Effects of pore and differential pressure on compressional wave velocity and quality factor in Berea and Michigan sandstones

Manika Prasad* and Murli H. Manghnani†‡

ABSTRACT

Compressional-wave velocity ($V_P$) and quality factor ($Q_V$) have been measured in Berea and Michigan sandstones as a function of confining pressure ($P_c$) to 55 MPa and pore pressure ($P_p$) to 35 MPa. $V_P$ values are lower in the poorly cemented, finer grained, and microcracked Berea sandstone. $Q_V$ values are affected to a lesser extent by the microstructural differences. A directional dependence of $Q_V$ is observed in both sandstones and can be related to pore alignment with pressure. $V_P$ anisotropy is observed only in Berea sandstone. $V_P$ and $Q_V$ increase with both increasing differential pressure ($P_d = P_c - P_p$) and increasing $P_p$. The effect of $P_p$ on $Q_V$ is greater at higher $P_c$. The results suggest that the effective stress coefficient, a measure of pore space deformation, for both $V_P$ and $Q_V$ is less than 1 and decreases with increasing $P_p$.

INTRODUCTION

Knowledge about the pore and confining pressure dependences of the compressional-wave velocity ($V_P$) and attenuation ($Q_V^{-1}$) in reservoir rocks is an important prerequisite for relating laboratory measurements to in-situ rock properties, and for interpreting seismic measurements in terms of subsurface petrophysical parameters. The effect of pore pressure ($P_p$) on velocity and attenuation is of special interest, since high pore pressures that are nearly equal to lithostatic pressures can be encountered in beds that are bound by impermeable rocks (Grenn and Wang, 1986). The importance of pore and confining pressures on compressional ($V_P$) and shear-wave ($V_S$) velocities in various types of sedimentary rocks (e.g., sandstones, chalk) has been reported (Brandt, 1955; Christensen and Wang, 1985; Coyner and Cheng, 1985; Gangi, 1991) where velocities were found to be dependent upon effective pressure $P_e = P_c - nP_p$, $n$ being the effective stress coefficient. Some studies have also related effective stress to fluid permeability $k$ (Zoback and Byerlee, 1975; Bernabé, 1987; Berryman, 1992). Since permeability can be a dominant factor in controlling loss mechanisms in porous media (Biot, 1956a and b; Stoll, 1989; Akbar et al., 1993), a study of the quality factor $Q$ (or attenuation, $Q^{-1}$) as a function of both confining and pore pressures is of special interest in seismic exploration for oil. It has been speculated that high pore pressure would lead to low velocity and $Q$ values caused by decreased effective pressures (Green and Wang, 1986). On the basis of velocity dispersion results, Winkler (1985; 1986) has predicted that saturated samples are more likely to resemble an undrained condition at higher (ultrasonic) frequencies. Since the pore fluid pressure generated during the short duration of an acoustic pulse does not have enough time to equilibrate, the rock will be in an unrelaxed state. In this state, the higher stiffness will contribute to higher velocities. Although the effect of pore pressure on velocity has been studied in various rock types (e.g., Jones and Nur, 1983; Gangi, 1991), its effect on attenuation is mostly unknown. Investigation of the effect of pore fluid pressure on attenuation properties of candidate reservoir rocks is particularly important for evaluating the reservoir properties. For example, the seismic inference of pore pressure buildup could provide useful information about the fluid content and pore geometry of a reservoir (Green and Wang, 1986). The purposes of this study are (1) to present compressional wave velocity ($V_P$) and quality factor ($Q_V$) for two specimens of Berea and Michigan sandstones, measured as a function of confining ($P_c$) and pore pressures ($P_p$), and (2) to discuss the implications of an effective pressure law for lithological interpretations of seismic data.

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EXPERIMENTAL PROCEDURE

Samples

Cube specimens of 18 mm length on each side were prepared from Berea and Michigan sandstones. The faces were ground on a glass plate and cleaned with a water jet and in an ultrasonic bath to remove rock flour. The faces are parallel to within 20 μm. Bulk and grain densities and porosity were determined by the Archimedes method. The microstructure of the samples was examined under optical microscope and scanning acoustic microscope (Briggs, 1985, 1992; Rodriguez-Rey et al., 1990; Prasad et al., 1995).

Microstructure

Scanning acoustic microscopy micrographs of the Michigan and Berea sandstone specimens are shown in Figure 1. These results have been discussed in detail elsewhere (Prasad and Manghnani, 1996; Prasad et al., manuscript in review), and the main features are given here. The Michigan sandstone is composed of rounded grains with a grain size of about 300–400 μm, and is well cemented. The low impedance contrast between grains and cement suggests a similar (siliceous) composition of grains and cement. The grains do not show any microcracking. In contrast, Berea sandstone is composed of angular grains (150–200 μm) which show microcracks. The grain contacts are somewhat jagged and are weakly cemented. The major difference between the sandstones is seen in their contact areas between grains. In Berea sandstone, this area resembles a microcrack or an elongated pore with large aspect ratio. The contact areas in Michigan sandstone resemble a greater to a group of more or less equant pores. These differences in microstructure will be considered further when comparing the variations in observed velocity and attenuation values.

Other measured physical properties of the samples are given in Table 1. The Michigan sandstone has a lower porosity, larger grain size, and well cemented grains.

Ultrasonic experimental setup

The pulse transmission technique (Birch, 1960) was used for compressional-wave velocity \( (V_P) \) measurements. The quality factor \( (Q_P) \) was calculated using the spectrum division method (Toksöz et al., 1979; Johnston and Toksöz, 1980; Sears and Bonner, 1981). Measurements were made in two perpendicular directions. In Berea sandstone, the measured directions were parallel \( (V_{Ph}, Q_{Ph}) \) and perpendicular \( (V_{Pv}, Q_{Pv}) \) to the visible bedding plane. In Michigan sandstone, where no bedding was present, the measurements were made parallel and perpendicular to the direction of the image.

Table 1. Physical properties of the samples.

<table>
<thead>
<tr>
<th></th>
<th>Berea sandstone</th>
<th>Michigan sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density (g/cm(^3))</td>
<td>2.282</td>
<td>2.362</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>21.18</td>
<td>16.94</td>
</tr>
<tr>
<td>Grain size (μm)</td>
<td>150–250</td>
<td>300–400</td>
</tr>
<tr>
<td>Permeability (md)</td>
<td>100</td>
<td>—</td>
</tr>
</tbody>
</table>

Fig. 1. Acoustic microscopy micrograph of Michigan and Berea sandstones at 1 GHz showing quartz grains, cementation, and pore structure. The scanned image of Berea sandstone (a) is 312 μm x 312 μm, that of Michigan sandstone (b) is 1000 μm x 1000 μm. Impedance contrasts in the micrographs are color coded: cyan through blue to white denote progressively higher impedance. Pore spaces and interfaces appear as cyan and blue areas. Grains are green to white colored. Michigan sandstone (b) has well cemented, rounded grains with few visible microcracks. Impedance (brightness) contrast within the grains is low. The grains in Berea sandstone (a) are angular (150–200 μm) and show microcracks. The grain contacts are somewhat jagged and are weakly cemented. The grain contacts are wider than in Michigan sandstone.
Pore Pressure Effects on V and Q

Fig. 2. Schematic diagram of the ultrasonic pulse transmission experimental setup showing details of the epoxy anvils and transducer holders.
visible, the measured directions were arbitrarily chosen as parallel \((V_{p_h}, Q_{p_h})\) and perpendicular \((V_{p_v}, Q_{p_v})\) to borehole axis.

The experimental setup consists of a digital Tektronix 7854 oscilloscope, an HP 214B pulse generator, and a preamplifier. A new sample-transducer assembly allows us to conduct the measurements in two directions in a sample under controlled pore and confining pressures. The cube sample, with 1 M Hz PZT-transducers attached to the faces, is enclosed in epoxy anvils, which prevents the mixing of confining and pore fluids. The cylindrical shape formed by the anvils was covered by a latex rubber membrane and sealed with O-rings to prevent the entering the pore fluid path. A high viscosity bonding medium (Dow Corning V9) was used to bond the transducers to the sample. The transducers are placed in brass holders which, together with the epoxy, provide a backing for the transducers. The electrical leads run through conduits in the anvils. When the anvils are assembled, all four transducers are positioned on the sample faces at the same height. Filter-stones placed on the remaining two faces of the cube facilitate passage of pore fluid through the sample. Figure 2 shows details of the epoxy anvils, transducer holders, electrical and pore fluid circuits.

This configuration allowed measurements at various confining and pore pressures up to 55 and 35 M Pa, respectively. The pressure limits were defined by the aluminum sample holder, electrical contacts, and the epoxy used in the anvils. The samples were saturated under a vacuum with 60 ppm brine prior to loading into the assembly.

Traveltimes were measured on the oscilloscope by digitizing a trace with 1024 points at a time sweep of 5 μs, thus allowing a time resolution of about 5 ns or about 0.2% error in velocity. A fiducial error in velocity measurement is estimated to be around 1% because of operator error in picking first arrival. Traveltime calibration was accomplished by using aluminum rods of different lengths. \(Q_p\) was measured by the spectral ratio technique (Toksöz et al., 1979; Johnston and Toksöz, 1980; Sears and Bonner, 1981) with the assumption of a constant \(Q\) over the bandwidth used (0.8-1.3 MHz). The signal from an aluminum cube of the same size was recorded at various pressure steps and used as a reference signal at that pressure. In this way, similar coupling and pressure conditions were maintained for the reference and sample. Figure 3 shows typical signals for aluminum, Lucite, and Berea sandstone samples along with their spectra. The signals are damped and no ringing is seen. The \(Q_p\) value for Lucite obtained from this signal was found to be 54, which is in agreement with reported values of 50 (Toksöz et al., 1979). Because of the short sample lengths, diffraction corrections were necessary (Sears and Bonner, 1981; Wepfer and Christensen, 1990). The tables of Benson and Kiyohara (1974) and K himunin (1972) were used for amplitude and phase corrections.

**RESULTS**

**Differential pressure experiments**

Figure 4 presents the increase in \(V_p\) with increasing differential pressure \((P_d = P_c - P_p)\). A constant low pore pressure of 0.1-0.2 M Pa was maintained to ensure full saturation during the experiment. Michigan sandstone, with larger grain size and lower porosity, has higher \(V_p\) values than Berea sandstone. At low \(P_p\), up to 15 M Pa, the rate of increase in \(V_p\) is higher in Berea sandstone; at higher \(P_p\), \(V_p\) changes only slightly with \(P_p\). In Michigan sandstone, \(V_p\) increases monotonically with increasing \(P_c\) to 40 M Pa. The different behavior of \(V_p\) gives an indication of the type of pores in the samples. A steep increase in \(V_p\) at low pressures is indicative of the closure of microcracks or pores with large aspect ratios (Lo et al., 1986; Wepfer and Christensen, 1990; Prasad et al., 1994).

The \(V_p\) anisotropy is defined as

\[
A_{V_p} = 200 \cdot \frac{(V_{p_h} - V_{p_v})}{(V_{p_h} + V_{p_v})}
\]

As seen in Figure 5, the average velocity anisotropy in Michigan sandstone is low (about 1-2%) but slightly above the experimental error, and it does not vary as a function of \(P_d\). Such a low velocity anisotropy is attributed to a lack of preferred grain orientation in its microstructure. O n the other hand, Berea sandstone with visible bedding has higher velocity anisotropy (8%) and it decreases with increasing \(P_p\) and attains a value of about 4% at \(P_p = 45\) M Pa. \(Q_p\) increases with increasing \(P_p\) in both sandstones (Figure 6); however, the increase is somewhat higher in Michigan sandstone.

The differences in \(V_p\) and \(Q_p\) values are related to the microstructural differences (see Figure 1). The higher \(V_p\) and \(Q_p\) values measured for the Michigan sandstone can be attributed to better cementation and intact grains. The better cementation can be evaluated as higher initial contact radius which causes a higher \(V_p\) (Winkler, 1983; Prasad and Messner, 1992). A steep gradient of \(V_p\) increase at low \(P_p\) and decrease of \(V_p\) anisotropy with \(P_p\) can be explained by deformation of elongated weak contact areas and closing of microcracks between grains in Berea sandstone (Lo et al., 1986). Michigan sandstone has stiffer contact areas that are more resistant to deformation at lower pressures.

A analogous to \(V_p\) anisotropy, \(Q_p\) anisotropy, defined as

\[
A_{Q_p} = 200 \cdot \frac{(Q_{p_h} - Q_{p_v})}{(Q_{p_h} + Q_{p_v})}
\]

shows negative values with increasing pressure \((Q_{p_v} > Q_{p_h})\), (Figure 7). In Berea sandstone, \(Q_p\) anisotropy decreases to negative values as differential pressure increases above 30 M Pa. A similar decrease in \(Q_p\) anisotropy with increasing confined pressure in deep sea drilling program (DSDP) sediments has been attributed to horizontally aligned water-filled elliptical pores (O'Brien et al., 1989).

A kbar et al. (1993) have shown that attenuation depends strongly on the pore orientation. \(Q_p\) is lower for wave propagation perpendicular to the long axes of elliptical pores than it is for waves traveling parallel to this direction. Using this analogy, the \(Q_p\) anisotropy observed in our experiments could be explained by the pore orientation rather than the preferred orientation of grains or bedding planes. This would also explain the low anisotropy in \(V_p\), which is not significantly affected by pore space (O'Brien et al., 1989). Figure 8 shows acoustic microscopy micrographs of the pore space distribution in Berea sandstone. Images of two faces are shown: (a) cut perpendicular \(h\)-direction of wave propagation) and (b) cut parallel \(v\)-direction of wave propagation) to the visible bedding plane. The arrows in Figure 8a mark alignment of pore spaces (black colored). The image of the face cut parallel to bedding (Figure 8b) does not show any alignment of pore spaces.
FIG. 3. Typical signals through aluminum, Lucite, and Berea sandstone samples are shown in time and frequency domain along with the spectrum divisions between aluminum and Lucite signals and aluminum and Berea sandstone signals.
This alignment of low impedance structures (pores) could be accentuated with increasing pressure and would lead to higher \( Q_P \)-values.

**Effect of pore pressure**

The 3-D surfaces showing the variations in \( V_P \) and \( Q_P \), as affected by \( P_p \) and \( P_d \) for both sandstones, are presented in Figures 9 and 10. The plots are made by Matlab routines of gridding and 3-D plotting, which use a 2-D interpolation between data points to construct the grids. The velocity plots for Berea and Michigan sandstones (Figure 9) show a strong dependence of \( V_P \) on \( P_p \) in contrast to a weak dependence on \( P_d \). The quality factor plots for both sandstones (Figure 10) show that \( Q_P \) changes not only with \( P_p \) but also with \( P_d \). This dependence of \( Q_P \) on \( P_p \) is greater at higher \( P_d \) and is more

**Fig. 4.** \( V_P \) versus differential pressure for Berea and Michigan sandstones measured in two directions denoted by the subscripts \( ph \) and \( pv \). Measurements were made at \( P_p = 0.1 \) MPa. Solid lines represent best fits obtained with the equation \( V_P^2 = A + B \cdot P_d + C \cdot e^{P_d/D} \).

**Fig. 5.** \( V_P \) anisotropy versus \( P_d \). Positive anisotropy implies that \( V_P^{ph} \) is greater than \( V_P^{pv} \). Measurements were made at \( P_p = 0.1 \) MPa. Solid lines represent exponential fits through the data points.

**Fig. 6.** \( Q_P \) versus \( P_d \) in both sandstones measured in two directions denoted by the subscripts \( ph \) and \( pv \). Measurements were made at \( P_p = 0.1 \) MPa. Solid lines represent best fits obtained with the equation \( Q_P^2 = A + B \cdot P_d + C \cdot e^{P_d/D} \).

**Fig. 7.** \( Q_P \) anisotropy versus \( P_d \). Positive anisotropy implies that \( Q_P^{ph} \) is greater than \( Q_P^{pv} \). Measurements were made at \( P_p = 0.1 \) MPa. Solid lines represent second degree polynomial fits through the data points.
pronounced in the case of Michigan sandstone. The increase in $V_p$ with increasing $P_p$ is between 1–2% (above experimental error) and the increase in $Q_p$ is between 15–20%.

**DISCUSSION**

The dependences of $V_p$ and $Q_p$ on both $P_p$ and $P_d$ suggest that the effects of $P_d$ and $P_p$ are not equal and opposite. Effective pressure ($P_e$) is used to define conditions when $P_p$ does not exactly cancel $P_d$:

$$P_e = P_c - n P_p,$$

where $n$ is the effective stress coefficient (Todd and Simmons, 1972; Christensen and Wang, 1985; Gangi, 1991). Differential pressure ($P_d$) is a special case when $n = 1$, and

$$P_d = P_e = P_c - P_p.$$  

The observation that $V_p$ and $Q_p$ depend on both $P_d$ and $P_p$, implies that $n \neq 1$. To test this observation, the data plotted in Figures 9 and 10 are replotted with $P_p = constant$, as shown for $V_p$ in Figure 11 and for $Q_p$ in Figure 12. A iso shown are best-fit plots of the form

$$V_p^2 = A + B \cdot P_c + C \cdot e^{-P_c/D}$$

(Greenfield and Graham, 1994), where $A$, $B$, $C$, and $D$ are constants. The velocity plots in Figure 11 show some change with increasing pore pressure. At low pore pressures, the $V_p$-curves are similar to the one at $P_p = 0$. At higher $P_p$, the change in slope at the elbow of the $V_p$-curves shifts toward higher $P_p$-values. Furthermore, the change in slope is more gradual at higher $P_p$.

During the $V_p$ and $Q_p$ measurements at varying $P_p$, there was some scatter in monitored $P_d$ values. Hence, equation (5) was used at each $P_p$ step to interpolate $V_p$ and $Q_p$ values for $P_d = constant$. These interpolated $V_p$ and $Q_p$ values are plotted in Figures 13 and 14, respectively. One consequence of $V_p$- and $Q_p$-dependence on $P_p$ and $P_d$ is that the slope of a straight line fitted to $V_p$ and $Q_p$ versus $P_p$ values at $P_d = constant$ is not equal to 0. For $V_p$, the variation is in the order of 1–2%, which is slightly higher than experimental error. For $Q_p$, the change with $P_p$ is much higher, between 15–20%. Furthermore, the increase in the slope of these linear fits with increasing pressure implies that this dependence on $P_p$ and $P_d$ is greater at higher $P_p$, and $n$ changes with pressure. The factor $n$ in the effective pressure equation (3) has been described as the effective stress coefficient or the coefficient of internal (pore space) deformation. The equation for $n$,

$$n = 1 - \frac{\partial V_p}{\partial P_p} \frac{\partial P_p}{\partial P_d}.$$

Fig. 8. A coustic microscopy micrographs of Berea sandstone made at low frequency (25 MHz). Images of two faces are shown: (a) cut perpendicular to bedding, $V_p$, $Q_p$. direction of measurement and (b) cut parallel to bedding, $V_p$, $Q_p$. direction of measurement. The scanned area is $15 \times 15$ mm. Pore spaces are low impedance areas and are coded with darker shades and black. In (a), the arrows mark pore alignment. (b) No distinct alignment of pore spaces is observed.

(Todd and Simmons, 1972; Christensen and Wang, 1985) was then solved for $V_p$ and $Q_p$ in both samples. \([\partial V_p/\partial P_p]_{P_p}\) values were evaluated from the slopes for the $P_p = constant$ curves shown in Figures 11 and 12 (see Table 2). For \([\partial V_p/\partial P_p]_{P_p}\) values, the slopes of the $P_p = constant$ straight line fits shown in Figures 13 and 14 were evaluated. An approximation of \([\partial V_p/\partial P_p]_{P_p}\), from the $V_p$ at $P_p = 0$ curve involves an assumption that this curve is duplicated at higher pore pressures. A higher pressure, this assumption would lead to a lower estimate of $n$. Table 2 shows a comparison of slopes and $n$ values for $V_p$ at various pressures. Two different sets are calculated from (1) $V_p$ at $P_p = 0$ and (2) $V_p$ at $P_p \neq 0$ curves. Referring to Figures 11 and 12 and Table 2, the slopes for $P_p = 0$ are lower than those for $P_p \neq 0$ for both sandstones. Table 3 gives the values of $n$ calculated for $V$ and $Q$ at different pressures. These calculated
Fig. 9. Pore and differential pressure dependences of $V_p$ in Berea and Michigan sandstones. The velocity variation is coded by a hot-color map. High velocity is marked white, low velocity is deep red.
FIG. 10. Pore and differential pressure dependences of $Q_{ph}$ in Berea and Michigan sandstones. The quality factor variation is coded by a hot-color map. High $Q_{ph}$ is marked white, low $Q_{ph}$ is deep red.
values of $n$ decrease with pressure for both samples (Table 3). At lower pressures (to 10 MPa), $n \approx 1$ and decreases to values of about 0.7 at 25 MPa.

In Figures 13 and 14, the separation between the $P_d = \text{constant}$ curves becomes narrower at higher pressures. At low pressures (up to 10 MPa), the $V_P$ and $Q_P$ curves (at $P_d = \text{constant}$) are almost horizontal and $n \approx 1$. At higher pressures, the slopes of $V_P$ and $Q_P$ curves (at $P_d = \text{constant}$) are higher and $n$ decreases with increasing pressure. This also follows from the observation that $V_P$ and $Q_P$ are dependent on both $P_d$ and $P_{p'}$.

Batzle and Wang (1992) have analyzed the seismic properties of various pore fluids as a function of pressure and temperature. Their empirical analyses show an increase in brine bulk modulus and density with increasing confining pressure. Brine viscosity changes only by a few percent up to 50 MPa. The small change in $V_P$ with $P_c$ could be explained by a pressure dependence of the bulk modulus of brine that increases from about 2.2 GPa at 0.1 MPa to about 2.5 GPa at 50 MPa (Batzle and Wang, 1992). However, the strong dependence of $Q_P$ on $P_p$ shows that additional factors should be considered to explain our results. The differences in the pore pressure dependence of $V_P$ and $Q_P$ in two sandstones is caused by their different contact areas as observed in the acoustic microscopy micrographs.

**Fig. 11.** $V_P$ changes in Berea and Michigan sandstones with $P_c$. The data are plotted with $P_{p'} = \text{constant}$. The solid and broken lines represent best fits obtained with $V^2 = A + B \cdot P_d + C \cdot e^{-P_d/D}$. $P_p$ values for these fits are marked by numbers.
Contact areas in the Berea sandstone are wider and weaker, and appear to be somewhat interconnected (Figures 1). In Michigan sandstone, contact areas are not very wide and are not interconnected and appear as equant pores (Figure 1). This comparison between the pore spaces of the two sandstones suggests that deformation of pore space during passage of an acoustic wave is larger in Berea sandstone than in the case of Michigan sandstone.

**CONCLUSIONS**

The variations in $V_P$ and $Q_P$ as a function of confining and pore pressures for Michigan and Berea sandstones are related to differences in their microstructure. Michigan sandstone is well cemented, coarser grained, and consists of intact grains. Consequently, $V_P$ and $Q_P$ values are higher. Berea sandstone is fine-grained and consists of microcracks and angular grains that are poorly cemented. Thus the measured $V_P$ and $Q_P$ values are lower. The measured $V_P$ and $Q_P$ values at elevated pore pressures show that at higher pore and confining pressures, pore pressure effects do not cancel confining pressure effects. Measurements of effective stress (Christensen and Wang, 1985; Gangi, 1991; Berryman, 1992), combined with pressure-dependent properties of the pore fluid (Batzle and Wang, 1992) are needed to describe the results fully. The effective stress coefficients for both $V_P$ and $Q_P$ are less than 1. Compared to

![Diagram](image-url)

**Fig. 12.** $Q_P$ changes in Berea and Michigan sandstones with $P_p$. The data are plotted with $P_c = $ constant. The solid and broken lines represent best fits obtained with $Q^2 = A + B \cdot P_d + C \cdot e^{P_d/P_p}$. $P_p$ values for these fits are marked by numbers.
Table 2. Values of $\left( \frac{\partial V_p}{\partial P_d} \right)_{P_p}$ and $n$ at different pressures.

<table>
<thead>
<tr>
<th>$P_c$ (MPa)</th>
<th>$\left( \frac{\partial V_p}{\partial P_d} \right)_{P_p} = n$</th>
<th>$\left( \frac{\partial V_p}{\partial P_d} \right)_{P_p} = n$</th>
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</thead>
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<tr>
<td>$P_p = 0$</td>
<td>$\left( \frac{\partial V_p}{\partial P_d} \right)_{P_p}$</td>
<td>$\left( \frac{\partial V_p}{\partial P_d} \right)_{P_p}$</td>
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<tr>
<td>$P_p \neq 0$</td>
<td>$\left( \frac{\partial V_p}{\partial P_d} \right)_{P_p}$</td>
<td>$\left( \frac{\partial V_p}{\partial P_d} \right)_{P_p}$</td>
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<td>5</td>
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<td>3.299</td>
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<td>1.809</td>
<td>1.413</td>
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<tr>
<td>15</td>
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<td>0.939</td>
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<tr>
<td>20</td>
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<td>0.815</td>
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<td>25</td>
<td>0.505</td>
<td>0.779</td>
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Fig. 13. $V_p$ changes in Berea and Michigan sandstones with $P_c$. The data are plotted with $P_d = \text{constant}$. Linear fits for $P_d = \text{constant}$ are shown by broken lines. The numbers are $P_d$ values for each fit. The solid line represents best fit from Figure 11.
$V_P, Q_P$ is more sensitive to variations in pore pressure and pore space deformation. The different pore pressure dependences of $V_P$ and $Q_P$ are explained by the type of contact areas between the grains in the two types of sandstones. Further studies of velocity and quality factor variations in other types of sandstones as a function of confining and pore pressures would also provide better understanding of the pore space deformation in such porous rocks.

**ACKNOWLEDGMENTS**

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### Table 3. Values of $n$ at different pressures.

<table>
<thead>
<tr>
<th>$P_c$ (MPa)</th>
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<th>Michigan</th>
<th>Berea</th>
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<td>25</td>
<td>0.776</td>
<td>0.615</td>
<td>0.813</td>
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**Fig. 14.** $Q_P$ changes in Berea and Michigan sandstones with $P_c$. The data are plotted with $P_d = \text{constant}$. Linear fits for $P_d = \text{constant}$ are shown by broken lines. The numbers are $P_d$ values for each fit. The solid line represents best fit from Figure 12.
REFERENCES


