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Recent advances in seismic lithologic analysis

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INTRODUCTION

An objective of seismic analysis is to quantitatively extract lithology, porosity, and pore fluid content directly from seismic data. Rock physics provides the fundamental basis for seismic lithology determination. Beyond conventional poststack inversion, the most important seismic lithologic analysis tool is amplitude-variation-with-offset (AVO) analysis. In this paper, I review recent progress in these two key aspects of seismic lithologic analysis.

In 1993, the Society of Exploration Geophysicists issued two books on AVO analysis that reviewed early work in the field (Allen and Peddy, 1993; Castagna and Backus, 1993). However, these volumes were effectively obsolete by the time they came to press—glaring omissions included hardly any discussion of AVO crossplotting or anisotropic AVO, and virtually nothing on long-offset and postcritical AVO, 3-D AVO, and statistical analysis of AVO anomalies. I therefore focus this discussion on the particularly important developments in AVO analysis that postdate these books.

Progress in rock physics has been thoroughly reviewed in books by Bourbie et al. (1987), Nur and Wang (1988), Wang and Nur (1992), and Mavko et al., (1997). There is insufficient space here to do justice to the work conducted at Stanford University alone, and it comprises only a fraction of the entire body of recent rock physics literature. The reader, therefore, is directed to these excellent publications for a general overview, while I address only a few key developments related to seismic lithologic analysis and apologize in advance for any omissions.

PROGRESS IN ROCK PHYSICS

Frequency and saturation dependence of velocities

The ultimate question in rock physics for direct hydrocarbon indication is *How do velocities changes when pore fluid content changes?* Another important question intimately tied to this one is *How does velocity and attenuation vary with frequency?* In particular, we wish to know how to use measurements made at sonic and ultrasonic frequencies and apply these to propagation of waves at seismic frequencies. More specifically, we need a rock physics model that can transform velocities from one saturation state to another. For close to half a century, seismic analysts have used the well-known Biot-Gassmann theory to accomplish such transformations. The current consensus appears to be that the theory is applicable at low frequencies if "patchiness" is appropriately considered (e.g., Knight et al., 1998; Mavko and Mukerji, 1998) but that squirt flow or other mechanisms are important at high frequencies or low permeabilities (e.g., Dvorkin and Nur, 1993). Variations in velocity-saturation curves appear to be related to unequal saturation in compliant and noncompliant pores and to spatial saturation heterogeneity (Endres and Knight, 1991; Mavko and Nolen-Hoeksema, 1994; Goertz and Knight; 1998). However, there may be additional mechanisms at work. For example, Batzle et al. (1997) experimentally found velocity variations due to fluid mobility changes for which a specific mechanism is yet to be identified. Brie et al. (1995) used the idea of an "effective" fluid modulus that can be derived from combined compressional and shear-wave velocity measurements to empirically deal with dispersion. Brie et al.'s approach is useful for practical applications, but as a strictly empirical method, it must be locally calibrated and tested.

Pore fluid properties

The classic synthesis of fluid properties information by Batzle and Wang (1992) has been continually updated; however, much of this data has unfortunately not found its way into the open literature. In particular, a standard reference for drilling-mud filtrate properties is needed to allow proper invasion correction of sonic log data. In general, working geophysicists need to develop a better understanding of pressure-volume-temperature relationships and corresponding properties of reservoir fluid mixtures than is commonly achieved in practice.

Complex lithologies and composite medium modeling

Berryman (1995) provides a comprehensive review. Perhaps the most significant developments of the past decade for our purposes are the extension of Gassmann's equations to multiple constituents by Berryman and Milton (1991) and

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the increasing use of differential self-consistent models for high-frequency moduli (e.g., Berge et al., 1993; Le Ravalec and Gueguen, 1996).

Shear-wave velocity prediction

The Krief et al. (1990) and Greenberg and Castagna (1992) algorithms have been refined by Xu and White (1995) and Goldberg and Gurevich (1998). Due to experimental error, however, it is difficult to demonstrate improvement of prediction error to better than about 5%.

Nonlinear behavior

Bonner and Wannamaker (1991) and Tutuncu et al. (1998a, b) among others have described strain amplitude dependence of velocities and attenuations that have yet to be integrated into the thinking of seismic lithology practitioners.

Anisotropy

Laboratory measurement of anisotropic parameters is still problematical due to scale effects and the difficulty of knowing a priori the symmetry class and axes orientations needed to optimize experimental design (C. Sondergeld and C. Rai, personal communication, 1999). A larger database of measurements is needed in the literature (e.g., Vernik and Liu, 1997), as are improved methods of estimating anisotropic paramaters for seismic modeling purposes (e.g., Ryan-Grigor, 1997). More measurements under triaxial stress (e.g., Dillen, 1999) are needed.

Time-lapse effects

Changes in reservoir velocities with time may be greater or less than predicted by mechanical fluid substitution due to changes in rock frame moduli caused by reservoir consolidation, microfracturing, effective stress variations, or other rock fluid interactions. T. Davis (2000 SEG Distinguished Lecture) has made field observations of significant changes in shear-wave velocity associated with reservoir production and enhanced recovery operations. Wang et al. (1998) demonstrate in the laboratory that time-lapse effects may be much larger than predicted by Biot-Gassmann theory.

PROGRESS IN AVO ANALYSIS

AVO attributes

Since Smith and Gidlow's (1987) introduction of the fluid factor, use of intercept-gradient crossplot-related indicators (e.g., Castagna and Smith, 1994; Foster et al., 1997) has become routine (e.g., Foster et al., 1993; Fatti et al., 1994; Nickerson and Cambois, 1998). AVO indicators are reviewed by Swan (1993). Castagna et al. (1998) provide equations that relate background trends to petrophysical relations and expand the Rutherford and Williams (1989) classification to include low-impedance reservoirs for which reflection coefficients decrease in magnitude with increasing offset (class IV sands). Cambois (1998) shows that noise can dominate the slope of background trends.

Pore fluid identification

Theoretically, AVO can be used to separate density and velocity contrasts, which could then be used to distinguish pore fluids types and saturations. The ability to identify partial gas saturations is of obvious importance. In practice, careful petrophysical control and detailed modeling and/or inversion can potentially be used to identify fluid type (e.g., Regueiro and Pena, 1996; Cardamone and Corrao; 1999). It is hoped that combined P-P and P-SV converted-wave AVO analysis will improve pore fluid identification.

Statistical AVO analysis

Increasingly, it is being recognized that AVO attributes should be accompanied by a measure of the probability of a particular outcome (i.e., hydrocarbons). Handling this problem from a rock physics and seismic modeling perspective is fairly straightforward (Castagna and Samake, 1998; Mavko et al., 1998; Dey et al., 1999; Houck, 1999; Sengupta and Mavko, 1999). What is more difficult is quantifying the uncertainty in hydrocarbon detection due to variations in seismic data quality. This involves transforming rock physics derived probability density functions into the real seismic-data domain (which requires more than simple forward modeling) and promises to be a fertile area for seismic research for years to come.

Prestack imaging

AVO analysis can be no better than the prestack imaging of the target. Proper migration improves the signal-to-noise ratio and lateral resolution of extracted AVO attributes (Mosher et al., 1996). Ross (1997) and Xu et al. (1993) among others discuss problems in AVO analysis in structurally complex situations.

3-D AVO analysis

Unfortunately, the advent of 3-D seismic data has not always been the boon to improved AVO analysis that might have been anticipated, and it is still common practice to do AVO studies on "high-quality" 2-D lines that cross a prospect occurring on a 3-D dataset. Part of the problem is logistical in that it is commonly the case that 3-D gathers are not preserved and only near-, mid-, and far-trace partial stacks are available for analysis. Also, for reasons of economy, 3-D data often have reduced fold and aperture. The largest problem, however, is related to the acquisition footprint (e.g., Canning and Gardner, 1998; Ronen and Liner, 2000) particularly troublesome for button-and-patch type geometries. Ultimately, 3-D imaging with proper amplitude handling and routine preservation of prestack gathers will result in far improved AVO analysis with 3-D data.

Noise suppression

In doing AVO analysis, CDP stacking, the most powerful noise suppression tool in the processing of seismic reflection data, is not available except in the form of limited range (partial) stacks. Thus, prestack noise suppression techniques are particularly important. In the past decade, prestack Radon filtering (e.g., Foster and Mosher, 1992) has proven to be a particularly useful technique. Weglein (1999) reviews the latest developments in multiple suppression and describes inverse scattering techniques that appear to be particularly promising for AVO analysis.

Velocity Analysis

Velocity analysis is perhaps the most critical aspect of AVO attribute extraction. The semblance statistic used in conventional velocity analysis implicitly assumes no amplitude variation with offset. This is particularly troublesome when amplitudes change sign with increasing offset and often result in improperly "flattened" seismic gathers at the target horizon. Kirlin (1992) and Sarkar et al. (1999) among others describe velocity analysis methods that are not confounded by AVO effects. Ursin and Ekren (1995) describe automated methods for dealing with residual NMO errors.

AVO inversion

In the presence of well control, conventional full-waveform AVO inversion can be a very useful technique (e.g., Buland et al., 1996; Mahob et al., 1999). In the absence of well control, the genetic algorithm approach is preferred (e.g., Mallick, 1999); however, no inversion method can overcome the fundamental nonuniqueness of the problem (e.g., Drufuca and Mazzotti, 1995) and a very good starting model is usually needed for inversion to be helpful. Thus, it is more appropriate to view traditional AVO inversion as an interpretation aid, in that it can provide an earth model that is "near" an initial interpretation while also being compatible with the seismic observations. The one-step waveform-based linear inversion of Simmons and Backus (1996), by assuming a background that obeys petrophysical trends, uses AVO prediction error as a useful means of detecting AVO anomalies. Perhaps the most important (but least discussed or studied) aspect of AVO inversion is the prestack amplitude correction or calibration that is applied to the data prior to inversion. It remains to be proven that deterministic amplitude calibration applied predrill is generally adequate for quantitative inversion. In most cases, some form of statistical amplitude balancing is required (Rutherford, 1993; Ross and Beale, 1994).

AVO for thin beds

Tuning of base and top reservoir reflectors and interference with nearby strong reflectors or within stratigraphically complex reservoirs remains problematical. Bakke and Ursin (1998) and Dong (1999) among others discuss the importance of correcting or at least assessing the importance of tuning effects. Swan (1993) provides insight into how such effects may be compensated for.

N-dimensional AVO

With the relative cost of multicomponent recording continuing to fall, there is no question that AVO analysis will eventually routinely involve a minimum of three-components (plus a hydrophone for ocean-bottom cables) and use P-S in addition to P-P reflections. Nine component acquisition may be resurrected at some point if economics allow. With computer capacity continuing to evolve at an exponential rate, handling of massive volumes of data will become routine. Ultimately, multicomponent datasets will routinely be acquired in three dimensions, possibly with downhole instrumentation and/or vertical hydrophone cables, in a time-lapse mode. Much research will be required to perfect data integration and amplitude preservation for such complex datasets.

Using the entire prestack gather

In the past decade, prestack analysis has been extended to increasingly far offsets, with offset-to-depth (O/D) ranges sometimes exceeding two. In addition to providing more aperture for imaging and AVO analysis, the introduction of very far offsets has created new challenges. These include handling nonhyperbolic moveout, inadequacies of Zoeppritz approximations, increased contribution of anisotropy, and postcritical angle effects. The exploration community has little experience dealing with very far offset data because these historically have been muted out in processing, and we are only recently starting to understand how to interpret such data.

Nonhyperbolic moveout

Ross (1997) demonstrates how higher order moveout corrections can be used to properly flatten events with large O/D ratios and, consequently, extract more accurate attributes. Anisotropy causes characteristic "hockey sticks" on gathers that are not properly NMO corrected with hyperbolic moveout (F. Hilterman, 1999, SEG Distinguished Lecture). Higher-order or anisotropic moveout correction is required.

Inadequacies of the Zoeppritz approximations

Approximations to the Zoeppritz equations generally assume small contrasts in elastic parameters and small angles of incidence, and fail as the critical angle is approached (e.g., Castagna et al., 1998). Lavaud et al. (1999) attack this limitation by inverting the full Zoeppritz equations at large offsets using an optimal combination of layer parameters, although even this may not be sufficient due to complications discussed below. Chen and Castagna (1999) showed that even at small angles of incidence (less than 30°) the curvature term (third coefficient) should be corrected by addition of the square of the normal incidence reflection coefficient.

Contribution of anisotropy

Anisotropy affects AVO analysis by (1) causing nonhyperbolic moveout and corresponding errors in attribute extraction, (2) introducing angle dependent transmission losses, and (3) modifying angles of incidence, the reflection coefficients at the target (e.g., Carcione et al., 1998), and the location of the critical angle (e.g., Bork et al., 1997). Ruger (1997) provides the most accurate and useful approximation to the anisotropic Zoeppritz equations. It includes the effects of contrasts in anisotropic (Thomsen) parameters across an interface, although average anisotropies may also significantly alter the reflection coefficients (Chen and Castagna, 1999). Azimuthal anisotropy may confound AVO analysis or be used as a fracture characterization tool (e.g., Ramos and Davis, 1997; Lynn et al., 1999, MacBeth and Li, 1999).

Critical and postcritical angle effects

A common pitfall in interpretation of amplitudes at far offsets is mistaking large amplitude increases near the critical angle for Poisson's ratio effects. In fact, the location of the critical angle depends only on the P-wave velocity ratio across an interface and has no direct relationship to Poisson's ratio contrasts. Postcritical complications include large reductions in P-wave reflection amplitude and interference (due to shear-wave mode conversion), phase shifts introduced by complex reflection coefficients, and appearance of refracted head waves (e.g., Borejko et al., 1998) which may be confused with primary reflections. Phase shifts and head waves may both be readily misidentified as "hockey" sticks caused by anisotropy. A further postcritical complication results from inhomogeneous waves in an attenuating medium. Carcione (1999) concludes that AVO studies should not be based on forward models and processing techniques that neglect vector attenuation.

CONCLUSIONS AND DISCUSSION

In the presence of abundant well control, quantitative analysis of poststack seismic data has proven to be an effective method for reservoir characterization (e.g., Sheriff, 1992). However, without well control, accurate quantitative estimation of rock parameters has proven elusive and routine application of seismic lithologic analysis rarely exceeds the identification of anomalous behavior. In order to achieve improved quantitative parameter estimation, geophysicists will need to (1) use and integrate all available data (this means, in part, using the entire dataset before stack, including information that is usually muted out in current practice), (2) continue to make progress in understanding of rock physics and its use in seismic analysis, (3) recognize that the earth is far more complex than a stack of isotropic Goupillaud layers, (4) properly deal with uncertainty and nonuniqueness, and (5) bring in additional independent information by exploiting as much of the full seismic wavefield as possible and making time-lapse measurements.

Seismic lithologic analysis is highly complex and promises to become more so in the future. There are so many pitfalls that many potential practitioners are led to doubt the usefulness of the method. On the other hand, there are many success stories in exploration and reservoir characterization, and there are highly competent organizations that use seismic lithology methods effectively. This means there is tremendous opportunity waiting for those that are willing to invest the time, effort, and capital needed to properly exploit the technology.

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