Velocity Dispersions in Sandstones

De-Hua Han and Amos Nur, Stanford University

ABSTRACT

Ultrasonic compressional (V_p) and shear (V_s) velocities were measured on 69 sandstone samples, at dried and water-saturated states under external confining pressure up to 50 MPa and internal pore pressure 1 MPa. Porosities of the samples ranged from 5 to 30 percent and volume clay content of the samples ranged from 0 to 50 percent. These velocity data were treated to estimate velocity dispersion on saturated sandstones with frequencies from 1 MHz to 1 Hz using the Biot-Gassmann theory proposed by Winkler (1985, 1986). Biot velocity dispersions (BVD) were defined as differences between the high- and the low-frequency (say 1 Hz) limits calculated from the Biot theory. Apparent velocity dispersions (AVD) were defined as discrepancies between the ultrasonic saturated velocity and the low-frequency limit of the Biot theory. Both BVD and AVD are normalized by ultrasonic water-saturated velocity. In our samples, the BVD are about 1 percent or less, increasing with increasing porosity and effective stress, and decreasing with increasing clay content. For well cemented sandstones, especially clean sandstones, the AVD agree well with the BVD, which is similar to dispersion behavior of fused glass beads noted by Winkler (1985). For poorly cemented shaly sandstones, the AVD (4 to 9 percent) are much greater than the BVD. This suggests presence of some non-Biot absorption/dispersion mechanisms. The non-Biot velocity dispersions (NBVD) appear to decrease with increasing porosity and effective stress, and increase with increasing clay content. The effects of porosity, clay content and effective stress are all suppressed by increasing grain cement, contact and compaction.

INTRODUCTION

Velocities of a formation can be obtained by three methods, each with its own distinctive frequency bandwidth. Seismic reflection works typically with the range 10-100 Hz. Sonic logging tools work within the limits 15,000-60,000 Hz. Core measurements are within the range 100 KHz-3MHz. Naturally the following questions are raised: What are the discrepancies among these velocities with different frequencies? How are these velocities related to each other ?

The acoustic velocities in water-saturated rocks are known to vary with frequency. However, direct measurement of the velocity dispersion in broad and contiguous frequency bands, especially near seismic frequencies is very difficult. By comparison with velocities measured from field, core measurements may differ because of scale heterogeneity such as macrocracks or faults. These discontinuities dominate seismic or sonic measurement while microcracks affect ultrasonic measurement (Moos and Zoback, 1983; Murphy, 1984). These results bring more confusions: Does velocity dispersion exist? If yes, how large is it in the above frequency ranges? Which parameters dominate in the velocity dispersion?

Murphy (1984) calculated the intrinsic dispersion of Sierra White granite from dry and water saturated ultrasonic data using the Biot-Gassmann-Domenico relation. Winkler (1985, 1986) systematically developed this technique giving insight into intrinsic velocity dispersion from seismic to ultrasonic frequencies. The two assumptions underling in this technique have been discussed in detail by Winkler (1985, 1986). The first assumption is that velocities in saturated rocks in the limit of zero frequency (say 1 Hz) can be predicted from dry velocities using the Biot-Gassmann equation (Biot, 1956a, b; Gassmann, 1951). The second is that acoustic velocity in dry rocks is independent of frequency. This assumption has been supported by experiments (Peselnick and Outerbridge, 1961; Spencer, 1981). Any discrepancy between measured velocity at ultrasonic frequency and calculated velocity at low frequency, say 1 Hz, is assumed, to be caused by intrinsic dispersion. The sample description and experimental technique was described in detail by Han et al. (1986).

DISPERSION CALCULATION

The expressions for the low- and high-frequency limits of the Biot theory can be found in the work by Biot (1956a, b) and related works such as Gassmann (1951), Geertsman and Smit (1961), Stoll (1974), Johnson and Plona (1982), and Winkler (1985, 1986).

When calculating velocity of the Biot low-frequency limit, the bulk modulus K_m for clean and shaly sandstone matrixes is estimated from the empirical relations present by Han et al., (1986 a, b) in departure from Winkler's technique. Water-wetting effects on shear modulus are considered to obtain the 'drained' modulus of the Biot-Gassmann equation.

BIOT VELOCITY DISPERSIONS

The calculated BVD of V_p versus porosity for 69 sandstones at confining pressure 40 MPa and pore pressure 1 MPa are presented in Figure 1a. For most samples, the BVD were less than 1 percent. Clean sandstones have higher BVD compared to shaly samples with similar porosities. The BVD of the clean sandstones exhibit a linear increase with increasing porosity. For shaly sandstones, the BVD also tend to decrease with increasing porosity. Scatter among the BVD indicates that other parameters may also play a role. The plot of the BVD versus clay content reveals that clays in sandstones can suppress the BVD significantly (Figure 1b). Our calculation also suggests that at low differential pressure (9 MPa) the BVD are slightly less than those at high pressure (39 MPa), a result consistent with Winkler's (1985) result. The Biot dissipation/dispersion mechanism is dominated by global coupling between a viscous pore-fluid and a solid frame. If fluid is locked to the frame, the Biot loss and dispersion will be eliminated, whatever the frequencies are.

APPARENT VELOCITY DISPERSIONS

Calculated AVD versus porosity and clay content for 69 water saturated samples at differential pressure 39 MPa are shown in Figure 2 a and b. The AVD ranges between 1 and 9 percent, larger to much larger than the BVD. These data suggest strongly that non-Biot dissipation/dispersion mechanisms exist in sandstones. It is possible that dispersions with a wide range may correlate with various properties of the sandstones.

For clean sandstones, calculated 'drained' shear moduli agree (less than 1 percent difference) with the 'dry' shear moduli. In these rocks the AVD and the BVD agree as well. These results strongly suggest that for clean sandstones, there are no water wetting effects on the shear modulus and only the Biot dispersion exists for shear velocity dispersion.

The AVD of the compressional velocity calculated for clean sandstones are from 1 to 3 percent. For Fontainbleau sandstones, discrepancies between the AVD and BVD are about 1 percent or less. This suggests that their non-Biot dispersions are very small; for well cemented samples, non-Biot dispersions can be neglected. These well cemented sandstones are similar to fused glass beads (Winkler, 1985), both having AVD which are quite consistent with the predicted BVD. For less cemented clean sandstones, AVD increase with dependence on the cementation, compaction and pore geometry of the rock.

Gulf sandstone samples are well-cores most of which are poorly cemented with clay content above 10 percent. The AVD range from 0.04 for high porosity samples to about 0.09 for low porosity samples with high clay content. The AVD are considerably larger than the BVD for these rocks. This implies that non-Biot absorption/dispersion mechanisms dominate the AVD in Gulf sandstones. Most interesting is that by contrast with the BVD, AVD decrease with increasing porosity and effective stress, and increase with increasing clay content. These results indicate that properties of the non-Biot mechanisms are entirely different from those of the Biot mechanism.

Sandstones from quarries are fairly well cemented. The AVD of V_p for these sandstones range from 1 to 6 percent. These values are higher or much higher than the Biot dispersions. For well cemented samples, including all the P-sandstones, the AVD do not show clear correlation with the porosity or clay content. A reasonable explanation of this is that good cementation and compaction of these samples suppress the effects of porosity and clay content on the dispersion.

CONCLUSION

From our measurements and calculations for sandstones, several conclusions can be drawn. They are valid for V_p of water saturated sandstones at frequencies ranging from 1 Hz to MHz and a differential pressure of 39 MPa.

1. The BVD are less than 1 or about 1 percent. Clean sandstones have the highest BVD, about 1 percent or less, corresponding to shaly sandstones with the same porosities. The BVD increase with increasing porosity and differential pressure, and decrease with increasing clay content.
2. For well cemented and compacted sandstones, especially clean ones, the AVD are 1 or 2 percent. Both compressional and shear velocities of the clean sandstones measured at ultrasonic frequencies are in agreement with the high-frequency limit of the Biot theory. The behavior of these rocks is similar to fused glass beads (Winkler, 1985).
3. The AVD for the less cemented and compacted sandstones

range from 2 to 9 percent which is much larger than the BVD. This suggests that NBVD dissipation/dispersion mechanisms dominate the AVD in these rocks. The NBVD decrease with increasing porosity and differential pressure, and increase with increasing clay content, in contrast to the BVD. However, effects of porosity and clay content on the AVD appear clearly only as at higher values and are suppressed by increasing degrees of grain cementation and compaction.

4. Our results suggest that NBVD are most likely dominated by a local flow mechanism. Strength of local flow depends not only on pore structures but also on elastic moduli of the rock matrix. The former relates to pore shape, size and orientation. The latter relates to cement, cement material, type of grain-grain contact and differential pressure.

5. Velocity measurements made at ultrasonic frequencies are valuable for estimates of seismic velocity and intrinsic dispersion using the Biot-Gassmann equation.

REFERENCES

Biot, M. A., 1956, Theory of propagation of elastic waves in a fluid-saturated porous solid,

I. Low frequency range: J. Acoust. Soc. Am. 28, 168-178.

II. High frequency range: J. Acoust. Soc. Am. 28, 179-191.

Gassmann, F., 1951, Elastic waves through a packing of spheres: Geophysics, 16, 673-685.

Greetzman, J., and D. C. Smiti, 1961, Some aspects of elastic wave propagation in fluid-saturated porous solids, Geophysics, 26, 169-181.

Han D., A. Nur and F. D. Morgan, 1986 a, Effects of porosity and clay content on wave velocities of sandstones: Geophysics, 51, 11

Han D., A. Nur and F. D. Morgan, 1986 b, Velocity measurement and empirical modeling in sandstones: SPWLA 27th Symposium, Paper. OO.

Johnson, D. L., and T. J. Plona, 1982, Acoustic slow waves and the consolidation transition: J. Acoust. Soc. Am., 72, 556-565.

Moos, D., and M. D. Zoback, 1983, In situ studies of velocity in fractured crystalline rocks: J. Geophys. Res., 88, 2345-2458.

Murphy, W. F., 1984, Seismic to Ultrasonic velocity drift: Intrinsic absorption and dispersion in crystalline rock: Geophys. Res. Let., 11, 1239-1242.

Peselnick, L., and W. F. Outerbridge, 1961, Internal friction in shear and shear modulus of Solenhofen limestone over frequency range of 10^7 cycle per second: J. geophys. Res., 84, 581-588.

Spencer, J. W., 1981, Stress relaxations at low frequencies in fluid-saturated rocks: attenuation and modulus dispersion, J. Geophys. Res. 86, 1803-1812.

Stoll, R. D., 1974, Acoustic waves in saturated sediments: in Physics of Sound in Marine Sediments, edited by L. Hampton, pp. 19-39, Plenum, New York, 1974.

Winkler, K. W., 1985, Dispersion analysis of velocity and attenuation in Berea sandstone: J. Geophys. Res., 90, 6793-6800.

Winkler, K. W., 1986, Estimates of velocity dispersion between seismic and ultrasonic frequencies: Geophysics, 51, 183-189.

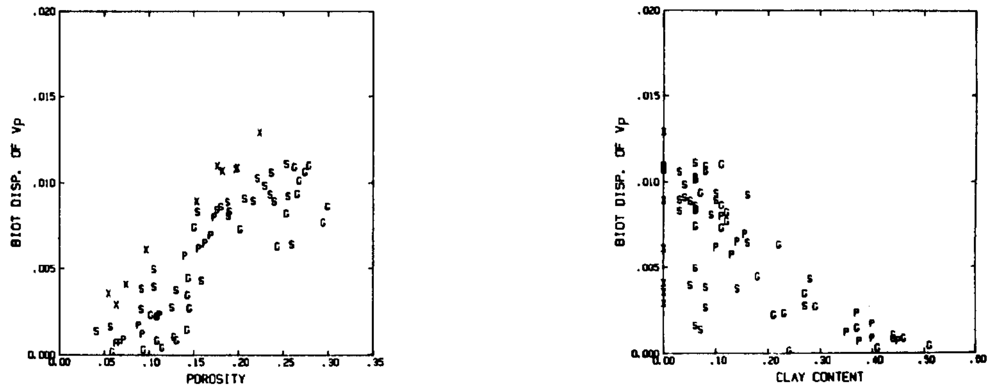

FIG. 1. BVD of V_p versus porosity, left, and clay content.

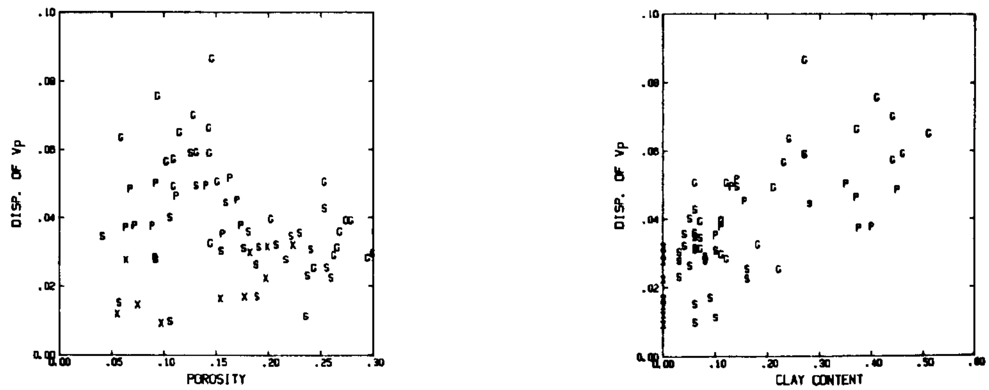

FIG. 2. AVD of V_p versus porosity, left and clay content.