

Velocity and resistivity changes during freeze-thaw cycles in Berea sandstone

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ABSTRACT

We report on simultaneous measurements of resistivity, compressional (V_p), and shear (V_s) velocities made during the temperature cycling of Berea sandstone while at elevated pressure. Temperatures were cycled through the freezing point of the saturating brine. The responses of resistivity and velocities are in phase but are asymmetrical as the brine freezes and thaws. Limited freezing causes no discernible damage to the core. Free water is present below the nominal freezing point of the brine. V_p , V_s , and resistivity change by 16%, 24%, and 500%, respectively, over the temperature range of -4°C to $+6^{\circ}\text{C}$ at 6.9 MPa confining pressure.

INTRODUCTION

Freezing and thawing of fluids in rock has applications to seismic exploration in permafrost regions and deep-water environments. This process is critical to understanding the meaning of data collected on cores that are preserved by freezing. Numerous authors have investigated the effects of freezing water, brines, or water-gas mixtures on the velocity of sound through rock (Timur, 1968; King, 1977; Pandit and King, 1979, 1983; Remy et al., 1994; Berge et al., 1999; Helgerud, 2001) and sediments (Nakano et al., 1972; Kurfurst, 1976; Stoll and Bryan, 1979; King, 1984; Zimmerman and King, 1986; King et al., 1988). Resistivity and velocity changes have been measured on parallel plugs in separate experiments (Pandit and King, 1979). These changes have also been measured on the same sample in separate tests (King, 1977; Pandit and King, 1983; King et al., 1988) and, more importantly, on samples that were potentially altered as a result of previous testing. *Supercooling*, a term used by Nankano et al. (1972), has been documented in some studies in clay-rich unconsolidated materials. For example, hysteresis in velocities upon temperature cycling of unconsolidated sediments has been observed by Nakano et al. (1972) and King (1977) and attributed to su-

percooling. The influence of clay fraction on V_p in unconsolidated sediments during freezing was studied by King (1984).

The majority of these studies focused on compressional wave observations and did not measure shear velocities. In all of these studies, very few experimental conditions (i.e., the confining, axial pressures, or saturants) are the same. In none of these studies were the electrical and acoustic (V_p and V_s) properties measured simultaneously in the same experiment. However, this body of research collectively defines the now-accepted premise that both compressional velocity and resistivity increase in a saturated sample temperature cycled from high to low through the freezing point of the saturating fluid. Based on indirect evidence, multiple authors have concluded, but not verified, that the water in larger pores freezes first (Timur, 1968; Pandit and King, 1979; Zimmerman and King, 1986). Pandit and King (1979) found that free water remained in the pore space even at -15°C , with distilled water as a pore fluid. The fraction of free water increases with pore-fluid salinity. What is not clear is how the process of freezing occurs in the pore space, or whether the process of partially freezing a fluid in the pore space damages the rock. Unconsolidated sediments are dominated by grain-boundary contact processes and as such are a different class of materials than indurated rocks like sandstones and carbonates. We are concerned here with a very limited set of observations that pertain to indurated rock, Berea sandstone.

EXPERIMENTAL TECHNIQUES

Samples of Berea sandstone in the form of right circular cylinders (25 mm in diameter by 25 mm in length), with measured porosities $\phi = 17.8\%$ and 20.1% and permeabilities $k = 117$ and 340 md, were pressure saturated at 13.8 MPa with NaCl brine (25,000 ppm or ~ 0.43 M) after evacuating for 24 hours. The plugs were cored perpendicular to bedding, trimmed to length, and polished to a flatness of less than 0.025 mm runout across the diameter. The results from the 17.8% porosity sample are discussed here.

Samples were weighed before and after saturation to evaluate the level of brine saturation and were determined to be at 99% of total saturation. The samples were then jacketed in rubber sleeves and in-

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served in a servo controlled hydrostatic pressure vessel designed by New England Research, White River Junction, Vermont. The confining pressure fluid was mineral oil. Pore pressure was maintained at atmospheric while confining pressure and temperature were varied during the experiments. Thus, velocities were measured under drained conditions. Simultaneous measurements of compressional and polarized shear velocities and resistivity were made on each sample at elevated, confining pressures to 20.6 MPa and over a temperature range of -4°C to $+6^{\circ}\text{C}$.

Temperature of the system is controlled by fluid (antifreeze) pumped from a programmable chiller (Julabo F32) through copper coils wrapped around the external diameter of the pressure vessel. The coils and vessels are jacketed with 5 cm of insulation and a reflective Mylar covering. Temperatures are monitored with an array of platinum resistance sensors mounted inside the confining fluid and in the sample assembly directly above the sample. The temperature at the sample inside the assembly is used to trigger data acquisition. Temperature resolution is $\pm 0.5^{\circ}\text{C}$. Temperature response is limited by the large thermal inertia of the massive pressure vessels (20.3 cm diameter by 61 cm long). Velocities are measured using a standard pulse transmission technique (Schreiber et al., 1973), in which a negative voltage spike between 30 and 300 volts is applied

to a transmitting 1-MHz piezoelectric crystal. The sound wave is detected by another 1-MHz piezoelectric receiving crystal and fed to an 8-bit, 25-MHz digitizer. All waveforms are stored for subsequent analyses. Velocities are calculated from handpicked arrival times, transducer delays, and the sample lengths.

Resistivities are measured over a frequency range of 0.02–100,000 Hz using a two-electrode configuration (see Pearson et al., 1986). An Agilent 33220A function generator serves as a programmable source. The signal through the sample is compared to that through a standard resistor at each programmed frequency. Phase and amplitude calculations over all frequencies provide quality-control diagnostics. Resistivity measurements are typically contaminated at low frequencies by dielectric phenomena and at high frequencies by inductive processes. Following Pandit and King (1979), we select a frequency at which the response is dominated by resistance and report the measured resistivities at a frequency of 1000 Hz. Resistivities are calibrated on known sample standards and via cross-lab measurements. Resistivity of the saturating brine is measured using a standard cell and found to be $0.26 \Omega\text{m}$ at 21.1°C .

Several experiments were conducted over a number of cycles at elevated confining pressures and at constant and varying temperatures. We report on two experiments: one consisting of four pressure cycles to 20.6 MPa confining pressure at a constant temperature of 1°C , and a second consisting of eight temperature cycles with a range of -4°C to $+6^{\circ}\text{C}$, while at a constant confining pressure of 6.9 MPa.

VELOCITIES AND RESISTIVITIES DURING PRESSURE CYCLES

In these experiments, a saturated sample of Berea sandstone is held near 1°C while confining pressures are cycled between 0.6 and 20.6 MPa. Velocity and resistivity measurements are recorded at roughly 3.44 MPa increments. At this temperature, the saturating brine is not expected to freeze ($F_p = -1.5^{\circ}\text{C}$). Compressional waveforms captured during four cycles are presented in Figure 1. The repeatability of the waveforms between cycles indicates that there is no physical damage caused during the pressure cycling. Strong amplitudes are associated with higher pressures and weak amplitudes with low pressures.

Velocities are determined by picking arrival times from the digitized waveforms, subtracting transducer delay times, and dividing the time into the sample length. Velocities for both P- and S-waves during the four cycles are summarized in Figure 2. Velocities are expected to increase nonlinearly with increasing confining pressure; nonlinear behavior is indicative of cracks being present. The shape of the velocity response suggests that there exists a spectrum of cracks having different aspect ratios. Note also that at 6.9 MPa, a population of open cracks exists. Maximum velocities are generally observed to increase with increasing number of pressure cycles. This general increase cannot be linked to systematic temperature changes during testing. In the first cycle velocities, both V_p and V_s clearly are lower than those of subsequent cycles. Larger differences in velocities between pressure cycles are observed for V_s than V_p , although this is hidden by the plot scale. The percent change in V_p is 27%, whereas that for V_s is 75%, in pressure cycles two through four. Velocity differences between cycles decrease with increasing confining pressure. Figure 3 presents a summary of the measured V_p , V_s , resistivity, and pressure recorded over four pressure cycles plotted versus time. Peak velocities occur at the peak pressure for both V_p

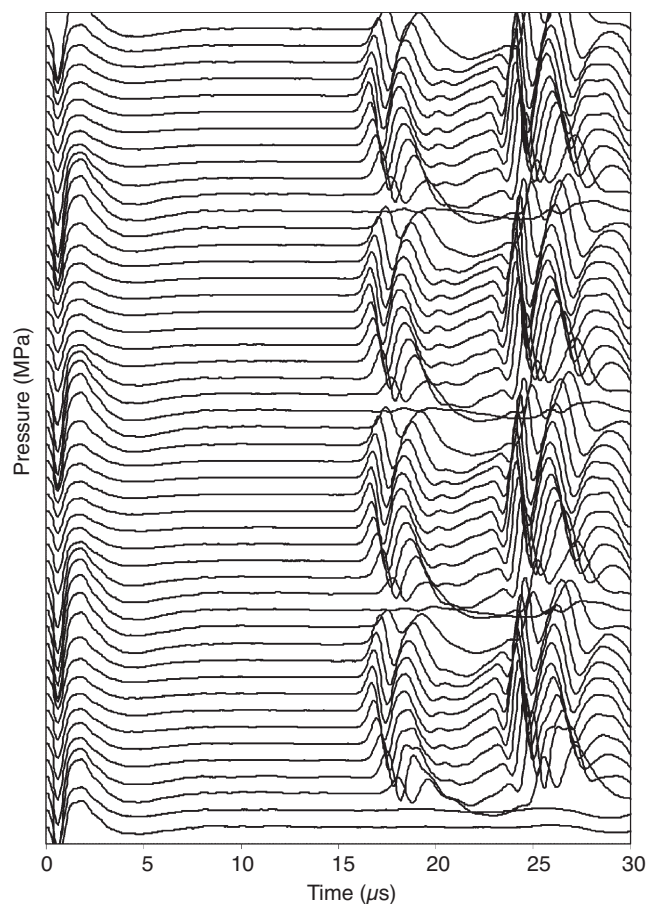


Figure 1. Recorded P-wave waveforms during the confining pressure cycling of a brine saturated Berea sandstone sample at about 1°C . The pressure was cycled from 0.6 to 20.5 MPa. Only the first 30 μs of the waveforms are shown. Note that after the first cycle the confining pressure was never allowed to go below 0.6 MPa. Repeatability is evident in the recorded traces.

and V_s . Resistivity shows little to no change and has a slight increase through each cycle. These responses are expected and validate the measurement techniques. Accuracy of the velocities depends upon signal quality, but precision depends more on the ability to track a particular phase in the signal. Documenting changes requires precision. Precision for both V_p and V_s is greater than accuracy, with precision in V_p being $\pm 0.1\%$. Variability in S-wave arrivals makes both precision and accuracy estimates difficult. With the lengths and velocities in these samples and good signal quality, V_p accuracy is $\pm 1\%$, whereas V_s accuracy is $\pm 1.5\%$ – 2% . Resistivity is calibrated against standard resistors and independent measurements using different experimental equipment.

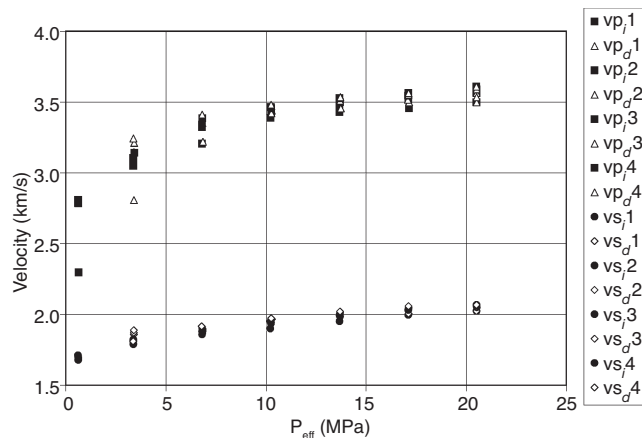


Figure 2. Velocities measured on Berea sandstone during confining pressure cycling from 0.6 to 20.5 MPa. The compressional velocities show better reproducibility than the shear velocities. The nonlinear response is caused by cracks. After the first cycle, the measured velocities are essentially within experiment uncertainty. The percent change in V_p is 27%, whereas that for V_s is 75%, in pressure cycles two through four. Subscripts i and d refer to observations made during increasing and decreasing pressures, and numbers 1–4 refer to the pressure cycle.

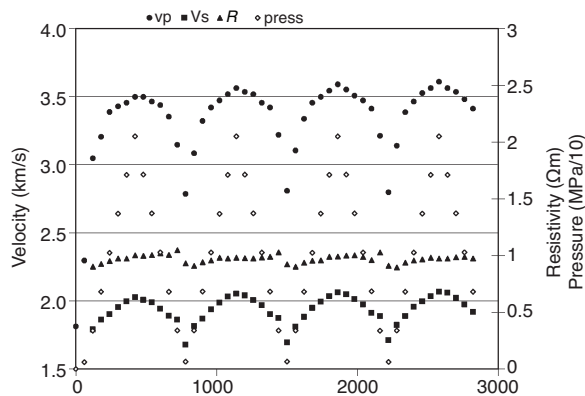


Figure 3. Summary of measured V_p , V_s , resistivity R , and pressures during four pressure cycles of Berea sandstone. Confining pressure varied from 0.6 to 20.5 MPa. The sample is completely brine saturated. As expected, V_p and V_s responses are in phase with the independent variable, confining pressure. Resistivity is basically insensitive to the pressure changes. The temperature during pressure cycling was held at 1°C .

VELOCITIES AND RESISTIVITIES DURING TEMPERATURE CYCLES

A series of temperature cycling experiments are run at different confining pressures. Here we present the results obtained at a confining pressure of 6.9 MPa. The temperature is cycled between -4°C and $+6^\circ\text{C}$, with equilibration times an average of 1 hour for a 1°C change. Thus, an average of 5 hours are required for each cycle. The P-wave waveforms shown in Figure 4 were collected over a continuous five day period. Figure 4 shows the initial portion of the digitized P-wave waveforms from 5 to $30\ \mu\text{s}$. The stronger first arrivals correspond to the lowest temperatures in each cycle, whereas the weaker P-wave arrivals correspond to the highest temperatures. In each cycle, the arrivals abruptly change when transitioning from warm to cold but appear to taper more gradually in time when transitioning from cold to warm. Arrival times are picked from greatly expanded versions of these waveforms. The arrivals appear quite reproducible between cycles. Shear velocities and resistivities are measured simultaneously with P-wave velocities.

Figure 4 documents the observed asymmetry in compressional arrival times during freezing and thawing cycles. These arrivals are used with sample lengths to compute velocities. Figure 5 presents a summary of the normalized velocities, resistivities, and temperature for these temperature cycles are plotted against time. Actual temper-

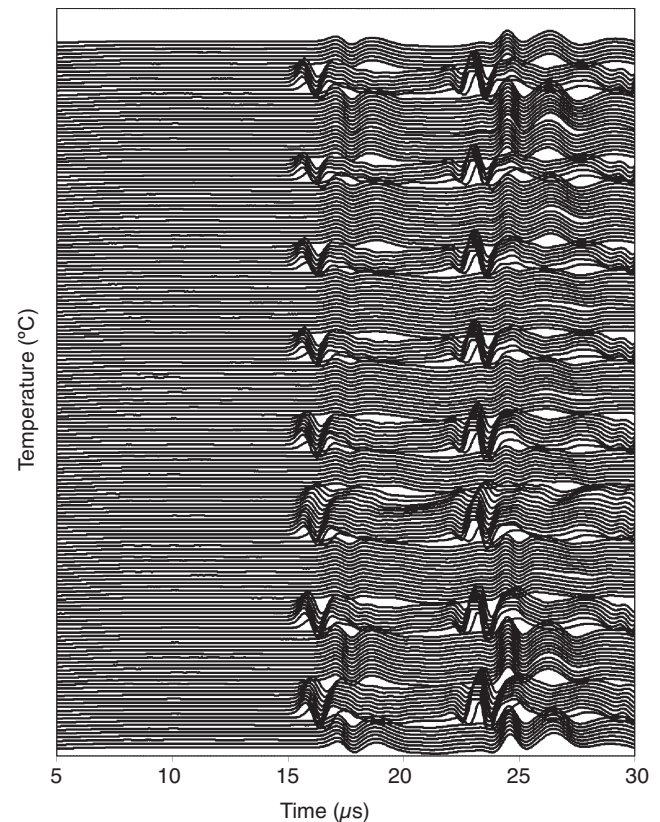


Figure 4. Compressional waveforms recorded during eight freezing and thawing cycles. Confining pressure is 6.9 MPa for all cycles. Measurements are made in the drained state (i.e., pore pressure was equal to atmospheric). Temperature during the cycles varied from -4°C to $+6^\circ\text{C}$. Only the portions of the recorded waveforms between 5 and $30\ \mu\text{s}$ are plotted. Early and strong arrivals are associated with the freezing cycles.

atures are plotted on a Celsius scale. Temperatures vary from about -4°C to $+6^{\circ}\text{C}$. There are noted differences between the first and remaining cycles. Beginning with the second cycle, behavior appears consistent for all properties. At temperatures above freezing, velocities and resistivities are both low, while at temperatures below freezing, both increase dramatically. Perhaps the most striking observation is the rapidity and simultaneity of both the velocity and resistivity changes. Acquisition is triggered one hour after achieving the set

temperature. There is an asymmetry in the freezing and thawing, which at this stage of the investigation we attribute to the system rather than the sample; slower experiments are planned. The maxima observed in velocities and resistivities correspond to the minima in temperature. Because resistivity and elasticity are driven by different physical phenomena, the synchronicity of these responses requires explanation. Average changes in resistivity from low to high

temperature are from 48.1 to $8.0\ \Omega\text{m}$; V_p varied from 3.94 to $3.28\ \text{km/s}$, and V_s varied from 2.16 to $1.80\ \text{km/s}$. These represent 500% , 16% , and 24% changes in resistivity, V_p , and V_s , respectively. Note that these measured values are markedly different than those predicted by Carcione et al. (2003) in their modeling of Berea sandstone. Our velocities are slightly less than those reported for Berea by Pandit and King (1979). However, Pandit and King (1979) applied an axial stress of $13.8\ \text{MPa}$ and measured velocities along the axial direction. The abrupt changes in velocities and resistivities take place near the freezing point of brine. Velocities displayed this behavior in the Pandit and King (1979) study while resistivity displayed the greatest change near 0°C .

INTERPRETATION OF TEMPERATURE RESPONSES

Changes in resistivity reflect the loss of porosity because of the formation of nonconductive ice. Using Archie's law $R/R_w = a/\phi^m$ and the measured resistivity R , along with the independently measured values of $a = 1$, $m = 1.9$, and $R_w = 0.26\ \Omega\text{m}$, the apparent porosity and porosity reduction caused by the ice formation is calculated (see Figure 6). The cementation exponent is measured as a function of pressure and varied from 1.90 to 1.91 when pressure is increased from 3.5 to $34.5\ \text{MPa}$. It is assumed that the sample was originally 100% saturated with the $25,000\ \text{ppm}$ NaCl brine. Average resistivity values at the warmest temperatures are calibrated to the measured Helium porosity $\phi = 17.8\%$. Figure 6 shows the calculated porosities and measured temperatures as a function of time. Brine resistivities are corrected for temperature using Arps relation (Arps, 1953)

$$R_{w,T2} = R_{w,T1} \left[\frac{T_1 + 21.5}{T_2 + 21.5} \right],$$

where T is given in $^{\circ}\text{C}$, and for the increased salinity as salt is excluded from ice forming in the pore volume using the following relation (Dresser, 1982):

$$R_w = 0.0123 + \frac{3647.5}{C_w^{0.955}},$$

where C_w is the salinity in ppm.

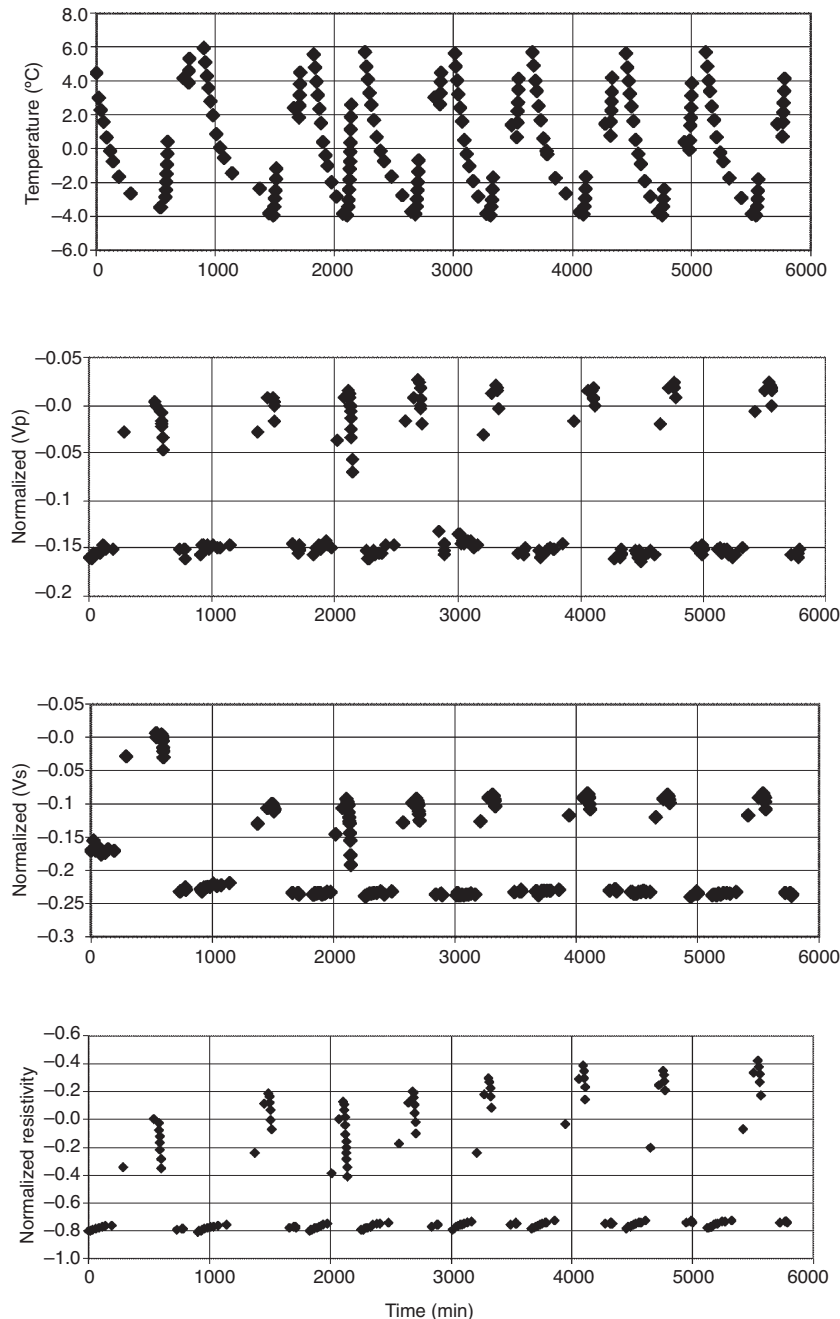


Figure 5. A panel of four plots showing normalized changes in V_p , V_s , and resistivity as a function of time during the temperature cycling experiment of saturated Berea sandstone. Normalization was based on the largest response in the first cycle. The top panel shows the actual temperature during cycling. Analysis given in the text indicates that no more than 60% of the pore water is frozen at the lowest temperature (-4°C). Highest velocities and resistivities are associated with the lowest temperatures.

Figure 6 indicates that at temperatures near -4°C , no more than 60% of the pore water is frozen. At an equivalent pore fluid molarity and temperature, Pandit and King (1979) estimate that 50% of the pore water is frozen. One immediate implication of this observation is that one should control core preservation temperatures to minimize mechanical damage. This may be more significant for consolidated cores. We have not explored the range of temperatures over which mechanical damage is inhibited.

Berea is a well consolidated rock; thus, one does not expect large changes in overall rigidity when the pore fluids freeze. Calculations indicate that rigidity changes little until all the water freezes, which it never does in our experiments. The composite of ice and water has the properties of water until the ice-ice or ice-matrix contacts are achieved. Changes in compressional velocities would be expected when replacing brine ($K = 2.25$ GPa) with that of an ice-brine mixture (ice; $K = 7.9$ GPa). Note that fluid density change from the original value of 1.05 gm/cc would be minimal because ice has a density of 0.92 gm/cc. With only about half of the pore fluid frozen, it is difficult to explain the increase in V_s with the onset of freezing because the change in V_s should be driven largely by a density change.

If the role of freezing were to effectively reduce crack density, then both V_s and V_p would be expected to increase. If the samples are 100% saturated with brine, then there can be no interface at a pore or crack throat between different phases, and therefore, no additional capillary pressure to depress the freezing point in smaller pores. Clennell et al. (1999) provide a formalism to calculate the effect of capillary pressures on depressing freezing points of fluids in porous media. Studies of mixed phase freezing in porous materials indicate that pore structure, clay mineralogy, and water saturation also can have a strong influence (Nakano et al., 1972; King, 1984; Anderson et al., 2003; Uchida et al., 2004) and generally lower freezing points at low water saturations.

The magnitude of the changes in V_p and V_s are about 15.5% and 23.8%, respectively. Shear velocity changes more than compressional velocity. Closely examining King's (1977) data shows changes in V_p of 28%, 50%, and 72% for sandstones (SS1, SS4, and SS5) having porosities of 14%, 15%, and 17%, respectively. The corresponding changes in V_s for samples SS1 and SS5 are 39% and 89%, respectively. While two sands (SS4 and SS5) are recognized to be shaley, clay content was not reported. It would appear that the velocity responses are caused by more than a simple porosity model can explain. In fact, a 72% change in V_p and 89% change in V_s (sample SS5) cannot be explained, even by freezing all the fluid in the pore space. Perhaps we can discount the shear velocity measurements as King (1977) acknowledged the difficulty in picking poor quality arrivals. In another study, V_p and V_s changes recorded over a similar temperature interval for Berea saturated with 0.3 M brine are about 21% and 31%, respectively, (Pandit and King, 1979). These are inconsistent with our observations.

The pore space in a rock is complicated in detail but can be modeled effectively by mixing distributions of cracks and pores and allowing fluid communication between these features. If, as the temperature drops, water in the pores begins to freeze, forming an ice-water mixture and changing the effective bulk modulus of the fluid but not the shear modulus, then changes in V_p would be expected to exceed those in V_s . As the ice percentage increases, it bridges and supports pore openings, suddenly increasing V_s . These behaviors are not observed in this or previous studies. In fact, the change in V_s is consistently more than the change in V_p as ice forms. We also know

from this and previous studies (Pandit and King, 1979) that at the temperature of the experiment, only about 50% of the water freezes. It thus becomes difficult to explain the behaviors of both V_p and V_s with the simple freezing of water in equant pore space. On the other hand, if the other elements of pore space (i.e., cracks) are preferentially frozen, then we can explain the behavior of both V_p and V_s . Cracks having low aspect ratios are very compliant and even in small concentrations can dramatically affect moduli and velocities (Kuster and Toksoz, 1974; O'Connell, 1984). Possible mechanical damage induced by the volume expansion accompanying ice formation in cracks is minimized because ice can displace the unfrozen fluid in any connected larger pore bodies. This reasoning is also in accord with the synchronicity of resistivity and velocity responses. Freezing in the smaller, connected features of the microstructure would remove fluid conduction paths between large pore bodies, increase the salinity in the larger pores, and increase the measured resistivity.

If the samples are shaley, then one must also examine the model used to interpret resistivity measurements. Velocities reported by King (1977) and Pandit and King (1979) are made under a uniaxial pressure of 3.4 and 13.8 MPa, respectively, while resistivity measurements are made under a hydrostatic pressure to 0.34 MPa. Timur (1968) reports increases upon freezing in V_p for Berea ($\Phi = 18.1\%$), Boise ($\Phi = 26\%$), and Navajo ($\Phi = 13\%$) sandstones of 30%, 51%, and 22%, respectively, while at a uniaxial pressure of 31.7 MPa. Over the more limited temperature range used in this study, we expect and observe smaller changes in V_p . Unfortunately, Timur (1968) did not measure shear velocities. Pandit and King (1979) report measurement of velocities and resistivities for Berea and Boise sandstone and Salem limestone. Resistivities and velocities are measured on different plugs and in different apparatuses. Velocities were measured in the direction of an applied axial load of 13.4 MPa at a confining pressure of 0.35 MPa. Most of the resistivity and velocity changes take place over a temperature range of 0°C to 1.5°C . Thawing from about -15°C to -1.5°C produces very little change, and it appears linear in temperature. These experiments were carried out as thawing experiments only. Velocity experiments show that changes begin at temperatures corresponding roughly to the freezing point of the saturating brines, consistent with the depression of the freezing point with increased salinity. However, resistivity changes appear to start abruptly at 0°C regardless of the saturant salinity. Pandit and King, (1979) conclude that not all

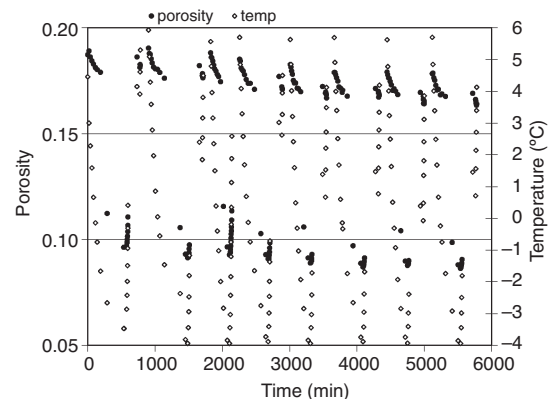


Figure 6. Calculated porosity changes based on measured resistivity changes. Calculations include changes in salinity associated with ice formation. Porosity reduction is roughly 60% because of ice formation in pores over the cycled temperature range.

the water freezes, even at temperatures as low as -15°C . This is consistent with our observations.

Previous investigators used the Wyllie's time average equation (Timur, 1968; Pandit and King, 1979) or the Kuster and Toksoz (1974) formulation (King, 1977; Zimmerman and King, 1986; King et al., 1988) to explain laboratory observations during freezing of rocks and high porosity unconsolidated materials. The inappropriateness of each has become evident over time. Recently, more sophisticated models for multiphase systems have been proposed (e.g., LeClaire et al., 1994; Carcione and Seriani, 1998; Jakobsen et al., 2000; Carcione et al., 2003). Carcione and Seriani (1998) used a modified form of LeClaire et al.'s (1994) expressions to model the P-wave responses observed by Timur (1968). After making assumptions about water-ice partitioning and how to mix the moduli effects of ice, they obtained reasonable agreement with observations for P-waves. The LeClaire et al. (1994) model assumes a continuous film of water on all rock surfaces, which separates the ice from the grains. LeClaire and Cohen-Tenoudji (1995) used this theory to explain observed velocities during freezing in glass powder samples having a porosity of 30%. When dealing with unconsolidated materials and suspensions, it is appropriate to consider the fluid as a continuous wetting phase. Sheng (1991) proposed a model that uses electrical measurements, Archie's Law, to fix parameters for DEM elastic models. This model assumes a fluid-cement mixture is replaced by a grain of a particular shape. It does not permit the inclusion of pore shapes, which we know are present from the pressure dependence of velocities. Berea is a typical well-consolidated sandstone with distributions of grain shapes and pores. We, therefore, used a self-consistent model (Budiansky and O'Connell, 1976;

O'Connell and Budiansky, 1977; O'Connell, 1984) that explicitly treats the spectrum of cracks and pores, incorporates fluid viscosities, allows differential pore pressures between cracks and pores, and makes no assumption as to the existence of a continuous film of water to model the expected elastic response.² Strong pressure dependence of velocities in Berea sandstone (see Figure 2) clearly indicates the existence of a crack spectrum. Crack densities ε are calculated from equation 62 of Budiansky and O'Connell (1976) (repeated below to correct some typographical errors) using the measured wet velocities, the barred values ($\bar{V}_p, \bar{V}_s$), and matrix velocities for quartz ($V_p = 6.04 \text{ km/s}$; $V_s = 4.05 \text{ km/s}$):

$$\varepsilon = \frac{9[1 - (\bar{V}_s/V_s)^2][3(\bar{V}_p/\bar{V}_s)^2 - 4][5(V_p/V_s)^2 - 8] - 4[(V_p/V_s)^2 - (\bar{V}_p/\bar{V}_s)^2][3(\bar{V}_p/\bar{V}_s)^2 - 2]}{32(\bar{V}_p/\bar{V}_s)^2[3(\bar{V}_p/\bar{V}_s)^2 - 4][3(V_p/V_s)^2 - 4]}.$$

Calculations indicate that effective crack densities are the highest at the highest temperatures and lowest at the lowest temperatures. If the fluids in the small pores freeze, we expect the effective crack density to decrease consistent with our calculations using the above equation. We realize that this suggestion might be different than what has been suggested previously (e.g., Timur, 1968; King, 1977; Pandit and King, 1979; Zimmerman and King, 1986); however, it is consistent with the observations at low pressures, in which at the onset of freezing there is a rapid jump in velocities in clay free rocks (e.g., Timur, 1968). It is also consistent with rapid velocity changes at the onset of thawing observed by Pandit and King (1979), accepting their assertion that only $\sim 50\%$ of pore water is frozen. Computed relative changes in V_p and V_s for a water-saturated quartz rich rock as a function of crack density and porosity are plotted in Figure 7, with initial porosity 17.8%. Velocity responses follow along the isoporosity lines. Subsequent reduction in temperature leads to a reduction in bulk porosity and velocity changes along the vertical path II. The predicted net changes for V_p and V_s are 18% and 22%, respectively. The predicted responses closely agree with our observations. Furthermore, the greater change predicted in V_s is also observed in this experiment, as well as others (Pandit and King, 1979). If, on the other hand, we change only porosity, we move vertically from our starting point in Figure 7 and predict an equal change in magnitude for V_p and V_s of around 12%. The former interpretation is in better agreement with current observations. Freezing of fluids in the cracks not only removes cracks as a compressible component but affects the rigidity as well because ice has a finite value of shear modulus.

CONCLUSIONS

Simultaneous elastic and resistivity measurements on brine-saturated cores of Berea sandstone, undergoing freezing and thawing, suggest that the process involves preferential freezing in the smaller cracks and pores and progresses to the larger pore bodies. Reproducibility of the measurements further suggests that there is little or no damage during the temperature-limited thermal cycling. Lowering temperatures to -4°C results in little more than half the bulk pore space freezing. Simultaneous increases in V_p , V_s , and resistivity upon freezing are consistent with models where conduction involves both pores and cracks but is critically linked by cracks or pore throats. Preferential freezing of brine in cracks simultaneously breaks conduction and reduces effective crack densities. The O'Connell and Budiansky model for the elastic response predicts the

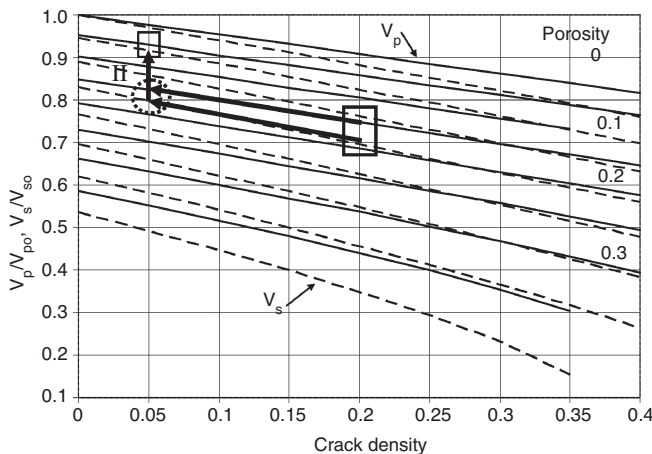


Figure 7. Modeled saturated response of V_p and V_s as porosity and crack density change. Calculations are based on a self-consistent model for a porous, cracked solid (O'Connell, 1984). Solid and dashed curves are modeled responses for normalized V_p and V_s , respectively. The lines represent isoporosity with values starting at zero and ending at 0.35 in steps of 0.05. The starting position, when completely saturated with brine, is the black rectangle at a crack density of about 0.2. The dark arrows indicate a possible path during the initial freezing of water in the cracks. The path stops at a crack density of 0.05. The rectangle at a crack density of roughly 0.05 is the location of the final velocity values when half the bulk porosity freezes.

²Sheng (1991) proposed a DEM model that uses electrical measurements to constrain the elastic model, which includes both electrical and elastic properties. We thank the reviewer who brought this to our attention.

same sense of change in V_p and V_s as observed; however, a larger change in V_s than V_p is predicted and observed. The predicted magnitudes of velocity changes are also approximately correct. Based on this interpretation, velocity measurements during the freezing of saturated core can provide estimates of crack densities. This interpretation also provides a practical guideline for preserving a frozen core.

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