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COMPUTATIONAL METHODS FOR IMPROVING THE RESOLUTION OF
SUBSURFACE SEISMIC IMAGES

Progress Report

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Principal Investigators: Ken Lerner and Dave Hale

Co-Investigators: Norman Bleistein and Jack Cohen

Colorado School of Mines

Golden, Colorado 80401

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ABSTRACT

Our interactive modeling for Gaussian beam modeling in two-dimensional, triangulated complex geologic structure, has been generalized to include transmission losses at interfaces, and density and Q-characterization of attenuation in layers. Also, multiple reflections and the option to model data from VSP acquisition geometry have been included. Shortcomings when the structure contains first-order discontinuities, however, limit the full geologic complexity that presently can be modeled by the Gaussian beam method. Other studies of wave filtering that arises for waves propagating nearly parallel to bedding reveal the importance of tunneling *evanescent filtering* on the propagating wavelet. Likewise, for reflections from steep interfaces, we have developed a dip-divergence correction to compensate for shortcomings in the conventional divergence correction for energy spreading.

A new direction this past year, which we will be pursuing in the year ahead is analysis of errors in migration and dip-moveout (DMO) that arise when conventional imaging processing, which ignores anisotropy, is applied to data acquired where the subsurface is transversely isotropic. We are also developing approaches for taking anisotropy into account in these important imaging processes. Similarly, we have developed an efficient approach to performing DMO on P-SV-mode-converted data. Our interests in taking anisotropy into account have led us to study the importance of anisotropy in the overburden on reflection amplitude variations with offset (AVO).

INTRODUCTION

Under this contract, our studies at first centered on two important problems in computational seismology, both aimed at the accurate and computationally efficient representation of seismic wavefields and at devising computationally efficient ways of improving the accuracy and precision of subsurface images from surface reflection seismic data. The first of these has been the development of new methods of representing two-dimensional (2-D) and (eventually) three-dimensional (3-D), structurally complex subsurface geologic models in the computer, the aim being to improve the efficiency of numerical modeling and seismic migration of data from structurally complex subsurface areas. The second of these major areas of study was to improve understanding of phenomena associated with waves that propagate substantially parallel to sedimentary bedding for a large part of their travel through the subsurface, as happens with surface seismic reflections from steep interfaces and in waves recorded in cross-well studies.

We have developed an interactive two-dimensional Gaussian-beam modeling program for waves propagating in structurally complex models characterized by an optimized triangulation of the medium. That program now allows calculation of waves associated with specified multiple reflections within the medium, and incorporates

amplitude losses attributable to (1) geometrical divergence (or spreading) in a “2.5-D” medium, (2) a constant-Q model of absorption, and (3) reflection and transmission at reflecting boundaries in models with complex variation in both velocity and density. Although wavefield solutions are qualitatively plausible for media with smooth velocity variation, reciprocity tests reveal fundamental limitations of the Gaussian beam method that must be overcome before the method can be trusted for subsurface models of general complexity (e.g., models of faulting and truncation at unconformities described by first-order discontinuities at reflectors). Although extension to three-dimensions would be of value for models of an “acceptable” level of complexity, we believe that it is best to pursue definition of just what is that acceptable level of complexity in two dimensions before proceeding to 3D.

Analytic and numerical modeling in media with vertical velocity variation has allowed us to gain an understanding of the dependence of, and develop a first-order correction for, amplitude losses on zero-offset data due to geometrical spreading of waves from steep reflectors. For models of media with expected subsurface velocity variation, the correction beyond that conventionally applied in seismic data processing, is substantial—on the order of 100 percent in some situations—and can thus be of importance, for example, in studies of bright spots, and eventually in interpretation of reflection-amplitude variations with source-to-receiver offset (AVO studies). The latter problem requires extension of the ideas developed to date to an efficient, first-order correction for nonzero-offset data.

Also, for waves propagating sub-parallel to bedding in thin-layered media, we have extended understanding of the stratigraphic filtering associated with short-period multiple reflection paths to include *evanescent filtering*, which arises for waves beyond critical angle in high-velocity layers. For reflections from steep interfaces, this evanescent filtering, which has a different wavelength dependence than does the stratigraphic filtering, can dominate the waveform filtering that arises during propagation. The resulting dependence of waveform filtering on reflector dip has important implications in the need for deconvolution to be a dip-dependent process.

Both the geometric-spreading and dip-dependent filtering are the tip of the iceberg in analysis and improved processing of data associated with largely sub-parallel propagation through a thin-layered medium. For example, as a result of the large transfer coefficients beyond critical angle, we expect that mode conversion between P- and SV-waves in elastic media, as opposed to the acoustic media studied to date, will likely be a larger issue than is evanescent filtering.

Related work during the contract period has included analysis of errors in seismic migration and dip-moveout (DMO) that arise when algorithms that ignore anisotropy (as is done routinely throughout the seismic exploration industry) are applied to data that are both anisotropic and vertically inhomogeneous. Results of our numerical studies show that DMO error for transversely isotropic (TI) media varies considerably from one medium to another, depending on the four elastic parameters that define P-wave propagation in such media, while vertical velocity variation is of little

consequence. In contrast, migration error not only depends greatly on the four elastic parameters, it also is much influenced by a combination of the velocity gradient and migrated reflection time. We suspect that of the four Thomsen (1986) parameters that describe transversely isotropic media, only two— δ and ϵ —largely control the errors in both DMO and migration that arise when anisotropy is ignored. To aid in these studies, we have developed an efficient method, based on Huygens' principle for modeling reflection seismic data in TI media with linear velocity variation and general symmetry-axis orientation. We believe that the methodology developed for this modeling will also provide an extension of the above-mentioned Gaussian beam modeling (and migration) to general TI media.

Also during this past contract period, we have developed an efficient approach for performing DMO on mode-converted data, e.g., data obtained with vertically oriented sources and radial-horizontally oriented receivers, aimed at recording SV-waves generated by P-waves that encounter reflectors at depth. The approach is a minor, no-cost modification of frequency-wavenumber domain DMO used conventionally in the processing of P-waves.

We plan to continue our work in improved representation of seismic wavefields, coming to grips with limitations of the Gaussian beam method for producing wavefields and, thus, synthetic seismograms in two-dimensionally complex subsurface structure, and embarking on the extension to three dimensions. Second, through analysis similar to that done under the zero-offset assumption, we wish to verify our expectation that the dip-dependent divergence correction, so efficiently applied to poststack data, is sufficient for characterizing the dip dependence of the divergence correction necessary for nonzero-offset data. Further, we wish to extend the study on evanescent filtering in acoustic models to elastic media, in which P-SV-wave mode conversion may be the dominant issue. We also seek to pursue in greater generality the implications of ignoring anisotropy in the critically important imaging procedures of poststack and prestack migration and DMO, and to devise computationally efficient methods for doing DMO, and poststack and prestack migration in anisotropic media, as well as investigate the possibility of using DMO as a means of inversion to determine one of the elusive, but critically important, anisotropy parameters (Thomsen's ϵ parameter) that describe transversely isotropic media.

The ramifications of taking the true anisotropic character of the subsurface into account in seismic data processing and interpretation are widespread. One example of interest is the use of AVO analysis for lithologic identification. With our developed capability for incorporating anisotropy into analytic and numerical studies in elastic media, we also wish to investigate the influence of anisotropy on the interpretation AVO information.

TRIANGULATION-CHARACTERIZATION OF AND GAUSSIAN BEAM MODELING IN COMPLEX GEOLOGIC MODELS

The processing of surface seismic data for imaging of the subsurface is relatively robust for many geologic provinces throughout the world. Nevertheless, the challenge of increasing the resolving power of seismic imaging for improved characterization of reservoirs and in areas of increasingly complicated subsurface structure requires efficient algorithms for modeling and migration of seismic data in such complex areas. One effort under the current contract has been to develop improved methods for representing complex subsurface Earth structure in a computer. Spatial data structures generally used by explorationists to describe the subsurface properties are either inefficient, requiring large computational resources, or inaccurate, failing to represent complex geologic structures of interest.

Hale and Cohen (1991) developed software to generate two-dimensional computer models of complex geology. Their method represents the models as a mesh of triangles, with the mesh described by a data structure in computer memory that contains the *adjacency topology* of the model, as well as the values of subsurface parameters at specific vertex locations. A mesh of triangles can flexibly characterize complex subsurface models that can, for example, include velocity lenses, normal and reverse faults, unconformities, and overhanging dome structures. Additionally, with the adjacency topology, computing time is not wasted in searching for the triangles and model parameters in the vicinity of any arbitrary point in the model.

This triangulation technique is thus designed to support efficient and accurate computation of seismic wavefields for models of the Earth's interior. Hale (1991) used this triangulation approach to perform dynamic ray tracing and create synthetic seismograms based on the method of Gaussian beams. Rüger (1993) has extended this methodology to allow an increased variety of ray-theoretical experiments. Specifically, it is now possible (see Figure 1) to define a reflection and transmission sequence for each interface (thus allowing computation of wavefield contributions from selected multiple reflections) and to incorporate attenuation and density variations. In addition, Rüger has added an option to perform Fresnel-volume ray tracing (Červený and Soares, 1992), as well as corrections for reflection and transmission losses at interfaces, and for two-and-one-half dimensional (2.5-D) spreading (i.e., out-of-plane spreading). A further addition (Figure 2) allows simulation of vertical seismic profiling (VSP) acquisition geometries, again for complex geologic models.

However, despite these enhancements, and the ability of the program to generate synthetic seismograms with plausible realism, difficulties remain in attempts to compute accurate synthetic seismograms if strong lateral velocity inhomogeneities are present. Specifically, when a many-shot seismic profile is generated and data are sorted into common-midpoint gathers, Rüger finds that the expected reciprocity for interchanged source and receiver positions is violated. This failure is evidence that the wavefield is incorrectly computed whenever beams pass too close by regions of

FIG. 1. Ray tracing in a complex subsurface model. This model includes sharp-edged interfaces and lens-type structures. Lithological interfaces are represented by black lines. The shading denotes the seismic velocity field. Also shown as black lines are raypaths corresponding to one type of interface multiple. The white lines are edges of auxiliary triangles used in the model building.

the model with strong heterogeneity, the very type of geologic complexity that we wish to model with the triangulation. Rüger has developed diagnostics to help assess whether or not the Gaussian beam method is encountering a serious problem with the heterogeneity in a given problem. Moreover, he has made practical modifications to the Gaussian beam approach that reduce the severity of the departures from reciprocity found in the studies, the most important being a restriction on the distance over which beams will be allowed to contribute to the computed wavefield at any given location. Some smoothing of the model parameters can allow more accurate computation of wavefields; current studies are aimed at assessing whether or not the smoothing that is necessary is acceptably small so that the computed wavefield adequately represents the wavefield for the original, heterogeneous model.

While the computation of high-frequency seismograms based on the method of Gaussian beams offers the promise of great efficiency advantage for complex geologic structure, the above fundamental limitation in the Gaussian beam approximation must be addressed in order for one to claim that the Gaussian beam method can truly generate accurate synthetic seismic data for models of the complexity often encountered in practice and that can be described by the triangulation method. We would hope to extend the method to description of and seismic modeling within geologic models having 3-D complexity. Because the heterogeneity limitation of the Gaussian beam method is well exemplified by problems in two dimensions, however, we have been investigating and characterizing these limitations in 2D before embarking on the extension to 3D. We judge this effort to be worthy given that, for 2-D

FIG. 2. Synthetic VSP data generated by the extended version of acoustic modeling program in triangulated media.

problems, the Gaussian beam method in complex models is already two orders of magnitude faster than accurate finite-difference modeling methods, and for 3D the speed advantage should be much greater yet.

THE $v(z)$ PROBLEM

Dip-dependent divergence correction

In current seismic data processing, an amplitude-correction factor that varies over four or more orders of magnitude from early to late reflection time is required to bring the weak reflections from late recording times into balance with the strong early reflections. Routinely, the *divergence* correction applied in practice takes into account the spreading of energy due to variation of velocity with depth, but under the assumptions that reflectors are horizontal and that source-to-receiver offset is zero; that is, raypaths are assumed to be vertical. As Fazzari (1992) shows, for reflections from steep interfaces, such as the flanks of salt domes, the former assumption is invalid. Spreading of energy for waves that turn significantly from vertical is not so great as that for waves that propagate vertically down to and back from horizontal interfaces. Thus, the divergence correction for reflections from steep interfaces should be smaller than that based on vertical raypaths. Thus, conventional divergence correction over-amplifies amplitudes of reflections from steep interfaces (see Figure 3). The extent of over-correction depends on the details of the velocity variation with depth.

The divergence correction for reflections from a steep interface is obtained by numerically integrating the dynamic ray-tracing equations to obtain the appropriate raypath and the in-plane spreading function, which is just the Jacobian that describes the coordinate transformation from rectangular coordinates in the propagation plane to ray coordinates in that plane. For a velocity function representative of the Gulf of Mexico, Fazzari shows that the conventional divergence correction can over-amplify amplitudes of reflections from steep interfaces by as much as 50 or 100 percent. Seismic imaging of the subsurface for purposes of lithologic identification as well as structural detail requires processing such that amplitude variations observed in the final data characterize true variations in reflectivity of the subsurface, uncorrupted by artifacts of the processing. Amplitude distortions as large as those revealed in this study would preclude anything but qualitative analysis of seismic amplitude for lithologic identification.

Given a general idea of the vertical velocity variation, Fazzari shows how amplitudes in stacked data can be efficiently corrected with a dip-dependent divergence correction function. As long as velocity does not vary significantly in the lateral direction, the dynamic ray-tracing required for the computation need be done only once, to determine correction factors that are then stored for subsequent application to the data. The divergence correction developed to date is applicable to data from 2-D seismic lines oriented normal to the direction of geologic strike. In principle, the

FIG. 3. (a) Contours of amplitude error that results from applying the conventional divergence correction to a medium described by the interval velocity used to migrate the data. (b) CMP stack of Gulf of Mexico data. (c) Migrated data with amplitudes adjusted by the dip-dependent divergence correction. (d) The difference: conventionally corrected amplitudes minus dip-dependent divergence corrected amplitudes.

divergence correction could be readily extended to treatment of 3-D data, but then the correction would be both dip- and azimuth-dependent, thus necessitating decomposition of data into dip and azimuth components—a processing step that may be so computationally intensive as to be impractical. Likewise, dip-dependent divergence correction for finite-offset data would entail expensive two-point ray tracing, and must compensate for geometrical spreading along both the raypath from the shotpoint to the reflection point and the raypath from the reflection point to the receiver, for every receiver associated with a given shot. Fazzari argues, however, that the departures of the divergence correction for finite-offset from those for zero-offset are second-order relative to the correction for dip, investigated here. Thus, subject to further study, the efficient, poststack divergence correction developed here may be sufficient for areas where velocity variation is dominantly controlled by depth.

Wave propagation in thin-layered media

Studies of sonic well logs show that a major portion of the stratigraphic column of the Gulf of Mexico, as is true elsewhere, is made up of alternating layers of sand and shale. Only recently has the surface seismic method been able to image, with accuracy, steep structures, such as the flanks of overhanging salt domes that have intruded into the sedimentary sequence (Hale et al. 1992; Ratcliff, 1992). Seismic waves reflected from the near-vertical (and steeper) interfaces of features such as salt-dome flanks spend a significant amount of their travel paths propagating close to the horizontal—rather parallel to the sedimentary bedding. In thin-layered media, these horizontally traveling waves behave differently from the well-understood vertically traveling ones. In an investigation of synthetically modeled seismograms for such situations, Deng (1992; 1993) shows that the waves experience attenuation and dispersion that varies with reflector dip in a way that cannot be simply explained by the familiar *stratigraphic filtering* (O'Doherty and Anstey, 1971) studied recently by Banik et al. (1985a, 1985b) and White et al. (1990). Waves traveling through a sequence of thin layers at high angles from vertical are also distorted by the process of *evanescent filtering*, whereby only the lower frequencies of the inhomogeneous waves are able to *tunnel* through high-velocity layers, while the higher frequencies experience more rapid exponential decay in traveling through those layers (Figure 4).

In a given sedimentary environment, a trade-off exists between the influence of stratigraphic filtering and evanescent filter, the former dominating for reflections from low-dip interfaces, and the latter for reflections from steep interfaces. Details of this trade-off depend on the wavelength of the propagating waves relative to the thicknesses of the sedimentary layers. Stratigraphic filtering changes with dip for two reasons: (1) with increasing raypath angle from the vertical, the length of travel through any given layer increases, thus, in effect, altering the relationship between wavelength and layer thickness, and (2) for waves that travel at and beyond critical angle, reflection coefficients are substantially larger than those for reflections from near-normal incidence. The net result is that transmitted energy becomes relatively

FIG. 4. Snapshots at time = 0.55 s of seismic waves propagating through three-layer media from a point source at the origin with a $v_1 = 2000$ m/s upper layer, a $v_2 = 6000$ m/s middle layer, and a $v_3 = 4000$ m/s lower layer. The critical offset is 420 m, and the dominant frequency of the source signal is 10 Hz. (a) thick high-velocity layer between $z = 600$ and 900 m. (b) thin high-velocity layer between $z = 600$ and 675 m.

more impoverished in the higher frequencies as reflector dip increases, particularly where the layering is thin relative to signal wavelength. In contrast, at larger propagation angles from vertical, the amplitude decay for transmitted waves that become evanescent is most severe for the higher frequencies or, equivalently, is greatest when the signal wavelength is small relative to the layer thickness. Thus, we find that evanescent filtering dominates for large propagation angles, primarily where the layering is not thin relative to typical signal wavelength (see Figure 5). Evanescent filtering is of no issue until reflector dip becomes large.

These observations and interpretations hold for zero- or small-offset seismic data; i.e., data acquired at receiver locations close to the source. For large source-to-receiver offset, even for modest reflector dip it is possible for the travel path in the direction down-dip from the reflector to become near-horizontal, so that evanescent filtering again becomes significant. To date, the modeling has treated the propagation medium as acoustic. The proposed extension of this analysis to elastic media should show a similar trade-off in the importance of stratigraphic and evanescent filtering, with the added complication of strong-amplitude mode conversion between P- and SV-waves.

For seismic data processing aimed at increasing the resolution of reflection data, this numerical investigation has provided the beginnings of understanding of the need to do deconvolution that is simultaneously dip-dependent and offset-dependent.

FIG. 5. Zero-offset reflections from a vertical interface in four layered media. The velocity in each medium has a linear trend of $1.6 + 0.5z$ (km/s) and a sinusoidal variation with bed thickness (a) 250 m, (b) 150 m, (c) 100 m and (d) 60 m, respectively. The dominant frequency of the source signal is 10 Hz.

IMAGING OF DATA FROM TRANSVERSELY ISOTROPIC MEDIA

Migration of data from transversely isotropic media

Difficult and unreliable as it is to measure anisotropy in the field, and as infrequently as it is done, it is nevertheless currently recognized and accepted that the Earth's subsurface is anisotropic—often, considerably so. Given the sensitivity of imaging accuracy to the velocity used, migration founded (as in practice) on the erroneous assumption that a medium is isotropic can be expected to be inaccurate for steep reflectors. Larner and Cohen (1993) have estimated errors in interpreted reflection time and lateral position as a function of reflector dip for transversely isotropic models in which the symmetry axis is vertical and the medium velocity varies linearly with depth. Also, their models were restricted to media in which the ratios of the various elastic moduli are independent of depth (so-called *factorized transversely isotropic inhomogeneous* [FTI] media). Their tests with reflector dips up to 120 degrees on a variety of anisotropic media show errors that are tens of wavelengths for dips beyond 90 degrees when the medium (unrealistically) is homogeneous. For a given anisotropy, the errors are smaller for inhomogeneous media; the larger the velocity gradient, the smaller the errors. For gradients that are representative of the subsurface, lateral-position errors tend to be minor for dips less than about 60 degrees, growing to two-to-five wavelengths as dip passes beyond 90 degrees (see Figure 6).

These errors are independent of reflector depth and root-mean-square (rms) velocity to the reflector, but depend significantly on their ratio; i.e., on migrated reflection time. Migration error, which is found to be unrelated to the ratio of horizontal to vertical velocity, is such that reflections with later migrated reflection times tend to be more severely over-migrated than are those with earlier migrated reflection times. Over a large range of dips, migration errors that arise when anisotropy is ignored, but inhomogeneity is honored, tend to be considerably smaller than those encountered when inhomogeneity is ignored in migrating data from isotropic inhomogeneous media.

Dip-Moveout (DMO) of data from transversely isotropic media

Given the complexity possible for subsurface structure, moveout for reflections within common-midpoint (CMP) gathers can have all manner of complication. Nevertheless, the approximation that moveout for P-wave reflections is hyperbolic over typical spreadlengths is adequate in much routine practice. Moreover, Levin (1979) and (1990) has shown that the hyperbolic approximation remains valid for homogeneous, transversely isotropic media. Levin (1990) modeled the moveout, within CMP gathers, of reflections from plane-dipping reflectors beneath homogeneous, transversely isotropic media. For some media, when the axis of symmetry for the anisotropy

FIG. 6. Normalized position errors (measured in wavelengths at 30 Hz) as a function of reflector dip for the four media studied by Levin (1990) and Lerner and Cohen (1993), for three values of approximate migrated reflection time $2D/V_{rms}$. All models have the same velocity gradient, $k = 0.6 \text{ s}^{-1}$.

was vertical, he found departures in stacking velocity from predictions based on the familiar cosine-of-dip correction for isotropic media.

Larner (1993) has done similar tests, again with transversely isotropic models with vertical axis of symmetry, but now allowing the medium velocity to vary linearly with depth while restricting the anisotropic behavior to being *factorized anisotropic inhomogeneous* (FAI), that is, the ratios of the four pertinent elastic coefficients that govern P-wave behavior in transversely isotropic media are independent of position in the medium. As Shearer and Chapman (1988) have shown, the restriction to FAI media with linear velocity variation with depth affords simplicity and efficiency in the traveltime computations required for our analysis. Specifically, for such media the required two-point ray tracing is done analytically, with no costly numerical integration.

Results for the same four anisotropic media studied by Levin show behavior of dip-corrected stacking velocity with reflector dip that, for all velocity gradients considered, differs little from that for the counterpart homogeneous media. As with isotropic media, traveltimes in an inhomogeneous, transversely isotropic medium can be modeled adequately with a homogeneous model with vertical velocity equal to the vertical rms velocity of the inhomogeneous medium.

Our interest in stacking-velocity behavior stems from implications for quality of CMP-stacked data following either normal-moveout (NMO) or dip-moveout (DMO) correction. Dip moveout is the imaging process that maps nonzero-offset reflection seismic data to a condition that simulates zero-offset data so that when the data are stacked, reflections with a broad range of reflection slope are preserved for the subsequent migration process. Routinely, DMO is based on the assumption that the subsurface medium is homogeneous, and, increasingly, DMO is based on velocity v increasing with depth z —so-called $v(z)$ DMO. In neither case, however, is anisotropy taken into account. The primary purpose of this study was to assess, at least for the models considered here, implications of ignoring anisotropy in DMO when the subsurface is transversely isotropic.

Larner (1993) finds that for only one of the transversely isotropic media considered here—shale-limestone—would $v(z)$ DMO fail to give an adequate correction within CMP gathers. For the shale-limestone, fortuitously the constant-velocity DMO gives a better moveout correction than does the $v(z)$ DMO (Figure 7).

DIP-MOVEOUT OF MODE-CONVERTED DATA

We have developed a frequency-wavenumber ($f-k$) method for doing dip-moveout (DMO) for P-to-SV mode-converted waves. The method (Alfaraj and Larner, 1993) requires only slight modification to the existing Hale's DMO method for ordinary P-waves. To modify Hale's DMO method to mode conversion, one needs to know only the velocity ratio. The DMO operator here differs from the elliptical P-wave operator

FIG. 7. Residual moveout Δt at offset $X = 3000$ m as a function of reflector dip for four media—data uncorrected for dip (gray), DMO corrected with $v(z)$ DMO (black), and DMO corrected with constant-velocity DMO (dotted). The vertical velocity gradient is $k = 0.6 \text{ s}^{-1}$ in all cases. $v(z)$ DMO, with anisotropy ignored, is adequate for both the weakly anisotropic Berea sandstone and the moderately anisotropic Cotton Valley shale.

in two aspects. First, the operator is distorted, the distortion being controlled by the ratio of the SV-wave velocity to the P-wave velocity. In effect, one side of the operator is squeezed and the other stretched. Second, the operator is laterally shifted, and in a time-varying manner. Using a modified version of the “squeezing trick” of Hale and Artley (1992), we obtain squeeze and stretch factors that modify the conventional DMO operator so that it is appropriate for mode-converted waves. These factors depend on, but are not highly sensitive to, the ratio of SV- to P-wave velocity, and are readily extendable so that velocity variations with depth can be approximately treated.

Tests on synthetic data show that the method is capable, to a great extent, of transforming mode-converted data to zero offset. Although not too sensitive to the choice of velocity ratio, the DMO process must account for mode conversion when dealing with mode-converted data. Not only can the mode-converted DMO method correct reflections from dipping reflectors, but also from horizontal ones, in which

case reflections are simply shifted laterally to their appropriate, zero-offset locations. For both horizontal and dipping reflectors, reflections are properly DMO-corrected regardless of the sign of dip.

PLANS FOR THE COMING YEAR

Gaussian Beam modeling in complex geologic models

As exemplified in Figures 1 and 2, above, the efficient ray-tracing in triangulated, complex models now includes multiply-reflected rays in either surface-seismic or offset VSP acquisition configurations. However, reciprocity tests obtained by interchanging the positions of sources and receivers show unacceptable differences in wavefield computed by Gaussian beam modeling that we attribute to known shortcomings of the Gaussian beam method when the beams travel near discontinuities in the model velocity structure. While the problem is not of serious concern for models with relatively smooth velocity variation, we believe that it needs to be addressed before, or at least concurrently with, the extension of the modeling method to 3-D media. An approach that we will pursue is to choose models with first-order velocity discontinuities and with complexity that can be adequately treated with more-costly finite-differences. We will repeat the finite-difference modeling for models of progressively smoother velocity variation until the computed wavefield departs significantly from that for the original model. We will then perform Gaussian beam migration on a range of models extending from the original one until a model is sufficiently smooth for our reciprocity test to ascertain that the Gaussian beam modeling has been accurate. Of primary interest is the question of whether or not overlap exists between a range of models that yield wavefields close enough to that for both the original discontinuous model and models that are adequately handled by the efficient Gaussian beam method. The answer to this question has importance to the applicability of Gaussian beam depth migration (now gaining acceptance in the seismic exploration industry) in structurally complex areas.

During the coming year, we intend to extend the Gaussian beam modeling approach in triangulated media to treat transversely isotropic, 2-D media. The extension of triangulation model-characterization in two dimensions to tetrahedral characterization in 3D, and thence Gaussian beam modeling and migration in three-dimensionally complex media, will likely occupy our efforts for the next three years. Successfully completed, this 3-D modeling program will have significant computational advantage over finite differences and advantages in model complexity over Kirchhoff methods.

Prestack divergence correction for large-moveout reflections

Given the large dependence of the divergence correction on reflector dip that we have observed in zero-offset data, we would like to ascertain whether or not similar

sensitivity exists as source-to-receiver offset varies. Such variation would have implications for amplitude-versus-offset (AVO) analysis and for optimization of common-reflection-point (CRP) stacking. We shall study divergence as a function of reflector dip and offset to ascertain if special correction is necessary in data processing and, if so, seek an approximate correction that can be efficiently implemented.

Mode-conversion in thin-layered media

Interesting and important as is the dip-dependent waveform filtering that arises in our study of acoustic waves reflected from steep interfaces, we expect an even more important contribution to the filtering to arise in elastic media. In such media, mode conversion between P- and SV-waves is extensive as a result of the large reflection coefficients for waves traveling nearly parallel to bedding. We shall extend the finite-difference modeling used in our previous study of evanescent filtering to elastic media in order to assess the added complication in waveform filtering that results from the mode conversion. While it is doubtful that the added phenomena of mode conversion will suggest tailoring of dip-dependent deconvolution to counteract the specific filtering that arises, the study may give added weight to the need for doing such dip-dependent deconvolution.

Migration of data from transversely isotropic media

The numerical analysis conducted by Larner and Cohen drew upon the efficient, analytic ray tracing possible in media that are factorized transversely isotropic (FTI) with linear velocity variation (Shearer and Chapman, 1988; and Červený, 1989). Moreover, the analysis was done on four selected anisotropic media that were not as representative of typical anisotropy as might be desired. We plan to extend the analysis in two important ways. First, we shall lift the restriction that the medium be FTI, generalizing to media that are simply transversely isotropic, with arbitrary orientation of symmetry axis and velocity variation that no longer need be linear in space. We shall develop and test this approach on synthetic data, and apply it to Gulf of Mexico data in the vicinity of salt domes to find out if it can explain puzzling problems in the imaging of the flanks of some salt domes, problems which heretofore seem to be related to lateral velocity changes in the sediments near the salt. Second, we would like to generalize the analysis from the four selected anisotropic media to a systematic study of transversely isotropic media characterized by the range of expected values of the Thomsen (1986) anisotropy parameters.

We also wish to pursue development of Gaussian beam depth migration for transversely isotropic media with general orientation of symmetry axis. This approach largely preserves the efficiency of the Gaussian beam method for isotropic media. Its utility will depend primarily on one's ability to estimate the parameters that essentially characterize traveltime behavior in a TI medium—the Thomsen parameters δ

and ϵ . While the anisotropy parameter δ can be reasonably estimated from comparison of stacking velocities in surface seismic data and vertical traveltimes in VSP data, the second important parameter, ϵ , is more elusive. Analytic expressions for stacking velocity in TI media as a function of reflector dip suggest the possibility of using the moveout of reflections from reflectors of differing dip in the estimation ϵ . We shall investigate the practicality of using such information to improve estimation of ϵ and continue our analysis of migration error to ascertain the accuracy needed for values of δ and ϵ used in TI migration.

Dip-Moveout of data from transversely isotropic media

As with the study of migration error in transversely isotropic media, we plan to lift the restriction that the medium be FTI, generalizing to media that are simply transversely isotropic and velocity variation that no longer need be linear in space. Also, we would again like to generalize the analysis from the four selected anisotropic media to a systematic study of transversely isotropic media characterized by the range of expected values of the Thomsen (1986) anisotropy parameters.

With an analytic expression we have developed for stacking velocity as a function of reflector dip in TI media characterized by the Thomsen parameters δ and ϵ , we now see how to extend the method of DMO to treat homogeneous, TI media with vertical symmetry axis. Further, we shall investigate problems in DMO that may arise when the TI symmetry axis is non-vertical, and seek a generalization of DMO for TI media that might accommodate such tilting of the symmetry axis. Another extension of DMO for TI media that we will pursue is adaptation to vertical variation in propagation velocity.

Preliminary results suggest that moveout and DMO for factorized transversely isotropic (FTI) media, i.e., media for which ratios of all pertinent elasticity coefficients are independent of position, are characterized primarily by only two of the Thomsen parameters, δ and ϵ , perhaps by only the difference $\delta - \epsilon$ between the two parameters. This difference is a measure of the departure of a medium from being elliptically anisotropic. We wish to pursue thoroughly the dependence of accuracy for DMO that ignores anisotropy (as is done in routine seismic-data-processing practice) on this difference.

In principle, a DMO algorithm that would take anisotropy into account can be expected to give superior treatment to that of isotropic DMO. The formula for NMO velocity provides a basis for building dip-moveout algorithms in anisotropic media. It can also be used to overcome the ambiguity in the inversion of reflection moveouts for anisotropic parameters by including dip-dependence of moveout velocities in the inversion procedure. It remains to be seen how robust would be the anisotropic DMO given difficulties in estimating the critical difference in Thomsen parameters, $\epsilon - \delta$.

Body-wave radiation patterns and amplitude versus offset (AVO) in anisotropic media

It is well known that the angular dependence of reflection coefficients may be significantly distorted in the presence of elastic anisotropy. However, the influence of anisotropy on amplitude-versus-offset (AVO) analysis is not limited to reflection coefficients. AVO signatures in anisotropic media are also distorted by the redistribution of energy along the wavefront of the wave traveling down to the reflector and back up to the surface. Significant anisotropy above the target horizon may be rather typical of sand-shale sequences commonly considered in AVO analysis. Unless properly corrected for, propagation phenomena in anisotropic media may seriously distort the character of AVO anomalies.

We wish to examine the influence of P- and S-wave radiation patterns on AVO in the most common anisotropic model — transversely isotropic media. Our starting point would be a hopefully concise analytic solution based on the weak-anisotropy approximation. Such an expression would provide a convenient way to estimate the impact of the distortions of the radiation patterns on AVO results. Our expectation, again, is that the shape of the P-wave radiation pattern in the range of angles most important to AVO analysis ($0 - 45^\circ$) will mostly be dependent on the *difference* between Thomsen parameters ϵ and δ . The distortions of the SV-wave radiation pattern are likely to be even more significant than those for the P-wave.

The anisotropic directivity factor for the incident wave may be of equal or greater importance for AVO than the influence of anisotropy on the reflection coefficient. Therefore, interpretation of AVO anomalies in the presence of anisotropy would require an integrated approach that takes into account not only the reflection coefficient but also the wave propagation above the reflector. For analysis of the influence of the radiation pattern in inhomogeneous, transversely isotropic media, we intend to model wave propagation using finite-difference, elastic-wave modeling code developed by Fei (1993).

We will investigate the extension of an algorithm for the triangulation-characterization of complex geologic models from two dimensions to three. We will also investigate the limits of model complexity for which Gaussian beam modeling and migration are applicable. It is unlikely that discontinuities in model velocities need be first-order in order that modeling and imaging programs accurately treat realistically complex subsurface media, but we do not know as yet what degree of smoothing will be simultaneously acceptable for accurate Gaussian beam processing and for accurate imaging of seismic data. Also, we shall extend the Gaussian beam modeling and migration to be applicable to media that are transversely isotropic, as well as structurally complex.

Given the large dependence of the divergence correction on reflector dip that we have observed in zero-offset data, we would like to ascertain whether or not similar sensitivity exists as source-to-receiver offset varies. Such variation would have implications for amplitude-versus-offset (AVO) analysis and for optimization of common-

reflection-point (CRP) stacking. We shall study divergence as a function of reflector dip and offset to ascertain if special correction is necessary in data processing and, if so, seek an approximate correction that can be efficiently implemented.

Interesting and important as is the dip-dependent waveform filtering that arises in our study of acoustic waves reflected from steep interfaces, we expect an even more important contribution to the filtering to arise in elastic media. In such media, mode conversion between P- and SV-waves is extensive as a result of the large reflection coefficients for waves traveling nearly parallel to bedding. We shall extend the finite-difference modeling used in our previous study of evanescent filtering to elastic media in order to assess the added complication in waveform filtering that results from the mode conversion. While it is doubtful that the added phenomena of mode conversion will suggest tailoring of dip-dependent deconvolution to counteract the specific filtering that arises, the study may give added weight to the need for doing such dip-dependent deconvolution.

We will extend work of the past contract period on divergence correction to a consideration of the importance of, and efficient methods for, applying a divergence correction on unstacked data. Also, because our study to date of evanescent filtering for waves that travel sub-parallel to reflectors has been limited to waves in acoustic media, we would like to extend the analysis to elastic media because of the unquestionable importance of mode conversion for waves propagating at large incidence angles at reflecting boundaries.

Probably more often than not, the subsurface is better modeled as transversely isotropic than isotropic, so migration and DMO approaches that ignore the Earth's anisotropy yield inaccurate imaging of the subsurface, particularly of steep reflectors. We will generalize our studies of migration error and dip-moveout (DMO) error to transversely isotropic media that are not limited to being factorized anisotropic inhomogeneous with linear velocity variation. Moreover, we will extend the analysis to one that systematically studies errors as a function of the full range of Thomsen (1986) parameters that describe P-wave propagation in transversely isotropic media. Also, we will examine the influence of P- and S-wave radiation patterns on AVO in the most common anisotropic model — transversely isotropic media. The anisotropic directivity factor for the incident wave may be of equal or greater importance for AVO than the influence of anisotropy on the reflection coefficient.

PEOPLE

During the past year, our research group within the Center for Wave Phenomena (CWP) has experienced a significant change of personnel that has resulted in the loss of the particular computational expertise of Dave Hale followed by the considerable gain in breadth of expertise of the group through the addition of John Scales (computational seismology, optimization and inversion methodology), Ilya Tsvankin (elastic wave propagation, especially as it relates to analysis of anisotropic media and

implications for seismic data processing and interpretation), and Michael Zhdanov (geophysical inversion theory and practice, both seismic and electromagnetic). These new personnel bring great breadth of expertise to the research and education within CWP, and are currently actively pursuing aspects of the proposed research topics, as well as projects in reservoir characterization in cooperation with another industry-sponsored consortium at CSM, the "Reservoir Characterization Project" (RCP), led by Professor Tom Davis.

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