Final report on the project "Inversion of multicomponent seismic data and rock physics interpretation for evaluating lithology, fracture and fluid distribution in heterogeneous anisotropic reservoirs" (award #DE-FG03-98ER14908)

Center for Wave Phenomena, Colorado School of Mines
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The report covers the work performed by the Center for Wave Phenomena (CWP) on the project "Inversion of multicomponent seismic data and rock physics interpretation for evaluating lithology, fracture and fluid distribution in heterogeneous anisotropic reservoirs" from September 15, 2001 – November 14, 2004. In addition to the publications listed at the end of the report, the deliverables include algorithms and codes for processing and inversion of multicomponent seismic data in anisotropic media and for modeling of seismic signatures of fracture systems. Most of this software is available from CWP as part of Seismic Unix (SU) – a package of programs for Unix-based machines.

SUMMARY OF RESEARCH RESULTS

1. New method for processing and inversion of multicomponent seismic data

Due to the high cost of shear-wave excitation, the difficulty of placing sources on the sea floor, and often poor quality of SS-wave data, it has become a practice in reflection seismology to replace pure SS reflections with mode-converted PS-waves. Converted waves are of particular importance in offshore seismic, where they represent the only available type of shear energy. For a number of exploration scenarios, PS-waves provide valuable information about the subsurface structure and anisotropic medium parameters that cannot be inferred from conventional PP-wave data. Kinematics and waveforms of reflected PS-waves, however, possess such undesirable features as moveout asymmetry, reflection point dispersal and polarity reversal, which preclude application of conventional velocity-analysis methods to mode conversions.

Rather than using PS-waves directly, we developed a method for constructing SS-wave reflections (if they are not physically excited in the survey) from PP and PS data. The original version of this technique (Grechka and Tsvankin, 2002a) is based on picking of PP and PS traveltimes on prestack data and identification (correlation) of the PP and PS events from the same interfaces. The key idea of the method is to match the reflection slopes (horizontal slownesses) on common-receiver PP and PS gathers. This matching allows us to find the coordinates of receivers that record PP- and PS-waves reflected at exactly the same (albeit unknown) subsurface points and to determine the traveltime of the SS primary reflection as a simple combination of the PP and PS times. The constructed SS-wave moveout can then be processed by velocity-analysis methods designed for pure reflection modes (see below).

To avoid traveltime picking on prestack data, we generalized the above algorithm (often called the "PP+PS=SS" method) to operate directly with recorded traces of PP- and PS-waves (Grechka and Dewangan, 2003). By designing a special convolution of PP- and PS-wave seismograms, it is possible to compute full-waveform SS data well-suited for moveout inversion and, potentially, for AVO (amplitude variation with offset) analysis.

The PP+PS=SS method has the following attractive features:

1. Although it is necessary to establish correlation between the PP and PS sections, no information about the velocity field or anisotropic parameters is required to obtain SS-waves with the correct kinematics from the PP and PS data.
2. The moveout of the output SS-waves is symmetric with respect to zero offset and can be processed by algorithms designed for pure-mode reflections.
3. The reflection-point dispersal of PS-waves has no influence on the generated SS data.
3. The portion of PS data in the vicinity of the polarity reversal (where the PS amplitudes are small) can be muted out without compromising the processing results.

Publications: Grechka and Tsvankin (2002a), Grechka and Dewangan (2003) (see the list of publications). A presentation based on these results was recognized as one of the best papers at the Annual Meeting of the Society of Exploration Geophysicists (SEG) in San Antonio (2001). The paper by Grechka and Tsvankin (2002a) received Honorable Mention for Best Paper in Geophysics Award of the SEG.

2. Multicomponent stacking-velocity tomography

The PP+PS=SS method described above provides a basis for anisotropic velocity analysis of multicomponent data. This procedure allows us to replace PS-wave moveout, which is generally asymmetric with respect to zero offset, with the symmetric SS-wave moveout that can be described (on conventional-length spreads) by the normal-moveout (NMO) velocity in 2D and the NMO ellipse in 3D. To carry out interval parameter estimation in heterogeneous anisotropic media, we developed a tomographic inversion technique that operates with the NMO ellipses, zero-offset traveltimes, and reflection slopes of both PP- and SS-waves ("stacking-velocity tomography").

Although this algorithm does not use the far-offset information (i.e., nonhyperbolic moveout), it has significant advantages over conventional reflection tomography. The first advantage, which is critically important in anisotropic media, is related to computational efficiency. The NMO ellipse (and, therefore, the multiazimuth, multi-offset hyperbolic moveout as a whole) can be computed by tracing only one zero-offset ray for each reflection event at a given CMP location (Grechka and Tsvankin, 2002c). Hence, the number of rays to be generated in forward modeling is reduced by orders of magnitude, which makes anisotropic traveltime tomography computationally feasible for complex subsurface models. Second, it is possible to derive semi-analytic expressions for the NMO ellipse even in arbitrarily anisotropic media, if the model is structurally simple. Such solutions help to identify the parameters (or the parameter combinations) constrained in the inversion of NMO velocities. Third, restricting the range of source-receiver offsets reduces the influence of lateral heterogeneity on reflection traveltimes, and the velocity field can be estimated separately for blocks of relatively small lateral extent. Within each block, the layers can be treated as homogeneous, and the interfaces can be approximated by simple smooth surfaces described by low-order polynomials. Then, global smoothing can be applied to build the laterally varying anisotropic velocity field and reflecting interfaces.

Publications: Grechka, Pech, and Tsvankin (2002a,b).

3. Tomographic inversion for transversely isotropic and orthorhombic media

The most common anisotropic model for sedimentary formations is transverse isotropy (TI) with arbitrary orientation of the symmetry axis, Application of the multicomponent moveout inversion to multiazimuth reflections from a dipping interface beneath a homogeneous TI layer shows that for a range of reflector dips and tilt angles of the symmetry axis it is possible to build the anisotropic velocity field in the depth domain. The most notable exception is horizontally layered VTI (TI with a vertical symmetry axis) media, where even long-spread (nonhyperbolic) moveout of PP- and PSV-waves does not constrain the vertical velocities (Grechka and Tsvankin, 2002d). In contrast, for HTI (TI with a horizontal symmetry axis) models the inversion procedure is quite stable for both horizontal and dipping reflectors. We also developed stacking-velocity tomography (see above) for layered TI media with curved interfaces and studied its stability in the presence of noise and vertical heterogeneity.

Orthorhombic media with a horizontal symmetry plane adequately describe seismic signatures recorded over many naturally fractured reservoirs. Our tomographic algorithm was extended to orthorhombic media and applied to estimate Tsvankin's anisotropic parameters and the azimuths of the vertical symmetry planes using multiazimuth PP and SS (the fast S_1 and slow S_2) reflections. The feasibility of the parameter estimation is strongly dependent on reflector dip and orientation. For a horizontal reflector beneath a single orthorhombic layer, the vertical velocities and reflector depth cannot be found from conventional-spread reflection traveltimes alone. If the reflector is dipping, the inversion is ambiguous when the dip plane is close to one of the vertical symmetry planes of the orthorhombic layer above it. The parameter estimation becomes possible if the dip direction deviates by more than 10° from the nearest symmetry plane. For orthorhombic models composed of homogeneous layers separated by plane or curved interfaces, the inversion of noise-contaminated reflection data is sufficiently stable only if the vertical velocities are constrained *a priori*.

Publications: Grechka, Pech, and Tsvankin (2002a,b; 2004).

4. Application of anisotropic velocity analysis to multicomponent field data

The PP+PS=SS method of constructing SS reflection data and anisotropic multicomponent stacking-velocity tomography were applied to PP and PS data acquired on a 2D line over the Lower Tertiary Siri reservoir in the North Sea (Grechka, Tsvankin, et al., 2002a,b). The computed traveltimes of SS reflections from several horizons were used to estimate the effective SS-wave NMO velocities, which were combined with the PP data in the tomographic velocity analysis. Comparison of the vertical and NMO velocities of the PP- and SS-waves provides clear evidence of anisotropy in the section above the reservoir.

The interval parameter estimation was performed under the assumption that the section is composed of VTI layers. Since the subsurface structure is close to horizontally layered, the reflection data cannot be uniquely inverted for the VTI parameters without additional information. The parameter-estimation algorithm produced a family of equivalent VTI models that fit the PP and PS (or SS) traveltimes equally well. Although the range of variations in Thomsen's anisotropic parameters ϵ and δ for the equivalent models is rather wide, it does not include isotropic media ($\epsilon = \delta = 0$), which implies that accurate matching of both PP and PS data is impossible without accounting for anisotropy. To overcome the nonuniqueness in the inversion of reflection data and build a VTI depth model, we used P-wave check shots acquired in a borehole drilled on the processed line. Throughout the section $\epsilon > \delta$, with the largest values of both anisotropic coefficients observed in the depth range 0.7–1.5 km where ϵ reaches almost 0.25 (Figure 1).

The time section of PS-waves generated for this line using the estimated VTI model has a much higher quality than does the conventional isotropic section (Figure 2). In particular, the anisotropic processing substantially improved the image of the top of the reservoir and provided a crisp picture of faulting in the shallow part of the section. We also carried out anisotropic imaging of PP data and demonstrated that PP and PS images provide complementary information about the subsurface.

The same methodology was successfully used to process a four-component ocean-bottom cable line in the Gulf of Mexico (Grechka and Dewangan, 2003). The NMO velocities of the recorded PP-waves and computed SS-waves indicate a substantial magnitude of anisotropy, especially in the shallow part of the section. Although the joint inversion of the PP and SS data did not produce a unique result, we were able to map the effective anisotropic parameter χ constrained by the ratios of the NMO velocities and vertical traveltimes of the PP- and SS-waves.

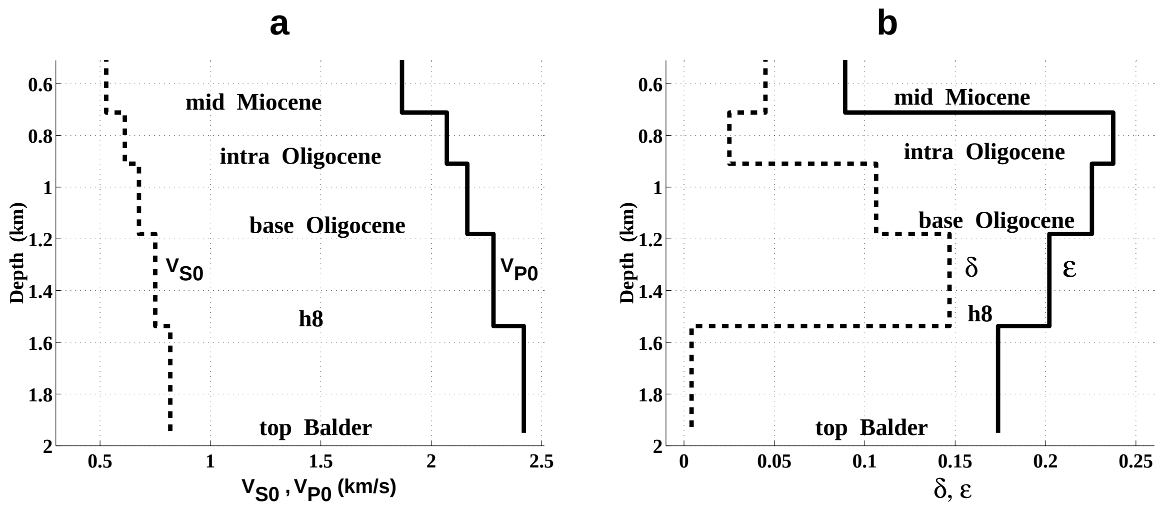

FIG. 1. Inversion of the reflection and check-shot data acquired above the Siri reservoir. (a) Interval vertical velocities V_{S0} (dashed) and V_{P0} (solid); (b) interval anisotropic coefficients δ (dashed) and ϵ (solid).

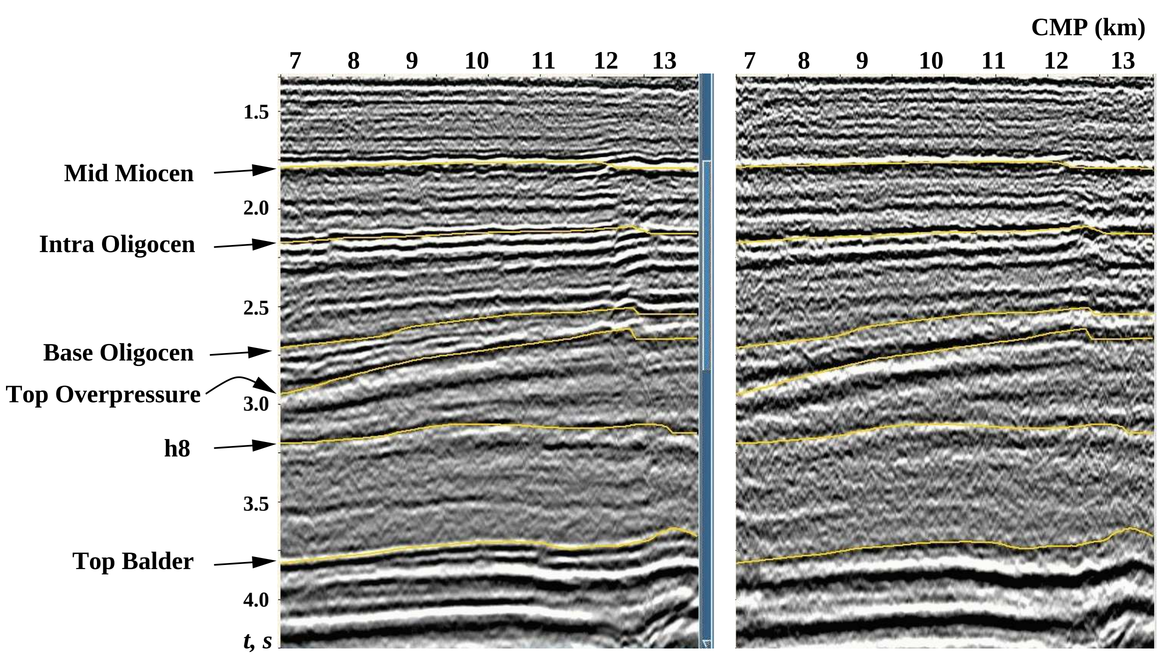

FIG. 2. Common-conversion-point stacks for the estimated VTI model (left) and the isotropic model with $\epsilon = \delta = 0$ (right).

Publications: Grechka, Tsvankin, et al. (2002a,b), Grechka and Dewangan (2003).

5. P-wave migration velocity analysis for VTI media

One of the main challenges in anisotropic velocity analysis and imaging is simultaneous estimation of velocity gradients and anisotropic parameters from reflection data. Approximating the subsurface by a factorized VTI medium (i.e., a medium where the ratios of the stiffness coefficients are constant) provides a convenient way of building vertically and laterally heterogeneous anisotropic models for prestack depth migration of P-wave data.

We devised an algorithm for P-wave migration velocity analysis (MVA) designed for models composed of factorized VTI layers or blocks with constant vertical and lateral gradients in the vertical velocity V_{P0}. The anisotropic MVA method is implemented as an iterative two-step procedure that includes prestack depth migration (imaging step) followed by an update of the medium parameters (velocity-analysis step). The residual moveout of the migrated events, which is minimized during the parameter updates, is described by a nonhyperbolic equation whose coefficients are determined by 2D semblance scanning.

For piecewise-factorized VTI media without significant dips in the overburden, the residual moveout of P-wave events in image gathers is governed by four effective quantities in each block: (1) the NMO velocity $V_{\rm nmo}$ at a certain point within the block, (2) the vertical velocity gradient k_z, (3) the combination $\hat{k}_x = k_x \sqrt{1+2\delta}$ of the lateral velocity gradient k_x and the anisotropic parameter δ, and (4) the anellipticity parameter $\eta \equiv (\epsilon - \delta)/(1+2\delta)$. We showed that all four parameters can be estimated from the residual moveout for at least two reflectors within a block sufficiently separated in depth. Inversion for the parameter η also requires using either long-spread data (with the maximum offset-to-depth ratio no less than two) from horizontal interfaces or dipping events.

To find the depth scale of the section and build a model for prestack depth migration using the MVA results, the vertical velocity V_{P0} needs to be specified for at least a single point in each block. When no borehole information about V_{P0} is available, a well-focused image can often be obtained by assuming that the vertical-velocity field is continuous across layer boundaries. A synthetic test for a three-layer model with a syncline structure confirms the accuracy of our MVA algorithm in estimating the interval parameters $V_{\rm nmo}$, k_z, $\hat{k}_x$, and η and illustrates the influence of errors in the vertical velocity on the image quality.

The MVA methodology was also applied to an offshore data set acquired by Chevron Overseas Petroleum Co. in West Africa. Since our velocity-analysis method accounts for lateral velocity variation, it produces more accurate estimates of the anisotropic parameters than those previously obtained with time-domain techniques. The values of the anisotropic parameter η found for the massive shales exceed 0.2, which confirms that ignoring anisotropy in the study area can lead to substantial imaging distortions, such as misstacking and mispositioning of dipping events. While some of these distortions can be removed by using anisotropic time processing, further marked improvement in image quality is achieved by prestack depth migration with the estimated factorized VTI model.

Publications: Sarkar and Tsvankin (2003, 2004a,b).

6. Analysis of SV-wave image gathers in homogeneous and factorized VTI media

One of the main problems in the velocity analysis of P-wave data for VTI media is the need for *a priori* information in building a model for depth imaging. Including SV-wave moveout in the parameter-estimation procedure, either alone or in combination with P-waves, can help in positioning the reflectors at the correct depth using only reflection traveltimes. In order to develop a foundation for shear-wave migration velocity analysis (MVA) in VTI media, we studied SV-wave image gathers obtained after prestack depth migration.

For purposes of the moveout inversion of SV-waves, it is convenient to parameterize the model in terms of the NMO velocity V_{nmo} of horizontal SV events, the anisotropic parameter σ, which largely controls SV-wave velocity, and Thomsen parameters ϵ and δ. The moveout of horizontal events on image gathers is close to hyperbolic and depends just on V_{nmo} out to offset-to-depth ratios of about 1.7. Because V_{nmo} differs from the vertical S-wave velocity, flattening moderate-spread gathers of SV-waves does not ensure the correct depth of the migrated events. The influence of the parameter σ on the migrated depth of horizontal events rapidly increases as the offset-to-depth ratio approaches two. Estimation of σ, however, is hampered by the dependence of long-spread SV-wave moveout on another anisotropic parameter, ϵ. Therefore, although V_{nmo} and σ are sufficient to constrain the vertical S-wave velocity V_{S0} and reflector depth, the tradeoff between σ and ϵ on long-spread gathers introduces non-negligible errors in V_{S0}.

The parameters V_{nmo}, σ, and ϵ also control the moveout of dipping SV events, but in the presence of dip both σ and ϵ influence migrated depths even at small offsets. For factorized $v(z)$ VTI media with a constant SV-wave vertical-velocity gradient k_{zs}, flattening of two or more horizontal events requires the correct NMO velocity at the surface, the gradient k_{zs} and, for large offsets, the parameters σ and ϵ. On the whole, the ambiguity in the estimation of σ and reflector depth from SV-wave moveout highlights the need to combine P- and SV-wave data in migration velocity analysis for VTI media.

Publication: Al-Zayer and Tsvankin (2004).

7. Nonhyperbolic moveout inversion of PP and PS data in layer-cake VTI media

Nonhyperbolic moveout of P-waves in horizontally layered VTI media can be used to estimate the anellipticity coefficient η in addition to the NMO velocity. Those two parameters are sufficient for time processing of P-wave data (despite a certain instability in the inversion for η), but they do not constrain the vertical velocity V_{P0} and the depth scale of the model. It was suggested in the literature that this ambiguity in the depth-domain velocity analysis for layer-cake VTI media can be resolved by combining long-spread reflection traveltimes of PP- and mode-converted PSV-waves.

We showed that the reflection traveltimes of horizontal PSV events help to determine the ratio of the P- and S-wave vertical velocities, the NMO velocity of SV-waves, and give a more accurate estimate of η. However, nonhyperbolic moveout of PSV-waves turns out to be mostly controlled by wide-angle P-wave traveltimes, and does not provide independent information for the inversion. As a result, even for a single-layer model and uncommonly large offsets, the traveltimes of PP- and PSV-waves cannot be inverted for the vertical velocity and anisotropic parameters ϵ and δ. To reconstruct the horizontally layered VTI model from surface data, it is necessary to combine long-spread traveltimes of pure (non-converted) P and SV reflections.

Publication: Grechka and Tsvankin (2002d).

8. 3D description of the quartic moveout coefficient and nonhyperbolic reflection moveout

Nonhyperbolic (long-spread) moveout provides essential information for a number of seismic inversion/processing applications, particularly for parameter estimation in anisotropic media. We derived an exact analytic expression for the quartic moveout coefficient A_4 that controls the magnitude of nonhyperbolic moveout of pure (non-converted) modes (Pech, Tsvankin, and Grechka, 2003). Our result takes into account reflection-point dispersal on irregular interfaces and is valid for arbitrarily anisotropic, heterogeneous media. All quantities needed to compute A_4 can be evaluated during the tracing of the zero-offset ray, so long-spread moveout can be modeled without time-consuming multiazimuth, multioffset ray tracing.

The general equation for the quartic coefficient is then used to study azimuthally varying nonhyperbolic moveout of P-waves in a dipping transversely isotropic (TI) layer with an arbitrary tilt ν of the symmetry axis. Assuming that the symmetry axis is confined to the dip plane, we employed the weak-anisotropy approximation to analyze the dependence of A_4 on the anisotropic parameters. The linearized expression for A_4 is proportional to the anellipticity coefficient $\eta \approx \epsilon - \delta$ and does not depend on the individual values of the Thomsen parameters. Typically, the magnitude of nonhyperbolic moveout in tilted TI media above a dipping reflector is highest near the reflector strike, while deviations from hyperbolic moveout on the dip line are substantial only for mild dips.

The azimuthal variation of the quartic coefficient is governed by the tilt ν and reflector dip ϕ and has a much more complicated character than the NMO-velocity ellipse. For example, if the symmetry axis is vertical (VTI media, $\nu = 0$) and the dip $\phi > 30°$, A_4 goes to zero on two lines with different azimuths where it changes sign. If the symmetry axis is orthogonal to the reflector (this model is typical for thrust-and-fold belts), the strike-line quartic coefficient is defined by the well-known expression for a horizontal VTI layer (i.e., it is independent of dip), while the dip-line A_4 is proportional to $\cos^4 \phi$ and rapidly decreases with dip. The high sensitivity of the quartic moveout coefficient to the parameter η and the tilt of the symmetry axis can be exploited in the inversion of multiazimuth, long-spread P-wave data for the parameters of TI media.

The exact expression for the coefficient A_4 was also applied to P-wave reflections from a dipping interface overlaid by a medium of orthorhombic symmetry (Pech and Tsvankin, 2004). The weak-anisotropy approximaton for A_4 in a homogeneous orthorhombic layer is controlled by the anellipticity parameters $\eta^{(1)}$, $\eta^{(2)}$, and $\eta^{(3)}$, which are responsible for time processing of P-wave data. If the dip plane of the reflector coincides with the vertical symmetry plane $[x_1, x_3]$, A_4 on the dip line is proportional to the in-plane anellipticity parameter $\eta^{(2)}$ and always changes sign for a dip of 30°. The quartic coefficient on the strike line is a function of all three η–parameters, but for mild dips it is mostly governed by $\eta^{(1)}$ – the parameter defined in the incidence plane $[x_2, x_3]$. Whereas the magnitude of the dip-line A_4 typically becomes small for dips exceeding 45°, the nonhyperbolic moveout on the strike line may remain significant even for subvertical reflectors.

The character of the azimuthal variation of A_4 depends on reflector dip and is quite sensitive to the signs and relative magnitudes of $\eta^{(1)}$, $\eta^{(2)}$, and $\eta^{(3)}$. The analytic results and numerical modeling show that the azimuthal pattern of the quartic coefficient can contain multiple lobes, with one or two azimuths of vanishing A_4 between the dip and strike directions. The high variability of the azimuthal signature of the quartic coefficient and its sensitivity to the η–parameters can be exploited in the inversion of P-wave data for orthorhombic media (see below).

Publications: Pech, Tsvankin, and Grechka (2003), Pech and Tsvankin (2004).

9. Inversion of multiazimuth nonhyperbolic moveout

The azimuthally varying nonhyperbolic moveout in anisotropic media can provide valuable information for characterization of fractured reservoirs and seismic processing. We applied the results of Pech and Tsvankin (2004; see above) to the inversion of multiazimuth, long-spread P-wave data for the orientation of the vertical symmetry planes and five key moveout parameters – the symmetry-plane NMO velocities $V_{\text{nmo}}^{(1)}$ and $V_{\text{nmo}}^{(2)}$ and the anellipticity parameters $\eta^{(1)}$, $\eta^{(2)}$, and $\eta^{(3)}$. The inversion algorithm is based on a coherency operator that computes the semblance for the full range of offsets and azimuths using a generalized version of the Alkhalifah-Tsvankin nonhyperbolic moveout equation. To make the 3D semblance search more efficient, the starting model is obtained by estimating the NMO ellipse from the hyperbolic moveout term and applying 2D inversion of nonhyperbolic moveout for the parameters $\eta^{(1)}$ and $\eta^{(2)}$ in the symmetry-plane directions.

The moveout equation provides a close approximation to the reflection traveltimes in layered anisotropic media with a uniform orientation of the vertical symmetry

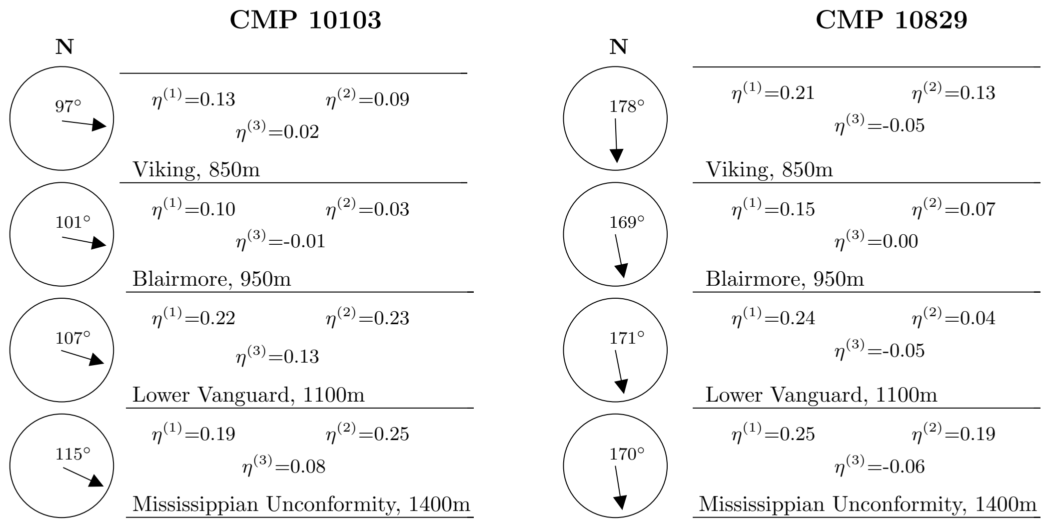

FIG. 3. Results of nonhyperbolic moveout inversion for two common-midpoint locations (CMP 10103 and 10829) at Weyburn field. The inversion was applied to P-wave reflections from four major horizons: the Viking horizon, the maximum offset-to-depth ratio $x/z = 2.5$; the Blairmore, $x/z = 2.0$; the Lower Vanguard, $x/z = 1.9$; and the Mississippian Unconformity, $x/z = 1.8$. All η parameters are the effective values for the medium above the reflector. The arrows mark the estimated direction of the semi-major axis of the NMO ellipse; the number by each arrow is the azimuth of the axis with respect to the north.

planes. Numerical tests on noise-contaminated data for a single orthorhombic layer show that the inversion yields satisfactory results if the offset-to-depth ratio reaches at least 2.5. The best-constrained parameters are the azimuth φ of one of the symmetry planes and the velocities $V_{\rm nmo}^{(1)}$ and $V_{\rm nmo}^{(2)}$, while the resolution in $\eta^{(1)}$ and $\eta^{(2)}$ is somewhat compromised by the tradeoff between the quadratic and quartic moveout terms. The largest uncertainty is observed in the parameter $\eta^{(3)}$ that influences only long-spread moveout in off-symmetry directions. The symmetry-plane orientation φ can still be estimated, albeit with a lower accuracy, if an orthorhombic layer is overlain by an azimuthally isotropic (VTI or purely isotropic) medium.

The inversion algorithm was successfully tested on multiazimuth P-wave reflections recorded at Weyburn Field in Canada. Taking azimuthal anisotropy into account increased the semblance values for most long-offset reflection events in the overburden, which indicates that fracturing is not limited to the reservoir level. (The offset-to-depth ratio and the thickness of the reservoir were not sufficient to apply the method to the reservoir horizon.) The estimated symmetry-plane directions (Figure 3) are close to the azimuths of the off-trend fracture sets determined from borehole data and shear-wave splitting analysis. The effective anellipticity parameters reach values as large as 0.25; a more detailed interpretation of the results, however, requires layer-stripping of the nonhyperbolic moveout term. The effective moveout parameters estimated by our algorithm also provide input for P-wave time imaging and geometrical-spreading correction in layered orthorhombic media.

Publication: Vasconcelos and Tsvankin (2004).

10. Modeling of geometrical spreading in anisotropic media

Geometrical spreading is highly sensitive to elastic anisotropy and thus can strongly influence the amplitude signature of reflected waves recorded over anisotropic formations. For purposes of reflection data processing, it is convenient to express geometrical spreading through the reflection traveltime measured at the earth's surface. Such expressions are particularly important for azimuthally anisotropic models in which variations of geometrical spreading with both offset and azimuth can significantly distort the results of AVO (amplitude variation with offset) analysis.

We obtained a general expression for the inverse relative geometrical-spreading factor L^{-1} as a simple function of the spatial derivatives of reflection traveltimes. Our result is valid for arbitrarily anisotropic, heterogeneous media as long as the wavefield is adequately described within the framework of ray theory. By employing the generalized Alkhalifah-Tsvankin nonhyperbolic moveout equation (see above), the factor L^{-1} can be represented through the effective moveout coefficients. This formulation was then applied to P-wave reflections in an orthorhombic layer to evaluate the distortions of the geometrical spreading for a typical azimuthally anisotropic model.

The weak-anisotropy approximation, verified by numerical tests, shows that azimuthal velocity variations make a significant contribution to the geometrical spreading, and the existing VTI equations for the factor L^{-1} cannot be applied even in the vertical symmetry planes. The shape of the azimuthally dependent function L^{-1} is close to an ellipse for offsets smaller than the reflector depth but becomes more complicated for larger offset-to-depth ratios. The overall magnitude of the azimuthal variation of the inverse geometrical spreading for the moderately anisotropic model used in the tests exceeds 25% for a wide range of offsets.

Publication: Xu, Tsvankin, and Pech (2003).

11. Inversion of multicomponent VSP data

Vertical seismic profiling (VSP) can be used for estimating in-situ anisotropy with a higher resolution and accuracy than that provided by reflection data. We devised an inversion algorithm to estimate all 21 stiffness coefficients c_{ij} of the most general anisotropic medium from the polarizations and slownesses of P-waves and two split S-waves acquired in multiazimuth VSP surveys. There is no need to assume the anisotropic symmetry in advance because it can identified from the structure of the stiffness matrix.

We discussed three different scenarios of inverting noise-contaminated data. First, if the overburden is laterally homogeneous, the horizontal slownesses measured at the surface are preserved at the receiver locations. This leads to a linear inversion scheme designed to estimate the stiffnesses c_{ij}. Second, if the S-wave horizontal slowness is unknown, the stiffness marix can be estimated in a nonlinear fashion simultaneously with the horizontal slownesses. The third scenario involves a nonlinear inversion for c_{ij} using only the vertical slownesses and polarization vectors of P- and S-waves. The inversion proved to be stable and robust only for the first two scenarios. In contrast, errors in the estimated stiffnesses increase substantially when the horizontal slowness components of both P- and S-waves are unknown. The method was successfully applied to a data set from a fractured reservoir at Vacuum field, New Mexico, where the medium was found to be orthorhombic with a subhorizontal symmetry plane.

Publication: Dewangan and Grechka (2003).

12. Feasibility of seismic characterization of multiple fracture sets

The processing and inversion methods described above enhance our ability to use seismic data in characterizing anisotropic, heterogeneous fractured formations. Successful exploration and development of naturally fractured reservoirs often requires estimation of the parameters of multiple fracture sets. The goal of this work was to determine the maximum number of fracture sets of a certain rheological type which can be resolved by inverting the effective stiffness tensor obtained from seismic data. The main underlying assumption was that an estimate of the complete effective stiffness tensor had been obtained, for example, from multicomponent, multiazimuth surface seismic and VSP surveys. Although typically only a subset of the stiffness elements (or some of their combinations) may be available, this study helps to establish the limits of seismic fracture-detection algorithms.

The number of uniquely resolvable fracture systems depends on the anisotropy of the host rock and the rheology and orientation of the fractures. Somewhat surprisingly, it is possible to characterize fewer vertical fracture sets than dipping ones, even though in the latter case the fracture dip has to be found from the data. For the simplest, rotationally invariant fractures embedded in either isotropic or VTI host rock, the stiffness tensor can be inverted for up to *two* vertical or *four* dipping fracture sets. In contrast, only one fracture set of the most general (micro-corrugated) rheological type, regardless of its orientation, is constrained by the effective stiffnesses. These results can be used to guide the development of seismic fracture-characterization algorithms that should address important practical issues of data acquisition, processing, and inversion for particular fracture models.

Publication: Grechka and Tsvankin (2003).

13. Inversion for the parameters of two orthogonal fracture sets

Completing the work started under the previous DOE project, we carried out modeling and inversion of the effective parameters of the orthorhombic model formed by two orthogonal vertical fracture sets embedded in a VTI matrix. Although the number of the microstructural (physical) medium parameters is equal to the number of effective stiffness elements (nine), we show that for this model there is an additional relation (constraint) between the stiffnesses or Tsvankin's anisotropic coefficients.

As a result, the same effective orthorhombic medium can be produced by a range of equivalent models with vastly different fracture weaknesses and background VTI parameters, and the inversion of seismic data for the microstructural parameters is nonunique without additional information.

Reflection moveout of PP- and PS-waves can still be used to find the fracture orientation and estimate (in combination with the vertical velocities) the differences between the normal and shear weaknesses of the fracture sets, as well as the background anellipticity parameter η_b. Since for penny-shaped cracks the shear weakness is close to twice the crack density, seismic data can help to identify the dominant fracture set, although the crack densities cannot be resolved individually.

If the VTI symmetry of the background is caused by intrinsic anisotropy (as is usually the case for shales), it may be possible to determine at least one background anisotropic coefficient from borehole or core measurements. Then seismic data can be inverted for the fracture weaknesses and the rest of the background parameters. On the whole, seismic characterization of reservoirs with multiple fracture sets and anisotropic background typically requires measurements made on different scales (surface seismic, borehole, cores).

Publication: Bakulin, Grechka, and Tsvankin (2002).

14. Characterization of micro-corrugated vertical fractures

We examined the effective medium produced by the most general (in terms of the linear-slip theory) parallel vertical fractures in a purely isotropic host rock. In contrast to the conventional treatment of fractures as penny-shaped cracks, our model accounts for coupling between the *normal* (to the fracture plane) stress and *tangential* jump in displacement (and vice versa). This coupling may be caused by at least two common physical mechanisms – micro-corrugation of fracture faces or misalignment between the fracture strike and the principal axes of stress.

Despite its low (triclinic) symmetry, the effective medium is described by just nine independent effective parameters and possesses several distinct features which help to identify the physical model and estimate the fracture compliances and background velocities. For example, the polarization vector of the vertically propagating fast shear wave S_1 and the semi-major axis of the S_1-wave normal-moveout (NMO) ellipse from a horizontal reflector always point in the direction of the fracture strike. Moreover, for the S_1-wave both the vertical and NMO velocities along the fractures are equal to the shear-wave velocity in the host rock. The NMO ellipses of the P- and S_2-waves, however, have different orientations and are not necessarily aligned with the fractures.

Analysis of seismic signatures in the limit of small fracture weaknesses allows us to select the input data needed for unambiguous fracture characterization. The fracture and background parameters can be estimated using the NMO ellipses from horizontal reflectors and vertical velocities of P-waves and two split S-waves, combined with a portion of the P-wave slowness surface reconstructed from multiazimuth, walkaway VSP (vertical seismic profiling) data. The stability of the parameter-estimation procedure is verified by performing nonlinear inversion based on the exact equations.

Publication: Grechka, Bakulin, and Tsvankin (2003).

15. Characterization of dipping fracture sets

Although it is believed that natural fracture sets predominantly have near-vertical orientation, oblique stresses and some other mechanisms may tilt fractures away from the vertical. We studied the effective medium produced by a single system of obliquely dipping rotationally invariant fractures embedded in a VTI background rock. This model is monoclinic with a vertical symmetry plane that coincides with the dip plane of the fractures.

Multicomponent seismic data acquired over such a medium can be used to estimate the fracture orientation. For example, the vertically propagating fast shear wave S_1 (and the converted PS_1-wave) is typically polarized in the direction of the fracture strike. The normal-moveout (NMO) ellipses of horizontal reflection events are co-oriented with the dip and strike directions of the fractures, which provides an independent estimate of the fracture azimuth. However, the polarization vector of the slow wave S_2 at vertical incidence *does not* lie in the horizontal plane – an unusual phenomenon that can be used to evaluate the fracture dip. Also, for oblique fractures the shear-wave splitting coefficient at vertical incidence becomes dependent on fracture infill (saturation).

A complete medium-characterization procedure includes estimating the fracture compliances and orientation (dip and azimuth), as well as the Thomsen parameters of the VTI background. We demonstrate that both the fracture and background parameters can be obtained from multicomponent, multiazimuth data using the vertical velocities and NMO ellipses of PP-waves and two split SS-waves (or the traveltimes of PS-waves) reflected from horizontal interfaces. Numerical tests corroborate the accuracy and stability of the inversion algorithm based on the exact expressions for the vertical and NMO velocities.

Publication: Grechka and Tsvankin (2003).

16. Analysis of PP- and PS-wave reflection coefficients

Amplitude-variation-with-offset (AVO) analysis of multicomponent, multiazimuth data is an efficient fracture-characterization tool, in particular for thin reservoirs. We derived linearized approximations for PS-wave reflection coefficients at a planar weak-contrast interface separating two weakly anisotropic halfspaces. The general expressions were further simplified and analyzed for interfaces separating any two of the following models: isotropic, VTI, HTI, and orthorhombic. Numerical tests reveal good agreement between the exact and approximate reflection coefficients for most models believed to be typical for the subsurface.

The approximations were used in the joint linear inversion of the PP- and PS-wave reflection coefficients for both VTI and azimuthally anisotropic media. Stable estimation of the medium parameters requires high-quality, good-coverage data and *a priori* knowledge of the ratio of the P-to-S vertical velocities and one of the velocity or density contrasts across the interface. For orthorhombic media, however, the inversion cannot be performed without additional constraints.

This work provides an analytic basis for the amplitude inversion methods we plan to develop within the framework of the new project. The results give a clear indication that the uncertainty in AVO analysis can be significantly reduced by using multicomponent (PP, PS, SS), multiazimuth data.

Publications: Jílek (2002a,b).

17. Anisotropic inversion of seismic data for stressed media

Despite its universal presence in the subsurface, nonhydrostatic stress is often ignored as a source of elastic anisotropy. We applied nonlinear theory of elasticity to relate the anisotropic parameters of a stressed VTI solid to the magnitudes of the principal stresses. According to our analysis, nonhydrostatic stress should make the medium symmetry close to orthorhombic, if one of the principal stresses is parallel to the symmetry axis of the VTI material. Under the assumption of weak background and stress-induced anisotropy, each effective anisotropic parameter reduces to the sum of the corresponding Thomsen parameter of the VTI background and a parameter associated with the nonhydrostatic stress.

The theoretical predictions were tested on physical-modeling data acquired over a block of Berea sandstone that exhibits intrinsic transverse isotropy. The anisotropic parameters in the vertical plane normal to the stress remain close to those of the unstressed material, while the parameters in the orthogonal vertical plane grow almost linearly with increasing stress. The measured anisotropic parameters for a wide range of stresses are sufficiently close to the theoretically predicted values. The experimental results indicate that nonlinear elasticity may provide a suitable framework for estimating pore pressure and 3D stresses from multicomponent seismic data.

Publication: Sarkar, Bakulin, and Kranz (2003).

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