CANADIAN JOURNAL OF EXPLORATION GEOPHYSICS
VOL 26, NOS. 1 & 2 (DECEMBER 1990), P 104-112

EFFECT OF DIFFERENT PORE FLUIDS ON SEISMIC VELOCITIES IN ROCKS

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ABSTRACT

Compressional and shear wave velocities were measured in the laboratory in rocks saturated with air, water, light oil (normal decane) and heavy oil (oil C), respectively, using the ultrasonic pulse transmission method. As expected, the compressional wave velocities were different in the same rock sample with different pore fluids, while the shear wave velocities were much less sensitive to the pore fluid difference.

The experimental results also reveal that wave velocities and their temperature dependency in rocks saturated with heavy oil are pronouncedly different from those in the same rocks saturated with water or light oil. It is possible that reflection boundaries for seismic waves exist at the light/heavy oil saturation boundaries. These seismic reflections could be as strong as those at the gas/water saturation boundaries. Consequently, the term "oil" used in seismic and acoustic logging interpretations might have been oversimplified; one should specify whether it is light or heavy oil when referring to oil saturations.

INTRODUCTION

Seismic methods have been playing a major role in the exploration for hydrocarbon reservoirs. The successes in the past have been due to detecting structures which may bear hydrocarbons (e.g., anticlines, faults, etc.). Only since the "bright-spot" era has the effect of pore fluid properties been seriously taken into consideration in seismic interpretation. Extended studies of velocities in various rocks have been carried out by numerous investigators. Unfortunately, most studies were done on rocks saturated with water or air, and very few experiments have been carried out on velocities and their behaviors with changing pressure and temperature in rocks saturated with hydrocarbons.

In the past, seismic methods have rarely been used in hydrocarbon recovery assessment, in spite of the growing need to better understand various recovery processes. A major problem in reservoir evaluation and production is the realization of the complexity of most reservoirs, which leads to large uncertainties in estimated total recovery, recovery rates and recovery methods. There is little doubt that seismic methods can play a major role in helping to solve production and recovery problems. Ideally, we would like to know, using seismic waves, where reservoir fluids will be moving from and to in the reservoir during production and enhanced oil recovery processes. To do this, we first must understand the seismic properties of various reservoir fluids and rocks saturated with these fluids and their responses to the changes of reservoir conditions caused by production or recovery processes.

Not only can the rocks in a reservoir be quite inhomogeneous, but their pore fluids can be a mixture of several distinct phases with a complex spatial distribution. For example, can a seismic wave be reflected at a light/heavy oil boundary within a formation? how much of a seismic response can be seen as one fluid is displaced by another? In response to such problems, we carried out a series of experiments in the laboratory on wave velocities in two different reservoir rocks saturated with water, air, a light oil and a heavy oil, respectively, as a function of both pressure and temperature. The experimental results show that velocities and their responses to temperature changes in the rock sample saturated with heavy oil are different from those in the same sample saturated with water or light oil. It is possible that reflections of seismic waves exist at light/heavy oil saturation boundaries. Such reflections could be as strong as those at gas/water saturation boundaries, which

Manuscript received by the Editor April 17, 1990; revised manuscript received July 25, 1990.
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The laboratory experiments which led to this paper were conducted while Z. Wang was a summer employee at ARCO Oil and Gas Company in 1987. The authors would like to thank Billy Smith for his help during the experiments, John Castagna and Keith Katahara for their comments and discussions, and the anonymous reviewers for their helpful comments and suggestions.

means that "bright spots" on seismic profiles could occur not only at gas/liquid but also at liquid/liquid saturation boundaries.

Experiments

Method

The ultrasonic pulse transmission method was employed in the experiments. The apparatus consists of an electronics package and a mechanical package. The electronics package is used for pulse generation and data acquisition, while the mechanical package controls the physical condition (pore and overburden pressures and temperature) of the rock samples.

High-voltage pulses generated by the pulse generator are sent down to the transmitting acoustic transducer attached to the rock sample which converts electrical pulses to mechanical vibration. The mechanical waves are then picked up by the receiving transducer and converted back to electrical signals which are first amplified and then sent to a digital oscilloscope for the transit-time measurements.

The velocities (both compressional and shear) are simply calculated through

$$V_{p,s} = \frac{L(P,T)}{\Delta t(P,T)_{p,s}},$$

where p, s represent compressional and shear waves, $L(P, T)$ is the sample length corrected for temperature and pressure, and $\Delta t(P, T)$ is transit time through the sample. The dominant frequency of the waves is about 0.6 MHz. A more detailed discussion of this and similar techniques can be found in Simmons (1965) and in the "suggested methods for determining sound velocity" by the International Society of Rock Mechanics (1978).

The entire sample and transducer assembly is exposed to a high pressure and temperature environment inside a pressure vessel. Overburden pressure is controlled by pumping hydraulic fluid into the pressure vessel, and pore pressure is controlled by a fluid pump. Temperature is controlled by using a heating coil surrounding the pressure vessel and by a digital temperature controller.

Sample preparation and saturation

The rock samples for the experiments were cut into cylinders with a diameter of 3.8 cm and length of about 6.4 cm. The end surfaces of the samples were finely ground to assure good contacts between the samples and transducers. After this preparation, the rock samples were cleaned thoroughly with distilled water and vacuum dried in an oven at 60°C for several days. They were then ready to be saturated. The saturation of light pore fluids (n-decane and water) was done in the pressure vessel after the dry (air saturated) measurements by injecting pore fluid into the evacuated sample. The saturation of the heavy oil in the rocks was more complicated due to the oil's high viscosity. We first jacketed the sample-transducer assembly with a plastic tube with the heavy oil in between the sample and the transducers. The assembly was then placed in a vacuum oven at 60°C for several hours to extract air from both the rock and the heavy oil. Afterwards, the rock-oil transducer assembly was mounted into the pressure vessel under an overburden pressure of 80 MPa and temperature of 60°C for 4 to 7 days to assure full saturation. We must note, however, that we were unable to measure the degree of heavy oil saturation.

After the sample was saturated, the temperature was reduced gradually under high pressure. The excess heavy oil was taken out by releasing the pore pressure line to ambient pressure. The sample was then ready for measurement.

Sample descriptions

The rock samples used in the experiments were Berea sandstone and a sample from a heavy-oil producing formation. The composition of the Berea sandstone was analyzed by petrographic point counting and is listed in Table 1. The formation rock is a dolomitic chert with porosity of 15 percent and is composed of mainly quartz and dolomite. Its composition was determined by x-ray analysis and is listed in Table 2.

The pore fluids used were distilled water, normal decane, air and a heavy oil (oil C). Normal decane (n-decane) is a pure paraffinic hydrocarbon with a chemical formula of $C_{10}H_{22}$. Its density at room condition is 0.734 g/cc (equivalent to 62° API). The acoustic velocity in n-decane can be found in Wang et al. (1990). The heavy oil (oil C) is a 10° API oil and has viscosity of 28 Pa.s (28000 cp) at 30°C. The acoustic velocity in oil C versus temperature and pressure is shown in Figure 1.

Measurements

Velocities were measured as a function of both pressure and temperature. In the measurements, pore pressures were controlled at 10 MPa for water- and n-decane-saturated rocks and at atmospheric pressure for air- and heavy-oil-saturated samples.

Composition	Volume %	Composition	Volume %
Quartz	67.0	Clay	1.9
Mica	0.9	Opaque	2.3
Feldspar	3.2	Carbonate	0.9
Others	5.6	Porosity	18.2

Table 1. Mineral composition of the Berea sandstone sample.

Composition	Volume %	Composition	Volume %
Quartz	55.8	Clay	5.8
Dolomite	17.2	Pyrite	2.6
Feldspar	1.8	Phosphate	1.8
		Porosity	15.0

Table 2. Mineral composition of the dolomitic chert sample.

The same rock sample was used for different pore fluid saturations. A sample was first used for air saturation. After the velocities were measured through a pressure-temperature cycle, it was evacuated and saturated with distilled water. After the velocity measurements on the water-saturated sample, the sample was placed in a vacuum oven at moderate temperature (60°C) to dry. Then it was saturated with n-decane for the velocity measurements. Finally, the sample was saturated with the heavy oil after n-decane was extracted from the rock sample. The residual water or n-decane saturation was very low (< 2%) after the drying process, since both water and n-decane evaporate easily under vacuum and temperature.

A potential problem of using the same rock sample for four measurement (air, water, n-decane and heavy oil saturations) was that velocity hysteresis might exist, since for each measurement process the rock was confined up to 85 MPa. We felt that any hysteresis effects would be less severe than inconsistencies arising from inhomogeneities among separate samples, particularly for the dolomitic chert. However, to eliminate or minimize any hysteresis, we pressurized the samples for several cycles before any measurements were made.

Experimental Results

Velocities in air-saturated rocks

The variations of compressional (V_p) and shear (V_s) velocities in the air-saturated ("dry") Berea sandstone with temperature at various differential pressures ΔP (difference between overburden and pore pressures) are shown in Figure 2. Both V_p and V_s are strongly dependent on pressure in the low pressure range, which confirms the previous observations of Toksöz et al. (1976) and others that Berea sandstone may contain a substantial amount of low-aspect ratio pores (or cracks). Increasing pressure tends to close the low-aspect ratio pores and, hence, creates better contacts between the rock grains, because such pores are more compliant than more equidimensional (high-aspect ratio) pores. Closures of cracks and better contacts, in turn, decrease the porosity and increase the moduli of the rock sample. Further increasing pressure in the higher pressure range has less effect on the velocities because cracks may have already been closed. Both V_p and V_s decrease as temperature increases, ranging from 2.5 to 10.5 percent per 100°C, depending on pressure.

The variations of V_p and V_s in the dolomitic chert with temperature and differential pressure are shown in Figure 3. Unlike those in the Berea sample, both V_p and V_s in the chert increase almost linearly with pressure and there are no rapid increases in the low pressure range. This phenomenon indicates that the dolomitic chert may not have a high content of low-aspect ratio pores. Both V_p and V_s also decrease as temperature increases. Such decreases are caused mainly by the weakening and softening of the rock and possibly by different thermal expansions of the mineral constituents of the rock (Kern, 1982).

Velocities in water-saturated rocks

In Figure 4, V_p and V_s in the Berea sample saturated with water are shown versus temperature and differential pressure. The effect of pressure on the velocities (both V_p and

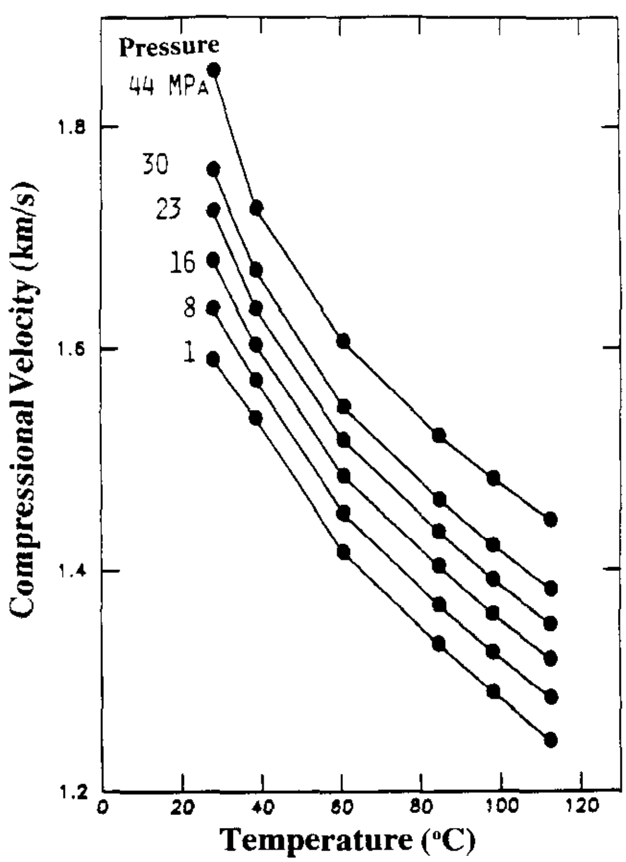

Fig. 1. V_p in oil C (10° API) as a function of temperature and pressure.

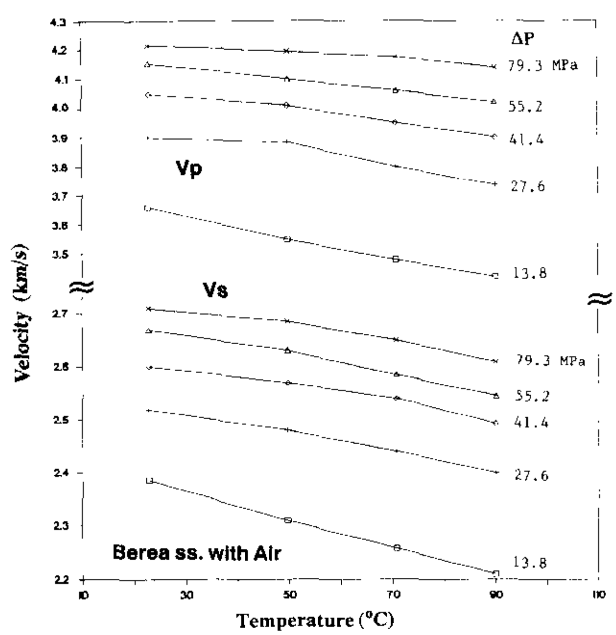

Fig. 2. V_p and V_s in the Berea sandstone sample with air.

V_s) is similar to that observed in the dry rock. However, as is typical, water saturation increases V_p and decreases V_s. The increase of V_p is caused by the water being much less compressible than air, and, consequently, substituting water for the air in the rock pores increases the bulk modulus of the rock. The decrease of V_s is caused by the increased density of the rock when saturated with water. Since both air and water do not support shear stresses, water saturation does not change the shear modulus (if not considering the effects of wetting and viscosity). As in the air-saturated rock, both V_p and V_s in the water-saturated Berea sandstone decrease, but not as strongly, as temperature increases. Again, this decrease becomes less significant at high pressures.

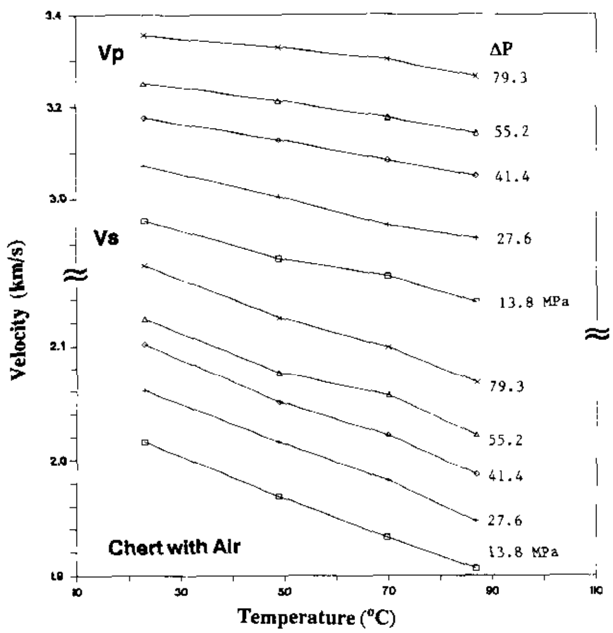

Fig. 3. V_p and V_s in the dolomitic chert sample with air.

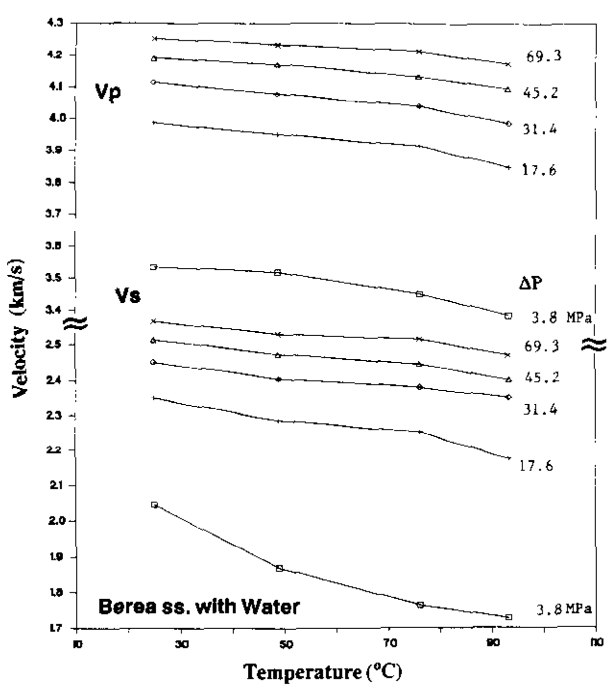

Fig. 4. V_p and V_s in the Berea sandstone sample with water.

Velocities in light oil-saturated rocks

In Figure 5, V_p and V_s in the Berea sandstone sample saturated with n-decane are shown versus temperature and differential pressure. The velocities behave very similarly to those in the same rock sample saturated with water, except that the effects of saturation are smaller since n-decane is more compressible and has a lower density than water. The increase in V_p and decrease in V_s upon n-decane saturation are less significant.

The variations of V_p and V_s with temperature and differential pressure in the dolomitic chert saturated with n-decane are shown in Figure 6. As for the same sample saturated with air, both V_p and V_s decrease as temperature increases and increase as pressure increases.

Velocities in heavy oil-saturated rocks

The V_p and V_s in the heavy oil-saturated Berea sandstone sample are shown in Figure 7 as a function of temperature and differential pressure. Heavy oil saturation increases both V_p and V_s. The increase in V_p is again caused mainly by the increased bulk modulus of the rock, and the increase in V_s is probably caused by the viscous relaxation effect of the pore fluid, as we will explain later. Furthermore, any dispersion (i.e., the velocity is a function of wave frequency) caused by fluid coupling will also contribute to the velocity increases since we are using ultrasonic frequencies. As temperature increases, both V_p and V_s decrease faster than those

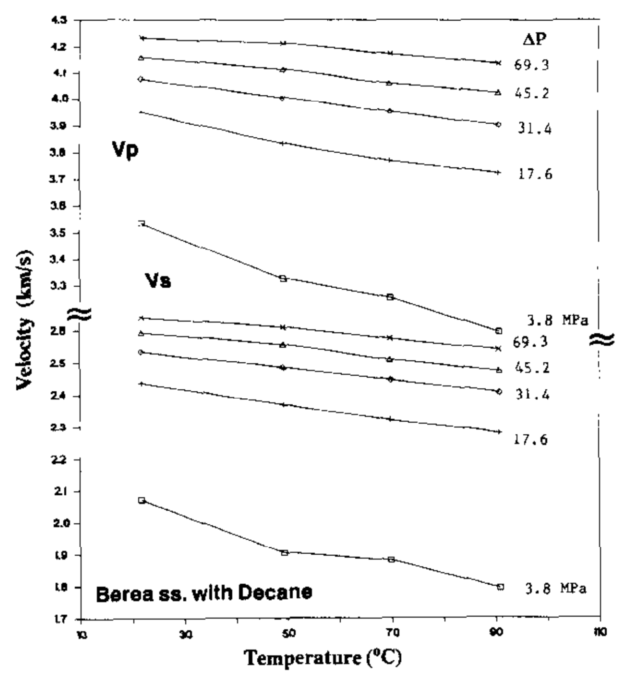

Fig. 5. V_p and V_s in the Berea sandstone sample with n-decane.

in the same sample with either air, water or n-decane. For example, V_p decreases by 14 percent and V_s by 17 percent at low differential pressure (ΔP = 3.8 MPa) and V_p by 11 percent and V_s by 9 percent at high differential pressure (ΔP = 69.3 MPa) in the temperature range from 22° to 92°C. These larger decreases are related to the faster decrease of the bulk modulus and viscosity of the heavy oil as temperature increases.

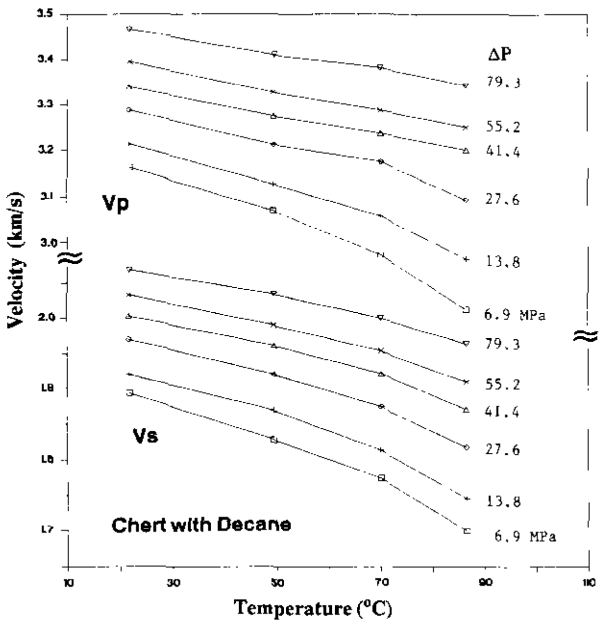

Fig. 6. V_p and V_s in the dolomitic chert sample with n-decane.

For the dolomitic chert saturated with heavy oil, V_p and V_s versus temperature are shown in Figure 8. The pressure responses of both V_p and V_s are very similar to those in the same sample saturated with other fluids (air and n-decane). The heavy oil saturation increases V_p but still decreases V_s, which again suggests that the dolomitic chert indeed does not contain many low-aspect-ratio pores.

As observed in the Berea sandstone, both V_p and V_s decrease faster with increasing temperature in the heavy oil-saturated chert than those in the same sample saturated with other fluids (air and n-decane). As temperature increases from 22° to 88°C, both V_p and V_s decrease by about 8 percent to 9 percent. However, unlike that in the Berea sandstone, this amount of decrease is essentially the same at any pressure in the measurement range, which suggests that the dolomitic chert contains mostly round pores that are still open at high pressures.

Effect of Different Pore Fluids

Figure 9a shows V_p and V_s as a function of temperature at a differential pressure of 17.6 MPa in the Berea sandstone sample saturated with the four different pore fluids. Liquid saturation increases the compressional wave velocities in the rock. Such increases are predicted by both the Gassmann relation (Gassmann, 1951) and the Biot theory (Biot, 1956) to be caused by the bulk modulus increase of the rock-fluid aggregate. The effect of the heavy oil saturation is much larger than expected. Since the bulk modulus and density (and hence V_p) of the heavy oil are very close to those of water at room condition, we would expect, according to either Biot theory or Gassmann equation, V_p in the heavy oil-saturated rock sample to be similar to that in

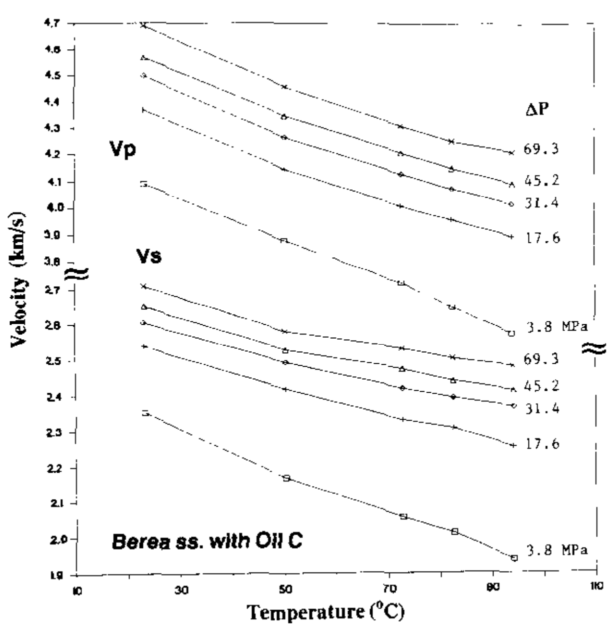

Fig. 7. V_p and V_s in the Berea sandstone sample with oil C.

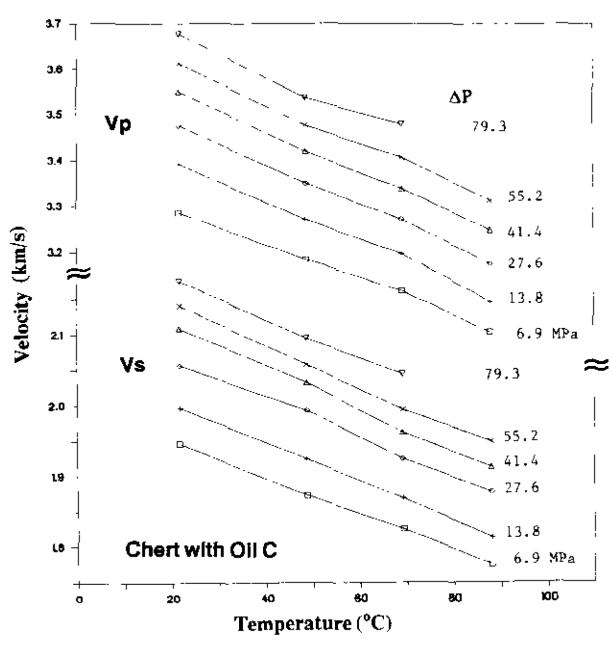

Fig. 8. V_p and V_s in the dolomitic chert sample with oil C.

the same sample saturated with water. Such a discrepancy of the measured V_p from that expected may be caused by factors such as dispersion, chemical interaction and interfacial energy, and the contribution of the increased shear modulus due to viscous relaxation of the pore fluid, etc.

Velocity dispersion usually occur in liquid-saturated rocks. That is, wave velocity increases with increasing frequency of the wave. Such a phenomenon is caused by the inertial effect of the pore fluid (Biot mechanism), pore pressure gradients caused by the compliance heterogeneity of the pores ("local flow" mechanism, O'Connell and Budiansky, 1977; Mavko and Nur, 1978), and the pore fluid viscous relaxation effect. Quantitative analyses and discussions on velocity dispersions are the subject of a separate paper (Wang and Nur, 1990).

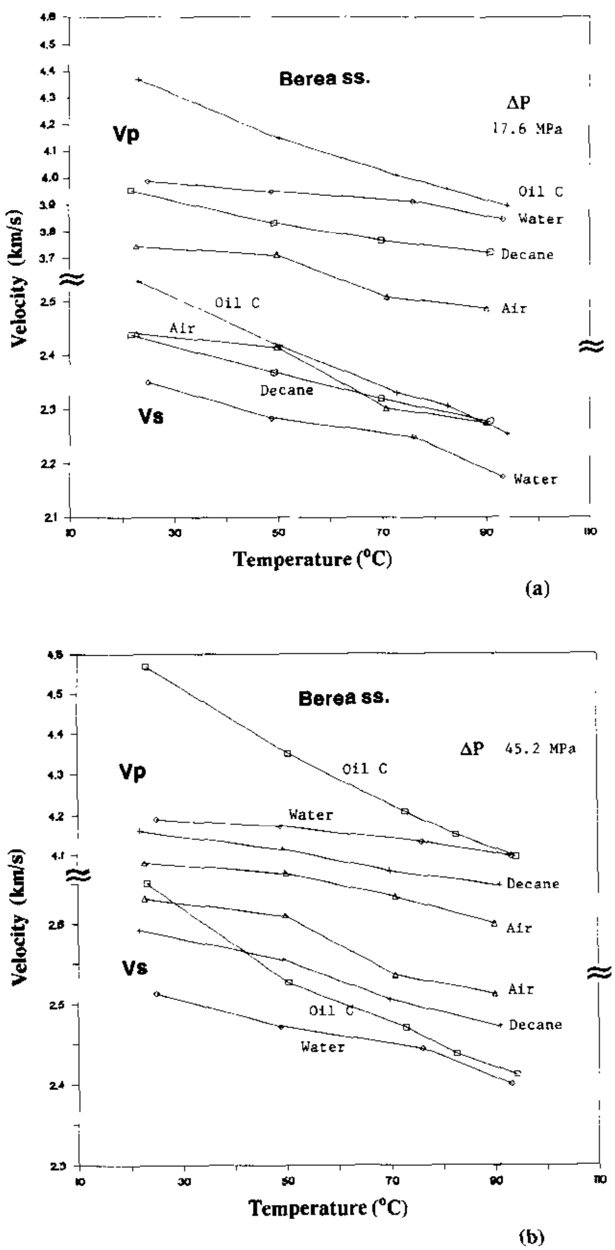

Fig. 9. Effect of different pore fluids on V_p and V_s in the Berea sandstone sample at differential pressures of 17.6 MPa **(a)** and 45.2 MPa **(b)**.

The increased shear modulus of the rock with heavy oil saturation also contributes to the increase in V_p since V_p is related to both the bulk and shear moduli. As seen in Figures 9a and 9b, V_s is systematically higher in the Berea sandstone sample with the heavy oil than those in the same sample with air, water or n-decane, which may be caused by the viscous skinning effect of the shear waves. According to the theory of wave propagation in fluids (Thurston, 1964), shear waves penetrate into viscous fluids a "skin depth" factor,

$$\delta = \left[\frac{\eta}{\rho \pi f}\right]^{1/2},$$

where η and ρ are the shear viscosity and density of the fluid, respectively, and f is the frequency of the shear wave. Shear waves in a rock sample saturated with viscous fluids can penetrate through those cracks and pores with short axis in the direction of wave propagation shorter than the "skin depth" of the wave. Consequently, the shear modulus of the rock is increased. For the Berea sample with the heavy oil, the skin depth at 30°C (η = 28 Pa.s) is about 0.12 mm which may be longer than the diameter of many pores or crack-tips in this sandstone (ρ = 1000 kg/m^3 and f = 0.6 MHz). For the same sample with water, the viscous skin depth is only about 0.73 microns which is shorter than the diameter of most pores in this rock. Therefore, according to such a theory, shear waves can travel through many low-aspect-ratio pores or thin cracks filled with heavy oil but not with water. Hence, shear wave velocities are higher in the rock saturated with heavy oil.

As temperature increases, the viscosity of the heavy oil decreases exponentially (from 28 Pa.s at 30°C to 0.25 Pa.s at 110°C), so that V_s in the heavy oil-saturated rock becomes closer to that in the same rock saturated with other liquids. The viscous skinning effect on V_s is only a secondary factor. The primary factor is the density of the pore fluid. Therefore, even though the viscous skinning effect increases the overall shear modulus of the rock, the increase in V_s is only nominal due to the added density to the rock sample.

Figure 9b shows that the effect of liquid saturation on V_p and V_s in the Berea sample is decreased at a higher differential pressure (45.2 MPa), due to the closure of the thin cracks. At higher differential pressures, the shear viscous skinning effect is smaller since only the round or high-aspect-ratio pores are open. Furthermore, the viscosity decrease of the heavy oil caused by increasing temperature reduces the viscous skin depth rapidly to the value less than the average diameter of the round pores.

Figures 10a and 10b show V_p and V_s in the dolomitic chert saturated with three different pore fluids (air, n-decane and the heavy oil) as a function of temperature at differential pressures of 13.8 MPa and 41.4 MPa, respectively. V_p is increased, while V_s is decreased, systematically by the liquid saturants. The slight decrease of V_s in the chert when saturated with the heavy oil indicates that the density effect, not the viscous skinning effect, is dominant.

The V_p/V_s and Poisson's ratio increase with increasing differential pressure in gas-saturated rocks but decrease with increasing differential pressure in the low pressure range when the rocks are saturated with liquids (Figures 11 and 12). The ratio V_p/V_s is defined as

$$\frac{V_p}{V_s} = \left[\frac{K}{\mu} + \frac{4}{3}\right]^{1/2},$$

where K and μ are the bulk and shear moduli, respectively, and Poisson's ratio is

$$\nu = \frac{1}{2} \cdot \frac{\left(\frac{V_p}{V_s}\right)^2 - 2}{\left(\frac{V_p}{V_s}\right)^2 - 1}.$$

In Berea sandstone (Figure 11), the V_p/V_s and Poisson's ratio reveal that as differential pressure increases, K increases faster than μ in dry rocks, and μ increases faster than K in liquid-saturated rocks in low-pressure ranges. Increasing differential pressure deforms the pores of the rocks, so that both K and μ increase. For a liquid-saturated rock, since the pore liquid is very incompressible, K is less sensitive to pressure changes, while the closure of thin cracks in the rock increases μ more than K in the low pressure range which results in the decreases of V_p/V_s and Poisson's ratio.

In the dolomitic chert sample saturated with liquids, V_p/V_s and Poisson's ratio hardly change with pressure, which means both K and μ increase at the same rate as differential pressure increases (Figure 12). This restates that the chert does not contain many thin cracks or low-aspect-ratio pores.

In the Berea sandstone sample, different liquid saturants also affects V_p/V_s and Poisson's ratio, mainly caused by the fluid compressibility, density and viscous skinning effects on the velocities. At shallower depth, say less than 1000 m (equivalent to an overburden pressure of 26.5 MPa), V_p/V_s in the air-saturated Berea sandstone is around 1.55 (ν = 0.14), whereas it is about 1.73 (ν = 0.25) or 1.69 (ν = 0.23) when the rock is water or oil saturated (Figure 11). In the dolomitic chert, V_p/V_s and Poisson's ratio of the gas-saturated rock sample are also lower than those of the liquid-saturated sample (Figure 12). This shows that V_p/V_s and Poisson's ratio may well be a useful indicator for delineating gas from liquid in reservoir rocks.

APPLICATION

The experimental results show that pronounced differences exist between the measured compressional wave velocities in light oil- (n-decane) and heavy oil- (oil C) saturated rocks, especially in the Berea sandstone sample. This suggests that a saturation boundary between light and heavy oils might also be a reflection boundary for seismic waves. We calculated the reflection coefficients at the n-decane/heavy oil saturation boundary in the Berea sandstone and, as a comparison, the reflection coefficients at the air/water saturation boundary in the same sandstone. The calculated results are shown in Table 3.

Berea Sandstone	Reflection Coefficients			
	T = 23°C		T = 91°C	
Saturation Interface	ΔP (MPa)		ΔP (MPa)	
	17.6	45.2	17.6	45.2
N-Decane — Oil C	0.0636	0.0598	0.0346	0.0201
Air — Water	0.0742	0.0573	0.0889	0.0609

Table 3. P-wave reflection coefficients at the n-decane/oil C and air/water saturation boundaries in Berea sandstone.

At low temperatures (most heavy oil reservoirs have low reservoir temperatures), the reflection coefficients of seismic waves at the light/heavy oil saturation boundary could be as strong as those at the air/water saturation boundary in the same rock, which means "bright spots" may exist not only at the gas/liquid but also at the liquid/liquid saturation boundaries, in our case light/heavy oil boundaries. Consequently, light/heavy oil saturation boundaries could be detected by seismic methods.

The dispersion analysis (Wang and Nur, 1988, 1990) shows, according to either Biot theory or the local flow mechanism, that laboratory frequencies (0.6 MHz) and seismic frequencies (10 to 200 Hz) may have equivalent results for heavy oil-saturated rocks. This means that in the seismic frequency band the velocities are about equal to those measured at 0.6 MHz frequency in the laboratory for heavy oil-saturated rocks. This suggests that the seismic reflection coefficient could be even larger than that measured in the laboratory at the light/heavy oil boundaries in the seismic frequency band, since the velocities in light oil-saturated rocks are slightly lower at seismic frequencies due to dispersion.

The reflection coefficients at the light/heavy oil saturation boundaries are dependent on both differential pressure and temperature. At higher differential pressures, the effect of different pore fluids is smaller due to the closure of cracks and thin pores, so that the reflection coefficients are smaller. As temperature increases, V_p in heavy oil-saturated rocks decreases due to the rapid decrease in V_p and viscosity of the heavy oil, so that the reflection coefficients at the light/heavy oil saturation boundary decrease.

The light/heavy oil saturation boundaries may exist in the oil fields. For instance, in the Lagunillas field, Venezuela, the shallowest oil has an API gravity of 12 degrees. The oil becomes gradually lighter downdip. At a depth of 1500 m, the API gravity of the oil is 20 degrees. In this reservoir, the heavier oil overlies the lighter oil, which is physically impossible if there is continuity of the vertical permeability and if the fluid is Newtonian. The explanation of Dickey and Hunt (1972) is that the shallow oil has become highly asphaltic as a result of loss of its light ends in water

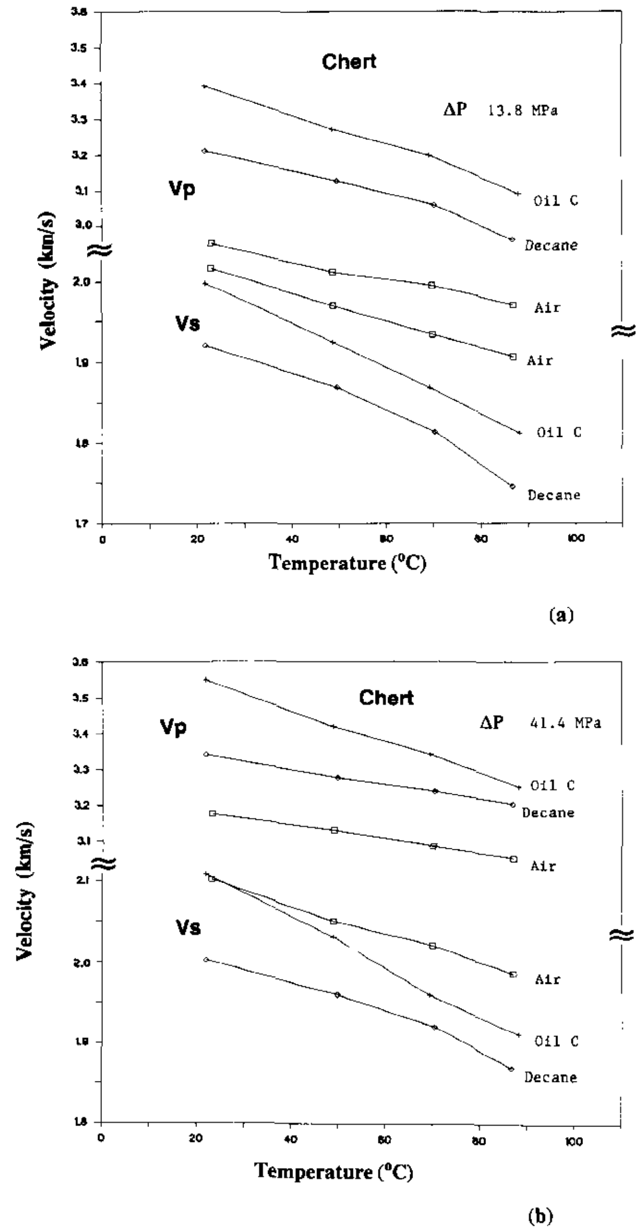

Fig. 10. Effect of different pore fluids on V_p and V_s in the dolomitic chert sample at differential pressures of 13.8 MPa **(a)** and 41.4 MPa **(b)**.

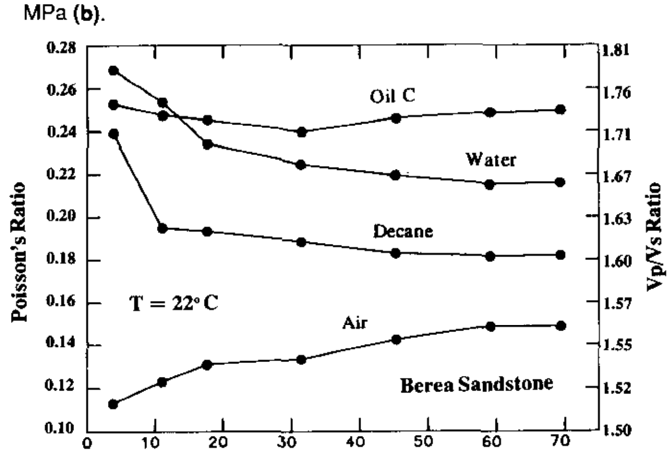

Fig. 11. Effect of different pore fluids on V_P/V_S and Poisson's ratio of the Berea sandstone sample at 22°C.

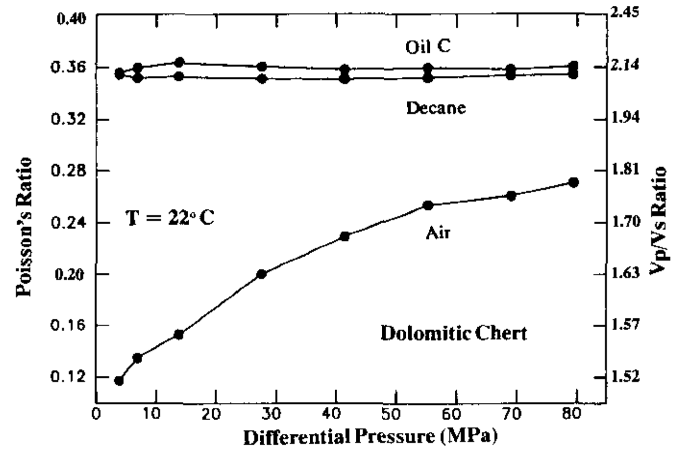

Fig. 12. *Effect of different pore fluids on* V_P/V_S *and Poisson's ratio* of the dolomitic chert sample at 22°C.

solution. Asphalts, which are non-Newtonian, might have formed a gel which prevented the gravitational adjustment of the fluids and the leakage of the oil at the outcrop.

Summary and Conclusion

The experimental results show that the velocities in fluid-saturated rocks are affected by the pore fluid properties. Bulk modulus and density of the pore fluid are the two primary factors. In crack-rich rocks, the viscosity of the pore fluid also affects velocities in rocks. When its viscosity is high, the pore fluid does not have enough time to reach equilibrium during a half period of the wave, so that the measured velocities (both V_p and V_s) are higher. This phenomenon would be especially common in crack-rich rocks such as granites and many sandstones. Another effect of the pore fluid viscosity is that it increases the measured shear wave velocities in crack-rich rocks through the viscous skinning effect. However, this viscous skinning effect is only secondary; the primary effect on the shear wave velocity is the density of the pore fluid.

Field seismic methods may not be able to resolve the differences in V_p/V_s and Poisson's ratio among the cases where the rock is saturated by light oil, heavy oil or water. However, pronounced differences do exist between V_p/V_s and Poisson's ratio of a gas-saturated and a liquid-saturated rock; V_p/V_s and Poisson's ratio in gas-saturated rocks are always lower.

The experimental results show that it is possible that seismic impedance contrasts exist at the light/heavy oil saturation boundaries in reservoir rocks. Seismic reflections at light/heavy oil saturation boundaries could be as strong as those at air/water saturation boundaries in the same rock. It is suggested that the term "oil" might have been oversimplified in seismic and log interpretations. One should *specify whether it is light or heavy oil when referring to oil* saturants.

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