Chapter 3

Rugged Topography

Wave-equation datuming overcomes several of the problems that seismic data recorded on rugged surface topography presents to routine image processing. The main problems are that standard, optimized migration and processing algorithms assume data are recorded on a flat surface, and that the static correction routinely applied to compensate for topography is inaccurate for waves that do not propagate vertically. Common-midpoint (CMP) velocity analysis and migration velocity analysis after static shift can be severely affected by the non-hyperbolic character of the reflections. In this chapter, I show how to alleviate these problems by applying wave-equation datuming to upward continue the data with a known velocity and process the data from a flat datum.

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 providing the best possible image. Even when good quality data are recorded in these terrains, the processing challenges that arise due to topography, the presence of high-velocity rocks near the surface, and complex subsurface velocity can impede conventional processing and subsequent interpretation.

The distorting effects of rugged topography are a serious problem in mountainous overthrust regions and wave-equation datuming provides a useful method of transforming data to a planar datum and determining the sub-surface velocity structure. The datuming eliminates the distortion caused by the topography and allows standard wave-based processing methods such as velocity analysis and migration to be applied efficiently.

The role of wave-equation datuming in land data applications has not been established; however, the new concept that I present in this chapter is my definition of where wave-equation datuming fits into the processing flow and how it can be used to improve velocity estimation and imaging. I apply wave-equation datuming to an overthrust data set from the Canadian Rockies and show how the process provides a clear improvement over conventional statics processing. I show how wave-equation datuming transforms the data to a regular grid and how velocity estimation and imaging is improved. Because the data are regrided onto a flat datum, further processing is streamlined and structural interpretations are easier to incorporate into the analysis.

3.1 Processing and imaging overthrust data with rugged topography

In this section I give an overview of processing overthrust data with rugged topography. I describe what is commonly done and where wave-equation datuming fits in the process. I also describe related work in the area of wave-equation datuming and migration from topography.

3.1.1 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 towards 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, but during processing, data are often corrected to a local floating datum which is CMP consistent rather than to a final output datum. This is done to minimize nonhyperbolic distortions caused by static shift. When the assumption of vertical raypaths 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 by Tilander and Mitchel, 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 trajectory 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 layer, the refraction model often does not match the geologic reality of mountainous terrain (Bevc, 1991). Although useful near-surface information may be gleaned from refraction analysis, it is 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.

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. When there is significant noise in the data, which does not support the wave equation, it may be safer to rely on statics and stacking to improve the image rather than try to "force" a solution with wave-equation datuming. However, when the data quality is adequate, the incorporation of wave-equation datuming into the processing flow can offer significant benefits.

3.1.2 Related work on rugged topography and wave-equation datuming

Wiggins (1984) and Reshef (1991) implicitly include effects due to topography in their migration algorithms. Wiggins uses a Kirchhoff formulation to directly incorporate topography in prestack migration from a nonflat surface. Reshef's phase-shift migration method is also used to directly migrate data. 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 nonflat 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. Not only is the static shift required before the migration, but this technique cannot be applied to the computationally attractive phase-shift algorithms, because it includes the nonphysical characteristic of zero velocity. In order for all of the above methods to work, the velocity must be known. The more general and problematic situation is one for which the velocity structure is unknown. 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 to the data.

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. They use 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 error associated with the refraction velocity and layer determination. Their final results show some ungeological features that were determined by the refraction analysis. In particular, their refraction model shows an unintuitive thickening of the low-velocity layer over a topographic high. This thickening often occurs because tunneling or diving waves are misidentified as refracted arrivals (Bevc, 1991). In portions of their final stack that correspond to topographic highs, static shift produces a better result than wave-equation datuming.

3.2 Static shift vs. wave-equation datuming

The industry-standard method of redatuming is to perform static shifts of data traces. This is adequate when the near-surface raypaths are nearly vertical or when the shifts are small. The static shift method is commonly applied to correct for near-surface velocity variations due to weathering layers and for topographic effects. 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.

The problem with many land data sets is that the topography distorts the data so much that it is not possible to pick coherent reflection events or to estimate velocity. In these situations, wave-equation datuming is necessary.

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 due to 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. 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.

3.2.1 Synthetic examples

The real data examples in this chapter will involve prestack datuming, but 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 the zero-offset synthetic data from

Chapter 2.

Figure 3.1 is a comparison of static shift and wave-equation datuming applied to the same synthetic data displayed in Figure 2.7. Although both methods unravel the topographic distortion, the curvature of the diffracted events is substantially different. This difference in curvature is due to the inaccuracy of the static shift; in this situation the assumption of vertical raypaths is invalid.

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 3.2. In this case, time-migration has been applied after static shift downward in Figure 3.2a and after static shift upward in Figure 3.2b. 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 which is built on the assumption that the data obey the wave equation. This includes methods such as normal-moveout correction (NMO), dip-moveout correction (DMO), NMO stack, prestack migration, and velocity analysis. This may partially explain the common observation that DMO applied to overthrust data often has detrimental effects (Tilander and Mitchel, 1995; Burke and Knapp, 1995).

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 3.2 where the data have been migrated after upward and downward continuation. Accurate images are formed in both cases.

3.3 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 3.3. 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. Figure 3.4 is a representative plot of receiver interval for one shot gather, and Figure 3.5 is a plot of shot spacing for the

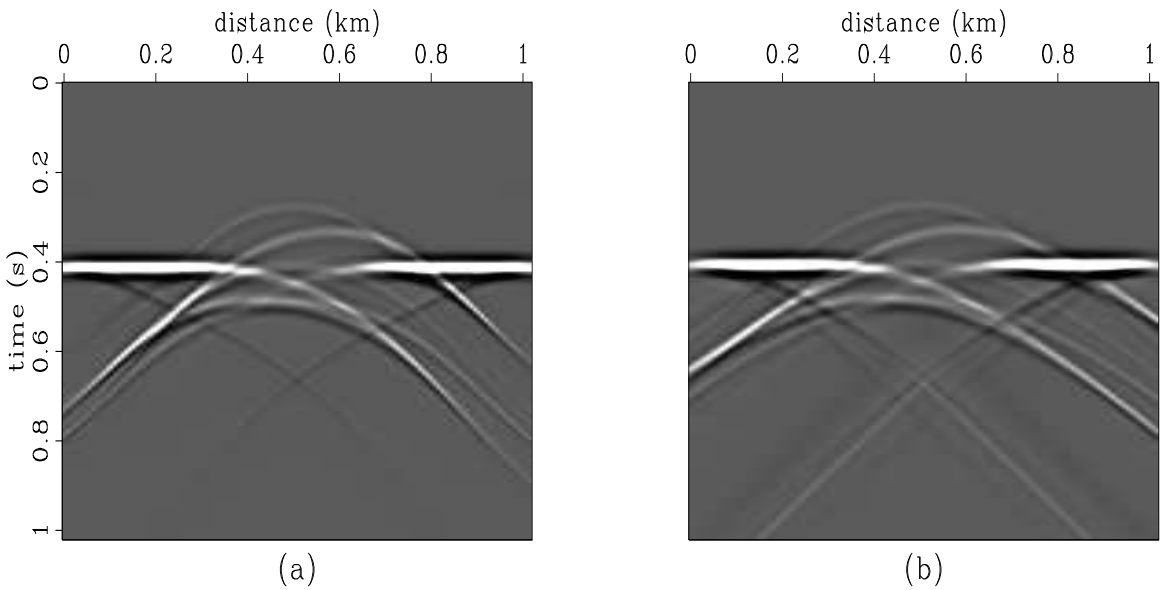

FIG. 3.1. (a) Static shift upward and (b) wave-equation datuming upward. The two processes result in events with differing curvature. Panel b is the same as Figure 2.7b and is reproduced here for ease of comparison. Topo-statdat [CR]

entire line. The receiver spacing is fairly regular, but the shot spacing is more variable.

As shown in Figure 3.6, 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.

3.3.1 Upward continuing the shot gathers

The distortion of the raw shot gathers (Figure 3.3) due to 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 be due to 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 take care of the high-frequency component, I shift the data statically using the result of a commercial maximum power residual statics program[1]. The residual statics solution is then applied to the data. In general, this process may have to be iterated,

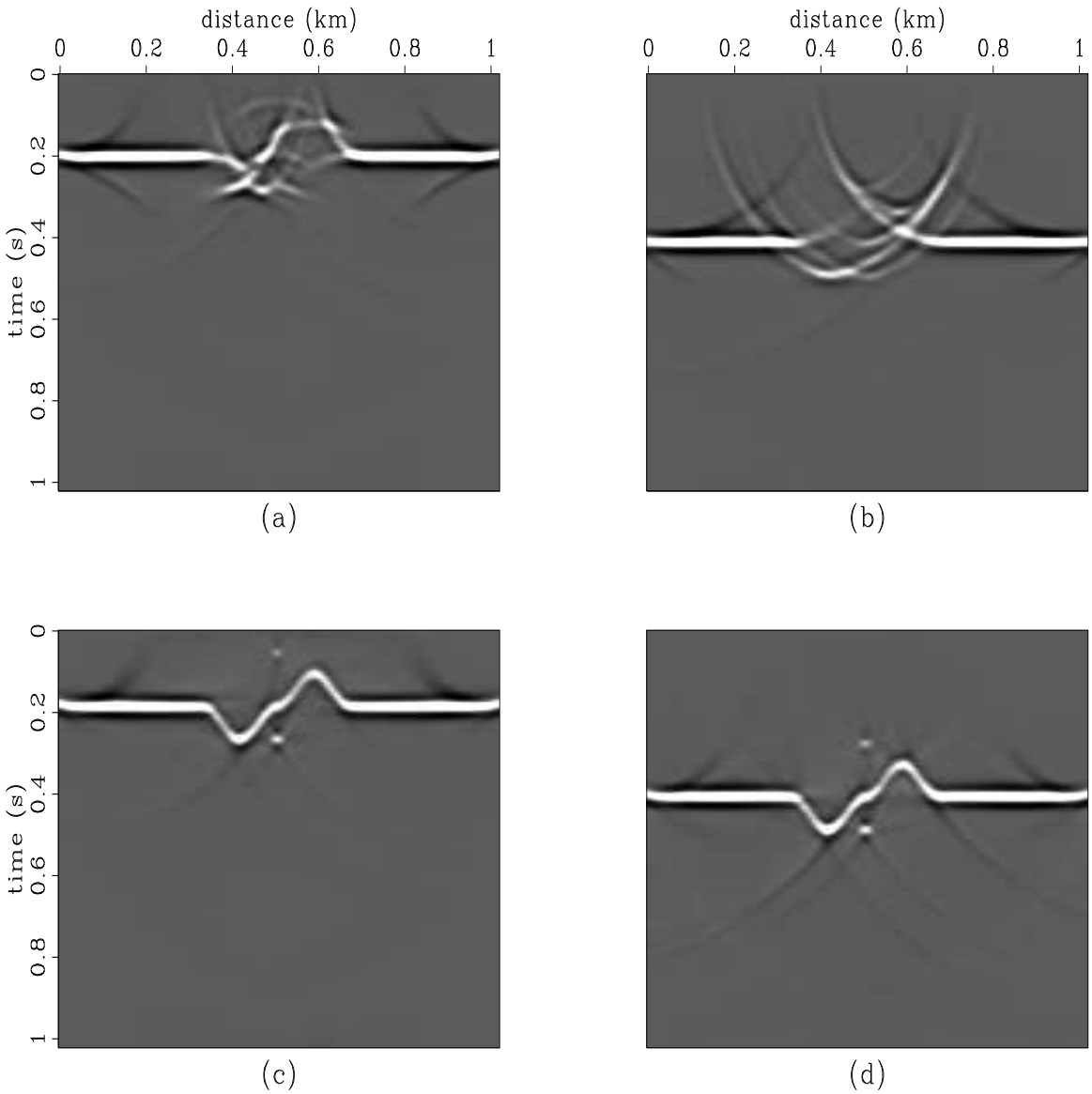

FIG. 3.2. (a) Static shift downward followed by time migration, and (b) static shift upward followed by time migration. The process of static shift distorts the wavefield so that migration fails. (c) Wave-equation datuming downward followed by time migration, and (d) wave-equation datuming upward followed by time migration. Wave-equation datuming preserves the proper kinematics so that subsequent wave-based processing can be successfully applied. Panels c and d are the same as Figures 2.11b and 2.9b and are reproduced here for ease of comparison. Topo-sdmig [CR]

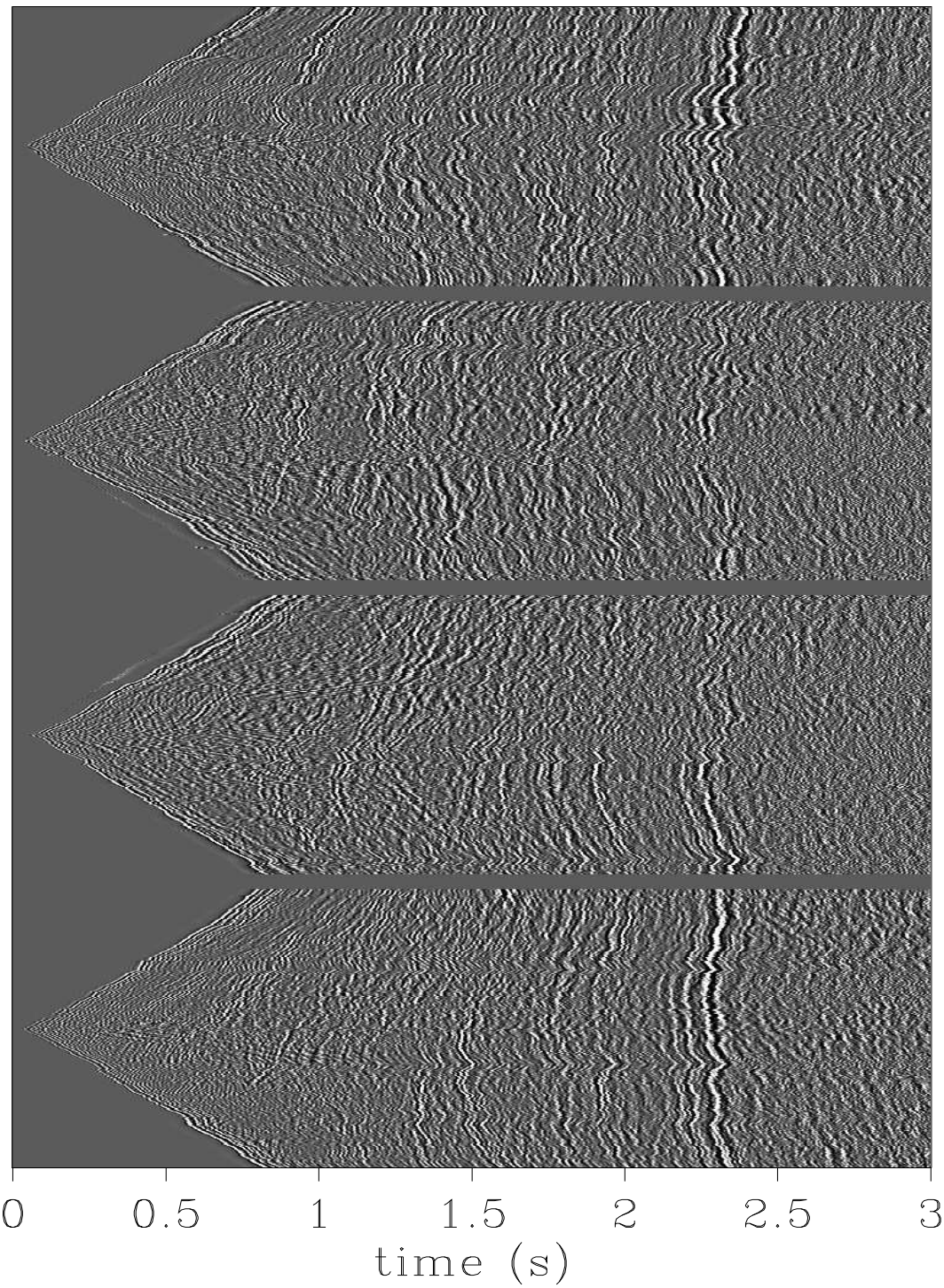

FIG. 3.3. Representative shot gathers from the Canadian overthrust data set Topo-rawshots [R]

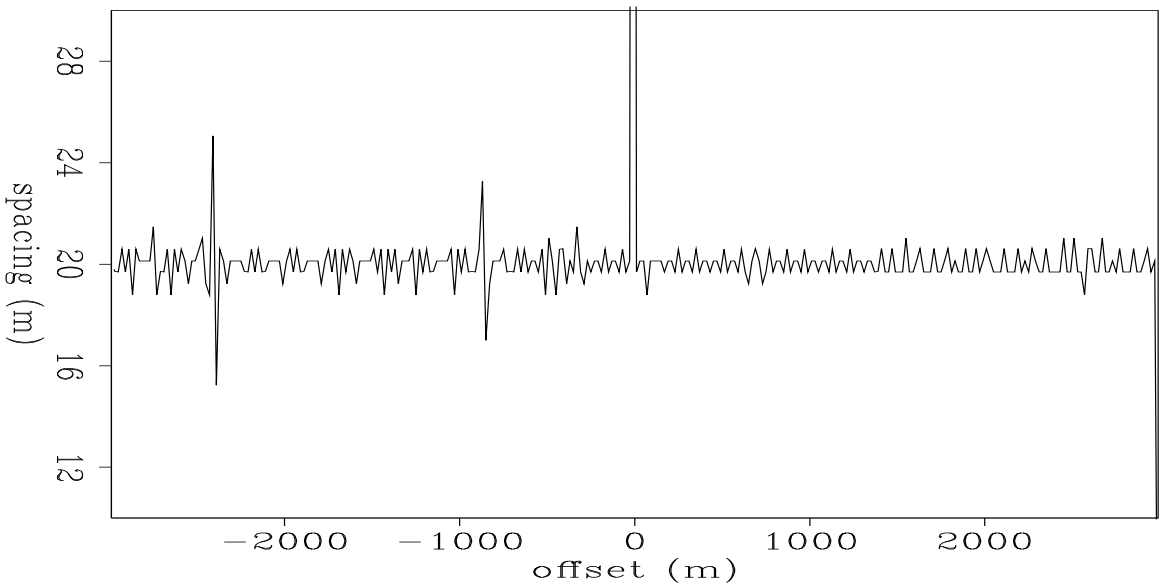

FIG. 3.4. Receiver interval along the seismic line is fairly constant. This representative plot is for shot number 50, and is typical for the line. Topo-gxdiff [R]

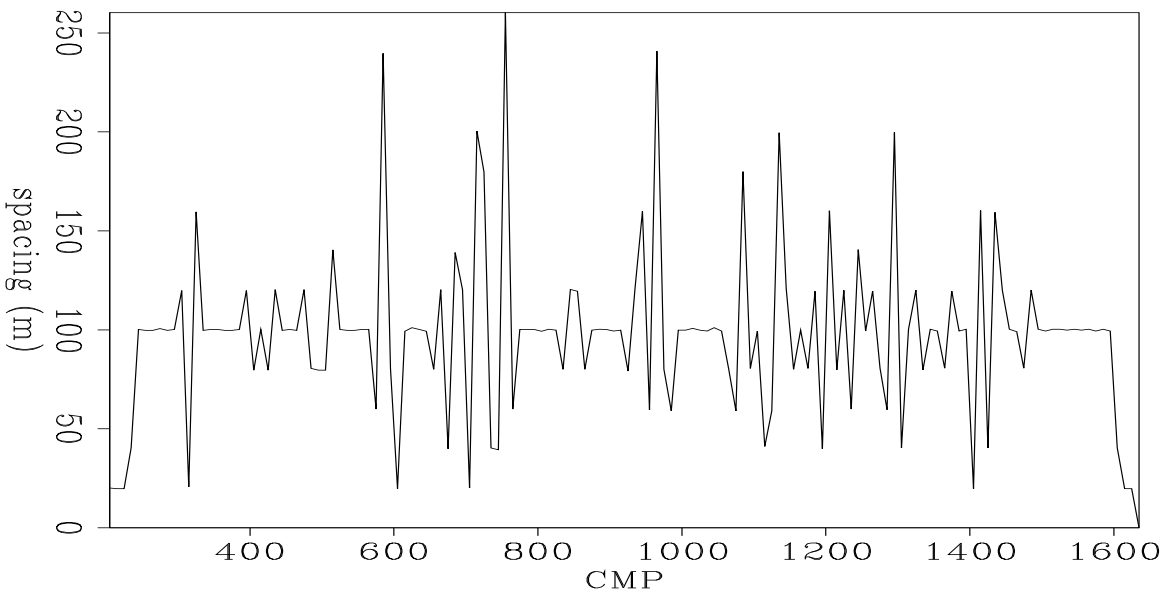

FIG. 3.5. Source interval along the seismic line is variable. Topo-sxdiff [R]

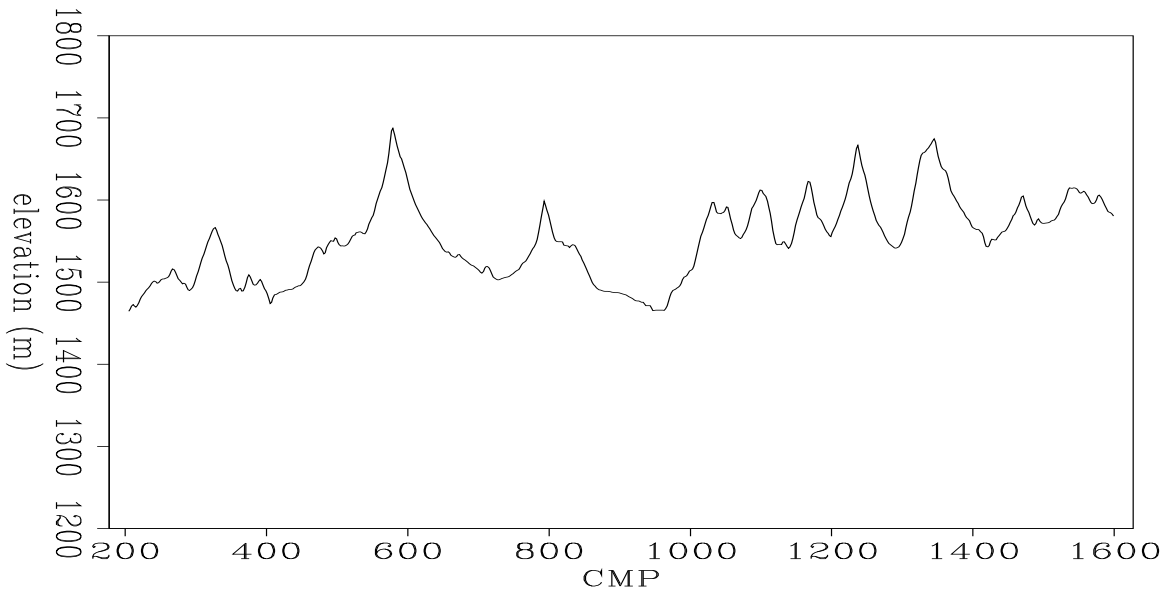

FIG. 3.6. Topography along the seismic line varies in excess of 200 m. Topo-cdpelev [R]

depending on the data and the statics solution.

Figure 3.7a shows the first shot gather from the overthrust data set. The residual statics correction has been applied in Figure 3.7b. The data now look much more continuous, but the long wavelength distortion is still pronounced. Figure 3.7c is the result of applying wave-equation datuming to the static-corrected gather. The receivers are now at the final output datum elevation of 1700 m.

Figures 3.8 and 3.9 show shot number 53 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 3.10 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 3.11, the events have better lateral continuity after wave-equation datuming. Wave-equation datuming also brings out events which were not visible, or not readily detectable before.

Another benefit of wave-equation datuming is seen in this example. There are some steep-dip noise events on the inner offsets of the original and static corrected gathers. Evidently, the array design of this survey was adequate to suppress most of this noise, but

[1]The residual statics solution was generated by Christof Stork of Advance Geophysical Co. using ProMAX software.

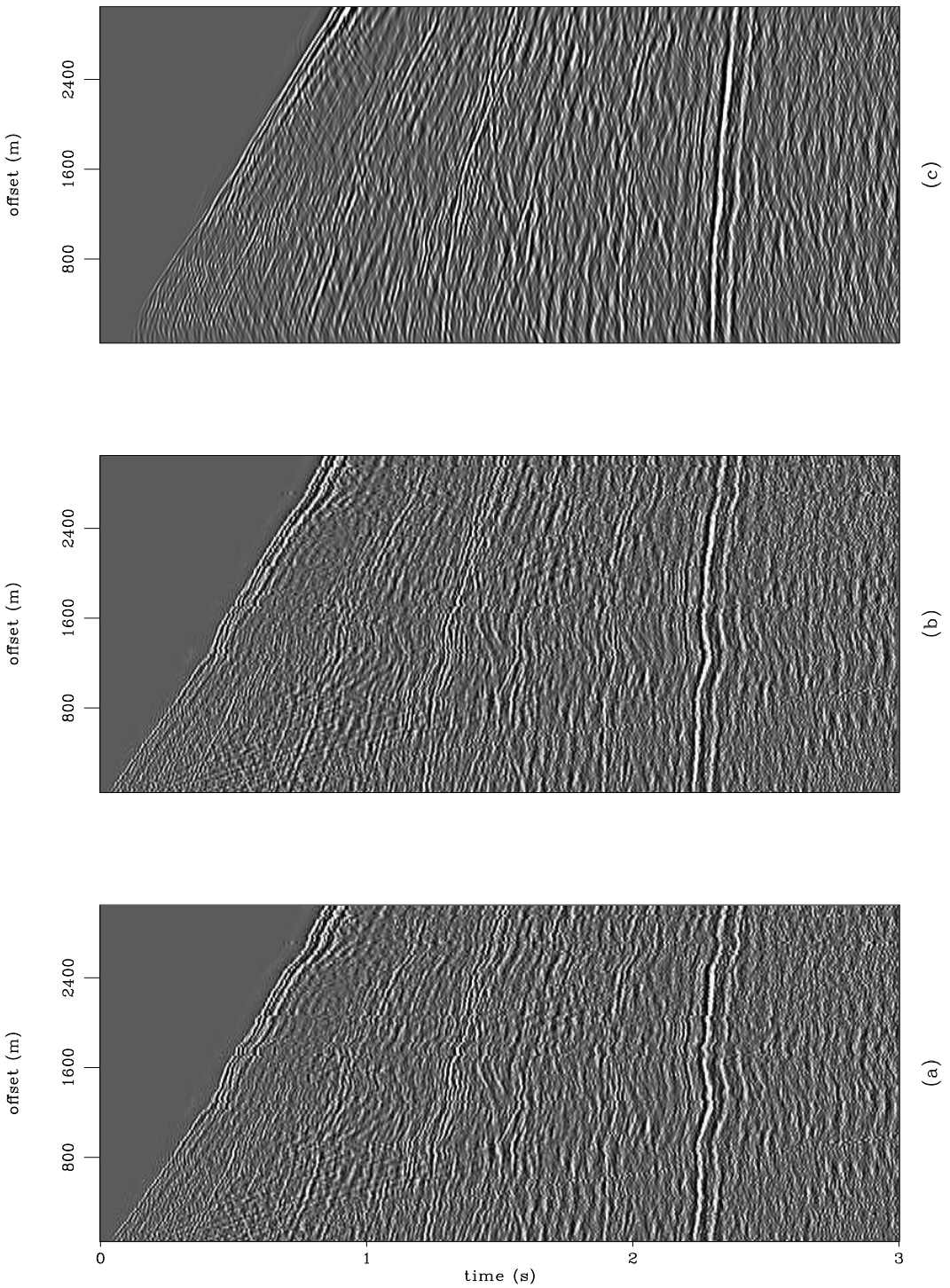

FIG. 3.7. First shot gather from the Canadian overthrust data set. (a) Raw gather, (b) residual statics applied, (c) wave-equation datuming applied. Movie. Topo-shotseq1 [CR]

on some land data sets it can be a significant problem. After wave-equation datuming, the steep-dip noise events have been eliminated because wave-equation datuming implicitly removes events that have dip angles which exceed those that can be reconstructed with a given extrapolation velocity.

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 3.10, since it only involves a bulk shift of all the traces within the gather. To complete the redatuming task, I upward continue the data in common receiver gathers as outlined in Chapter 2.

Figure 3.12 shows shot gather 53 after both common shot and receiver gathers have been upward continued to a regularly grided 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. 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 also been removed by the datuming operation.

The best wave-equation datuming results are usually obtained when both sources and receivers are closely spaced at equal intervals. In this case, shots are spaced, on average, at five times the receiver interval. Nonetheless, wave-equation datuming works well for this example. This is due to the fact that the propagation velocities are so fast that the data are not severely aliased, if at all. The issue of under-sampled shot spacing becomes detrimental to wave-equation datuming when propagation velocities are slow and when there is substantial moveout.

I will demonstrate in the next section that working with the wave-equation datumed gathers offers a distinct advantage for subsequent wave-based operations such as stacking and migration.

Figure 3.13 is a plot of the gathers from Figure 3.3 after wave-equation datuming 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 due to the complex velocity structure rather than to topographic and near-surface effects.

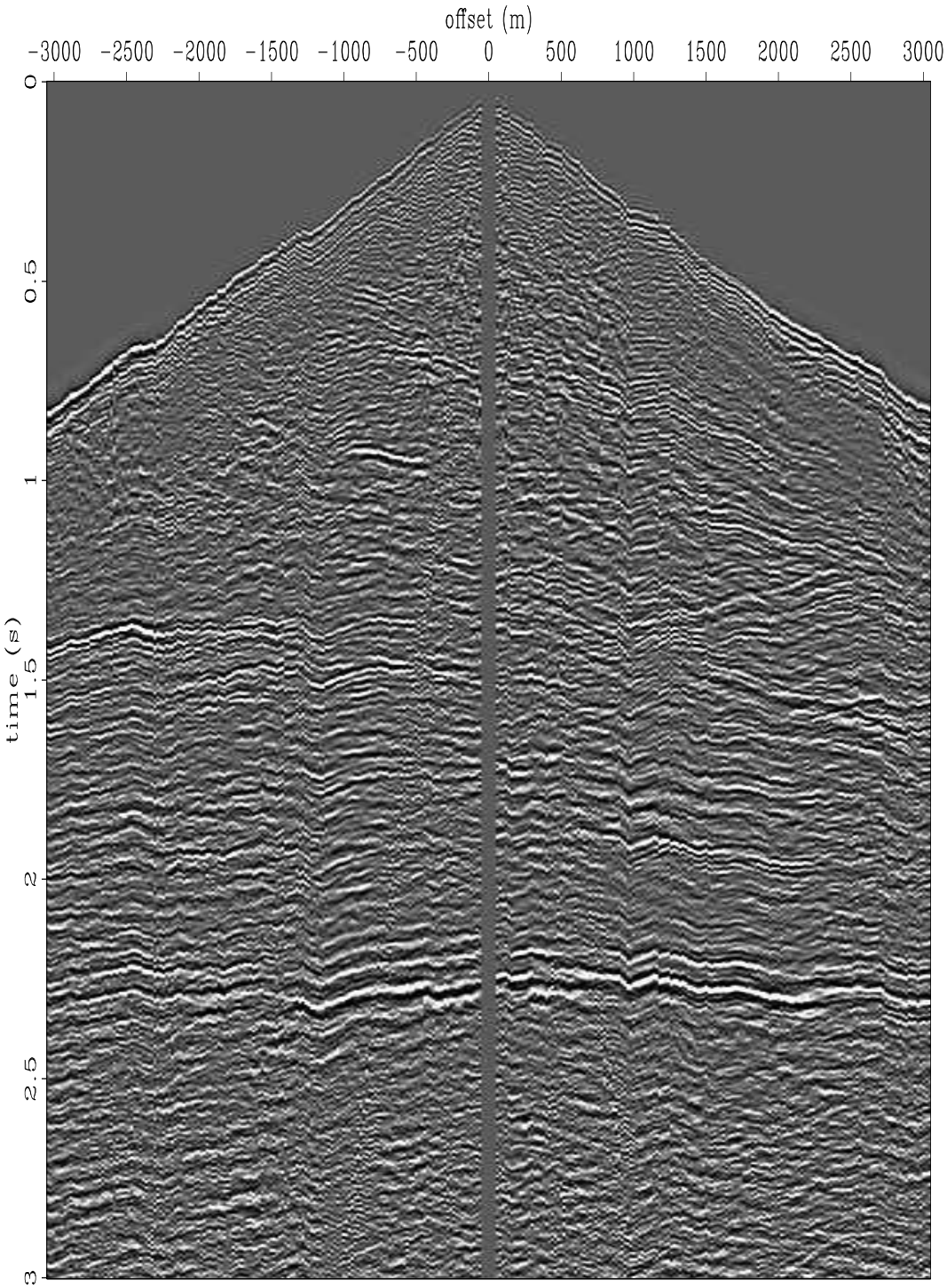

FIG. 3.8. Shot gather 53 from the Canadian overthrust data. Topo-shot.52 [R]

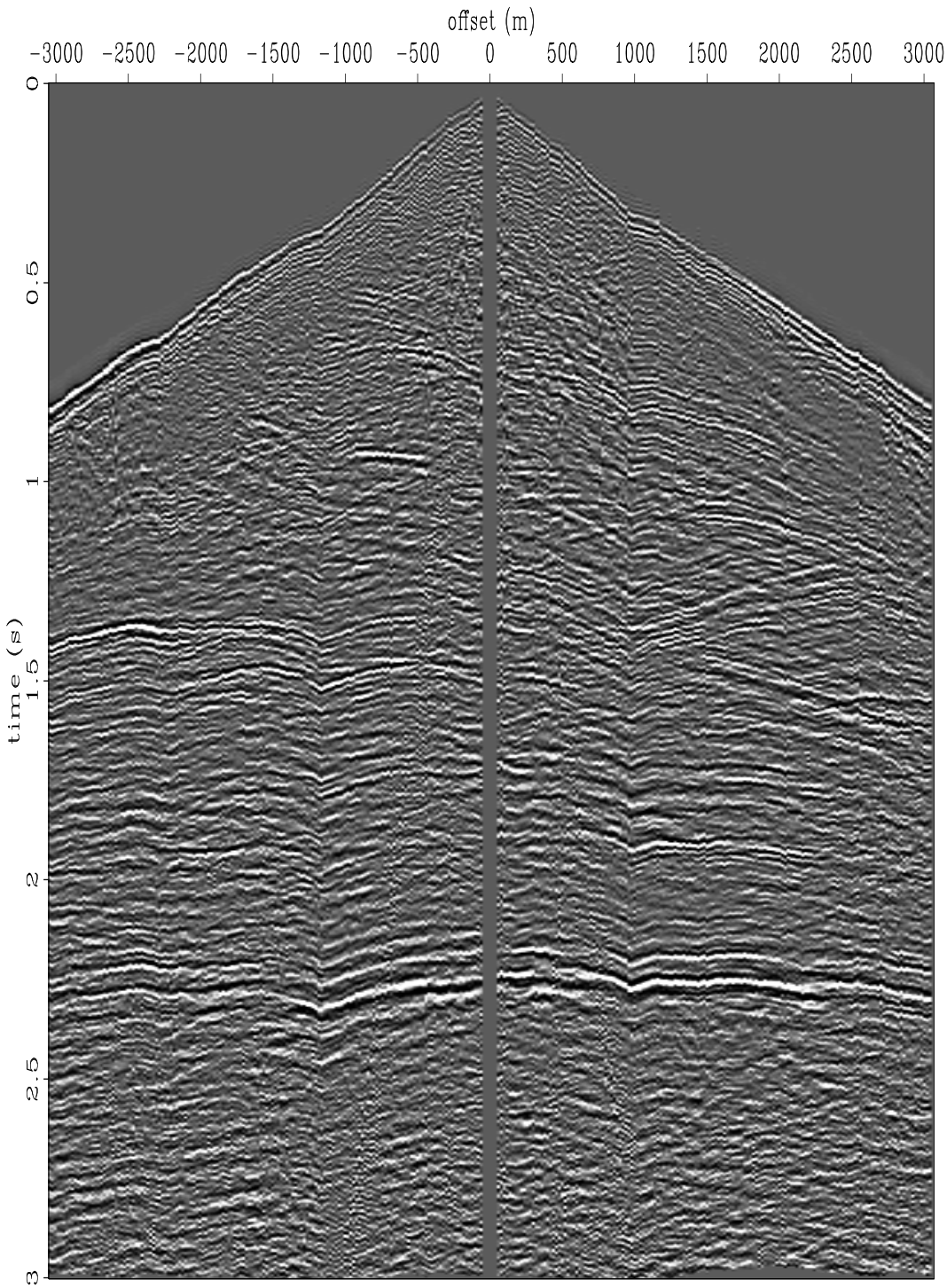

FIG. 3.9. Shot gather 53 after residual statics. Movie. Topo-resid.52 [CR]

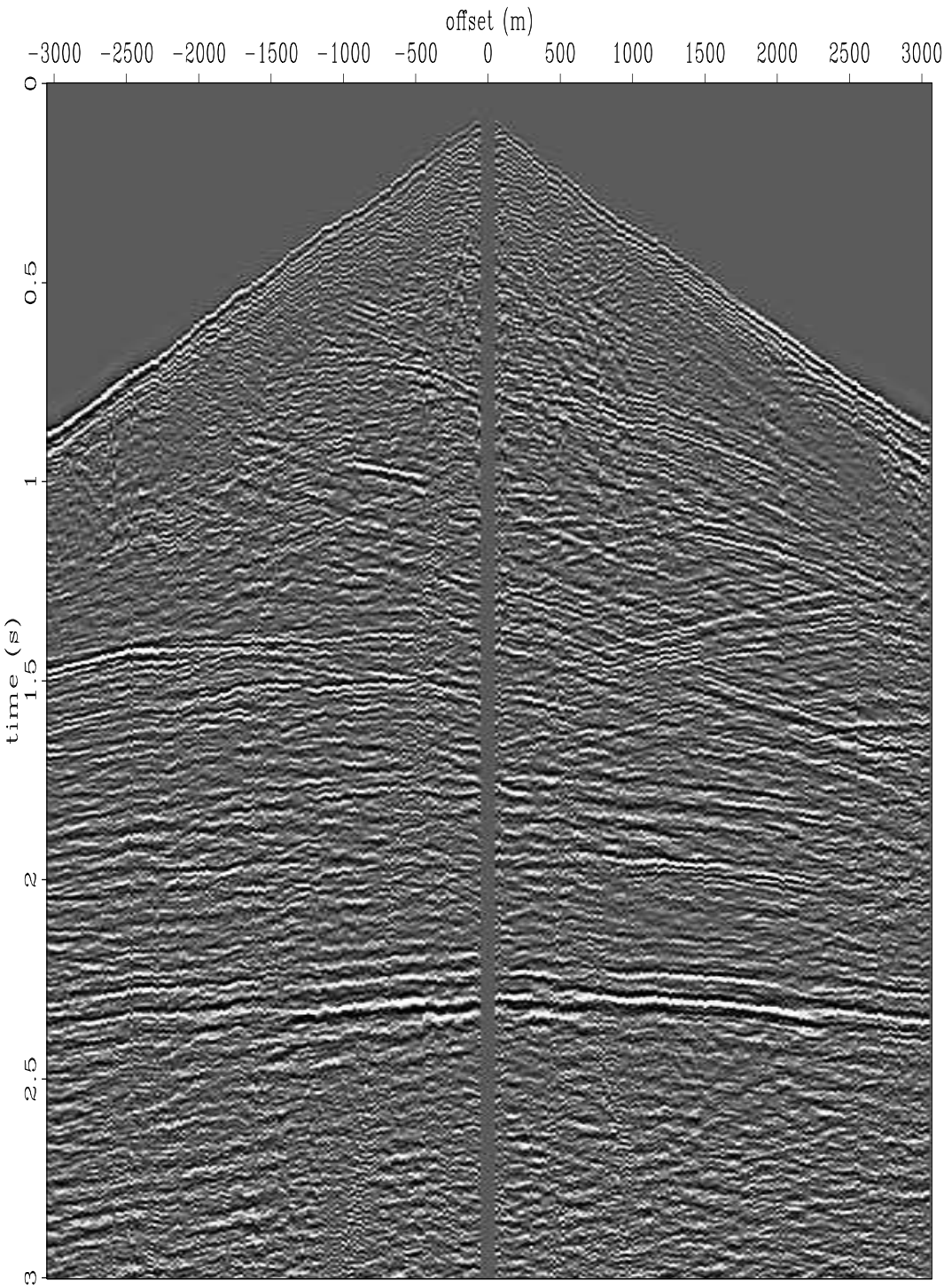

FIG. 3.10. Shot gather 53 after residual and elevation statics. Movie. Topo-elvstat.52 [CR]

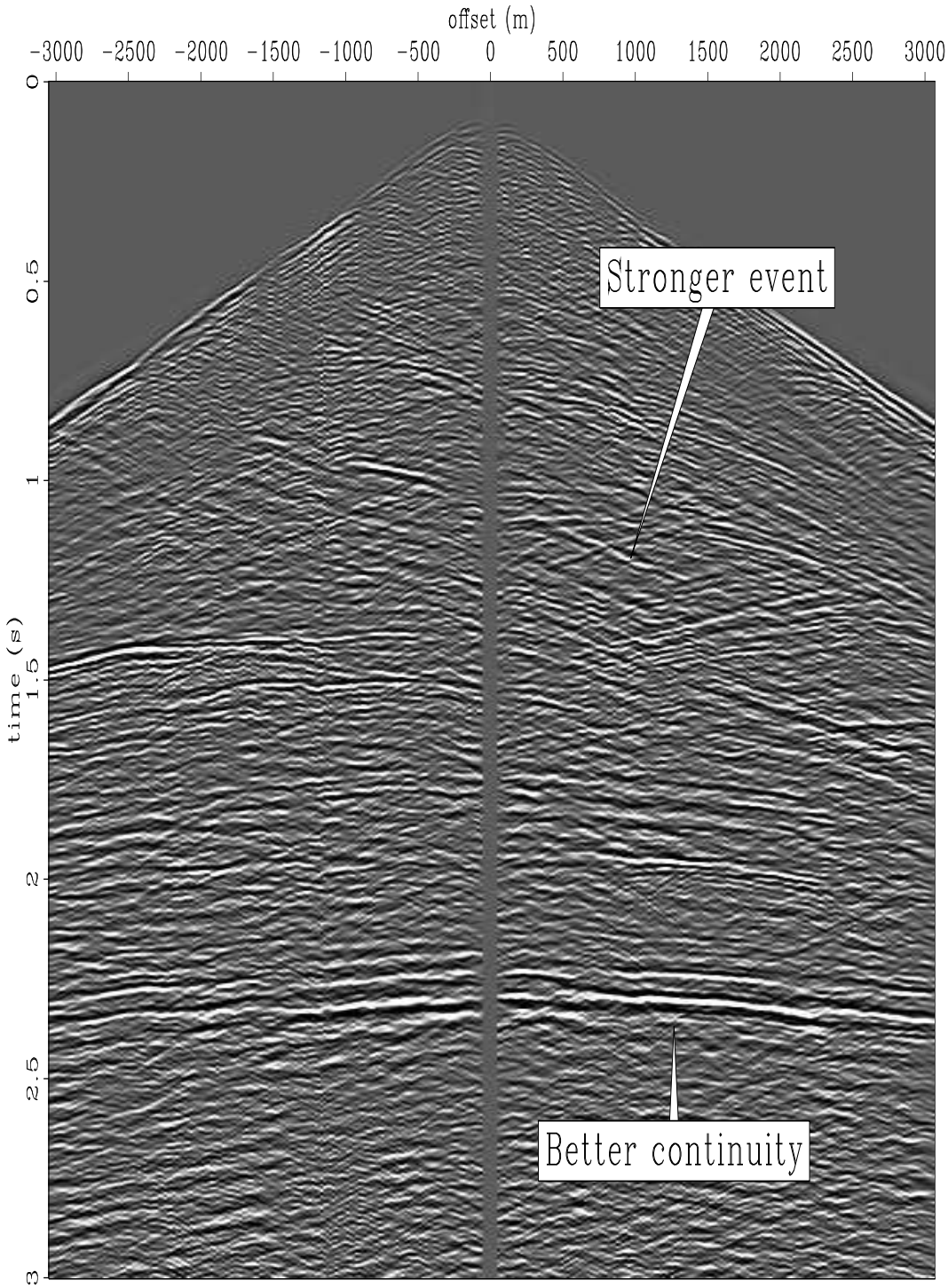

FIG. 3.11. Shot gather 53 after residual statics and wave-equation datuming. Movie. Topo-wedup.52 [CR]

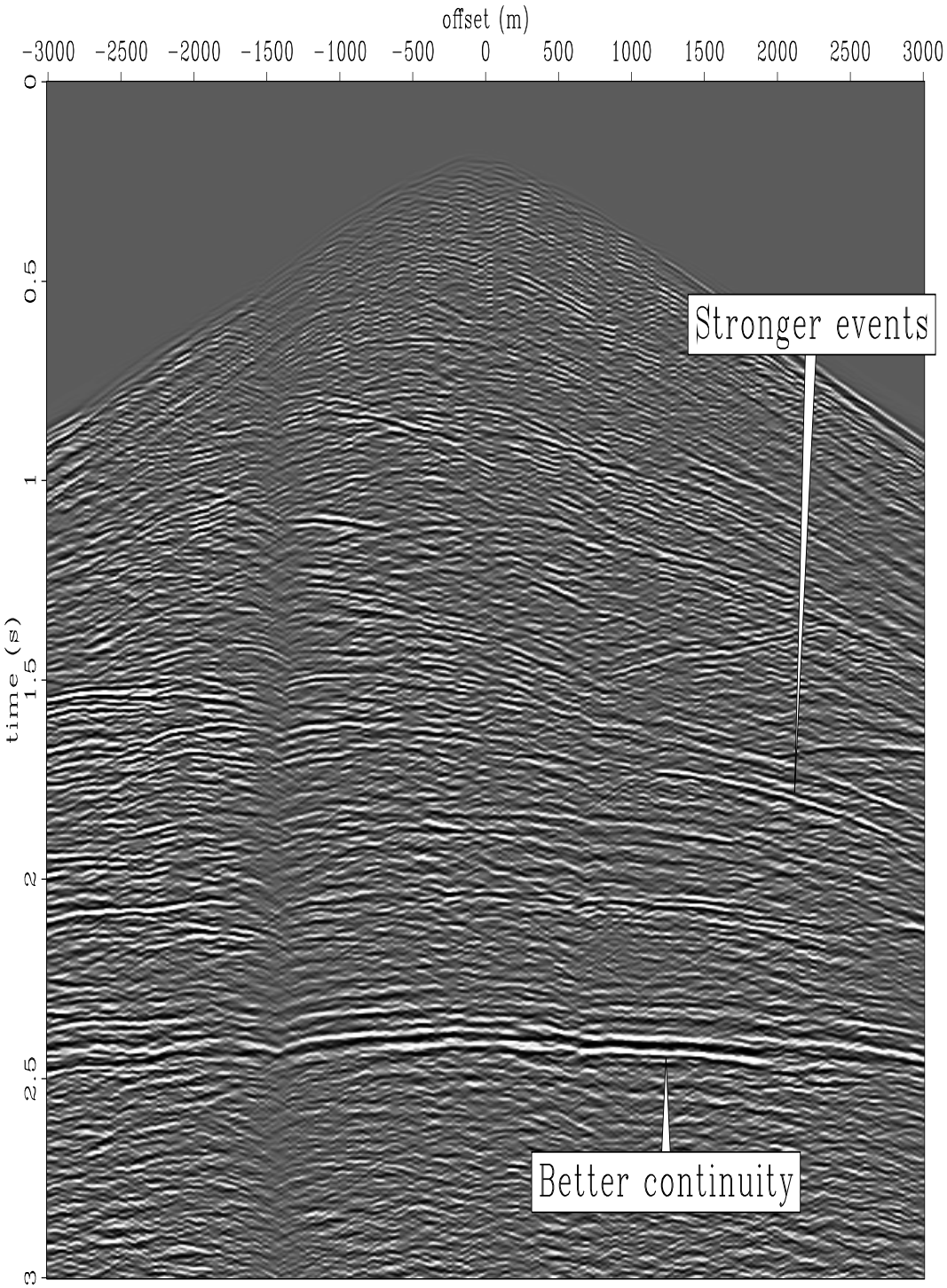

FIG. 3.12. Shot gather 53 after residual statics and wave-equation datuming of shot and receiver gathers. Movie. Topo-wedsgup.52 [CR]

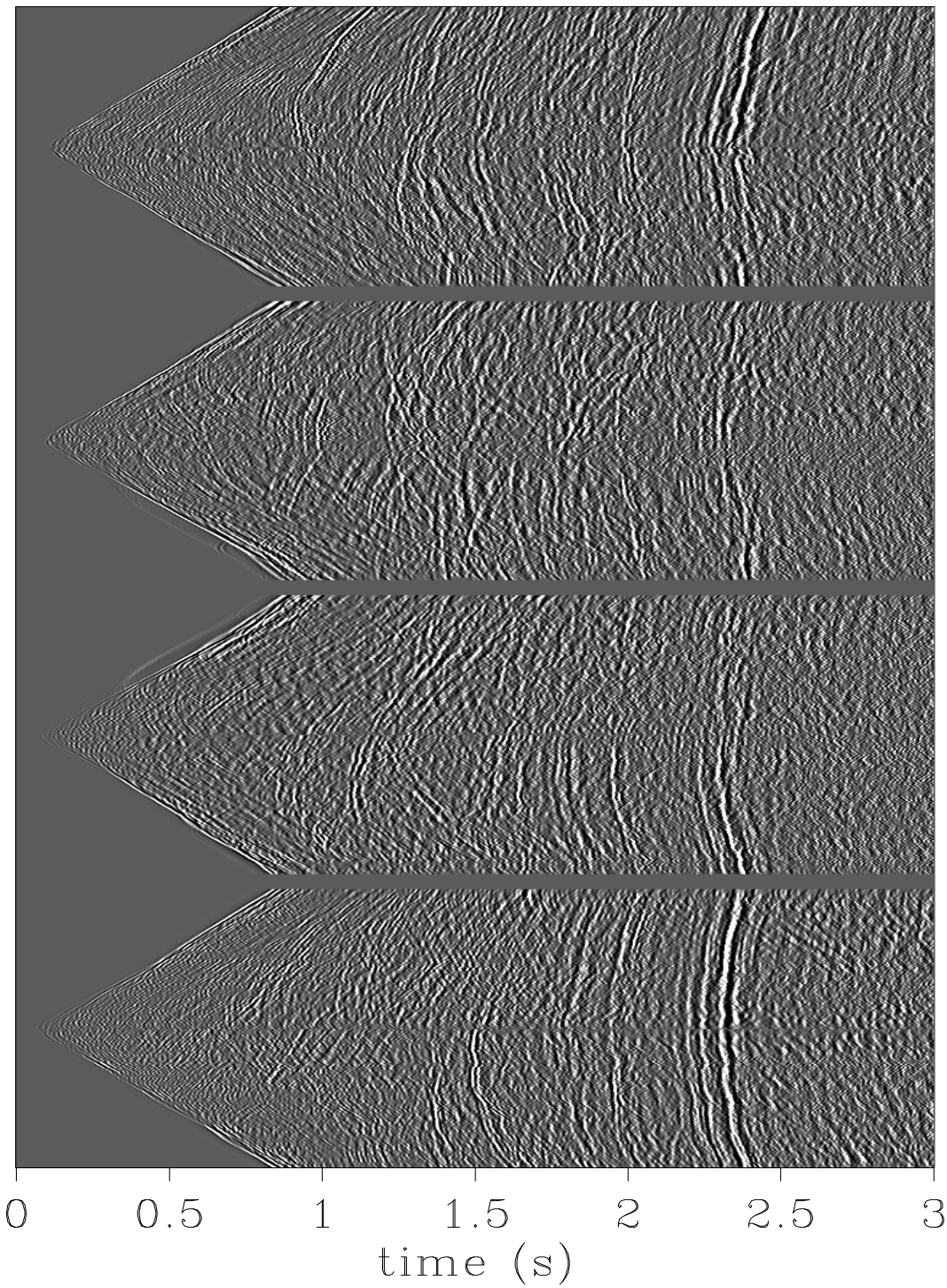

FIG. 3.13. The shot gathers from Figure 3.3 after residual statics and wave-equation datuming. The topographic distortions have been removed. Movie. Topo-datshots [CR]

3.3.2 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. Wave-equation datuming can not only transform data to a flat processing datum, it can also regularize it onto an evenly sampled computational grid. This is useful for iterative migration velocity estimation because the fastest algorithms are 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 3.14 through 3.17 I will illustrate the superiority of wave-equation datuming for this task.

Figures 3.14 and 3.15 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 3.15) than after elevation statics (Figure 3.14). This is particularly evident 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 a little 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 3.16 and the result of migration after wave-equation datuming is displayed in Figure 3.17.

As before, better event continuity is preserved in Figure 3.17 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 corner of the image are better imaged. The dipping event extending from CMP 200 to 500 is more continuous after datuming. In Figure 3.17, this event can be followed to CMP 1000 at 1.8 s where it pinches out. This interpretation could not be confidently made using the image in Figure 3.16.

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 3.15 have collapsed nicely to image the near-surface structure. One of the most prominent structural features that is imaged in Figure 3.17 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 3.17 than in Figure 3.16

Figure 3.17 is a good starting image that is much easier to interpret than Figure 3.16. Geological boundaries could be readily defined and used to build a preliminary interval velocity model which 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 correction step, both images in Figure 3.16 and 3.17 went through the same processing flow.

3.4 Applications to 3-D data

As discussed in Chapter 2, 3-D Kirchhoff datuming has the same algorithmic form as 2-D datuming. The Kirchhoff algorithm is well suited to 3-D data because it can accommodate any geometry; however, the same types of sampling issues which apply to 3-D migration

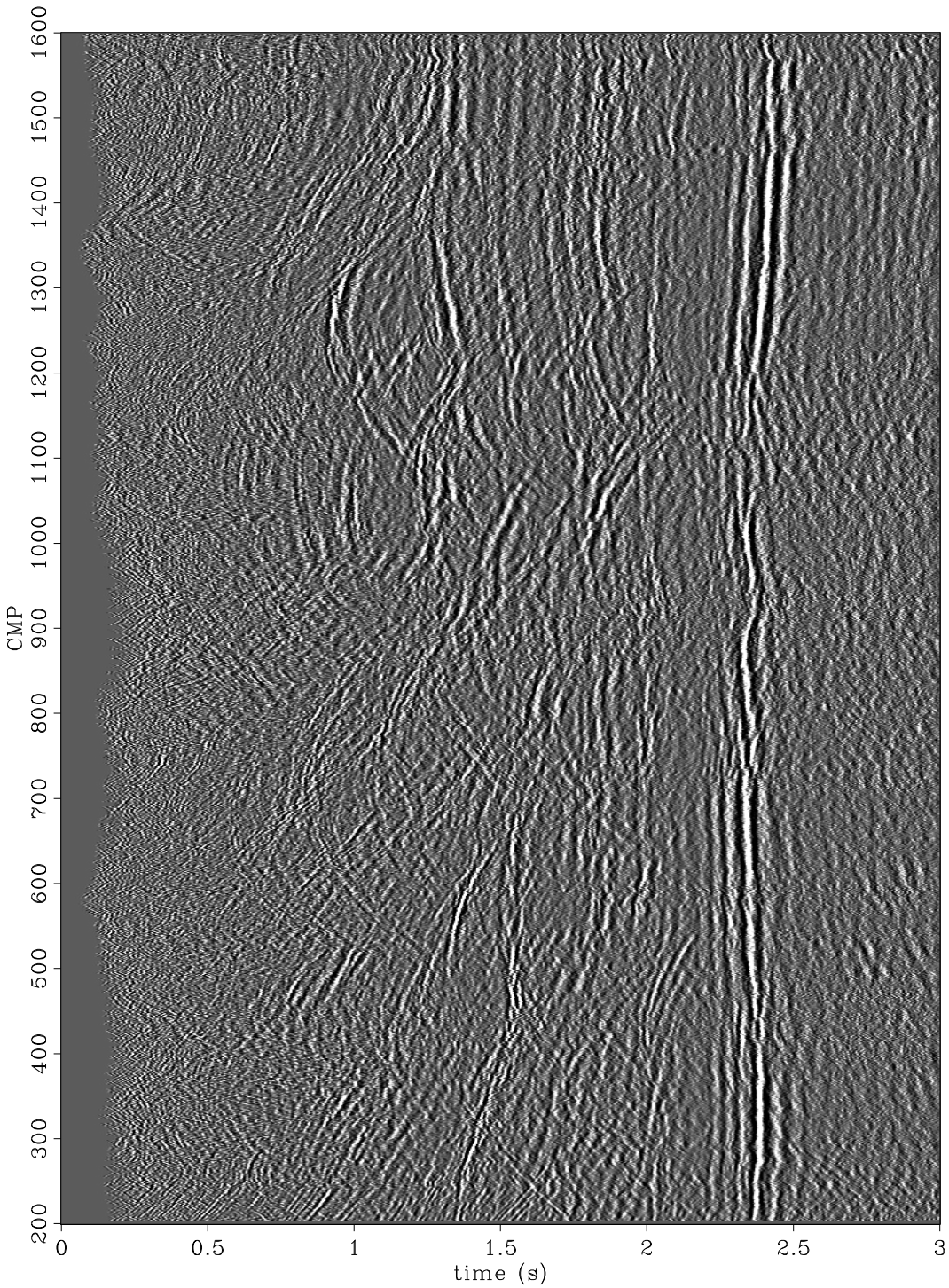

FIG. 3.14. NMO and stack after static shift. Topo-stat1elev3300 [CR]

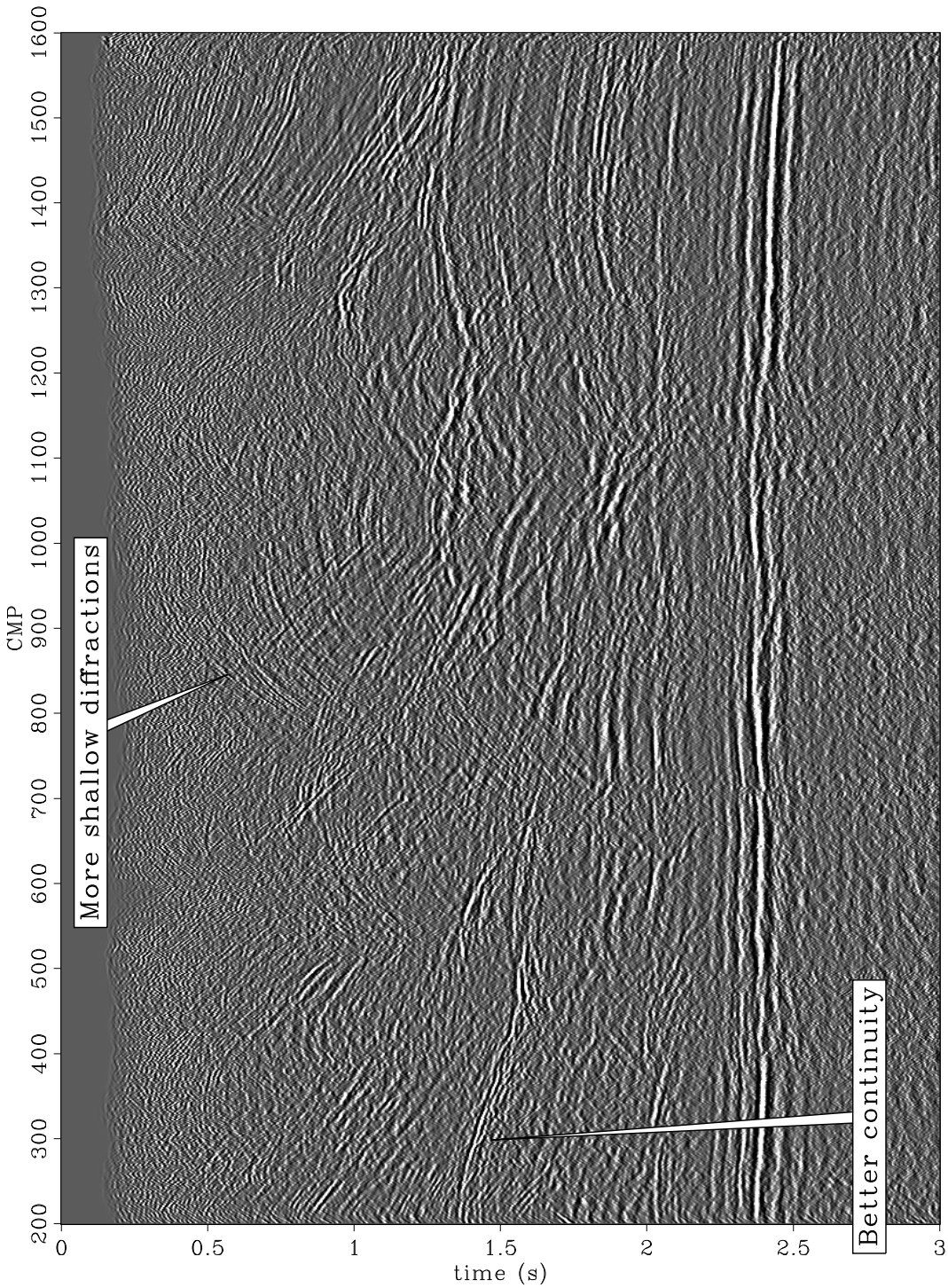

FIG. 3.15. NMO and stack after wave-equation datuming. Movie. Topo-st1wed [CR]

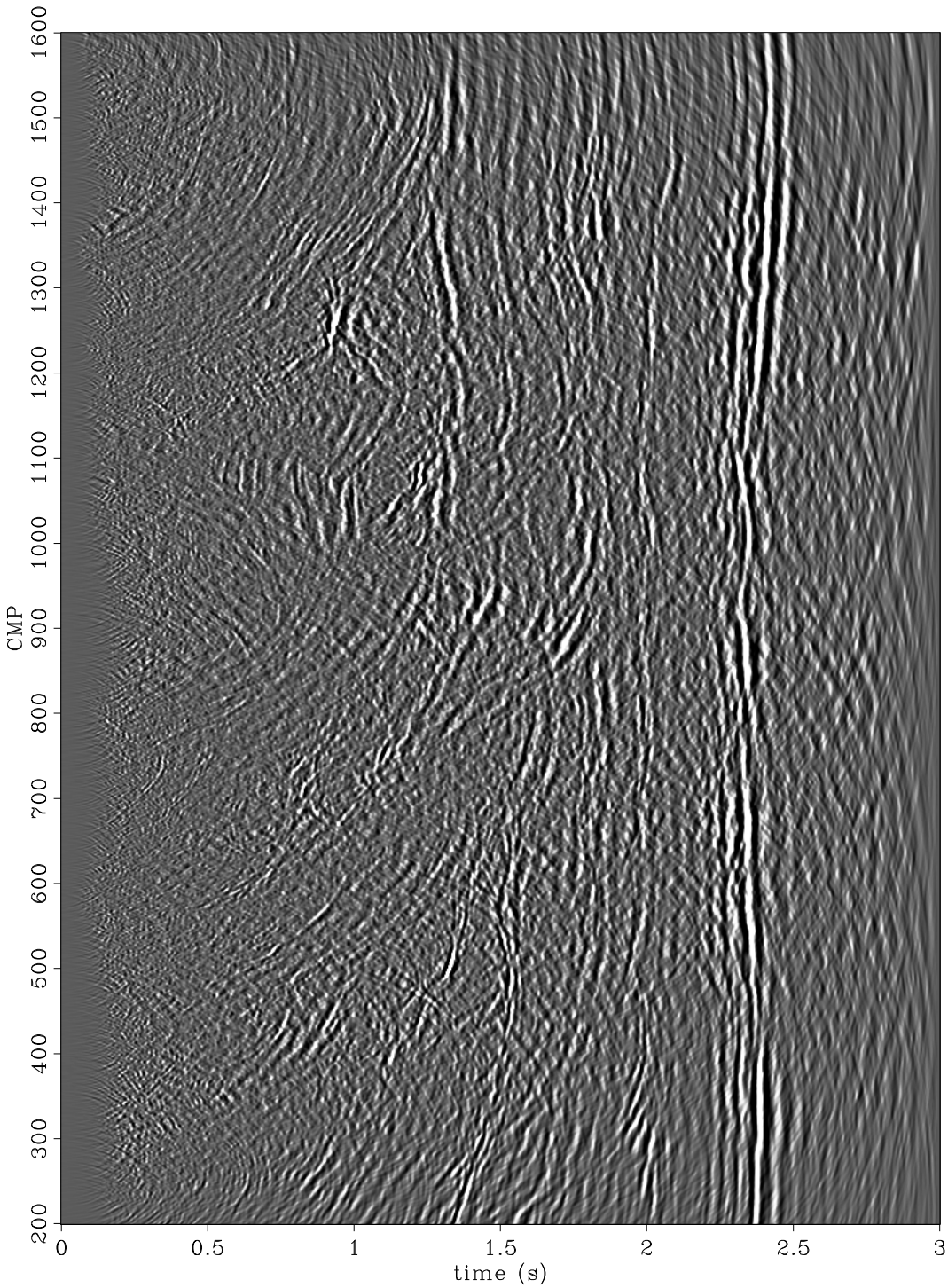

FIG. 3.16. Post-stack time migration after static shift, NMO, and stack. Topo-pmigstat [CR]

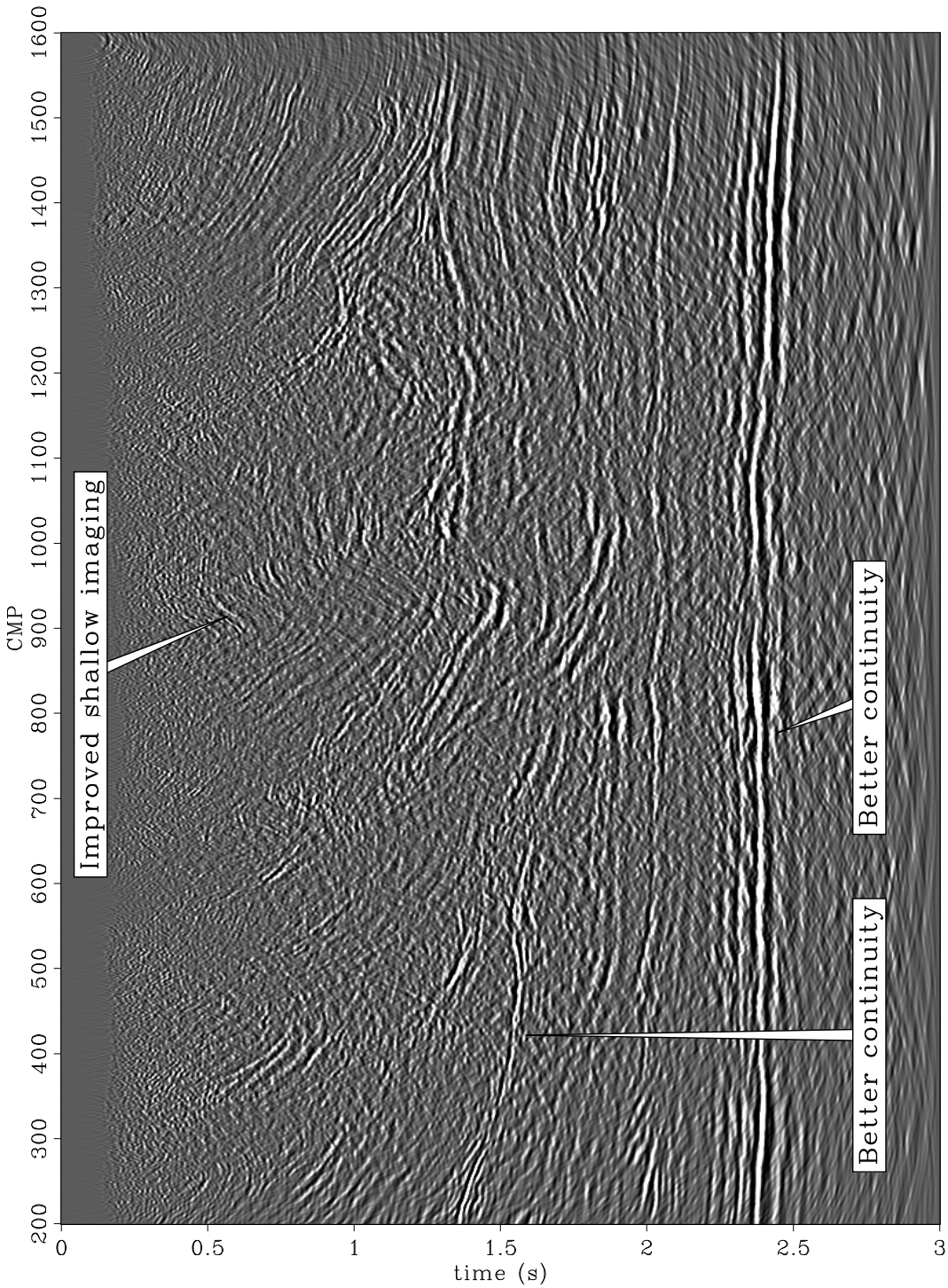

FIG. 3.17. Post-stack time migration after wave-equation datuming, NMO, and stack. Movie. Topo-pmigwed [CR]

will apply to 3-D datuming.

In many cases, the success of the datuming result will be highly dependent on data coverage. The simplest 3-D land acquisition geometry is one in which receivers cover the whole acquisition surface; sources are shot into this patch array. If the source and receiver locations cover the same area, datuming by extrapolating shot and receiver gathers can be implemented in a very straightforward manner. The critical issue is that the source sampling is often much sparser than the receiver sampling in 3-D. This could require data interpolation and lead to an increase in data volume.

Under conditions where the near-surface propagation is nearly vertical, but not close enough to vertical for static shifts to be valid, it would be adequate to perform 2-D Kirchhoff extrapolation along lines of shots and receivers. This could be viewed as a compromise that is better than statics, but which assumes that out-of-plane near-surface propagation is minimal.

3.5 Summary

Wave-equation datuming cannot replace statics in all applications, and it is not a panacea to be applied under all circumstances, but 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 redatuming. 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.

Redatuming is applied early in the processing flow and it will affect all subsequent processing. Proper redatuming to a flat surface is crucial for algorithms which 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 in this chapter, I showed 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.