Issues in rock physics and implications for DHI interpretation

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Seismic techniques for direct hydrocarbon indication rely on the changes in seismic character which accompany changes in pore fluid content. Interpretation and modeling of direct hydrocarbon indicators (DHIs) require an understanding of the factors affecting seismic velocities and reflection coefficients which are, in turn, dependent on pore fluid properties, rock frame properties, and fluid substitution within a given rock frame. Recent developments in rock physics have greatly increased our general understanding in these areas but have also revealed complications that require further research.

In the past decade, notable progress has been made in several areas which are particularly important for DHI analysis. These include:

Shear-wave velocity prediction. In 1985, in conjunction with Ray Eastwood, two of us (Castagna and Batzle) published the "mudrock trend" in GEOPHYSICS. This equation allows rough estimation of shear-wave velocities in clastic basins and has been extensively used in AVO analysis and other applications, particularly when little other information about rock properties is available. The following year, one of us (Han), along with Nur and Morgan, published detailed relationships between compressional- and shear-wave velocities, porosity, clay content, and effective stress for well consolidated shaly sandstones. A very robust algorithm for shear-wave velocity estimation in mixed lithologies, developed by Matt Greenberg and Castagna, was published in *Geophysical Prospecting* in 1992.

Pore fluid properties. Another development in 1992 was a GEOPHYSICS paper by Batzle and Wange on pore fluid properties. It thoroughly reviewed the pressure, temperature, and composition dependence of gas, oil, and brine bulk modulus, density, and viscosity. Their equations have been incorporated into a variety of commercial modeling packages.

Rock frame properties. Castagna, Batzle, and Kan presented a methodology for extracting frame modulus trends, needed for fluid substitution calculations, from ultrasonic laboratory measurements on monomineralic brine-saturated rocks in SEG's 1993 book *Offset-Dependent Reflectivity — Theory and Practice of AVO Analysis.* James Berryman has shown how to properly combine frame properties for mixed lithologies.

Rock fluid interactions. Work by Gary Mavko, Jack Dvorkin, Amos Nur, James Berryman and many others suggests that Biot-Gassman theory can be refined and improved.

These developments have resulted in greatly improved DHI interpretation capabilities. The purpose of this article is to review some of these developments, discuss their impact (real and potential) on the exploration paradigm, and suggest directions for further research which is urgently required.

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Pore fluid properties. DHI modeling requires an understanding of the effects of pore fluid properties on formation density and seismic velocities. Formation compressional velocity and density are dependent on the pore fluid bulk, modulus, and density while the shear-wave velocity is not affected by pore fluid bulk modulus and only weakly affected by the pore fluid density. As pointed out by Ostrander in his classic 1984 paper in GEOPHYSICS, this is the basis for gas detection using AVO. However, we can be somewhat more quantitative than the general statement that gas is much more compressible and much less dense than water. Within the past decade, geophysicists have become far more aware of the dependence of pore fluid properties on composition, pressure, and temperature. Prior to the mid-1980s it was common practice to use a given bulk modulus or density for gas, oil, and water irrespective of reservoir conditions. Wang, along with Nur in 1986 and with the addition of Batzle in 1988, showed at SPE annual meetings that oil bulk moduli and densities vary significantly and systematically with changing pressure, temperature, and composition. At SEC's 1988 Annual Meeting, Hwang and Lellis showed bright spots in the Gulf of Mexico which were caused by high gas-oil ratio oils. In his classic 1987 paper, Chiburis used AVO to reliably detect oil reservoirs in carbonates. This achievement was met with great skepticism by workers who understood the similarity between "dead" oil and brine bulk moduli at standard temperature and pressure. We now know that "live" oil at reservoir conditions may have a bulk modulus that is significantly lower than brine modulus. In a 1992 GEOPHYSICS paper, Clark studied oil properties at in-situ temperature and pressure conditions and showed related bright spots. In their thorough 1992 review, Batzle and Wang developed equations to predict gas, oil, and brine properties as a function of temperature, pressure, and composition. For proper DHI analysis, it is now fairly routine to use these equations to calculate pore fluid properties versus depth. This often requires close integration with engineers, geologists, and geochemists.

However, the effects of gas in brines requires further study. Using a poorly documented equation by Dodson and Standing given in a 1945 drilling and production handbook published by API, expected variations of brine modulus with dissolved gas content were tentatively plotted (with many apologies) in an appendix added to a 1993 review paper by Castagna, Batzle and Kan on rock physics for AVO analysis and shamefully published by SEG, much to its discredit (where were you Don Steeples?). These plots indicated that dissolved gas could produce a two-fold decrease in brine modulus, a result that seemed extreme to many. These results are contradicted by measurements made by Osif and published in *Reservoir Engineering* in February 1988. Osif's data suggest a much smaller effect at high pressures than that predicted by Dodson and Standing.

Additional work is also needed for us to fully comprehend the effects of phase changes which accompany reservoir pressure and temperature changes. For example, if oil reservoir pressure drops during production, gas may come out of solution and dramatically change the seismic response. When preparing reservoir monitoring schemes or using producing fields and analogs for undrilled prospects at virgin pressure, phase changes due to changes or differences in reservoir pressure must be considered. An outstanding paper by A.W. Siewart on this subject was presented at the VII Congreso Venezolano Geofisica in 1994 and is currently undergoing revision for publication in *TLE.*

Frame properties and fluid substitution. Determination of frame bulk and shear moduli for fluid substitution is problematical. Measurement of dry rock modulus is fairly straightforward; however, due to chemical interactions, pore fluids may alter the frame properties and the dry rock properties may not be applicable for fluid substitution. Given a valid model relating fully water-saturated and frame moduli, one could use measured compressional and shear-wave velocities for the water-saturated rock to calculate frame moduli. Gassman's equations are commonly used to do this. These equations are the low frequency limit of the more general Biot theory for wave propagation in poroelastic media. However, if the frame properties are derived from ultrasonic laboratory measurements using Gassman's equations, the predicted frame and gas-sand Poisson's ratios may be too high. For a suite of sandstones, we have found that frame bulk modulus is about equal to frame shear modulus for dry samples. This relationship also holds for fully water-saturated sandstones when Biot's high frequency equations assuming no fluid-solid coupling are used. However, when frame moduli are extracted from laboratory measurements on fully water-saturated sandstones using Gassman's equations, frame bulk modulus tends to be larger than frame shear modulus (this corresponds to a higher frame Poisson's ratio).

Castagna, Batzle, and Kan (1993) provide frame moduli trends for sandstones, limestones, shales, and dolomites. For mixed lithologies, these trends are generally averaged in some way. However, as shown experimentally by Han and others, the effects of clay or weak cementation may be highly nonlinear. In addition, Gassman's equations are not strictly valid for mixed lithologies. We suspect that this may be a significant issue for shaly rocks.

Sonic log readings in gas sands. Despite the critical importance of sonic log information for gas-sand modeling and interpretation, a number of important issues remain poorly investigated and unresolved:

1) It is well established that free gas in the formation results in high signal attenuation. This loss of sonic signal strength can be intensified by attenuation due to gas in the drilling mud and large scattering losses resulting from propagation of the sonic signal across large impedance contrasts at gas-sand bedding boundaries. Furthermore, the low Poisson's ratio of gas sands relative to surrounding material results in relatively poor excitation of the sonic signal (compressional head wave) in the formation. These factors combine to make sonic log cycle skipping extremely common in gas sands. Although helpful as a gas indicator on the logs, the effect is obviously unwanted for seismic modeling purposes.

2) In shallow, unconsolidated gas sands, the formation P-wave velocity may be less than that of the drilling fluid. As conventional sonic logging relies on the generation of a refracted compressional head wave in the formation (something which does not occur when the formation velocity is less than that of the drilling fluid), conventional P-wave logs often "flat-top" near the fluid velocity in gas sands. This often goes unrecognized in the log editing process.

3) Logging accuracy is further hindered by formation damage and the invasion of drilling fluid into the formation pore space surrounding the borehole. As all the formation gas is not necessarily flushed by invasion, one would expect a very small effect at seismic frequencies, where Gassman's equations predict that sandstone compressional velocities are much more sensitive to the presence or absence of gas than to the precise gas saturation. However, sonic frequency laboratory measurements, conducted by Murphy at Stanford and found in his 1982 dissertation, show a much more regular and gradual change of velocity with saturation. Thus, all sonic logs should be corrected for invasion and dispersion prior to seismic modeling. More work is needed to determine the best way to accomplish this.

Overall, there may be some merit to the idea of acquiring dipole sonic logs to predict seismic frequency gas-sand compressional velocity using measured sonic shear-wave velocity and trend curves.

Dispersion and attenuation in gas sands. It is generally assumed that velocity dispersion between sonic and seismic frequencies is on the order of a few percent (see, for example, the 1994 paper by De and coworkers in GEOPHYSICS). This suggests that dispersion may be important for time-to-depth conversion, but that check-shot calibration is adequate to correct seismic-to-sonic velocity differences. However, it is also well known that (1) dispersion is a necessary result of frequency dependent attenuation and (2) frequency dependent attenuation is extremely high in gas sands. One can conclude indirectly then that gas sands should exhibit abnormally large dispersion. Gas-sand velocity dispersion between sonic and seismic frequencies may be sufficient to significantly alter normal incidence reflection coefficients and AVO response. A dispersion correction more specific than check shot calibration may be required for proper gas-sand modeling. As existing poroelastic wave propagation theories have not been shown to adequately predict the frequency dependence of velocity and attenuation in realistic reservoir gas sands, this is an important area of ongoing research.

Conversely, some attempts have been made to measure dispersion in the seismic frequency band, and to use the quantity as a DHI (this is a tough problem for a variety of reasons). Laboratory measurements and theoretical treatments for two-phase pore fluids suggest that attenuation may be highest for noncommercial gas saturations.

This effect is being studied by a number of workers as a means of seismically distinguishing noncommercial from commercial gas accumulations (this is another tough problem).

Conclusions. DHI analysis requires an understanding of the relationships between seismic response and pore fluid properties. Establishment of these relationships requires knowledge concerning the elastic properties of the pore fluid and the rock frame and models for rock-fluid interaction. Although the systematics of pore fluid bulk modulus and density variation with pressure, temperature, and composition are fairly well established, additional calibration is needed, especially for gas-water mixtures. Furthermore, the effects of phase changes are not yet readily dealt with. Frame modulus trends also need additional calibration and the effects of mixed lithologies require further research. Sonic log velocities are often incorrect in gas sands: improved correction methodologies are awaiting development. Additional theoretical and experimental investigations of rock-fluid interactions are necessary before we can hope to accurately predict the frequency dependence of attenuation and velocity. This capability would enable the transformation of sonic logs to seismic velocity logs, especially in gas sands, and would provide a foundation for further research into the use of seismic attenuation and dispersion as hydrocarbon indicators.

Suggestions for further reading. Castagna never misses an opportunity to recommend Smith and Gidlow's 1987 paper in *Geophysical Prospecting* or Chiburis' work (presented at SEG Annual Meetings in 1984 and 1987 and featured in SEC's 1993 book). Also highly recommended is SEG's new book *Amplitude Variation With Offset: Gulf Coast Case Studies* by Allen and Peddy.

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Mike Batzle is research scientist at the Colorado School of Mines. He was found in a shipping crate along with ARCO'S rock physics lab which was donated to CSM. This laboratory has the capability of making velocity and attenuation measurements over a continuous frequency band from seismic to sonic frequencies under in-situ temperature and pressure conditions and pore fluid saturations. He can be reached at 303-384-2067.

De-Hua Han is research scientist at the Geotechnology Research Institute of HARC. He is conducting integrated rock physics research which utilizes a state-of-the-art rock physics laboratory which was donated by Unocal. He is currently forming an industry-supported rock physics consortium. Further information is available at 713-363-7915 (email:s32deha@gtri.harc.edu).