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SONIC AND ELECTRICAL PROPERTIES OF PARTIALLY SATURATED TIGHT-GAS SANDS

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Final Report

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ABSTRACT

This study was aimed at relating the seismic and the electrical properties of tight-gas rocks to their pore-space geometry, permeability, and level of water saturation. Here we report results of a laboratory experimental study of wave propagation in Cotton Valley and Spirit River Sandstones as a function of partial water saturation and wave frequency. We find that wave velocities and the velocity ratio are sensitive to the presence of gas. Furthermore, wave attenuation is sensitive to the amount of gas in the pore space. Ultrasonic measurements in tight-gas sands tend to yield higher velocity values, due to the inability of the pore fluid pressure to homogenize during the passage of waves.

Laboratory measurements were made also of the complex electrical response of selected tight rocks, and compared with "normal" permeability Berea Sandstone. The results show that the dielectric property of tight-gas sands is very sensitive to partial water saturation, and may give not only insight into the nature of the pore space, but also provide a practical measure of S_w in situ.

1. INTRODUCTION

In recent years, significant progress has been made in understanding the acoustic velocities and attenuation of unconsolidated sands (Stoll, 1979; Murphy, 1982b) and high porosity ($\phi > 10\%$) sandstones (Spencer, 1981; Winkler and Nur, 1982; Murphy, 1982a). Relatively little, however, is known about the acoustic properties of low porosity ($\phi < 10\%$) sandstones. The only data available for tight sands regarding the sensitivity of velocities to partial gas saturation are by Gregory (1976). We are aware of no published attenuation measurements in tight sandstones. As the production of natural gas widens to ever more marginal reservoirs (such as tight gas sands with permeabilities as low as ~ 100 -1000 nd), increasing reliance is being placed on high resolution seismic reflections and borehole sonic logs to aid in reservoir evaluation (fig. 1). For tight sands techniques are required which not only reveal the presence of gas but also indicate the degree of partial gas saturation (Walls, 1981). More therefore needs to be learned about the acoustic properties of these rocks.

Gregory's (1976), as well as our results, have shown that no effect of partial gas saturation is sufficiently strong for resolution in situ at ultrasonic frequencies. In this paper we show however that the 1-10 kHz range, compressional velocity, V_p , and the ratio of compressional to shear velocity, V_p/V_s , are quite sensitive to undersaturation. Furthermore the specific attenuations Q_p^{-1} and Q_s^{-1} show a strong dependence on partial saturation. Simultaneous measurements of V_p , V_s , Q_p^{-1} , and Q_s^{-1} may provide significant information not only about the presence of gas but also about the degree of gas saturation.

It is well established that in unconsolidated sands, V_p is sensitive to the presence of small amounts of gas in the pores (Gassman, 1951; Domenico, 1974, 1976, 1977; Elliott and Wiley, 1975). This effect is, of course, the basis for the "bright spot" technology, which has made a significant contribution to the discovery of natural gas throughout the world. The effect was originally inferred from approximate relations between theory and laboratory measurements. For example, the measurements were made at high ultrasonic (>0.5 MHz) frequencies (Elliott and Wiley, 1975; Domenico, 1976, 1977). Brown and Korringa (1979) have shown however that the behavior at seismic frequencies cannot be directly inferred from Gassman (1981) relations. Nonetheless, the qualitative agreement between the measured dependence on gas saturation and the dependence predicted by the low frequency limit (the Biot-Gassman relations) is such that it has led to the direct extrapolation of the ultrasonic results to seismic frequencies. Thus in practice, velocity dispersion has been considered inconsequential.

The situation in tight sands is more subtle. Gregory's (1976) measurements were made at 1 MHz. Dispersion was assumed small and the behavior was thus applied without correction to seismic frequencies (fig. 2). Gregory's (1976) measurements show V_p is nearly unaffected by slight undersaturation and weakly dependent on partial water saturation, S_w , throughout the higher ranges (i.e., $S_w > 0.3$). The S velocity is observed to be roughly independent of S_w in the higher ranges. Here we will show that in tight sandstones at high ultrasonic frequencies, waves are controlled by unrelaxed moduli, whereas at low frequencies, they are controlled

Fig. 1. Acoustic techniques for reservoir delineation.

Fig. 2. Frequency spectrum of interest to geophysical exploration.

by relaxed ones. In tight sandstones, therefore, consideration of frequency, attenuation, and dispersion is essential for predicting from laboratory measurements the in situ response in borehole and seismic frequencies.

This paper is a report of an experimental study of tight sandstones. Section 2 is a comparison between grain contacts, pore structure, and relevant physical properties of tight sands with unconsolidated sands and high porosity sandstones. In sections 3 and 4, we report on measurements of extensional and shear velocities, V_e , V_s , Q_e^{-1} , and Q_s^{-1} as a function of continuously varying S_w in Fort Union sandstone ($\phi = 8.5\%$), in Cotton Valley sandstone ($\phi = 3.3\%$) and a Spirit River sandstone ($\phi = 5.4\%$) which were taken at frequencies ranging from 50 Hz to 7 kHz.

Ultrasonic velocities as a function of S_w and effective pressure, P_e , are discussed along with the general ultrasonic problem in sections 5 and 6.

2. BACKGROUND

Tight sandstones are a relatively unfamiliar class of sedimentary rocks. It is most instructive to discuss them in a diagenetic context, because we know significantly more about unconsolidated sands and high porosity sandstones (Murphy and Walls, 1981).

Pore Network Geometry

During the primary stages of diagenesis, as sands consolidate and progressively lose porosity (fig. 3), there is an increase in grain contact area, increase in the number of contacts per grain, and increase in the pore network tortuosity. Consequently, in tight sands, wave velocities are generally higher and permeability is lower than in more porous rocks. Beyond these continuous diagenetic changes there is also a change in the local pore network geometry which occurs as a high porosity sandstone becomes a low porosity sandstone. As we shall later see, this change controls the acoustic properties in tight sands.

In high porosity sandstones, typically large (~ 20 m) high aspect ratio, pores are well connected by large (> 10 m) pore throats. This geometry results in rounded pore channels (figs. 4, 5, 6). These channels which control permeability (fig. 6), are insensitive to effective pressure. They also provide large capacity for pore fluids stress waves (Murphy, 1982c). Low aspect ratio pore tips or cracks (~ 1 μ m), which are more compliant, control the frame moduli (fig. 6) but contribute little to the porosity and permeability.

In low porosity sandstones, large pores, if any, are sparsely distributed, and connectivity is provided by more compliant, sheet-like capillaries, ~ 10 μ m in width (figs. 4, 5, 6). These capillaries contribute a significant volume to the porosity, and they are the dominant microstructural factor for most physical properties in tight sandstones. For example, in SR6521.6, a typical Spirit River tight sandstone (fig. 7), the reduction in normalized pore volume is 12.5% as confining pressure P_c goes from 0 to 25 MPa. The corresponding porosity decline is less than 3% in typical high porosity sandstones (Fatt, 1953).

TABLE I. SAMPLE DESCRIPTIONS

	AGE, LOCATION	CLASSIFICATION	POROSITY		QUARTZ								MEAN GRAIN SIZE μ m	SORTING	GAS PERMEABILITY	
			%	QUARTZ	OVERGROWTH	CHERT	FELDSPAR	CLAY	CALCITE	DOLOMITE	OTHERS	AT STP			IN DARCIES	
Schuler-Cotton Valley Ss. SCV9594	Late Jurassic Schuler Member Cotton Valley Formation East Texas Basin	Subquartzarenite	5.1	71.9	12	3	2	1	4	1	-	100	moderately well sorted	1.6×10^{-5}		
SCV10500		Subquartzarenite	3.3	72	15	2	1	1	4	5	-	100	moderately well sorted	1.1×10^{-6}		
Fort Union Ss.	Paleocene 10579.5-10574.7 ft. Pinedale Anticline Green River Basin	Fluvial Sub- Greywacke	8.5	42	10	-	5	11	10	10	12	125-150	poorly sorted			
Spirit River Ss. SR6556.5	Cretaceous Spirit River Member Falher Formation Deep Alberta Basin	Lithicarenite	7.1	48.8	14.3	13.3	-	2.9	-	7.3	-	100-125	poorly sorted	5.8×10^{-5}		
SR6521.6		Lithicarenite	4.6	39.8	10	12.4	0.5	3.3	-	15.2	-	100-125	poorly sorted	1.9×10^{-5}		
SR7227		Lithicarenite	5.4	41.1	10.8	23	0.5	6.6	-	10.4	2	125-150	poorly sorted	2.1×10^{-5}		
St. Peter Ss.	Ordovician Missouri	Orthoquartzarenite	8	91.9	8	-	-	0.1	-	-	-	200-250	well sorted			
Massillon Ss.	Mississippian Glenmont, Ohio	Subquartzarenite	23	88	3	-	2	5	-	-	2	150-200	1.225	7.37×10^{-1}		
Berea 100 Ss.	Mississippian Amherst, Ohio	Subquartzarenite	19.8	82	4	-	0.5	4	-	-	1.5	150	1.335	5.2×10^{-3}		
Ottawa Sand	Ordovician Ottawa Formation Ottawa, Illinois	Quartz sand	38	99.9	-	-	-	-	-	-	-	149-174	extremely well sorted	>10

(a)

(b)

(c)

Fig. 3. Sketch of the fabric of the three general types of granular sedimentary materials:

- a) unconsolidated sands,**
- b) high porosity consolidated sandstones, and**
- c) low porosity or tight sandstones.**

Fig. 4. SEM photomicrographs of high porosity Massilon sandstone (a-b) and Schuler-Cotton Valley sandstone (c-d). The scale in microns is given by the bar at the base of each photomicrograph.

Fig. 5. Photomicrographs of thin sections impregnated with light blue epoxy. High porosity sandstones (a-b) and low porosity sandstones (c-d). a, b, c, and d are in the same positions as in figure 4. Grain size is roughly 100 microns in each photomicrograph.

Fig. 6 The pore geometry of a high porosity sandstone may be thought of as a tortuous network of pores connected by open pore throats with near-contact gaps merely as ancillary wings (a), while the pore geometry of a low porosity sandstone may be thought of as a network of isolated pores in which the near-contact gaps provide the connectivity (b).

Fig. 7. Normalized pore volume change vs. confining pressure
in SR 6521.6 low porosity sandstone.

Permeability

Figure 8 compares the dependence of gas permeability on effective pressure P_e in two porous sandstones and two tight sandstones. At 20 MPa, the high porosity values exhibit less than a 10% reduction, while the low porosity sandstones have dropped roughly an order of magnitude.

Another important effect has been discussed at length by Walls (1981). In partially saturated sandstones, capillary forces will tend to drive the pore water into the narrow ($<10 \mu\text{m}$) gaps between grains (cf. Defay and Prigogin, 1966). Walls (1981) has shown that in Spirit River sandstone, increasing S_w from 0 to 0.7 reduces gas permeability up to three orders of magnitude. As S_w increases, more and more the water is imbibed into the sheet capillaries, progressively isolating the larger pores in which most of the gas resides. This effect on gas permeability is a principal reason why accurate knowledge of S_w is so important for in situ tight gas and reservoir evaluation.

Velocities

Measurements of P and S velocities vs. effective pressure P_c for three vacuum dry samples (fig. 9) were obtained by a standard ultrasonic pulse transmission technique (Nur and Simmons, 1969; Gregory, 1976). This technique yields signal velocities, $\hat{V}_p$ and $\hat{V}_s$, which in significantly dispersive media, are equivalent to the group velocities, $\bar{V}_p$ and $\bar{V}_s$, respectively. The group velocities are related to the phase velocities by

$$\bar{V}_p = \left[\frac{d(\omega/V_p)}{d\omega} \right]_{\omega_m}^{-1} \quad \text{and} \quad \bar{V}_s = \left[\frac{d(\omega/V_s)}{d\omega} \right]_{\omega_m}^{-1} \quad (1)$$

where ω is the angular frequency, and ω_m is the center angular frequency of the group of waves. Differentiating (1), we find that the group velocity is given by

$$\bar{V}_p = V_p \left[1 - \frac{\omega_m}{V_p} \left(\frac{\partial V_p}{\partial \omega} \right)_{\omega_m} \right]^{-1} \quad (2a)$$

and

$$\bar{V}_s = V_s \left[1 - \frac{\omega_m}{V_s} \left(\frac{\partial V_s}{\partial \omega} \right)_{\omega_m} \right]^{-1} \quad (2b)$$

When the phase velocity is independent of frequency, $\bar{V} = V$. Assuming that there is no velocity dispersion in vacuum-dry rocks, $\left(\frac{\partial V_p}{\partial \omega} \right)_{\omega_m} = 0$ and $\left(\frac{\partial V_s}{\partial \omega} \right)_{\omega_m} = 0$, or $\hat{V}_p = \bar{V}_p = V_p$ and $\hat{V}_s = \bar{V}_s = V_s$. In figure 9, a 100% increase in both V_p and V_s accompanies a 15% porosity decrease from Ottawa sand to Massillon sandstone;

Fig. 8. Normalized permeability, H/H_0 , vs. effective pressure in sandstones. Massilon and Berea sandstones are high porosity sandstones. SCV9594 and SR6556.5 are low porosity sandstones.

Fig. 9. Ultrasonic velocities vs. effective pressure in the three general types of vacuum-dry granular sedimentary rocks.

and a 25% velocity increase accompanies the 18% decrease in ϕ from Massillon to Cotton Valley sandstone. Velocities in vacuum-dry granular materials are given by Murphy (1982a),

$$V_p = \left(\frac{K_d + \frac{4}{3}\mu_d}{\phi\rho_s} \right)^{1/2}, \quad V_s = \left(\frac{\mu_d}{\phi\rho_s} \right)^{1/2} \quad (3)$$

where K_d is the dry frame bulk modulus, μ_d is the dry frame shear modulus, and ρ_s is the density of the solid grains, $\sim 2.65 \text{ g/cm}^3$ for quartz grains. The velocities in dry low- ϕ sandstones are not always higher than in high- ϕ sandstones as shown in figure 10. Note the relatively small velocity dependence on P_e in the St. Peter sandstone. This rock has unusually well cemented, ball-in-a-seat type grain contacts (Murphy, 1982b).

Due to recent interest, the ratio V_p/V_s in attempting to distinguish gas-related bright spots from lithologic discontinuities, Ostrander (1981) has proposed using V_p/V_s or to identify lithologies (Tatham, 1982). We have plotted V_p/V_s vs. V_p for several vacuum-dry rocks (fig. 11).

Figure 12 presents V_p/V_s results for rock at several states of saturation. This Ottawa sand data shows a large increase in $\bar{V}_p$ and $\bar{V}_p/\bar{V}_s$ with full saturation as anticipated from theory. In contrast, the data for the consolidated sandstones, particularly the tight Cotton Valley, show only very small differences between $\bar{V}_p$ or $\bar{V}_p/\bar{V}_s$ values taken at $S_w = 0.7$ and full saturation. This saturation effect is surprisingly small in view of a host of theories (e.g., Walsh, 1965) which predict a large effect upon full saturation. In this paper we show that the effect is actually large but only at lower frequencies, where the pore fluid is in the relaxed state. In other words, velocities are frequency dependent or dispersive in fluid-bearing rocks.

3. VELOCITIES AND ATTENUATION AT ACOUSTIC FREQUENCIES

Fort Union Sandstone

Using a resonant bar technique (e.g., Winkler and Nur, 1982), we have measured the extensional velocity V_e and Q_e^{-1} at 5850-6286 Hz, and V_s and Q_s^{-1} at 3902-4548 Hz in a Fort Union sandstone ($\phi = 8\%$) as a function of continuously varying S_w . Finally a 15% increase is observed in both V_e and V_s from $S_w = 0.03$ to a dry state in which the samples have equilibrated with a relative humidity between 0.01 and 0.02 (fig. 13).

Resonant frequencies are measured to 1 part in 10^3 and converted to phase velocities using the relation $V = 2Lf$, where L is the sample length and f is the frequency. Dissipation values are obtained by measuring the time constant of resonant decays ($\tau = Q/\pi f$). Relative precision is within 2%, and the accuracy is estimated to be 5-10%. The velocities and attenuation are measured as a function of S_w on a continuously drying sample (Murphy, 1982a). The saturating

Fig. 10. Ultrasonic velocities vs. effective pressure in various vacuum-dry, low-porosity sandstones.

Fig. 11. V_p/V_s plotted against V_p as a function of effective pressure for the data from figure 9.

Fig. 12 $\bar{V}_p/\bar{V}_s$ vs. $\bar{V}_p$ as a function of effective pressure in the three different material types at full water saturation and at 70% water saturation.

Fig. 13. V_e and V_s vs. % water saturation ($S_w = 0.10 - 1.00$)
in Fort Union sandstone at ~ 5 kHz.

water is 2 megohm H_2O which has been deaerated by evacuation for 2 days. Temperature and relative humidity are held steady through the drying period at 22°C and 0.30, respectively. The sample length is 24 cm.

The results are shown in figures 13 and 14. In figure 13, V_s increases sharply by 5% as S_w decreases from 1.0 to 0.9 followed by weak dependence to $S_w = 0.4$, and by further decrease below $S_w = 0.3$. V_e increases slightly (i.e., 0.1%) with initial undersaturation followed by a 10% decrease as S_w declines from 0.92 to 0.3. From $S_w = 0.3$ to 0.1, V_e increases roughly 5%.

The quality factor in shear Q_s (fig. 14) at full saturation is 5.3, or $1000/Q_s \approx 200 Q_s^{-1}$ and drops monotonically with decreasing $S_w = 1.0$ to 0.3. Small variations occur between $S_w = 0.85$ and 0.7 and between $S_w = 0.4$ and 0.5. Q_e at full saturation is 9.6. Q_e^{-1} is largest at $S_w = 0.79$, crossing Q_s^{-1} near 0.8. At lower S_w $Q_e^{-1} > Q_s^{-1}$ and Q_e^{-1} , dependence on S_w emulates that of the S dependence.

Cotton Valley Sandstone (Schuler Member)

A set of shear data was obtained from a drying experiment on a sample from the Schuler member of the Cotton Valley sandstone (SCV10500 $\phi = 3.3\%$) (fig. 15). The samples were 20 cm long cylindrical cores. The frequency range was 6256 to 6603 Hz. V_s decreases by 5% from full saturation to $S_w = 0.5$, and increases by 5% from $S_w = 0.5$ to the dry state. Q_s is 6.7 at full saturation. The decrease in Q_s^{-1} with S_w is steep from 149 at $S_e = 1.0$ to 58 at $S_w = 0.69$, and more moderate from 51 at $S_w = 0.63$ to 7.4 at $S_w \approx 0$.

Schuler-Cotton Valley and Spirit River Sandstones

We measured the frequency dependence in tight sands at lower frequencies in saturated Cotton Valley sandstone ($\phi = 3.3\%$) and a Spirit River SR7227 ($\phi = 5.4\%$) using a torsional pendulus technique (Peselnick and Outerbridge, 1961). Frequencies are varied by changing the interial mass attached to the base of the sample. The samples jacketed with Saran Wrap are housed in a humidity chamber similar to the resonant bar. Temperature is held constant at 22°C, and relative humidity is kept at 0.96.

In figure 17, are the results. We observe in SCV10500 at 300% in Q_s^{-1} from a frequency of 73 to 638 Hz (fig. 17). In SR7227, Q_s^{-1} roughly doubles from 58 to 495 Hz.

4. DISCUSSION OF THE ACOUSTIC RESULTS

From the measured values of V_e , V_s , Q_e^{-1} , and Q_s^{-1} we calculate the compressional wave velocity, V_p , the compressional wave specific attenuation

Fig. 14. V_e and V_s vs. moisture content ($S_w = 0 - 0.10$) in Fort Union sandstone at ~ 5 kHz.

Fig. 15. $1000/Q_e$ and $1000/Q_s$ vs. % water saturation ($S_w = 0.10$ - 1.00) in Fort Union sandstone at ~5 kHz.

Fig. 16 Shear wave velocity and specific attenuation vs.
 % water saturation ($S_w = 0 - 1.0$) in SCV 10500
 at ~6.5 kHz.

Q_p^{-1} , and the bulk compressional specific attenuation, Q_k^{-1} , (Murphy, 1982a). We estimate that the resulting error in the computed values is less than 10% in both velocities and Q^{-1} .

Velocities

Measured V_s and calculated V_p values are shown in figure 18. From full saturation to $S_w = 0.9$, V_p drops sharply by 20%, followed by a more gradual decrease. Below $S_w = 0.4$, $V_p = V_e$ due to the low Poisson's ratio, ν . These results suggest that at frequencies below 10 kHz, tight sandstone gas saturation, greater than 0.2 may be recognized in situ by its anomalously low compressional velocity in sonic log or by strong reflections. At high ultrasonic frequencies (Gregory's 1976) tight sandstones show only a weak gas saturation effect. This suggests that laboratory determined ultrasonic measurements are giving unrelaxed velocities, which are higher than those encountered at the lower borehole and seismic frequencies.

Also plotted in figure 18 are theoretically computed values of V_p and V_s as a function of S_w , given by

$$V_p = \left(\frac{M_r}{\rho_c} \right)^{1/2} \quad V_s = \left(\frac{N_r}{\rho_c} \right)^{1/2} \quad (4)$$

M_r and N_r are the corresponding frequency or relaxed modulus, given by

$$M_r = \frac{(K_s - K_{wr})^2}{K_s \left(1 - \phi - \frac{K_{wr}}{K_s} + \phi \frac{K_{wr}}{K_r} \right)} + K_{wr} + \frac{4}{3} \mu_{wr} \quad (5)$$

and

$$N_r = \mu_{wr} \quad (6)$$

The rock density is

$$\rho_c = (1 - \phi) \rho_s + \phi \rho_s S_w. \quad (7)$$

K_s is the bulk modulus of the solid grains, ρ_w is the density of the water and K_f is the bulk modulus of the fluid given by

$$\frac{1}{K_f} = \beta_g (1 - S_w) + \beta_s S_w, \quad (8)$$

where β_g is the compressibility of the gas and β_w is the compressibility of the water. K_{wr} and μ_{wr} are the low frequency or relaxed water-wetted frame bulk and shear moduli, respectively. The values used to compute the velocities in figure 18 are given in Table II.

Fig. 17. $1000/Q_s$ vs. frequency from 50 to 700 Hz in SCV10500 and SR7227 at $S_w \approx 0.98$

Fig. 18. Calculated V_p and measured V_s vs. % water saturation ($S_w = 0.10 - 1.00$) in Fort Union sandstone at ~ 5 kHz.

Table II. Input parameters for Biot Gassman relations plotted in Figure 17.

β_w	β_g	K_s	$K_{\omega r}$	$\mu_{\omega r}$	ϕ	ρ	ρ
$(\text{GPa})^{-1}$		GPa			%	kg/m^3	
4.5×10^{-1}	7.6×10^3	35	8.27	8.28	8.5	2650	1000

FORT UNION
SANDSTONE

The values of K_{wr} and μ_{wr} are somewhat arbitrary because (i) measurements for the fully relaxed case have not been made, and (ii) no satisfactory theory with predictive power has yet been published. A theoretical model having predictive potential is proposed in Murphy (1982c). In this paper, figure 19 suffices to demonstrate the relevant point. Figure 19 shows schematically the general frequency-dependent frame moduli normalized by the relaxed frame modulus plotted against frequency. As our measurements at 4-6 kHz are supposed to be near $\log(\omega\tau) \sim 0$, we have chosen our K_{wr} and μ_{wr} to be $\sim 1\%$ less than the lowest calculated values from both the E and S measurements. Consideration of the low value of V_s at full saturation was suppressed simply because we do not understand it.

Attenuation

Figure 19 shows the calculated Q_d^{-1} and Q_p^{-1} plotted along with the measured Q_e^{-1} and Q_s^{-1} . Errors in the computed values are estimated at 10% in P and 20% in K. We find that above $S_w \approx 0.8$, the bulk compressional loss is negligible, with $Q_p^{-1} \ll Q_s^{-1}$. At $S_w = 0.8$ $Q_p^{-1} = Q_s^{-1}$, at lower S_w , $Q_p^{-1} > Q_s^{-1}$. The lowest value of Q_k at $S_w = 0.79$ is calculated to be 3.6. At this point, Q_p^{-1} is nearly twice as large as Q_s^{-1} .

In fully and partially saturated tight sandstone, Q_p^{-1} is frequency dependent in the acoustic frequency range (fig. 17). For example, Fort Union's dependence on S_w is qualitatively similar to that observed in Massilon sandstone (Murphy, 1982a). V_p and $1000/Q_s$ are largest at full saturation; F_p declines and Q_p^{-1} rises to a peak near $S_w = 0.8$; and $Q_p^{-1} < Q_s^{-1}$ in fully saturated sandstone, and $Q_p^{-1} > Q_s^{-1}$ in partially saturated sandstone.

However, the Fort Union measurements differ in details from the Massilon data, even after correction for the difference in frequency between the two data sets. The losses above $S_w = 0.40$ in the Fort Union sandstone are greater, and the Massilon Q^{-1} data show distinctly different behavior in various segments of its dependence on S_w . From full saturation to $S_w = 0.1$, Q_s^{-1} is sensitive to water saturation only above $S_w = 0.85$, and Q_p^{-1} shows a strong peak, but is weakly dependent on water saturation below $S_w = 0.6$. In contrast, Q_s^{-1} vs. S_w in Fort Union sandstone exhibits nearly a uniform slope above $S_w = 0.3$; and Q_p^{-1} , although it shows a strong peak, depends quite smoothly on S_w throughout the entire range of water saturations.

The dependence of Q^{-1} on S_w may provide an indicator for the degree of partial saturation in situ. In figure 10, we have plotted V_p/V_s and Q_p^{-1}/Q_s^{-1} vs. S_w . This figure shows that the measured ratio V_p/V_s is sufficient to distinguish full from partial water saturation. If V_p/V_s is greater than 2, the rock is fully water saturated. Together figures 14 and 19 show that the

Fig. 19. Theoretical dispersion, as a function of water saturation, of the real part of the frame modulus normalized to the real part of the relaxed frame modulus.
 $\tau \approx 10^{-3} - 10^{-4}$ sec.

acquisition of all four properties V_p , V_s , Q_p^{-1} , and Q_s^{-1} , is sufficient to distinguish three different ranges of partial water saturation. If $1.5 < V_p/V_s < 2$ and $Q_p^{-1}/Q_s^{-1} < 1$, then $0.8 < S_w < 1.0$. If $1.5 < V_p/V_s < 2$ and $Q_p^{-1}/Q_s^{-1} > 1$, then $0.6 < S_w < 0.8$. And if $V_p/V_s < 1.5$, $1000/Q_p$ and $1000/Q_s < 100$ and $Q_p^{-1}/Q_s^{-1} < 1.5$, then $S_w < 0.6$. Of course, these bounds must be reset for in situ temperature and pressure conditions.

5. ULTRASONIC MEASUREMENTS

In order to test the hypothesis that ultrasonic pulse transmission measurements yield unrelaxed group velocities for fully and partially saturated tight sandstones, several ultrasonic experiments were performed. The results demonstrate that the ultrasonic signal velocities, $\hat{V}_p$ and $\hat{V}_s$, measured at 200-800 kHz, show a markedly different dependence on S_w than do the acoustic phase velocities, V_p and V_s , measured from 4 to 6 kHz. All samples are vertical cores whose axes are perpendicular to bedding.

Fort Union Sandstone

We have measured ultrasonic P and S velocities in Fort Union sandstone. The samples were taken from the same 10 cm x 25 cm well core as were those in the acoustic measurements. A pulse transmission technique was used in which P and S transducers were clamped with axial pressures less than 0.5 MPa at opposite ends of the 2.2 cm cylindrical sample. Frequencies were roughly 200 kHz. Measurements were obtained as a function of continuously varying S_w in a drying experiment. The sample was unjacketed, the pressure was atmospheric; temperature was 22°C; and relative humidity was held at 0.3 in the humidity chamber.

Results are shown in figure 20. The P group velocity, $\bar{V}_p$, declines 12.5% very gradually from full saturation to $S_w = 0.7$. Between $S_w = 0.7$ and 0.4, the dependence is flat. And below $S_w = 0.4$, $\bar{V}_p$ drops again roughly 15%. After a 5% increase from full saturation to $S_w = 0.0$, the S group velocity, $\bar{V}_s$, is observed to be roughly independent of S_w .

In figure 21, we have plotted the P/S velocity ratios for the values taken at both acoustic and ultrasonic frequencies. Note that at full saturation, the acoustic V_p/V_s is 2.08, while the ultrasonic $\bar{V}_p/\bar{V}_s$ is 1.9.

Schuler-Cotton Valley Sandstone

Ultrasonic measurements were conducted also on a 2.2 cm sample of Cotton Valley sandstone (SCV10500) with porosity $\phi = 3.3\%$ (fig. 22). $\bar{V}_s$ is virtually independent of water saturation. $\bar{V}_p$ declines 6% from full saturation to

Fig. 20. Ultrasonic $\bar{V}_p$ and $\bar{V}_s$ vs % water saturation
 ($S_w = 0.10 - 1.00$) in Fort Union sandstone.

Fig. 21. Comparison of ultrasonic $\bar{V}_p / \bar{V}_s$ and acoustic V_p / V_s vs. % water saturation in Fort Union sandstone.

Fig. 22. Ultrasonic $\bar{V}_p$ and $\bar{V}_s$ vs. % water saturation
($S_w = 0$ to 1.0) in SCV 10500.

$S_w = 0.85$, is flat between 0.8 and 0.6, and decreases gradually 15% from $S_w = 0.60$ to a laboratory dry condition.

Pressure Dependence as a Function of Saturation

We have measured $\bar{V}_p$ and $\bar{V}_s$ in several rock types [SCV9594 ($\phi = 5.1\%$), St. Peter sandstone ($\phi = 8.0\%$), SR6556.5 ($\phi = 7.1\%$), and SR6521.6 ($\phi = 4.6\%$)] under effective pressures ranging from 0 to 50 MPa. Measurements were made at three states of saturation (1) vacuum ($<25 \mu\text{m}$) dry ($S_w \approx 0$), (2) partially saturated ($S_w = 0.7$), and (3) fully water saturated ($S_w = 1.0$). The pulse transmission technique we used is similar to those described in Nur and Simmons (1969) and Gregory (1976). Frequencies were roughly 800 kHz.

We find in all cases (fig. 23) that $\bar{V}_p (S_w = 1.0) > \bar{V}_p (S_w = 0.7) > \bar{V}_p (S_w = 0)$, and that the difference between fully and 70% partially water saturated $\bar{V}_p$ is less than 4%. In most cases, $\bar{V}_s (S_w = 0.8) > \bar{V}_s (S_w = 1.0) > \bar{V}_s (S_w \approx 0)$. In SR6556.5, a relatively strong confining pressure effect pushes $\bar{V}_s (S_w \approx 0)$ across the fully and partially saturated values at a pressure near 25 MPa. St. Peter, an 8% porosity sandstone with relatively aspect ratio and spherically isotropic pores, exhibits $\bar{V}_s (S_w = 0) > \bar{V}_s (S_w = 0.7) > \bar{V}_s (S_w = 1.0)$.

6. DISCUSSION OF DISPERSION

Mounting evidence suggests that fully and partially saturated sandstones respond to small stress waves as linear viscoelastic materials (Spencer, 1981; Murphy, 1982a; Brennan and Stacey, 1981; Strick, 1981). The dominant relaxation mechanism appears to behave macroscopically as a standard linear solid (Zener, 1948) having a narrow distribution of relaxation times in a high porosity sandstone (Spencer, 1981; Murphy, 1982a), and a somewhat broader distribution of relaxation times in a tight sandstone (Murphy, 1982c). In a standard linear solid the relations among phase velocity, specific attenuation, and frequency, as sketched in figure 24, are given by

$$V_p = V_{pu} \left(1 - \frac{\Delta M / M_u}{1 + w^2 \tau^2} \right)^{1/2} \quad (10a)$$

and

$$V_s = V_{su} \left(1 - \frac{\Delta N / N}{1 + w^2 \tau^2} \right)^{1/2} \quad (10b)$$

where τ is the characteristic relaxation time, and the modulus dispersions, $\Delta M / M$ and $\Delta N / N$, are related to Q_p^{-1} and Q_s^{-1} , respectively, by

$$\frac{\Delta M}{M} = \left(\frac{1 + w^2 \tau^2}{w \tau} \right) Q_p^{-1} \quad (11a)$$

and

Fig. 23. Ultrasonic $\bar{V}_p$ and $\bar{V}_s$ vs. effective pressure at three states of water saturation: dry ($\diamond$), 70% partially saturated ($\circ$), and full saturated ($\square$). Measurements are shown for four low porosity sandstones: (a) SCV9594, (b) St. Peter sandstone, (c) SCR6556.5, and (d) SR5421.5.

Figure 23a

Figure 23b

Figure 23c

Figure 23d.

Fig. 24. Velocity dispersion and specific attenuation as a function of normalized frequency in a standard linear solid. Velocity dispersion is normalized to the unrelaxed velocity.

$$\frac{\Delta N}{N} + \left(\frac{1 + w^2 \tau^2}{w \tau} \right) Q_s^{-1} \quad (11b)$$

The dispersion and attenuation are maximum when $W = \frac{1}{\tau}$. It is important to note that the two extremes in phase velocity are achieved where Q_s^{-1} is still appreciable. In other words, the range of significant velocity dispersion is narrower than the range of significant Q_s^{-1} frequency dependence. The low frequency extreme is the relaxed velocity. The high frequency extreme is the unrelaxed velocity.

In sandstones, we interpret the dominant relaxation mechanism to be local water flow in pores to and from compliant contact gaps during each cycle of compression and rarification. As mentioned above in section 4, the long wave period at sufficiently low frequency allows water flow to diffuse the wave induced local pressure gradients in the fluid. This case is governed by the Biot-Gassman relations. As very short periods flow cannot develop, the water behaves as a compressible solid, essentially adding a component stiffness to a composite elastic solid.

The Biot-Gassman relations (Gassman, 1951; Geertsma and Smit, 1961; Domenico, 1974, 1977) are the low frequency limit of Biot's (1956) theory. Brown and Korringa (1975) have shown that these relations govern the general low frequency or relaxed limit wherein the sufficiently long wave period provides water flow the necessary time required to equilibrate local wave induced pore pressure gradients in the fluid. The Biot-Gassman relations have been shown (Murphy, 1982c) to describe successfully the dependence of V_p and V_s on S_w in Massillon sandstone at low acoustic frequencies (i.e., 20-550 Hz). Clearly, the Biot-Gassman predictions for Fort Union sandstone demonstrate qualitative and quantitative discrepancy from the 3-6 kHz data. Thus, figure 18 coupled with the $1000/Q_s$ frequency dependence observed in figure 17, suggests that these velocities measured in the higher acoustic range (i.e., 1-20 kHz), are not entirely relaxed values for tight sandstones. This further supports the contention that ultrasonic measurements yield unrelaxed group velocities. It is perhaps important to emphasize that the V_p drop with under saturation is surely sharper in the low seismic frequency range where the velocities are completely relaxed, than that which we have measured at borehole frequencies.

Biot's (1956) inertial coupling mechanism predicts for Fort Union sandstone a center frequency of 1 MHz. The predicted S loss is too small at 5 kHz. The thermoelastic mechanism of Kjartansson and Nur (1982) is similarly refuted by the large loss in shear. Surface mechanisms (Spencer, 1981; Murphy, 1982a), which are quite likely operative at high saturations and are especially important at very low saturations, cannot explain the strong dependences on S_w in the higher saturation ranges.

Contact relaxation controlled by local water flow to and from near-contact gaps depends on two microstructural factors: (i) compliant sites for pore pressure generation and (ii) the admittance or local permeability of the pore neighborhoods in close proximity to the sites. The higher losses in both P and S follow from a higher percentage population of low aspect ratio pores in Fort Union than in Massillon sandstone (cf. Palmer and Traviolia, 1980). The loss in S is strong at full saturation in Massillon sandstone and declines sharply with slight undersaturation. In the high or partial saturation ranges in Fort Union sandstone, sufficiently low local permeability and high capillary forces cause the local pore

neighborhoods to behave as if the rock were fully saturated. As these neighborhoods progressively drain, $1000/Q_s$ declines gradually. The continuing gradual decline below $S_w = 0.4$, results from the removal of water from the grain surface. This effect does not transpire in Massilon until low moisture contents (Murphy, 1982a) because Massilon has a much lower pore surface to pore volume ratio.

In Fort Union sandstone, neither the 4-6 kHz V_p and V_s nor the ~ 200 kHz $\bar{V}_p$ and $\bar{V}_s$ are relaxed velocities. Both measurements are in the transitional range (fig. 24). By comparing figure 20 with figure 17, we find that the difference between the acoustic V_p and V_s and the ultrasonic $\bar{V}_p$ and $\bar{V}_s$ is roughly (i) 10% in P and 25% in S at full saturation, (ii) 28% in P between $S_w = 0.95$ and 0.7, and (iii) 20% in both P and S below $S_w = 0.7$. These observations are consistent with the attenuation data shown in figure 18. As $1000/Q_s$ is significantly larger than $1000/Q_p$, we expect that phase velocity dispersion in S to be larger than in P at full saturation (fig. 25). The peak in $1000/Q_p$ at $S_w = 0.8$ is related to a high P dispersion in that range of water saturation (fig. 25). And below $S_w = 0.7$, $1000/Q_p \approx 1000/Q_s$ and the P and S dispersions should be roughly the same.

We caution that the observed velocity differences are not a direct measure of the phase velocity dispersion from ~ 5 kHz to ~ 200 kHz not only because the phase and group velocities may differ, but also because the sample configurations in the two measurement systems differ considerably. In the resonant bar technique, the sample is supported at the midpoint, and the ends are free. In the ultrasonic technique, the sample is lightly compressed along its axis. In this particular case however, we expect the error due to these factors to be no more than 5-10%.

Recall from equations (2a) and (2b) that the difference between the group and the phase velocities goes as $\frac{\partial V}{\partial \omega}$ at the frequency of the measurement. All evidence suggests that the relaxation peak in the tight sandstones is centered between 100 Hz and 10 kHz. We therefore expect $\frac{\partial V}{\partial \omega}$ in the high ultrasonic frequencies to be quite small. The signal velocity measurement, particularly the 800 Hz pressure data, ought to be quite close to the actual phase velocity.

Our measurements of ultrasonic $\bar{V}_p$ and $\bar{V}_s$ vs. S_w and P_e as a function of saturation agree well with Gregory's (1976) 1 MHz data for three Travis Peak sandstones ($\phi = 4.45, 4.58, 8.02$). Like ours, Gregory's ultrasonic data are not fully consistent with the Biot-Gassman relations nor do they conform to our acoustic measurements. In fact, both our ultrasonic results and Gregory's show a closer resemblance to his 1 MHz velocity vs. S_w measurements in Chugwater ($\phi = 11.0$), Green River ($\phi = 11.7$), and Tensleep ($\phi = 15.2$) sandstones, and even to those in Bandera ($\phi = 17.9$) and Berea ($\phi = 10.11$) sandstones. The effect of water saturation is relatively weak in all of these measurements. This weakness and the similarity between the high and low ϕ sandstones indicates that ultrasonic measurements are unrelaxed in consolidated sandstones in general.

Fig. 25 Schematic of P and S velocity dispersions in Fort Union sandstone at three different states of water saturation. Calculations were made by assuming $\tau = 2 \times 10^{-4}$ and inputting the relevant measured Q^{-1} values from fig. 20 into equations (10) and (11).

In order to compare the water saturation effect on ultrasonic $\bar{V}_p$ and $\bar{V}_s$ with that of acoustic V_p and V_s in a high ϕ sandstone, we have measured $\bar{V}_p$ and $\bar{V}_s$ as a function of continuously varying S_w at ~ 200 kHz and as a function of P_e at ~ 800 kHz in a Massilon sandstone ($\phi = 23\%$). Results are shown in figures 11, 12, and 20 through 23d. An axial pressure ~ 0.5 MPa was applied to achieve an adequate coupling for the measurements in figure 26. We find that at ~ 500 Hz the data are well described by the Biot-Gassman relations (i.e., completely relaxed), while the ~ 500 kHz data appear again to be unrelaxed. Consequently, these observations suggest considerable dispersion between ~ 500 Hz and ~ 500 kHz in fully and partially saturated Massilon sandstone.

7. CONCLUSIONS

To conclude, we find the following in tight sandstones:

- i) Low aspect ratio pores ($< 10 \mu\text{m}$) form the pore neighborhood and network connectivities, and dominate rock compliance.
- ii) At borehole frequencies, V_p and V_p/V_s are sensitive to partial gas saturation. More precisely, V_p and V_p/V_s drop 20% as S_g goes from 0 to 0.1.
- iii) At 3-6 kHz, Q_p and Q_s are very sensitive to partial gas saturation. $1000/Q_s$ is 189 at full saturation and declines linearly and steeply with decreasing S_w . $100/Q_p$ is less than 100 at full saturation, abruptly jumps to a peak, ~ 200 , at $S_w = 0.8$, and then declines linearly with S_w , emulating $100/Q_s$.
- iv) Borehole measurements of V_p , V_s , Q_p , and Q_s may delineate the range of partial gas saturation. Further laboratory measurements are required under pressure.
- v) Ultrasonic pulse transmission measurements yield unrelaxed group velocities in consolidated sandstones. In predicting velocities at borehole and seismic frequencies, such measurements if uncorrected for dispersion will lead not only to significant quantitative errors, say roughly in the order of 10-15%, but exhibit unrelaxed qualitative relationships which may be strongly misleading.
- vi) These results in low- ϕ sandstones when compared to results in high- ϕ sandstones (Murphy, 1982) tend to refute Biot's (1956) inertial coupling mechanism and to support contact relaxation involving local water flow.

PART II. ELECTRICAL PROPERTIES OF TIGHT GAS SANDS

1. INTRODUCTION

Laboratory measurements have been made to study the electrical response of tight gas sands. The measurements were made with an HP LCR meter and an impedance analyzer. The samples were prepared as thin disks, with diameters of 2" and diameter to thickness ratios of greater than 10 to 1. A two-electrode technique was used with platinum electrodes sputtered onto the flat faces of the disks. In the first part of the study, the resistivity and dielectric constant of Berea sandstone (standard high porosity sandstone) and Spirit River sandstone (tight gas sand) were studied as a function of frequency and degree of water saturation. Complex impedance plots were then used as a means of data presentation and analysis with the aim of modeling the electrical response of the tight gas sands.

2. EXPERIMENTAL RESULTS

Figure 1 shows the resistivity data for Berea. The measurements were made at 10 spot frequencies between 10 kHz and 10 MHz. The indicated degree of water saturation with tap water varies from 100% water saturated to 0% water saturated, which corresponds to a room-dry sample. Resistivity is strongly frequency dependent in the dry sample with resistivity decreasing with increasing frequency. There is little, if any, frequency dependence for the saturated sample. At all frequencies, the resistivity decreases with increasing water saturation.

Figure 2 shows the resistivity data for Spirit River. The degree of water saturation with tap water was varied from 72% to 1%. In this sample also, resistivity shows a stronger frequency dependence in the dry sample than in the wet sample with resistivity decreasing with increasing frequency. At all frequencies, the resistivity decreases with increasing water saturation. The resistivity of Spirit River is consistently lower than that of Berea. This is taken to indicate a significant contribution from surface conduction in Spirit River which has a higher clay content than Berea.

The dielectric constant of Berea sandstone as a function of frequency and water saturation is shown in figure 3. The dielectric constant shows a frequency dependence in the wet sample, initially decreasing rapidly with increasing frequency. The dry sample shows very little frequency dependence. At all frequencies, the dielectric constant increases with increasing water saturation.

The dielectric constant of Spirit River (fig. 4) shows an initial large decrease with increasing frequency for the 72% saturated sample. This effect becomes less pronounced as the degree of saturation decreases. The dielectric constant decreases with decreasing water saturation below 200 kHz. Above this frequency there does not appear to be a consistent relationship between water saturation and dielectric constant. The dielectric constant of Spirit River is always higher than the corresponding value in Berea. This is also attributed to the higher clay content in Spirit River.

BEREA #2 RESISTIVITY

FIGURE 1: Berea sandstone: log resistivity versus log frequency for various levels of water saturation (S_w).

Figure 2: Spirit River sandstone: log resistivity versus log frequency for various levels of water saturation (S_w).

DIEL CONST

Figure 3: Berea sandstone: dielectric constant versus log frequency for various levels of water saturation (Sw).

DIEL CONST

Figure 4: Spirit River sandstone: dielectric constant versus log frequency for various levels of water saturation (S_w).

3. COMPLEX IMPEDANCE AND X-R PLOTS

Complex impedance plots have been used to study the electrical response of samples over a frequency range from 5 Hz to 13 MHz. The imaginary part of the impedance, the negative reactance ($-X$) is plotted against the real part of the impedance, the series resistance (R) for various frequencies. From the resulting X-R plots, equivalent electrical circuits for the samples can be determined.

Some of the first data presented as X-R plots included only 10 spot frequencies between kHz and 10 MHz. There appears to be a general trend with those plots when the level of water saturation in a rock sample varies from dry to saturated. Figure 5 shows three X-R plots for Berea sample at three states from dry at the top of the figure, to saturated at the bottom of the figure. The X-R plot for a dry Berea looks essentially like a straight line. As the level of water saturation increases the curvature increases until a complete semicircle comes into the frequency range. The X-R plot for the dry sample is probably the high frequency end of a large semicircle that cuts the real axis at a low frequency, below the lower limit of our frequency range.

More data were collected across the frequency range from 5 Hz to 13 MHz. This frequency coverage provides more complete X-R plots. Figure 6 is the X-R plot for a room-dry Berea sandstone. It appears again as a straight line. The same sort of plot is obtained for a dry Westerly granite (fig. 7). For the partially saturated Berea sandstone the X-R plot is a depressed (centered below the real axis) and slight distorted semicircle with a tilted straight line appearing at the low frequency end (fig. 8). Similar plots are obtained for a partially saturated Westerly granite (fig. 9). The room-dry Spirit River produces the same sort of plot on a different scale, as the partially saturated Berea (fig. 10).

Attempts have been made to model the frequency response of the room-dry Spirit River sandstone. The basic circuit chosen for the analysis of this type of frequency response is a modified Debey circuit. The low frequency response of a tilted straight line is interpreted to be the response due to polarization at the sample-electrode interface, thereby providing a means of correcting for this effect in experimental results.

4. CONCLUSION

Laboratory measurements of different samples at various frequencies and with varying degrees of water saturation have demonstrated the dependence of resistivity and the dielectric constant on these two parameters. Complex impedance plots are used to model the electrical response of rocks and to derive equivalent circuits. It is hoped that this method will lead to a better understanding of the processes controlling the electrical response of rocks.

Figure 5. Complex impedance plots for Berea sandstone in 3 states from dry to saturated.

Figure 6. Complex impedance plot for room dry Berea sandstone.

Figure 7. Complex impedance plot for room dry Westerly granite

X
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Figure 8. Complex impedance plot for partially saturated Berea sandstone.

Figure 9. Complex impedance plot for partially saturated Westerly granite.

Figure 10. Complex impedance plot for room-dry Spirit River sandstone.

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