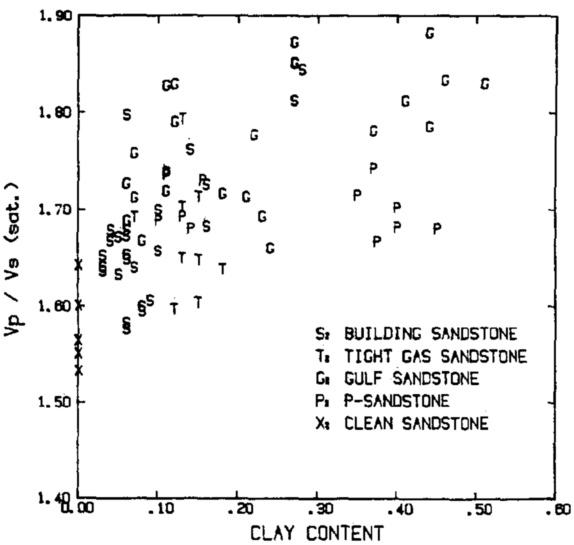

FIG. 9. Velocity ratios V_p/V_s at $P_c = 40$ MPa and $P_p = 1$ MPa versus clay content.

data for dry samples. One reason for the scatter is that velocities for several Gulf sandstones are systematically lower than other samples with the same porosity and clay content. Some Gulf sandstones with high clay content are poorly consolidated. It thus appears that water saturation affects the velocities in shaly sandstones as a function of differing degrees of consolidation, via interactions between the pore fluid (water) and the clays.

The shear and bulk moduli for our dry samples are computed from velocities and densities by equations (10). It is commonly expected that the shear modulus should remain constant or increase only slightly as rock is saturated from its dry state (Gassmann, 1951; Biot, 1956; Kuster and Toksöz, 1974; O'Connell and Budiansky, 1974). This assumption agrees with our data for clean sandstones (Figure 10). The data for shaly sandstones, however, display a more complex situation. The ratios of shear moduli G(sat) to G(dry) deviate significantly from the expected value of 1 (Figure 10a). King (1966) and Toksöz et al. (1976) have alluded to possible interactions between pore fluid and clay minerals as processes to soften rock matrix and decrease the shear modulus. We present data in Figure 10a to show how such interaction affects shear moduli for shaly sandstones. The ratio of G(sat)/G(dry) shows (excluding the poorly consolidated G sandstones) a decreasing trend with increasing clay content, suggesting that shear moduli of clays can be significantly reduced by water saturation. Many data, from Gulf sandstones in particular, deviate from this trend with their ratios of G(sat)/G(dry) being greater than 1 even though they have high clay contents.

The effects of water saturation on the bulk modulus of rock were studied by several researchers (Gassmann, 1951; Biot, 1956; Nur and Simmons, 1969; Kuster and Toksöz, 1974; O'Connell and Budiansky, 1974) who showed that water can significantly increase bulk moduli of rocks. This agrees with data for clean sandstones (Figure 10b). However, effects of clay content on the bulk modulus upon water saturation have

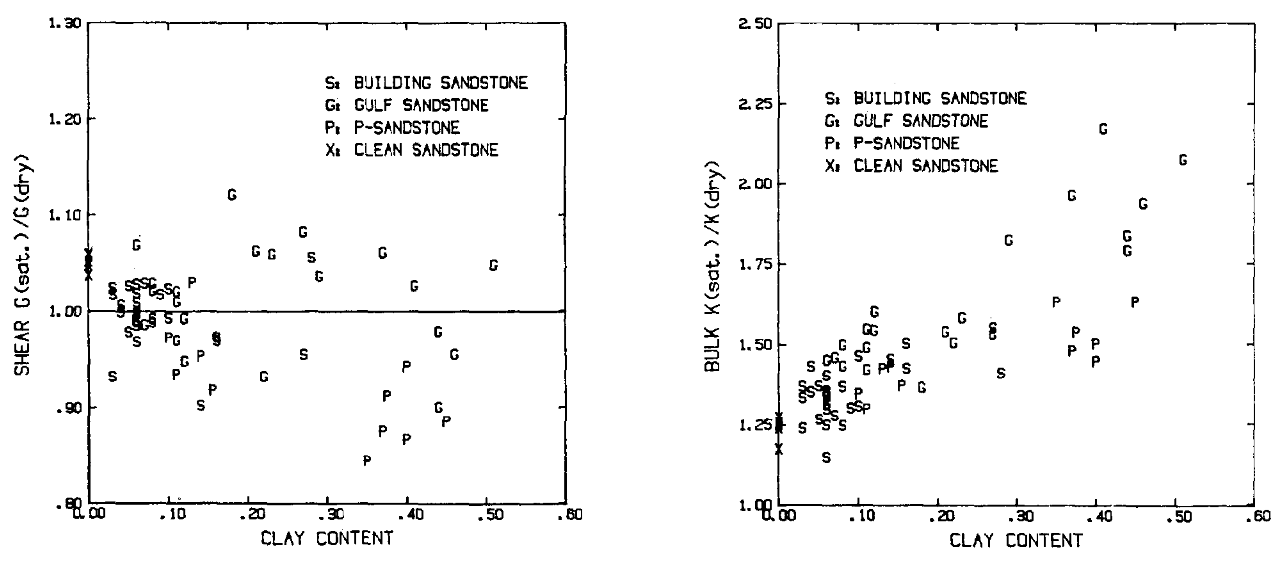

FIG. 10. The shear modulus (a) and bulk modulus (b) ratios of saturated (s) over dry (d) state versus clay content.

not been mentioned in the literature. Our data show that the ratio of K(sat)/K(dry) increases from 1.25 for clean sandstones to over 2.0 for some samples with a high clay content (Figure 10b). This large effect of increasing K(sat) suggests that bulk moduli of saturated clays are much greater than those for dry clays, in contrast to the effect on shear moduli. This effect on K may be the consequence of water-saturated micropores being more structurally rigid than vacuum-dry ones. Though the data are scattered, it is clear that most Gulf sandstones have larger K(sat)/K(dry) ratios than do other samples, especially those with high clay content.

Moreover, the P-wave amplitude ratio of A_p(sat)/A_p(dry) reveals that for Gulf sandstones this ratio is greater than 1, as opposed to the effect for all other sandstones (Figure 11). This result again suggests that Gulf sandstones are systematically different from the other sandstones in our study.

Indeed, most Gulf sandstones are poorly consolidated and show larger porosity reductions than do other sandstones with increasing P_d. Moreover, Gulf sandstone clays are mainly composed of illite and montmorillonite, which differ from other sandstones in that their clays are mainly composed of kaolinite. It appears that in these rocks one of the effects of water saturation is to stiffen the contacts between the quartz grains. This effect is particularly pronounced in poorly consolidated sandstones, possibly because grain contacts are already loose.

The combined effects of water saturation and matrix hardening on the moduli of shaly sandstones may explain much of the scatter in Gulf sandstone data presented in Figures 10 and 11. More accurate petrographic description of these rocks may be required in the future.

Finally, owing to differing responses of bulk modulus K and shear modulus G to the water saturation versus the clay content for shaly sandstones, the differences between velocity ratios V_p/V_s of fully saturated (s) and dry (d) samples can be more clearly related to the clay content and porosity as follows:

$$D = (V_p/V_s)_s - (V_p/V_s)_d = 0.018 + 0.36\phi + 0.47C, \quad (14)$$

with a correlation coefficient of 0.89. The effect of the clay content on D is shown in Figure 12. This effect is greater than that of the porosity in equation (14). This relation suggests that the velocity ratio may be used as an index of saturated states in shaly sandstones.

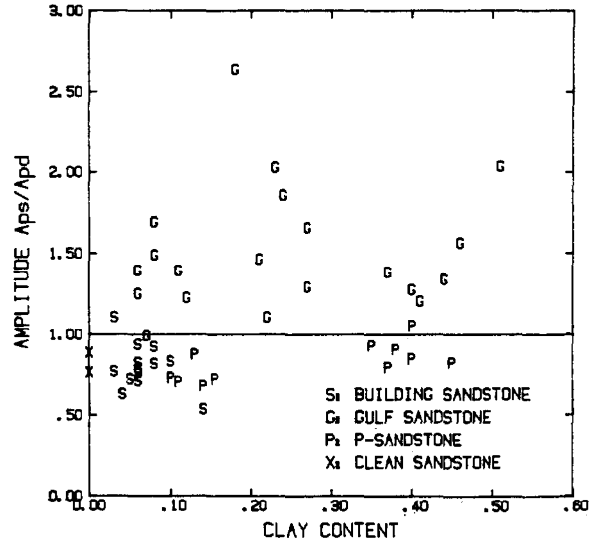

FIG. 11. The amplitude ratio A_p(sat)/A_p(dry) versus porosity at P_c = 40 MPa and P_p = 1.0 MPa.

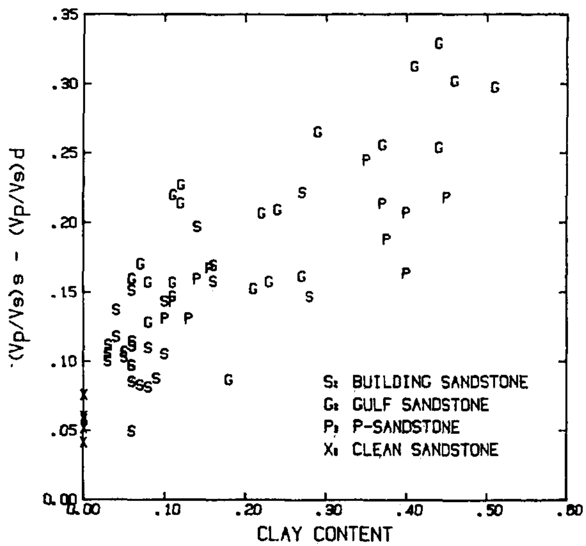

FIG. 12. Differences of velocity ratios V_p/V_c between saturated (s) and dry (d) samples versus clay content at P_c = 40 MPa and P_p = 1 MPa.

EXAMINATION OF GASSMANN'S EQUATION

Our velocity data for dry and saturated sandstones are used to test Gassmann's (1951) relations:

$$\frac{K_w}{K_m - K_w} = \frac{K_d}{K_m - K_d} + \frac{K_f}{\phi(K_m - K_f)} \quad (15)$$

and

$$G_w = G_d, \quad (16)$$

where K_w, G_w and K_d, G_d are the bulk and shear moduli of saturated and dry sandstones, respectively, and K_m and K_f are matrix and pore-fluid bulk moduli. These relations coincide with the low-frequency limit of the Biot equations (Biot, 1956). Because our data were obtained at high frequencies (10^5–10^6 Hz), the dependence of moduli on frequency may be explored.

If we assume that velocities in dry rocks at high frequencies are equal to the corresponding low-frequency values (Winkler, 1985), Gassmann's equation can be used to estimate the saturated moduli at low frequencies.

The bulk modulus of the matrix depends upon clay content. For shaly sandstones, we simply assume that the bulk modulus can be computed by equation (10) while substituting the velocities of equations (7) and (8) (assuming zero porosity). The bulk modulus for water is $K_f = 2.2$ GPa, calculated from the compressibility data for water by Robert (1975). With these values and the K_d values obtained from the velocity and density data, we compute K_w. The computed bulk modulus K_w is systematically less than the measured value (Figure 13). As bulk modulus increases (the porosity decreases), deviations increase, up to around 10 percent. Good agreement between data and computed values is found at porosities greater than 0.25. The systematic deviations of computed values from measured values suggest that the dispersion of bulk modulus with frequency depends somewhat on the porosity. Nevertheless, it appears that laboratory data in the megahertz range can be used in the seismic frequency range through the above approach.

Figure 13 shows quite a bit of scatter which might be caused by the effects of clay content. Further study of the effects of the porosity and clay content on velocities using Gassmann's equation, adjusted to the seismic frequency range by the above approach, might prove valuable.

CONCLUSION

On the basis of our experimental results, we conclude that in water-saturated shaly sandstones, compressional velocity V_p and shear velocity V_s are linearly related to porosities of from 2 to 30 percent and to clay contents of from 1 to 50 percent. The effect of clay content in reducing velocity is about 1/3.2 as great as the effect of porosity for V_p and 1/2.6 times as great for V_s.

Generally, the effects of porosity and clay content on the shear velocity V_s are larger than on the compressional velocity V_p. Thus, a sample with high porosity and clay content tends to have a high V_p/V_s ratio.

P- and *S*-wave velocities V_p and V_s of clean sandstones are significantly higher than for shaly sandstones with the same porosity. The matrix velocities 5.59 km/s for V_p and 3.52 km/s for V_s obtained from equations (7) and (8) with porosity and clay content set to zero are significantly lower than the corresponding velocities for quartz aggregates, i.e., 6.05 km/s for V_p and 4.09 km/s for V_s (Robert, 1982). This difference implies that a small amount of clays (1 or 2 percent volume fraction) can significantly soften the sandstone matrix, leading to reduced velocities.

The effects of all clays on velocities, other than the first 1 percent or so, are described by equations (7) and (8). The effect depends upon the volume clay fraction. A simple model by Minear (1982) shows that to first order these clays are arranged as lamina in the rocks or as grains between the sand grains. Furthermore, the effects of clays on velocities V_p and V_s are more from the reduction of the shear modulus than from the bulk modulus.

The interactions between clay minerals and water also influence elastic moduli and velocities. The pore fluid (water) appears to decrease shear modulus while increasing bulk modulus of the clays in sandstones. In poorly consolidated sandstones, however, water-saturated clays tend actually to stiffen grain contacts. Consequently, bulk and shear moduli increase as a result of better grain contacts in water-saturated clays. Differences in consolidation among dry sandstones are nearly overwhelmed by the effects of water saturation.

The differing responses of shear and bulk moduli G and K in relation of water saturation versus clay content indicate that the differences between V_p/V_s ratios for saturated and dry samples increase with increasing clay content.

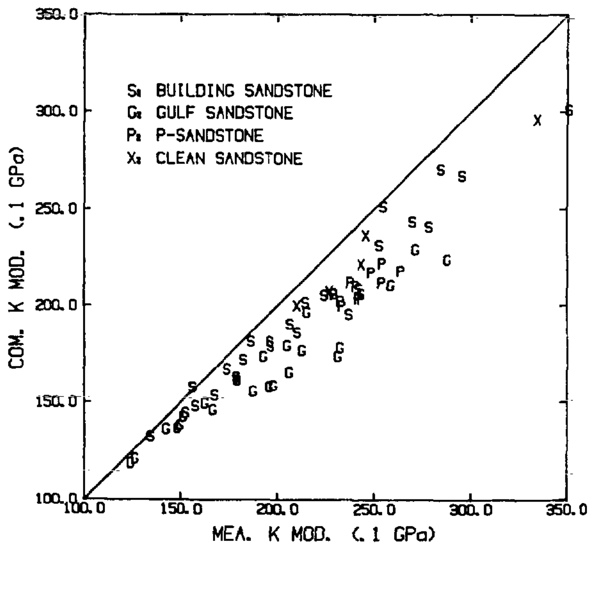

FIG. 13. Computed bulk moduli for fully saturated samples from velocity data of dry samples (assumed to be independent of frequency; Winkler, 1985) using Gassmann's relation versus measured data on 63 samples. The bulk modulus for rock matrix is calculated from equations, and that for water is 2.2 GPa. Deviations of data from the solid line can be considered estimates of bulk modulus dispersion with frequency, from zero to the megahertz range.

ACKNOWLEDGMENT

The authors thank C. Tosaya and D. Yale for helpful suggestions to start this study. Thanks are also due to B. Turner, A. Christina, L. Yale, and K. Velasco for collecting data from thin-section analysis, SEM and petrographic microphotography and analysis, and data-base management. Thanks are also due to B. Quinn for extensive reviewing of the final draft.

This research was supported by a grant from the Division of Engineering, Mathematics, and Geosciences, Office of Energy Research, U.S. Department of Energy.

REFERENCES

Benzing, W. M., 1978, V_p/V_s relationships in carbonates and sandstones: laboratory data: Presented at the 48th Ann. Internat. Mtg., Soc. Explor. Geophys., San Francisco.

Biot, M. A., 1956, Theory of propagation of elastic waves in fluid saturated porous solid: J. Accoust. Soc. Am., **28**, 168–178.

Birch, F., 1960, The velocity of compressional waves in rocks to 10 kilobars, 1: J. Geophys. Res., **65**, 1083–1102.
Costagna, J. P., Batzle, M. L., and Eastwood, R. L., 1985, Relationship between compressional wave and shear wave velocities in clastic silicate rocks: Geophysics, **50**, 551–570.
De Martini, D. C., Beard, D. C., Danburg, J. S., and Robinson, J. H., 1976, Variation of seismic velocities in sandstones and limestones with lithology and pore fluid at simulated in situ conditions: Proc. EGPC exploration seminar.
Domenico, S. N., 1984, Rock lithology and porosity determination from shear and compressional wave velocity: Geophysics, **49**, 1188–1195.
Eastwood, L. R., 1983, Basis for interpretation of V_p/V_s ratios in complex lithologies: Presented at the Soc. Prof. Well Log Anal. 24th Ann. Mtg., paper G.
Gassmann, F., 1951, Elastic waves through a packing of spheres: Geophysics, **16**, 673–685.
Geertsma, J., 1961, Velocity log interpretation: the effect of rock bulk compressibility: Soc. Petr. Eng. J., **1**, 235–248.
Geertsma, J., and Smit, D. C., 1961, Some aspects of acoustic wave propagation in fluid-saturated porous solids: Geophysics, **26**, 169–181.
Gregory, A. R., 1977, Aspects of rock physics from laboratory and log data that are important to seismic interpretation: Am. Assn. Petr. Geol. Memoir 26, 15–46.
Johnson, W. E., 1978, Relationship between shear-wave velocity and geotechnical parameters: Presented at the 48th Ann. Internat. Mtg., Soc. Explor. Geophys., San Francisco.
Kevin, B. H., 1981, Factors affecting acoustic compressional velocities and an examination of empirical correlations between velocities and porosities: Presented at the Soc. Prof. Well Log Anal., 22nd Ann. Mtg., paper PP.
King, M. S., 1966, Wave velocities in rocks as a function of changes in overburden pressure and pore fluid saturations: Geophysics, **31**, 50–73.
Kowallis, B., Jones, L. E. A., and Wang, H. F., 1984, Velocity-porosity-clay content; systematics of poorly consolidated sandstones: J. Geophys. Res., **89**, 10355–10364.
Kuster, G. T., and Toksöz, M. N., 1974, Velocity and attenuation of seismic waves in two-phase media, I: Theoretical formulation: Geophysics, **39**, 587–606.
Mavko, G. M., and Nur, A. M., 1978, The effect of nonelliptical cracks on the compressibility of rocks: J. Geophys. Res., **83**, 4459–4468.
Minear, M. J., 1982, Clay models and acoustic velocities: Presented at the 57th Ann. Mtg., Am. Inst. Min. Metall. Eng., New Orleans.
O'Connell, R. J., and Budiansky, B., 1974, Seismic velocities in dry and saturated cracked solids: J. Geophys. Res., **79**, 5412–5426.
Nur, A., and Simmons, G., 1969, The effect of saturation on velocity in low porosity rocks: Earth Plan. Sci. Lett., **7**, 183–193.
Pickett, G. R., 1963, Acoustic character logs and their application in formation evaluation: J. Petr. Tech., **15**, 659–667.
Quirein, J. A., Baldwin, J. L., Terry, L., and Hendricks, M., 1981, Estimation of clay types and volumes from well log data—an extension of the global method: Presented at the Soc. Prof. Well-Log Anal. 22nd Ann. Mtg., paper Q.
Rafavich, F., Kendall, C.H.St.C., and Todd, T. P., 1984, The relationship between acoustic properties and the petrographic character of carbonate rocks: Geophysics, **49**, 1622–1636.
Raymer, D. S., Hunt, E. R., and Gardner, J. S., 1980, An improved sonic transit time-to-porosity transform: Presented at the Soc. Prof. Well Log Anal. 21st Ann. Mtg., paper P.
Robert, C. W., 1975, CRC handbook of chemistry and physics: F-18.
Robert, S. C., 1982, 1982 CRC handbook of physical properties of rocks: **2**, 213.
Tatham, R. H., 1982, V_p/V_s and lithology: Geophysics, **47**, 336–344.
Toksöz, M. N., Cheng, C. H., and Timur, A., 1976, Velocities of seismic waves in porous rocks: Geophysics, **41**, 621–645.
Tosaya, C., 1982, Acoustical properties of clay-bearing rocks: Ph.D. dissertation, Stanford Univ.
Tosaya, C., and Nur, A., 1982, Effects of diagenesis and clays on compressional velocities in rocks: Geophys. Res. Lett., **9**, 5–8.
Walsh, J. B., and Grosenbaugh, M. A., 1979, A new model for analyzing the effect of fractures on compressibility: J. Geophys. Res., **84**, 3532–3536.
Winkler, K. W., 1985, Dispersion analysis of velocity and attenuation in Berea sandstone: J. Geophys. Res., **90**, 6793–6800.
Wyllie, M. R. J., Gregory, A. R., and Gardner, L. W., 1956, Elastic wave velocities in heterogeneous and porous media: Geophysics, **21**, 41–70.
——— 1958, An experimental investigation of factors affecting elastic wave velocities in porous media: Geophysics, **23**, 459–493.

APPENDIX

Values of bulk density D_w, clay content (volume percent), compressional velocity V_p(km/s), shear velocity V_s(km/s), and porosity ϕ for the 75 sandstones of this study, at differential pressures of 5, 10, 20, 30, and 40 MPa.

SAMP. #	Dw	CLAY	5 MPa			10 MPa			20 MPa			30 MPa			40 MPa		
			Vp	Vs	Φ	Vp	Vs	Φ	Vp	Vs	Φ	Vp	Vs	Φ	Vp	Vs	Φ
1	2.33	0.00	4.26	2.53	.1846	4.44	2.69	.1838	4.58	2.84	.1831	4.64	2.89	.1825	4.66	2.91	.1821
2	2.31	0.00	4.08	2.39	.2006	4.27	2.54	.2001	4.34	2.66	.1996	4.40	2.70	.1992	4.42	2.72	.1989
3	2.53	0.00	5.15	3.17	.0670	5.27	3.39	.0661	5.42	3.49	.0652	5.47	3.56	.0644	5.52	3.60	.0646
4	2.39	0.00	4.61	2.91	.1550	4.71	3.01	.1547	4.76	3.06	.1544	4.78	3.08	.1542	4.81	3.10	.1539
5	2.32	0.00	4.16	2.59	.1988	4.32	2.73	.1984	4.40	2.81	.1980	4.43	2.82	.1976	4.46	2.85	.1973
6	2.25	.10	3.43	2.02	.2382	3.49	2.10	.2377	3.58	2.16	.2368	3.64	2.20	.2361	3.68	2.22	.2355
7	2.24	.16	3.02	1.72	.2635	3.15	1.81	.2625	3.22	1.91	.2615	3.29	1.97	.2605	3.36	1.99	.2597
8	2.24	.10	3.35	1.92	.2432	3.47	2.03	.2425	3.58	2.10	.2416	3.64	2.15	.2409	3.69	2.17	.2403
9	2.38	.28	3.51	1.88	.1640	3.59	1.96	.1629	3.71	2.02	.1611	3.77	2.05	.1599	3.82	2.07	.1589
10	2.45	.06	4.57	2.85	.1091	4.62	2.89	.1082	4.66	2.93	.1072	4.70	2.96	.1063	4.73	3.00	.1056
11	2.23	.04	3.58	2.01	.2334	3.74	2.17	.2324	3.84	2.29	.2314	3.89	2.33	.2305	3.92	2.35	.2297
12	2.38	.03	4.40	2.62	.1580	4.45	2.68	.1572	4.51	2.74	.1562	4.55	2.78	.1553	4.60	2.81	.1546
13	2.47	.05	4.37	2.56	.1090	4.50	2.68	.1081	4.61	2.80	.1071	4.68	2.85	.1062	4.73	2.89	.1056
14	2.18	.06	3.56	1.98	.2575	3.63	2.01	.2568	3.69	2.05	.2556	3.72	2.07	.2546	3.74	2.08	.2536
15	2.53	.07	4.90	2.94	.0447	4.99	3.02	.0439	5.09	3.09	.0427	5.16	3.14	.0419	5.20	3.17	.0412
16	2.41	.27	3.67	1.94	.1289	3.79	2.03	.1280	3.93	2.15	.1270	4.01	2.20	.1262	4.06	2.24	.1256
17	2.36	.06	4.02	2.33	.1829	4.13	2.44	.1823	4.22	2.52	.1817	4.26	2.54	.1811	4.30	2.57	.1807
18	2.25	.16	3.24	1.81	.2590	3.34	1.91	.2583	3.43	1.98	.2573	3.49	2.02	.2564	3.54	2.05	.2557
19	2.50	.06	4.81	3.00	.0582	4.83	3.04	.0579	4.88	3.08	.0575	4.91	3.10	.0572	4.94	3.12	.0569
20	2.47	.14	3.85	2.14	.1339	3.96	2.21	.1332	4.07	2.31	.1322	4.17	2.37	.1315	4.23	2.41	.1309
21	2.35	.06	4.03	2.35	.1785	4.14	2.46	.1777	4.23	2.55	.1771	4.28	2.59	.1765	4.32	2.62	.1761
22	2.28	.04	3.58	2.06	.2100	3.73	2.18	.2092	3.91	2.30	.2084	3.98	2.36	.2078	4.03	2.40	.2072
23	2.34	.05	3.79	2.16	.1908	3.94	2.28	.1900	4.08	2.41	.1891	4.14	2.47	.1885	4.18	2.50	.1880
24	2.57	.08	4.41	2.68	.0935	4.51	2.77	.0928	4.60	2.86	.0920	4.65	2.90	.0916	4.69	2.94	.0912
25	2.57	.08	4.65	2.82	.0940	4.72	2.91	.0934	4.80	2.98	.0928	4.85	3.02	.0924	4.88	3.05	.0920
26	2.27	.03	3.58	2.15	.2397	3.69	2.24	.2389	3.79	2.30	.2380	3.84	2.34	.2374	3.89	2.37	.2369
27	2.34	.06	3.71	2.15	.1928	3.92	2.33	.1920	4.04	2.43	.1913	4.11	2.48	.1907	4.15	2.51	.1903
28	2.30	.03	3.66	2.13	.2194	3.77	2.23	.2184	3.86	2.32	.2176	3.91	2.37	.2170	3.95	2.39	.2165
29	2.28	.06	3.70	2.11	.2246	3.85	2.26	.2236	3.94	2.33	.2226	4.00	2.37	.2219	4.03	2.40	.2213
30	2.31	.09	3.73	2.23	.1927	3.86	2.35	.1917	3.98	2.45	.1905	4.04	2.50	.1895	4.08	2.54	.1887
31	2.51	.13	4.18	2.40	.0902	4.34	2.53	.0876	4.48	2.65	.0857	4.58	2.75	.0848	4.62	2.80	.0835
32	2.57	.13	4.30	2.42	.0682	4.52	2.52	.0660	4.57	2.66	.0636	4.76	2.75	.0624	4.77	2.80	.0612
33	2.55	.12	4.32	2.38	.0755	4.57	2.87	.0735	4.72	3.03	.0712	4.77	3.19	.0700	4.78	3.23	.0690
34	2.54	.13	4.45	2.29	.0689	4.54	2.41	.0671	4.67	2.49	.0653	4.72	2.60	.0638	4.79	2.67	.0624
35	2.56	.12	4.63	2.59	.0370	4.80	2.77	.0348	4.95	2.90	.0330	4.99	3.02	.0320	5.00	3.13	.0313
36	2.61	.15	4.92	3.06	.0314	5.11	3.14	.0284	5.18	3.18	.0273	5.22	3.23	.0268	5.23	3.26	.0264
37	2.57	.07	4.73	2.61	.0365	4.88	2.75	.0345	4.97	2.97	.0324	5.09	3.07	.0315	5.23	3.09	.0312
38	2.54	.18	4.66	2.73	.0450	4.82	2.84	.0425	4.99	2.99	.0404	5.06	3.09	.0395	5.13	3.13	.0390
39	2.62	.15	4.87	2.90	.0260	5.00	2.95	.0245	5.08	3.06	.0235	5.10	3.09	.0229	5.11	3.10	.0225
40	2.61	.15	4.44	2.51	.0672	4.53	2.60	.0642	4.61	2.70	.0627	4.67	2.72	.0617	4.68	2.73	.0612
41	2.55	.38	4.11	2.41	.0683	4.23	2.49	.0665	4.30	2.56	.0651	4.33	2.59	.0641	4.37	2.62	.0634
42	2.56	.40	4.04	2.30	.0762	4.10	2.36	.0747	4.16	2.41	.0735	4.21	2.46	.0725	4.24	2.49	.0719
43	2.49	.37	3.81	2.13	.1170	3.91	2.22	.1153	3.99	2.28	.1138	4.04	2.30	.1127	4.08	2.34	.1118
44	2.53	.40	3.97	2.29	.0932	4.08	2.38	.0918	4.18	2.45	.0903	4.21	2.50	.0892	4.24	2.52	.0885
45	2.55	.35	3.89	2.20	.0983	3.97	2.28	.0964	4.05	2.35	.0947	4.12	2.40	.0935	4.17	2.43	.0927
46	2.57	.45	4.03	2.30	.0738	4.12	2.39	.0713	4.22	2.48	.0697	4.28	2.53	.0685	4.32	2.57	.0677
47	2.41	.13	3.92	2.23	.1437	4.10	2.39	.1425	4.31	2.54	.1413	4.40	2.60	.1407	4.47	2.64	.1402
48	2.42	.14	3.98	2.28	.1668	4.10	2.39	.1656	4.21	2.47	.1646	4.28	2.53	.1637	4.32	2.55	.1632
49	2.38	.10	3.81	2.13	.1593	3.96	2.26	.1582	4.10	2.39	.1571	4.18	2.45	.1565	4.24	2.51	.1560
50	2.38	.11	3.78	2.04	.1772	3.95	2.18	.1760	4.11	2.31	.1747	4.17	2.38	.1741	4.22	2.43	.1735

SAMP. #	Dw	CLAY	5 MPa			10 MPa			20 MPa			30 MPa			40 MPa		
			Vp	Vs	Φ	Vp	Vs	Φ	Vp	Vs	Φ	Vp	Vs	Φ	Vp	Vs	Φ
51	2.38	.16	3.76	2.06	.1739	3.91	2.21	.1726	4.03	2.32	.1716	4.13	2.38	.1701	4.19	2.42	.1696
52	2.40	.44	3.42	1.74	.1360	3.52	1.81	.1322	3.62	1.90	.1302	3.66	1.94	.1288	3.71	1.97	.1278
53	2.38	.46	3.37	1.81	.1380	3.44	1.87	.1360	3.53	1.93	.1339	3.59	1.97	.1323	3.64	1.99	.1310
54	2.35	.51	3.33	1.75	.1246	3.43	1.86	.1205	3.54	1.94	.1178	3.63	1.98	.1160	3.68	2.01	.1146
55	2.09	.11	2.86	1.51	.3061	3.01	1.60	.3039	3.11	1.69	.3019	3.16	1.73	.3005	3.20	1.75	.2993
56	2.12	.12	2.94	1.57	.3004	2.99	1.65	.2987	3.08	1.72	.2970	3.13	1.75	.2956	3.17	1.77	.2945
57	2.35	.27	3.44	1.72	.1575	3.60	1.86	.1551	3.78	2.01	.1525	3.90	2.08	.1512	3.99	2.13	.1500
58	2.35	.27	3.55	1.76	.1535	3.70	1.94	.1505	3.83	2.03	.1479	3.93	2.11	.1467	4.00	2.16	.1454
59	2.20	.22	2.93	1.47	.2492	3.08	1.64	.2475	3.24	1.79	.2458	3.31	1.86	.2446	3.36	1.89	.2435
60	2.19	.12	3.05	1.53	.2590	3.22	1.71	.2574	3.41	1.84	.2554	3.49	1.90	.2541	3.55	1.94	.2531
61	2.41	.37	3.41	1.79	.1504	3.54	1.90	.1480	3.65	2.00	.1458	3.73	2.08	.1440	3.76	2.11	.1430
62	2.48	.44	3.58	1.92	.1146	3.64	2.00	.1129	3.74	2.08	.1113	3.80	2.13	.1095	3.84	2.15	.1089
63	2.47	.41	3.63	1.91	.1035	3.76	2.03	.0991	3.85	2.12	.0965	3.92	2.16	.0947	3.97	2.19	.0937
64	2.37	.27	3.65	1.88	.1506	3.74	2.00	.1493	3.88	2.09	.1461	3.95	2.15	.1445	3.98	2.19	.1434
66	2.17	.08	3.27	1.85	.2675	3.42	2.00	.2656	3.57	2.13	.2641	3.62	2.17	.2632	3.67	2.20	.2625
66	2.25	.06	3.15	1.73	.2724	3.33	1.84	.2710	3.50	2.00	.2696	3.56	2.06	.2686	3.61	2.09	.2679
67	2.12	.11	3.12	1.66	.2835	3.28	1.84	.2818	3.46	1.98	.2803	3.52	2.03	.2793	3.56	2.07	.2785
68	2.17	.07	2.98	1.50	.2705	3.13	1.75	.2692	3.33	1.89	.2674	3.43	1.95	.2664	3.50	1.99	.2655
69	2.14	.07	3.04	1.60	.2789	3.23	1.81	.2774	3.43	1.96	.2760	3.53	2.05	.2750	3.58	2.09	.2742
70	2.29	.11	3.32	1.76	.2065	3.48	1.91	.2052	3.69	2.08	.2037	3.81	2.17	.2028	3.88	2.23	.2021
71	2.47	.21	3.71	2.08	.1177	3.90	2.18	.1146	4.08	2.32	.1118	4.19	2.42	.1100	4.25	2.48	.1089
72	2.39	.06	3.96	2.16	.1567	4.17	2.36	.1548	4.42	2.53	.1529	4.54	2.66	.1516	4.61	2.73	.1508
73	2.47	.23	3.91	2.14	.1100	4.09	2.30	.1071	4.27	2.46	.1047	4.35	2.55	.1031	4.42	2.61	.1021
74	2.64	.24	4.10	2.28	.0651	4.31	2.54	.0631	4.44	2.64	.0605	4.56	2.72	.0594	4.60	2.77	.0586
75	2.38	.18	3.67	2.02	.1514	3.85	2.17	.1490	3.93	2.27	.1466	4.01	2.32	.1452	4.07	2.37	.1442

* Dw: saturated bulk density in gm/cc; CLAY: clay volume fraction; Vp, Vs: velocity in km/s.