Experimental Measurement of Elastic Frame Properties

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Introduction

An adequate interpretation of seismic reflection amplitudes and amplitude versus offset responses requires appropriate knowledge of the in situ rock properties. Both seismic velocity and mass density depend on both the saturation state of the material and the effective stresses to which the materials are subject. Laboratory measurements of these properties, despite scaling issues, do provide information useful to the interpretation of the data, particularly if pore fluid pressure effects cannot be ignored. This contribution focuses on the technical details of a system to measure both P and S wave velocities in a saturated porous rock from the Western Canadian Sedimentary Basin. Some preliminary results from simultaneous measurements of P and S wave velocities on a series of these samples under dry conditions as well as one water saturated sample are shown. Relevant elastic moduli are extracted from this information and future directions for the work are discussed.

The seismic velocity and density of Gassmann's (1951) relation is used to estimate the low seismic frequency velocity response of a porous rock under liquid saturated conditions. If the porosity ϕ, the dry frame K_d, the fluid K_f, and the mineral bulk moduli K_s are known and assuming that the shear modulus μ^{eff} is not changed by liquid saturation, then the effective saturated bulk modulus K_{eff}, and mass density ρ^{sat} are given by:

$$K_{eff} = K_d + \frac{(1-K_d/K_s)^2}{\frac{1-K_d/K_s-\phi}{K_s}+\frac{\phi}{K_f}} \quad \text{and} \quad \rho^{sat} = (1-\phi)\rho_S + \phi\rho_f$$

and the saturated P- and S-wave velocities are given by the usual formulae with the appropriately substituted moduli:

$$V_P^{sat} = \sqrt{\frac{K_{eff}+\frac{4}{3}\mu}{\rho^{sat}}} \quad \text{and} \quad V_S^{sat} = \sqrt{\frac{\mu^{eff}}{\rho^{sat}}}$$

The intrinsic values of K_s and K_f are usually relatively easy to find (e.g., Batzle and Wang, 1992; Bass, 1995). The greatest uncertainty limiting the successful application of Gassmann's equation is a lack of knowledge of the dry frame bulk modulus K_d and dry shear frame modulus μ_d. Some consensus has arisen that these values can be estimated from P- and S-wave velocities measured on "dry" (i.e. unsaturated) samples; this philosophy is employed in this study although it will require further validation in the future.

Sample descriptions

Representative samples of the porous sandstones were cut from existing core. Details of the core lithologies and sampling depths are given in Table 1. Both the 'sandstones' and 'conglomerates' appear to be essentially composed of the same material, although the conglomerates are the primary reservoir target. Table 1 includes bulk density calculated by measuring sample mass and volume. Porosities in Table 1 are extracted from existing core analyses or have been inferred from the bulk density under the assumption that the solid or grain density of each sample is the same, it is anticipated that both He and Hg porosimetry will be carried out on these samples shortly using a Quantachrome™ He Porosimeter and a Micromeretics ™ Mercury Porosimeter as well as a Micromeretics GeoPycnometer, now being tested in the rock physics laboratory. The samples have been further characterized using both thin section and scanning electron microscopy but this is beyond the scope of this presentation.

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Table 1. Geological parameters for the samples

	Depth (m)	Lithology	Porosity (%)	Density (kg/m^3)[3]
SB002	2403.7	Conglomerate	2.9[1]	2520.26
SB003	N/A	Sandstone	3.3[1]	2511.27
SB004	2437.5	Conglomerate	9.4[2]	2328.10
SB005	2438.2	Conglomerate	7.4[2]	2428.46
SB006	2450.5	Conglomerate	5.6[1]	2450.50
SB007	2451.0	Conglomerate	5.6[1]	2451.00
SB008	2455.1	Sandstone	5.4[1]	2455.10
SB009	2457.7	Sandstone	5.3[1]	2457.70

1. Porosity calculated from bulk density under the assumption of constant grain density of quartz.
2. Porosity as provided from core analysis.
3. Density as measured in the laboratory.

Experimental configuration and procedure

An ultrasonic pulse velocity measurement apparatus was used to determine P-wave and S-wave velocity. The experimental setup (Figure 1) consists of a pulse generator, pressure vessel and a digitizing oscilloscope (Gagescope™) .The pulse generator is linked to an ultrasonic source transducer that uses piezoelectric (PZT) crystals to convert an electrical pulse into compressional or shear waves. The generated wave is transmitted though the sample and is recorded by an oscilloscope. The signal is digitized at an interval of 8 nanoseconds. The first extremum (peak or trough) was here defined to be the sample transit time. The transit time of the first extreme is picked to calculate the velocity. The velocity determined is simply the quotient of the sample length and transit time. The frequency of the transducer is centered about 1 MHz.

The new experimental configuration (Figure 1) that we have recently constructed now consists of two pressure systems, a confining pressure system and a pore pressure system, where pore fluids can be introduced and their pore fluid pressure can be varied as needed. The confining pressure system can measure velocities under pressure up to 200 MPa; in this study measurements were made to a peak pressure of 60 MPa that corresponds roughly to overburden lithostatic stress on these samples in situ. The precision of the pressure is as low as 0.25 MPa with a hand-monitored pump. The new pore pressure system is used to simulate pressure changes in gas & oil reservoirs. Sample preparation consists of placing aluminum buffer caps with P and S wave transducers on each end of the cylindrical sample. This arrangement is then hermitically sealed. The prepared sample is then put in a pressure vessel filled with hydraulic oil for velocity measurement. Our updated high pressure instrument not only adds pore pressure variations as a variant in monitoring velocity changes but also improves the precision of the velocity measurement by eliminating the effect of time delay and system time shift.

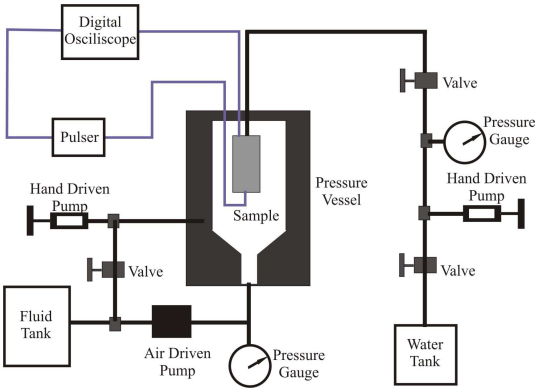

Figure 1. The experimental configuration mainly consists of the confining pressure system, the pore pressure system and the signal acquisition system

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Experimental results

The velocity versus pressure curves for the cycles achieving the greatest pressure without sample leakage are summarized in Figure 2. From the figure, we can see that both of the P-wave and S-wave velocities increase with effective pressure. At low effective pressures, the velocities increase sharply most likely because micro fractures have closed. The velocities are then relatively stable at high effective pressures. Some problems were encountered with leakage of confining fluid into the pore space and the velocities are only reported to 20 MPa of confining pressure in these cases. This technical difficulty has now been solved.

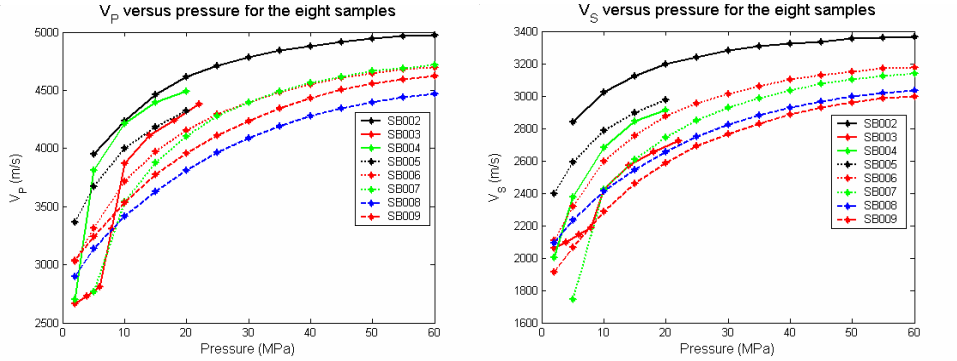

Figure 2. Velocity versus pressure during pressurization cycles achieving the greatest pressure without sample leakage (excluding SB002 and SB004 which did leak) for the P-wave (top panel) and S-wave (bottom panel). Velocities measured on samples SB002 to SB005 inclusive may be suspect due to leakage of the sample during pressurization; partial saturation of the pore space with the pressure vessel hydraulic fluid may explain the generally higher wave speeds in these materials. The remaining samples SB006 to SB009 remained dry during the measurements.

For all of the samples, the bulk and shear moduli increase with differential pressure. Figure 3 (SB005) also shows that both of the bulk and shear modulus increases after the dry sample is saturated with hydraulic oil, as reported by other authors (Khazanehdari, 2003) however the mechanism inferred to cause the changes in that paper, swelling of clays, is not likely operable in these samples as they contain non-swelling kaolinite.

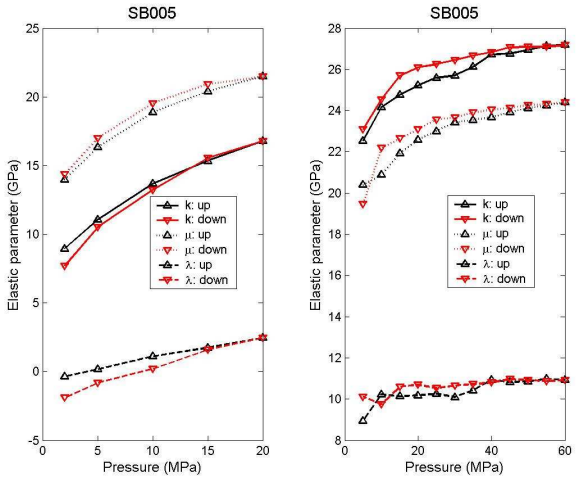

Figure 3. Comparison of changes in elastic moduli with confining pressure of the dry (Fig. 3a) and partially saturated (Fig. 3b) for sample SB005.

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Fluid substitutions are an important concept in seismic attribute studies because they provide the interpreter with a valuable tool for modeling various scenarios that might explain an observed AVO anomaly at seismic frequencies or can assist in interpreting time-lapse seismic responses. The most commonly used approach is to employ Gassmann's equation relating the bulk modulus (K_{eff}) of a rock to its porosity, frame, and fluid properties as described earlier (Figure 4).

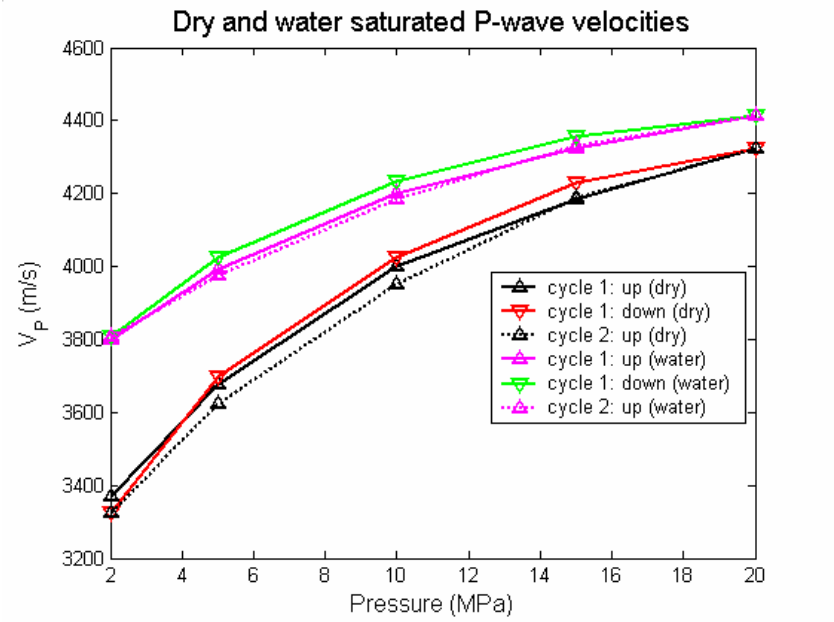

Figure 4. Comparison of the P-wave velocity for the dry samples as tested in the lab, and calculated water-saturated sample SB005 using Gassmann's equation.

Conclusion

The initial testing of samples in this research indicates that P-wave velocity, S-wave velocity, frame bulk and shear moduli are all highly pressure-dependent. They increase sharply at low effective pressure and then tend to stabilize at higher pressures, perhaps as micro-cracks have closed. Future work will include examining velocity variations with changes in lithology, reservoir fluid type and pore pressure.

Acknowledgements

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