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The Ninth International Workshop on Seismic Anisotropy (9IWSA)

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The ninth International Workshop on Seismic Anisotropy (9IWSA) was held on March 26-31, 2000, at Camp Allen Conference Center, about 20 miles from Houston, Texas. The 9IWSA organization committee is listed above and was chaired by Leon Thomsen.

Below are the abstracts of the 58 papers presented at 9IWSA. Please see http://www.seg.org/9iwsa for expanded abstracts and proceedings of 9IWSA.

We thank BP, Elf, Schlumberger, and Texas A&M University for helping make this Workshop accessible to all, and pleasant for all.

REFERENCE

Ikelle, L. and Gangi, A., Eds., 2001, Anisotropy 2000: Fractures converted waves, and case studies: Proc. 9th Internat. Workshop on Seismic Anisotropy: Soc. Expl. Geophys.

THE HISTORICAL ROOTS OF SEISMIC ANISOTROPY

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Edward Szaraniec, *Cracow University of Technology*

The beginning of research in seismic anisotropy can be fixed precisely. When Maurycy Pius Rudzki assumed his duties as the first "Professor of Geophysics" at the Jagiellonian University in Cracow in early 1896, he stated that his research would be directed at seismology, and primarily at the propagation of seismic waves in anisotropic media. During the next 20 years he published regularly on the subject. There are five major papers that deserve to be studied even today.

SHEAR-WAVE SPLITTING IN A CRITICA CRUST: II - COMPLIANT, CALCULABLE, CONTROLLABLE, FLUID-ROCK INTERACTIONS

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The pervasive distributions of stress-aligned fluid-saturated microcracks present in almost all in situ rocks are so close to fracture criticality and loss of shear-strength that the Earth's crust is a critical interactive non-linear system with self-organized criticality. Some effects are subtle and easily ignored. Others are so common and familiar that we have developed one-off explanations in terms of conventional non-critical physics to describe their behavior and occurrence. Recognition of criticality leads to a new understanding of pre-fracturing deformation of in situ rock with massive implications for almost all dynamic processes in the crust, including reservoir characterization, hydrocarbon recovery, the progress of fluid-fluid fronts, and the build-up of stress before fracturing, faulting, and earthquakes. In particular, because the statistics of critical systems behave in characteristic ways (critical point universality) that are largely independent of the sub-critical (conventional) physics, the response of such critical systems can sometimes be calculated with surprising accuracy. As a consequence, a largely parameterless model of anisotropic poro-elasticity (APE) matches a wide variety of phenomena associated with shear-waves and fluid-rock-crack interactions in the crust. This opens the possibility of monitoring the internal crack deformation of the rockmass, calculating the response to potential changes, and controlling by feedback the response to changing conditions. This implies that the compliant stress-sensi-

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tive rockmass is heterogeneous at all scale lengths and necessarily varies from place to place and from time to time. Low-frequency, long-wavelength measurements may be valid, but high-frequency (probably greater than 100Hz), short wavelength (probably sub-meter, certainly sub-centimeter), high-resolution observations cannot be extrapolated from place to place (Gaussian averages are inappropriate), and may degrade with time. Since the progress of fluids through porous microcracked rock depends intrinsically on such detailed rock-fluid-crack interactions, criticality is crucial for understanding the behavior of fluid-fluid fronts in producing reservoirs. Consequently, the high resolution measurements needed to monitor the behavior of producing reservoirs need to be made specifically at the time and place they are required.

ESTIMATION OF FRACTURE PARAMETERS OF ORTHORHOMBIC MEDIA FROM REFLECTION SEISMIC DATA

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Vladimir Grechka and Ilya Tsvankin, *Center for Wave Phenomena, Department of Geophysics, Colorado School of Mines, Golden, Colorado*

Existing geophysical and geological data indicate that orthorhombic media with a horizontal symmetry plane should be rather typical for naturally fractured reservoirs. Here, we consider two orthorhombic models, one of which contains parallel vertical fractures embedded in a transversely isotropic background with a vertical symmetry axis (VTI medium), and the other is due to two orthogonal sets of rotationally invariant fractures in a purely isotropic host rock.

Using the linear slip theory, we obtain simple analytic expressions for the anisotropic coefficients of the effective orthorhombic models. Under the assumptions of weak anisotropy of the background medium and small compliances of the fractures, all effective anisotropic parameters reduce to the sum of the background values and the parameters due to each fracture set. For the model with a single fracture system, this result allows us to eliminate the influence of the VTI background by evaluating the differences between the anisotropic parameters defined in the vertical symmetry planes. The parameter-estimation procedure can be based on azimuthally-dependent reflection signatures of *P*-waves alone. It is beneficial, however, to combine *P*-wave data with the vertical traveltimes, normal-moveout (NMO) velocities or AVO gradients of *PS*-waves.

If the model contains two orthogonal fracture sets, the anisotropic parameters can be estimated by means of two inversions performed independently within the vertical symmetry planes.

CONSTRAINTS ON THE INTERPRETATION OF *P*-WAVE AVOA FOR FRACTURE CHARACTERIZATION

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A new methodology for *P*-wave AVOA (amplitude variation with offset and azimuth) analysis has been applied to the 3D-4C OBC (ocean bottom cable) data from Valhall. This AVOA analysis showed evidence of azimuthal anisotropy that has been attributed to aligned fracturing. However interpretation of AVOA data, for fracture characterization, is highly model-dependent such that even the fracture strike direction can be ambiguous. Therefore forward modeling is necessary to constrain the interpretation of the AVOA.

This work uses effective medium modeling and calculated AVO to constrain the interpretation of the AVOA in the data at Valhall and thus determine the fracture properties and orientations. Comparison of forward modeling with the data indicates that to produce the observed levels of anisotropy there needs to be a large crack density of thin fractures with a fracture-fill that is more likely liquid than gas. The modeling also indicates that communication of fluid to the matrix pore space will be minimal, implying a low-permeability matrix. Furthermore, the higher levels of observed anisotropy can only be modeled if the most positive near-offset AVO gradient is in the direction perpendicular to the fracturing. Thus, based on these constraints, high resolution maps of fracture magnitudes and orientations were produced from the AVOA data. The observed fracture patterns show compartmentalization and orientations that are consistent with faulting interpreted from 3D-coherency analysis. This work also provides insight into the regional stress field and local perturbations to this.

COMBINING *P-P* AVOA AND NMO DISTINGUISHES GAS FROM WATER IN FRACTURES

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A technique is developed for distinguishing between gas and water-filled fractures using P-wave data. The method relies upon combining the azimuthal AVO signature for a fractured reservoir with its interval moveout time. A crossplot of these attributes provides a robust and simple indicator, irrespective of the offset and azimuth distribution at the bin location. The technique is applicable to reservoirs whose production is assisted by the presence of natural fractures, where saturation maps can help to better quantify and assess pathways for flow.

AVO-A RESPONSE OF AN ANISOTROPIC HALF-SPACE BOUNDED BY A DIPPING SURFACE FOR QP-QP, QP-QSV AND QP-QSH DATA: INVERSION

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We present an analysis of amplitude variations with offsets and with azimuths (AVO-A) of an anisotropic half-space bounded by a dipping surface. The purpose of this analysis is to find correlations between anisotropic parameters; as such correlations can reduce the number of parameters in seismic inversions. By analyzing the response of a dipping reflector instead of a horizontal one, we have integrated the fundamental problem of lateral heterogeneity versus anisotropy in our study. Our analysis is limited to the three scattering modes which dominate ocean bottom seismic (OBS) data: qP-qP, qP-qSV and qP-qSH. If the overburden is assumed isotropic, the AVO-A of each of these three scattering modes can be cast in terms of a Fourier series of azimuths, ϕ,

$$R_{avaz}(\phi) = F_0 + \sum_{n=1}^{4} \left[F_n \cos(n\phi) + G_n \sin(n\phi) \right]$$

where F_0, F_n and G_n are the functions which describe the seismic amplitude variations with offset (AVO) for a given azimuth. The AVO function F_0 is null for qP-qSH scattering, if the acquisition plane is parallel to the dip direction. The forms of AVO functions are similar to those of the classical AVO formulae; for instance, the AVO functions corresponding to qP-qP scattering mode can be interpreted in terms of intercept and gradient, although the resulting numerical values can differ significantly from those of an isotropic case or horizontal reflectors. The maximum number of parameters in a given AVO function is five.

One of the benefits of describing the AVO-A as a Fourier series is that the contribution of amplitude variations with azimuths (AVAZ) is decoupled from that of AVO. The AVAZ is characterized by the functions $\{1, \cos\phi, \sin\phi, \cos 2\phi, \sin 2\phi, \cos 3\phi, \sin 3\phi, \cos 4\phi, \sin 4\phi\}$ which are mutually orthogonal. Thus, the AVO-A inversion can be formulated as a series of AVO inversions where the AVO behaviors are represented by the functions F_0, F_n and G_n. Moreover, the 3ϕ and 4ϕ terms of the Fourier series are negligible compared to the other terms of the series. If the coordinate system of seismic acquisition geometry coincides with the crystallographic axis of the rock formation, this series corresponding to qP-qP and qP-qSV simplifies even further; it reduces to F_0 for azimuthally isotropic symmetry and to F_0, F_2 and F_4 only for orthorhombic symmetry. The series corresponding to qP-qSH scattering is reduced to G2 and G4 for these two symmetries.

THE MOBIL ONSHORE TEXAS 3-D FULL-AZIMUTH FULL-OFFSET P-WAVE SURVEY

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Grant Geophysical acquired a 42.8 square mile 3-D full-azimuth full-offset P-wave reflection survey in south central Texas, with Mobil Exploration and Producing US, Inc. as underwriting original participant. The target formations were the Edwards carbonate and the Austin Chalk (14,000-15,500 ft depths). The goal of the 3-D survey was to provide structural and stratigraphic information about the targets, as well as fracture azimuth and relative fracture density. The reflection horizon maps showed low amplitude lineations that were interpreted as faults when seen on both azimuths, because displacement was also observed at the reflector therein. Low amplitude lineations seen on only one azimuth were interpreted as high-fracture-density zones. Consistency between the azimuth of the low amplitude lineations and the azimuthal variation in interval velocity (for the appropriate interval) is observed, which increases the confidence level in the interpretation.

MULTICOMPONENT TRUE-AMPLITUDE ANISOTROPIC IMAGING

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Numerical implementation of multicomponent Kirchhoff imaging requires the computation of several ray quantities: traveltimes, slowness, polarization vectors, and geometrical spreading. Here, we show how estimates of all kinematic and dynamic quantities needed in the multicomponent imaging can be computed without ray-tracing in the case of 1-D layered media.

FIRST EVALUATION OF AZIMUTHAL ANISOTROPY OVER THE VALHALL FIELD

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A 3D-4C Ocean bottom seismic survey was acquired by BP on the Valhall field, Norwegian Block 8, North Sea, in 1998. Previous 2D-4C studies have shown the potential of shear waves (in fact converted waves or C-waves) to penetrate through a gas cloud and illuminate the target otherwise invisible to P-waves. Although the primary objective of this multicomponent survey was to improve the structural imaging of the crest of the field, there were a number of secondary objectives. They include establishing the potential for jointly utilizing the C-wave and P-wave data for reservoir characterization and lihtology prediction, determining stress and fracture orientation, and analyze possible 4D effects.

This paper presents the preliminary results for the evaluation of the presence of azimuthal anisotropy. The main effect of azimuthal anisotropy is to split shear waves into a fast (S1) and a slow (S2) mode. These modes propagate according to the principal directions of the fracture system. The first step in 3D shear wave processing is to rotate the multicomponent data in the Radial and Transverse axes. The Radial axis corresponds to the source-receiver direction, and the Transverse axis to its perpendicular. In this coordinate system, without azimuthal anisotropy effects, all the shear energy should be concentrated in the Radial component. The shear wave splitting effect generated by azimuthal anisotropy can result in a significant amount of energy being recorded by the Transverse component (when the Radial-Transverse coordinate system differs from the main fracture direction). If this phenomenon is not properly addressed during the processing sequence, it will result in a significant loss of high frequency for the C-wave image. Therefore, a careful analysis of azimuthal anisotropy can lead not only to the detection of fracturation, but to an improved resolution. A preliminary stack of the Radial and Transverse components for the Valhall survey shows a significant amount of energy in the Transverse component at the target level. Before carrying out the azimuthal anisotropy study, it is essential to make sure that this observation is not due to another cause. In particular, a careful analysis of vector fidelity demonstrated that the inherent anisotropy of the acquisition system was not responsible for this anomaly. Then, the methodology described by Garotta and Granger (1988) was applied to 3 swathes of the Valhall survey. This method uses the ratio of Radial to Transverse energy for a range of azimuth stacks to identify the direction of anisotropy. The data are then rotated into the fast (S1) and slow (S2) directions, and the difference in arrival time between these two data sets gives a measure of fracture density. Preliminary results are encouraging in the sense that they provide a significant time delay between S1 and S2, and that the main directions of anisotropy make sense geologically. As a result, an improved resolution is obtained from the C-wave image.

A CASE STUDY OF ANISOTROPIC VELOCITY ANALYSIS FOR 4C SEISMIC DATA

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Over recent years, various methods have been presented for quantifying polar anisotropy and compensating for its effects using either *P*-wave, *PS*-wave or both. Here, we present a double-scanning method and demonstrate how the anisotropic parameter σ and the NMO velocity ratio (γ_n) can be estimated from 4-C sea-floor seismic data. This is achieved by performing a semblance analysis over γ_n and σ using an anisotropic double-squared-root (DSR) equation for *P-SV* moveout (*PS*-moveout). The analysis requires the prior knowledge of the *P*-wave NMO velocity v_{pn} and the vertical velocity ratio γ_n. Compared with the existing methods, this approach improves the results of *PS*-moveout correction at far offsets, reduces error propagation and magnification, and yields more stable estimates of anisotropic parameters. The method is applied to a 4C dataset from the North Sea (courtesy of Shell Expro).

3-D DESCRIPTION OF DIP MOVEOUT OF *PS*-WAVES AND APPLICATION TO PARAMETER ESTIMATION IN VTI MEDIA

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We present a concise parametric description of both common-midpoint (CMP) and common-conversion-point (CCP) gathers of *PS*-waves for arbitrary anisotropic, horizontally layered media above a plane dipping reflector. This analytic representation can be used to generate 3-D (multiazimuthal) CMP gathers without time-consuming two-point ray tracing and obtain such attributes of *PS* moveout as the slope of the traveltime surface at zero offset and the coordinates of the moveout minimum.

In addition to providing an efficient tool for forward modeling, our formalism helps to carry out joint inversion of *P* and *PS* data for transversely isotropic media with a vertical symmetry axis (VTI). If the medium above the reflector is laterally homogeneous, *P*-wave reflection moveout is fully controlled by the normal-moveout (NMO) velocity from a horizontal reflector [$V_{nmo,P}(0)$] and the "anellipticity" parameter η and, therefore, cannot constrain the vertical velocity needed for depth migration. Combining *P*-wave moveout with the traveltimes of the converted *PS*(*PSV*)-wave makes it possible to obtain the interval vertical velocities of the *P*- and *S*-waves (V_{P0} and V_{S0}) and Thomsen parameters ε and δ.

For 3-D surveys with a sufficiently wide range of source-receiver azimuths, all four relevant parameters (V_{P0}, V_{S0}, ε and δ) can be estimated using moveout from a *single* mildly dipping reflector. In this case, the *P*-wave NMO ellipse determined by 3-D (azimuthal) velocity analysis is supplemented with azimuthally dependent traveltimes of the *PS*-wave.

ANISOTROPIC VELOCITY ANALYSIS USING MODE CONVERTED S-WAVES

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Sedimentary rocks are usually anisotropic because of fine scale layering and the preferred orientation of nonspherical grains and anisotropic minerals. In order to extend seismic processing to anisotropic media, an anisotropic velocity model is required. For transversely isotropic media with a vertical axis of symmetry, Alkhalifah and Tsvankin (1995) have shown that a single anisotropy parameter η; together with the small-offset normal moveout (NMO) velocity for PP-reflections is sufficient to perform all time-related processing of P-wave data. Although P-waves form the basis of most commercial seismic surveys, shear waves provide unique information concerning subsurface lithology and pore fill. Recent developments allow multi-component seismic data to be acquired at the seafloor. By using measurements of the small-offset travel-times of PP and PSV reflections to determine the parameters of ANNIE, a simple three-parameter model proposed by Schoenberg et al. (1996) for shales, reliable estimates of η; can be made in the absence of any depth or vertical velocity information. The long-offset (non-hyperbolic) travel-time moveout of both PP and PSV reflections from a horizontal reflector in a laterally homogeneous medium is accurately predicted by this approach, despite the fact that only small-offset data is used in the analysis. Thus the wide-offset moveout curves for both PP and PSV reflections from a horizontal reflector in a laterally homogeneous medium can be adequately described using only the small-offset travel-times of PP and PSV reflections.

APPROXIMATE REFLECTION COEFFICIENTS OF PS-WAVES IN ANISOTROPIC MEDIA

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Due to the complexity of the exact reflection and transmission coefficients, their approximations are of great importance in AVO analysis, especially in anisotropic media. Whereas several approximations for anisotropic PP-wave reflection coefficients have been discussed previously in the literature, the influence of anisotropy is commonly ignored in the case of the converted PS-wave reflection coefficients. Adequate approximations for PS-wave reflection coefficients may provide a powerful tool for a joint PP and PS inversion of AVO attributes for the medium parameters.

Here, I present first-order approximations for converted-wave displacement reflection coefficients R_{PS1} and R_{PS2} at a weak horizontal interface separating two weakly anisotropic media with arbitrary symmetry. The general expressions are specified for an interface between two orthorhombic media with differently oriented vertical symmetry planes using Thomsen-type notation. I also obtained simple approximations valid for small incidence angles (approximately up to 15°). The final expressions can be applied to any combination of isotropic, VTI, HTI and orthorhombic halfspaces.

ISSUES RELATED TO 4-C COARSE-LAYER STRIPPING OF 3-D PS-WAVE DATA

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Delineating reservoir fractures by exploiting S-wave birefringence is an important application of 3-D converted P to S-wave (PS-wave) data. Issues of survey design, attenuation/dispersion, and transverse isotropy with a vertical axis impact the ability to unravel S-wave properties for fracture characterization. Data collected with wide azimuths is advantageous because it allows the estimation of fracture orientation independent of propagation effects and provides measurements at multiple-azimuths.

MULTIWAVE OIL FIELD PROSPECTING ON CLAY RESERVOIRS

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Land multiwave seismic (combined using of the different wave type) have showed possibility the oil field in clayey reservoirs prospecting. Some of combined seismic parameters anisotropy characterized is in good agreement with oil productivity in this type of reservoirs.

INVERSION OF QP WAVE TRAVELTIMES IN INHOMOGENEOUS ANISOTROPIC MEDIA

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We propose an iterative procedure for determining the lateral variation of all 21 elastic parameters from qP-wave traveltimes. The procedure consists of two basic steps: In the first step, an isotropic starting model is updated using weak-anisotropy formulae. In this way, the 15 qP-wave weak-anisotropy (WA) parameters are determined. In the second step, the WA parameters (a generalization of Thomsen's parameters) serve as a starting point for refining the estimate of all 21 parameters. Any of several assumptions can be used for specifying initial values of the remaining 6 parameters. Once this has been done, all 21 elastic parameters are iteratively updated until the difference between the observed and calculated traveltimes converges. The only additional assumption is that the variation of the elastic parameters with respect to spatial coordinates in the model box is trilinear.

We tested the procedure using a synthetic multi-azimuth multi-source offset-VSP experiment. Traveltimes were picked from noiseless qP-wave synthetics generated by sources distributed along 6 profiles intersecting at the mouth of the borehole with the receivers. The model earth was vertically inhomogeneous, with hexagonal-symmetry anisotropy with a nearly horizontal axis of symmetry. (The model is meant to simulate a cracked medium with a slightly tilted system of vertical parallel cracks.) The SVD technique was used to solve the system of linear equations resulting from the inversion problem. For qP waves, the calculated phase-velocity surfaces match those for the true model. For qS waves, while the calculated phase-velocity surfaces showed roughly the proper angular variation, there is a nearly constant offset from those for the true model. The performed tests show that a single iteration is insufficient for accurate recovery of the structure, and that qP-wave data alone are insufficient for reliable inversion of a complete set of 21 elastic parameters.

We also tested the procedure on experimental data. The qP-wave traveltime data measured during an experiment in the vicinity of the Underground Research Laboratory (URL) in Manitoba, Canada were inverted for elastic parameters. The data from 36 events recorded at 16 receivers yielded a very good spatial and angular coverage of the volume in which the elastic parameters were to be determined. At the top, our result displays an anisotropy close to orthorhombic symmetry. At the bottom, however, we find a more generally anisotropic result. The phase velocity generally increases with depth. Maximum velocities at the top of the model are in a direction parallel to the axis of the tunnel. At the bottom, the maximum velocities are again in a horizontal direction, but rotated about 30 degrees off of the axis of the tunnel. The strength of the anisotropy decreases with increasing depth. If the anisotropy were caused by a system of parallel cracks, this could indicate that there are two approximately perpendicular crack systems, one containing vertical cracks, with faces approximately parallel to the axis of the tunnel, and the other system with horizontal cracks.

NMO-VELOCITY SURFACES AND DIX-TYPE FORMULAE IN ANISOTROPIC MEDIA

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The most stable portion of pure-mode reflection moveout recorded on conventional spreads is determined by the normal-moveout (NMO) velocity. Here, we introduce the concept of NMO-velocity *surfaces* formed by NMO velocities plotted at a fixed common-midpoint (CMP) location as radius-vectors along all possible directions of CMP lines in 3-D space.

We show that the NMO-velocity surface is quadratic and usually takes the shape of an *ellipsoid*, a *one-sheeted hyperboloid*, or an *elliptical cylinder*. The cross-section of this surface by the horizontal plane yields the NMO ellipse. NMO-velocity surfaces provide a natural basis for building Dix-type averaging and differentiation formulae in anisotropic heterogeneous media. These Dix-type equations take a particularly concise form for a stack of homogeneous anisotropic layers separated by plane arbitrarily dipping interfaces.

In transversely isotropic media with a vertical symmetry axis (VTI), the presence of intermediate dipping interfaces makes the *P*-wave NMO ellipse recorded at the surface dependent on the individual values of the interval anisotropic coefficients ε and δ. Hence, for some laterally heterogeneous VTI models *P*-wave reflection data may provide enough information for anisotropic *depth* processing. This conclusion is confirmed by an example of successful tomographic inversion for a two-layer model composed of a VTI and isotropic layer.

VELOCITY ANALYSIS FOR TILTED TI MEDIA: A PHYSICAL-MODELING EXAMPLE

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Transverse isotropy with a tilted symmetry axis (TTI media) has been recognized as a common feature of shale formations in overthrust areas, such as the Canadian Foothills. Since conventional processing algorithms fail to produce accurate seismic images beneath TTI layers, it is important to be able to reconstruct a velocity model suitable for *anisotropic* depth migration. Here, we present the results of anisotropic parameter estimation on a physical-modeling data set acquired at the University of Calgary by Leslie and Lawton. This model represents a simplified version of a typical overthrust section from the Alberta Foothills, with a horizontal reflector overlaid by a bending transversely isotropic layer. Assuming that the TTI layer is homogeneous and the symmetry axis stays perpendicular to its boundaries, we invert *P*-wave normal-moveout (NMO) velocities and zero-offset traveltimes for the symmetry-direction velocity V_0 and the anisotropic parameters ε and δ. Crucial information about the parameter ε is provided by the reflection from the bottom of the model that crosses one of the *dipping* TTI blocks. Our estimates of the anisotropic coefficients ($\varepsilon = 0.16 \pm 0.06$ and $\delta = 0.09 \pm 0.06$) are close to their actual values for this model ($\varepsilon = 0.16$ and $\delta = 0.08$). The error bars, associated primarily with the uncertainties in picking the NMO velocities and traveltimes from the semblance panels, can be reduced by modifying the acquisition geometry. It should be emphasized that the moveout inversion also gives an accurate estimate of the thickness of the TTI layer, thus reconstructing the correct *depth* scale of the section.

ANELLIPTIC TIME PROCESSING, FROM NMO TO DMO

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The processing of deep-offshore seismic data acquired with long streamers involves appropriate algorithms taking into account the non-hyperbolic shape of the reflection curves and the inadequacy of the standard DMO. The seismic signatures of the effects corresponding to bedding or VTI anisotropy are indistinguishable. Since the shifted hyperbola NMO equation seems to describe perfectly both effects, we propose to parameterize them with the VTI anisotropy parameter η. In the case of the layered VTI model, our shifted hyperbola moveout correction using the actual effective values of V_{nmo} and anellipticity η produces a better result than Alkhalifah's VTI NMO. The DMO operator derived from the anelliptic shifted hyperbola equation fits quite accurately to the monotonous part of Alkhalifah VTI DMO operators. This anelliptic dip moveout depends on effective η only. The outstanding effective η values seem to be connected to the non-hyperbolic velocity analyses occurring at the same levels.

ANISOTROPIC PRE-STACK DEPTH MIGRATION: AN OFFSHORE AFRICA CASE STUDY

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Paul Williamson Paul Sexton, and Joachim Mispel, *Elf Geoscience Research Centre*

Pre-stack depth migration is widely used as the best tool for imaging and velocity model QC and refinement, but is mostly applied isotropically even when there is evidence of anisotropy. We outline a methodology for use in anisotropic contexts and apply it to a line of data from offshore W. Africa dominated by massive shales. The results show that the anisotropy in the shale increases with depth, and the prestack migrated data is sufficiently sensitive to the anisotropy that a thin layer of sand showing little or no anisotropy can be detected, and must be included in the model to get flat common image gathers everywhere. This suggests that the use of anisotropy as a lithology-discriminating attribute may be feasible on a depth scale of only a few wavelengths. In any case anisotropy determination is important for precise application of other lithoseismic methods such as AVO.

A SYNTHETIC EXAMPLE OF ANISOTROPIC *P*-WAVE PROCESSING FOR A MODEL FROM THE GULF OF MEXICO

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Transverse isotropy with a vertical symmetry axis (VTI media) is the most common anisotropic model observed in sedimentary basins. Here, we apply *P*-wave processing algorithms developed for VTI media to a 2-D synthetic data set generated for a typical model from the Gulf of Mexico. The model has a moderate structural complexity and includes a salt body and a dipping fault plane.

We pick the NMO (stacking) velocities from conventional semblance panels and, using the Alkhalifah-Tsvankin dip-moveout (DMO) inversion method, obtain the zero-dip NMO velocity $V_{nmo}(0)$ and the anisotropic coefficient η responsible for the dip dependence of *P*-wave NMO velocity in laterally homogeneous VTI media. We perform prestack depth migration for the reconstructed anisotropic model and two isotropic models with different choices of the velocity field. The anisotropic migration result has a good overall quality, but reflectors are mispositioned in depth because the vertical velocity could not be obtained from surface data in our model.

The isotropic migrated section with the NMO velocity $V_{nmo}(0)$ substituted for the isotropic velocity also has the wrong depth scale and lower quality in the focusing of dipping events compared to the anisotropic result. Still, the image distortions are not significant because the parameter η, which controls NMO velocity for dipping reflectors, was rather small. In contrast, the isotropic section migrated with the vertical velocity V_0 has a poor quality (although the depth of the subhorizontal reflectors is correct) due to the fact that in VTI media V_0 can be used to stack neither dipping nor horizontal events.

FROM TI TO WAMAST MEDIA FOR QP ELASTIC WAVES

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Although explicit analytic expressions exist for the velocities and for the polarizations of the 3 bulk elastic waves propagating in an arbitrary anisotropic medium of infinite extension (e.g. Helbig, 1994), the complexity of these equations limits their practical use, except in some highly degenerate cases (isotropy, transverse isotropy…). However in some special cases of particular interest for seismic exploration these equations get much simpler forms. This is the case for qP waves, which constitute the great majority of data acquisition in seismic exploration, in weakly anisotropic media such as most of sedimentary rocks in contrast with monocrystals (e.g., Thomsen 1986). For instance it is striking to note that, under the weak anisotropy assumption and for a fixed azimuth λ, the directional dependence of the qP-wave velocity of media of symmetry as low as monoclinic with a horizontal symmetry plane is formally identical to that of vertical transversely isotropic (VTI) media (Mensch and Rasolofosaon, 1997). More precisely, if the vertical direction is taken as the reference direction, the qP-wave velocity equation is exactly the same as for VTI media except that the anisotropy parameters ε and δ are no longer constant but depend on the azimuth λ (see Figure 1)

The most important practical consequence is that all the seismic algorithms for qP-waves in the time domain developed for the VTI case can directly be applied to the monoclinic case azimuth by azimuth by taking for each azimuth λ the corresponding anisotropy parameters $\varepsilon(\lambda)$ and $\delta(\lambda)$. Note that in the triclinic case an additional perturbative correction $\Delta V_{\text{triclinic}}$ has to be added to the qP-velocity equation. However $\Delta V_{\text{triclinic}}$ is an odd function of the angle θ from the vertical direction. As a consequence in geometries of propagation where the "unperturbed isotropic" seismic ray pattern is symmetric with respect to the vertical direction the overall contribution of $\Delta V_{\text{triclinic}}$ to the kinematics cancels. This is the case for surface seismic experiments in horizontally layered media, a very common starting assumption in seismic processing. For instance, using these properties the non hyperbolic moveout equations and the generalized Dix layer stripping process known for VTI media (e.g. Alkhalifah 1997) have been extended to Weakly Anisotropic Media of Arbitrary Symmetry Type (WAMAST) by Tabti and Rasolofosaon (1998).

Regarding the amplitudes the VTI equations and the general equations are also surprisingly similar. For instance the qP-wave reflection coefficient at a plane interface between two weakly contrasted VTI media (e.g. Thomsen 1993 and Rüger 1995) can be generalized to the case of monoclinic media with a horizontal symmetry plane simply by using the same receipe as for kinematic problems (see figure 2) and by adding a perturbation depending on the contrast in the shear-wave birefringence γ in a vertical direction between the two media in contact (Psencik and Vavycuk, 1997).

The same receipe applied to the problem of qP-wave Green's functions in weakly anisotropic multilayered media, although not being correct in theory, also surprisingly gives satisfactory results (Tabti and Rasolofosaon, 1999).

ANALYTICAL INVERSION OF A STACK OF WEAKLY ANISOTROPIC LAYERS

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Using the seismic-reflection method, we carry out a 3D study of a stack of horizontal layers characterized by contrasted anisotropic properties (from TI with a vertical axis of symmetry to monoclinic).

The inversion proposed here requires two mathematical descriptions of the common midpoint reflection time-distance curve of the anisotropic medium:

- The first one called the exact equation was obtained using the P-wave phase velocity expression for weakly anisotropic media of arbitrary symmetry proposed by Mensch and Rasolofosaon 1997. This equation contains the following unknown parameters: vertical velocity, thickness and anisotropy coefficients.
- The second equation describing also the travel time of P-waves in the medium is called the approximate equation. It is a 4-parameter mathematical approximation whose deviation from the exact equation is lower than the seismic sampling interval. It contains the measurable parameters needed for the inversion. This equation corresponds to the combination of two hyperbolae tangent at a point (xc, tc) which is analytically well known. The physical meaning is that the wavefronts can be described by two tangent circles in a given azimutal plan.

The common midpoint time-distance curve is thus defined by 4 independent parameters for each azimuth. 13 independent values can be obtained from measurements in 4 different azimuthal orientations every 45 degrees instead of 16 since one of the parameters, the zero-offset travel time, is azimuthally invariant.

The inverse problem consists in evaluating the 10 unknown parameters (monoclinic case) of the exact equation using the 13 independent values defining the 4 approximate equations.

The modeling of seismic traces in anisotropic media was achieved using the program ANRAY (Gajewski and Psencik 1987) to produce a synthetic data set. On this, the parameter measurements were done using the PSCAN theory (de Bazelaire 1988). The results from the inversion depict a good agreement with true model parameters.

Finally, this technique can be applied to a stack of anisotropic media by processing the inversion individually on each of them. To achieve this, using an analogous method with the one of Dellinger and Muir 1992, we need to find geophysical invariants which can transmit the measurements of the current layer through the upper multi-layered stack.

EXPERIMENTAL DETERMINATION OF THE ELASTIC COEFFICIENTS OF ANISOTROPIC MATERIALS WITH THE SLANT-STACK METHOD

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Anisotropy is present in many of the rocks through which seismic waves pass. However, our understanding of anisotropy is quite limited and leads to errors in processing and modeling. To better comprehend this anisotropy, one must be able to measure the phase velocities of the waves propagating through the material. Through the use of the slant-stack (Radon) transform, one is able to directly determine the phase velocities as functions of propagation direction. The elastic constants of the material may then be determined by an inversion.

BENDING RAY-TRACING AND REFLECTION TOMOGRAPHY IN TI MEDIUM

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An original formulation of anisotropy in TI media is introduced in the bending ray-tracing *jerry*. Comparisons of PP and PS travel times generated by *jerry* with those of a reference ray-tracer, in several models, show very good agreement even for the toughest models. The calculation of travel time derivatives with respect to anisotropy parameters allow their determination by reflection tomography. On a simple example a methodology to recover a complete subsurface model from PP and PS traveltimes has been developed. This methodology yields very low misfits for an estimated model quite close to the true model, except for δ.

CASE STUDY OF A PRAGMATIC APPROACH TO V(Z) VTI PROCESSING ON 2D OFFSHORE WEST AFRICA DATA

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The aim of this poster is to show the results of two parallel sequences of complete time processing on real 2D data from offshore West Africa, where the presence of anisotropy is common. The first sequence called isotropic, remains conventional whereas the second one, called "anisotropic", attempts to take v(z) VTI anisotropy into account. Improvements in this second sequence are due to a non-hyperbolic moveout correction, a modified elliptic dip moveout (DMO) and a 2D anisotropic phase-shift time migration. Theoretically an elliptic DMO cannot accurately correct strongly dipping events. But a trick, consisting in stretching the offsets, permits to enhance in the stack the focusing of seismic events, corresponding here to quite sloping faults. The main advantage of such a DMO methods is that, no a priori anisotropic model is necessary. Despite this deviation from a correct v(z) anisotropic processing, the proposed sequence leads however to satisfying results in comparison with a classical seismic processing.

GREEN'S FUNCTIONS FOR QP-WAVES IN MULTILAYERED WAMAST MEDIA: EXPLICIT ANALYTIC EXPRESSIONS

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Analytic expressions for Green's functions of elastic waves in multilayered arbitrary anisotropic media have been published in the literature (e.g. Ben-Menahem and Sena, 1990). However most of the quantities (traveltime, wave front curvature... etc.) defining these expressions are not explicitly given but must be numerically estimated, for instance using ray tracing codes. Here we derive explicit analytic equations for qP-wave far-field "high-frequency" Green's functions in multilayered models constituted by Weakly Anisotropic Media of Arbitrary Symmetry Type (WAMAST) or triclinic media. The method is mainly based on the velocity parametrization of Mensch and Rasolofosaon (1997), on the PP-wave reflection/transmission coefficients derived by Psencik and Vavrycuk (1997) and on the nonhyperbolic moveout equation of Tabti and Rasolofosaon (1998) in WAMAST media. Our equations are tested on a synthetic model with layers of contrasted anisotropy type (from isotropic to triclinic) and strength (anisotropy parameters from 0 to about 20%). All the results (in terms of traveltime, displacement amplitude, polarisation vector and normal vector) are in a good agreement with the results obtained with ray tracing codes even for relatively large incidence angles (up to 45°). Furthermore these equations allow for a considerable reduction in computation time. Compared to ray tracing codes, in our tests, a time reduction by a factor of a few hundreds was obtained. Thus, these equations are particularly adapted to time and true amplitude migration softwares (which is the primary motivation of these developments), or more generally, to inversion softwares for which particularly intensive computation of direct problems are needed.

REFERENCE ELLIPSOIDS FOR ANISOTROPIC MEDIA

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Perturbation techniques are common tools to describe wave propagation in weakly anisotropic media. The anisotropic medium is replaced by an average isotropic medium where wave propagation can be treated analytically and the correction for the effect of anisotropy is computed by perturbation techniques, of 1st order mostly. This works well for anisotropies of up to 10%. Some materials (e.g., shales), however, can exhibit a much stronger anisotropy. In this case a background medium is required which still can be treated analytically but allows to consider stronger P-wave anisotropy. In this paper we present an averaging technique to compute a best-fitting ellipsoidal medium to an arbitrary anisotropic medium. Ellipsoidal media can still be treated analytically for many applications but allow to consider strong P-wave anisotropy. The averaging of the arbitrary anisotropic medium can be carried out globally (i.e., for the whole sphere) or sectorially (e.g., for seismic waves propagating prominently in the vertical direction). We derive linear relations for the coefficients of the ellipsoidal medium which depend on the elastic coefficients of the anisotropic medium. Numerical examples for different rocks demonstrate the improved approximation of the anisotropic model using the ellipsoidal medium compared to the average isotropic medium.

AVO-A RESPONSE OF AN ANISOTROPIC HALF-SPACE BOUNDED BY A DIPPING SURFACE FOR QP-QP, QP-QSV AND QP-QSH DATA: THEORY

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In this paper, we present an analysis of amplitude variations with offsets and with azimuths (AVO-A) of an anisotropic half-space bounded by a dipping surface. The purpose of this analysis is to find correlations between anisotropic parameters; as such correlations can reduce the number of parameters in seismic inversions. By analyzing the response of a dipping reflector instead of a horizontal one, we have integrated the fundamental problem of lateral heterogeneity versus anisotropy in our study. Our analysis is limited to the three scattering modes which dominate ocean bottom seismic (OBS) data: qP-qP, qP-qSV and qP-qSH. By formulating the AVO-A of each of these three scattering modes as a Fourier series of azimuths, we found that the effect of dip, the amplitude variations with offsets (AVO) and the amplitude variations with azimuths (AVAZ) can all be decoupled. As a result of this decoupling, the AVO-A inversion can be formulated as a series of AVO inversions. The maximum number of parameters to be inverted in each AVO inversion is four.

MULTICOMPONENT *P-SV* PRESTACK MIGRATION FOR TRANSVERSE ISOTROPY

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Compensating for the effects of vertical transverse isotropy (VTI) is critical for improving *P-SV* (*C*-wave) imaging in marine 4C data processing. Here, we develop explicit expressions for performing multicomponent *P-SV* Kirchhoff prestack time migration for transverse isotropy. The key step is the use of a *P-SV* double-square-root (DSR) equation ex-pressed in terms of Thomsen anisotropic parameters. This allows the use of semblance analysis to estimate these aniso-tropic parameters as initial guesses, and an efficient implementation of anisotropic prestack migration. Multicompo-nent data from the North Sea are used to illustrate the method.

3-D PS-WAVE DATA: FIELD DATA DIFFERENCES BETWEEN WAVE PROPAGATION IN THE MAXIMUM HORIZONTAL STRESS DIRECTION VERSUS MINIMUM HORIZONTAL STRESS DIRECTION

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3D 4C ocean bottom seismic data are being collected for reservoir characterization purposes, including structure, stratigraphy, aligned porosity, stress direction determinations, and fluid-flow pathway delineation. Wide-azimuth data acquisition is recommended because we are enabled thereby to examine at least 4 limited-azimuth volumes of P-S1 and P-S2 in order to study the various quantities of interest. The simplest directions of wave propagation are thought to be the principal azimuths, in which the reflected signal is more concentrated on the “inline phone, while the transverse phone usually reaches a local minimum of reflected energy. However, there are fundamentally different and potentially useful phenomena present when the P-S1 and the P-S2 limited-azimuths are compared. For waves propagating in the minimum horizontal stress direction, the transverse phone may contain P-S signal on the farther offsets, if a point singularity exists within the recording spread. As the magnitude of the layer-induced anisotropy (TIV) increases, relative to the crack anisotropy (TIH), the point singularity present in the minimum horizontal stress direction moves from the far offsets to the near offsets. The local variation in the magnitude of the layer anisotropy thus may be mappable by tracking how the P-S signal appears on the transverse phone for waves propagating in the minimum horizontal stress direction.

CAN WE EXTRACT FRACTURE INFORMATION FROM 3D MARINE STREAMER DATA

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Azimuthal *P*-wave AVO has been used successfully for characterizing a variety of fractured gas reservoirs in land 3D data. However, the application of P-wave fracture detection to marine data is a challenge because of the lack of azimuthal coverage in marine streamer surveys. Here we present a case study from the North Sea to demonstrate how fracture orientations can be estimated from 3D marine streamer data combining with crossed 2D lines.

The data include a 3D survey shot ten years ago using a two-streamer 3D boat. Super gathers are formed from the two streamers combined with crossed 2D lines from other vintage surveys to overcome the lack of azimuthal coverage. This gives rise to at least three azimuthal gathers for each CDP point along any particular crossed 2D line. The approach requires careful data processing to match the acquisition geometry, phase and amplitude characteristics of the 2D and 3D surveys. Azimuthal AVO analysis is then carried out for each CDP point along the crossed 2D lines. In this way, the lateral variation in fracture orientations can be determined, and the results agree with previous analysis of orthogonal 2D lines.

PROCESSING OF ANISOTROPIC IMAGES FOR UPSCALING AND FRACTURE DETECTION

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Attribute and multi-resolution analyses are applied to quantify fracture patterns (FPs). All attributes are computed using the analytic image $\mathbf{M}+i\mathbf{M}^H$, where $\mathbf{M}^H$ is the imaginary part derived from $\mathbf{M}$ by convolving with a 2-D Hilbert transform operator. Multi-resolution analysis based on wavelet transforms is used for noise filtering in a time-frequency sense, and for analyzing the FPs with respect to scale. Filtering in the scale domain consists of zeroing wavelet coefficients corresponding to the noise energy. If the wavelet window function has a broad width, a gross FP is obtained. If the window becomes narrow, a detailed FP with high-frequency components is obtained.

A theoretical expression which relates the characteristics of fracture-induced anisotropy at adjacent scales is used to achieve scale decomposition and upscaling. Based on this expression, FPs are represented by anisotropic matrices, and each matrix is a composition of two anisotropic matrices at fracture-related scales. Each of these two matrices may be further subdivided into another two matrices at lower scales and so on. This is a recursive scale decomposition which starts from the low-pass wavelet-based approximation of the input FP. The fracture density at each scale is estimated from the Taylor series expansion of the anisotropic matrix using a second-order iterative inversion technique.

To perform a feasibility test of the theory, we consider an orthorhombic structure composed of two orthogonal FPs with isotropic and VTI phases. VSP processing examples from the North Sea are also presented.

ESTIMATION OF FRACTURE PARAMETERS OF MONOCLINIC MEDIA FROM REFLECTION SEISMIC DATA

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Geophysical and geological data acquired over naturally fractured reservoirs often reveal the presence of multiple subvertical fracture sets, which make the effective medium monoclinic. Here, we discuss modeling and inversion of the anisotropic parameters for two types of fractured media with monoclinic symmetry.

The first model is formed by two different non-orthogonal sets of rotationally invariant vertical fractures in an isotropic host rock. Using exact NMO equations, we devise a complete fracture-characterization procedure based on the vertical velocities of the *P*- and two split *S*-waves (or converted *PS*-waves) and their NMO ellipses from a horizontal reflector. Our algorithm yields the azimuths and compliances of both fracture systems, as well as the *P*- and *S*-wave velocities in the isotropic background medium.

In the second model, which contains a single set of *micro-corrugated* fractures, monoclinic symmetry stems from the coupling between the normal and tangential (to the fracture faces) slips. This coupling causes a dependence of the shear-wave splitting coefficient at vertical incidence on the *fluid content* of the fractures – a phenomenon that cannot be explained by conventional fracture models.

SEISMIC CHARACTERIZATION OF RESERVOIRS CONTAINING NON-ORTHOGONAL FRACTURE SETS

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Azimuthal anisotropy in rocks can result from the presence of one or more sets of partially aligned fractures with orientations determined by the stress history of the rock. A shear wave propagating in an azimuthally anisotropic medium splits into two components with different polarizations if the source polarization is not aligned with the principal axes of the medium. In the presence of two or more non-orthogonal sets of vertical fractures, the symmetry of the medium may be approximated as monoclinic with a horizontal plane of mirror symmetry if, in the absence of fractures, the rock is transversely isotropic (TI) with the symmetry axis perpendicular to the bedding plane. For such a medium, the fast and slow polarization directions for vertically propagating shear waves are not parallel or perpendicular to any of the fracture planes but lie in directions given by the principal axes of a second rank fracture compliance tensor. This tensor is independent of the normal compliance of the fractures. For offsets typical of surface seismic acquisition, the azimuthal variation in P-wave AVO at fixed offset varies with azimuth as $\cos 2(\phi,\phi_2)$ where ϕ is the azimuth measured with respect to the fast polarization direction for a vertically polarized shear wave. ϕ_2 depends on both the normal and shear compliance of the fractures and may differ from zero if the ratio of the normal to shear compliance of the fractures varies significantly between fracture sets. If this ratio is similar for all fractures ϕ_2 is approximately zero and the principal axes of the variation in P-wave velocity with azimuth for fixed offset is determined by the principal axes of the second rank fracture compliance tensor. At larger offsets, terms in cos $4(\phi\text{-}\phi_4)$ and cos $6\phi\text{-}\phi_6)$ become necessary to accurately describe the azimuthal variation in AVO.

LOCAL ESTIMATION OF ANISOTROPY PARAMETERS FROM WELL SEISMIC POLARISATION DATA

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One source of information on anisotropy which has, to date, been little used, is the polarisation of direct arrivals in walkaway surveys. While these data may be noisier than other types, they are sensitive only to the local properties of the medium. In this paper we propose an inversion scheme using observations of polarisations and slownesses along the well at the receiver string. We apply this to a 3D walkaway VSP from the North Sea. Severe selection of the data was required to recover the underlying information. The estimated anisotropy was reasonably consistent with that obtained by an alternative, proven method.

SOME RESULTS IN EQUIVALENT MEDIUM THEORY

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I continue to be interested in extending effective medium theory from the purely kinematic Backus treatment to a first-order dynamic theory for layered media. I examine some simple elastic relations and show that a class of layered models has, for propagation normal to the layering, densities away from zero frequency that are different for P- and S-mode waves. This result is accommodated by replacing the conventional scalar, frequency-independent mass density parameter with a frequency-dependent 2nd-rank inertia tensor. Some consequences are discussed, the most important being the need to estimate both impedance and velocity sufficiently to determine the (visco-elastic) parameters of homogeneous effective media. A binary, isotropic layered model provides a simple and compelling illustration of the need for a frequency-dependent, anisotropic inertia tensor away from zero frequency.

POLYADIC FORMULATION OF LINEAR PHYSICAL LAWS

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Physical fields are represented by polyadics (or tensors) of different valence (rank, order) written as ${}^{R}\Sigma$, ${}^{H}\varepsilon$, etc, where the integers R, H, ... indicate the respective valences. A physical law describes the dependence of a first field on second field. The physical law is linear, if each component ("coordinate") with reference to an arbitrary vector base of the first (dependent) field quantity ${}^{R}\Sigma$ is proportional – not necessarily with identical weights – to all components of the second (independent) field quantity ${}^{H}\varepsilon$. In the framework of the polyadic calculus such a proportionality is formulated as a "multiple dot product" written in the form

$$ {}^{H}\Sigma = {}^{2H}\mathbf{G} \overset{H}{.} {}^{H}\varepsilon $$

The valence of the "constitutive polyadic" ${}^{R+H}\mathbf{G}$ is equal to the sum of the valences of the other two polyadics. The coordinates of ${}^{R+H}\mathbf{G}$ define the weights with which the components of the independent polyadic enter in the constitution of each component of the dependent polyadic. For R=H the physical law is a proportionality between two field quantities of the same valence. This type of proportionality – expressed as

$$ {}^{H}\Sigma = {}^{2H}\mathbf{G} \overset{H}{.} {}^{H}\varepsilon $$

– is the main subject of this discussion. For such physical laws between "equivalent" field quantities one can postulate a second relation between the dependent polyadic and the independent polyadic expressed as a scalar 2W. This scalar is the multiple dot product of the dependent polyadic ${}^{H}\Sigma$ and the independent polyadic. Together with the physical law this scalar can be written in the form

$$ {}^{H}\varepsilon \overset{H}{.} {}^{H}\Sigma = 2\mathbf{W} = {}^{H}\varepsilon \overset{H}{.} {}^{2H}\mathbf{G} \overset{H}{.} {}^{H}\varepsilon $$

The existence of this scalar implies the symmetry of the constitutive polyadic ${}^{2H}G$, that is, ${}^{2H}\mathbf{G} = {}^{2H}\mathbf{G}^{\mathbf{T}}$, where the superscript T indicates "polyadic transposition". Many physical laws are expressed as symmetric relationships of this type with H=1 or H=2.

Symmetric polyadic relationships can be expressed with reference to an arbitrary external vector base, but often the expression with respect to the orthonormal polyadic base defined by the eigenH-adics of the constitutive polyadic ${}^{2H}\mathbf{G}$ is to be preferred.

The most interesting case for H=2 is that of elasticity, where the constitutive tetradic ${}^{4}\mathbf{G}$ is the stiffness-tetradic and the scalar W is the energy density stored at each point of a strained body. Within the framework of elasticity, 2W for H=1 is the normal stress.

For any H, the concepts of normal and tangential stress can be extended to "radial" and "tangential" values of ${}^{2H}G$. Stationary radial and tangential values at a point of a field allow the generalization of classical theorems known for stress and strain, such as Cauchy's and Lamè's quadrics and Mohr's plane representation of the stress–strain relationships. From a generalization of Mohr's circle one can derive a general criterion of proportionality, closely related to the failure criterion in the theory of materials.

If one uses dyadic bases to study physical laws with valence H=2, it is necessary to introduce an auxiliary 9-

dimensional space closely linked to the core of the problem. Note that in order to simplify the discussion, we speak only of a three-dimensional base space. Generalization to other dimensionalities – e.g., to plain stress with dimensionality 2 – are obvious. This auxiliary 9-dimensional space allows the use of some intuitive concepts of 9-dimensional Euclidean geometry. The basic concepts of this geometry were established within the Polyadic Calculus (Ruggeri 1996), but are outside the scope of this discussion. It is not difficult to generalize the geometric concepts to arbitrary valence H and to establish the N-dimensional analytic geometry associated with the physical laws, with $N = 3^H$. They follow immediately if one regards the linear law as a linear transformation (a mapping) of the N-dimensional space defined by the independent H-adic into the N-dimensional space defined by the dependent H-adic through a 2H-adic operator $^{2H}\mathbf{G}$ (the constitutive polyadic). For elasticity, H=2, N=9, and the polyadics involved are the dyadics stress and strain and the stiffness tetradic. Some aspects of the geometry hidden in these laws imply interesting experimental work to define the polyadic operator. For some purposes, the symmetry of $^{2H}\mathbf{G}$ can be used to reduce the dimensionality of the auxiliary space to $N^* = H(H+1)$. For the case of elasticity H=2, $N^* = 6$; This is closely similar to Kelvin's (1856) formalism.

As vector bases for H=2, we shall use those that are invariantly defined by the eigenvectors of the eigendyadics of ^{4}G. In practice, the tetradic (characterizing a medium in the field) will be defined by its coordinates with respect to an arbitrary vector base; to each vector base corresponds a certain representation by coordinates. Departing from any one of these sets of coordinates and the corresponding vector base, we shall show how to determine for monoclinic media the invariant coordinates of the tetradic with respect to the eigensystem of any one of its eigendyadics. We shall also show that there exist a special vector base – different from any of the eigensystems we called the *monoclinic vector base* – which is characteristic of the medium and the physical property under consideration. This means that in describing two physical quantities of valence 2 connected by a symmetric tetradic relationship in a monoclinic medium, any two observers can reach the same monoclinic vector base as reference, even if they started with entirely different vector bases. Starting from two sets of experimentally determined $^4\mathbf{G}$ coordinates of a monoclinic medium; one can establish the existence of the monoclinic vector base, with respect to which one can tabulate the "canonical stiffnesses" of that medium.

FOURTH-ORDER ELASTIC-MODULI TENSORS BY INSPECTION

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A common approach to generating fourth-order elastic-moduli tensors for linear, anisotropic elastic media is to start with the most complex case – the least symmetric case – of triclinic symmetry in which all 81 elastic constants are non-zero and 21 of them are independent. Then the relationships between the 21 independent elastic constants are determined for the higher symmetry (less anisotropic) cases by using the coordinate transformations which, for each symmetry class, leave the material invariant. The most symmetric (least anisotropic) case is the isotropic case for which there are only two independent moduli and only 15 non-zero components for the elastic-modulus tensor. In this paper, we start with the isotropic case and add fourth-order tensors which satisfy the symmetry classes by inspection, continually increasing the number of independent constants as the symmetry decreases (or anisotropy increases). For example, for the cubic-symmetry case, we show that only one new independent elastic constant is needed and only one new fourth-order tensor is required. All other possible fourth-order tensors that satisfy cubic symmetry can be composed of linear combinations of the first three chosen. In addition, we show that we can generate elastic-moduli tensors (for all symmetry classes) which are orthogonal under the double-dot product; these sets simplify the inversion of stiffness tensors into compliance tensors and vice versa. A generalization of the Gram-Schmidt orthogonalization process is used to generate these orthogonal tensors.

ELASTIC WAVE SCATTERING BY ANISOTROPIC FRACTURES

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The angular dependence of transmission and reflection coefficients of elastic waves incident upon a partially closed fracture with imperfect contacts are affected by the applied static shear stress. This effect can be quantitatively described using an extended form of the linear-slip interface model with coupling (off-diagonal) components in the compliance matrix In this paper, the transmission and reflection coeffients of elastic waves on a sheared fracture are examined for an elastic anisotropic background medium with "up-down" symmetry across the fracture and an anisotropic fracture compliance matrix resulting from an applied static shear stress.

SEISMIC DETECTION OF FLUID SATURATION IN ALIGNED FRACTURES

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The application of fracture-induced anisotropy has evolved from the estimation of fracture orientation and intensity to the prediction of fluid saturation and permeability anisotropy in fractured reservoirs. In order to model the seismic response of natural fractures, it is essential to understand the microscopic details of fractures as fluid flow is controlled by micro-structures of fracture or fault planes. The general understanding is that a fracture is a cluster of small cracks, and a fault is a cluster of fractures. Cracks often exist as clusters at different scales. We suggested that published fracture models can be broadly classified into three groups: (1) a plane distribution of small cracks, (2) a plane distribution of contacts, and (3) a thin layer of a constant aperture with the appropriate material infill. All three types of fractures can be mathematically represented as a planar boundary across which the stresses are continuous, whereas the displacements are discontinuous. In this study, we examine the sensitivity of fracture compliance to fluids, and derive simple analytical expressions which link seismic anisotropic measurements to pore or fracture fluids. We show that the normal to shear compliance ratio is directly related to fluid saturation, and to the *P*- and *S*-wave reflectivities and the effective Thomsen's anisotropic parameters, and thus can be estimated from seismic data. Existing laboratory and field data are used to verify the results.

BEHAVIOR OF DYNAMIC ELASTIC CHARACTERISTICS OF RANDOM LAYERED MEDIA

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An effective media is characterized from component contributions of layers with random thickness and elastic properties. The Feynman diagram technique is utilized for statistical decryption of this medium. Subsequently, the Dyson equation is deduced and the general expression for averaged elastic constants is obtained. It is important to point out that resultant elastic constants are nonlocal functions of coordinate and time. These moduli become complex values subsequent to Fourier transformation, which accounts for space and time dispersion as a function of wave vector and frequency.

This work presents the formulae for calculation of the dynamic elastic constants for the characterized media. The real parts of these elastic moduli reflect dispersion of longitudinal and shear waves. The imaginary parts determine attenuation from the direction of the wave vector. These dependencies provide the anisotropy of the studied characteristics.

Obtained formulas work for arbitrary ratios of thickness and wavelength. This provides a mechanism for investigations of thin layered media. A numerical calculation will be presented.

BODY WAVE VELOCITY DISPERSION IN LAYERED PERIODIC MEDIA

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Medium consisting of two periodically alternating isotropic layers is considered. The direct body waves propagating at different frequencies along and normal to the layers are studied. Each of these waves is characterized by wave number(s) k following from solution to dispersion equation constructed for studied wave. It is shown that, commonly, solutions to the dispersion equations have many branches giving roots for the wave number. For waves propagating in the layers, the branches are continuous curves relative to frequencies. Curves obtained for P-wave propagating normal to the layers are periodic and exhibit gaps (forbidden zones). The facts that the group wave velocities must be positive and displacements are real functions are taken as conditions for the root selection. At limiting case of low frequencies, the solutions to dispersion curves are unique for each wave and characterize the effective properties of medium having hexagonal elastic symmetry. In this case, the solution is compared to that obtained in correlation approximation for thin-layered medium. Media containing layers of different materials are considered.

ELASTIC-MODULI OF HOMOGENEOUS AND ANISOTROPIC POROUS MEDIA

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Macroscopic constitutive equations for homogeneous and anisotropic porous media are constructed by volume averaging pore scale constitutive equations. The porous medium considered, consists of an elastic solid with interconnected void spaces filled with a chemically inert viscous fluid. The two constituents are assumed homogeneous in their material properties and porosity is spatially uniform, but the distribution of pores and interfaces are uneven.

The links to the constituents elastic constants and contributions to the macroscopic anisotropy due to the ordered distribution of microstructure are explicit in the macroscopic elastic-moduli derived here. For the most general case all together 22 parameters have entered in the constitutive equations which can be viewed as a 21 component fourth rank tensor, akin to linear elasticity, plus an additional scalar constant.

VELOCITY AND ATTENUATION OF ISOTROPIC, CRACKED (OR POROUS) ROCKS VARIATION WITH FREQUENCY AND PRESSURE

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The variation of velocity and attenuation in cracked or porous rocks with frequency is evaluated under the assumption that the elastic medium is a Standard Linear Solid. Previous workers have also used this assumption by assuming that the elastic moduli of an elastic medium are complex — i.e., with real and imaginary parts — and functions of frequency. Here we take a different approach by expressing the constitutive equation for an isotropic, elastic medium in its tensor form. The constitutive equation is assumed to be a function of the tensor stress, stress rate, strain and strain rate. The constitutive equation itself has neither complex material parameters nor frequency-dependent parameters. The parameters depend only on the state variables for the medium – namely, the stress, strain and their rates (with time). No temperature dependence is taken into account in this simple model, but it can be incorporated in a straightforward way. The scalar form of this constitutive equation has been used, successfully, to describe the transient and "steady-state" behavior of rocks (e.g., rocksalt) under constant stress or constant strain rate.

In expressing the constitutive equation in this form, it is clear that there are low-frequency and high-frequency limits to the velocity and the attenuation (or Qs). The low-frequency velocities depend on the drained moduli for the fluid-saturated, porous or cracked rock while the high-frequency velocities depend on the undrained moduli. Because, in general, the drained moduli are smaller than the undrained moduli, the high-frequency velocities are larger than the low-frequency ones. The results of this model, then, can be related to those obtained from more phenomenological "squirt" models. In addition, the constitutive equation emphasizes the importance of the permeability of the rock to its pore fluids and the importance of the viscosities of these fluids. In this way, the effects of partial saturation can also be understood.

The parameters of the constitutive equation of the Standard Non-Linear Solid are functions of effective pressure (and temperature). Their pressure dependence can be determined by using an asperity-deformation model — such as the "bed-of-nails' model — and thus, the behavior of the velocities and Qs as a function of pressure understood, both qualitatively and quantitatively. Because these parameters are functions of pressure and temperature, the behavior of the solid is nonlinear. However, for small-amplitude seismic waves, the nonlinear effects are small and are neglected here.

ON FREQUENCY SCALING IN ANISOTROPIC PORO-ELASTICITY

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The interpretation of seismic anisotropy in terms of stress aligned microcracks depends on velocity models which incorporate the effects of crack geometry and orientation. These models follow from Eshelby's (1957) theory for the deformation of an ellipsoidal inclusion under stress.

An anisotropic poro-elastic model has been developed by Zatsepin and Crampin (1997) to describe the response of the elastic properties of rock to the imposition of differential stress. The driving process is migration of fluid along intercrack pressure gradients and subsequent preferential crack closing. However, the calculation of the induced velocity changes relies on crack models which assume that fluid cannot move at the time scale of a seismic wave. This may well be a good approximation for high frequency (1MHz) laboratory experiments, but will generally not be so for low frequency (100Hz) field data. The restriction that the fluid should not move also essentially rules out the possibility of modeling attenuation.

To address these concerns we have derived a new (initially isotropic) velocity model (Chapman et al. 2000) which, although based rigorously on Eshelby's theory, allows for the movement of fluid. We assume that the elements of pore space, thin cracks and spherical pores, lie on the vertices of a random lattice with fluid exchange taking place between neighboring elements as a result of pressure gradients arising due to differences in shape, orientation and position along the axis of wave propagation. This arrangement automatically ensures conservation of fluid mass. We find that the system supports the propagation of a fast and slow P-wave, in accordance with Biot's (1956) theory, together with one shear wave. The model is consistent with Gaussmann's Theorem at zero frequency, but is strictly valid only for low concentrations of cracks and pores. All waves show significant velocity dispersion.

In Figure 1 we present the results of modeling shear-wave velocity and Quality factor against the logarithm of frequency for two different values of (isotropic) effective stress. The imposition of effective stress is modeled by a reduction in the crack density. At sonic frequencies the main mechanism is fluid flow (squirt flow) between cracks of differing orientations and between cracks and spherical pores. At frequencies above 100 kHz the dominant mechanism is viscous relaxation of fluid inside individual cracks. It should be noted that a stress-sensitive, frequency independent imaginary part has been specified for the elastic tensor to model inter-granular friction.

This study suggests that the crack distributions which cause seismic anisotropy also have a strong effect on velocity dispersion and attenuation. It is hoped to develop the modeling to cover the imposition of differential stress and subsequent shear-wave splitting, as well as to extend the analysis of resonant bar experiments which was begun in Chapman et al. 2000.

APE: MODELING OF TEMPORAL CHANGES IN SHEAR-WAVE SPLITTING

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Low aspect ratio cracks are the most compliant part of rocks and respond to pressure changes. The anisotropic poro-elasticity theory (APE) provides a quantitative relationship that describes the differential opening and closing of low aspect ratio cracks under changing sub-surface pressure conditions (Zatsepin and Crampin, 1997). The effective elastic constants are calculated using the Eshelby formulation (Eshelby, 1957) and the seismic response with shear-wave splitting as its most important phenomenon can be modeled. The parameters of APE are the overburden pressure, maximum and minimum horizontal stresses, and the pore-fluid pressure. In hydrocarbon exploration the pore-fluid pressure is the variable parameter. In a CO2 injection program in a fractured dolomite reservoir two 3D 9C seismic surveys were acquired over a period of six weeks and the pore-fluid increases were monitored (Roche, 1997). Analysis of the stacked data shows a velocity decrease and an increase of shear-wave splitting in the area of the injection well. Crampin et al. (1996) observed a similar behavior of shear-wave splitting in an over-pressurized reservoir in a Caucasus oil field. An APE model incorporating the given pressure changes matches the observations under the assumption of a heavily fractured reservoir rock and this example shows that shear-waves can provide valuable information in reservoir geophysics as fluid movement is triggered by pressure changes.

CHARACTERIZATION OF CRACK DISTRIBUTION AND OF MATRIX ELASTIC ANISOTROPY IN ROCKS-FABRIC ANALYSES VERSUS ULTRASONIC INVERSIONS

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We analyze the relation between rock fabric, expressed by the preferred orientation of rock-forming minerals and microcracks, and elastic anisotropy of crystalline and sedimentary rock samples. Detailed analyses of mineralogical composition, textures and microcrack fabrics were performed (e.g. Siegesmund et al., 1993, Dürrast and Siegesmund, 1999). In addition, ultrasonic anisotropy measurements were carried out on the same samples at different confining pressures (e.g., Arts 1993). By comparing the elastic tensors of the rocks at the final confining pressure (where most of the microcracks are closed) and at a lower pressure level we can separate the portion of anisotropy induced by microcracks from the portion caused by mineral alignment (Arts et al., 1994). In contrast to previous work, no a priori knowledge on the anisotropy type (triclinic, monoclinic, orthotropic...) and on the spatial orientation of the symmetry elements (planes, axes) of the cracked rock and of the intact rock is initially assumed. Furthermore, no restrictive assumptions on the orientation distribution function and on the shape of the cracks are needed. The results clearly show that the elastic anisotropy characteristics, whether it is related to the microcracks or to the rock-forming minerals, is clearly correlated with the directly observed rock fabrics.

A THEORETICAL PARADIGM FOR DESCRIBING HYSTERESIS AND NONLINEAR ELASTICITY IN ANISOTROPIC ROCKS

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Many experimental studies on the elastic properties of rocks have unambiguously established a number of robust results. These are the most important:

- rocks are generally anisotropic, e.g., their elastic response depends on the direction of the observation (e.g. Babuska and Cara, 1991, or Bourbié et al., 1987),
- rocks exhibit a nonlinear response e.g. the exerted stress is related to the observed strain by an elastic stiffness which depends on the stress level (e.g., Johnson and Rasolofosaon, 1996), and
- hysteresis is characteristic of the stress-strain relation in rocks, in other words, the stress is function of the current strain and the strain history (e.g., Holcomb, 1981).

In this study a model is proposed that addresses simultaneously these three elastic behaviors. The model is an extension of the scalar hysteresis model of Preisach, Krasnoselskii and Mayergoyz (PKM) to vector- and tensor constitutive equations.

F. Preisach (1935) introduced the concepts under discussion as a description of ferromagnetic hysteresis. The model can account simultaneously for non-linearity and losses under cyclic magnetization. Krasnoselskii understood that Preisach's model was not merely a new physical model but also a fertile mathematical concept of which he developed the formalism (e.g. Krasnoselskii and Pokrovskii, 1983). This model has been widely used and popularized by Mayergoyz (1991). Recently the ideas have been applied to other non-linear (and non-conservative) properties of media (e.g. Ortin, 1992, McCall and Guyer, 1994 for elastic properties).

Under the Preisach concept, the behavior of a medium is modeled by assuming a large number of bi-stable "cells". Each cell changes from a "lower" state S_{low} to a "higher" state S_{high} when the increasing (magnetic-, electric-, stress-) field F passes through the value F_{up}. It reverts to S_{low} when the decreasing field passes through the value $F_{down} < F_{up}$ (see Fig. 1). The "state" can be, respectively, magnetization, electric polarization, or strain.

It is convenient to make the individual state-step $\Delta S = S_{high} - S_{low}$ identical for all cells. With this proviso, each cell can be represented in the 2D "Preisach-space" by its coordinates (F_{up}, F_{down}), see Figure 2. All cell points lie on or below the bounding line $F_{down} = F_{up}$. For a hysteretic (and lossy) cell (represented by a point below the boundary line) the field step $F = F_{up} - F_{down}$ is positive. Non-hysteretic (and conservative) cells are represented by points on the bounding line. In view of the identical state step for all cells, the change of state for a given change of field is proportional to the number of cells in the field range (representing points in the corresponding band in Preisach space), the state-compliance for a given field value is thus proportional to the density of cells for that field value. If there are non-conservative cells (represented by points off the bounding line) the state-compliance for decreasing field can differ from that for increasing field. The map of the density of the bi-stable cells in the Preisach space (F_{up}, F_{down}) is the central part of the Preisach model.

For ferromagnetism, the Preisach model has a direct physical interpretation: a cell corresponds to a unit-domain. Larger domains are represented by the corresponding number of cells [by identical ones if the domain behaves like an elementary domain, otherwise by a cluster of Cells]. The two states of a cell are, respectively, the "down" and "up" saturation magnetization. For other field/state pairs such a physical interpretation may be possible, but lacks experimental verification and thus remains another "model".

It should be realized that the classical Preisach theory is a scalar theory. Extension of the theory to vector fields have been described (e.g. Mayergoyz, 1988) mainly by introducing scalar Preisach models for each direction of space. The acceptance of such vector models is not as firm as that of the scalar Preisach model. This is mainly due to the fact that such models fail to correctly take into account the effect of field perpendicular to the chosen direction. Here we overcome this difficulty by making use of the representation of the elastic tensor by its eigensystem (eigenstiffnesses and eigenstrains), see Helbig 1994, based on the pioneering ideas of Kelvin (1895). To each eigensystem is associated a density map of bi-stable cells such as the one shown on Fig. 2. Such a method can deal with both vector- and tensor-fields. Although we mainly focus here on elastic tensor field we emphasize, as previously mentioned, that the theory is general and can be applied to magnetic, electric or any other phenomenon as far as the tensor state and the tensor field are of the same rank. In the presentation we shall describe the basic ideas leading to the proposed unifying theory, then we shall discuss in detail the anisotropic PKM theory and some of its most important predictions. Finally we shall suggest specific elastic experiments that could lead to the determination of the physical parameters of the proposed model.

SINGULAR DIRECTIONS IN ANISOTROPIC MEDIA

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Singular directions (multiple roots of the Christoffel equation) exist in nearly all stable elastic media. With the exception of those in isotropic and transversely isotropic media, all singular directions are isolated. Isolated singular directions can be identified in a sufficiently dense polarization display, thus it is important to understand how the existence and the orientation of special directions is related to the elastic parameters of the medium. Singular directions allow the determination of the non-diagonal terms of the stiffness matrix.

QUASI-ISOTROPIC APPROACH FOR QUASI-SHEAR WAVES IN INHOMOGENEOUS WEAKLY ANISOTROPIC MEDIA

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In isotropic regions, S waves can be modeled using the ray method for isotropic media. In strongly anisotropic regions, the independently propagating qS1 and qS2 waves can be modeled using the ray method for anisotropic media. The latter method breaks down in weakly anisotropic regions, however, where the split qS waves couple. The zeroth-order approximation of the quasi-isotropic approach (QI) was designed for just such weakly anisotropic media, where neither the ray method for isotropic nor anisotropic media applies.

We describe the basic principles of the QI approach and its theoretical relation to the ray methods for isotropic and anisotropic media. We then test the ranges of validity of all three asymptotic methods using simple synthetic models, and test the accuracy of the QI approach in particular by comparing its results with an exact analytic solution and with the results of a full-wave-equation numerical method, the reflectivity method. The comparison shows that the QI approach more than spans the gap between the ray methods: it can be used in isotropic regions (where it reduces to the ray method for isotropic media), in regions of weak anisotropy (where the ray method for anisotropic media breaks down), and even in regions of moderately strong anisotropy (in which the qS waves decouple and thus could be modeled using the ray method for anisotropic media).

ALFORD ROTATION 14 YEARS LATER: WHAT HAVE WE LEARNED?

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Alford rotation is a widely used method for separating "fast" and "slow" split shear waves for a variety of multicomponet seismic data. The original model underlying Alford rotation assumes two orthogonal pure-shear modes, such as might occur for a zero-offset experiment over a horizontally layered vertically fractured earth, or for a crossed-dipole survey through a transversely isotropic earth. In practice, Alford rotation is used whenever multi-source multi-receiver data is recorded, whether the model fits the situation or not. Despite its theoretical limitations, it has often worked surprisingly well.

In the years since Alford's method was first made public, several generalizations of alford rotation have been proposed (often the same few methods under various different names). All of these methods become consistent for the original Alford geometry, but can produce different results for more general data. Faced with a diversity of opinions, how can we tell which is "3correct"?

I will begin by recapitulating Alford's original talk (using his original slides), and then show how his method can be recast in terms of anisotropic ray tracing. This allows us to place it on a (somewhat) firmer theoretical foundation, and provides an answer to the question "what is the correct generalization of Alford rotation?" at least for certain simple geometries.

INTERACTIVE THREE COMPONENT VSP PROCESSING AND INTERPRETATION

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It is developed PC oriented complex for fast and effective interactive 3C VSP processing and interpretation based on persistent comparison inverse and direct problem solution.

EFFECTS OF OVERBURDEN ANISOTROPY AND ATTENUATION ON SEISMIC INVERSION RESULTS FOR RESERVOIR PARAMETERS

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Most sedimentary basins in the world have a relatively thick overburden column above the main target units. These overburden layers often show a significant amount of attenuation as well as angle dependent velocity variations. If, however, the overburden is assumed to be isotropic and elastic, which is usually the case in traditional seismic processing, errors will be introduced when the seismic data are inverted for reservoir parameters. Studies on a synthetic Earth model fairly representative for North Sea reservoirs, including overburden anisotropy and attenuation, have shown that seismic inversion which ignores anisotropy and attenuation may give significant errors in the target zone parameters. Ignoring overburden anisotropy affects P- and S-wave velocity estimates as well as traveltimes, while ignoring attenuation mainly affects the S-wave velocity estimates, giving errors up to 20% or more. This illustrates the importance of correcting for angle dependent parameters as well as attenuation in the overburden when estimating parameters for the underlying target zone.

A 3D VTI EIKONAL SOLVER FOR EFFICIENT ACOUSTIC TRAVEL TIME COMPUTATION

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Traveltime computation is efficiently achieved through direct numerical resolution of the eikonal equation on a 3D computational grid. Efficiency may even be improved when solving the eikonal equation in the celerity domain. Neglecting the effects of anisotropy in the calculation of traveltime maps leads inevitably to either misfocusing or misdepthing of seismic events during the seismic imaging process. Thus, in the present paper, we propose to extend efficient P wave traveltime computation to the simplified case of Vertical Transverse Isotropic (VTI) media, which is nevertheless of the most interest in surface reflection seismic. Based on an "acoustic" explicit eikonal equation for VTI media (Alkhalifah, 1998), the calculation of quasi-P traveltimes with our numerical resolution method in the celerity domain proves to be particularly efficient, stable and accurate. In line with seismic contractor needs, we propose a data-based parameterization for the quasi-P VTI model used by the eikonal solver. The three independent anisotropic parameters are: the NMO velocity associated with short spread curvatures, an elliptical parameter equivalent to the ratio between vertical and NMO velocities and finally the well-known anelliptical parameter η governing the long offset behavior of NMO curves.

CAUSTICS IN QSV RAYFIELDS OF HEXAGONALLY ANISOTROPIC AND VERTICALLY INHOMOGENEOUS MEDIA

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The study of qSV-wave caustics, associated with a point source in a transversely isotropic medium with a constant, vertical velocity gradient, produces some unusual results. Caustics, generated in anisotropic-inhomogeneous media, are qualitatively different from the generic caustics associated with both isotropic-inhomogeneous and anisotropic-homogenous media. The fact that the caustics in anisotropic-inhomogeneous media originate at the source provides a partial explanation of the differences noted —; namely that the angle between the caustics at their intersection is finite, and that the Maslov index (e.g., Chapman and Drummond, 1982) jumps twice. Both behaviors have significant mathematical and geophysical ramifications and merit further investigation.

COMPARISONS OF V(*θ*) EQUATIONS IN TI MEDIUM

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In TI media, exact phase velocity equations $v(\theta)$ are complex and difficult to exploit. Moreover, traveltimes are not equally sensitive to the different parameters in the phase equations. Thus, in order to find simpler but still accurate equations for $v(\theta)$, with relevant (sensitive) parameters, we examine different formulations found in the literature and we also derive new, original approximations of the phase velocity equations. After comparing all those approximations it turns out that the system of equations we derive from Alkhalifah's work is simple and accurate enough to be used for ray-tracing and reflection tomography.

DOUBLE EMPIRICAL KINEMATIC EQUATIONS FOR SV-WAVES IN TRANSVERSELY ISOTROPIC MEDIA-EIKONAL AND NON-HYPERBOLIC MOVEOUT EQUATIONS

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The qP-wave kinematics in transversely isotropic media is weakly dependent on the vertical shear wave velocity β_0. Neglecting empirically this dependence, Alkhalifah (1997 and 1998) proposed simple eikonal and non-hyperbolic moveout equations by setting β_0 to zero in some parts of the original equations. Here we achieve similar results for the SV-wave.

First we use the fact that, at least for weakly anisotropic media, the directional dependence of the SV-wave velocity and of the P-wave velocity are formally identical (Thomsen, 1986). More precisely, for the qP-wave the three parameters are the vertical P-wave velocity α_0 and the anisotropy parameters ε and δ. The corresponding parameters for the SV-wave are the vertical S-wave velocity β_0, the anisotropy parameter ε_{SV}, which is zero because the SV-wave propagates with the same velocity in the vertical direction and in the horizontal direction, and the equivalent of δ for SV-wave

$$\delta_{SV} = \sigma = \left(\frac{\alpha_0}{\beta_0}\right)^2 (\varepsilon - \delta).$$

For any time-domain processing the two parameters for the qP-wave are the NMO velocity

$$V_{NMO}^{P} = \alpha\sqrt{1+2\delta}$$

related to the NMO short spread curvature and the anellipticity parameter

$$\eta = \frac{\varepsilon - \delta}{1+2\delta}$$

which is responsible for the non-hyperbolic behavior of the reflection curve. As a consequence the corresponding processing parameters for the SV-wave are:

SV-NMO-short-spread-curvature

$$V_{NMO}^{SV} = \beta_0\sqrt{1+2\sigma}$$

SV-anellipticity

$$\eta_{SV} = \frac{\varepsilon_{SV} - \delta_{SV}}{1+2\delta_{SV}} = \frac{-\sigma}{1+2\sigma}$$

Furthermore, because of this formal correspondence, in principle any time-domain algorithm developed for the qP-wave can be directly used for the SV-wave. We use this "double empirical" technique for adapting the eikonal and non-hyperbolic moveout equations of the qP-wave to the case of the SV-wave. Numerical tests show that such a technique gives satisfactory results both for velocity analysis and for imaging.