Attenuation and velocity dispersion at seismic frequencies

M. Batzle, Colorado School of Mines, De-hua Han*, Houston Advanced Research Center, and J. Castagna, ARC0 Exploration and Production Technology

Summary

Attenuation and velocity dispersion are strongly dependent on pore fluids, particularly partial gas saturation, and thus could become valuable direct hydrocarbon indicators. Unfortunately, application of these properties is not frequent due to incomplete understanding of the phenomena and lack of appropriate tools to extract the information. Laboratory measurements at frequencies and amplitudes encompassing the seismic range have confirmed the strong dependence on partial gas saturation. However, attenuation is decreased by confining pressure, dropping rapidly as pressure increases. Attenuation peaks will also depend on specific rock characteristics. Absorption peaks seen in one frequency band may not be apparent in others.

Fluid mobility also influences rock inelastic properties. Most of the observed losses are due to relative motion of fluid in the pore space. For a constant pore fluid type, permeability will control the motion and dissipation thus making attenuation a permeability indicator. For variations in viscosities, mobility also will be dependent on frequency, and attenuation and dispersion may indicate fluid type.

Introduction

Seismic attenuation (l/Q) is strongly dependent on lithology and pore fluid properties and could become a powerful interpretation tool. The associated dispersion has been observed when comparing seismic, check shot, and well log data. Although a promising attribute, attenuation is not commonly used because of incomplete and contradictory theories, sparse laboratory data, and lack of robust techniques to derive l/Q from seismic or well data.

Attenuation effects have been used in a very qualitative sense for several years as direct hydrocarbon indicators (e.g. Tanner and Sheriff, 1976). More recently, Klimentos (1995) used the ratio of compressional to shear attenuations as hydrocarbon indicator in well logs. Similar measurements were made by De et al. (1994) but with less favorable results.

Theoretically, many models have been proposed, such as those of Biot (1956), O'Connell and Budiansky (1977), Walsh (1994). Divorkin and Nur, 1993, Squirt flow in combined Biot and local (squirt) into a more general theory. Unfortunately, the different mechanisms proposed often give contradictory results.

Wave attenuation and dispersion in vacuum dry rock is relatively negligible (Spencer, 198 1). Porous rocks containing fluids show a strong frequency-dependent attenuation. Variations in fluid properties such as modulus, viscosity, and polarity have a strong influence on l/Q (Clark, 1980; Winkler et al., 1982; Murphy, 1983; Tittmann et al., 1984; Jones, 1986; and Tutuncu et al., 1995). These results indicate that the dominant l/Q mechanism is the interaction and motion of fluid in the rock frame rather than intrinsic losses either in the frame or fluids themselves. Squirt flow is believed to be the primary loss mechanism in consolidated rocks although the inertial Biot mechanism may be important in highly permeable rocks (Vo-Thanh, 1990; Yamamato et al., 1994).

In this paper, we present data collected over a broad low frequency band. Our measurements focus on partial fluid saturation and fluid mobility. Ultimately, this type of data will resolve the mechanisms involved and help develop attenuation into a useful geophysical tool.

Measurements

Measurements of attenuation (l/Q) in our investigation were made in the frequency range from 5 to 2500 Hertz. This encompasses the seismic range and extends into range of recently developed low frequency logging tools. Values become strongly amplitude dependent at higher strain levels, so measurements must also be restricted to levels similar to those in seismic and sonic data.

Our technique uses a forced deformation, or stress-strain technique described by Smith et al. (1988) and similar to that employed by Spencer (1981) and Paffenholz and Burkhardt (1989). Samples are mounted in parallel with an aluminum standard. A sinusoidal force is applied and rock modulus is determined by the ratio of the sample to standard strains. Determination of axial strain provides Young's modulus, horizontal strain yields Poisson's ratio. For an isotropic medium, these two values permit calculation of all other elastic properties. Attenuation is derived from the phase shift between driving force and sample strain. Generally, with the low attenuations typical of consolidated rocks, phase angles are less than onedegree. Our measurements are restricted to Q values less than about 100.

The samples assembly is mounted in the deformation frame contained in a pressure vessel. Temperatures, confining and pore pressures can be controlled independently. Gas is used as a confining medium and pore fluids can be circulated during the experiment. The sides of the sample are sealed with **a thin epoxy** coating to minimize boundary flow effects.

Figure 1 shows the effect of both pressure and saturation on attenuation in Berea Sandstone. Under vacuum dry conditions, little attenuation is observed, confirming the necessity for pore fluids to produce measurable attenuation. At 95 % brine saturation at low pressure (0.7 MPa), attenuation becomes substantial and increases with frequency. At higher pressure (8.6 Mpa), attenuation is decreased significantly although the frequency dependence is approximately constant. This kind of behavior is consistent with the squirt-flow mechanisms. As both the compliance of individual fractures and permeability is reduced due to increasing overburden pressure, l/Q is reduced. However, the consistant behavior with frequency may imply that other pore geometric effects remain approximately the same.

A similar behavior is observed in carbonates. Figure 2 displays the shear attenuation for the dry and partially saturated cases. Although several partial saturations were measured (20 to 95%) the general merging of data indicates that there is little distinction among various saturation levels for this rock within our frequency band. The Biot loss mechanism has been shown to be inadequate to describe this behavior (Yin, 1992)

Figure 3. shows compressional velocity dispersion in sandstone as fluid viscosity changes. In this case, the saturating fluid is glycerin and the viscosity is varied by several orders of magnitude by changing the temperature. This suite of data is similar to the data collected at higher frequency by Vo-Thanh (1991). Again, little frequency dependence is seen in the dry sample. in addition, the dry rock is relatively unaffected by a temperature increase from 20 to 60 Celsius. When glycerin is introduced, two effects become immediately obvious: velocities are dispersive and the low frequency velocity is initially decreased. As the glycerin becomes more viscous at lower temperatures, velocity dispersion shifts to lower frequencies, as would be expected for relaxation mechanisms dependent on fluid motion. The initial decrease in velocity could be due either to frame softening effects, or perhaps to partial saturation (pore pressure = 0 here and glycerin is a viscous fluid which may restrict its distribution).

Conclusions

Measurements show clearly that seismic wave attenuation and velocity dispersion are substantial for partially saturated rocks. Both of these properties decrease rapidly with increasing effective pressure. These data are in agreement with local flow mechanisms within the rock.

Changing fluid mobility as indicated by changing viscosity alter both the magnitude of the dispersion and frequency response. The measured data suggests that the magnitude of the dispersion increases with reduced fluid mobility and shifts to lower frequencies. Reductions in permeability may have a similar effect.

Acknowledgments

The Gas Research Institute supported much of this work under contract number 5090-210-3339. Some of the data was collected by B.J. Smith, now at the University of Texas, Southwest Medical School. We would also like to thank ARCO Exploration and Production Research and Eddie Howell, Eric Pastemack, Nader Dutta, and Robert Siegfried for their support during the early development of our equipment and research.

References

Biot, M. A., 1956, Theory of propagation of elastic waves in a fluid saturated porous solid, II, Higher frequency range: J. Acoust. Soc. Am., 28, 179-l 91.

Clark, V. A., Effects of volatiles on seismic attenuation and velocity in sedimentary rocks: Ph.D. dissertation, Texas A & M University.

De, G. S., Winterstein, D. F., and Meadows, M. A., 1994, Comparison of P- and S-wave velocities and Q's from VSP and sonic log data: Geophysics, 59, 1512-1529.

Divorkin, J., and Nur, A., 1993, Dynamic poroelastisity: a unified model with the squirt and the Biot mechanisms: Geophysics, 58,524.523.

Jones, T. D., 1986, Pore fluids and frequency-dependent wave propagation in rocks: Geophysics, **51,** 1939-1953.

Klimentos, T, 1995, Attenuation of P- and S-waves as a method of distinguishing gas and condensate from oil and water: Geophysics, 60, 447-458.

Murphy, W. F., Effects of microstructure and pore fluids on the acoustic properties of granular sedimentary materials: Ph.D. dissertation, Stanford University, 255 pp.

O'Connell, R. J., and Budiansky, B., 1977, Viscoelastic properties of of fluid-saturated cracked solids: J. Geophys. Res., **82, 5719-5736**.

Paffenholtz, J., and Burkhardt, H., 1989, Absorption and modulus measurements in the seismic frequency and strain range on partially saturated sedimentry rocks: J. Geophys. Res., 94, 9493-9507.

Smith, B. J., **Batzle,** M. L., and Segalman, D. J., 1988, Low frequency seismic attenuation measurements using bonded strain gages: **Proc**. Am. Geophys. Un. annual meeting, San **Fransisco**.

Spencer, J. W., 198 1, Stress rexations at low frequencies in fluid-saturated rocks: Attenuation and modulus dispersion: J. Geophys. Res., 86, 1803-l 8 12.

Taner, M. T., and Sheriff R. E., 1976, Application of amplitude, frequency, and other attributes to stratigraphic and hydrocarbon determination, in: Seismic stratigraphy - applications to hydrocarbon exploration, C. E. **Payton,** ed., AAPG, Tulsa, **301-327.**

Tittmann, B. R., Bulau, J. R., and Abel-gawad, M., 1984, Dissipationof elastic waves in fluid saturated rocks, in Johnson, D.L., and Sen, P. N., Physics and chemistry of porous media: Am. Inst. Phys.

Tutuncu, A. N., Sharma, M. M., and Podio, A. L., 1995, An experimental investigation of the role of pore fluids on the nonlinear behavior of rocks: Abtst., SEG annual meeting, Houston, 886-889.

Vo-Thanh, D. 1990, Effects of fluid viscosity on shear-wave attenuation in saturated sandstones: Geophysics, 55,712.722.

Vo-Thanh, D. 1991, Effects of fluid viscosity on shear-wave attenuation in partially saturated sandstone: Geophysics, 56,' 1252-1258.

Walsh, J. B., 1995, Seismic attenuation in partially saturated rocks: J. Geophys. Res., 100, **15407-15424**.

Winkler, K. E., and Nur, A., and **Gladwin,** 1979, Friction and seismic attenuation in rocks: Nature, **277,528.53 1.**

Yin, C.S., 1992, Wave attenuation in partially saturated porous solids: Ph.D. dissertation, Columbia University, 96 pp.

Yamamato, T., Nye, T., and **Kuru,** M., 1994, Porosity, **permeability,** shear strength: Crosswell tomography below an iron foundary: Geophysics, 59 1530-1541.

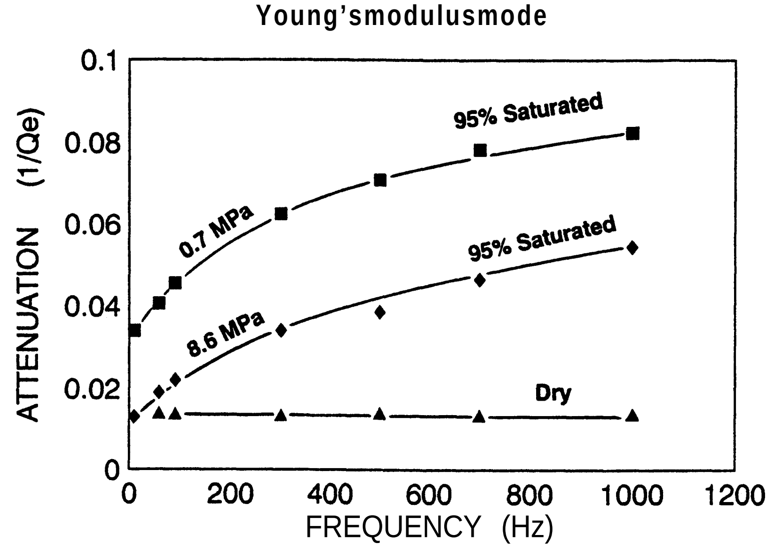

Figure 1. Attenuation in Berea Sandstone at both dry and partial brine saturation. Attenuation increases substantiaily with partial saturation, but increasing effective pressure decreases the magnitudes of 1/Qe.

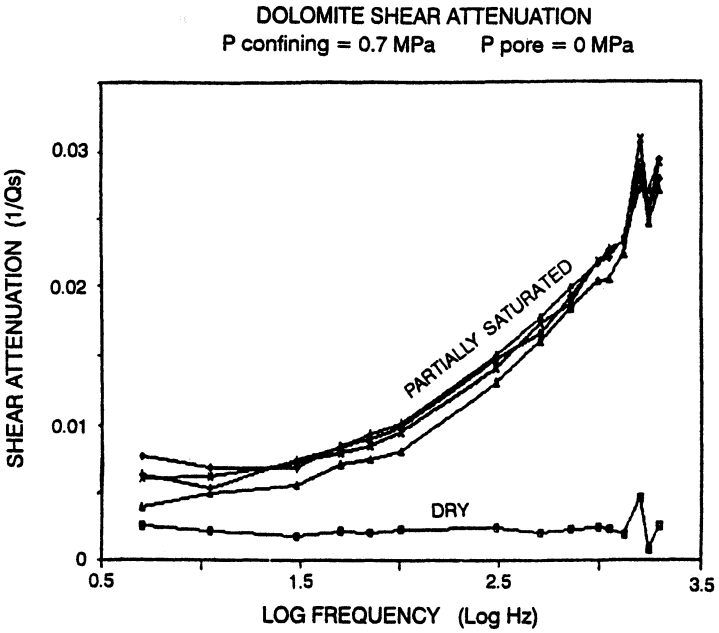

Figure 2. Shear attenuation for dry and partially saturated dolomite as a function of logarithmic frequency

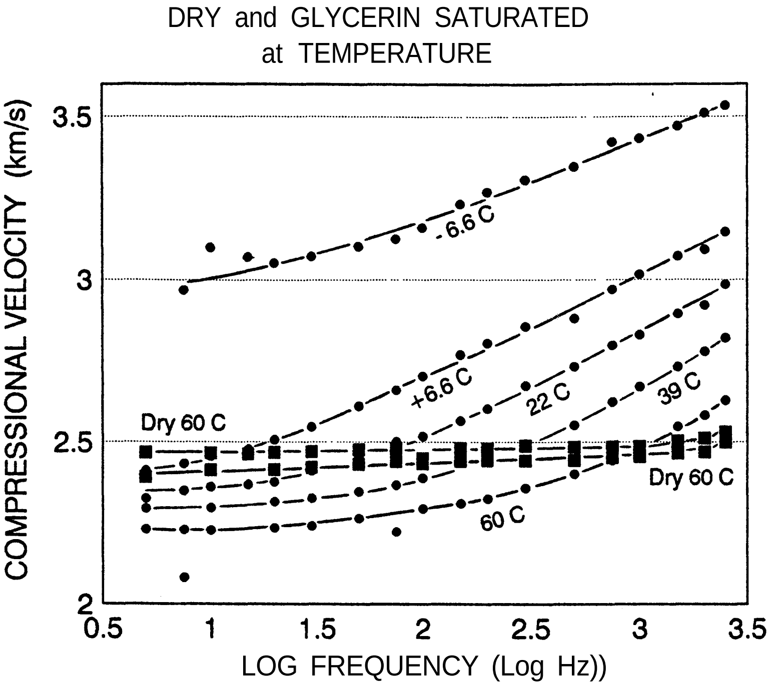

figure 3. Compressional velocity as a function of logarithmic frequency and temperature for dry and glycerin saturated sandstone.