CORE ANALYSIS TO CALIBRATE GEOPHYSICAL INTERPRETATION

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Abstract This paper comprises a brief review of some aspects of rock and fluid properties and their effects on acoustic measurements. We illustrate the effect of pore geometry, saturation, fluid type and shaliness on velocity measurements on cores and we present some field applications of these laboratory measurements including qualitative and quantitative interpretation of seismic, repetitive seismic and sonic data.

INTRODUCTION

Traditionally, seismic measurements have been widely used in oil and gas exploration to image structural features of the earth's interior and to detect potential hydrocarbon reservoirs. Recently, new geophysical techniques such as 3D seismic, repetitive seismic, well-to-well tomography, vertical seismic profiling, amplitude versus offset, and full waveform sonic have been developed to increase our capability to image more complicated and finer scale geological stuctures. In addition, these techniques provide a considerable amount of potential information on rock properties and their lateral variability within reservoirs. However, to convert the information contained in wave propagation characteristics into rock properties, there is a first order need to evaluate in a quantitative manner how physical properties of reservoir rocks, such as porosity, saturation and lithology, influence wave propagation. This problem can be approached using core measurements under controlled conditions of pressure, temperature, fluid saturation and fluid type, provided we understand how measurement scale and frequency affect wave propagation phenomena.

The first part of this paper comprises a short review on the effect of porosity, pore geometry, lithology, saturation and fluid type on velocity measurements. In the second part, we illustrate, through examples of seismic, sonic, well-to-well seismic and repetitive seismic data, how core analysis may serve as a guide for quantitative and qualitative interpretation. In the final discussion, we point out some of the limitations of acoustic measurements on cores.

SOME ASPECTS OF ROCK AND FLUID PROPERTIES AND THEIR EFFECTS ON VELOCITY MEASUREMENTS

The effect of porosity, fluid type and mineralogy on velocity measurements has been recognized for a long time in log and core analysis. Wyllie et al. (1956) first proposed to relate compressional velocity V_p to porosity ϕ using the time-average equation:

$$\frac{1}{V_p} = \frac{\phi}{V_{fl}} + \frac{1-\phi}{V_m} \qquad (1)$$

where V_{fl} and V_m are the compressional velocities of the fluid and the mineral phase, respectively.

However, the time-average equation has encountered limited success in well logging interpretation of sonic data for three primary reasons:

- the effect of gas or low velocity fluid cannot be accommodated.
- time-average relation does not hold for shear velocity.
- shaly sands are not satisfactorily modeled.

Furthermore, the time-average relation implies that among all pore parameters (volume, shape and size), only pore volume has an effect on velocity.

In the following, we illustrate some of the shortcomings of the time-average equation looking at the effect of pore geometry , fluid saturation and fluid type, and shaliness on velocity-porosity relationships.

Porosity and pore geometry

Porosity is one of the factors that has the greatest effect on velocity measurements. However, because of the various degrees of compaction, cementation, and diagenesis, pore volume is not a sufficient parameter to describe the influence of pores on velocity measurements. We show in this section how pore volume and pore geometry may influence acoustic measurements in sediments and rocks.

Figure 1a illustrates the range of variability of velocity and porosity in clastic sediments and rocks including suspensions (data from Hamilton ,1956), unconsolidated sands (data from Domenico, 1976) and consolidated clay-free sandstones (data from Han et al., 1986). Note the presence of two distinct trends in the velocity-porosity relationship that are attributed to two stages of consolidation:

- For suspensions and soft marine sediments, where mechanical interactions between particles are negligible, dependence of velocity on porosity follows the lower bound also called Wood's relation (Wood,1941).
- For unconsolidated and consolidated sediments, contacts between particles and pores shape govern rigidity and stiffness of the material and velocity departs abruptly from the lower bound. The general trend is a decrease of velocity with increasing porosity and this is related to compaction and the degree of cementation.

We also show in Figure 1b, values of velocity and porosity measured at various effective total stresses (from 0.1 to 40 MPa) for a subset of the data shown in Figure 1a (consolidated clay free sandstones). Note that the velocity-porosity trend due to stress is rather different from the general one due to cementation and compaction. Stress affects mostly velocity measurements and has a smaller impact on porosity reduction. Such behavior is primarily due to crack closure or elastic deformation at grain contacts that tend to increase the rock stiffness without greatly affecting its porosity.

The role of pore geometry on velocity has been adressed by many authors who proposed theories or models to account for the effect of pore shape and stiffness on rocks elastic properties (Walsh, 1965; Kuster and Toksoz , 1974; Mavko and Nur, 1978). These studies have shown that rock compressibility, and hence velocity, is dependent on pore aspect ratio and that round pores are much stiffer than elongated pores or cracks. Similarly, for granular materials, elastic theory has been used to relate the stress dependence of velocity to elastic deformation at grain contacts (Mindlin, 1949; Digby, 1981; Walton, 1987).

More generally, it is possible to estimate the range of variability of velocity for a given porosity using bounding methods for elastic moduli (Voigt, 1928; Reuss, 1929; Hashin and Shtrikman, 1963). Although these bounds are too far apart for any predictive purpose, they convey qualitative information regarding the stiffness of the pore space. An actual velocity value close to the upper bound will correspond to stiff, rounded, or vuggy pores whereas proximity to the lower bound will indicate porosity which consists also of cracks and/or uncemented loose grain contacts.

The effect of vuggy porosity on velocity measurements is shown in Figure 2 for a set of dry dolomite samples. From thin section analysis and macroscopic observations two types of pores were identified:

- vugs of diameter ranging from .5 to 5 mm.
- very small and thin pores at the interface between minerals.

Small pores were a common feature for all the samples whereas vugs were only observed on a subset of the samples.

The data of Figure 2 confirm that for a given porosity, velocity is significantly higher in samples that contain vugs due to the low compressibility of spherical pores. These observations show that to a first order, velocity is strongly related to porosity but that second order parameters such as pore geometry or pore stiffness can cause scatter in the velocity-porosity relationship.

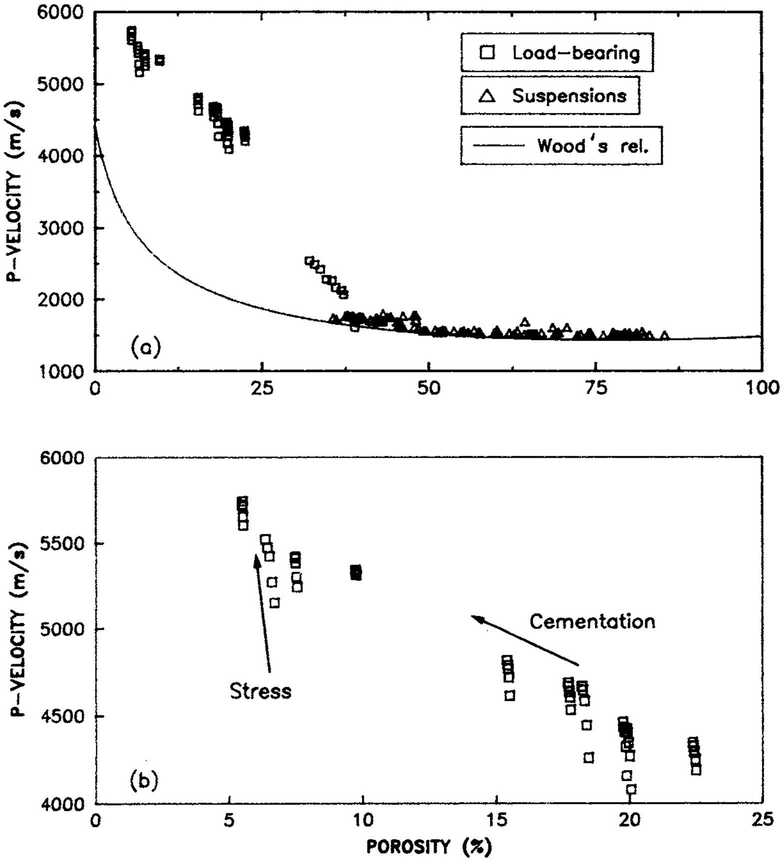

FIGURE 1 Velocity vs. porosity in clastic sediments and rocks: Influence of consolidation (Figure a), and stress (Figure b)

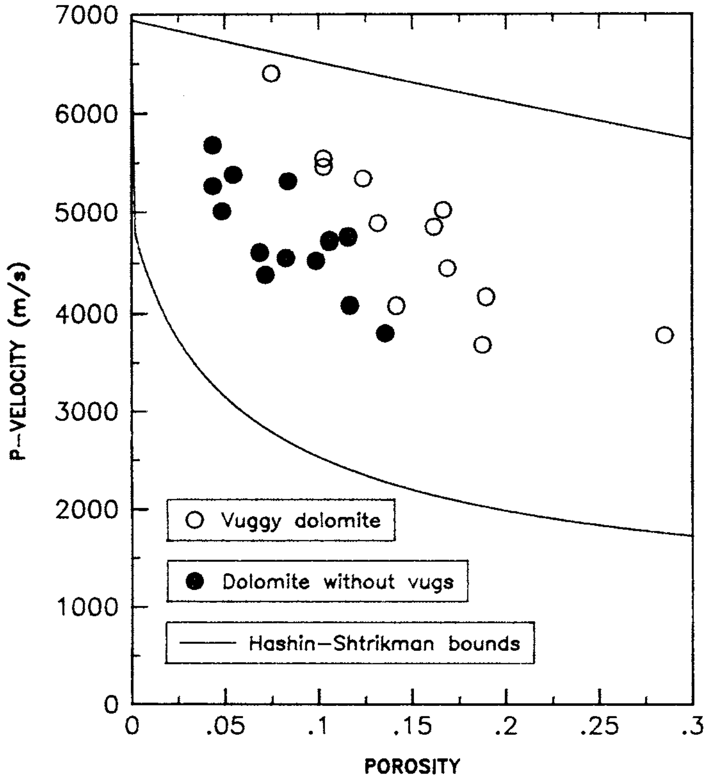

FIGURE 2 **Effect of vuggy porosity on compressional wave velocity and porosity.**

Clay content

In addition to pore geometry, clay content and clay distribution within the pore space can have a marked imprint on the velocity-porosity relationship in shaly sands. In Figure 3, we show a plot of core velocity vs. porosity measured on shaly sandstones (Han et al., 1986) and unconsolidated sand-clay mixtures (Yin et al., 1988). This data set outlines the scattering effect of clay on the velocity-porosity relationship which cannot be represented accurately using the time-average equation. Han et al. found that data measured on shaly sandstones could be fitted using least square regressions with the following simple relationships for P and S velocities:

$$V_p(km/s) = 5.59 - 6.93\phi - 2.18C \qquad (2)$$

$$V_s(km/s) = 3.52 - 4.91\phi - 1.89C \tag{3}$$

where C is clay content expressed as a fractional volume. These empirical relationships were found to be consistent with a model for shaly sands proposed by Marion et al. (1989) to account for the effect of dispersed clay on velocity and porosity.

The results of these studies imply that any model or empirical expression that describes the relationship between velocity and porosity in shaly sands must include information regarding the degree of shaliness.

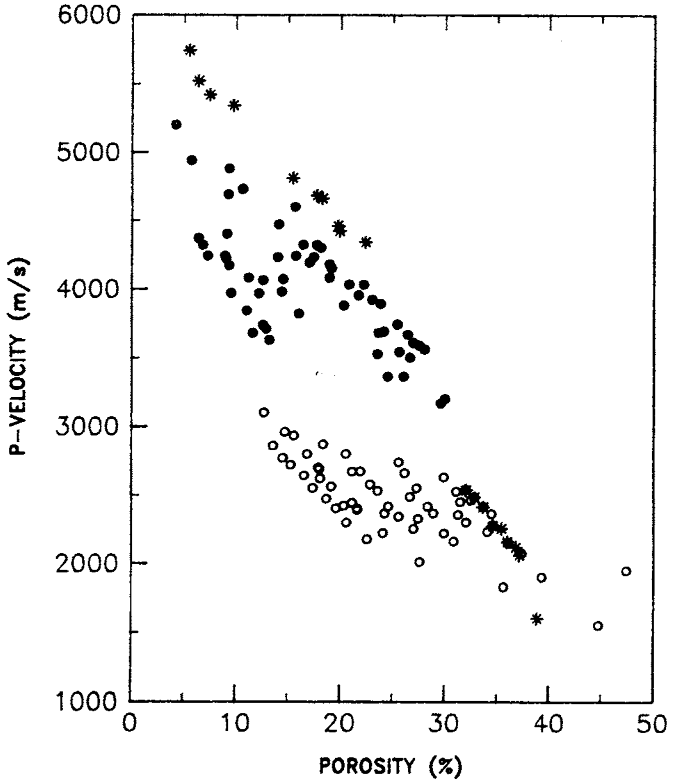

FIGURE 3 Effect of clay content on compressional wave velocity and porosity: • shaly sandstones, ∘ shaly sands, ∗ clean sands and sandstones .

Saturation

We have shown in a previous section that pore volume and pore shape have a strong influence on velocity. We show here that the influence of pore parameters on velocity may be sensitive to the level of fluid saturation.

Theories were first proposed by Gassmann (1951) and Biot (1956) to account for the effect of fluid on velocities in rocks. Theoretical predictions have been confirmed at least qualitatively by many experimental studies (King, 1966; Nur and Simmons, 1969; Domenico, 1976; Gregory, 1976). Experimental results presented in Figure 4 show a typical dependence of velocity on saturation. Going from a dry to a fully saturated rock, compressional velocity increases upon saturation due to a decrease of the fluid compressibility. The magnitude of the increase in velocity with saturation varies with stress and is proportional to porosity and the compressibility of the rock skeletal frame. In contrast, shear velocity shows very little variation with saturation.

We will show in the following section one principal application of these experimental results: the detection of gas pockets in seismic exploration using both compressional and shear wave measurements.

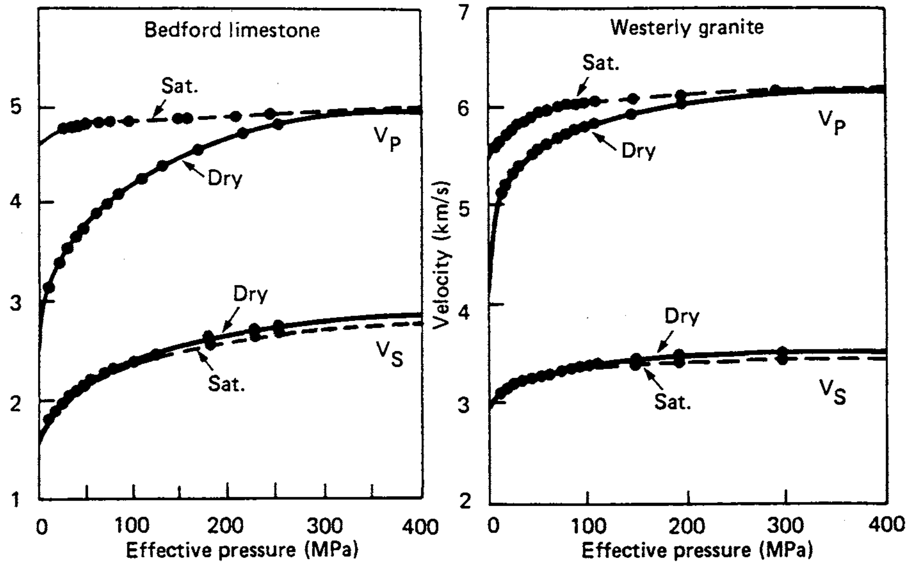

FIGURE 4 Velocity vs. Pressure in dry and saturated conditions for Bedford Limestone and Westerley granite (after Nur and Murphy (1981).

Fluid type and temperature

Various studies have dealt with the effect of fluid type on velocities, but few of them have been concerned with real reservoir fluids such as live oils or tar (Tosaya et al., 1987; Wang, 1988). It appears from these studies that velocity in oil saturated rocks depends (1) on the type of oil (specifically on its API gravity) and (2) on temperature. The variations of compressional wave velocity with temperature are mostly related to changes of oil compressibility with temperature as shown in Figure 5 and to changes of oil viscosity that mostly affect shear velocity. For tar sand, compressional velocity can decrease as much as 30% with increasing temperature whereas velocity in water saturated sand decreases by only 3-5 %. We will see in a following section the potential impact of these measurements on the monitoring of thermal fronts in EOR using seismic measurements.

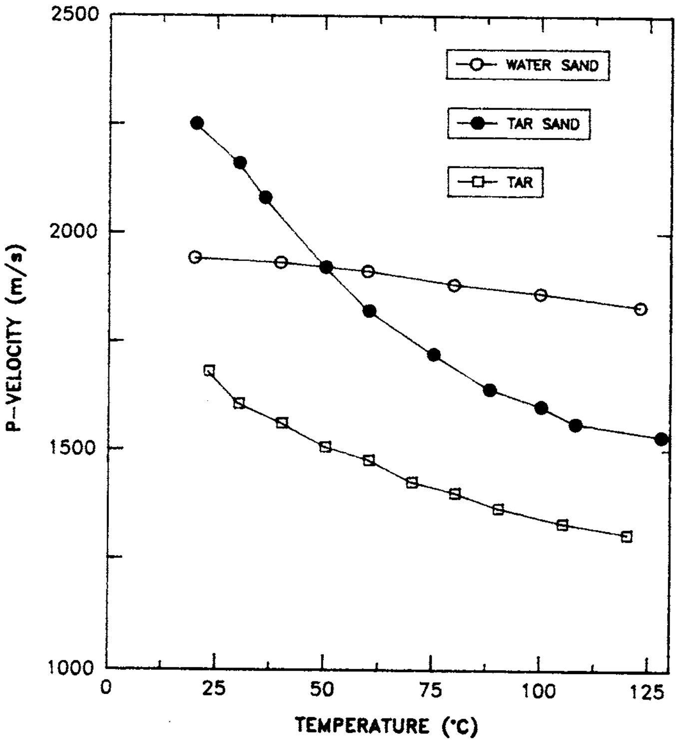

FIGURE 5 **Compressional wave velocity vs. temperature in tar and tar sand (after Wang, 1988).**

APPLICATION TO SEISMIC AND SONIC INTERPRETATION

Qualitative interpretation of seismic sections: bright spots

Domenico (1974) first showed how results of laboratory experiments on the effect of saturation on velocity could apply to seismic data. His study revealed that reflectivity associated with an interface between shale and oil-saturated sand is quite different from the reflection generated by a shale-gas sand interface and that reflection amplitude is increased significantly when gas is present in the reservoir. On seismic sections, this appears as an amplitude anomaly called a "bright spot" that had been recognized for a long time by exploration geophysicists as a possible marker for gas (Figure 6). Unfortunately, amplitude anomalies may also be attributed to lateral variations of lithology or anomalously high pore pressure zones. However, results from laboratory experiments (Domenico, 1974, 1984, Castagna et al., 1985; Han et al, 1986) showed that both compressional and shear velocity should be sensitive to lithological variations or overpressured zones whereas the presence of gas could only be detected from the compressional waves. These experimental results were confirmed by field seismic measurements in which combined acquisition of compressional and shear wave data was performed to discriminate between gas, on the one hand, and lithology or overpressured zones, on the other (McCormack et al., 1984; Ensley, 1985).

Porosity map using well-to-well seismic

One of the problems faced by reservoir engineers is the need to estimate as accurately as possible the spatial distribution of petrophysical properties or geological features within a reservoir. Because of its improved resolution over standard seismic measurements, well-to-well seismic is potentially a good candidate for reservoir description. Lucet and Mavko (1990) have very recently presented results of a study in which a velocity tomogram from Harris et al. (1990) is converted into a porosity map of the reservoir. In the approach proposed by Lucet and Mavko, core measurements are used to establish the relationship between velocity, porosity and lithology. In the example shown in this study, tomographic data were acquired in shaly sands in the Gulf of Mexico and the relationships of Han et al. (1986) was used. A shaliness map was first generated using the velocity tomogram and cokriging techniques. The porosity map was then obtained by combining the velocity tomogram, the shaliness map and the relationship between porosity, velocity and shaliness obtained from core measurements.

Seismic monitoring of thermal fronts in EOR processes

The use of seismic waves to detect thermal fronts in EOR processes is based on the sensitivity to temperature of velocity in hydrocarbon-saturated rocks. Seismically, changes in velocity due to thermal heating of the reservoir can be detected either from a pull-down of the base of the reservoir on the seismic section, due to a decrease in velocity in the heated zone, or from a change in the reflection amplitude at the top of the reservoir (Britton et al., 1983; Greaves and Fulp, 1987; Macrides et al., 1988). Furthermore, results from laboratory experiments shown in Figure 5 seem to agree quantitatively with recent 3-D seismic monitoring of steam flooding in a tar sand reservoir (den Boer and Matthews, 1988) where the estimated decrease of velocity in the heated zone is of the order of 30 %.

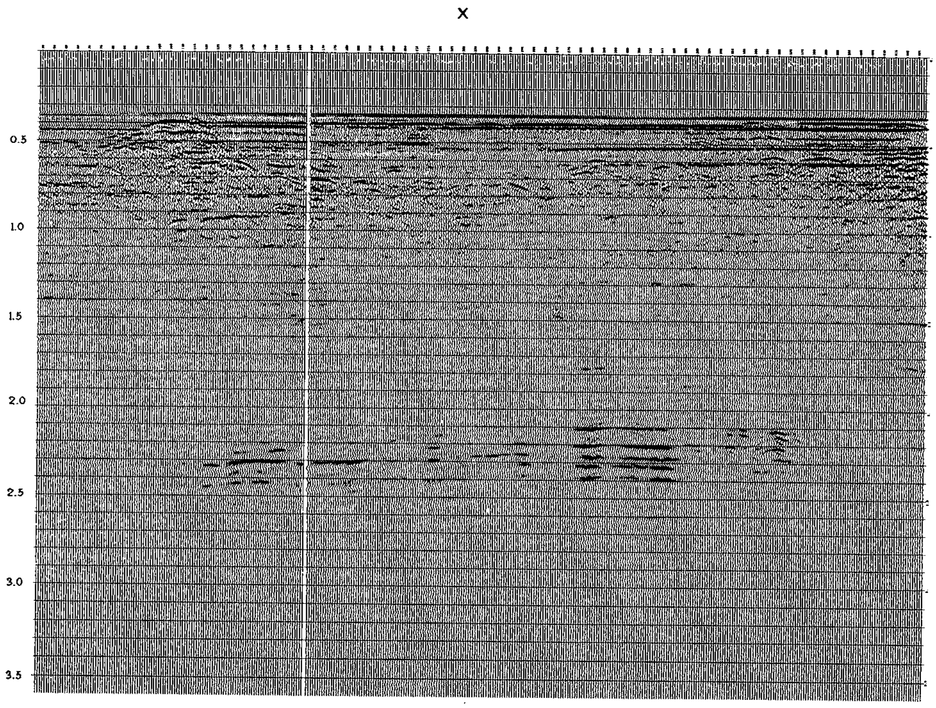

FIGURE 6 **Bright spot at the gas-liquid interface (After Kjartansson, 1979).**

Calibration of sonic logs

From a surface feophysical perspective, conventional sonic logs are mostly used to generate synthetic seismograms to calibrate seismic measurements and are seldom used as a quantitative interpretation tool in their own right as, for example, in petrophysics. The new generation of full-waveform sonic tools that provide measurements of compressional, shear and Stoneley waves, opens new perspectives for quantitative interpretation in terms of mechanical, lithological and petrophysical properties. The role of core measurements is to provide an estimate of velocity in a few discrete locations in order to calibrate sonic waveform measurements and establish the relationships between acoustic, petrophysical, lithological and mechanical properties of rocks.

An example of the calibration of a sonic log using core measurements is shown in Figure 7. Velocity and its reciprocal, transit time, was measured under confining pressure on dry and brine saturated samples. No systematic difference can be observed between laboratory data (squares in Figure 7) at simulated in-situ conditions and sonic data (bold line). Note, however, that there are local sharp variations of transit time observed on cores that are not represented within the sonic log. Using simple upscaling techniques (travel time averaging justified by layer thicknesses) applied to our core measurements we simulate a velocity profile (thin line) for which core vertical resolution is comparable to the sonic tool resolution. We find a very good agreement between the reconstructed and the actual sonic. For depth intervals that feature rapid variations of velocity (1885-1889 m.), the agreement is within 3 %.

Once calibration is completed, quantitative interpretation of the sonic log is performed using relationships derived from core measurements. We show in Figure 7, a porosity profile obtained from the sonic log using a relationship derived from velocity and porosity measurements on cores. Good agreement between predicted (bold line) and measured porosity is observed. Porosity predicted using time-average equation is also shown for comparison (thin line). Note that time-average matches fairly well core porosity for low porosity rocks but underestimates porosity in the reservoir zone.

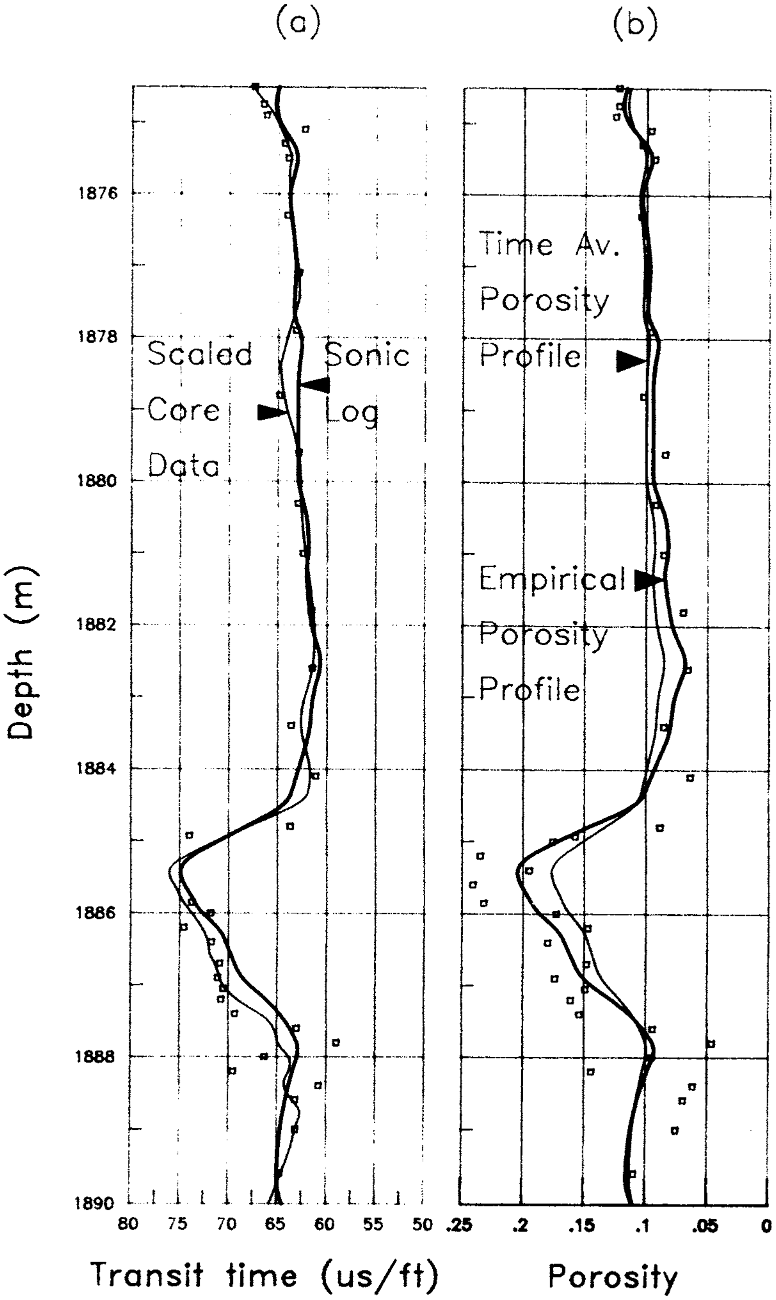

FIGURE 7 Calibration of (a) compressional-wave sonic log and (b) sonic-predicted porosities with core data.

FROM CORES TO SEISMIC AND SONIC MEASUREMENTS: EFFECT OF FREQUENCY AND SCALE

We have shown in the previous section how results from core analysis could be used towards qualitative and quantitative interpretation of seismic and sonic data. However, it should be remembered that because of the difference in wavelength and frequency between laboratory and seismic and sonic measurements, direct use of laboratory results to seismic and sonic interpretation should be done with caution.

Because velocity in fluid-saturated rocks varies with frequency, it is of great concern to quantify velocity dispersion when extrapolating laboratory results to seismic or sonic frequencies. Few laboratory studies have been conducted on velocity dispersion due to sample size limitations (Spencer, 1981; Winkler, 1983, Murphy, 1985; Lucet, 1990). These studies identified fluid motion as the predominant influence upon velocity dispersion in saturated rocks. These observations are consistent with Biot theory that predicts velocity dispersion due to relative motion between fluid and solid. At high frequencies, fluid motion is decoupled from the solid frame motion whereas at low frequencies fluid and solid are "locked". However, velocity dispersion predicted by Biot theory generally underestimates experimental velocity dispersion (Winkler, 1985) and other mechanisms such as "local flow" or "squirt flow" at the scale of the pore have been suggested (O'Connel and Budiansky, 1977; Mavko and Nur, 1979) as possible mechanisms for dispersion. Recently, Mavko and Jizba (1990) proposed a method to estimate the effect on local flow of local distributions of compressibilities in the pore space to account for velocity dispersion in saturated rocks.

Hence, it appears from these studies that the effect of frequency on velocity can be represented qualitatively and quantitatively for homogeneous rocks. However, because of the wavelength differences between seismic, sonic and laboratory measurements, the volume investigated by these various techniques are markedly different and laboratory results may not be representative at the seismic or sonic scales. This is especially true when the medium is composed of thinly layered beds that may be homogeneous at the scale of a core but induce dispersion and anisotropy at the seismic scale.

The averaging process performed by seismic waves when layer thicknesses are small relative to the wavelength was described analytically by Postma (1955), Backus (1962), and Heilbig (1984) and was confirmed experimentally by laboratory experiments (Melia and Carlson, 1984) and by recent numermeasurements.

Note that upscaling problems are common to many other measurements such as permeability, capillary pressure and saturation, where the results obtained on cores must be extrapolated to a much larger scale in simulation processes of reservoir performance. However, because of the wide spectrum and frequency overlap of the various measurement techniques (10-100 Hz for seismic, 100-1000 Hz for well-to-well seismic, 1-10 KHz for sonic, 10-1000 KHz for laboratory) seismic wave propagation appears to be one of the most favourable areas for applying scaling-up concepts with the object of validating measurements at progressively larger scales.

CONCLUSION

We have shown in this paper how porosity, pore geometry, fluid saturation, fluid type and shaliness can affect velocity measurements on rocks and how core analysis can be used as a guide for qualitative and quantitative interpretation of seismic and sonic data. We have also described briefly how differences between core, well-log and seismic properties can be attributed to the effects of frequency and of the scale of heterogeneity on velocity measurements.

REFERENCES

BACKUS, G.E. (1962). Long-wave anisotropy produced by horizontal layering. *J. Geophys. Res.*, **67**, 4427-4440.

BIOT, M.A. (1956). Theory of propagation of elastic waves in a fluid saturated porous solid, *J. Acoust. Soc. Am.*, **28**, 168-191.

BOURBIE, T., COUSSY, O., and ZINSZNER, B. (1986) *Acoustics of porous media*, Technip, Paris.

BRITTON, M.W., MARTIN, W.M., LEIBRECHT, R.J., and HARMON, R.A. (1983). Street ranch pilot test of fracture-assited steamflood technology. *J. Petro. Tech.*, **35**, 511-522.

CARCIONE, J.M., KOSLOFF, D., and KOSLOFF, R. (1988). Wave propagation simulation in an elastic anisotropic (transversely isotropic) solid. *Quart. J. Mech. Appl. Math.*, **41**, 319-345.

CARCIONE, J.M., KOSLOFF, D., and BEHLE, A. (1991). Long-wave anisotropy in stratified media *Geophys.*, **56**, 245-254.

CASTAGNA, J.P., BATZLE, M.L., and EASTWOOD, R.L. (1985). Relationships between compressional-wave velocities in clastic silicate rocks. *Geophys.*, **50**, 571-781.

DEN BOER, L.D. and MATTHEWS, L.W., (1988). Seismic characterization of thermal flood behavior. *Proc. of the 4th Int. Conf. on Heavy Crude and Tar Sands*

DIGBY, P.J. (1981). The effective elastic moduli of granular rocks. *J. Appl. Mech.*, **48**, 803-808.

DOMENICO, S.N. (1974). Effect of seismic reflectivity of sand reservoirs encased in shale. *Geophys.*, **39**, 759-769.

DOMENICO, S.N. (1976). Effect of brine-gas mixture on velocity in a unconsolidated sand reservoir. *Geophys.*, **41**, 882-894.

DOMENICO, S.N. (1984). Pock lithology and porosity determination from shear and compressional velocity. *Geophys.*, **49**, 1188-1195.

ENSLEY, R.A. (1985). Evaluation of direct hydrocarbon indicators through comparison of compressional and shear wave seismic data: a case study of the Myrnam gas field, Alberta. *Geophysics*, **50**, 37-48.

ESMERSOY, C., HSU, K., and SCHOENBERG, M. (1989). Quantitative analysis of fine layering effects: medium averaging versus synthetic sismograms. *Presented at the 59th Ann. Internat. Mtg., Soc. Expl. Geophys.*, Expanded abstracts 1083-1085.

GASSMANN, F. (1951). Elastic waves through a packing of spheres. *Geophysics*, **16**, 673-685.

GREAVES, R.J., and FULP, T.J. (1987). Three-dimensional seismic monitoring of an enhanced oil recovery process. *Geophys.*, **52**, 1175-1187.

GREGORY, A.R., (1976). Fluid saturation effects on dynamic elastic properties of sedimentary rocks. *Geophys.*, **41**, 895-921.

HAMILTON, E.L., SHUMWAY, G., MENARD, H.W., and SHIPEK, C.J. (1956). Acoustic and other physical properties of shallow-water sediments off San Diego.*J. Acoust. Soc. Amer.*, **28**, 1-15.

HAN, D., NUR, A., and MORGAN, D. (1986). Effect of porosity and clay content on wave velocity in sandstones. *Geophysics*, **51**, 2093-2107.

HARRIS, J.M., MAVKO, G., MOOS, D., and NOLEN-HOEKSEMA, R. (1990). Cross-well tomographic imaging of geological structures in Gulf coast sediments.*Stanford Seismic tomography project*, **1**.

HASHIN Z., and SHTRIKMAN, S., (1963). A variational approach to the elastic behavior of multiphase materials, *J. Mech. Phys. Solid*, **11**, 127-140.

HEILBIG, K. (1984). Anisotropy and dispersion in periodically layered media. *Geophysics*, **49**, 364-373.

KING, M.S. (1966). Wave velocities in rocks as a function of changes in overburden pressure and pore fluid saturants. *Geophys.*, **31**, 50-73.

KJARTANSSON, E. (1979) Attenuation of seismic waves in rocks. *PhD. Thesis*, Stanford , California.

KUSTER, G.T., and TOKSOZ, N.M. (1974). Velocity and attenuation of seismic waves in two-phase media, I. Theoretical formulations. *Geophys.*, **39**, 607-618.

LUCET, N. (1990). Vitesse et attenuation des ondes elastiques soniques et ultrasoniques dans les roches sous pression de confinement. *PhD. Thesis*, Universite de Paris VI, France.

LUCET, N., and MAVKO, G. (1990) . Images of rock properties estimated from a crosswell seismic velocity tomogram. *Presented at AGU annual meeting, December* , San Francisco, T41 A-7.

MACRIDES, C.G., KANASEWITCH, E.R., and BAHARATHA, S. (1988). Miltiborehole seismic imaging in steam injection heavy oil recovery projects *Geophys.*, **53**, 65-75.

MARION D.P., NUR, A. and ALABERT, F. (1989). Modelling the relationship between sonic velocity, porosity, permeability and shaliness in sand, shale, and shaly sand. *Trans. Soc. Pet. Well Log Anal.*, paper G.

MAVKO, G.M., and JIZBA, D. (1991). *J. Geophys. Res.*, **83**, 4459-4468.

MAVKO, G.M., and NUR, A.M. (1978). The effect of nonelliptical cracks on the compressibility of rocks. *J. Geophys. Res.*, **83**, 4459-4468.

MAVKO, G.M., and NUR, A.M. (1979). Wave attenuation in partially saturated rocks. *Geophys.*, **44**, 161-178.

McCORMACK, M.D., DUNBAR, J.A., and SHARP, W.W. (1984). A case study of stratigraphic interpretation using shear and compressional seismic data. *Geophys.*, **49**, 509-520.

MELIA, P.J., and CARLSON, R.L. (1984). An experimental test of P-wave anisotropy in stratified media. *Geophys.*, **49**, 374-378.

MINDLIN,R.G. (1949). Compliance of elastic bodies in contact. *Trans. ASME*, **71**, A-259.

MURPHY, W.F. (1985). Sonic and ultrasonic velocities: theory versus experiement. *Geophys. Res. Let.*, **12**, 85-88.

NUR, A., and MURPHY, W.F. (1981). Wave velocities and attenuation in porous media with fluids. *Proc. of 4th Int. Conf. on Continum models of discrete systems*, Stockholm, 311-327

NUR A., and SIMMONS, G. (1969). The effect of saturation on velocity in low porosity rocks. *Earth Planet. Sci. Lett.*, **7**, 183-193.

O'CONNELL, R.J., and BUDIANSKY, B. (1977). Viscoelastic properties of fluid saturated cracked solids. *J. Geophys. Res.*, **76**, 2022-2034.

PHILIPPE, J., and BOUCHON, M. (1989). Propagation of waves with long-wavelength in thinly layered and cracked media. *Presented at the 59th Ann. Internat. Mtg., Soc. Expl. Geophys.*, Expanded abstracts 1023-1024.

POSTMA , G.W. (1955). Wave propagation in a stratified medium. *Geophys.*, **20**, 780-806.

REUSS, A., (1929). Berechnung der fliessgrense von mischkristallen auf grund der plastizitatsbedingung fur einkristalle. *Zeitschrift fur Angewandte Mathematik and Mechanik*, **9**, 49-58.

SPENCER, J.W. (1981). Stress relaxation at low frequencies in fluid saturated rocks. *J. Geophys. Res.*, **86**, 1803-1812.

TOSAYA, C., NUR, A., VO-THANH, D., and DA PRAT, G., (1987). Laboratory seismic method for remote monitoring of thermal EOR, Soc. Pet. Eng. Res. Eng., **2**, 235-242.

VOIGT W. (1928) *Lehrbuch der Kristallphysik*, Teubner, Leipzig.

WANG Z. (1988). Wave velocity in hydrocarbons and hydrocarbon saturated rocks - with applications to EOR monitoring.*PhD. thesis*, Stanford University, California.

WALTON, K. (1987). The effective elastic moduli of a random packing of spheres. *J. Mech. Phys. Solids*, **35**, 213-226.

WALSH, J.B. (1965). The effect of cracks on the compressibility of rocks. *J. Geoph. Res.*, **70**, 381-385.

WINKLER, K. (1983). Frequency dependent ultrasonic properties in high porosity sandstones. *J. Geoph. Res.*, **88**, 9493-9499.

WINKLER, K. (1985). Dispersion analysis of velocity and attenuation sandstones. *J. Geoph. Res.*, **88**, 9493-9499.

WOOD, A.B. (1941). *A textbook of sound.* Lacmillan, New York.

WYLLIE, M.R.J., GREGORY, A.R., and GARDNER, G.H.F (1956). Elastic wave velocities in heterogeneous and porous media. *Geophys.*, **21**, 41-70.

YIN, H., HAN, D.H., and NUR, A. (1988). Study of velocity and compaction on sand-clay mixtures. *Stanford Rock and Borehole Project*, **33**.