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Flooding the topography: Wave-equation datuming of land data with rugged acquisition topography

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ABSTRACT

Wave-equation datuming overcomes some of the problems that seismic data recorded on rugged surface topography present in routine image processing. The main problems are that (1) standard, optimized migration and processing algorithms assume data are recorded on a flat surface, and that (2) the static correction applied routinely to compensate for topography is inaccurate for waves that do not propagate vertically. Wave-based processes such as stacking, dip-moveout correction, normal-moveout correction, velocity analysis, and migration after static shift can be severely affected by the nonhyperbolic character of the reflections.

To alleviate these problems, I apply wave-equation datuming early in the processing flow to upward continue the data to a flat datum, above the highest topography. This is what I refer to as “flooding the topography.” This approach does not require detailed a priori knowledge of the near-surface velocity, and it streamlines subsequent processing because the data are regridded onto a regularly sampled datum. Wave-equation datuming unravels the distortions caused by rugged topography, and unlike the static shift method, it does not adversely effect subsequent wave-based processing. The image obtained after wave-equation datuming exhibits better reflector continuity and more accurately represents the true structural image than the image obtained after static shift.

INTRODUCTION

Some of the last petroleum prospecting frontiers are in overthrust areas where rugged topography and irregular data coverage present significant processing challenges. The rugged terrain and complex structure make drilling very expensive, and since there is often little well control or a priori velocity information, it is critical to lower risk by extracting as much information out of the seismic data and provide the best possible image. Even when good quality data are recorded in these terrains, the processing challenges that arise because of the topography, the presence of high-velocity rocks near the surface, and complex subsurface velocity can impede conventional processing and subsequent interpretation.

Seismic imaging algorithms are generally applied to data that is datumed to a planar surface. In regions of mild topography where the near-surface velocity is much slower than the subsurface velocity and raypath emergence angles are small, a static shift is adequate for the transformation. However, when the near surface velocity is comparable to the subsurface velocity and raypath emergence angles are large, the static approximation becomes inadequate. Under these circumstances, a static shift distorts the wavefield and degrades the velocity analysis and imaging. In this case, it is necessary to propagate the wavefield numerically to some level datum. This wave-equation datuming process may be used to “flood” the topography by filling it with a replacement velocity and upward continuing the data through it.

The concept of wave-equation datuming was first presented in Berryhill (1979) for poststack applications, and later extended to prestack data (Berryhill, 1984). Unlike datuming with static shifts, wave-equation datuming removes the distortions caused by topography in a manner consistent with wavefield propagation. This ensures that subsequent processing steps that assume hyperbolic form, or even more complicated trajectories consistent with wave propagation, can be accurately applied.

I demonstrate how wave-equation datuming can be used to improve and simplify the early stages of processing and imaging by applying the process to an overthrust data set from the Canadian Rockies. In this example, wave-equation datuming provides a clear improvement over conventional statics processing. Because the data are regridded onto a flat evenly sampled datum, further processing is streamlined and structural interpretations are easier to incorporate into the analysis.

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Standard processing of overthrust data

Successful processing in overthrust areas has relied on heavy interaction between interpreters and processors (Burke and Knapp, 1995; Tilander and Mitchel, 1995). In recent years several advances have been made, not the least of which has been improved acquisition technology. Increased shothole depth, shot charge, and fold, go a long way toward increasing data quality. Data processing has generally consisted of early-stage filtering and noise suppression followed by iterations of static shift and preliminary velocity estimation. The final output datum is usually set above the highest topography. However, during processing, data are often corrected to a local floating datum that is common midpoint (CMP) consistent. This is done to minimize nonhyperbolic distortions caused by large static shifts. When the assumption of vertical raypaths implicit to static corrections is invalid, CMP velocity analysis will suffer. In this case, it is better to apply wave-equation datuming rather than large static shifts.

Because of the nature of overthrust data, it is often difficult to pick velocity from CMP semblance analysis; therefore, velocity is often estimated from constant velocity stacks and post-stack migration. When constant velocity stacks and migration are used, the data are shifted to the final output datum. This shift is done primarily so that an interpreter's insight can be incorporated in the velocity estimation. As pointed out in Tilander and Mitchel (1995), stacking to a floating datum in the presence of significant topography can introduce artificial structure. This hampers the interpreter's ability to use geological intuition in picking horizons and defining dominant structural style. The added benefit of shifting data to the final output datum is that fast and efficient algorithms can be applied to the estimation of migration velocity. If static shift is used to transform the data to the output datum and the assumption of vertical raypaths is not valid, the data will be distorted and the accuracy of the migration result will be compromised. If prestack wave-equation datuming is used instead of static shift, the event kinematics will not be distorted and the migrated image will be superior.

Refraction analysis is often used to determine low spatial frequency statics and to compensate for the weathering layer. The refraction statics solution is often used with a replacement velocity to correct data to either a floating or final datum. While this works well in regions of mild topography and well behaved weathering layers, the refraction model often does not match the geologic reality of mountainous terrain. Although useful near-surface information may be gleaned from refraction analysis, it is often more accurate to apply wave-equation datuming to the recorded data rather than to apply static shifts based on refraction analysis for the final datum correction (Schneider et al., 1995).

For extremely poor signal-to-noise data, wave-equation datuming may not be appropriate because it is likely to generate strong artifacts. In such situations, judicious use of datum statics and residual statics is more likely to be successful. However, when the data quality is adequate, the incorporation of wave-equation datuming into the processing flow can offer significant benefits.

Related work on rugged topography and wave-equation datuming

Wiggins (1984) and Reshef (1991) implicitly include effects caused by topography in their migration algorithms. Wiggins uses a Kirchhoff formulation to incorporate topography directly in prestack migration from a rugged surface. Reshef's phase-shift migration method is also used to migrate data directly. He performs downward extrapolation from a flat datum and adds data to the extrapolated wavefield each time the topographic surface is intersected. Both these methods allow direct migration of data recorded on a rugged topographic surface. Beasley and Lynn (1992) introduced an elegant and simple algorithm to correct for the error caused by the static time shift based on the "zero-velocity layer" concept. In their finite-difference migration, Beasley and Lynn migrate data after static shift by setting the velocity in the diffraction term to zero above the topography. Not only is the static shift required before migration, but this technique cannot be applied to the computationally attractive phase-shift algorithms, because it includes the nonphysical characteristic of zero velocity.

Yilmaz and Lucas (1986) and Berryhill (1986) demonstrate how to compensate for the raypath bending effects of a rugged ocean bottom with severe velocity contrast. They call the technique prestack layer replacement. The method uses wave-equation datuming twice, first to downward continue the wavefield from an initial surface to a datum, using a known velocity, and second to upward continue the wavefield from the datum to the initial surface, using a different velocity.

Schneider et al. (1995) apply the same layer-replacement idea to replace the low-velocity layer for an overthrust data set. They use refraction analysis to estimate velocity in the weathering layer, followed by wave-equation datuming to downward continue the data to the base of the layer with the estimated velocity, and then upward continue with a replacement velocity. Their results show some improvement over refraction statics, but there is some error associated with the refraction velocity and layer determination. In portions of their final stack that correspond to topographic highs, static shift produces a better result than wave-equation datuming. This may be because their refraction model shows an unintuitive thickening of the low-velocity layer over a topographic high, which may result from the misidentification of tunneling or diving waves as refracted arrivals.

For all of the above methods to work, the near-surface velocity must be known or reliably estimated. The more general and problematic situation is one for which the velocity structure is unknown or difficult to estimate. In this situation, I upward continue the data to some planar datum above the topography with a replacement velocity. This unravels the distortions caused by the rugged acquisition topography and allows standard velocity estimation and imaging techniques to be applied more accurately to the data.

STATIC SHIFT VERSUS WAVE-EQUATION DATUMING

The industry-standard method of datuming is to perform static shifts of data traces. The static shift method is applied commonly to correct for near-surface velocity variations caused by weathering layers and for topographic effects. This is adequate when emergence angles are small, so that the near-surface raypaths are close to vertical. However, at large emergence angles (Figure 1) static shifts do not correspond to raypaths consistent with wavefield propagation. In this section, I will use simple synthetic examples to show that when static shifts are large and the assumption of vertical raypaths is not valid, the wavefield is distorted by the static shift so that velocity analysis, migration, and any other wave-equation–based processing is severely degraded.

If the near-surface velocity structure is known, data can be downward continued through the near-surface velocity structure to some lower datum. In this type of situation, Shtivelman and Canning (1988) show the accuracy limitations of static shifting and the need to apply wave-equation datuming when differences in elevation are significant and the velocity model is complicated. For most land data, the near-surface velocity is not known. One method of eliminating distortions caused by topography is to upward continue the data to an arbitrary datum above the highest topography. This is analogous to upward-continuing marine data from the water bottom back to the original acquisition surface in marine layer replacement applications. The proper velocity to use for upward continuation should be close to the near-surface velocity. This choice of velocity is made so that excess ray bending is not introduced by the datuming process. Since near-surface velocity often varies along a seismic line, the datuming velocity is generally variable; however, for the examples shown here, a constant datuming velocity is used. Once the data have been upward continued to a higher datum, conventional velocity analysis can be performed. The result of velocity analysis, stacking, and migration after wave-equation datuming is superior to the result after static shift.

Thus, wave-equation datuming provides a way of extrapolating a distorted wavefield to a planar datum without requiring detailed knowledge of the near-surface velocity. Once the data is at the planar datum, the velocity structure can be determined.

All of the datuming examples in this paper are generated with a Kirchhoff wave-equation datuming algorithm. As depicted in Figure 2, each upward-continued output trace P_j is calculated by summing over the input traces P_i as

$$P_j(\omega) = \sum_i A_{ij}\sqrt{-i\omega}P_i(\omega)e^{i\omega\tau_{ij}}. \qquad (1)$$

A_{ij} is an amplitude term incorporating divergence and obliquity, ω is the temporal frequency measured in radians, and τ_{ij} is the traveltime between input location i and output location j. For 2-D data, the amplitude term is given by

$$A_{ij} = \frac{\Delta x}{\sqrt{2\pi r_{ij} v}}\cos\theta_{ij},$$

where v is the datuming velocity, Δx is the spatial sampling interval, θ_{ij} is the angle between the normal to the input surface and the traveltime path r_{ij} connecting input location i and output location j. A detailed derivation of equation (1) is presented in Bevc (1995). Equation (1) can be applied directly to zero-offset data. Prestack wave-equation datuming is a two-step process: equation (1) is applied first to all common shot gathers, and then to all common receiver gathers (Berryhill, 1984).

The Kirchhoff method was selected over recursive methods such as phase shift and finite difference because it is the most efficient for application to prestack data, and because it can accommodate irregular acquisition geometry. The chief drawback of the recursive methods is that they require a regular computational grid. The Kirchhoff method is not confined to a regular grid, so for the irregular geometries of land data acquired in rugged terrain and for 3-D implementation considerations, the datuming algorithm based on the Kirchhoff integral is the operator of choice. Furthermore, the Kirchhoff implementation handles the exact topographic elevations, not some discretized representation.

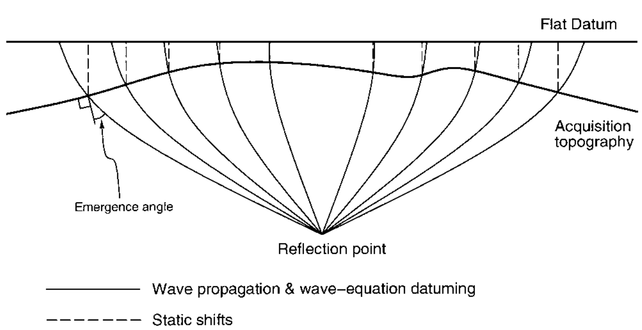

FIG. 1. Raypaths associated with wave-equation datuming (solid lines above topography), static shifts (dashed lines above topography) and wave propagation (solid lines below topography). The raypaths associated with static shifts do not honor Snell's law, and as emergence angle increases, they deviate significantly from the true raypaths. The raypaths associated with wave-equation datuming are an accurate continuation of the wave propagation raypaths at all emergence angles.

Synthetic examples

To provide insight as to how wave-equation datuming compares to static shift and for clarity of exposition, I will demonstrate a few concepts using zero-offset synthetic data.

The subsurface model for the synthetic data consists of an anticline, a syncline, and two point diffractors in a constant velocity medium of 2 km/s. Topography is modeled as a 200-m high cosine-shaped mountain (Figure 3). The result of zero-offset Kirchhoff modeling is shown in Figure 4. The effect of the topography is the creation of a low-frequency undulation that completely distorts the synthetic data.

Figure 5 is a comparison of static shift and wave-equation datuming applied to the synthetic data displayed in Figure 4. Although both methods unravel the topographic distortion, the curvature of the diffracted events is substantially different. This difference in curvature is a result of the inaccuracy of the static shift. In this situation, the assumption of vertical raypaths is invalid.

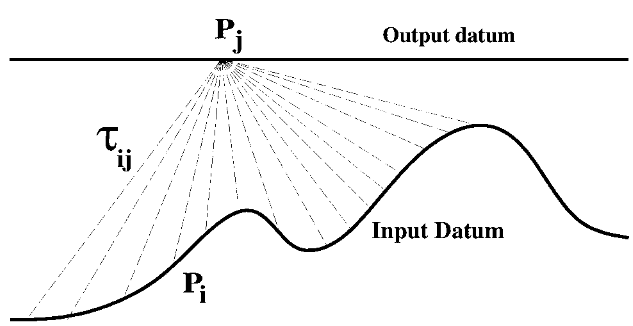

FIG. 2. Schematic representation of Kirchhoff upward continuation corresponding to implementation of equation (1). Each input trace P_i is filtered, time-shifted according to τ_{ij}, scaled, and summed into output trace P_j.

As mentioned earlier, detrimental effects occur when wave-based processing is applied after an inappropriate static shift. This is illustrated in the top two panels of Figure 6. In this case, time-migration has been applied after static shift downward in Figure 6a and after static shift upward in Figure 6b. In both cases, the static shift has distorted the data so badly that migration fails. A similar failure can be expected for any wave-based process applied to prestack data. In this case, I define *wave-based process* as any method that is built on the assumption that the data obey the wave equation. This includes methods such as normal-moveout (NMO) correction, dip-moveout (DMO) correction, NMO stack, prestack migration, and velocity analysis.

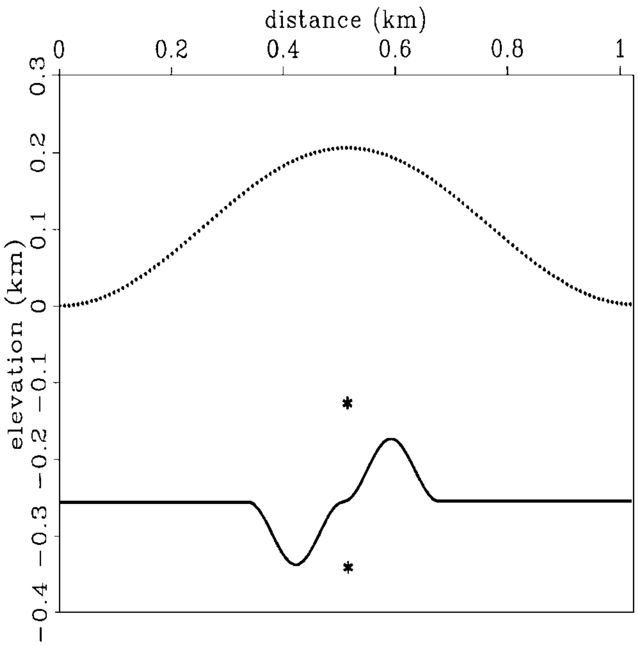

FIG. 3. Topography (dotted curve) and subsurface structure (solid curve) used to generate zero-offset synthetic data. The two point diffractors are depicted by asterisks above and below the anticline/syncline structure.

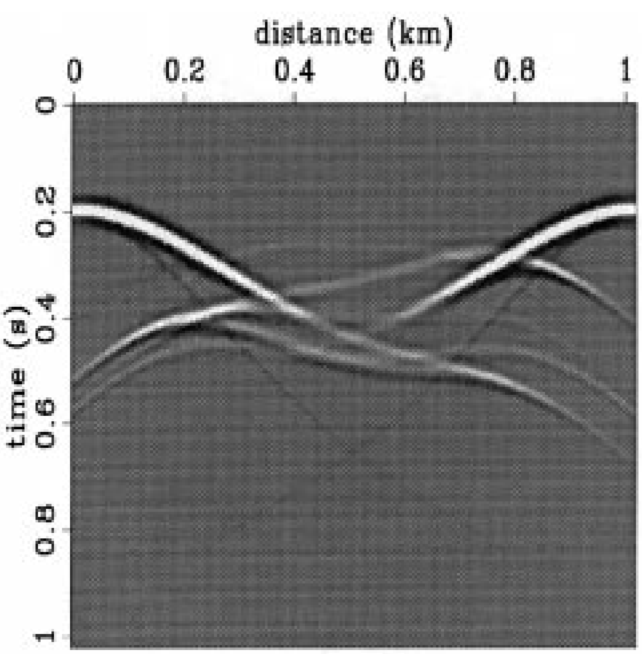

FIG. 4. Synthetic zero-offset data generated for the constant velocity model of Figure 3.

When the data are extrapolated to the flat datum by wave-equation datuming, the wavefield character of the data are preserved. This is demonstrated in the lower panels of Figure 6 where the data have been migrated after upward and downward continuation. Accurate images are formed in both cases.

CANADIAN OVERTHRUST EXAMPLE

The data set used for this study is a 2-D line acquired in the Canadian foothills. It has excellent signal quality and a very interesting complex structure. The similarity of nearby seismic lines, analysis of nearby wells, and success of 2-D prestack depth migration on nearby lines indicates that 3-D effects are minimal for this line.

Four representative shot gathers from the data set are plotted in Figure 7. There are 144 shots with 300 groups per shot. Shot and receiver spacing varies because of the rugged terrain, but the nearest offset is at 60 m, average shot spacing is 100 m, and average group spacing is 20 m. This results in 30 fold CMP coverage. The receiver spacing is fairly regular, but it does vary by up to 10 m. The shot spacing is less regular and varies from 20 to 250 m. This variable spacing can be readily accommodated with the Kirchhoff datuming implementation.

As shown in Figure 8, there is considerable topography along the line. The topography varies in excess of 200 m. That, coupled with the high near-surface velocities, makes this data set an excellent candidate for wave-equation datuming.

Upward continuing the shot gathers

The distortion of the raw shot gathers (Figure 7) caused by topography and near-surface effects can be broken down into two components: a high-frequency jitter and a low-frequency component associated with the topography. The high-frequency component can result from local velocity variations, surveying errors, or any other effects that often plague land data. Wave-equation datuming is only intended to remove the long wavelength effects of the topography. The high-frequency statics degrade the datuming result if they are not removed.

To compensate for the high-frequency component, I use static shifts computed with a commercial maximum power residual statics program. The effect of topography is compensated for during the residual statics calculation by applying elevation statics to the data. The residual statics are then applied to the original uncorrected gathers independent of the elevation statics.

Figures 9 and 10 show a shot gather before and after residual statics application. This shot spans an area approximately between CMP 500 and CMP 800, so it has significant topography along offset. Receiver elevation statics have been applied in Figure 11 to shift the data to the 1700 m datum. Most of the topographic distortion has now been removed from the events. However, as shown in Figure 12, the events have better lateral continuity after wave-equation datuming. Wave-equation datuming brings out events that were not visible or readily

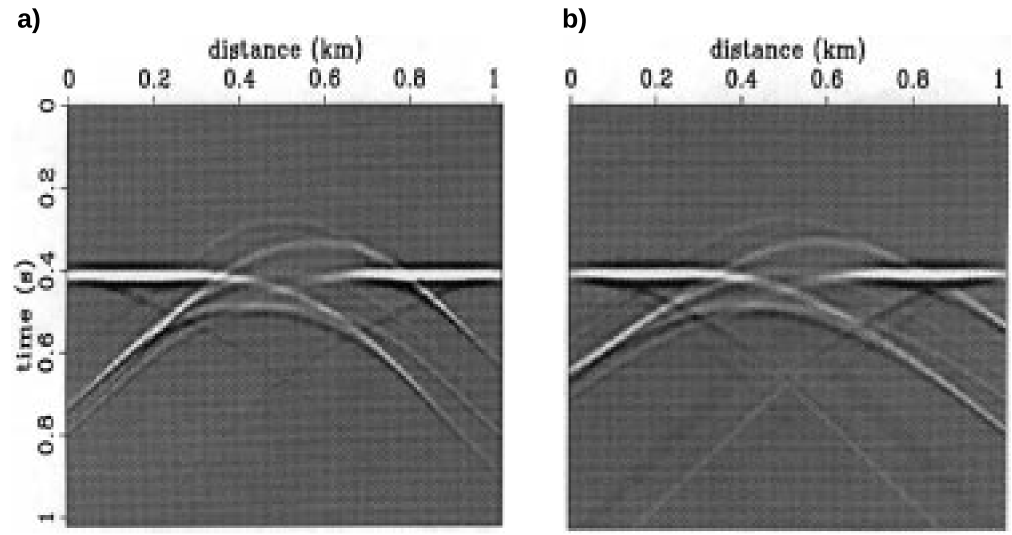

FIG. 5. (a) Static shift upward and (b) wave-equation datuming upward. The two processes produce events with differing curvature.

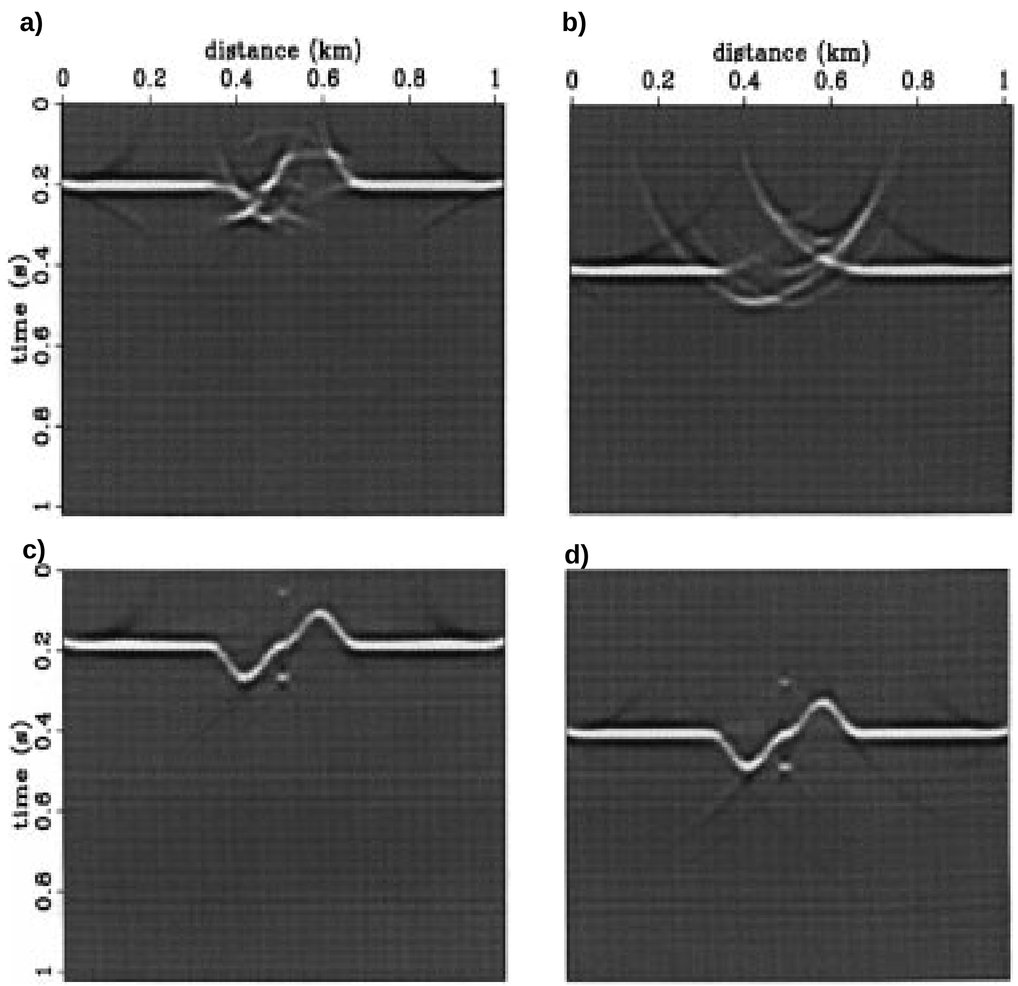

FIG. 6. (a) Static shift *downward* followed by time migration, and (b) static shift *upward* followed by time migration. The process of static shift distorts the wavefield so that migration fails. (c) Wave-equation datuming *downward* followed by time migration, and (d) wave-equation datuming *upward* followed by time migration. Wave-equation datuming preserves proper kinematics so that subsequent wave-based processing can be applied successfully.

detectable before, and it attenuates steeply dipping airwave and groundroll events.

So far, I have only applied elevation statics and datuming to the receivers alone. Application of the shot elevation static will not change the overall appearance of Figure 11, since it only involves a bulk shift of all the traces within the gather. To complete the datuming task, I upward continue the data in common receiver gathers.

Figure 13 shows the same gather after both common shot and receiver gathers have been upward continued to a regularly gridded output datum at elevation 1700 m. The shot gap has been filled in by the extrapolation operator. There is an area of weak reconstruction around offset −1500 m, where the original acquisition geometry has a substantial gap. It should be stressed that although wave-equation datuming does resample the data onto a regular grid, it does not solve the problems of irregular or insufficient sampling. The wave-equation–datumed gather shows numerous strong reflection events with good lateral continuity. There are many events present after datuming that were not identifiable before. The steep-dip and high-frequency noise has been removed by the datuming operation.

The applicability of wave-equation datuming is often limited when shots are spaced too far apart because the datuming operator may be aliased severely in the common receiver domain. Operator aliasing occurs for frequencies exceeding the spatial Nyquist sampling criteria:

$$f_{\text{max}} = \frac{1}{2(\partial t/\partial x)\Delta x}, \tag{2}$$

where the term $\partial t/\partial x$ is the spatial derivative of the datuming operator and Δx is the seismic trace spacing (Lumley et al.,

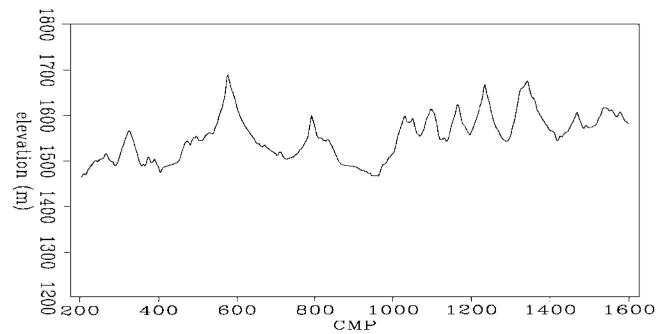

FIG. 8. Topography along the seismic line varies in excess of 200 m.

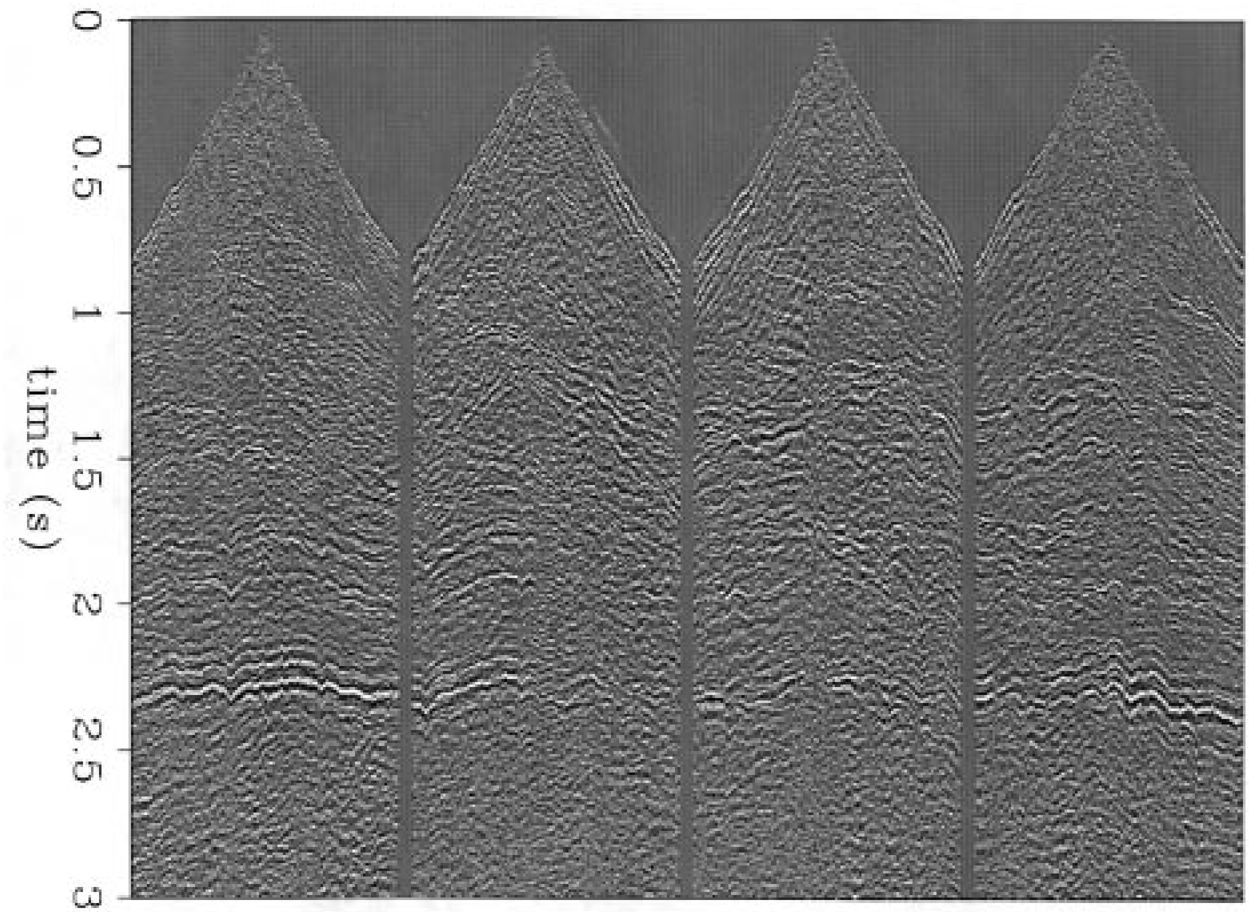

FIG. 7. Representative shot gathers from the Canadian overthrust data set. Distortions caused by topography and complex structure are evident.

1994). The maximum unaliased frequency $f_{\max}$ decreases as trace spacing and/or operator dip increase. Therefore, the best wave-equation datuming results are obtained when both sources and receivers are closely spaced at equal intervals, otherwise excessive low-pass filtering may be required to avoid operator aliasing. For the data shown here, shots are spaced, on average, at five times the receiver interval. Nonetheless, wave-equation datuming works well for this example. This is because of the fact that the propagation velocities are so fast that the data and the datuming operator are not aliased severely.

Figure 14 is a plot of the gathers from Figure 7 after wave-equation datuming the receivers to a datum elevation of 1700 m. In all cases, the application of wave-equation datuming results in well-behaved moveout trajectories. Most of the departure from hyperbolic moveout is now caused by the complex velocity structure rather than topographic and near-surface effects.

Stacking and migration

The complex structure apparent in this data set calls for prestack depth migration. This requires an accurate interval velocity model. This type of velocity model is usually obtained by integrating well information, geological information, interpreter input, and seismic information into the model building process. Subsequent migration velocity determination is then usually an iterative process involving techniques such as migration velocity analysis and tomography.

An early step in bringing seismic information into the model-building loop is to perform conventional velocity analysis and time migration. Wave-equation datuming is applied to data early in the processing flow, so in this section I will demonstrate its effectiveness in improving these early stages of imaging. Not only does wave-equation datuming transform data to a flat processing datum, but it can also regularize it onto an evenly sampled computational grid. This is useful for iterative migration velocity estimation because the fastest algorithms are usually optimized for regularly-sampled data.

Since this data is only 30 fold, conventional CMP velocity analysis is difficult because it is hard to pick the semblance peaks and to maintain geological consistency. As with many low-fold land data sets, a better strategy is to generate constant velocity stacks and to pick velocities where laterally continuous and geologically sensible reflection events stack coherently.

When this type of lateral continuity criteria is used to determine velocity using geological constraints, it is advantageous to stack with the data referenced to a flat processing datum. In this way, artificial structure is not introduced by the use of a floating datum. This process can be done using elevation statics, or wave-equation datuming. In Figures 15 through 18, I

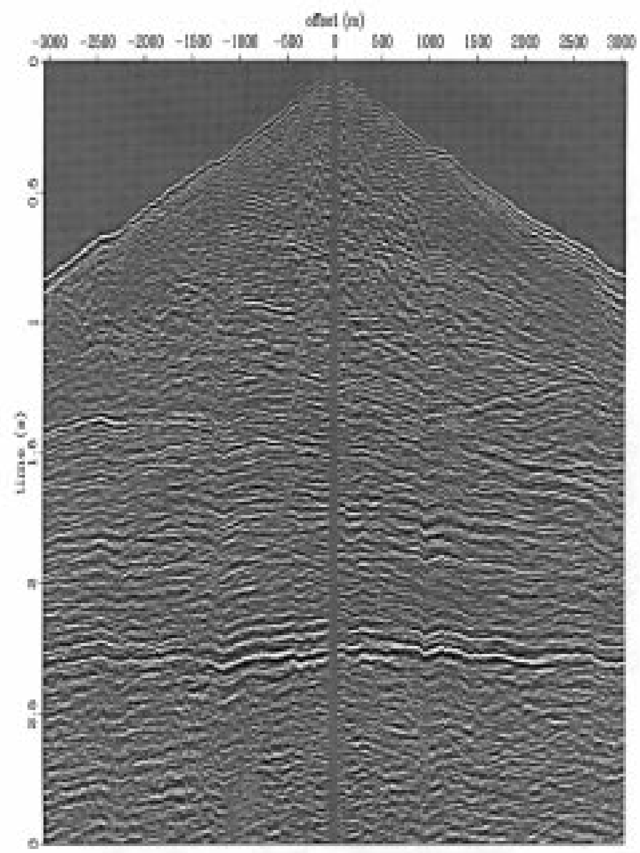

FIG. 9. A shot gather from the Canadian overthrust data. The effect of rugged acquisition topography can be seen throughout the gather, but it is especially evident in the first breaks and in the reflector at about 2.3 s.

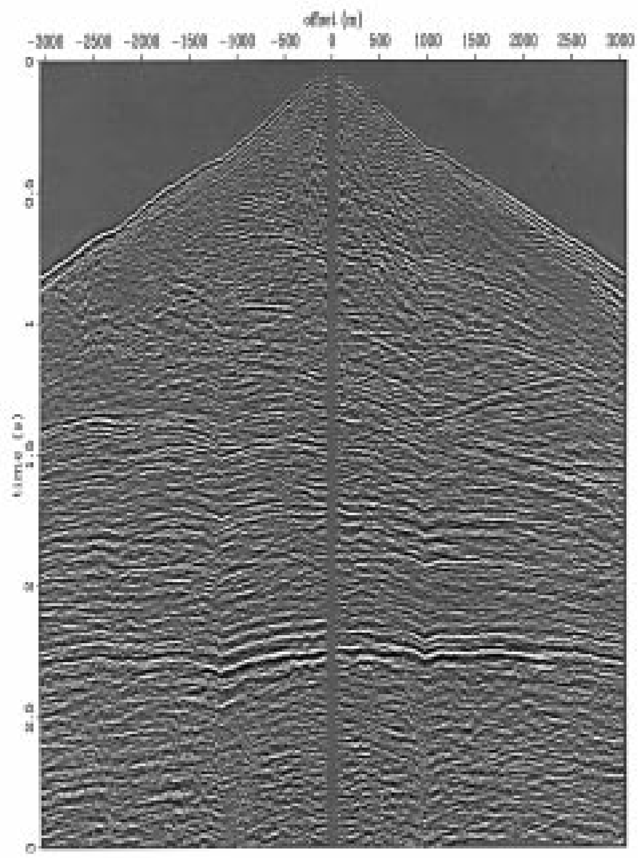

FIG. 10. The same shot gather as in Figure 9 after residual statics. The high spatial-frequency jitter has been reduced and events have better lateral continuity than in Figure 9.

will illustrate the superiority of wave-equation datuming for this task.

Figures 15 and 16 are the result of stacking the data after elevation statics and after wave-equation datuming using an approximate stacking velocity. The reflection event at about 2.5 s is the most prominent feature in the data. The stack displays better lateral continuity after wave-equation datuming (Figure 16) than after elevation statics (Figure 15). This is evident particularly between CMP 1000 and 1200 along the 2.5 s reflector. The dipping reflectors above 1 s and to the right of CMP 1300 are much better defined after wave-equation datuming than after static shift. Two other prominent features that look better after wave-equation datuming are the flat reflection event running across the section at about 2 s and the dipping event at about 1.5 s, running from CMP 200 to 500. The diffraction events in the middle of the stacked sections are harder to evaluate, but it is evident that there are more diffractions at early time in the wave-equation datumed stack.

After migration, the superiority of wave-equation datuming before stack over static shift becomes even more evident. The result of migration after static shift is displayed in Figure 17 and the result of migration after wave-equation datuming is displayed in Figure 18.

As before, better event continuity is preserved in Figure 18 after wave-equation datuming. The 2 s and 2.5 s reflectors running along the length of the section are more continuous, and the dipping events in the upper right-hand corner of the image are better imaged. The dipping event extending from CMP 200 to 500 is more continuous after datuming. In Figure 18, this event can be followed to CMP 1000 at 1.8 s where it pinches out. This interpretation could not be made confidently using the image in Figure 17.

The migration after static shift does not image the complex structures in the middle of the section as well as the migration after wave-equation datuming. The diffraction events in Figure 16 have collapsed to image the near-surface structure. One of the most prominent structural features that is imaged in Figure 18 is the dipping spoon-like event extending from coordinates (750, 1.2) to (950, 1.4). The whole structure in this region and above is fairly complex and is much better imaged in Figure 18 than in Figure 17.

Figure 18 is a good starting image that is much easier to interpret than Figure 17. Geological boundaries could be readily defined and used to build a preliminary interval velocity model that could then be further refined by prestack depth migration.

Better imaging of this data could be achieved by prestack migration or even by DMO before stack. However, the point here is to compare the effects of static shift and wave-equation datuming. The important point is that other than the datum

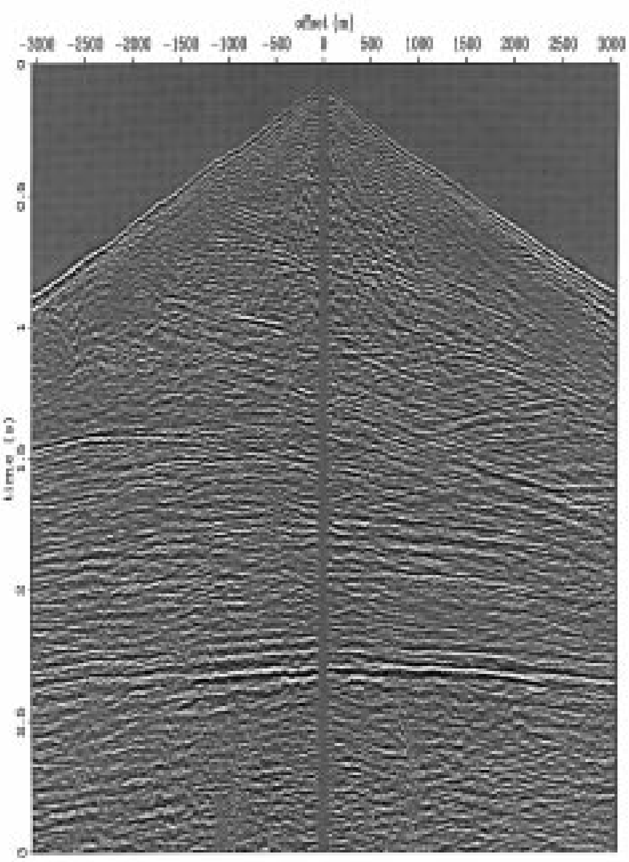

FIG. 11. The same shot gather as in Figure 9 after residual statics and receiver elevation statics.

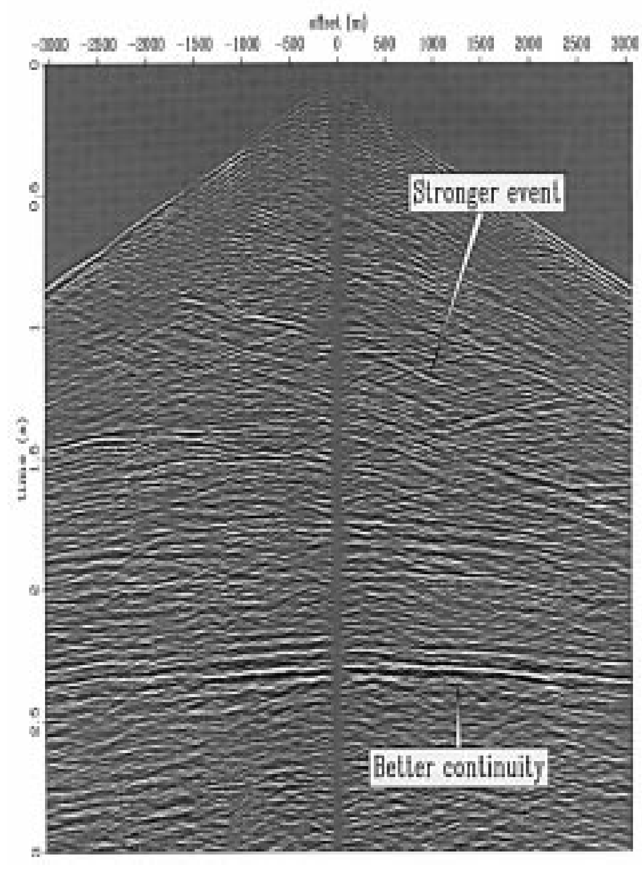

FIG. 12. The same shot gather as in Figure 9 after residual statics and wave-equation datuming. This result displays better lateral event continuity than Figure 11. Events are stronger, and there are more coherent events, especially at early times. Wave-equation datuming fills the shot gap, but in this display the shot gap has been zeroed so as not to detract from comparisons with Figure 11.

correction step, both images in Figure 17 and 18 went through the same processing flow.

CONCLUSIONS

Wave-equation datuming cannot replace statics in all applications, and it is not a panacea to be applied under all circumstances. Under certain conditions, when topographic relief is substantial and when the assumption of large static shifts is invalid, it is the most accurate and appropriate method of datuming. This can be very helpful in the early stages of data processing when not much is known about the geological structure and the subsurface velocity distribution.

Datuming is applied early in the processing flow, and it will affect all subsequent processing. Proper datuming to a flat surface is crucial for algorithms that assume hyperbolic form, such as velocity analysis. It is also advantageous because the most efficient DMO and migration algorithms assume a flat, regularly sampled processing datum. Since the datuming velocity is known, it can be incorporated into the prestack migration velocity field so that when the data are migrated from the flat datum, the effect of the datuming is counteracted.

In the example I presented here, I show that upward continuing the data to a flat regularly sampled processing datum with Kirchhoff datuming is superior to elevation statics. It offers a relatively painless way of obtaining a preliminary structural image that does not require a detailed knowledge of the subsurface velocity distribution. This is because stacking and migration velocities are more accurately and easily determined without the unnecessary complication of nonhyperbolic distortion, which would arise if the data were processed from the topography or after elevation statics.

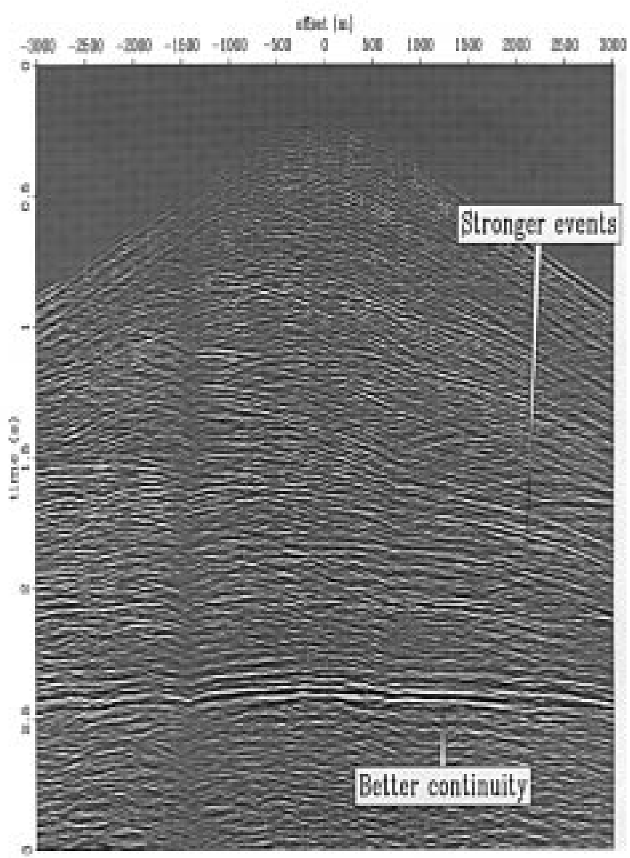

FIG. 13. The same shot gather as in Figure 9 after residual statics and wave-equation datuming of shot and receiver gathers. The shot gap has been filled, and there are more coherent events than in Figure 12.

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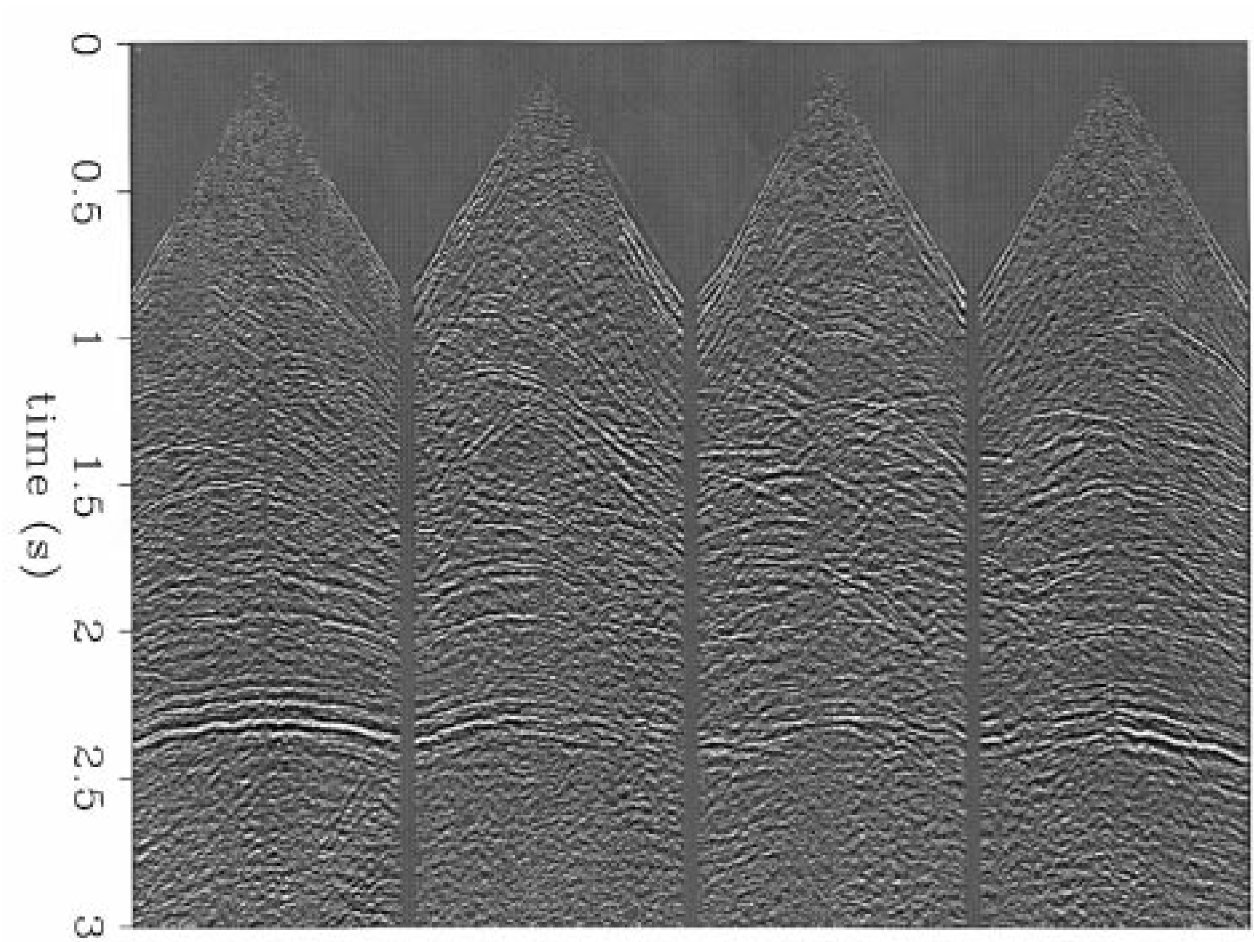

FIG. 14. The shot gathers from Figure 7 after residual statics and wave-equation datuming of the receivers to a flat datum. The topographic distortions have been removed.

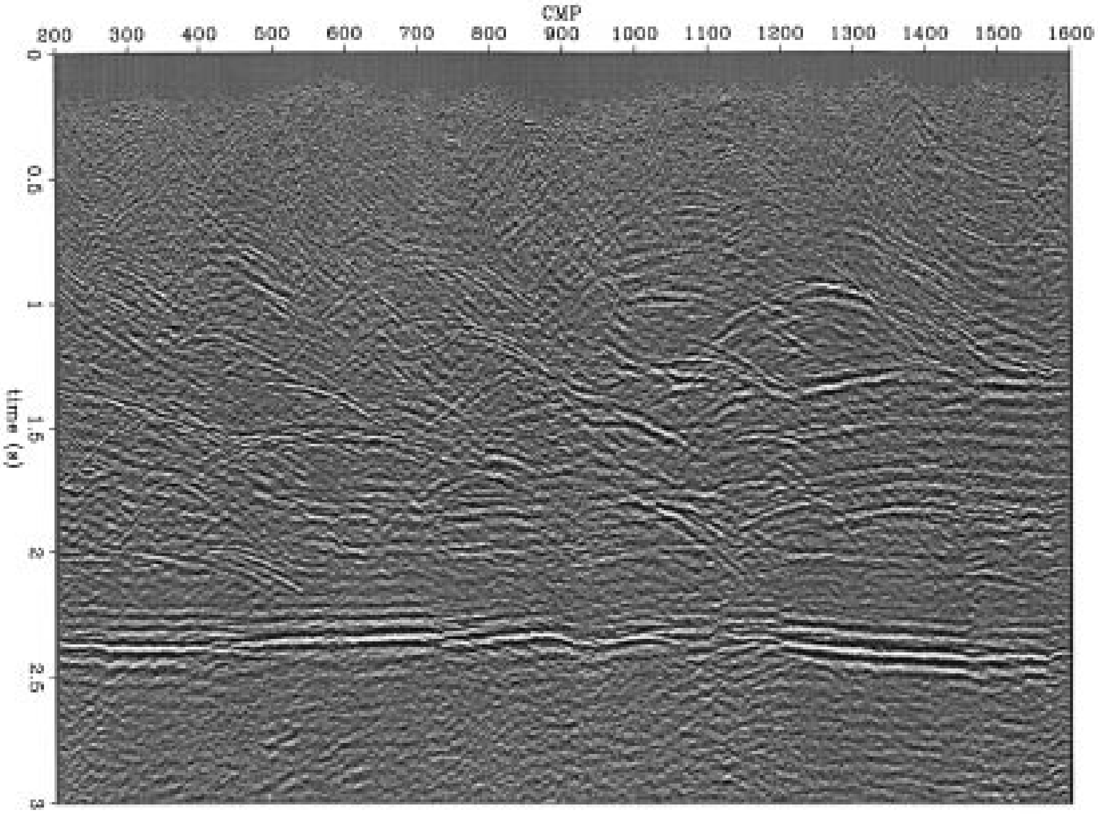

FIG. 15. NMO and stack after residual statics and elevation statics.

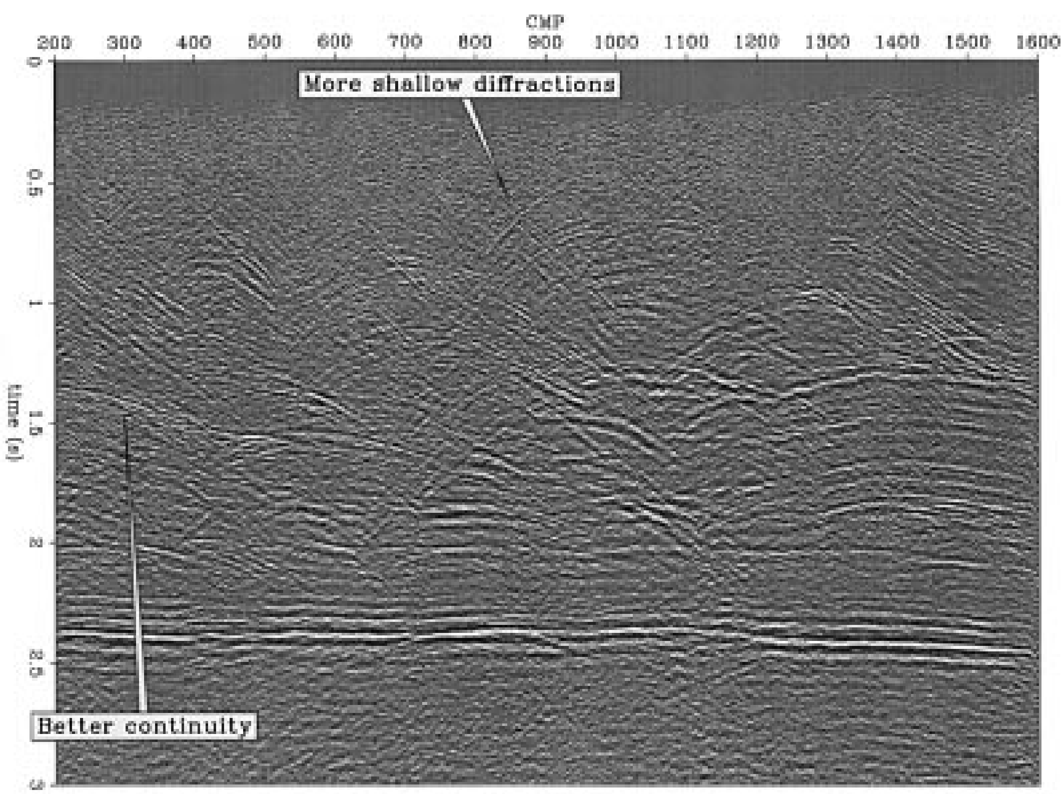

FIG. 16. NMO and stack after residual statics and wave-equation datuming.

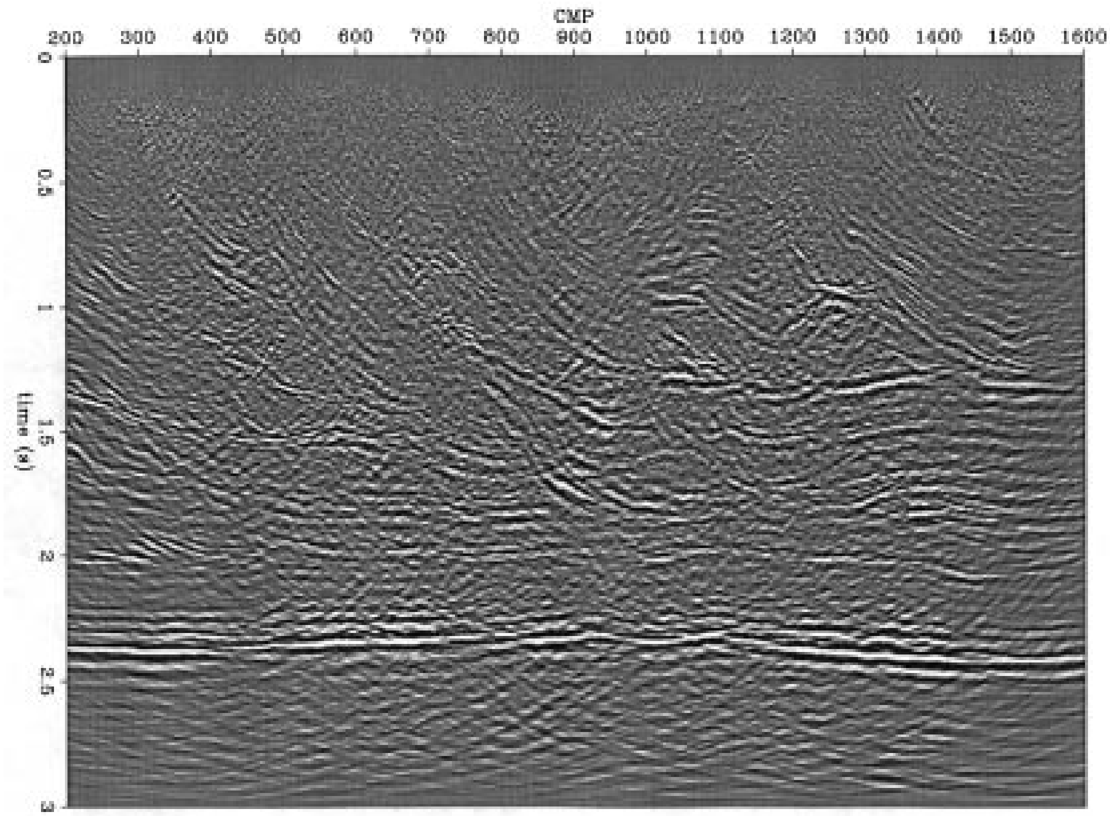

FIG. 17. Time migration after residual statics, elevation statics, NMO, and stack.

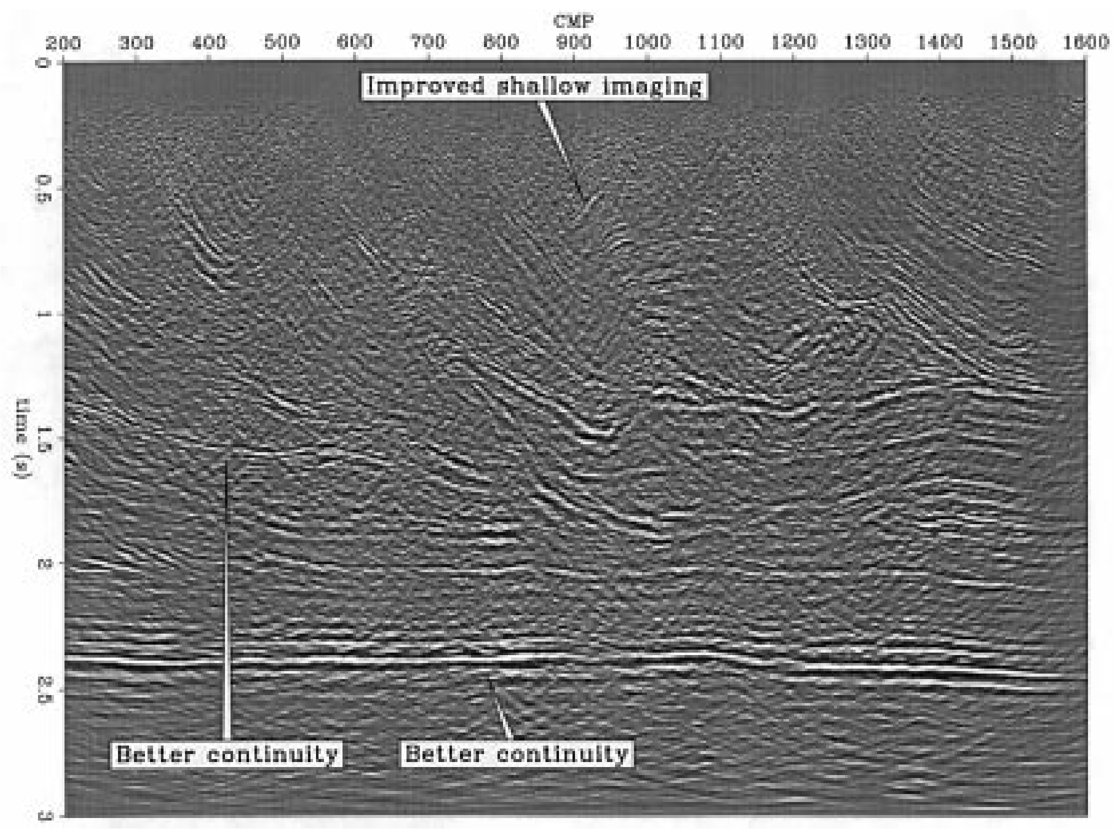

FIG. 18. Time migration after residual statics, wave-equation datuming, NMO, and stack.