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Special section on azimuthal dependence of *P*-wave seismic signatures—Introduction

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This special issue is based on papers presented at the post-convention SEG workshop on azimuthal dependence of P-wave signatures held in Dallas in 1997. The main motivation for analyzing the azimuthal variation of seismic traveltimes, amplitudes, attenuation, etc. is to obtain reliable information about azimuthal anisotropy in the subsurface. Another potential application of multiazimuth techniques is in finding and mapping desirable lateral heterogeneities that could "masquerade" as azimuthal anisotropy. The last topic has not yet been fully discussed (and is not addressed in the special issue), but several exploration and development scenarios contain oriented lateral heterogeneities (sand channels, etc.) that at the right scale length could be highly visible in properly processed wide-azimuth 3-D data.

The most common physical reasons for azimuthal anisotropy are systems of vertical (or steeply dipping) fractures or tilted transversely isotropic layers. Both types of azimuthally anisotropic models are discussed here, with an emphasis on issues related to fracture detection and characterization. In tight formations, the extraction of fluids is often impossible without exploiting the increased drainage provided by fracture networks. Therefore, geophysical characterization of fractured reservoirs is an extremely important problem from an economic standpoint.

"Sweet spots" of high fracture intensity are not always correlated with faults and other structural features and are difficult to detect using conventional exploration techniques. Effective exploitation of fractured reservoirs also requires determination of the orientation and connectivity of fractures, as well as their spatial relationships to other reservoir heterogeneities. Most existing seismic methods for fracture characterization are based on analysis of shear-wave splitting (e.g., Crampin, 1985; Thomsen, 1988; Winterstein and Meadows, 1991; Mueller, 1992). Since split S-waves travel along essentially the same raypath, the difference between their velocities and reflection amplitudes depends primarily on the anisotropic properties of the medium rather than on lateral heterogeneity. The shear-wave technology, however, has known shortcomings associated with the high cost of multicomponent surveys and problems in acquiring high-quality S-wave data suitable for reliable polarization and traveltime analysis. Also, whereas shear waves can be efficiently used to estimate the fracture intensity, S-wave splitting for near-vertical propagation is not as sensitive to the fracture content.

Recent experimental and theoretical studies have shown that the variation of P-wave seismic signatures with the source-receiver azimuth is also a reliable source of information about the magnitude and principal directions of azimuthal anisotropy. Advantages of P-wave methods include a relatively low cost, usually higher (than that for S-waves) data quality, and the possibility to use straightforward modifications of conventional processing algorithms. Unfortunately, standard 3-D processing procedures typically stack all azimuths, thus obliterating the azimuthal variation of moveout and amplitude. One of the goals of this special issue is to encourage acquisition of wide-azimuth 3-D data and development of processing methods that take advantage of the azimuthal variation of seismic signatures. It is likely that the increasing popularity of ocean-bottom surveys will help the industry to evaluate and appreciate the numerous benefits of acquiring a wide range of azimuths.

Although the issue is devoted to P-waves, we would like to emphasize the value of joint processing and inversion of P and S (or, especially, converted PS) data. Even for higher-symmetry anisotropic models, P-waves alone can constrain only a subset of the model parameters that may or may not be sufficient for purposes of fracture characterization. For instance, estimation of the crack density (for penny-shaped cracks) using P-wave data requires knowledge of the ratio of the vertical velocities of P- and S-waves (Tsvankin, 1997). Also, a serious problem in techniques based on the azimuthal variation of P-wave signatures is the interplay between azimuthal anisotropy and lateral heterogeneity. This and a number of other problems are discussed in the special issue, which is designed to give the big picture of the latest developments and foster further theoretical and experimental advances in this rapidly evolving technology.

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CONTENTS OF THE SPECIAL ISSUE

To better organize the issue, we have made an attempt to divide it into papers on theory, modeling, and methodology, on one hand, and case histories, on the other, although a number of contributions have both components and do not strictly fall into either category. Some interesting papers given at the post-convention workshop have not been submitted to the special issue; in these cases, we refer the reader to SEG abstracts and to publications in other journals (e.g., Corrigan et al., 1996; Craft et al., 1997).

Papers on theory, modeling, and methodology

Amplitude-variation-with-offset (AVO) and attenuation analysis.—Theoretical and modeling studies published during the last several years substantially improved our understanding of the azimuthal variation of AVO response for such anisotropic models as transverse isotropy with a horizontal symmetry axis (HTI) and orthorhombic media (e.g., Rüger 1997, 1998; Rüger and Tsvankin, 1997; Sayers and Rickett, 1997). Existing work, however, is mostly focused on the azimuthally dependent AVO gradient that corresponds to relatively small angles of incidence. The special-issue paper of Simoes-Filho et al. discusses the inversion of wide-angle P-wave reflection data for the parameters of HTI media. By employing a genetic algorithm that can be used for lower-symmetry models as well, the authors demonstrate that extending the angle coverage of reflection data helps to constrain the coefficients that cannot be obtained from the AVO gradient alone.

Recommendations for the use of wide-azimuth acquisition in the offshore environment are given by MacBeth and Li in their discussion of amplitude versus direction (AVD) analysis for P- and PS-waves. Amplitude processing of data from intersecting streamer lines made it possible to find the orientation of fractures in a North Sea reservoir.

The simple model of a coarse azimuthally anisotropic interval, however, is not adequate for many fractured reservoirs, which contain multiple layers that are thin compared to seismic wavelength. The paper of Schoenberg et al. outlines an efficient formalism for modeling reflection coefficients in thinly layered fractured media and describes azimuthally-dependent tuning phenomena which may significantly complicate AVO analysis.

Vertical seismic profiling (VSP) has traditionally been one of the most reliable sources of information about anisotropy. Leaney et al. extend the methodology of walkaway VSPs to multiazimuth surveys designed to detect and characterize azimuthal anisotropy in the presence of regional dip. By analyzing both amplitude and traveltime variations with azimuth recorded over a carbonate reservoir, they demonstrate that multiazimuth VSPs can be used to identify the fracture direction and, therefore, optimize the subsequent acquisition of surface 3-D surveys.

MacBeth discusses the intriguing potential for the azimuthal dependence of P-wave attenuation to be sensitive to the azimuthal difference in horizontal permeability. He shows that proper interpretation of the azimuthally varying reflection amplitude from the base of a fractured reservoir requires accounting for both the reflection coefficient and fracture-related attenuation.

Moveout analysis.—Recent progress in accounting for anisotropy in P-wave processing has been mostly associated with new techniques of moveout analysis and traveltime inversion. Most anisotropic velocity-analysis methods, however, are 2-D by nature and are designed for TI media with a vertical symmetry axis (VTI) (e.g., Alkhalifah and Tsvankin, 1995). Several papers of the special issue discuss 3-D extension of anisotropic moveout analysis and inversion of azimuthally varying reflection traveltimes for the anisotropic parameters. Although the contributions below deal mostly with normal-moveout (NMO) velocities and moderate-spread reflection moveout, the work of Sayers and Ebrom (1997) and Al-Dajani and Tsvankin (1998) indicates that for high-quality data, azimuthally varying nonhyperbolic (long-spread) moveout can also provide useful information for anisotropy estimation.

Li points out that the fracture orientation is particularly convenient to estimate by subtracting reflection traveltimes measured on acquisition lines perpendicular to each other. Two pairs of orthogonal lines are sufficient for detecting the direction of the symmetry axis (and, therefore, the azimuth of the fractures) of fracture-induced HTI media.

Several papers introduce techniques for 3-D azimuthal velocity analysis and parameter estimation based on the equation of the NMO ellipse. [As shown by Grechka and Tsvankin (1998), the azimuthal variation of NMO velocity of any pure mode is described by three independent parameters and typically has an elliptical form.] In their special-issue paper, Grechka and Tsvankin devise a correction of effective NMO velocity for lateral velocity variation in horizontally layered media that allows them to separate the NMO ellipses related only to azimuthal anisotropy. They apply a 3-D processing sequence, which also includes azimuthal semblance analysis and generalized Dix differentiation, to a wide-azimuth data set from the Powder River Basin to map fracture systems in several depth intervals.

Contreras et al. present a parameter-estimation procedure for HTI media based on P-wave NMO ellipses from horizontal and dipping reflectors. Whereas horizontal events constrain just one anisotropic parameter ($\delta^{(V)}$; Tsvankin, 1997), the addition of dipping events helps to evaluate the second relevant coefficient ($\epsilon^{(V)}$) and build an anisotropic velocity model suitable for P-wave depth imaging. A similar methodology has already been developed for the more complicated orthorhombic media (Grechka and Tsvankin, 1999).

Isaac and Lawton and Vestrum et al. discuss modeling and imaging of P-wave data in TI media with a tilted symmetry axis (TTI). The TTI model is believed to be rather typical for sediments uptilted by salt domes and for dipping shale layers in such structurally complex areas as fold-thrust belts of the Canadian Foothills. Both papers demonstrate that ignoring the presence of TTI layers above the target horizon leads to mispositioning of reflectors and other distortions in conventional (isotropic) imaging. Isaac and Lawton present a detailed study of migration errors on a physical model designed to simulate dipping clastic sequences. Vestrum et al. show on synthetic and field data that a more accurate and better focused image can be obtained by using anisotropic migration codes capable of handling tilted transverse isotropy. To determine the velocity field needed for anisotropic processing, they use migration velocity analysis on image gathers.

Case histories

Leslie and Lawton determine the anisotropic seismic parameters of steeply dipping marine shales in Alberta, Canada. Using P-wave data on lines parallel, perpendicular, and at 45° to the strike directions, they find that Thomsen's coefficient δ is rather small, whereas the parameter ϵ at one location reaches 0.25.

Pérez, Gibson, and Toksöz present field data that include three crossing 2-D P-wave lines of different azimuths, and compare those observations to converted PS data. The influence of fractures seen in azimuthal P-wave AVO analysis is in good agreement with the results previously obtained using PS-waves. The 3-D generalization of their work is given in the paper by Pérez, Grechka, and Michelena, who employed a combination of seismic methods for fracture characterization (3-D AVO and NMO analyses, 2-D rotation analysis of PS data, etc.). The azimuthal moveout analysis of P-wave data yielded the orientations of the fractures that are perpendicular to those obtained with the other methods; this discrepancy is attributed to the influence of static problems (overburden effects) and/or lateral velocity variations (heterogeneities).

The issue contains three papers describing field data studies from the continental United States funded by the US Department of Energy. Grimm et al. present results of the processing of a 3-D P-wave 37 mi^2 survey acquired in the Wind River Basin. Separation of the data into two limited-azimuth volumes made it possible to improve imaging and identify zones of high fracture intensity by analyzing azimuthally dependent velocity, reflectivity, and dominant frequency. The two processing azimuths were chosen parallel to the faster and slower P-wave directions, which turned out to be aligned with the dominant fault pattern and known fracture azimuths.

Lynn, Beckham, et al. discuss a data set acquired at Bluebell-Altamont field in Utah, which includes 2-D 9-component reflection seismic and a 9-component VSP survey. The measurements on two orthogonal lines (parallel and perpendicular to the known fracture azimuth) show that the azimuthal variation of the P-wave AVO gradient is proportional to the magnitude of the shear-wave splitting.

The Rulison field (Piceance Basin, Colorado) was the site of a 3-D P-wave survey described by Lynn, Campagna, et al. Stacking and migration of limited-azimuth volumes (oriented in accordance with the fast and slow P-wave directions) showed that the visible seismic faults were parallel to the trend of the faster velocity azimuth. The study identified a set of seismic attributes best correlated with commercial gas pay. On the whole, the aggregate of the field data papers presented in this volume demonstrate the feasibility of detection and mapping of subseismic faults and high-fracture-density zones by measuring the azimuthal variations of P-wave AVO response, interval velocity, etc.

THE ROAD AHEAD

Despite the impressive advances of the past several years, efficient application of azimuthally dependent P-wave signatures faces a multitude of problems. Most contributions to the special issue are focused on traveltimes and reflection coefficients; the azimuthal variation of the attenuation coefficient and frequency (e.g., associated with fluid-saturated fractures) is less understood. Calibration of P-wave data using mode conversions and pure shear waves, as well the joint inversion of azimuthally varying signatures of several different modes, is another area that requires extensive research efforts. It has already been shown that NMO ellipses and vertical velocities of P- and PS-waves in a horizontal orthorhombic layer can be inverted for all but one anisotropic parameters (Grechka et al., 1999), thus providing much more comprehensive information about fracturing than compressional data alone.

One of the most difficult problems in azimuthal moveout and AVO analysis is separating the influence of anisotropy and lateral heterogeneity on seismic traveltimes and amplitudes. Current moveout-based parameter-estimation techniques can handle either dipping interfaces in a medium composed of coarse homogeneous layers or weak lateral variation of the stiffnesses within horizontal layers. Unraveling a combination of laterally varying anisotropic velocity field with structural complexity is one of the biggest challenges for the future. Also, quantitative interpretation of the results of azimuthal AVO analysis requires an improved correction for the influence of amplitude focusing and other anisotropic propagation phenomena in the overburden.

The relationship between seismic signatures and rock-physics models of fractured media (e.g., Hudson, 1981; Schoenberg, 1980; Schoenberg and Sayers, 1995; Thomsen, 1995) remains a weak link in fracture-characterization methodology. Reliable estimation of fracture properties requires a quantitative analysis of the influence of such factors as fracture density, spacing, and connectivity on the effective anisotropic parameters and seismic measurements.

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