Stanford Exploration Project, Report 73, November 18, 1997, pages 143–157

Stanford Exploration Project, Report 73, November 18, 1997, pages 143–157

Lab measurement of elastic velocities in dry and saturated Massillon Sandstone

David Lumley, Dimitri Bevc, Jun Ji, Sándor Tálas[1]

keywords: *velocity, sandstone, amplitudes*

ABSTRACT

Lab measurement of physical rock properties, such as seismic compressional and shear velocities, can be an important link between in situ measurements of borehole lithology and the information content in remotely sensed surface seismic data. We made lab measurements of elastic velocities α and β in dry and saturated Massillon Sandstone rock samples. The rock samples were placed under a uniaxial force of 100 lb distributed over the core sample end surface area. P and S pulsed waves were transmitted through the rock sample and first-break arrival times were picked from P and S-mode waveforms. The first-break analysis gives dry rock P and S wave velocities of $\alpha_{dry} = 2918 \pm 32$ m/s and $\beta_{dry} = 1731 \pm 99$ m/s, and water-saturated rock velocities of $\alpha_{wet} = 3380 \pm 78$ m/s and $\beta_{wet} = 1744 \pm 201$ m/s, respectively. We also tested Gassmann's prediction of saturated velocity from the dry rock measurements, and found that Gassmann's relation gave incorrect and potentially misleading results, on the order of 20% less than lab measured saturated velocities.

INTRODUCTION

Lab measurement of physical rock properties can be an important link between in situ measurements of borehole lithology and the information content in remotely sensed surface seismic data. Borehole logs and core data provide direct high resolution measurements of physical properties in the immediate vicinity of a well bore. Surface seismic data, on the other hand, offer a relatively lower resolution measurement of earth material properties, but over a much larger area or volume scale. Lab measurement of seismic responses in rock core samples can help illuminate the role of pore geometry and pore fluid type/saturation in determining the velocity and impedance information extracted from surface seismic data. Core sample measurements, coupled with a suitable rock physics model, can also be useful in predicting unmeasured physical behavior. Estimation of saturated velocity or so-called fluid replacement cal-

[1]**email:** not available

culations using the Gassmann Equation are such examples commonly used in D&P reservoir geophysics analysis.

In the classic paper by Castagna et al. (1985), the authors develop empirical α/β relationships which identify various rock types by combining data from lab core, in-situ sonic, and field seismic measurements. Furthermore, Castagna et al. find that the Gassmann relation accurately predicts saturated velocities from dry rock measurements, especially when the dry shear modulus μ_d is about equal to the dry bulk modulus K_d. These combined results are important in reservoir geophysics work, in order to calibrate field seismic data to well log information and core sample data, and so potentially map out changes in lithology, pore geometry, pore fluid, and pore saturation in the reservoir target zone. As an excellent example, Lucet and Mavko (1991) integrated rock physics lab measurements with cross-hole velocity tomograms and well logs, and mapped images of porosity and shale content in a reservoir zone.

The purpose of our exercise was to get some "hands-on" experience in making rock physics measurements on rock samples in the laboratory. Our paper proceeds as follows. First we briefly describe the experimental setup. Next, we discuss the experimental procedure, and the measured data. The third section concerns our α and β velocity calculations and error analysis, including our Gassmann predictions of saturated α and β from the dry Massillon sandstone sample. Finally, we end with a discussion of our results and a summary.

EXPERIMENT

We made measurements for a stainless-steel plug, a dry core and a water-saturated core of Massillon Sandstone. The water saturation was achieved by a vacuum imbibition procedure, whereas the dry sample was oven-baked and then measured at standard room conditions. The porosity of the sandstone was measured in a pressure vessel by gas compressibility to be $\phi = 22.1\%$, and had a bulk dry density of $\rho_{dry} = 2030$ kg/m^3.

Figure **??** displays the experimental lab setup. A high voltage pulse generator (Velonex Model 345) was used to transmit waves through the given rock samples. We used a pulse width of about 90 nsec, and pulse amplitude of about 500 Volts. The pulse could be toggled between P and S-modes. The rock sample was held in place in a table-top clamp apparatus. Natural honey was used to couple the rock samples to the source and receiver transducers. A force gauge measured the 100 lb compression which was applied to the rock sample end surface areas by a manual press in a clamping mechanism.

A transmitted pulse is carried from the clamp apparatus to a Nicolet Model 2090 oscilloscope for waveform display. Along the way, the pulse is passed through a 20/40 dB linear amplifier (HP 465A), and an analog filter device (K–H Model 320) for bandpass filtering. We used a bandpass range of 1.5-100 kHz. The waveforms could be stored on the oscilloscope and then written to a floppy diskette.

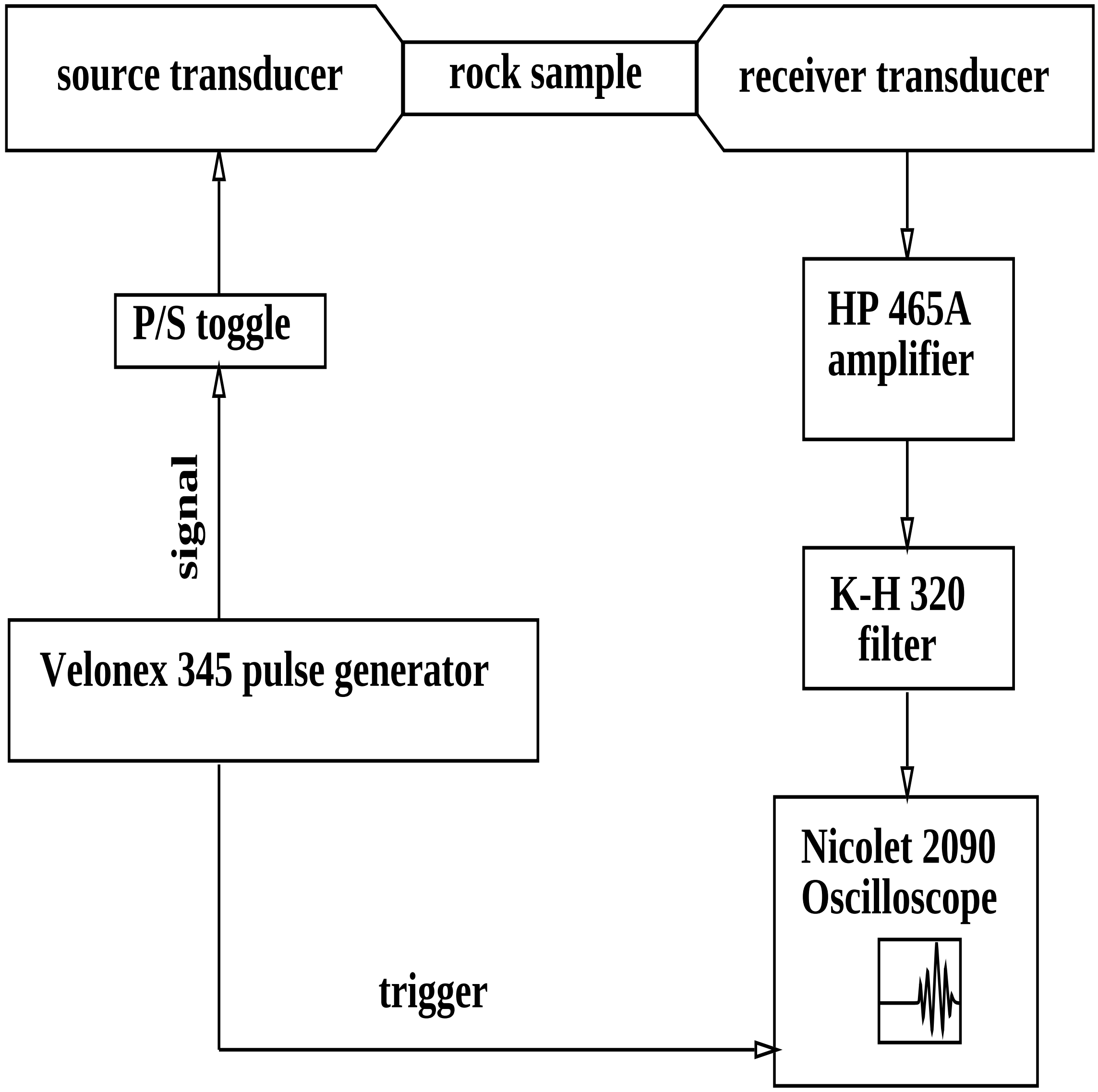

Figure 1: Experimental lab setup.

PROCEDURE AND DATA

The experimental setup was arranged for us by Hezhu Yin and the Stanford Rock and Borehole Group (SRB). We used the setup parameters described above to make the following measurements: P and S waveform first-break times t_α and t_β and waveform amplitudes A_α and A_β. The first-break times were picked at the zero-crossing of the onset of the waveform, and the amplitudes were measured from the first positive peak trailing the negative first motion of the arriving waveform. Each of the four of us made independent measurements, and all of our individual Massillon sandstone values are plotted in Figure **??**. In the remainder of the paper, we discuss only the values obtained by Experiment 3, which represents the median data set.

(1) We measured the source-receiver transducer delay times for the P and S modes, in the absence of any rock samples. This gave values of $t_\alpha = 23.30 \pm .05$ μs and $t_\beta = 45.80 \pm .05$ μs. The pulse amplitudes, at 20 dB gain, were $A_\alpha = 4.72$ V and $A_\beta = 6.08$ V. The P and S waveforms are plotted as trace 1 of Figures **??** and **??**.

(2) We made a reference velocity measurement on a stainless-steel plug, using honey to get good coupling between the source and receiver transducers. This gave values of $t_\alpha = 28.55 \pm .05$ μs and $t_\beta = 55.55 \pm .05$ μs. The length of the plug was measured to be 1.187 ± 0.001 inches. We measured the pulse amplitudes at 20 dB gain to be $A_\alpha = 2.16$ V and $A_\beta = 2.24$ V. The P and S waveforms are plotted as trace 2 of Figure **??** and Figure **??**.

(3) Next, we made velocity measurements on a core of dry Massillon Sandstone. The weak s/n ratio of these waveforms required 40 dB gain on the amplifier. The waveforms were not generally as clean as previously, probably due to some honey being absorbed by pores at the rock sample end surfaces. We picked the P-wave first-break time to be at $t_\alpha = 33.65 \pm .10$ μs, and the S-wave time at $t_\beta = 63.25 \pm 1.00$ μs. The large uncertainty in t_β is due to the complicated S waveform, probably obscured somewhat by P–S conversions, and P-wave edge diffractions off the end of the rock sample core. The length of the core was measured to be 1.189 ± 0.001 inches. The waveform amplitudes, at 40 dB gain, were measured to be $A_\alpha = 25.60$ mV and $A_\beta = 96.00$ mV, with similar uncertainty concerns as mentioned above. The P and S waveforms are plotted as trace 3 of Figure **??** and Figure **??**.

(4) Next, we made measurements on a water-saturated core of Massillon Sandstone. Again, we saw a lot of waveform distortion and contamination, particularly for the S-waves, and we needed to use 40 dB gain on the amplifier. The first-break times were picked to be $t_\alpha = 32.25 \pm .20$ μs, and $t_\beta = 63.15 \pm 2.00$ μs. The large t_β uncertainty is due to the complex waveform we had to interpret. The length of the core was measured to be 1.191 ± 0.001 inches. The amplitudes, at 40 dB amplifier gain, were picked with a similar amount of waveform uncertainty: $A_\alpha = 10.40$ mV, and $A_\beta = 6.40$ mV. The P and S waveforms are plotted as trace 4 of Figure **??** and Figure **??**.

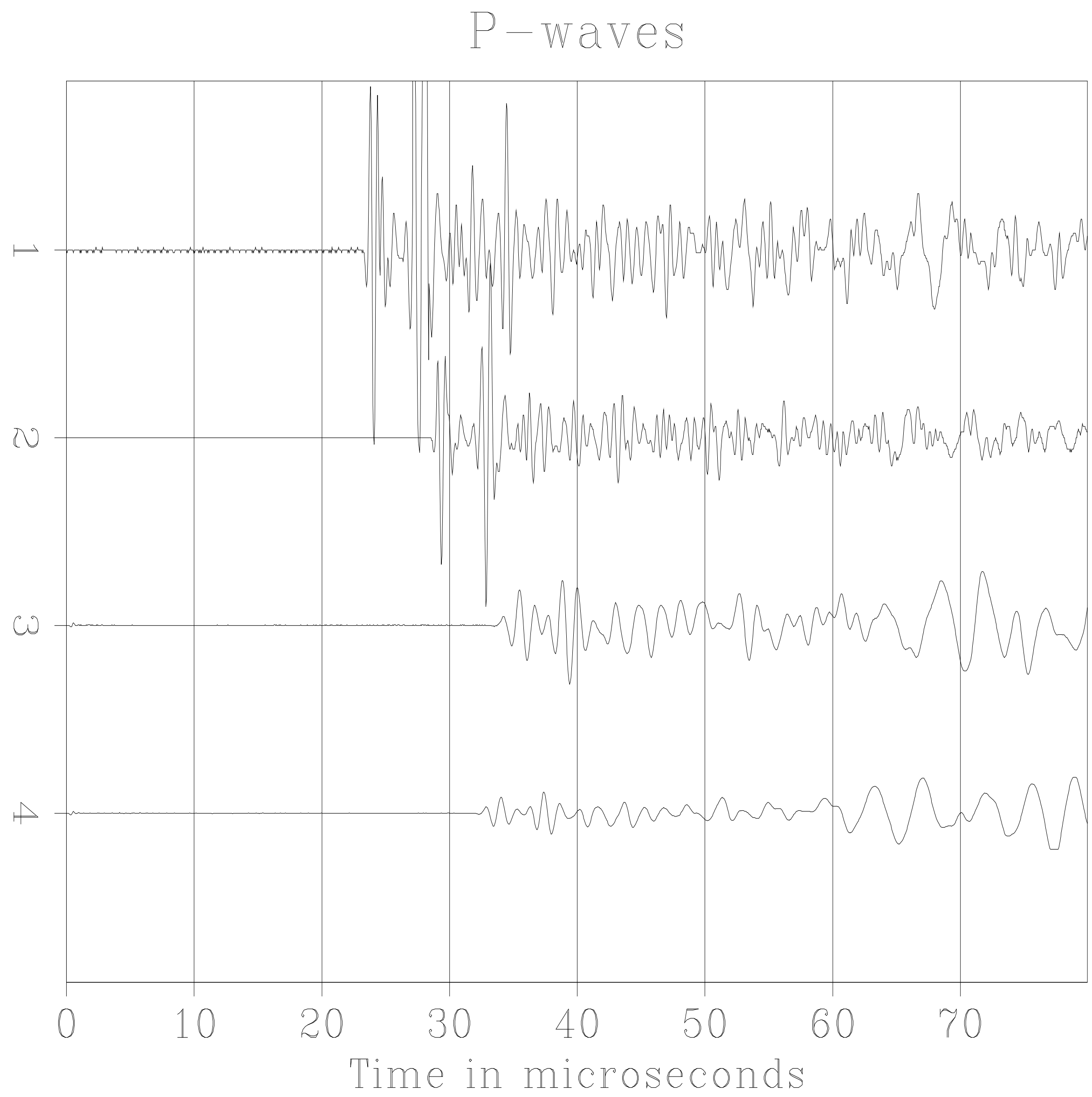

Figure 2: P-waveforms recorded for: (1) no sample in place, (2) steel plug, (3) dry Massillon sandstone, (4) saturated Massillon sandstone. Trace amplitudes are not to scale.

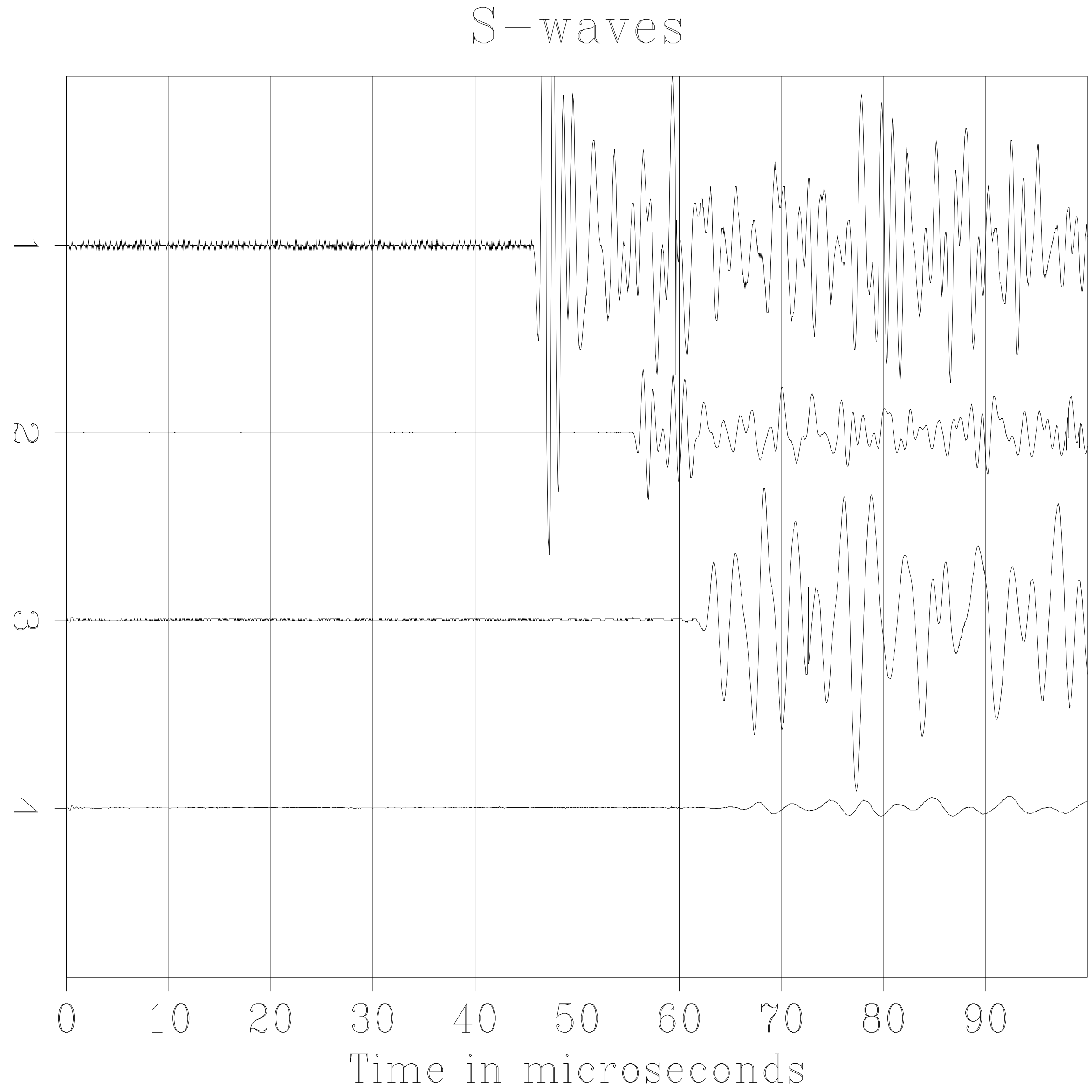

Figure 3: S-waveforms recorded for: (1) no sample in place, (2) steel plug, (3) dry Massillon sandstone, (4) saturated Massillon sandstone. Trace amplitudes are not to scale.

CALCULATIONS AND ERROR ANALYSIS

Velocities

The elastic velocities α and β of the samples can be calculated using the simple relations:

$$\alpha = L/(t_\alpha - t_o)$$

and

$$\beta = L/(t_\beta - t_o)$$

where L is the length of the rock sample, t_α and t_β are the appropriate P and S first-break arrival times, and t_o is the delay time for the wave to travel through the experimental instrument setup without the rock sample in place, as measured in procedure (1).

We can also calculate the absolute *rms* errors $\Delta\alpha$ and $\Delta\beta$ associated with α and β. Letting V stand for either α or β, the equations above can be generalized to

$$V = L(t - t_o)^{-1}.$$

The absolute error ΔV can be calculated by partial differentiation,

$$\Delta V = \left|\frac{\partial V}{\partial L}\Delta L\right| + \left|\frac{\partial V}{\partial t}\Delta t\right| + \left|\frac{\partial V}{\partial t_o}\Delta t_o\right| \ ,$$

and the relative error is evaluated to be

$$\frac{\Delta V}{V} = \frac{\Delta L}{L} + \frac{\Delta t}{(t - t_o)} + \frac{\Delta t_o}{(t - t_o)} \ .$$

This relative error estimate tends to be too conservative. A less pessimistic error is the *rms* relative error estimate:

$$\frac{\Delta V}{V} = \sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta t}{t - t_o}\right)^2 + \left(\frac{\Delta t_o}{t - t_o}\right)^2} \ .$$

Finally, the absolute error estimate can be determined from the relative error estimate as

$$\Delta V = V \cdot \frac{\Delta V}{V} \ .$$

We now show a detailed example of calculating α and $\Delta\alpha$ for dry Massillon sandstone. All other velocities will be calculated in the same manner, but we will not show those tedious detailed calculations. For dry Massillon sandstone, $t_\alpha = 33.65$ μs and $\Delta t_\alpha = 0.10$ μs. The P-wave delay time from procedure (1) is $t_o = 23.30$ μs with a measurement error estimate of $\Delta t_o = 0.05$ μs. The length of the core sample was measured as $L = 1.189$ inches with a measurement error of $\Delta L = 0.001$ inches. The P-wave velocity is

$$\alpha_{dry} = \frac{1.189\,\mathrm{in}}{(33.65 - 23.30)\mu\mathrm{s}} = 0.115\,\mathrm{in}/\mu\mathrm{s} = 2918\,\mathrm{m/s} \ .$$

The relative *rms* error in the P-wave velocity is

$$\frac{\Delta\alpha}{\alpha} = \sqrt{\left(\frac{0.001}{1.189}\right)^2 + \left(\frac{0.10}{10.35}\right)^2 + \left(\frac{0.05}{10.35}\right)^2} = 0.011 = 1.1\% \, .$$

The absolute *rms* error $\Delta\alpha$ is

$$\Delta\alpha = \alpha \cdot \frac{\Delta\alpha}{\alpha} = 2918 \cdot 0.011 = 32\,\mathrm{m/s} \, .$$

Finally, we can write the total velocity estimate as $\alpha_{dry} = 2918 \pm 32$ m/s.

Performing an identical set of analogous calculations for all of the lab measurements, we calculate the following velocities and *rms* error estimates:

$$\begin{aligned} \alpha_{steel} &= 5743 \pm 75 \text{ m/s}, & \beta_{steel} &= 3092 \pm 22 \text{ m/s}, \\ \alpha_{dry} &= 2918 \pm 32 \text{ m/s}, & \beta_{dry} &= 1731 \pm 99 \text{ m/s}, \\ \alpha_{wet} &= 3380 \pm 78 \text{ m/s}, & \beta_{wet} &= 1744 \pm 201 \text{ m/s}, \end{aligned}$$

Gassmann Saturated Velocity Predictions

In this section, we calculate saturated velocities for Massillon Sandstone using the dry sandstone measurements and Gassmann's Equation. Gassmann's Equation relates dry elastic moduli to fluid-saturated elastic moduli. For compressional moduli, Gassmann can be stated as follows:

$$K_s = \frac{K_m \cdot M}{1 + M} \ ,$$

where M is a normalized ratio of mineral, fluid and dry bulk moduli such that

$$M = \left(\frac{K_d}{K_m - K_d} + \frac{K_f}{\phi(K_m - K_f)}\right) \ ,$$

as rearranged from Equation 2.77 of Bourbié et al. (1987). Concerning shear moduli, Gassmann makes no distinction between dry and saturated properties:

$$\mu_s = \mu_d \ .$$

In the above expressions, K_m is the P modulus of the pure mineral skeleton, K_f is the P modulus of the saturating fluid, and K_d is the P modulus of the dry rock under study. K_s is the Gassmann theoretical P modulus of the dry rock after complete saturation with wetting fluid. Similarly, μ_s is the Gassmann theoretical shear modulus predicted to be the same as the dry bulk shear modulus μ_d. The underlying assumptions in Gassmann's Equation are: (1) the rock satisfies linear isotropic elasticity, (2) the rock skeleton is comprised of one single homogeneous mineral phase, (3) the wetting fluid is homogeneous and completely saturates the porosity, (4) the porosity ϕ is uniform throughout the sample, and (5) the measurements are made at low (asymptotically zero) frequency.

To evaluate K_s, values for K_m, K_f, K_d, and ϕ are required. The K values can be obtained through the generic relation

$$K = \rho(\alpha^2 - 4\beta^2/3) \ .$$

Using the given dry bulk density $\rho_{dry} = 2030$ kg/m^3, and the measurement $\alpha_{dry} =$ 2918 m/s, the dry P modulus can be calculated to be $K_d = 9.2$ GPa. Water was used as the wetting fluid, which has a velocity of $\alpha_f = 1500$ m/s, a density of $\rho_f =$ 1000 kg/m^3, and hence a P modulus of $K_f = 2.25$ GPa. The dry bulk density can be expressed as $\rho_{dry} = (1-\phi)\rho_m + \phi\rho_{air} \simeq (1-\phi)\rho_m$. Using a porosity of $\phi = 0.221$ gives a solid mineral density of $\rho_m = 2606$ kg/m^3. This value compares well with tabulated values of 2650 kg/m^3 for quartz, if one also accounts for a finite component of less dense feldspar in the sandstone. For the "pure" mineral bulk modulus, we calculated the Voigt average to be $K_m \simeq K_d(1-\phi)^{-1} = 11.8$ GPa. This value is probably truly an average of the quartz, clay and feldspar content in Massillon Sandstone, as it does not compare well with tabulated solid quartz values of $K_q = 38$ GPa. Substituting these values into Gassmann's relation gives a saturated P modulus of $K_s = 9.7$ GPa. The S modulus can be obtained as $\mu_s = \mu_d = \rho_{dry}\beta_{dry}^2 = 6.1$ GPa. The saturated density is $\rho_s = (1-\phi)\rho_m + \phi\rho_f = 2251$ kg/m^3. Finally, the saturated P and S velocities estimated by Gassmann are:

$$\alpha'_{wet} = \sqrt{\frac{K_s + 4\mu_s/3}{\rho_s}} = 2811\,\mathrm{m/s}$$

and

$$\beta'_{wet} = \sqrt{\frac{\mu_s}{\rho_s}} = 1644\,\mathrm{m/s} \ .$$

The final Massillon sandstone velocity results for each of our four independent experiments are plotted in Figure **??**. The median data set from Experiment 3 has been the focus of our current and upcoming discussion.

DISCUSSION OF RESULTS

Amplitude attenuation

We measured waveform peak amplitudes for the various samples, as discussed in the procedural section. The P and S amplitudes attenuated by a factor of about 2.5 from the source-receiver delay time measurement, to the stainless-steel plug measurement. This decay is probably due mostly to poor coupling, and some relatively small attenuation due to intrinsic Q, since the plug was only 1.187 inches long and made of the same material as the source-receiver transducer clamping apparatus.

We made similar measurements on the wet and dry Massillon Sandstone rock samples. The P-wave amplitude attenuated about a factor of 2.5 from dry to wet. In light of the stainless-steel result, this implies that the attenuation due to coupling and Q are not that different from that of stainless steel. However, the S-wave amplitude attenuated a factor of 15 from dry to wet, indicating a significant intrinsic Q-attenuation component. Intuitively, this might be explained as shear stresses being more efficient at "squirting" fluid through the available pore spaces, hence losing energy to friction heat-loss and the work required to permanently displace the fluid to a non-equilibrium position. This result could also be explained as destructive interference from P–S conversions and diffractions attenuating the direct S arrival. Finally, these amplitude measurements were made on one peak of the waveform. Attenuation would be more accurately studied by examining the amplitude frequency response by Fourier Transform spectral techniques over a more complete direct arrival waveform time series.

Velocity measurements

The P and S velocities measured for the stainless-steel core, $\alpha_{steel} = 5743 \pm 75$ m/s and $\beta_{steel} = 3092 \pm 22$ m/s, are approximately twice the Massillon Sandstone values, which seems reasonable. The measured stainless-steel α/β ratio γ is $1.86 \pm .04$, which is slightly stiffer than the Poisson solid value of $\gamma = 1.73$, as expected.

The P and S velocities measured for the dry Massillon Sandstone are $\alpha_{dry} = 2918 \pm 32$ m/s and $\beta_{dry} = 1731 \pm 99$ m/s. This represents an α/β ratio of $\gamma = 1.69 \pm .12$, which is a Poisson solid to within error bounds. The P and S velocities measured for the saturated Massillon Sandstone are $\alpha_{wet} = 3380 \pm 78$ m/s and $\beta_{wet} = 1744 \pm 201$ m/s. This represents an α/β ratio of $\gamma = 1.94 \pm .25$, which is not very Poisson-like, and is similar to the stainless-steel sample, neglecting the pessimistic error bounds. When water fills the pores, its effect is to "stiffen" the resulting saturated sample. This has a tendency to increase K_s and hence α_{wet}, compared to K_d and α_{dry}. However,

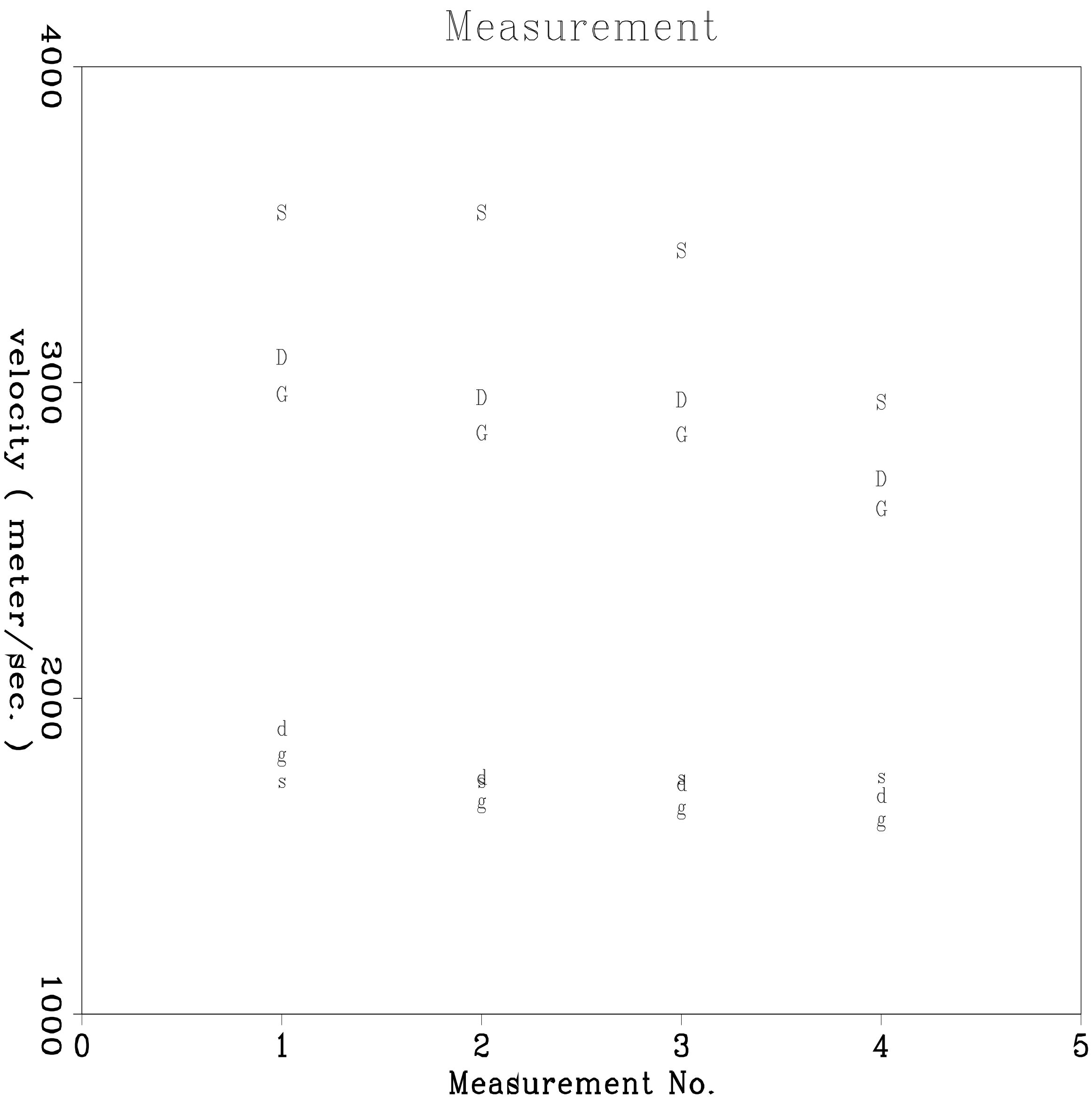

Figure 4: Massillon sandstone velocities measured in the lab and predicted by the Gassmann equation; D = P-wave velocity measured for the dry sample, S = P-wave velocity measured for the saturated sample, G = P-wave velocity predicted by the Gassmann equation, d = S-wave velocity measured for the dry sample, s = S-wave velocity measured for the saturated sample, g = S-wave velocity predicted by the Gassmann equation.

$\mu_s \simeq \mu_d$, and the increase in saturated density ρ_s over ρ_d implies that β_{wet} will be slightly smaller than β_{dry}. These intuitive predictions are fairly well validated by our lab measurements.

Gassmann saturated velocities

We used Gassmann's relation to predict the saturated Massillon velocities from the dry rock lab measurements. The Gassmann predicted values are: $\alpha'_{wet} = 2811$ m/s and $\beta'_{wet} = 1644$ m/s. The saturated shear velocity compares well with the measured value $\beta_{wet} = 1744 \pm 201$ m/s, however, the $\alpha_{wet} = 3380 \pm 78$ m/s value does not. It is significant that each of our four independent dry rock lab measurements gave a Gassmann saturated α prediction on the order of 20% less than the corresponding lab measurement of α saturated, as seen in Figure **??**. A possible explanation for this discrepancy may be that a significant amount of the 22.1% porosity is made up of clay content, which was not included in the Gassmann calculation. Clay would tend to expand in the pore space after saturation, and would thus stiffen the actual rock sample compared to Gassmann's theoretical rock model, resulting in a higher lab measurement of α_{wet}. Another possible explanation is that since the lab measurements were made at much higher frequencies (~50 kHz) than Gassmann assumes (zero frequency), velocity dispersion as a function of frequency may be significant. High frequencies allow less time for fluid to flow in the pore space, resulting in a stiffer rock matrix and higher lab measurement of α_{wet} than would be predicted by the low frequency Gassmann model.

Castagna et al. (1991) noted that their Gassmann predictions of saturated velocities were inaccurate when the dry shear modulus was significantly different from the dry bulk modulus, which is the case for our Massillon sandstone sample in which μ_d = 6.1 GPa and K_d = 9.2 GPa. In particular, they tabulate values for a Gulf Coast sandstone in their Table 1, which has a similar α and ϕ to our Massillon sample, and in which the Gassmann saturated β value is significantly lower than the lab measurement. In our case, the grossly underestimated saturated α value could be very misleading to a reservoir geophysicist trying to quantify predicted properties of oil or water-saturated reservoir sandstone given dry core samples from a nearby borehole.

CONCLUSION

Lab measurements of rock properties can be important in integrating borehole logging data and surface seismic data in order to map changes in lithology, pore geometry or fluid saturation in a reservoir. We made measurements on lab core samples of dry and saturated Massillon sandstone. We obtained the following dry rock velocity values: $\alpha_{dry} = 2918 \pm 32$ m/s and $\beta_{dry} = 1731 \pm 99$ m/s, and water-saturated rock velocities of $\alpha_{wet} = 3380 \pm 78$ m/s and $\beta_{wet} = 1744 \pm 201$ m/s, respectively. We also tested Gassmann's prediction of saturated velocity from the dry rock measurements, and found that Gassmann's relation gave significantly incorrect and potentially misleading results, on the order of 20% less than lab measured saturated velocities.

ACKNOWLEDGMENTS

We would like to thank Hezhu Yin for setting up the experimental lab equipment for us, and for his overall helpful assistance in the lab. We thank the Stanford Rock and Borehole Project (SRB) for the use of their lab, and especially thank Gary Mavko and Jack Dvorkin for teaching us about many interesting aspects of rock physics.

REFERENCES

Bourbié, T., Coussy, O., and Zinszner, B., 1987, Acoustics of porous media: Gulf Publishing Company, Houston.

Castagna, J. P., Batzle, M. L., and Eastwood, R. L., 1985, Relationships between compressional-wave and shear-wave velocities in clastic silicate rocks: Geophysics, **50**, 571–581.

Lucet, N. M., and Mavko, G. M., 1991, Images of rock properties estimated from a cross-well tomogram: 61st Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 363–366.