Amplitude-Versus-Offset Interpretation, Scaling Factors, and Other Challenges Associated With Acoustic Data Integration

Robert A. Skopec* and Christopher P. Ross**
* University of Aberdeen, Aberdeen, UK
** Oryx Energy Co., Dallas, Texas, USA

ABSTRACT

The need to obtain better shear wave data is becoming increasingly more important in petroleum exploration and production. Recent advancements in wireline multipole sonic logging and seismic amplitude processing provides an opportunity for improved formation evaluation and reservoir delineation. An important concern in sonic log and seismic interpretation is the non-uniqueness of the inversion process, i.e., extracting rock properties from acoustic waveforms. Ambiguity in acoustic inversion was overcome by constraining oversimplified models with laboratory data. The classical interpretation relating amplitude-versus-offset (AVO) to Poisson's ratio and other petrophysical properties is based on the idealistic assumptions of elasticity and isotropy. Correlation of AVO with rock properties is critical in determining whether or not variations of amplitude with incident angle are indicative of hydrocarbons.

Acoustic energy sources are poorly understood and the physics underlying compressional- and shear-wave data acquisition show marked differences. Elastic parameters when measured in the laboratory at ultrasonic frequencies were consistently higher than dynamic data measured by sonic logs. Results from the acoustic laboratory evaluation indicate that sample selection, orientation, partial fluid saturation, viscoelasticity, experimental conditions, and intrinsic rock properties cause large variations in acoustic response. This complicates further the challenge of acoustic data integration. The effects of scale can be significant, but manageable if fundamental rock and fluid properties are understood. To address issues associated with acoustic data integration, a program using reflection seismic, wireline log, and laboratory data was initiated to study the effects of scale (rock volumes) in sandstones.

INTRODUCTION

Prior to the advent of AVO, direct hydrocarbon indicator (HCI) techniques such as "bright spot" analysis proved to be unreliable and a more definitive method was needed. Many of the early inversion technique failures could be attributed to lack of petrophysical control. Since Ostrander's (1984) paper "Plane-Wave Reflection Coefficients for Gas Sands at Nonnormal Incidence," there has been incredible interest in AVO. There are two steps in an AVO inversion: 1) extraction of the rock properties from the common depth point (CDP) gather, e.g.- velocities, density, and calculation of Poisson's ratio, and 2) relating these rock properties to lithology and fluid saturation (Hilterman, 1990). In the Gulf of Mexico and many other locations AVO technologies are being used to reduce risk in exploration and development. Because there is uncertainty associated with determining V_p/V_s ratios from AVO measurements it is necessary to constrain AVO results with petrophysical data. Few seismic studies include a comprehensive evaluation of all available petrophysical data, e.g.-wireline log, core, and engineering data, and many AVO inversion failures can be attributed to oversimplification of the relationship between seismic amplitude and rock and fluid properties.

AVO THEORY

AVO analysis involves evaluation of reflection amplitudes at varying source-receiver offsets. Figure 1 illustrates the common midpoint (CMP) gather consisting of a set of raypaths sampling the same subsurface point at increasing offset distance and angle-of-incidence. The CMP gather is the starting point for AVO analysis. Shear-waves (S-waves) differ from compressional-waves (P-waves) in that their velocity is not significantly affected by changes in the fluid content of a rock. Gas within the pore space of a rock dramatically lowers P-wave velocity. Because the P-wave to S-wave ratio (V_p/V_s) is significantly different for gas-charged rocks as opposed to water-bearing rocks, gas-sand/shale or gas-sand/wet-sand reflectors are different when compared to most other reflectors.

Reflections associated with high porosity gas-bearing rocks oftentimes exhibit an increase in amplitude with offset when compared to gas-free reflectors (Figure 2). Because most reflections decrease with offset amplitude increases in AVO analysis are anomalous (Allen and Peddy, 1993). Physical rock parameters measured in the laboratory should be used to optimize AVO modeling (Skopec, 1994). Many seismic amplitude anomalies are not caused by economic hydrocarbon (gas) accumulations and false positive AVO response is problematic (Allen et al., 1993).

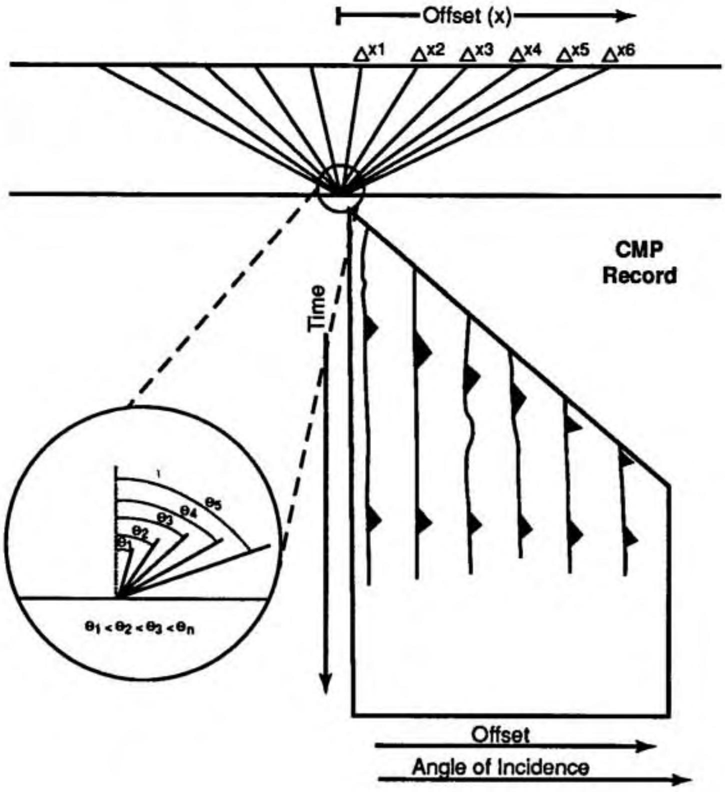

Figure 1. Raypaths imaging a common midpoint in the subsurface at increasing angles of incidence (Θ) and the common midpoint (CMP) record.

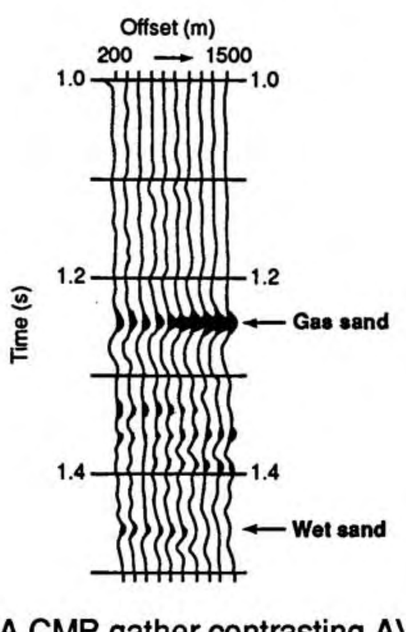

Figure 2. A CMP gather contrasting AVO response in a wet sand and gas sand.

POISSON'S RATIO

A plane *P*-wave striking an interface at normal-incidence causes no conversion to *S*-waves. At angles other than normal-incidence, some portion of the incident *P*-wave is converted to an *S*-wave (Figure 3). The partitioning of incident wave energy at a reflecting interface can be expressed by the ratio of incident to transmitted (refracted) or reflected displacement amplitudes, displacement potentials, or energy (Young and Braile, 1976). Zoeppritz (1919) developed equations to describe particle displacements and calculate reflection coefficients which require V_p, V_s, and density data for media above and below an acoustic interface. Zoeppritz's equations estimate the expected change in amplitude at any incident angle for any combination of rock properties. Several approximations (simplifications using more intuitive variables) to Zoeppritz's equations have been developed, e.g.-Bortfeld (1961) and Shuey (1985). The relationship of reflection coefficient versus angle-of-incidence can be modeled based on evaluating the sensitivity of rock properties using these approximations.

The *P*-wave reflection coefficient as a function of angle-of-incidence at an interface separating two media is strongly affected by the relative values in Poisson's ratio in the two media. The elastic constant, Poisson's ratio (σ) is the ratio of transverse strain to longitudinal strain, and can be expressed in terms of the V_p/V_s ratio for an isotropic elastic material as:

$$\sigma = ((V_p/V_s)^2 - 2)/(2(V_p/V_s)^2 - 2).$$

Poisson's ratio is a measure of the degree to which a media bulges as it shortens or thins as it is extended (Figure 4). Poisson's ratio varies from zero for a non-deformable solid to the theoretical limit of 0.5 for liquids. Typical values for σ (in Tertiary rocks) are listed in Table 1. Figure 5a shows the theoretical velocities for S- and P-waves at various gas saturations for an arbitrary porous medium (Allen and Peddy, 1993). The V_p/V_s ratio, and thus σ, decrease substantially when gas saturation reaches only a few percent (Figure 5b). As V_p/V_s increases so does σ. Small changes in V_p/V_s lead to large changes in σ at low V_p/V_s ratios (Figure 5c). Poisson's ratio may be determined dynamically using field or laboratory measurements of both V_p and V_s, or statically using conventional rock mechanics (loadframe) technology. Bulk-, shear-, and Young's moduli as well as estimates of compressive strength can be made if V_p/V_s is measured.

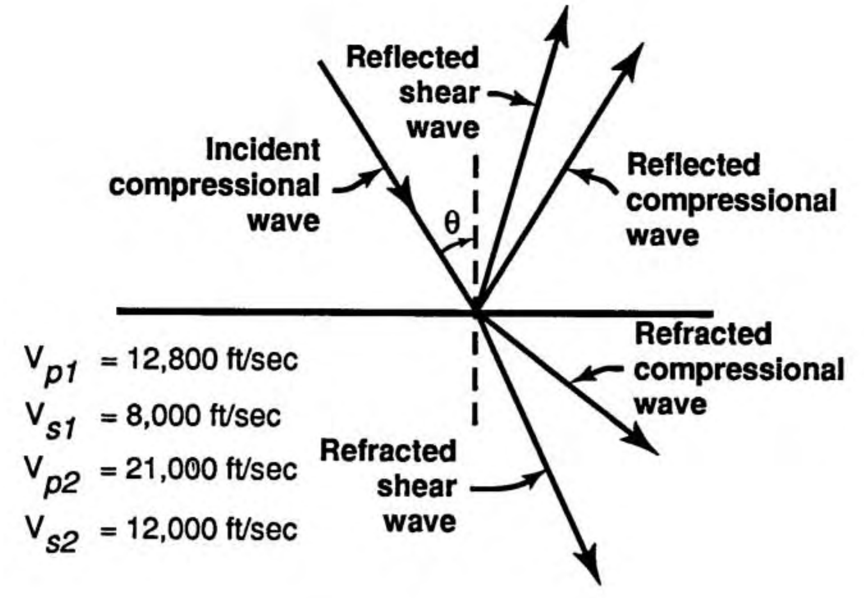

Figure 3. Partitioning of energy at an elastic boundary.

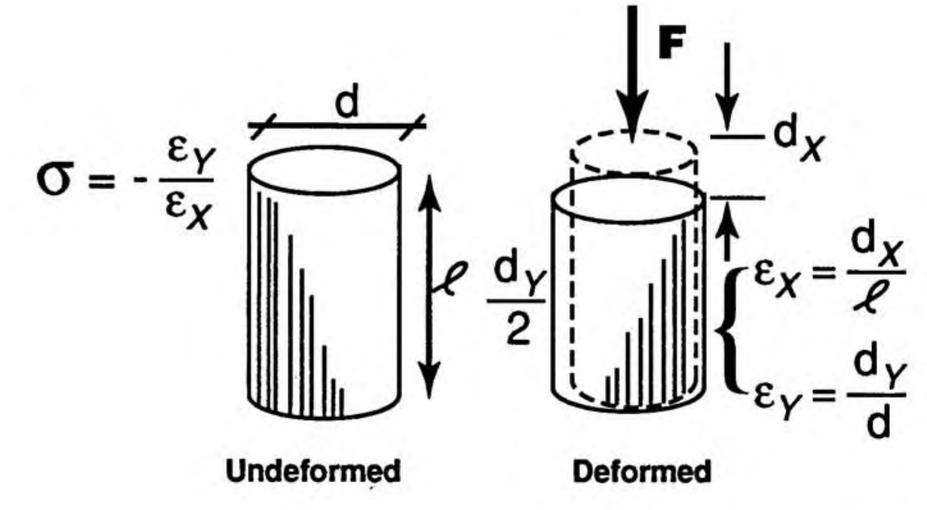

Figure 4. Poisson's ratio (σ).

Lithology	Poisson's Ratio (σ)
Shale	0.25 - 0.45
Sandstone	0.25 - 0.33
Unconsolidated Sandstone	0.30 - 0.40
Gas Sand	~ 0.10 - 0.18

Table 1. Values for Poisson's ratio (modified after Ross, 1992).

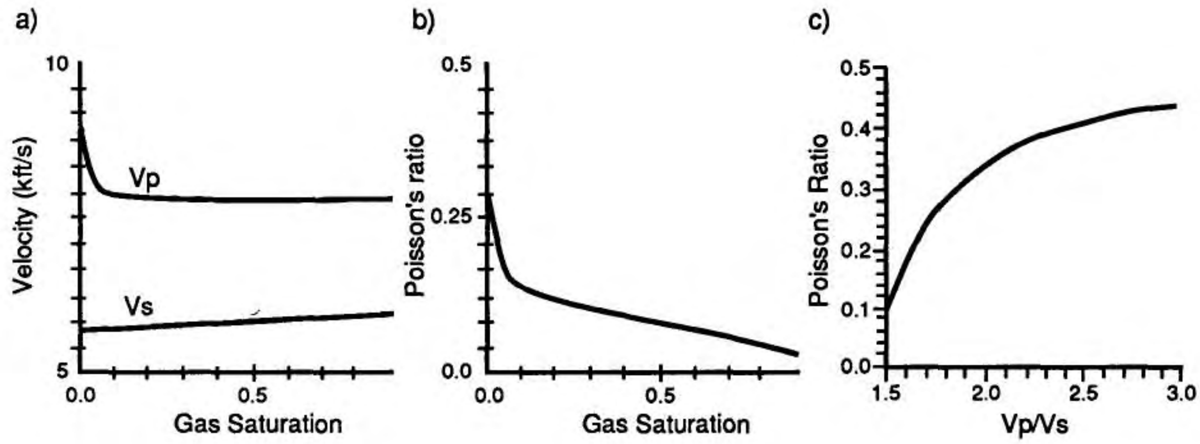

Figure 5. (a) P- and S- wave velocity as a function of partial gas saturation.
(b) Poisson's ratio versus gas saturation.
(c) *Vp/Vs* versus Poisson's ratio (from Allen and Peddy, 1993).

LABORATORY TESTING

Unlike the borehole and surface seismic environment, where the acquisition of shear-wave data is not always possible, shear-wave velocity can be measured in laboratory samples in all but the most unconsolidated rocks. Experiments can be conducted at reservoir conditions, e.g.- temperature and pressure (tensor stress distribution) under a wide range of frequencies. To evaluate the effects of dispersion low frequency data (seismic frequencies < 100 Hz) using dynamic, quasistatic (0.005 Hz), and static loading can be compared to ultrasonic acoustic data collected under the same conditions using conventional technologies (Abou-Sayed and Zheng, 1993). The intermediate (kHz wireline log) frequency range can be evaluated using pulse excitation methods, e.g.- resonance bar (column) and waveform inversion methods or continuous vibration torsional resonance methods (Bennel and Smith, 1991).

Unfortunately, a limited number of geophysicists use rock and fluid laboratory data in seismic modeling. As in reservoir simulation, there is a tendency for reservoir modelers to use preconceived or "textbook" values for critical input parameters. Because the inversion from seismic to petrophysical properties is non-unique, a better petrophysical understanding through rock property measurements from the laboratory would improve AVO inversion. In addition to measurement of Poisson's ratio and elastic moduli, other data useful in seismic modeling and inversion can be acquired if preserved full-diameter or rotary-drilled sidewall samples are available. Accurate laboratory measurements are dependent on having samples that reflect the properties of the reservoir under evaluation and the effects of sample disturbance and heterogeneity are often difficult to overcome. The most important techniques and data measured in the laboratory are: multifrequency P- and S-wave velocities at various fluid saturations; acoustic impedance and the calculation of reflection and transmission coefficients at acoustic interfaces; basic rock properties such as porosity, permeability, and mineralogical composition; rock frame and pore space characteristics using microscopy and mercury porosimetry in evaluating attenuation factors; poroelastic constants; acoustic and in-situ stress anisotropy using oriented core samples; and full waveform analysis to improve sonic log interpretation and improve estimates of the seismic absorption parameter (Q).

EXPERIMENTAL PROCEDURE

To validate AVO analysis as the seismic signature of lithology and fluid properties for several consolidated sandstones, P- and S-wave velocity measurements were made on plug samples. Tests were designed to assess variation of velocity and Poisson's ratio with increasing pressure and brine saturation. These data were then used to calibrate wireline sonic logs, model velocity and density behavior at partial fluid saturations, and model reflection amplitude variation with offset.

All plugs were oriented vertically and are sandstones representative of fluvial depositional environments. The rocks are classified as feldspathic litharenites or subfeldspathic arenites consisting mainly of quartz with only minor amounts of clay. P- and S-wave velocities were measured using an ultrasonic pulse transmission hydrostatic load system. Waveform analysis indicated an experimental frequency range of 50 to 200 kHz and all measurements were made at room temperature. Sample preparation was designed to approximate in-situ reservoir conditions, ensure mechanical integrity, and minimize mineralogical alteration. Velocity measurements were made at 0 (dry), 33, 70, and 100% brine saturation (partial gas saturations). At each of the partial saturation conditions, velocity measurements were made at four successively increasing confining pressures while maintaining pore pressure at atmospheric conditions for all partial fluid saturations and 200 psi pore pressure was applied at 100% brine saturation. Minor residual stress (hysteresis) effects were observed during pressure cycling. Basic rock property measurements were made according to API specifications, e.g.-density, porosity, and permeability.

DISCUSSION

The results of the laboratory acoustic study were used to predict fluid substitution behavior and validate AVO response. Figure 6 shows an averaged (exponential fit) of compresional- and shear-wave velocity with increasing pressure for several clean Miocene sandstones at 100% brine saturation. From 1000 to 5000 psi, P- and S-wave velocities increased with pressure as σ decreased from 0.26 to 0.23, respectively. Little increase in P-wave velocity was seen above 5000 psi, indicating closure of most microcracks. The S-wave velocity had the same relative change in velocity as the P-wave at 100% brine saturation.

Figure 7 illustrates the effects of increasing brine saturation on P-wave velocity and σ. As brine saturation increases from 0% (dry) to 100% (fully-saturated), P-wave velocity increases while S-wave velocity remains relatively constant. The observed differences in velocities are typical of consolidated sandstones. Poisson's ratio increases from 0.2 (dry) to nearly 0.3 (fully-saturated). For all samples and pressures, the difference in P-wave velocity between zero and 100% brine saturation ranged from 2 to 35% for various porosities and mineralogies. S-wave velocity decreases slightly with increasing water saturation because of an increase in sample bulk density.

Figure 8 is a cross-plot of σ versus P-wave velocity for several clean sandstones at various saturation conditions and 3500 psi (average net effective reservoir stress). This diagram clearly illustrates the dependence of σ on fluid saturation, which serves as the basis for AVO modeling. Sigma values for samples with partial brine saturation are between dry and fully-saturated conditions.

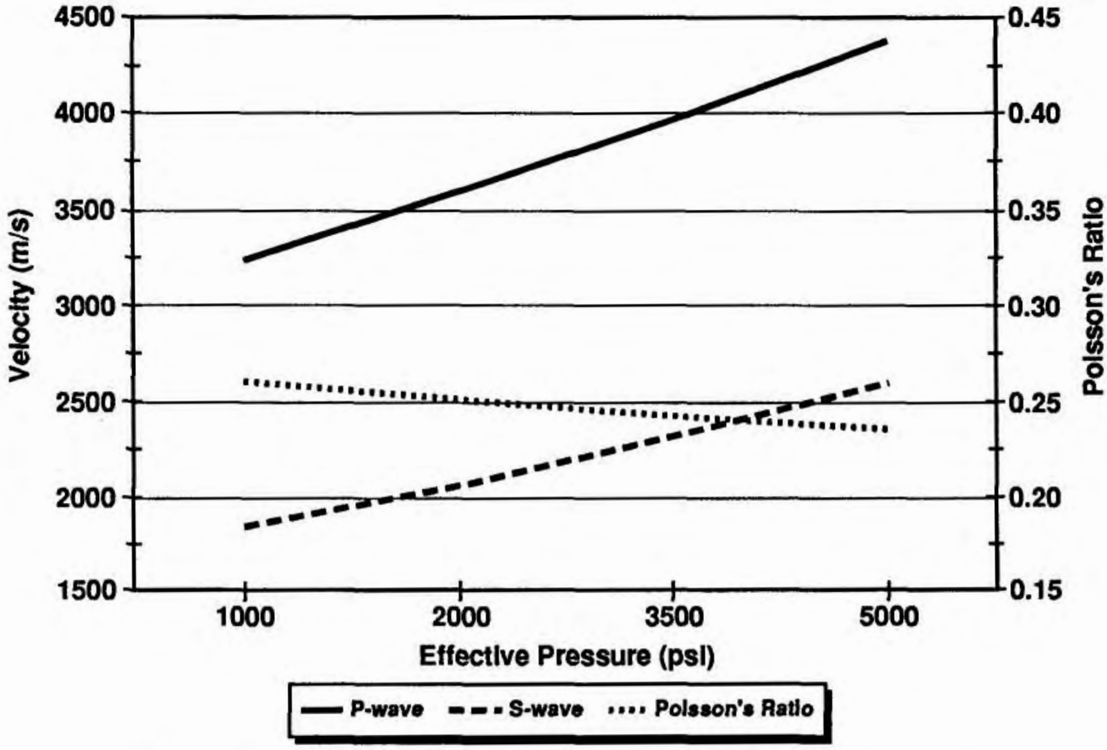

Figure 6. P-wave, S-wave, and Poisson's ratio variation with effective pressure.

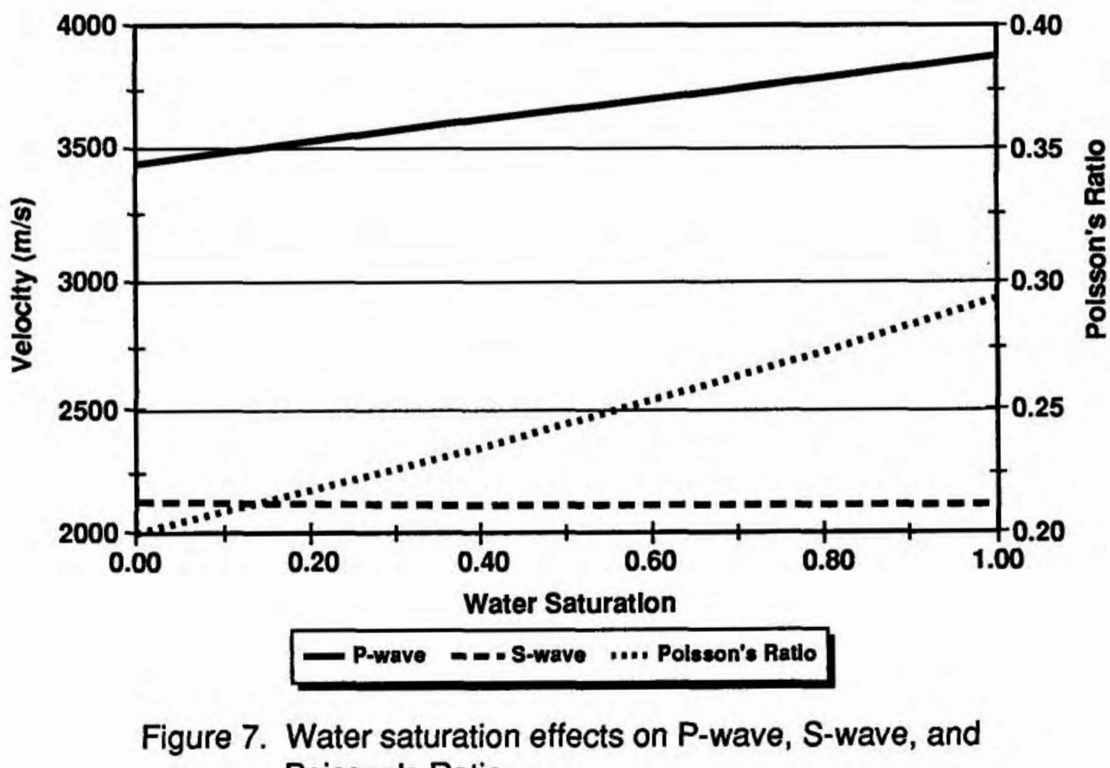

Figure 7. Water saturation effects on P-wave, S-wave, and Poisson's Ratio.

AVO modeling using Zoeppritz's equation was performed with gas-saturated (dry) and fully-saturated (wet) sandstone laboratory measurements and wireline shale values of Vp=3260 m/s, bulk density=2.46 g/cc, and σ=0.33. Laboratory shale data were unavailable because of sample consolidation and preservation problems. Although brine-filled sandstones have higher acoustic impedances (sandstone/shale reflection coefficient will be negative) the decrease in V_p for a gas-filled sandstone will decrease the acoustic impedance The resulting gas/shale reflection coefficient will be positive. Zoeppritz modeling demonstrates a decrease in amplitude-versus-offset for the wet-sand over shale interface while the gas sand over shale interface exhibits an increase, consistent with seismic (CMP) measurements.

Figure 9 is a plot of reflection coefficient (RC) versus incident angle (θ) for the encasing shale and dry/wet sands. The RC increases for the dry (gas) sand/shale from +0.008 (at normal incidence) to less than +0.06 at 30° θ. The fully brine-saturated wet sand/shale model produces a negative RC at normal incidence and becomes less negative at greater θ. Larger differences in σ would cause a greater rate of decrease in amplitude with offset. The reduction in σ with increasing gas saturation produces an increase in AVO and thus an increase in the slope of amplitude with offset. Note the larger normal-incidence amplitude for the wet sand/shale reflector where the average RC (from 0 to 30°) is greater than the average RC of the gas-sand/shale reflector. This infers that gas-charged sands encased by shale will be difficult to distinguish from wet-sands on a standard seismic display. However, positive amplitude-with-offset response is observable when advanced processing and rock property data are incorporated. The contrast in σ between dry (gas) and fully-saturated (wet) conditions causes illumination of these gas reservoirs with AVO techniques.

AVO INVERSION AND ACOUSTIC DATA INTEGRATION

AVO inversion involves the processing and evaluation of seismic and petrophysical data for modeling reservoir characteristics. Seismic processing of data for the calculation of reflection amplitudes as a function of either offset or angle-of-incidence cannot be conducted independently of petrophysical data analysis (Figure 10). Seismic amplitudes are not solely a function of rock properties and an increasing AVO response can be distorted by many complicating factors such as bandwidth and noise limitations (Ross, 1993). Dipole sonic (direct S-wave) wireline logging methods have improved the quality of synthetic seismograms for calibrating surface- and borehole-seismic data.

Few physical measurements scan as many scales as acoustic methods (Figure 11). Large-scale (seismic), intermediate-scale (borehole seismic, vertical seismic profile, and wireline-logging), and small-scale (laboratory methods) can be merged into a single interpretation scheme. Reconciling data collected at several scales is nontrivial. Differences in data can

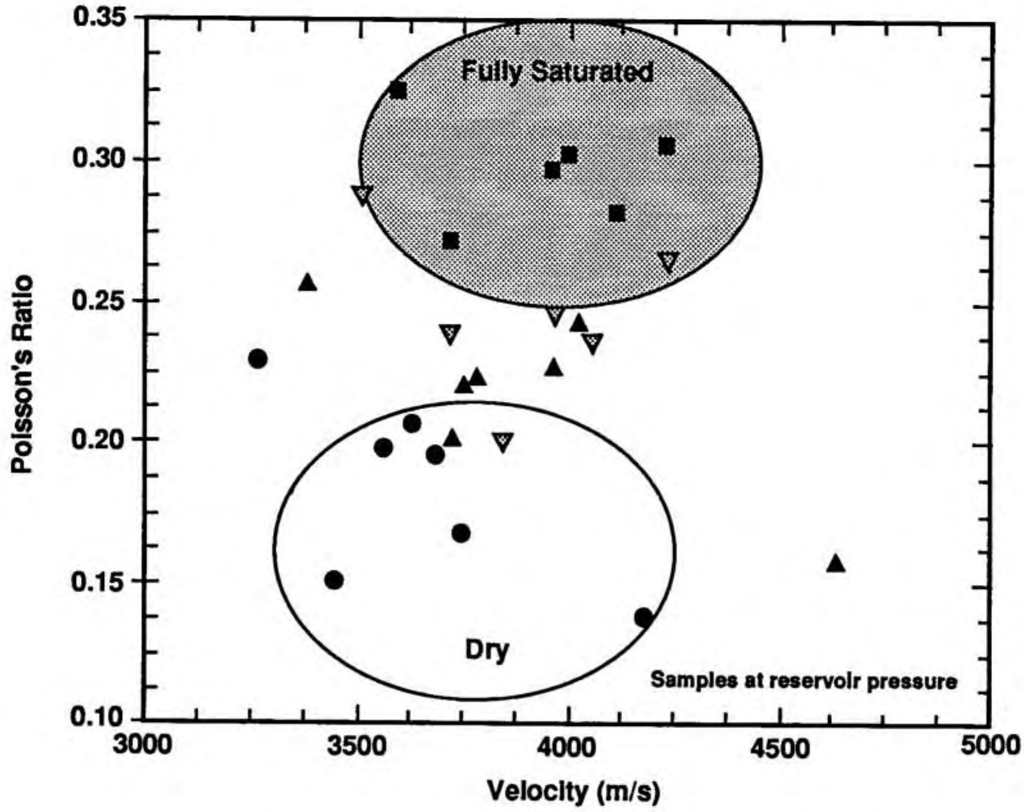

Figure 8. P-wave velocities versus Poisson's ratio for various saturation conditions.

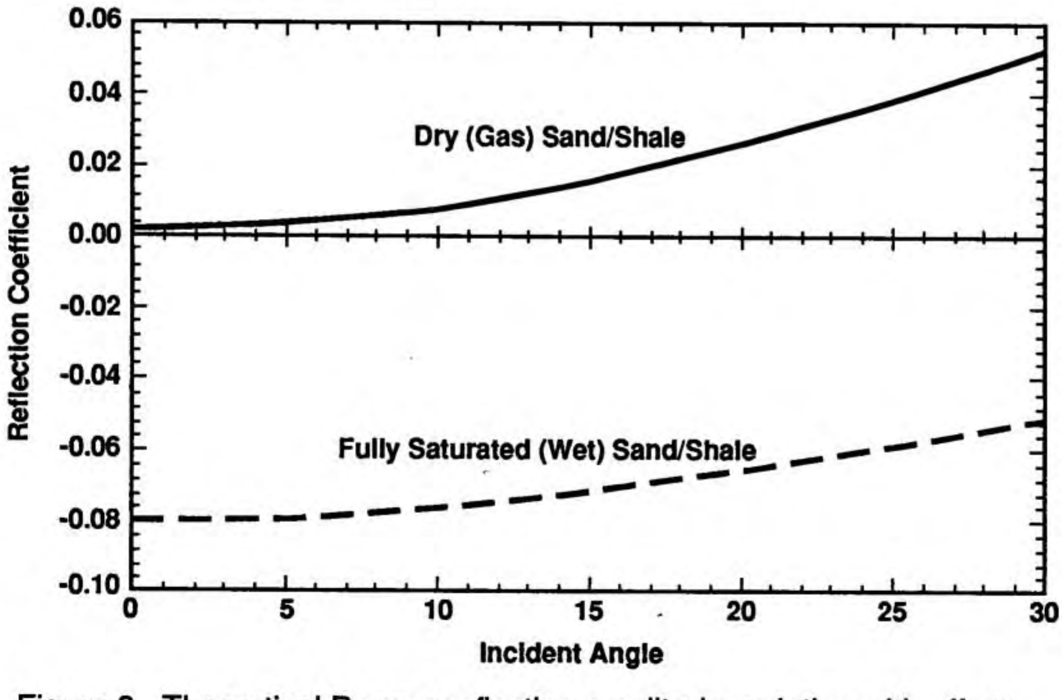

Figure 9. Theoretical P-wave reflection amplitude variation with offset for sandstone/shale interfaces using core measurements.

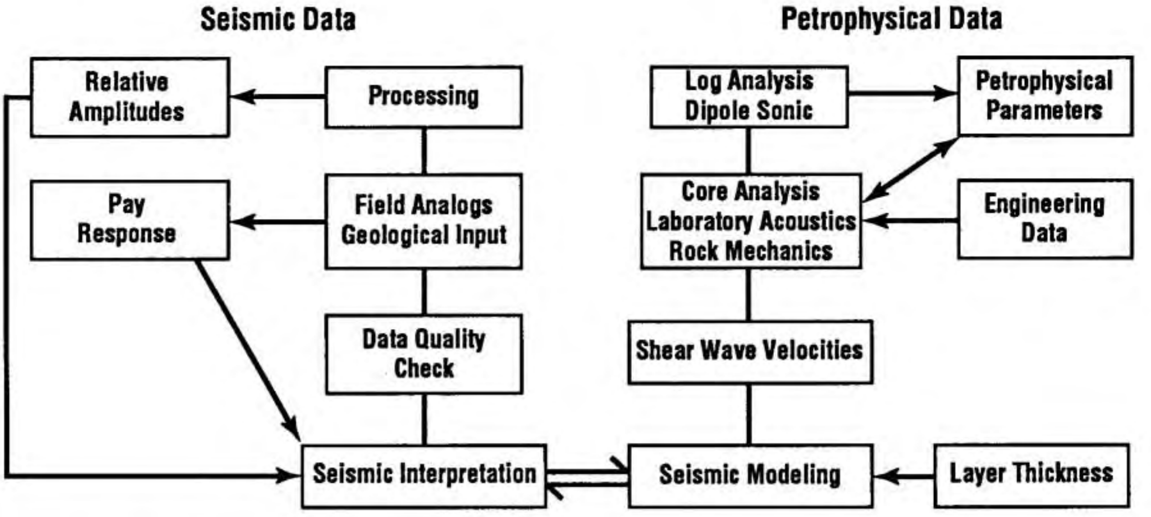

Figure 10. Flowchart showing the relationships between seismic and petrophysical data in AVO analysis (modified from Allen and Peddy, 1993).

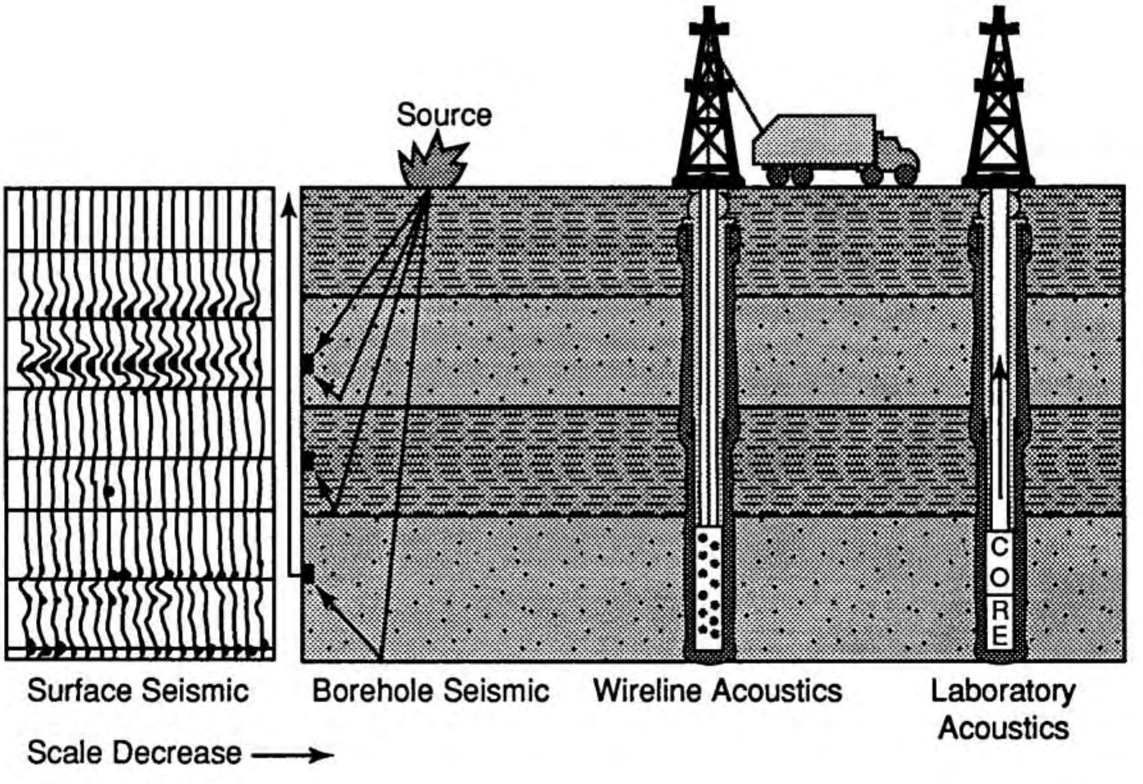

Figure 11. Acoustic data collected at various scales of measurement and resolution.

be attributed to measurement or sample volumes, acoustic anisotropy and reservoir heterogeneity, data acquisition and processing methods, strain amplitude and strain rate effects, time-effects (duration of stress), and experimental conditions (laboratory, borehole, and field).

CONCLUSIONS

AVO inversion and seismic modeling can benefit from an improved understanding of reservoir rock and fluid properties. Critical reservoir parameters measured from preserved core can provide a reliable means of calibrating seismic and borehole acoustic data. Laboratory data can reduce uncertainty in AVO modeling and influence exploration and production strategies. For consolidated sandstones, Poisson's ratio depends on fluid saturation and stress. Using standard equations, the sensitivity of rock properties on reflection coefficients versus angle-of-incidence can be calculated.

ACKNOWLEDGMENTS

The authors thank their respective employers for permission to publish this work. We also thank James Cantwell of Oryx Energy for drafting our figures.

REFERENCES

Abou-Sayed, A.S. and Zheng, Z., Some insights on the impact of loading frequencies on the mechanical properties of sandstones: Archie conference proceedings, 1993, 8p.

Allen, J.L. and Peddy, C.P., Amplitude variation with offset: Gulf Coast case studies: Society of Exploration Geophysicists (Tulsa), Geophysical Development Series, 126p.

Allen, J.L., Peddy, C.P., and Fasnacht, T.L., Some AVO failures and what (we think) we have learned: The Leading Edge (March), pp. 162-167.

Bennel, J.D. and Taylor Smith, D., A review of laboratory shear wave techniques and attenuation measurements with particular reference to the resonant column, *in* Shear Waves in Marine Sediments, J.M. Hovem et al. eds., Kluwer Academic Publishers (The Netherlands), pp. 83-93.

Bortfeld, R., Approximation to the reflection and transmission coefficients of plane longitudinal and transverse waves: Geophysical prospecting, 1961, **9,** p.485-502.

Hilterman, F., Is AVO the seismic signature of lithology? A case history of Ship Shoal-South Addition: The Leading Edge (June), 1990, pp. 15-22.

Ostrander, W.J., Plane-wave reflection coefficients for gas sands at nonnormal angles of incidence:Geophysics, 1984, **49, 10**, pp. 1637-48.

Ross, C.P., AVO in the presence of coherent noise: The Leading Edge (March), 1993, pp. 196-201.

Ross, C.P., Incomplete AVO near salt structures:Geophysics, 1992, **57**, pp.543-53.

Shuey, R.T., A simplification of the Zoeppritz equations: Geophysics, 1985, **50**, pp.609-14.

Skopec, R.A., Amplitude-versus-offset and rock properties: can laboratory data improve seismic interpretation?: EAPG Core Analysis for Reservoir Management Workshop Volume, 1994, 6p.

Young, G.B. and Braile, L.W., A computer program for the application of Zoeppritz's amplitude equations and Knot's energy equations: Bulletin Seismic Society America, 1976, **66**, pp.1881-85.

Zoeppritz, K.: Erdbebenwellen VIII B, On the reflection and penetration of seismic waves through unstable layers: Gottinger Nachr., 1919, **1**, pp.66-84.