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Migration of shallow seismic reflection data

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ABSTRACT

We present an analysis of migration effects on seismic reflection images of very shallow targets such as those that are common objectives of engineering, groundwater, and environmental investigations. We use an example of seismic reflection data from depths of 5 to 15 m that show negligible effect from migration, despite the apparent steep dip on the seismic section. Our analysis of the question of when to migrate shallow reflection data indicates it is critical to take into account the highly variable near-surface velocities and the vertical exaggeration on the seismic section. A simple set of calculations is developed as well as a flow chart based on the "migrator's equation" that can predict whether migration of an arbitrary shallow seismic section is advisable. Because shallow reflection data are often processed on personal computers, unnecessary migration of a large data set can be prohibitively time-consuming and wasteful.

INTRODUCTION

In this paper we examine the apparent need to migrate very shallow, high-resolution seismic reflection data in areas of low, near-surface seismic velocities. As a practical example, we will use an unmigrated seismic section presented by Miller et al. (1989) that shows prominent bedrock reflections from depths of about 10 m (Figure 1). Although this typical shallow-reflection section shows sufficient apparent dip of the bedrock surface that migration processing appears to be necessary to put the reflections in proper perspective, migration has negligible effect on its appearance (Figure 2).

If a reflector is shallow enough, the migration operator will shift the position of data points horizontally by less than a single trace or vertically by less than a time sample. In such cases migration does not have any effect on the seismic image. As shown later in this paper, calculations based on the migrator's equation (Stolt, 1978; Robinson, 1982; Chun and Jacewitz, 1981; Uren et al., 1990) predict the degree of need for migration of shallow-reflection data.

We present a general-case analysis of migration effects on seismic reflection images of very shallow targets typically found in engineering, groundwater, and environmental investigations. Targets for these projects commonly occur at depths between 2 and 50 m, which, for the purposes of this paper, are "shallow" depths. At these depths, interval velocities can vary by over an order of magnitude within individual data sets (Steeples et al., 1990). For this reason, such reflection data usually require special treatment in acquisition and processing, because of problems of scaling down from "conventional" seismic reflection surveys to a typical shallow reflection survey (Knapp and Steeples, 1986).

The scale problem has two aspects. The first aspect is that stacking velocities commonly differ by almost an order of magnitude between conventional and shallow surveys. [Remember that stacking velocities change less drastically than interval velocities. Stacking velocities are approximately the rms velocity, provided the reflectors are horizontal and the velocity varies only with depth (Sheriff, 1991).] Stacking velocities for conventional surveys are often in the 3000 to 5000 m/s range. In contrast, for very shallow surveys such as that shown in Figure 1, the stacking velocities may be as low as 200 to 1000 m/s. Second, commonly used display parameters (in seconds/inch and traces/inch) for shallow reflection data are often different from those used to display conventional seismic reflection data, because of the small geophone group intervals and high frequencies involved. However, the ratio of reflection time (not reflection depth) to horizontal distance on a typical seismic section is about the same for the two data types.

The net result of these two aspects is that the vertical exaggeration of the final seismic section is often much greater for shallow surveys than for conventional surveys. Conventional surveys are commonly displayed at a vertical exaggeration of between 0.5 and two, whereas shallow

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reflection surveys are commonly displayed at vertical exaggerations of three to five.

Plotting sections at greater than true dip can cause gently dipping reflectors to appear steeply dipping. An interpreter who sees only the stacked, unmigrated section may erroneously conclude that migration is needed. Because personal computers are commonly used to process shallow survey data, migration of large data sets can be prohibitively time consuming. Setting up the migration takes personnel time, and computer time on microcomputers is not free in the strictest sense, particularly when large processing jobs are under contractual deadline. Unnecessary migration is wasteful, so it is important that the vertical exaggeration of plotted sections be taken into account in both the processing and interpretation phases.

Typical sampling parameters for shallow seismic applications are in the range of 500 to 2000 samples gathered per trace at 0.10 ms to 0.50 ms intervals. The typical range of 0.100 to 0.500 s in total recording time is controlled by survey economics, as well as by primary target depths. Because of the large range in shallow seismic velocities, the depth range associated with a typical "shallow" record can vary from a few meters to hundreds of meters. Records representing hundreds of meters of depth typically respond

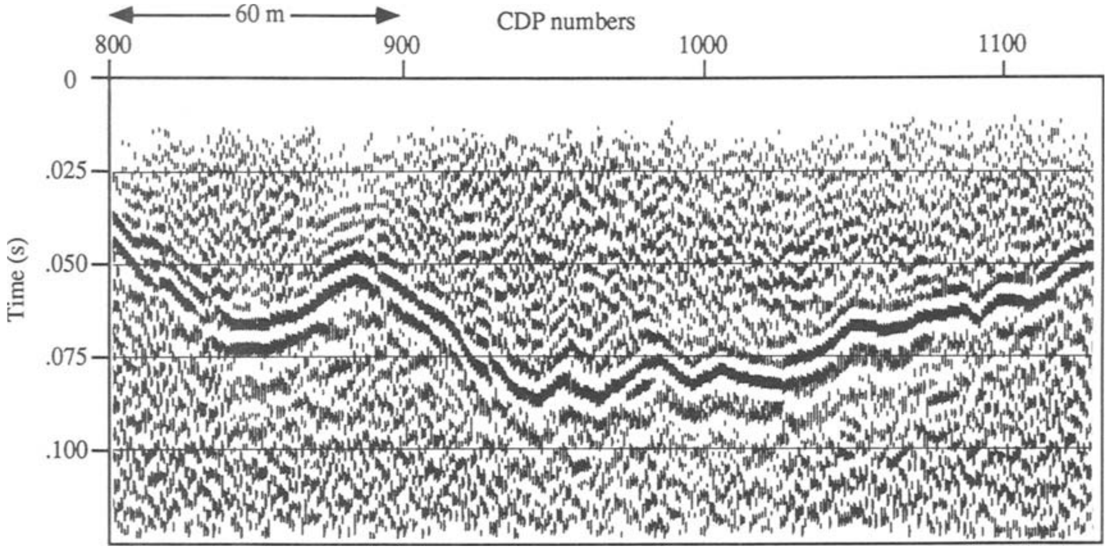

FIG. 1. Stacked shallow, high-resolution, seismic-reflection section from the Texas Panhandle. Details are given in the text.

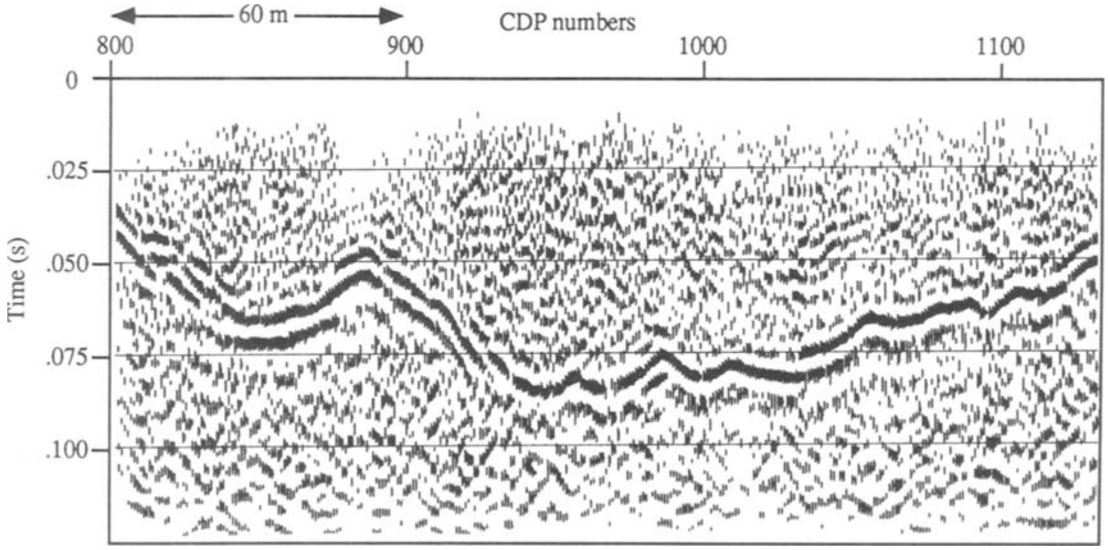

FIG. 2. Constant velocity *f-k* migration of the stacked section shown in Figure 1. Note that while changes in the section are obvious in areas of edge effects, there is little discernible change in the reflection character. In this case, subsurface interpretations based on the stack and the migration would not differ significantly enough to warrant migration of the data.

well to standard seismic processing. However, records at the low-velocity, small-time end of the shallow reflection spectrum often do not respond favorably to migration.

MIGRATION PROBLEMS

If dips are negligible, or if dip-moveout corrections are made, conventional stacked common-depth-point (CDP) sections provide a normal incidence representation of the subsurface. However, where dips on subsurface layers are significant, migration of a stacked section is often necessary to produce a geometrically accurate (vertical incidence) image. Three major classes of algorithms are available to perform the migration task. These are *f-k* migration (Stolt, 1978; Chun and Jacewitz, 1981; Sheriff and Geldart, 1983), finite difference migration (Claerbout, 1976; Claerbout, 1985; Yilmaz, 1987) and Kirchhoff (or diffraction stack) migration (Schneider, 1978; Yilmaz, 1987). Each class of algorithms has particular advantages and disadvantages. Certain problems are common to all migration algorithms. Migration can produce poor results if the data have a low signal-to-noise ratio (S/N), if the velocity structure is poorly determined or very complicated, or if the section has significant cross-dip (Warner, 1987; Yilmaz, 1987).

The migration problem affecting very shallow reflection data is that in many cases there may be no discernible difference between the migrated and unmigrated sections. This effect is analogous to a person standing close enough to a distortional mirror so that the distortion is negligible. The closer the seismic line is to the target beneath it, the less need there is for migration. In fact, migration by downward continuation has the effect of moving the image closer to the target. The need for standard migration processing becomes a function of depth to the target layer and of the vertical exaggeration that may steepen the apparent dips of the target layer.

QUALITATIVE EFFECTS OF MIGRATION

There are several basic principles associated with the effects of the migration process. Five of these basic principles will be pertinent during the following discussion. Three of these principles govern the geometric relationship between a dipping reflector segment before and after migration (Chun and Jacewitz, 1981; Yilmaz, 1987). Migration (1) steepens reflectors, (2) shortens reflectors, and (3) moves reflectors in the updip direction (Figure 3). These principles are only approximations, because migration does not perform strict point-to-point mapping. However, these ideas are useful tools for discussing the approximate behavior of dipping events and individual points on finite-length reflectors during the migration process.

The other two principles describe the true behavior of individual points in both the unmigrated and migrated coordinate systems. Because these principles involve the point responses in each coordinate system, they represent mapping operators used to move between the unmigrated and migrated images (Yilmaz, 1987). Migration (4) maps unmigrated diffraction curves into migrated points and (5) maps energy from individual unmigrated points into semicircles or ellipses in migrated space (Figure 4). Principles (4) and (5) are mathematically equivalent.

Because of principle (4), the migration process collapses unmigrated diffraction curves by summation of amplitudes along hyperbolic paths (Figure 4). Each hyperbolic sum is then assigned to the hyperbola apex position on the migrated section. Depth has a significant effect on the geometry of the diffraction summation problem.

Consider the case of two "shallow" diffraction hyperbolas with the same zero-offset traveltime (Figure 5). The traveltime curves (Figures 5a and 5b) and the normalized amplitude curves (Figure 5c) were calculated using the exploding diffractor model. Ray tracing was used to calculate the traveltimes. To calculate the amplitudes, a standard spherical spreading function (Sheriff and Geldart, 1982) was applied to the initial impulse amplitude. In addition, a directivity correction was made to compensate for nonvertical incidence. Vertical geophone orientation was assumed, and wavefield displacement (directivity) was assumed to be perpendicular to raypath at all points. No intrinsic attenuation was assumed.

One diffractor (Figure 5a) is at approximately 10-m depth with a *P*-wave velocity of 300 m/s, whereas the other diffractor (Figure 5b) is at approximately 100-m depth with a *P*-wave velocity of 3000 m/s. Because of spherical spreading and directivity, the amplitude of the shallower diffraction falls off with distance at a much greater rate than the deeper diffraction (Figure 5c). Near-surface rapid intrinsic attenuation would enhance this amplitude effect. The significant energy is thus limited to a small summation aperture. This limited aperture should be a great advantage when migrating the data. However, because the shallow reflector's energy is already concentrated at the apex, there is less need to migrate the data. In addition, migrating diffractions from shallow targets can cause an overall lowering of the coher-

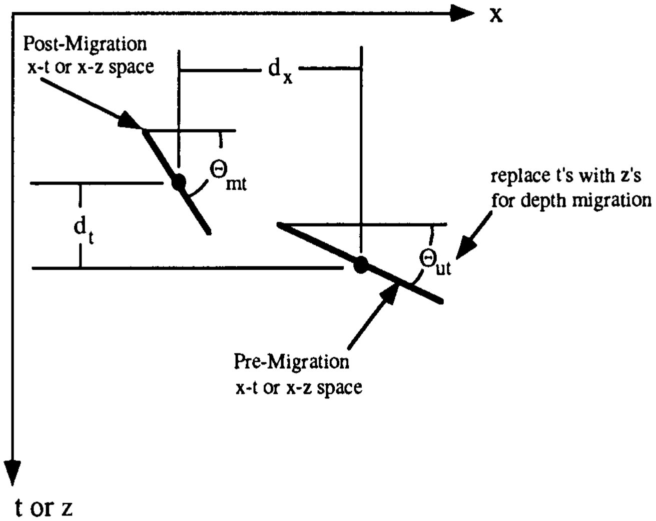

FIG. 3. The approximate behavior of points on a reflection under migration (after Chun and Jacewitz, 1981). Migration moves points updip, steepens reflectors, and shortens reflector segments. The effect of migration on individual reflectors can be monitored by the calculation of change parameters *dx*, *dt*, and the change in dip. Formulas for the calculation of these parameters are given in the text.

ency of a stacked seismic section, because the diffraction tails can easily be lower in amplitude than the ambient noise.

Since every point in a migrated section represents a summation along a finite aperture, the summation paths invariably cross each other on the unmigrated section. Each sample in unmigrated space thus contributes to the amplitude of several points in migrated space. The points on the migrated section that are influenced by each unmigrated sample are a function of the migration velocity. Principle (5) states that migration can alternatively be represented as the application of a "smearing" operator to each single point on the unmigrated section (Figure 4c and 4d). The operator distributes the single-point amplitudes in unmigrated space over a spherical or elliptical path of influence on the migrated section. Thus, the smeared amplitudes accumulate on the migrated section, adding constructively where reflectors occur and destructively where no reflectors occur. The smearing operator is the impulse response function of the migration at a given point. The operator varies with distance below the surface on the seismic section.

Examination of the migration impulse response functions (Figure 6) for the same depths and velocities used in Figure 5 shows a significant difference between the operators as a function of depth and velocity. The operator spreads the event energy evenly across many traces in the deeper case (Figure 6b), while barely changing the shape of the unmigrated point at shallow depth (Figure 6a). A plot of operator amplitude versus distance (or offset) from the unmigrated point shows that the shallow operator amplitude tapers off at a rate of about 3 dB/trace (Figure 6c), whereas the deeper operator maintains an even amplitude distribution for dozens of traces. The operator in the shallow example will therefore have little chance to shift events laterally during migration and will produce almost no effect on the unmigrated section.

QUANTITATIVE ASPECTS OF SHALLOW MIGRATION

The qualitative seismic-event migration described above can be quantified using methods derived from the so-called migrator's equation (Stolt, 1978; Robinson, 1982; Chun and Jacewitz, 1981; Uren et al., 1990). Chun and Jacewitz (1981) modified the migrator's equation to derive several simple formulas that describe the approximate movement of points on a dipping reflector from unmigrated to migrated time and depth sections. The formulas describing this movement for true depth migration in x-z space are:

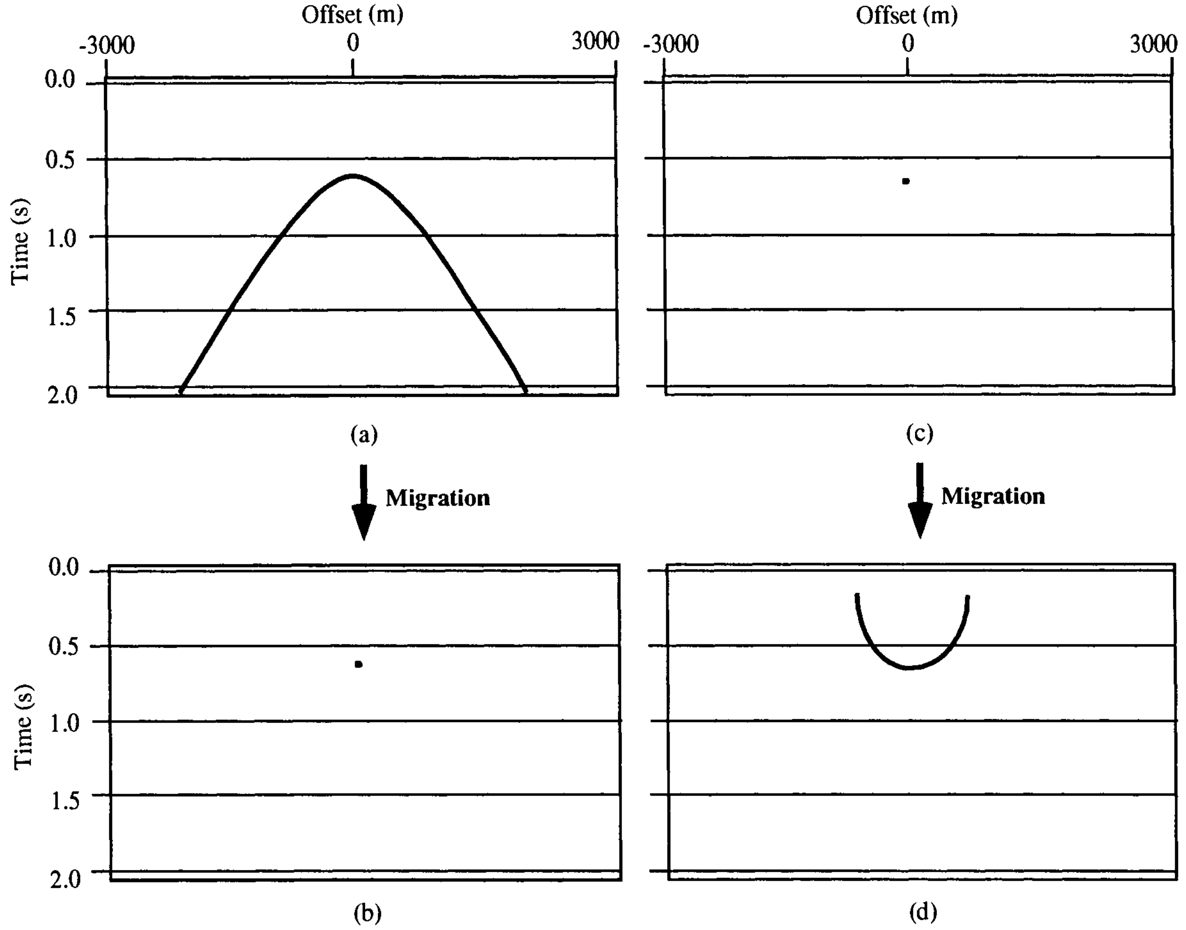

FIG. 4. Two equivalent conceptualizations of the migration process. In (a) the sum of all samples along the unmigrated hyperbola are assigned to the sample equivalent to the hyperbola apex in (b) the migrated section. Alternatively, the amplitude at the point on unmigrated section (c) is smeared over a circular or elliptical path on the migrated section (d). The migration of a single spike (c) yields the unit impulse response operator for the migration function (d). This provides a quantitative means of comparing migration operators for different velocities.

$$d_x = z \sin \Theta_{mz}, \quad (1)$$

and

$$d_z = z(1 - \cos \Theta_{mz}), \quad (2)$$

where Θ_{mz} is true dip angle on the depth section, d_x is the distance the point moved in the x-direction during migration, and d_z is the distance the point moved in the z-direction during migration (Figure 3). These formulas show that both components of movement during depth migration are linearly scaled by depth (z), which is one fundamental reason that migration of shallow reflection data may not be necessary.

The problem with using the depth factor for analysis is that the vast majority of seismic work is performed using seismic time sections, not depth sections. The formulas (modified from Chun and Jacewitz, 1981) can be rewritten in time-migration terms as:

$$\begin{aligned} d_x &= (v^2 t \tan \Theta_{ut})/4, \\ &= v^2 t D_{ut}/4, \quad (3) \\ d_t &= t\{1 - [1 - ((v \tan \Theta_{ut})/2)^2]^{1/2}\}, \\ &= t\{1 - [1 - (vD_{ut}/2)^2]^{1/2}\}, \quad (4) \end{aligned}$$

where v is the rms velocity, t is two-way traveltime, and Θ_{ut} is the apparent dip angle of the reflector on the stacked, unmigrated time section. Θ_{ut} is an awkward value to work with because of the mixed units on the time section. The value D_{ut} (equal to $\tan \Theta_{ut}$) is a more intuitive measure of the time dip. D_{ut} is the dip on the unmigrated time section expressed in s/m. Again, the result d_x is the distance a given point (x, t) is moved by a migration in the x-direction, and d_t is the equivalent distance moved in time.

Obviously, if d_x and d_t are less than the CDP spacing and the time sampling interval, respectively, then migration makes no discernible change in the stacked section. The CDP spacing and the sampling interval are thus the absolute limits on migration resolution. In practice, if d_x and d_t are equal to only a few sample intervals, the changes made in a section by migration are significant only if a detailed stratigraphic interpretation is required. For moderate dips, d_x usually contributes significantly more to the character change of the section than d_t regardless of the scale of the experiment. This means that a point on a dipping reflector typically moves farther in terms of traces (horizontal distance) than time samples (vertical distance) during migration. Equation (3) can be rewritten as (Chun and Jacewitz, 1981):

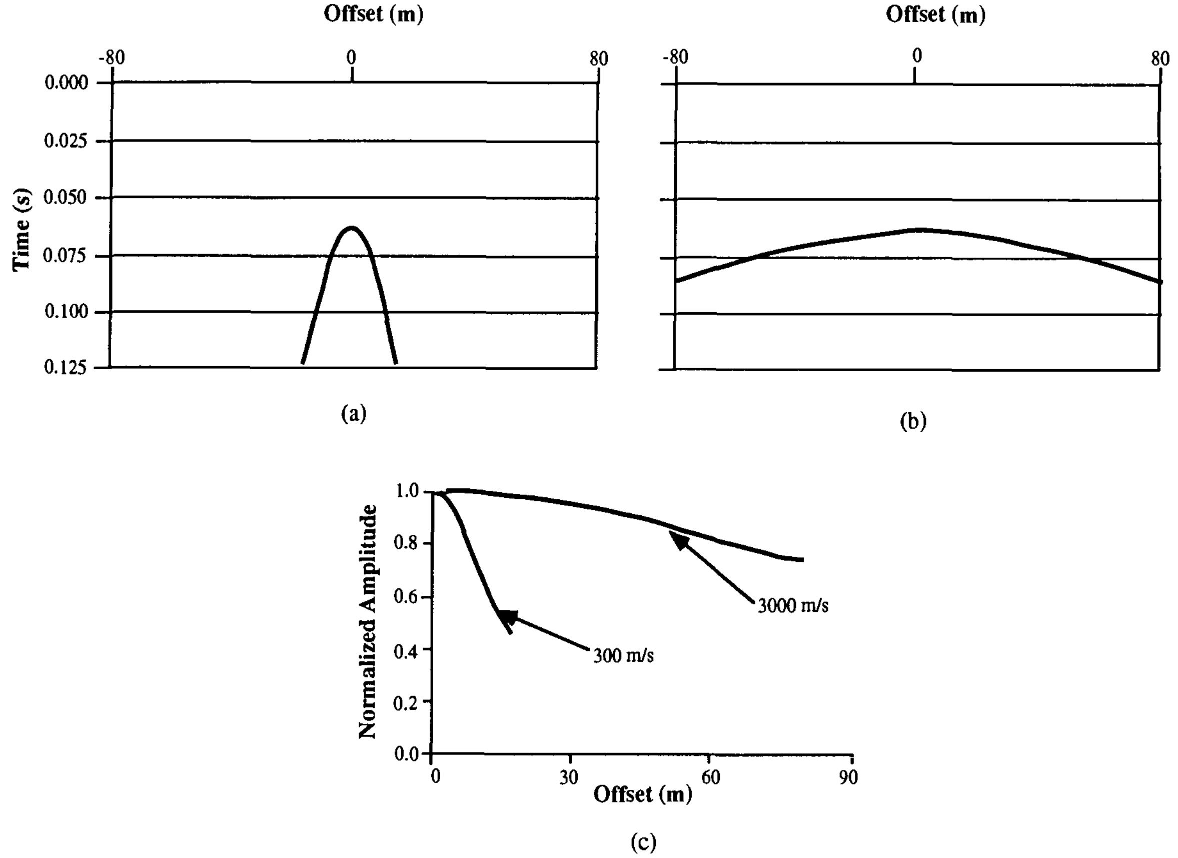

FIG. 5. Cartoon of two different diffraction patterns at the same two-way traveltime demonstrates the effect of changes in depth and velocity on the most basic signal element observed on stacked sections. A point diffractor generates a hyperbolic response over the entire section for a high medium velocity of 3000 m/s (b), while for a low velocity of 300 m/s (a), the hyperbola is more compact. A graph (c) of the relative amplitudes along the curves (assuming spherical spreading of P-waves and vertical geophones) shows that energy is more concentrated close to the apex of the slower diffraction curve and evenly spread across the section at the higher velocity. This demonstrates that, inherently, there is less need for migration at low velocities.

$$d_x = vzD_{ut}/2. \qquad (5)$$

Comparing equation (5) to equation (1) it is obvious that under depth migration d_x is linearly related only to z, but under time migration there is an extra scaling factor. The reason for this is that the apparent dip is a scaled function of the true dip. The extra scaling factor is rms velocity.

It is not surprising, then, that the behavior of shallow seismic reflections is critically tied to the highly variable near-surface velocity structure. Variation in near-surface velocities is an order of magnitude greater than the local velocity variations found at typical oil-production depths. Thus, equation (5) implies that, for shallow surveys involving very low seismic velocities, migration sensitivity may decrease as much as an order of magnitude below the migration sensitivity for deeper surveys. In such a situation, migration is not practical in the processing sequence.

Chun and Jacewitz (1981) were also able to plot the relative change in position for different velocities and constant apparent dip. A plot similar to theirs (Figure 7a) illustrates the effect of velocity on the combination of d_x and d_t discussed above. Migration moves the apparent position of a point on a dipping reflector updip an amount (d_x, d_t) in x-t space. The updip change in apparent position is a function of velocity (Figure 7a). As the migration velocity is increased, the position of the point traces an arcuate path away from the unmigrated position in x-t space. A similar plot (Figure 7b) was made with the parameters used in Figures 5 and 6. Again, for a reflector with a given apparent dip in x-t space, the apparent position of a point at 0.067 s changes greatly when migrated with a velocity of 3000 m/s, but the point is barely moved using a migration velocity of 300 m/s (Figure 7b).

The change in position was also compared with the limits of resolution (Figure 7b) for some common shallow, very high-resolution survey parameters (0.6-m CDP spacing, 0.5-ms sample interval). The change in position is significant for the high-velocity case, but it is actually less than the absolute resolution limits of the data in the low-velocity case. In practice, a change in position would have to be several traces and/or several time samples in magnitude to be noticeable on most seismic sections.

Besides the velocity-scaling and plot-scaling effects, another practical consideration that can exacerbate the resolution problem is the tradeoff between station spacing and spread length. Because of economic limitations, recording systems used in very shallow surveys have smaller channel capacities than those typically used in petroleum exploration. Channel capacities range from 12 to 48 for most shallow reflection applications and 120 or more for petroleum applications. It is necessary to have small station spacings to

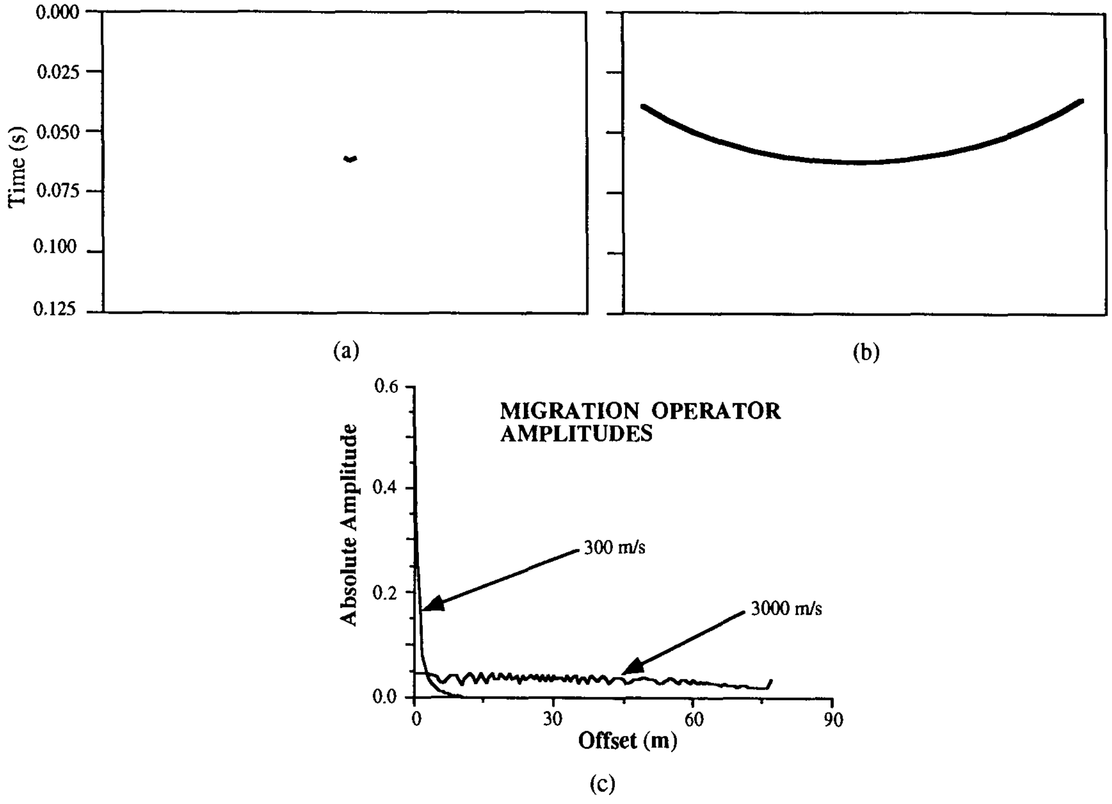

FIG. 6. The basic geometry of the unit impulse response (the actual effect of the migration on a given point) function for a shallow diffractor in a low-velocity (300 m/s) medium is shown in (a). The unit impulse response geometry for a deeper diffractor in a higher (3000 m/s) velocity medium is shown in (b). The actual migration operator values are shown in (c). Notice that a point on the high-velocity section will be smeared evenly over the entire section, while a point on the low-velocity section will be effectively smeared only over a few traces, as the operator amplitude drops off at a rate of almost 3 dB/trace (0.6-m spacing) near the operator's center point.

avoid spatial aliasing and to take full advantage of whatever horizontal resolution is available. Small station spacings are also necessary to maintain coherency of reflections (as well as suspected reflections and removable noise) on the field files. Competing against the need for small station spacings is the need for longer offsets to obtain more robust velocity and dip information that can only come from larger moveout times. The combination of limited channel capacity and low velocities may prevent the full utilization of the horizontal resolution limits of the survey. If the station spacing is not large enough to provide sufficient offsets, we may impair the sensitivity of a section to the process of migration.

A FIELD EXAMPLE

A shallow seismic reflection section (Figure 1) from the Texas Panhandle illustrates the small effect of migration on shallow data. The absolute migration resolution limits are the CDP interval of 0.6 m and the sampling interval of 0.5 ms (field sampling interval was 0.25 ms before resampling), similar to the parameters used to define the resolution limits in Figure 7. If the d_x and d_t parameters of equations (1) and (2) are near these limits, then little change should be noticeable on the migrated section.

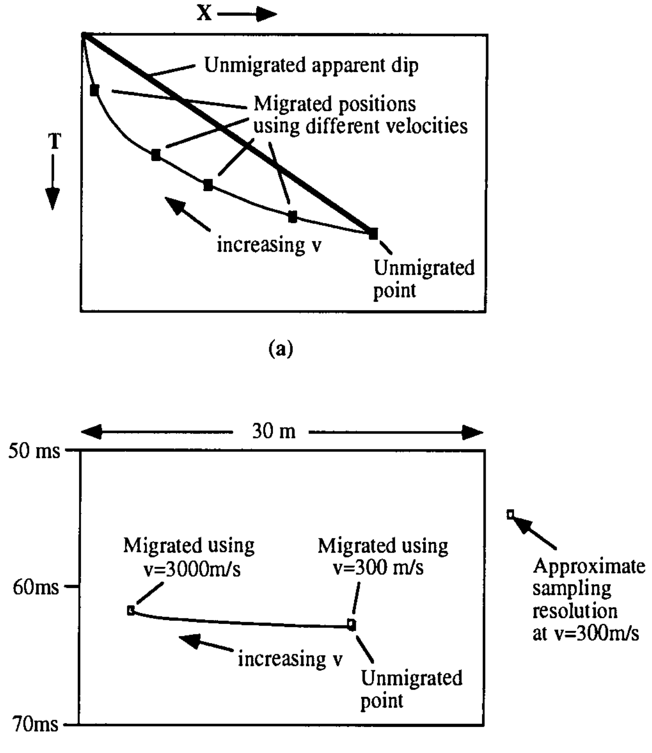

FIG. 7. (a) Approximate behavior of a single point on a dipping reflector migrated in x-t space. Migration with higher velocity moves the point a greater distance in the x-t plane. (b) Detailed view of a portion of "shallow" seismic x-t space comparing the behavior of a point on a dipping reflector migrated with two different velocities, 300 m/s and 3000 m/s. The size of the points reflects the absolute limits of resolution on the seismic section. Note that while the high-velocity migration significantly changes the position of the point, the low-velocity migration fails to move the point a resolvable distance.

The survey was conducted as part of an environmental study in Hutchinson County, Texas. Field parameters and detailed interpretations are reported in Miller et al. (1989). The section displays several characteristics commonly observed on shallow seismic sections. Shallow survey targets typically consist of a single top-of-bedrock reflector or a limited number of intra-alluvial events. In this survey the single reflector imaged is the dry-alluvium/bedrock interface. Because of the nature of the dry, unconsolidated material overlying the bedrock, the stacking velocities averaged a little over 300 m/s (Miller et al., 1989). This is near the lower end of the typical near-surface velocity range of 200–1000 m/s (Birkelo et al., 1987; Knapp, 1986). Depth to the main reflector ranged from 4 to 14 m.

The section was f-k migrated using the SierraSeis© processing system at the University of Kansas. Because of the single-layered nature of the geology, a constant velocity migration function was used.

A migrated section (Figure 2) produced with a velocity of 305 m/s shows that, except for edge effects at the base of the migrated section, very little change has occurred because of the processing. A detailed comparison of the two sections (Figures 1 and 2) shows only minute differences in the reflector. Those differences occur mainly in the small area displaying the steepest dip on the event.

Calculated values of d_x and d_t for this section predict that migration would make little difference in the interpretation of this seismic section. The values were calculated for a traveltime of 50 ms and for the steepest apparent dip on the section. The calculated values were relatively small, with a d_x of approximately 2 m and a d_t of less than 2 ms. The steepest dip on the stacked section could thus move at most 4 traces and 4 samples, corresponding to a maximum movement of at most a few millimeters at the plotting scales used for most shallow-reflection surveys. The maximum dip is observed over a very small area of the section. Over most of the section apparent movement of individual points on the reflector would be below the one sample resolution limit. In this case, the d_x and d_t criteria can be applied to the field data to predict the effect of migration on a particular data set.

One place where subtle improvement was provided by the migration is between CDP 930 and 1050. There appears to be some improvement in definition of the small peaks and troughs. Overall, however, the interpretation is not changed by migrating the data.

A PRACTICAL TEST FOR ARBITRARY DATA SETS

In this section, the individual steps necessary to test whether migration is appropriate for a given data set are presented. The basis for the test is the application of equations (3) and (4). Although these equations appear to be straightforward, there is often confusion concerning the definition of the angles and the trigonometric expressions on real seismic sections. For this reason the modified equations using the value D_{ut} for the dip should be used instead of those written in terms of Θ.

A flow chart of the procedure (Figure 8) demonstrates the steps necessary to complete the migration test, as enumerated step by step below.

1) A representative reflector with some dipping segments is picked for analysis.
2) The apparent time-dip on the steepest reflector segment is measured in s/trace.
3) The result from step 2 is divided by the CDP spacing in meters to yield a value in units of s/m. This number is the value for D_{ut} in equations (3) and (4).
4) The value for D_{ut} is then used, along with the stacking velocity and the average traveltime of the target event. These values are inserted into equations (3) and (4) to calculate d_x and d_t.
5) The values of d_x and d_t are then divided by the CDP spacing and the trace sampling interval, respectively. This division yields the maximum number of traces and samples that any point on the given reflector could move during migration.

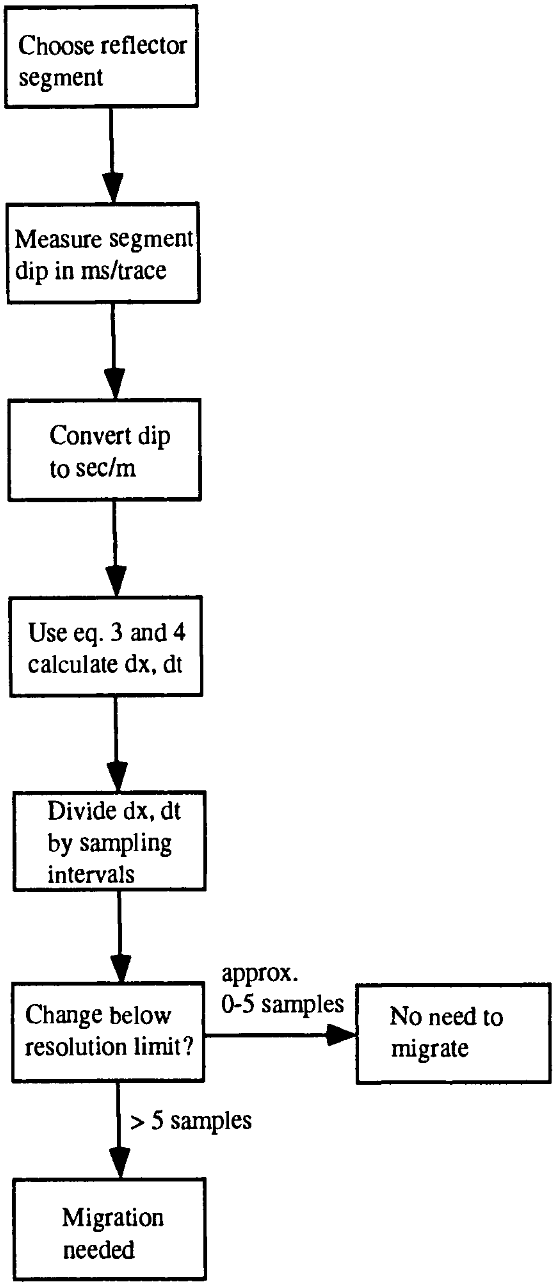

FIG. 8. Algorithm for evaluating the necessity of migrating shallow reflection data based on equations (3) and (4) in the text.

If these maximum values are less than one, then no change will occur in the reflector signal. If these values are greater than one but are less than approximately five sample intervals in size, then a slight change in reflection character may be detected at the ends of the steepest reflector segment, but change along the bulk of the reflector's length will still be below the detection limit. In either of the above cases migration probably need not be applied to the data. If the maximum potential change is many traces or time samples in magnitude, then migration is necessary. The number of samples or traces of movement that can be tolerated without needing migration will vary with the purpose and resolution limits of individual surveys.

CONCLUSIONS

Shallow targets less than 50-m deep are being imaged regularly with seismic reflection methods. In many cases, the stacking velocities used in these surveys are an order of magnitude lower than velocities found in standard petroleum surveys. Commonly used plotting parameters result in a vertical exaggeration factor of three to five on shallow seismic sections. As a result, dips appear to be three to five times steeper than reality.

In a constant-velocity medium with fixed reflector dip, the lateral movement of the reflected energy during migration depends only on the reflector depth. Shallow reflectors are sometimes sufficiently close to the earth's surface that migration provides little if any image improvement for the interpreter. This effect is analogous to a person standing close enough to a distortional mirror so that the distortion is negligible. The closer the seismic line is to the target, the less the need for migration.

In cases such as those described above and in the example shown in this paper, simple formulas, such as a modification of those derived by Chun and Jacewitz (1981), predict whether a standard migration operator will significantly affect the interpretation of the stacked section. Under circumstances commonly found in shallow seismic reflection surveys, migration will not result in changing an interpretation of a seismic section, unless a detailed interpretation of stratigraphic features near the survey's resolution limit is necessary.

By applying simple formulas, such as a modification of those derived by Chun and Jacewitz (1981), it is possible to predict whether a standard migration operator will significantly affect the interpretation of a stacked section.

Because many large, shallow-reflection surveys are processed commercially on personal computers, unnecessary migration can waste significant amounts of computer and personnel time. Analysis of the type described here predetermines whether migration should be included in the contracted processing flow.

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