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# COMPUTATIONAL METHODS FOR IMPROVING THE RESOLUTION OF SUBSURFACE SEISMIC IMAGES

Progress Report

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## ABSTRACT

We have implemented 2-D finite-difference modeling of elastic waves for study of seismic waves that propagate rather parallel to bedding, as in cross-well seismic surveys and reflections from steep reflectors in surface-seismic surveys. Snapshots of the propagating waves generated and displayed during the course of computation on a high-speed, interactive workstation show tunneling of evanescent waves, a phenomenon not predictable from the ray theory that is the basis of current velocity-determination methods. Accurate solutions from this program will be our standard for analysis of the more efficient, approximate (e.g., modified ray theory and paraxial wave equation) methods that we are developing.

We have also developed an interactive algorithm that characterizes geologic structure as a *Delauney* mesh, an optimum triangulation of a medium based on supplied node points. Current work is aimed at determining the data structure best suited for efficient ray tracing in 2-D and 3-D models, for use in high-resolution imaging and interactive estimation of velocity in media in which velocity varies both laterally and vertically.

We have developed two new methods for more accurate and more computationally efficient imaging of the subsurface. The first is a stable, accurate, and computationally efficient method for extrapolating 2-D seismic wavefields in depth. The second is an extension of this new depth extrapolation method to 3-D seismic surveys through a digital signal-processing device known as the McClellan transformation.

# INTRODUCTION

Our research is centered on two important problems in computational seismology. Both lie in the accurate and computationally efficient representation of seismic wavefields, and both are aimed at devising computationally efficient ways of improving the accuracy and precision of subsurface images.

The first problem is to develop and make use of accurate and computationally efficient descriptions of seismic waves that travel more or less horizontally through a geologically layered subsurface. This generic problem is directly applicable to attempts to use waves recorded in cross-borehole experiments for tomographic reconstruction of the p- and s-wave velocities of the medium between the boreholes. Also, wave propagation rather parallel to bedding now seems to be a paramount issue in attempts to image accurately, through migration of surface seismic data, very steep reflectors (i.e., 90 degrees and beyond) such as high-angle faults and the flanks of salt domes. In this report, this problem will be designated as the *v(z) problem* following from our current consideration of media in which the seismic velocity *v* is a function of depth *z* only.

The second problem is to develop new methods of representing both two- and three-dimensional subsurface geologic models in the computer. In many geologic provinces, hydrocarbon traps must be imaged in an environment of complicated subsurface structure, where velocity is a complex function of all three spatial coordinates *v(x,y,z)*. While seismic migration programs capable of accurately imaging complex subsurface structure exist today, such programs are costly to implement, and resulting image quality is highly dependent on the validity of the velocity information available. Unfortunately, such velocity information is generally least well determined where geologic structure is complex, and the process of estimating velocity under these circumstances has required iteration of the costly process of *depth migration*. The new methods that we are seeking for representing subsurface structure are aimed at facilitating the accurate and efficient computation of wavefields, with the ultimate goal of improving the efficiency of processes such as depth migration and velocity estimation. In this report, this problem will be designated as the *v(x,z) problem*, reflecting our interest in media in which seismic velocity varies with at least one lateral spatial coordinate as well as with depth.

The first two sections of this report cover developments in these two problem areas during the eight months since the beginning of DOE Grant DE - FG02 - 89ER14079. The third section describes new techniques for performing depth migration that are particularly efficient in 3-D imaging.

This DOE grant was initiated during a period of start-up for the two principal investigators, who entered academia just one year earlier. During this period, the computational facilities available to the project have improved greatly, providing the project with considerably enhanced interactive computational power than was initially envisaged. This report will review these important changes and implications for the next stages of research. Also, it will cover developments in the critical resource - people - both students and faculty.

## THE V(Z) PROBLEM

Ray-theoretical methods are well-known to be inadequate for the description of waves that propagate rather parallel to finely layered bedding. (By finely layered, we mean layers with thicknesses that are comparable to or smaller than the dominant wavelengths in the propagating seismic waves.) Our two intermediate goals for this problem are (1) to document and understand issues in wave propagation under such circumstances, and (2) to develop computationally efficient alternatives to wave theoretical methods that are presently available.

The initial methods that we have selected for describing wave motion employ finite-difference modeling of both acoustic and visco-elastic waves. We have implemented two different approaches, both on a high-speed, interactive workstation (the IBM RS/6000 advanced workstation, which will be discussed below): a 2-D acoustic-wave modeling program that operates in the time-space domain $(t,x,z)$, and a 2-D acoustic- or visco-elastic-wave modeling program that operates in the $(\omega, k,z)$ domain, where $\omega$ and $k$ are the Fourier duals of $t$ and $x$, respectively. The $(t,x,z)$-domain program involves finite-differencing of the derivatives in all three coordinates, whereas in the $(\omega,k,z)$-domain approach (Korn, 1987), finite-differencing of the Fourier-transformed data is done for just the depth coordinate $z$. Because the lateral spatial coordinate $x$ is transformed to wavenumber $k$ in the latter approach, medium velocity can vary only with depth. In contrast, the $(t,x,z)$-domain approach allows modeling through two-dimensional structure.

These particular approaches were selected because of several characteristics advantageous for our purposes. A competing approach, commonly used in earthquake and crustal seismology, is the reflectivity method (Kennett, 1983). That method, which also is applicable to media consisting of parallel layering, would be highly costly for the study of wave propagation in finely layered media. While it is capable of generating complete synthetic seismograms (i.e., including all multiples, refractions, surface waves), its cost grows as the number of layers. Cost of the finite-difference methods, in contrast, is not dependent on the structural complexity of the model (although cost is related to the ratio of the highest to lowest velocity in the model). Also, the finite-difference approaches are particularly well suited to active seismic-source problems, characteristic of surface seismic and cross-borehole applications in exploration. In particular, with ease, sources *and* receivers and be placed anywhere in the medium.

For our purposes, perhaps the most appealing feature of the finite-difference approaches is that they are naturally suited for implementation on a high-speed interactive workstation. Computations for wave-propagation problems of the scale of interest to us are completed in a few minutes on the RS/6000 workstation. Moreover, the implementation allows us to view a movie of *snapshots* of the expanding wavefield throughout the course of the propagation. Whereas snapshots of such propagating waves could be readily computed on large vector supercomputers such as the CRAY XMP, the process of downloading computed images from the large computer for replay by the scientist is cumbersome and time-consuming. We have found that the ability to visualize the propagation process in comfortably slowed-down *real time* provides significant advantage for scientific study. In a brief sitting at the workstation, one can study the development of amplitude and phase behavior for waves in a complex model, with sources and receivers placed at any desired positions. Rapidly, one can ascertain whether or not a particular choice of source and receiver positions would highlight some aspect of the wave motion under study. The computations can then be stopped in midstream, perhaps after only a minute or two, and the acquisition configuration changed for a new run. This interactive feature has also suggested to us a novel, interactive method for performing seismic migration that eliminates much of the cost typically incurred with non-interactive computing.

## Finite-difference model data

Figure 1 shows three selected snapshots during the course of propagation of an acoustic wave emanating from a line source in a simple layered medium. The depth cross-section shown in Figure 1a consists of horizontal layers of alternating high (black) and low (white) velocity. Imagine that the left edge of the section is the position of a vertical borehole, and suppose that a localized source is fired at a depth of 3.2 km, within one of the low-velocity layers. Figures 1b, c, and d show snapshots of the waves at 0.8, 1.6, and 2.4 s after detonation. The complex of upward and downward traveling waves that develops is the familiar result of multiple reflection and refraction at the many layer boundaries. The following features are worth noting.

1. because layer thickness varies with depth in the model, wavefronts are not symmetric about the source depth,

2. as we should expect, the highest amplitudes (stark black and white) are within the low-velocity layer that contains the source, but interestingly,

3. considerable energy is propagating horizontally in neighboring layers.

That horizontally propagating energy could not be predicted from ray theory. Its velocity is too low for waves propagating in the high-velocity layers; thus these waves must be evanescent within those layers. Yet, because the layer thicknesses are small compared with the dominant wavelength of the waves within the layers, seismic energy leaks, or tunnels, through the high-velocity layers into the low-velocity ones. Consequently, times of arrivals at a borehole on the right side of the depth section are not predictable from ray theory. Most tomographic analyses of cross-well seismic data today, however, are based on simple ray-theoretical computations of arrival times.

Similar thin-layer models, but with velocity generally increasing with depth, show similar complexity for wave-propagation paths corresponding to reflection of waves from steep interfaces in surface seismic experiments. Also, through study of models with layer thickness decreasing to a small fraction of a wavelength, we expect to learn about the transition to anisotropic media and the implications of that transition for tomographic analysis of cross-well data and imaging of reflections from steep seismic reflectors.

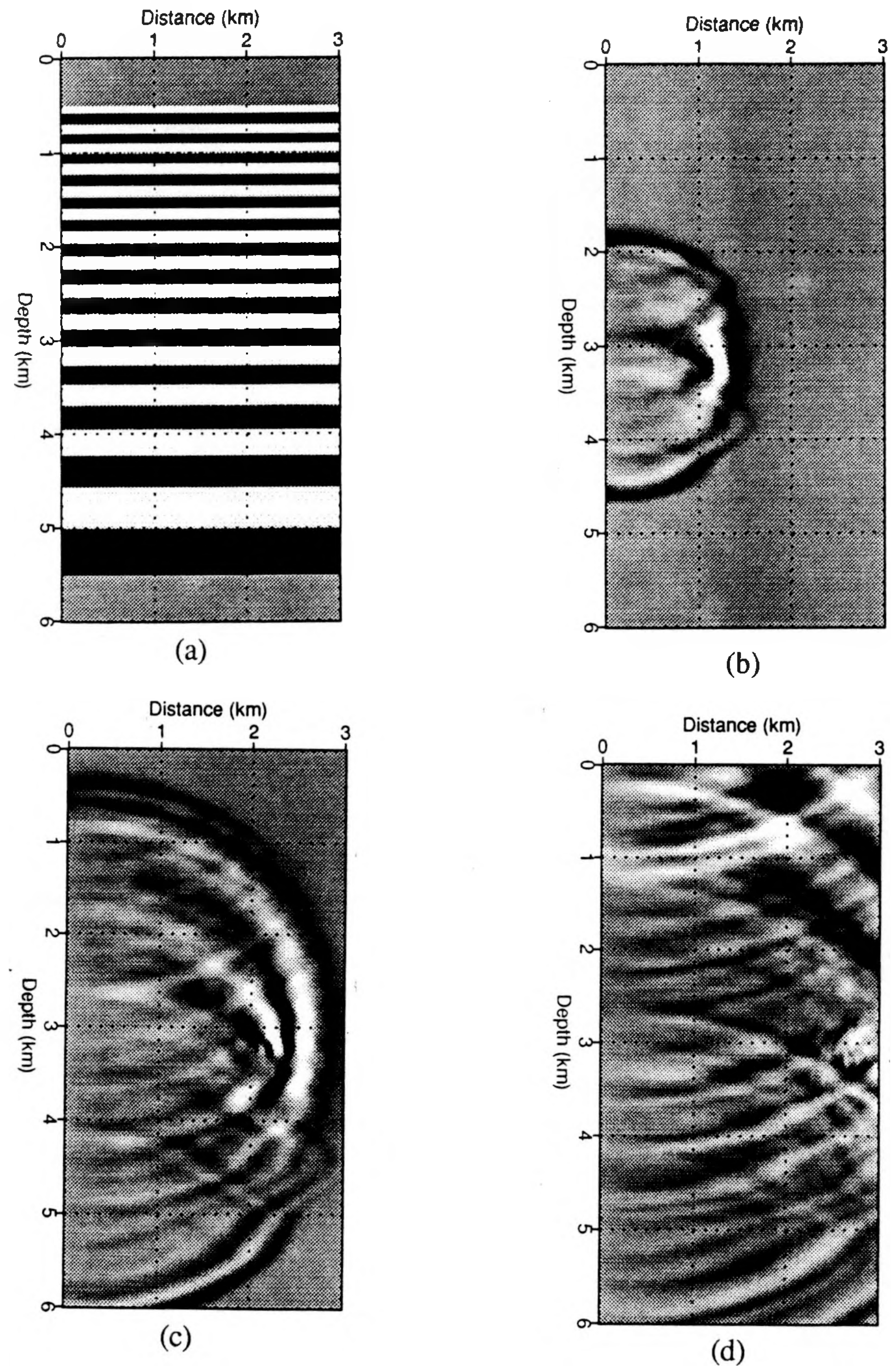


FIG. 1. Depth cross-section (a) of a thinly layered medium consisting of alternating high- and low-velocity layers, and snapshots of acoustic wave amplitude, computed by finite-difference modeling in the *(t,x,z)*-domain, at three different propagation times : 0.8 s (b), 1.6 s (c), and 2.4 s (d). Layer velocities are 2.5 km/s (black) and 1.5 km/s (white). Note that the wavefront propagates at a speed close to the average of the two.

Figure 2 displays synthetic seismograms computed for receivers placed at regular intervals down the vertical borehole along the right side of Figure 1a. These seismograms exhibit an asymmetric pattern of amplitudes and times of first arrivals about the source depth (3.2 km), again attributable to the general thickening of layers with increasing depth. The first (very weak) arrival, at about 1.5 s, suggests an average propagation velocity over the 3 km between wells of about 2 km/s. The figure also shows the complex of multiple-path trailing arrivals.

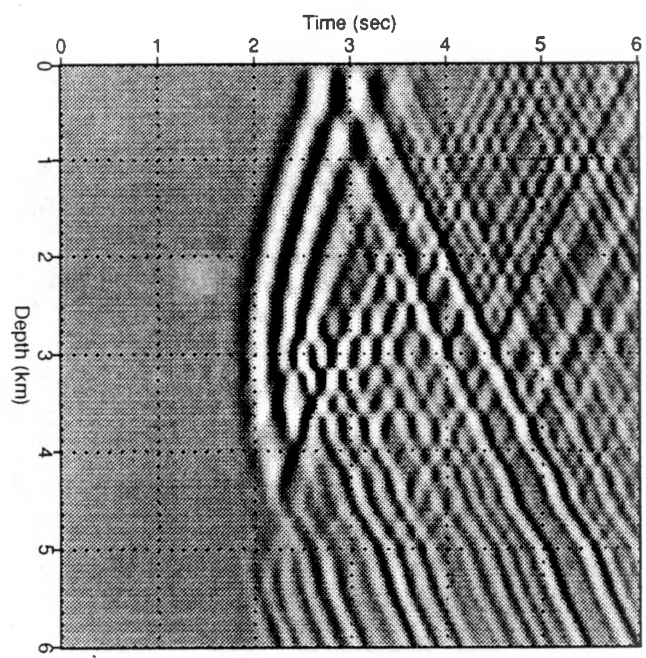


FIG. 2. Synthetic cross-well seismograms of acoustic waves measured at receivers down a vertical borehole along the right side of the depth model in Figure 1a. The source is at a depth of 3.2 km, within a low-velocity layer. These seismograms were computed by finite-difference modeling in the $(\omega,k,z)$-domain.

While acoustic-wave modeling is relatively efficient and exhibits interesting tunneling behavior, acoustic waves give an incomplete picture of wave motion, particularly for our problem of waves propagating rather parallel to interfaces. Figure 3 shows synthetic seismograms where, again, receivers are placed at uniform intervals down the borehole at the right of Figure 1a and the source is again at 3.2 km. Now, however, the medium is elastic, and Figure 3 displays the horizontal and vertical components of motion. For this model, the p-wave velocities are 2.5 and 1.5 km/s, and the s-wave velocities are 1.25 and 0.75 km/s.

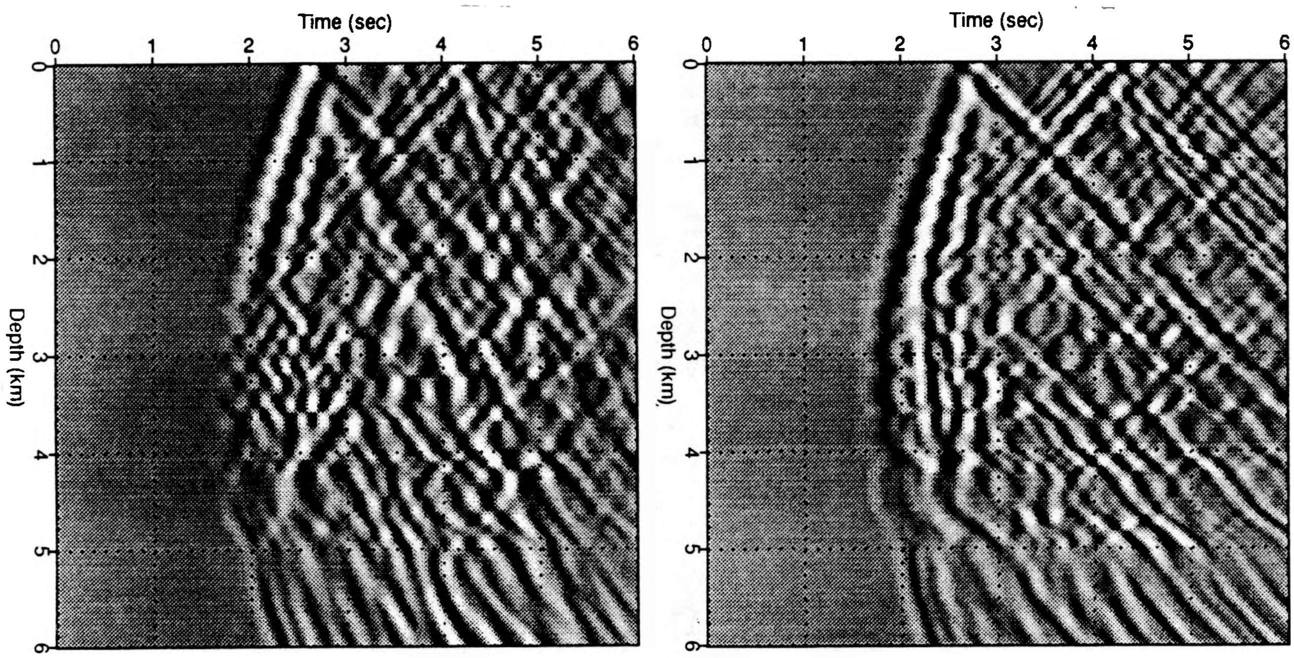


FIG. 3. Vertical (a) and horizontal (b) components of motion measured in a vertical borehole along the right side of a layered, but now elastic, medium such as that in Figure 1a. The p-wave velocities are the same as those of the model in Figure 1a, and the s-wave velocities are 1.25 and 0.75 km/s in the high- and low-velocity layers. The source is at a depth of 3.2 km, along the left side of the model.

The first arrivals in Figure 3 show more detail than do those in Figure 2. Also note the considerably increased complexity of both early and late motion in Figure 3. In particular, scattered shear waves (linear events with relatively large moveout) predominate in the horizontal motion and are strong, but less influential, on the vertical component. Clearly, the acoustic model fails to provide essential information about the wavefield when waves propagate parallel to the bedding.

This accuracy of the finite-difference modeling methods used here is likely to be greater than that necessary in cross-well tomography. A goal of our research is to devise alternative, considerably more efficient methods of simulating cross-well and surface-seismic data for models of this type, and it is essential that we have accurate data for comparison so that we can understand the artifacts that will likely arise from approximations made in faster computational methods.

### An alternative modeling approach

Consistent with their general application to whole-earth seismological problems, most approaches to the modeling of seismic waves, such as the reflectivity method and the Cagniard-de Hoop method (Hoop, 1960) emphasize far-offset approximations. Typical surface-seismic applications, in contrast, concentrate on relatively near offset (i.e., narrow reflection angles). The problem of interest here lies somewhat between the two. Rather than doing the full finite-difference modeling, we see promise in doing one-way, paraxial finite-difference modeling (Claerbout, 1985) in the x-direction, starting from an analytically determined solution along the vertical (borehole) axis containing the source. While the lateral propagation in this approach may be relatively straightforward and efficient, of importance is the accuracy of the solution along the vertical axis that is used as the boundary condition. We are addressing that solution, first, for a source near the boundary between two homogeneous media and then for a source embedded in a multi-layer medium.

### Modifications to the Cagniard-de Hoop Method

Wave propagation problems in stratified media are often solved by integral transform techniques. After transformation, the wave equation in two or three spatial dimensions and time is reduced to an ordinary differential equation. The Cagniard-de Hoop method is an analytical technique for inverting the integral transform solution. The method requires transforming a wavenumber integral into the form of a forward Laplace transform integral over a real variable, $t$. The technique promoted in the literature for doing this is to find a contour in the complex wavenumber domain along which the exponent of the integral representation is real. Often, a first step advocated in this approach is to fold over an integral with endpoints at infinity into an integral from zero to the (complex) point at infinity in the wavenumber domain. Then, the exponent is redefined as *-st* on this contour, and the necessary transformation of the representation to a Laplace integral is achieved.

The identification of the contour on which the exponent is real is not straightforward. We have found that this analysis is greatly facilitated by the following modification of the advocated approach:

1. Leave the endpoints of the contour of integration in the wavenumber domain at infinity;

2. Map the image of the given contour into a *complex t-plane,* and carry out the deformation of the contour to the real *t*-axis in this image plane.

In this form, the method echoes van der Waerden's approach to the method of steepest descents. Saddle points of the exponent become branch points in the *t*-domain; branch points of the exponent become regular but nonconformal points (angles of the mapping are not preserved there) of the *t*-domain; and singularities of the amplitude that do not correspond to these special points of the exponent are preserved by the change of variables.

For multi-layer problems, where both the exponent and the amplitude are complex, we have found that thinking of two complex domains as suggested here, greatly facilitates the analysis of the integral representation of the solution.

We have investigated this new approach for several of the classical problems solved by the Cagniard-de Hoop method, including the acoustic two-media problem and the elastic half-space problem. In these and other cases, we succeeded in obtaining new insights into the classical treatments. We will extend these results to the multi-media elastic case.

## Plans for the coming year

In addition to the approximate, one-way finite-difference modeling approach mentioned above, we hope to use insights and understanding gained from study of full finite-difference modeling results such as those shown in Figures 1 through 3 to see if ray theory might be "patched" or modified in some way that allows incorporation of features that presently require wave theory. Also, whatever progress we make toward understanding near-horizontal wave propagation in the v(z) model, improved imaging of the earth's subsurface requires that we extend our models to include such wave phenomena in media with geologic structure. We expect that we will learn from researchers who have been studying wave propagation in coal seams, and that techniques that we develop might have application to coal exploration problems, as well.

Further study will include analysis of anisotropic and generally inhomogeneous media, as well as media that are randomly inhomogeneous.

## THE V(X,Z) PROBLEM

The second large area of investigation during the past eight months centers on characterization of geologic models with lateral velocity variation. To date, our efforts have concentrated on two-dimensional models, but our thinking and design of approaches is geared toward 3-D models. At the outset of this work, we investigated several different approaches suggested by study in the field of computational geometry. Based on that study, we have presently settled on the *Delauney mesh* (Preperata and Shaves, 1985) as an appropriate starting point for generating the mesh of node points that will describe our models. The Delauney mesh is a tessellation scheme that seeks to subdivide a 2-D region into triangles (and 3-D region into tetrahedra) with node points located in accordance with the following criterion. For any quadrilateral, an internal new node point is added such that the minimum interior angle of the resulting two triangles is maximized. This criterion is one of several equivalent ones whose aim is to generate a triangulation based on supplied node points with triangles that are as equilateral as possible.

Figure 4 shows the Delauney mesh that resulted from node points supplied along the heavy line that represents the upper boundary of salt that has formed two diapirs. The thin lines define triangles that connect the supplied node points with new ones that the algorithm generates. As implemented, the program can generate a new mesh in response to new node points that an individual supplies interactively. In this way, the geophysicist can interactively modify the model with relative ease, inserting and deleting node points in the expectation that the Delauney algorithm will then parsimoniously generate a new mesh.

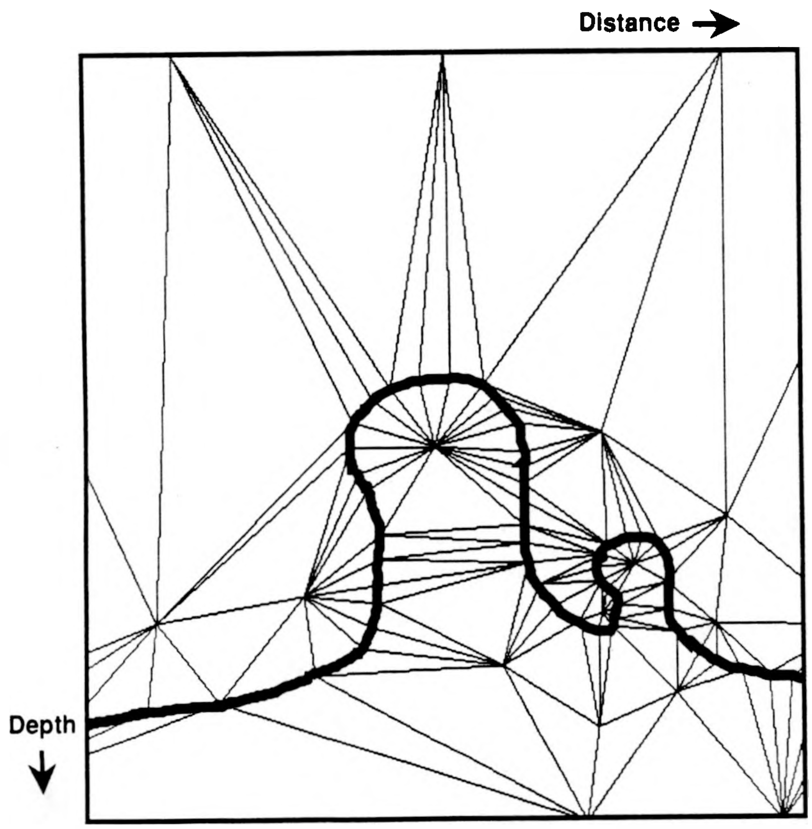


FIG. 4. Example of a Delauney mesh used to represent two overhanging salt diapirs.

Mesh generation, whether in two or three dimensions, is but one step in model characterization. The larger purpose is to develop a model characterization scheme that not only affords stable representation of subsurface structure but also is suited to an efficient scheme for modeling of seismic waves. We have investigated computational aspects of ray tracing in triangulated media and developed algorithms that should yield the desired efficiency in the tracing of rays through the mesh.

### Plans for the coming year

We have yet to analyze alternatives for data structures that will allow the most convenient and efficient definition of velocities and most efficient bookkeeping scheme for tracing rays through the mesh. In general, velocities will be assigned to the corners of each triangle. First a scheme will be developed to allow interactive input of velocity information as a function of spatial position; then the program will generate the velocity values at the node points created in the Delauney process. The larger problem is the ordering of the triangles (i.e., defining a method of identifying and pointing to neighbors of triangles) so that the ray tracing algorithm can know (without excessive searching) which triangles are encountered along a ray path. This problem is compounded in 3-D, where tetrahedra and their neighbors must likewise be efficiently identified.

Important applications toward which this effort is directed include (1) extension of the dip-moveout (DMO) method (which circumvents the high cost of prestack seismic imaging) for high-resolution imaging in media in which velocity varies laterally as well as vertically, and (2) interactive velocity estimation, again in media in which velocity varies in all spatial directions.

## COMPLETED RESEARCH

During the past year, we began and completed two investigations closely related to the research described in this progress report. First, we developed a new method for extrapolating seismic wavefields in depth (Hale, 1990a). This method yields a simple, accurate, and computationally efficient 2-D depth migration (imaging) process that handles both vertical and lateral velocity variations for seismic data recorded in 2-D surveys. Second, we extended this new depth extrapolation method to 3-D seismic surveys through a digital signal processing device known as the McClellan transformation (Hale, 1990b). In both of these investigations, our goal is to improve the resolution of subsurface seismic images through imaging algorithms that are both more accurate *and* more computationally efficient. The results of these investigations are highlighted below.

**Stable explicit depth extrapolation of seismic wavefields**

Geophysicists routinely extrapolate seismic wavefields in depth to obtain images of the subsurface. Typically, this depth extrapolation has been performed using *implicit* extrapolation methods even though implicit methods are more complex and, therefore, tend to be less efficient than *explicit* methods. One reason that implicit methods are popular is that they are easily guaranteed to be stable. In contrast, the most straightforward explicit extrapolation methods are unstable, tending to erroneously amplify wavefield amplitudes exponentially with depth.

We developed a new method, a modification of the so-called Taylor series method, for *explicit* depth extrapolation of seismic wavefields. This method, unlike other explicit depth extrapolation methods, is unconditionally stable.

Figures 5 and 6 show phase errors for explicit and implicit extrapolation methods, respectively. Phase errors correspond directly to errors in the lateral positioning of seismic reflectors in the depth migration process. In these figures, phase error is contoured as a function of wave propagation angle and *normalized frequency* - frequency (Hz) times the seismic trace spacing (m) divided by velocity (m/s). The phase errors contoured in Figure 5, corresponding to the new explicit method, are more or less independent of frequency. In contrast, Figure 6, corresponding to a typical implicit method, exhibits contours that are highly frequency-dependent, which implies that implicit depth-extrapolation methods tend to disperse low and high frequencies. The contour plots in Figures 5 and 6 indicate that this new explicit method is not only stable, it is more accurate over a range of frequencies than the implicit method considered here.

Figure 7 shows three *impulse responses* of a 2-D depth migration process based on the new explicit depth extrapolation method. The impulse response of a migration process gives the shape of the subsurface reflector that would give rise to an impulse (in both time and space) on recorded, zero-offset seismic data. For a homogeneous medium, the ideal impulse response is a concave upward semicircle. The semicircular shape of the impulse responses in Figure 7 implies that reflector dips (or propagation angles) of up to 60 degrees are accurately handled by the explicit extrapolation method. In contrast, Figure 8, corresponding to a typical, 2-D depth migration process based on implicit depth extrapolation, exhibits dip-dependent dispersion of low and high frequencies, as suggested by the contours in Figure 6. High frequencies are laterally mis-positioned for steep dips (high propagation angles), implying that lateral resolution is degraded by this implicit

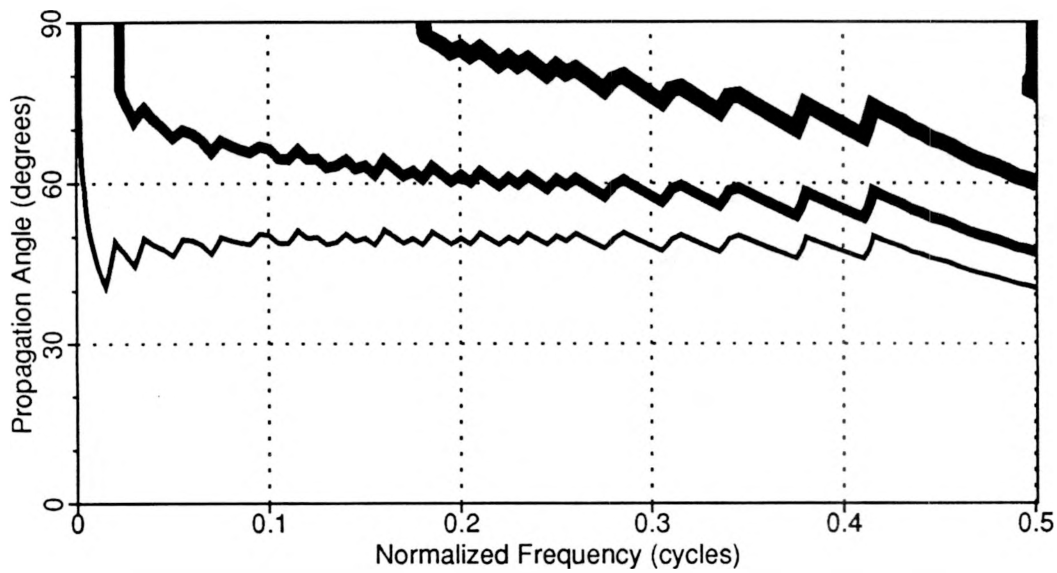


FIG. 5. Contours of phase error for the stable explicit extrapolation method. Normalized (dimensionless) frequency is frequency (Hz) times the horizontal sampling interval (m) divided by velocity (m/s). Contour values are 0.0005 (thin), 0.005 (medium) and 0.05 (thick) cycles. Because phase errors accumulate, 1000 depth extrapolation steps, for example, would result in about 1/2 cycle of phase error for a normalized frequency of 0.2 and a propagation angle of 50 degrees.

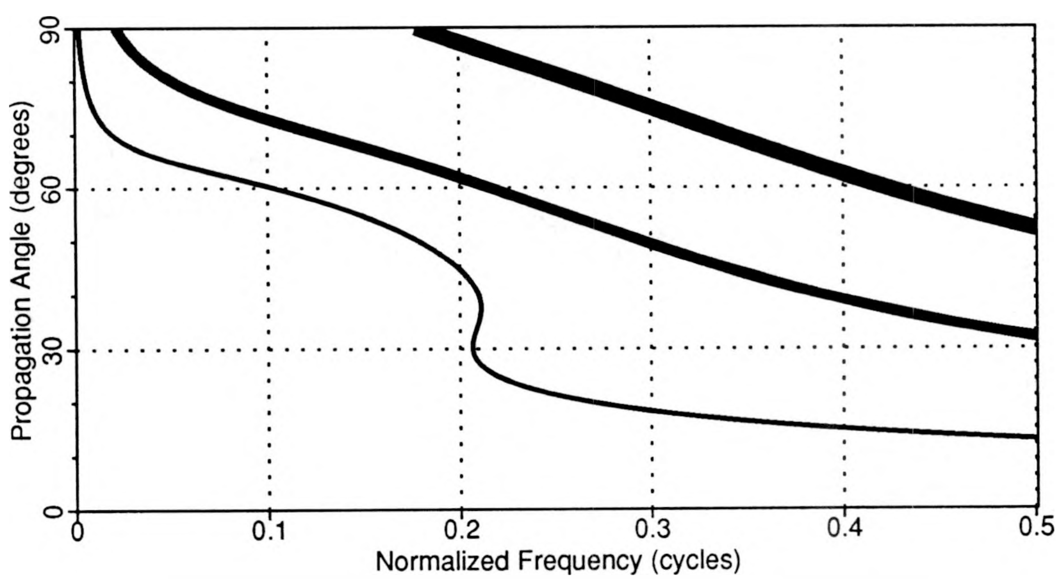


FIG. 6. Contours of phase error for a typical implicit extrapolation method. Compare with Figure 5.

extrapolation method. The high-amplitude cusp at the center of each heart-shaped impulse response is dispersed evanescent energy, which is not naturally attenuated by this implicit extrapolation method.

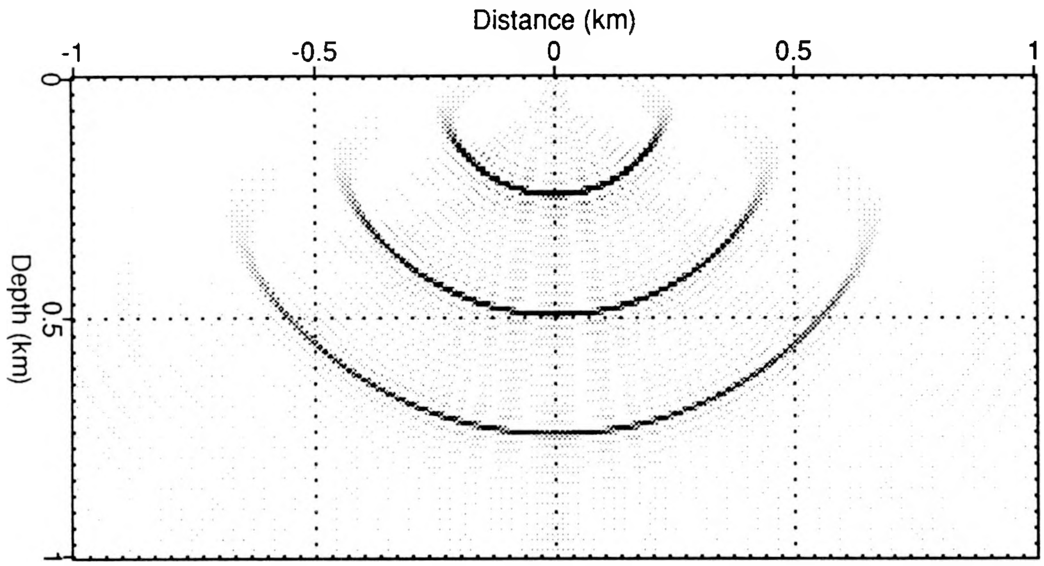


FIG. 7. Impulse responses of depth migration via stable explicit extrapolation. Note that the impulse responses are correctly positioned along concentric semicircles with centers at the origin, with no visible dispersion of low or high frequencies. Compare with Figure 8.

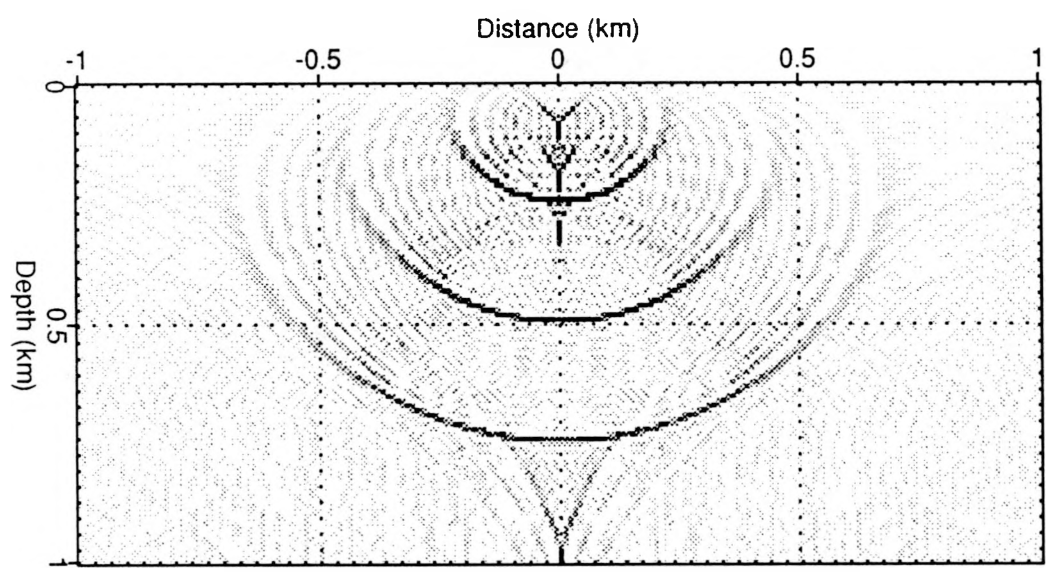


FIG. 8. Impulse responses of depth migration via implicit extrapolation. Note the dispersion of low and high frequencies at steep dips. Compare with Figure 7.

### 3-D depth migration via McClellan transformations

The advantages of explicit depth extrapolation in depth migration of 2-D seismic data may be easily and accurately extended to depth migration of 3-D seismic data through the use of McClellan transformations.

In a map view, with inline and crossline horizontal coordinates of a 3-D seismic survey, the ideal depth extrapolation filter for seismic wavefields has a circularly symmetric impulse response. Typically, this circular symmetry has been approximated by a process called "splitting", in which depth extrapolation is accomplished by a cascade of (1) extrapolation filters applied in the inline direction followed by (2) extrapolation filters applied in the crossline direction. Splitting, while computationally efficient, fails to produce the desired circularly symmetric impulse response, as shown in Figure 9a. This diamond-shaped impulse response implies that splitting will tend to mis-position seismic reflectors dipping obliquely to the inline and crossline directions of the 3-D survey.

To obtain circular symmetry, one might perform depth extrapolation of 3-D seismic data via a single two-dimensional convolution in both the inline and crossline directions simultaneously. However, this "direct convolution" approach is computationally much more costly than the splitting method.

An alternative and much less expensive approach is based on McClellan transformations, which transform the depth extrapolation filters used in 2-D depth migration to the circularly symmetric filters required for 3-D migration. Figure 9b shows the almost circularly symmetric impulse response of 3-D depth migration implemented via McClellan transformation. The transformation actually used here is an improved version of the original McClellan transformation.

The computational costs of four alternatives - splitting, the original McClellan transformation, the improved transformation, and direct convolution - are compared in Figure 10, for different lengths (10, 20, and 30) of depth extrapolation filters. Note that the cost of the improved transformation is only about three times that of splitting for the 20-coefficient extrapolation filters used to obtain the circular impulse response of Figure 9b. (The impulse response for the original McClellan transformation, although not shown here, exhibits only a slight distortion from circular symmetry.) Also, note that direct convolution, while potentially the most accurate method for depth extrapolation, is much more costly than the other methods.

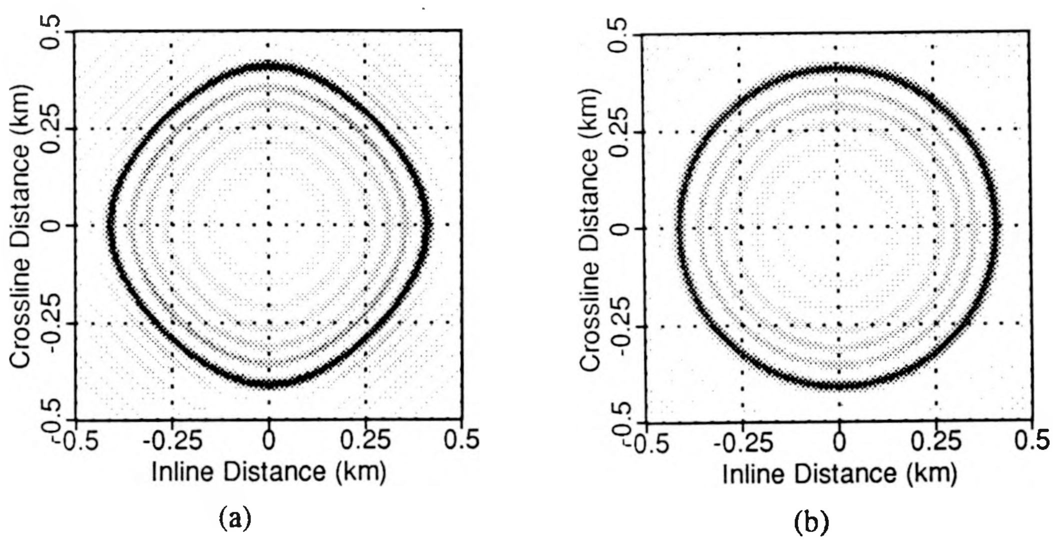


FIG. 9. Map view of impulse response of 3-D depth migration via (a) splitting and (b) an improved McClellan transformation. Depth migration via McClellan transformations produces a more accurate, nearly circularly symmetric impulse response.

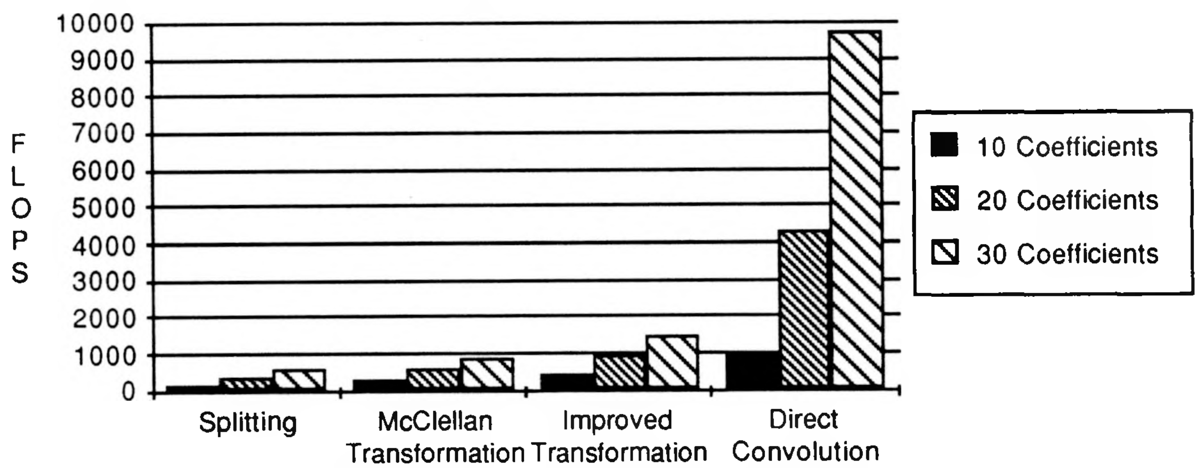


FIG. 10. Number of floating point operations (FLOPS) per output sample required by four different depth extrapolation methods. For each method, the number of FLOPS (computational cost) is plotted for 10-, 20-, and 30-coefficient depth extrapolation filters.

## COMPUTING

The computation environment surrounding our research project has changed favorably during the past eight months and will change dramatically during the summer. We now have six and will soon purchase a seventh NeXT workstation. These workstations provide an outstanding environment for scientific research and rapid, interactive development of computer software. More significantly, IBM announced last October that it had selected the exploration program at CSM to showcase IBM's cooperative support of academic research in integrated exploration. A significant part of the large support that IBM will bring to Colorado School of Mines, and to our research project, consists of the gift of 29 of the newly announced RS/6000 advanced interactive workstations. One of the principal investigators (Dave Hale) received a prototype of the new workstation in January 1990, and has found it to provide a combination of high-speed, interactive capability, and low-cost that is not matched with competing workstations today.

An indication of the boost that these workstations will provide our research is the fact that any one of the 29 workstations is faster than the university's current mainframe computer. Specifically, the workstation performance (18 MFLOPS) is particularly high for the type of computation that we do routinely, namely convolution. This speed, along with its interactive capability, makes the RS/6000 better suited for our research than is the CRAY supercomputer. IBM's substantial grant includes not only the RS/6000 workstations and 16 advanced PS/2 workstations, but also full-time cooperative research. For example, Dr. George Almasi, an IBM researcher from Yorktown Heights, New York, and co-author of the book *Highly Parallel Computing*, is a visiting professor working with us for a year investigating ways of accomplishing parallel computation for seismic problems with networked RS/6000 workstations, a loosely-coupled parallel computer.

As a result of this gift and the low-cost, high research performance of the NeXT workstations, combined with the reduced cost of memory for these workstations during the past year, we have spent only a portion of our anticipated computing budget. Also, despite the likelihood that we will do much more computing than originally planned for the coming years, we have significantly reduced computing costs in the budget for next year.

## PEOPLE

Our intent last year was to have two graduate students working half-time on this project. As must happen frequently, the notification that DOE had approved our proposal last year came after the deadline for students to decide on where they would do their schooling. Since the two principal investigators were both new to academia, neither had funds available to support graduate students until the DOE proposal was approved. By that time, some top students had decided to study elsewhere. We expect to be in a better position this coming year.

Fortunately, just at this time, a former colleague and outstanding researcher, Professor Zhiming Li, of the Beijing Petroleum University has just arrived to spend a year at the Colorado School of Mines as a Visiting Professor. Our plan is to use the remainder of the funds that were allotted for graduate students for this first grant-year to cover a portion of Professor Li's salary. We also may use some of the funds to cover a portion of his salary for next year (through next May). Dr. Li is one of the strongest research geophysicists in computational seismology. His arrival should provide a boost to our research comparable to that from the workstations that we will receive shortly.

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