Incorporating dip corrections in velocity analysis using constant velocity stacks

Paul Fowler

Abstract

A method is described for incorporating dip moveout correction in constant velocity stacks of common midpoint seismic data without prior specification of a velocity function. The kinematic dip moveout correction takes a particularly simple form in this velocity space. Velocity analysis can then be performed on the resulting three-dimensional data cube after dip correction. A stacked section corresponding to a specified velocity function can be extracted by interpolation between dip corrected constant velocity stacks. The method is limited to windows over which lateral velocity variation is small. If lateral variation is small enough over a sufficiently wide window of data, a migration step may be added at little additional cost, also before the velocity function must be specified.

Introduction

One of the persistent problems of imaging and interpreting seismic data is evaluating the earth velocity as a function of position. Most data processing uses common midpoint coordinates, in part because hyperbolic normal moveout (NMO) may be used to find a good approximation to the root mean square (rms) earth velocity, provided the earth does not change laterally too drastically in the area of the survey. This velocity function found from analyzing NMO in midpoint gathers can then be used for stacking the data to improve signal to noise ratio and to simulate a zero-offset section, which then may be migrated if needed for better imaging.

One problem with conventional velocity analysis and stacking is that it may have an undesired dip filtering effect. Reflectors with non-zero dip will give apparent NMO velocities which are consistently higher than the desired RMS earth velocity. Moreover, if conflicting dips are present, such as arise from fault planes, the apparent NMO velocity will not be unique. NMO and stack at a specified velocity will discriminate against real events which have a different apparent velocity due to dip. This problem has been approached in a variety of ways (Hale, 1983; Yilmaz and Claerbout, 1980; Judson, et al., 1978; Bolondi, et al., 1982). Following Hale, I will call this step of reconciling CMP stacking with the presence of dipping beds the dip moveout correction (DMO); the reader is referred to Hale's work for a much more thorough discussion of DMO than I will provide. In the present work I suggest a representation for DMO in a velocity space in which it it takes a particularly simple form. The DMO operation in the form suggested also has the advantage of being done prior to, and independent of, the estimation of a velocity function.

A second potential advantage of this method is the possibility of incorporating better judgements about the quality of the resulting stack into the subjective step of estimating velocities. Most velocity analysis is based upon comparing coherency of events over a range of constant stacking velocities. All NMO hyperbolas have the same zero slope at zero offset; the ability to discriminate between velocities comes from data recorded at larger offsets. Because data is only collected within a limited range of offsets, events can sometimes stack in fairly well over a range of velocities, especially at late times when all hyperbolas are flatter than at earlier times. To improve resolution of events, measures of power or energy are often used; plots of semblance coefficient as a function of time and velocity are a standard method. The improvement in resolution gained in this manner is at the expense of knowledge of the waveform. Direct examination of the constant velocity stacks allows one to exercise judgement about the best stacking velocity to use based upon information about the quality of the resulting stack. Incorporating dip corrections into constant velocity stacking can improve both the coherence of the velocity-time panels and the quality of the stacked midpoint-time sections. The incorporation of judgements about quality of the stack can best be realized if high quality graphics devices are available to allow the velocity space data cube to be examined interactively. As an ideal, I envision an interactive session in which the analyst or interpreter can examine the constant velocity stacks, select a reasonable velocity function and summon up on his or her screen the stacked section corresponding to that velocity function. He or she can identify those areas in which the image seems poor and try a new velocity function which may improve the picture he or she sees, without a significant wait or the need to send the data elsewhere for expensive reprocessing.

The algorithm described here makes use of approximations which are not valid in the presence of large lateral velocity variation. The dip information which is used at a specified location to correct the velocity estimates thus must be extracted only over a window with small lateral velocity variation. With larger lateral velocity variation the algorithm will misinterpret dips; with large enough lateral variation the assumption of hyperbolic NMO will break down as well.

Description of the algorithm

The notation I will use will be: h for offset, y for midpoint location, t for two-way travel time, v_{stack} for NMO stacking velocity, v_{DMO} for the NMO velocity after correction for dip effects (which will be interpreted as approximately equal to the rms earth velocity), and ω and k_y for the Fourier transformed t and y variables. In what follows I may sometimes speak as though the v axis is continuous rather than discrete; interpolation is implied. In his article on multiple velocity Stolt migrations, Rothman (1983), discusses a closely related interpolation problem.

Begin with seismic data sorted into common midpoint gathers, which we write as a function $q(y,h,t)$ of the indicated variables. Assume that the lateral velocity variation along y is small; a limited window of the data may need to be considered at a time if gradients are larger. The suggested processing sequence is:

i) Velocity decomposition by constant velocity stacking at an apposite range of velocities: $q(y,h,t) \rightarrow q(y,v_{stack},t)$

ii) Fourier transformation of the y and t axes to give a dip decomposition: $q(y,v,t) \rightarrow q(k_y,v_{stack},\omega)$

iii) Dip moveout correction by v-axis data shifting: $q(k_y,v,\omega) \rightarrow q(k_y,v_{DMO},\omega)$

iv) Inverse transformation back to y and t: $q(k_y,v_{DMO},k_t) \rightarrow q(y,v_{DMO},t)$

v) velocity analysis and selection of a zero-offset section by interpolation between the CV stacked sections: $q(y,v_{DMO},t) \rightarrow q_{f(v)}(y,t)$

The first step is just forming constant velocity stacks at a suite of velocities (or slownesses). Thorson and Yedlin (1980) have shown how, with appropriate weighting, such stacking may be viewed as a stationary phase approximation to the double square root equation. Stacking transforms the data to a (y,v,t) space. The flat beds will roughly image on each (v,t) plane along a curve tracing out the NMO velocity function. Selecting the data on the slice through the (y,v,t) data cube along this velocity function corresponds to the usual NMO and stack. The dipping bed images will lie off this curve; the purpose of DMO is to move them back to "where they belong", that is, to correct the apparent velocity of the dipping beds back to that of the flat beds, which is taken to be the rms earth velocity (the usual assumption). Dipping events thus may be pictured as mislocated in the wrong constant velocity (y,t) plane. Note that the needed correction is along the v axis only; the y

and t information is needed to find the local dip, but the data will not move in these directions

If we can validly ignore lateral velocity variation, the information needed to correctly reposition the dipping events is easily extracted from the data itself. We know the apparent velocity of a bed by the velocity plane in which it stacks coherently, and we can evaluate the time dip of it in the (y,t) plane. Fourier transform y and t to k_y and ω, and now the time dip information will be contained in the ratio k_y/ω. If velocity is laterally invariant, the actual earth dip θ of the reflector can be approximated by

$$\sin\theta = \frac{v_{DMO} k_y}{2\omega} \tag{1}$$

The factor of two enters because we are using two way travel times, or equivalently, half velocities. Kinematic ray theory predicts a change in moveout or stacking velocity for a bed with dip θ of

$$v_{stack} = \frac{v_{DMO}}{\cos\theta} \tag{2}$$

Equation (1) can be solved for $\cos\theta$:

$$\cos\theta = \sqrt{1 - \frac{v_{DMO}^2 k_y^2}{4\omega^2}} \tag{3}$$

Combining equations (2) and (3), we have

$$v_{stack} = \frac{v_{DMO}}{\sqrt{1 - \frac{v_{DMO}^2 k_y^2}{4\omega^2}}} \tag{4}$$

Equivalently,

$$v_{DMO} = \frac{v_{stack}}{\sqrt{1 + \frac{v_{stack}^2 k_y^2}{4\omega^2}}} \tag{5}$$

So in this dip and velocity decomposed space, (k_y, v, ω), the dip correction can be effected by nothing more than a re-interpolation, or one-to-one mapping of the v axis onto itself for each specified k_y and ω. The result of this mapping after transformation back into (y,v,t) coordinates should be the tighter clustering of the continuous bed reflections along the desired velocity curve in a (v,t) plane. The stacking velocities of all dipping reflectors should become closer to the correct rms velocities. Reflectors of different dips at a specified location should now image together in the same (y,t) velocity plane.

A dip filtering step is implicit in equation (4). To keep the square root in the denominator real and nonzero, dips must be limited to

$$\frac{k_y^2}{\omega^2} < \frac{4}{v_{DMO}^2} \tag{6}$$

This dip filtering is thus equivalent to treating only propagating energy and not evanescent. A potentially more important dip filtering effect is introduced by the finite range of velocities over which we stack. Specifically, if

$$\frac{k_y^2}{\omega^2} < \left[\frac{4}{v_{DMO}^2} - \frac{4}{v_{\max}^2}\right] \tag{7}$$

where $v_{\max}$ is the largest stacking velocity that we use, then equation (4) will assign a zero value to the point (k_y, v_{DMO}, ω). The effects of this pie slice dip filter will be inconsequential for the lower velocity panels, but will restrict the highest velocity stacked sections to retaining only low dip events after DMO. In fact, the very last velocity section can have only events of zero dip left after the DMO operation; any dipping events would have had to come from nonexistent higher velocity sections. Clearly, the highest velocity for the constant velocity sections must be sufficiently large to avoid artifacts from the sharp cutoff dip filter edges introduced by the truncation of the velocity axis. In practice, for the data set considered later in this paper, dip filter artifacts were noticeable only for the very highest velocity sections, which were well above any velocity we considered in extracting our final stacked sections. The edges of the dip filter could be tapered simply by muting down the overall amplitudes in the highest velocity stacked sections, since by equations (4) and (7), the data points that form the the edges of the dip filter originate in these highest velocity sections.

Once a velocity function is chosen, an imaged zero-offset section is produced by slicing diagonally down through the (v, y, t) data cube along that velocity curve, interpolating between (y, t) planes as needed. This step can be quite rapid if a simple interpolating function is used. The examples in this paper were produced using only a linear interpolator between velocity planes. A tapered sinc interpolator was tried, but the visible improvement in results was slight, and the computing time rose significantly. The potential advantage of fast interpolation is that the velocity analyst can temper his or her selections with a "preview" of the effect that velocity function will have on the quality of the final stacked section. One can thus hope to better avoid blunders in choice of stacking velocity, or to recover from such errors with only minor penalty: if the stacked section corresponding to the chosen velocity function is unsatisfactory, just interpolate a new slice along an improved velocity curve, and see the new section pop up on your screen...

A demonstration of the algorithm on field data

The algorithm described above for incorporating dip corrections into constant velocity stacks was tested on a portion of a data set provided by Western Geophysical. These data were collected in shallow water in the Gulf of Mexico; they are from the same set as those used by Hale (1983), Rothman (1983), and Rothman, Levin, and Rocca (1983). For comparison with Hale's results, the data used here correspond to the left portion of his figures 1.8 and 1.10 (Hale, 1983).

The stacked section in figure 1 was created by ordinary NMO and stack. A fault clearly cuts diagonally across the beds, but the fault plane reflection does not stack in well, because its steep dip gives it too high an apparent velocity. Hale (1983, figure 1.13) shows an example of how how this reflector appears as an anomalously high velocity event on a semblance velocity analysis. Figure 2a shows a constant velocity stack profile for the same midpoint (100) as used in Hale's illustration. The fault plane reflection is the strongest event visible; it is the prominent event just after 2.2 seconds at substantially higher velocities than the rest of the events.

The same common midpoint gathers from which figure 1 was generated were stacked at a range of constant velocities from 1500 m/s to 2700 m/s. Two of these constant velocity stacked sections are shown in figures 3 and 4. The first is at 2220 m/s and the second is at 2670 m/s. In figure 3, the flat beds in the middle of the section image well at the lower velocity, but the fault plane reflection does not appear clearly in the constant velocity stacks until the much higher velocity of figure 4 is used. To illustrate that a good variable velocity stack can be obtained by interpolating between constant velocity stacks, such an interpolated stacked section was extracted and is shown in figure 5. It is virtually identical to figure 1. The velocity function used for interpolating is shown in figure 6; it is the same as was used for figure 1. The assumption of lateral velocity constancy is violated significantly only in the lower velocities which characterize the fault zone. This velocity function was picked using both the velocity stacks and semblance plots.

Figures 7 and 8 show the same 2220 and 2670 m/s panels as in figures 3 and 4 after applying the dip correction algorithm described above. The fault plane reflection now appears in figure 7 at the same velocity as the flat beds it cuts through. The velocity of the panel in figure 8 is too high now to have many significant events stack in coherently; most events formerly visible have been shifted to lower velocity panels. Note that the dip filtering effect induced by truncation of the velocity axis restricts the data visible in figure 7 to low dips only; this panel represents the next to highest velocity used in this analysis. Figures 3,4,7 and 8 are all plotted with the same clipping level for comparison. Increasing the clip on figure 8 makes artifacts from the edges of the dip filter visible, (a faint cross

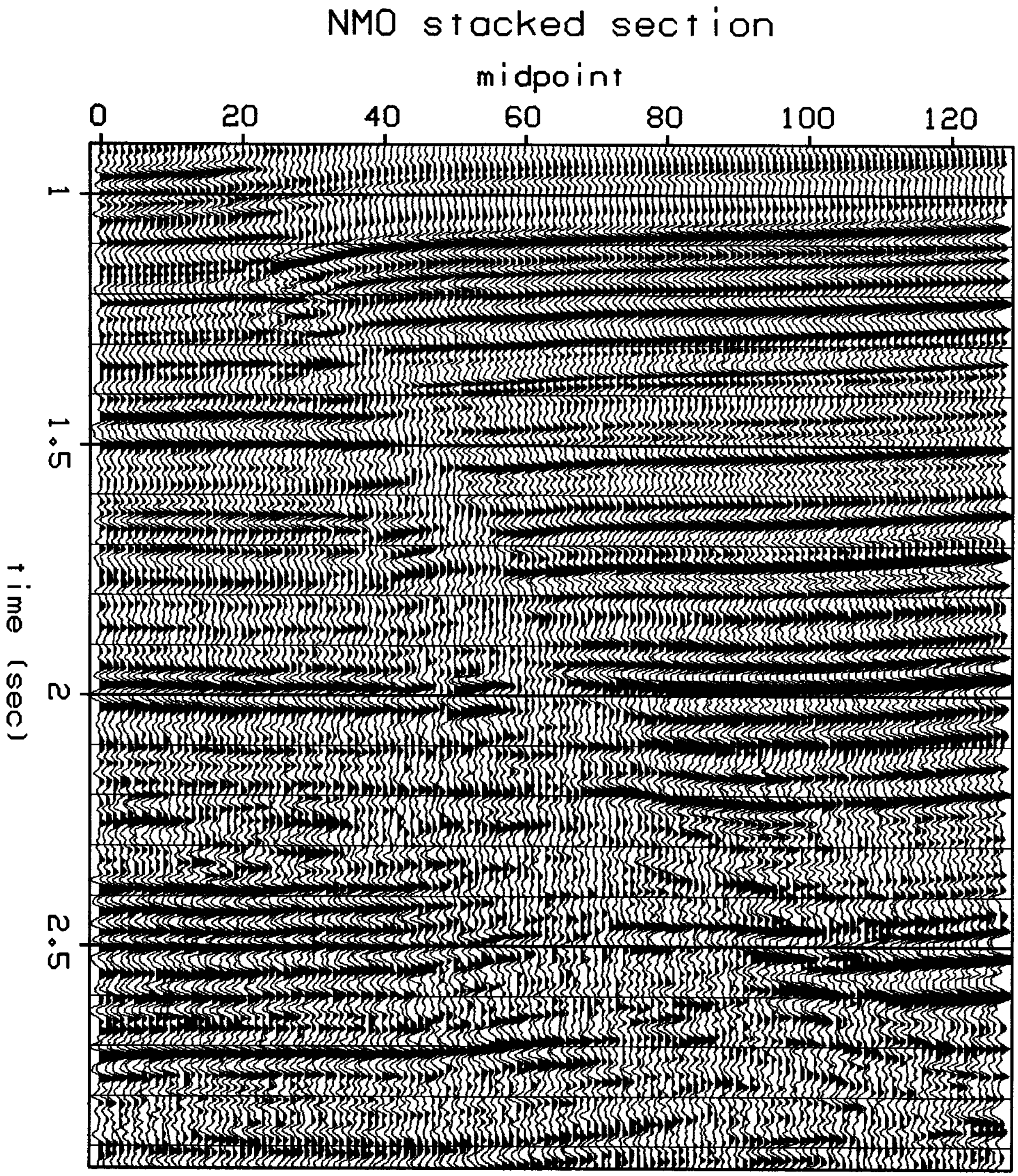

FIG. 1. Normal moveout stacked section of a portion of a data set from the U.S. Gulf Coast. Data provided by Western Geophysical.

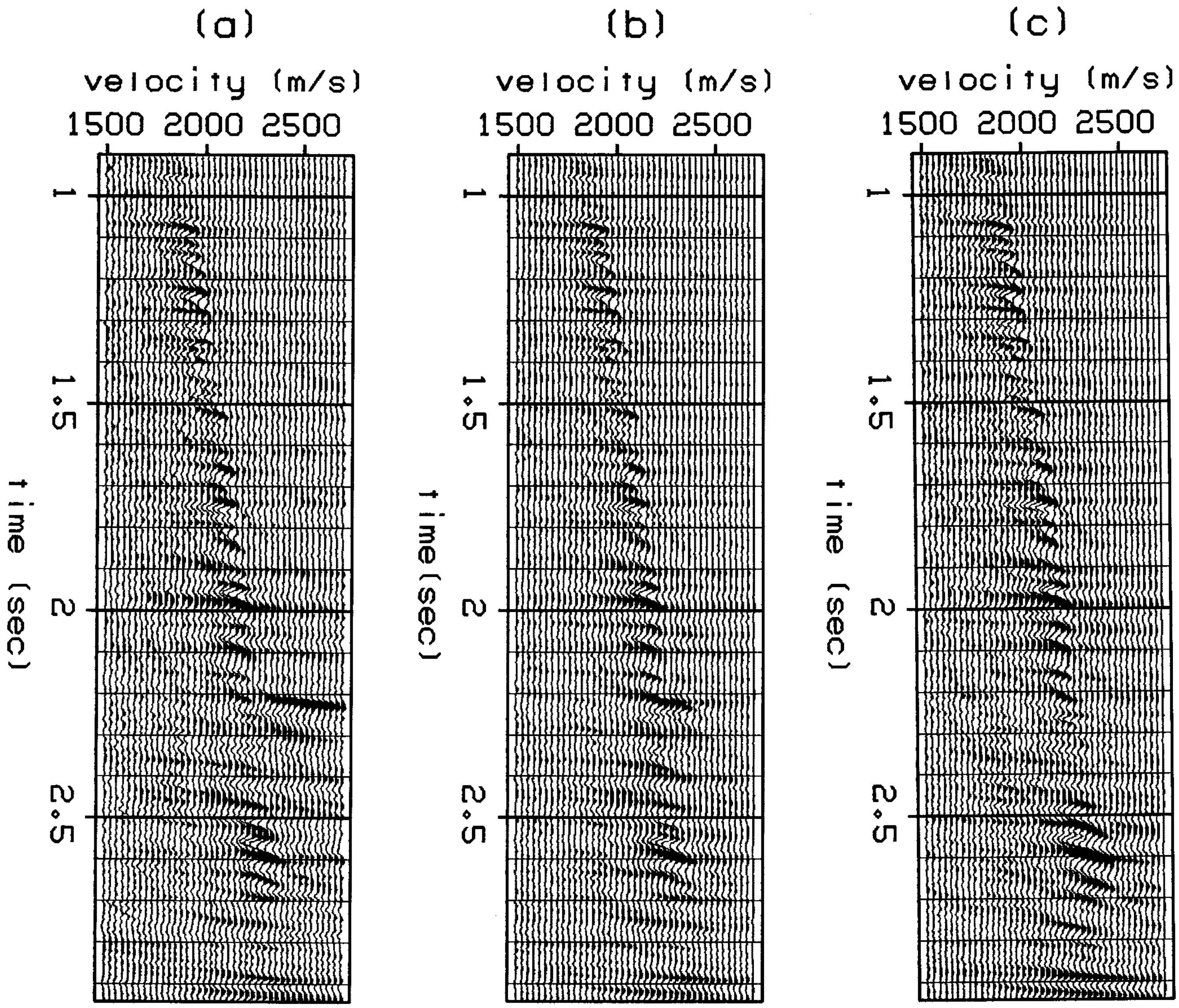

FIG. 2. Constant velocity analysis profiles for midpoint 100. a) before DMO b) after DMO c) after DMO and migration. Note the high velocity event in a) due to a fault plane reflection; in b) and c) it has been corrected to the velocity of the other events.

hatch grid), but such artifacts do not significantly contaminate any regions of interest at lower velocities. Figure 9 shows the stacked section derived by interpolation from the dip corrected constant velocity sections. The most obvious improvement over figure 5 is that the fault plane reflection is now visible. The steeply dipping tails of diffractions around the fault zone are also more visible.

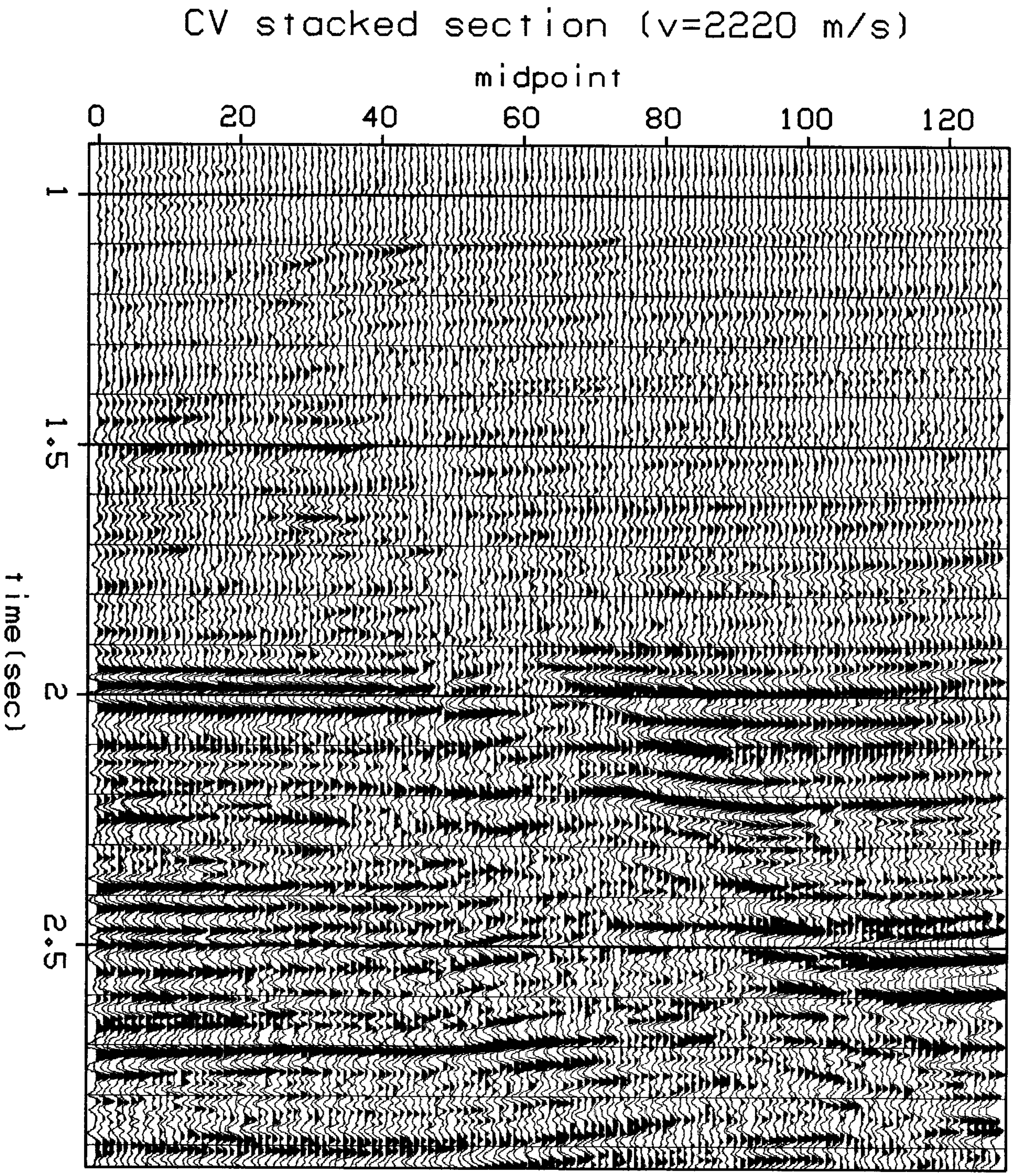

FIG. 3. Constant velocity stacked section using a velocity of 2220 meters/second.

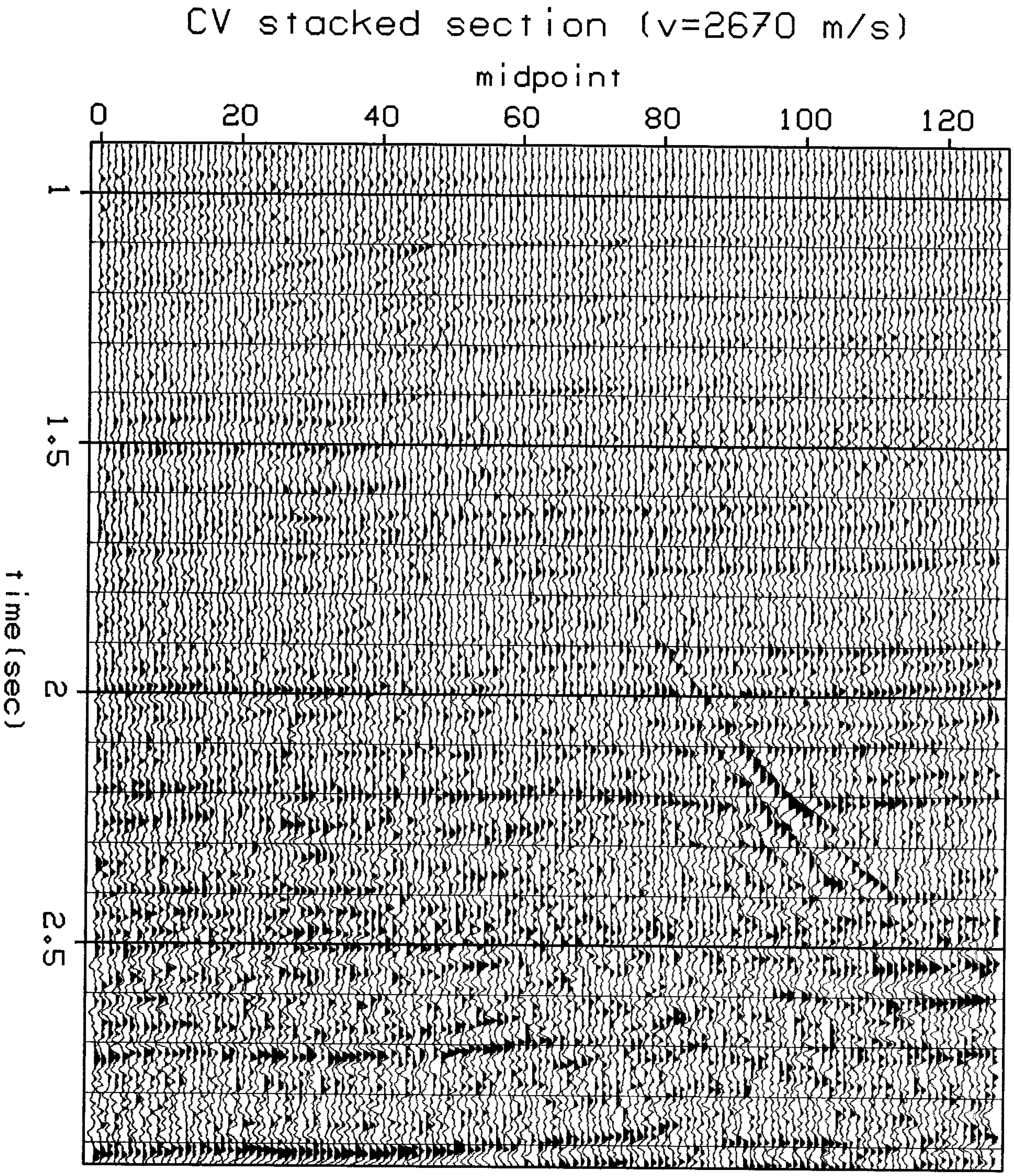

FIG. 4. Constant velocity stacked section using a velocity of 2670 meters/second. Note the fault plane reflection which stacks in at a high velocity because of its high dip angle.

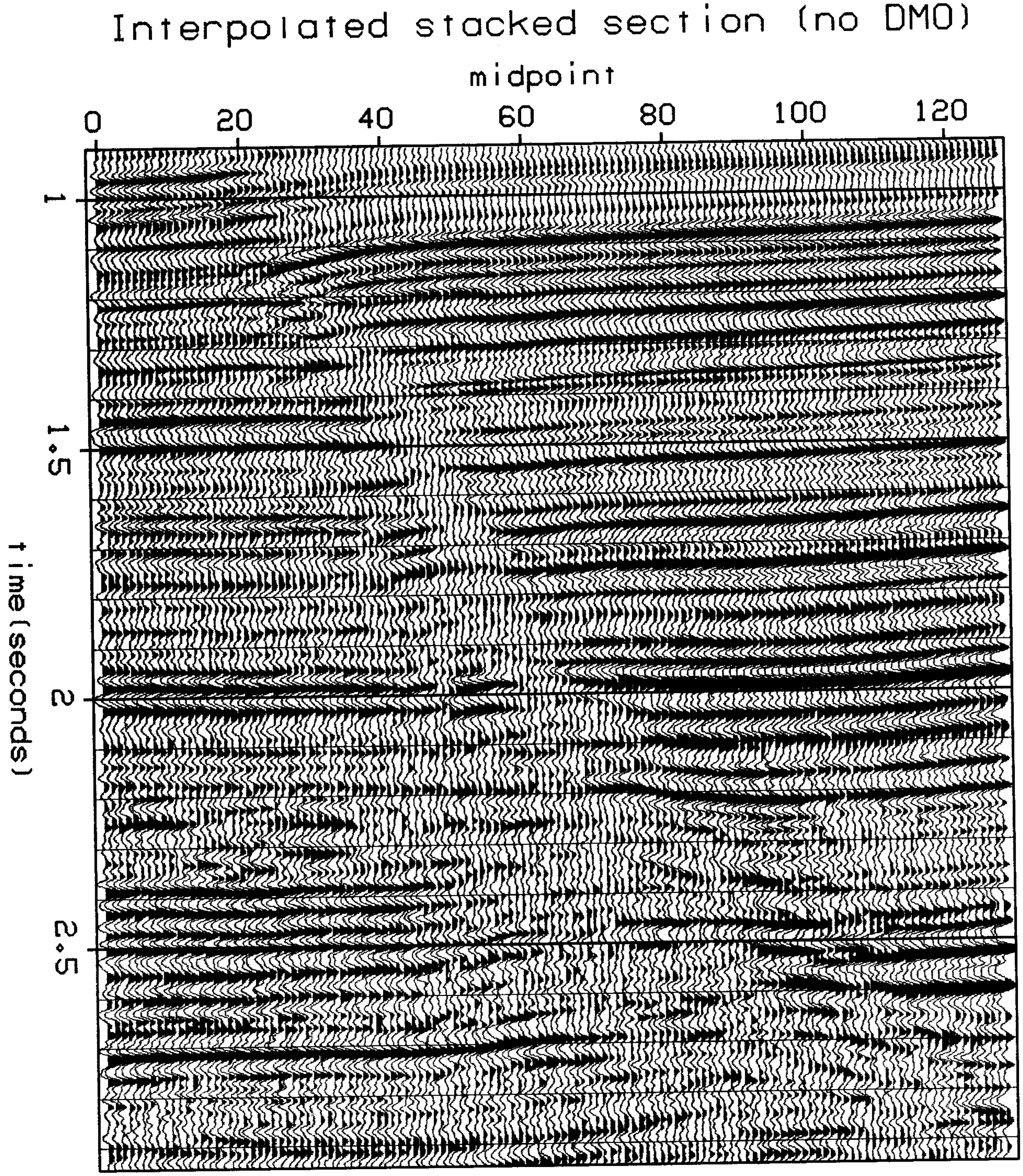

FIG. 5. Stacked section extracted from constant velocity stacks by interpolation. Compare with figure 1.

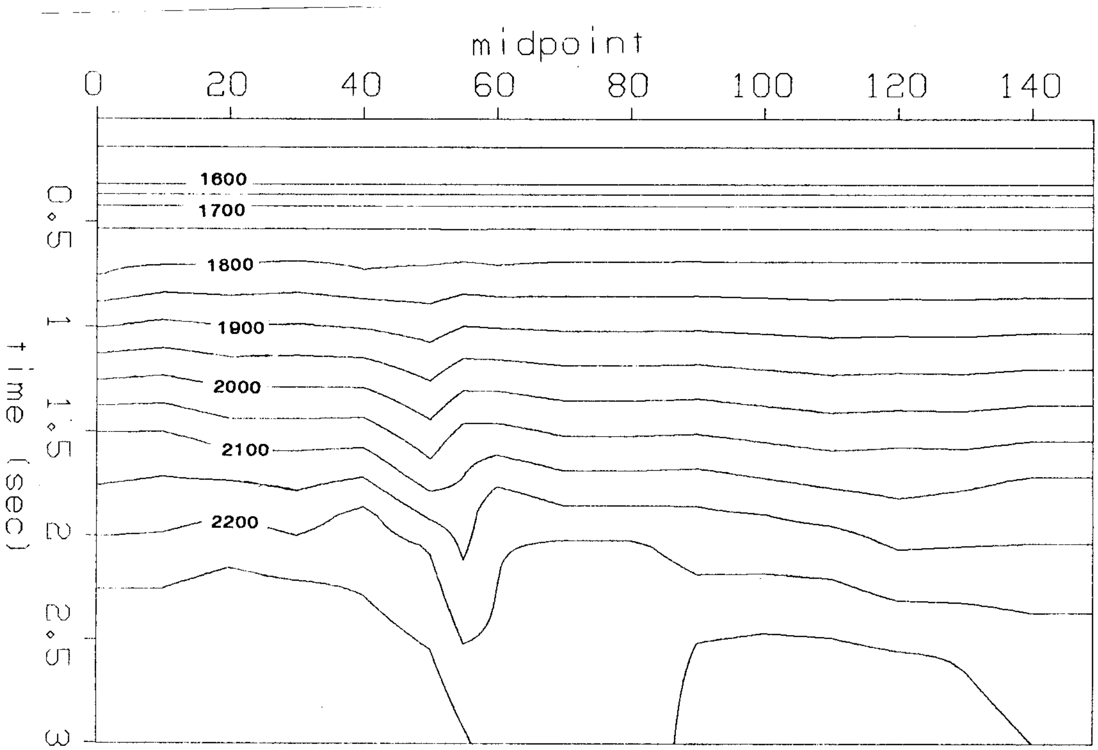

FIG. 6. Velocity function used for stacking figure 1 and for interpolating figures 5, 9, and 11. Contours are in intervals of 50 m/s.

Figure 2b shows the same constant velocity profile as figure 2a, after the DMO correction has been applied. The fault plane reflection no longer stands out at higher velocities, but has merged with the other events; DMO has made exactly the improvement in definition of the velocity function which we expected.

Migration after DMO of constant velocity stacks

If lateral velocity variations are small over a sufficient range of midpoints, it is possible to incorporate a migration step into this algorithm. The potential advantage seen here is that in cases of data in which a sizable amount of diffractive noise is present, the velocity analyst can benefit both from the cleaner section and velocity profiles resulting from the collapse of diffractions, and from the velocity information contained in the degree of focusing achieved by the migration. Moreover, for data of sufficiently high quality (such as that used in this example), the DMO corrected and migrated section extracted by interpolation can be of high enough quality to serve as a final product, rather than just a tool or byproduct of velocity analysis.

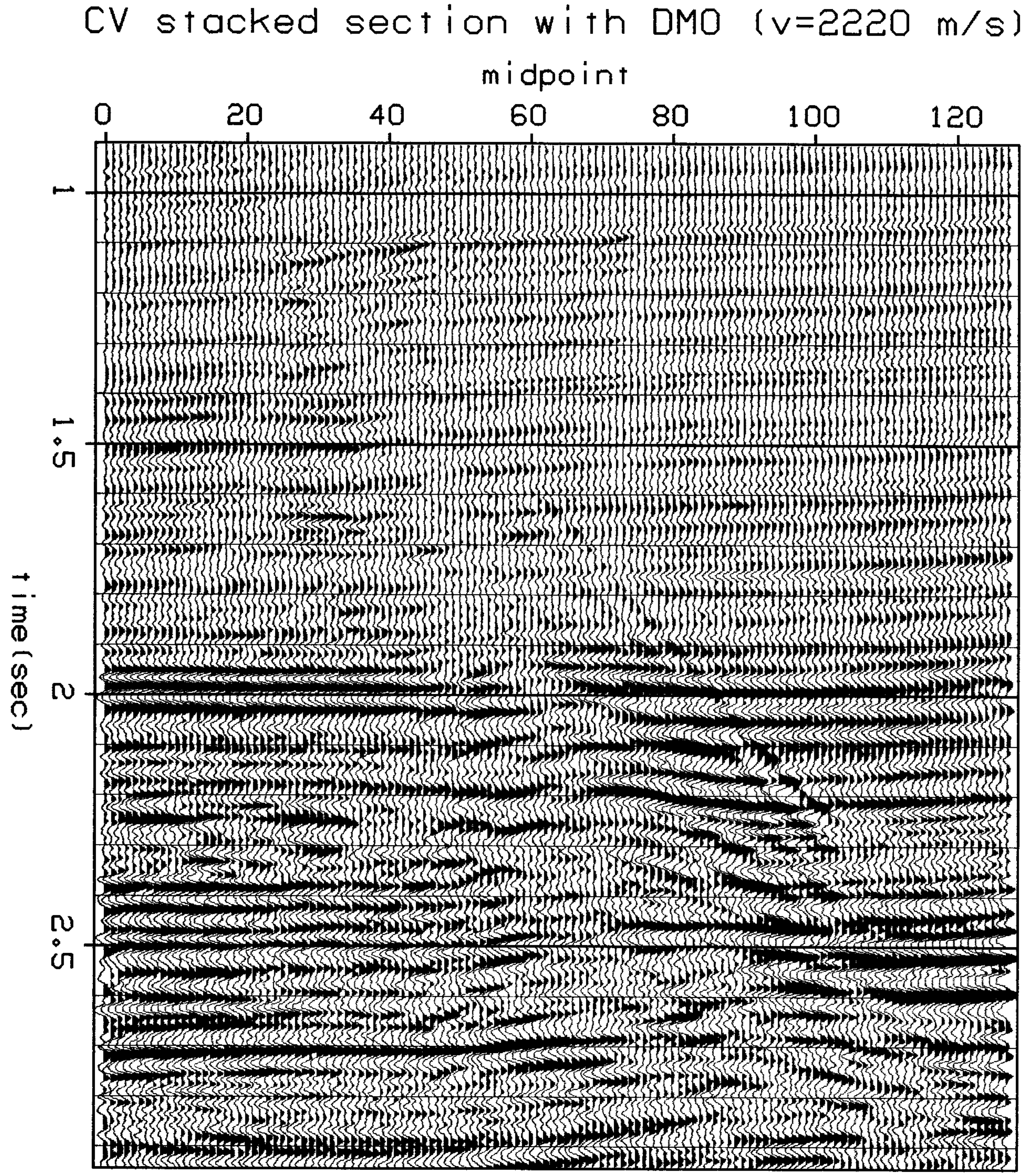

FIG. 7. Constant velocity (2220 m/s) section of figure 3 after dip moveout. The fault plane reflection now images at the same velocity as the flat beds it crosses.

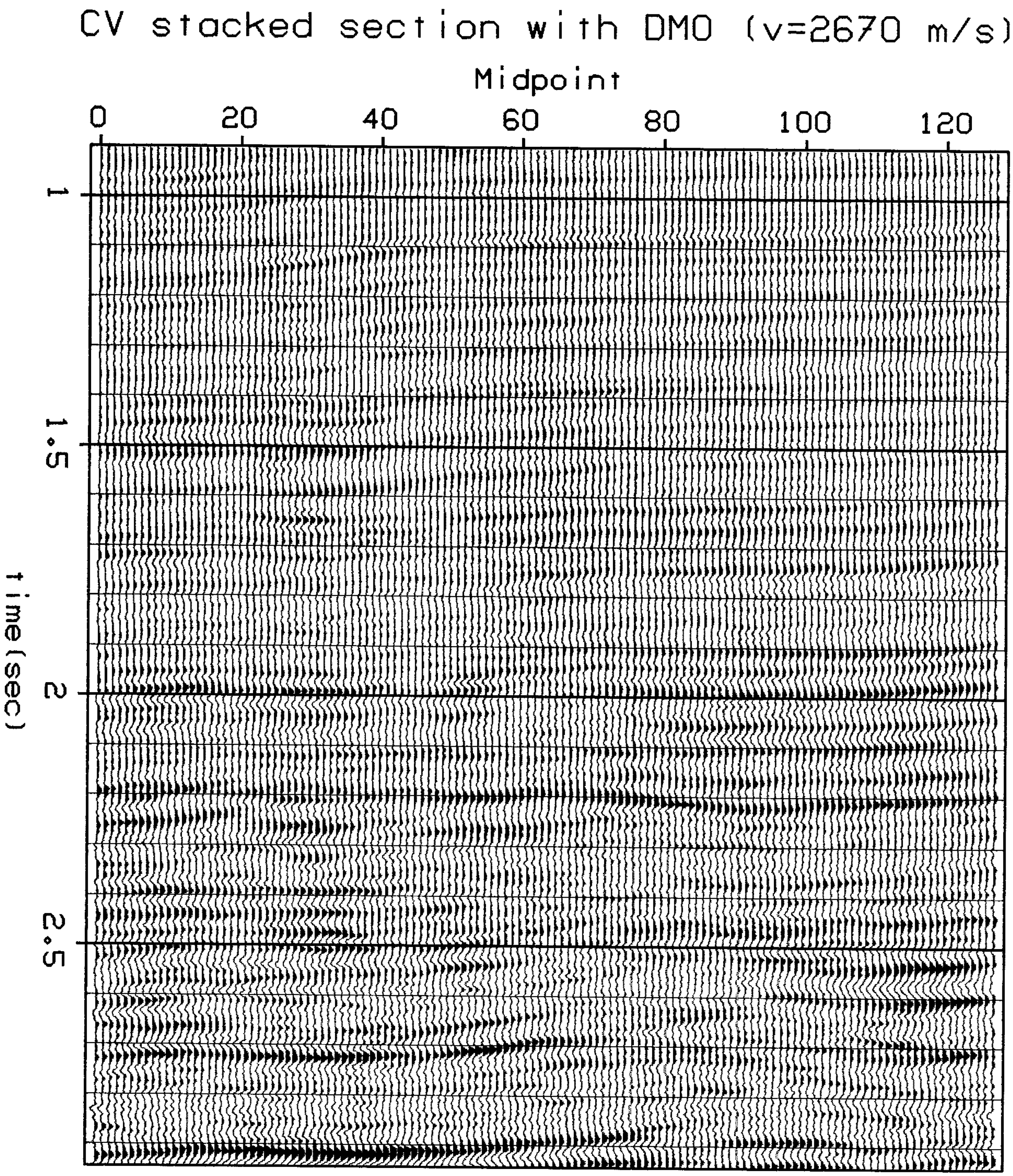

FIG. 8. Constant velocity (2670 m/s) section of figure 4 after dip moveout. The fault plane reflection is no longer visible.

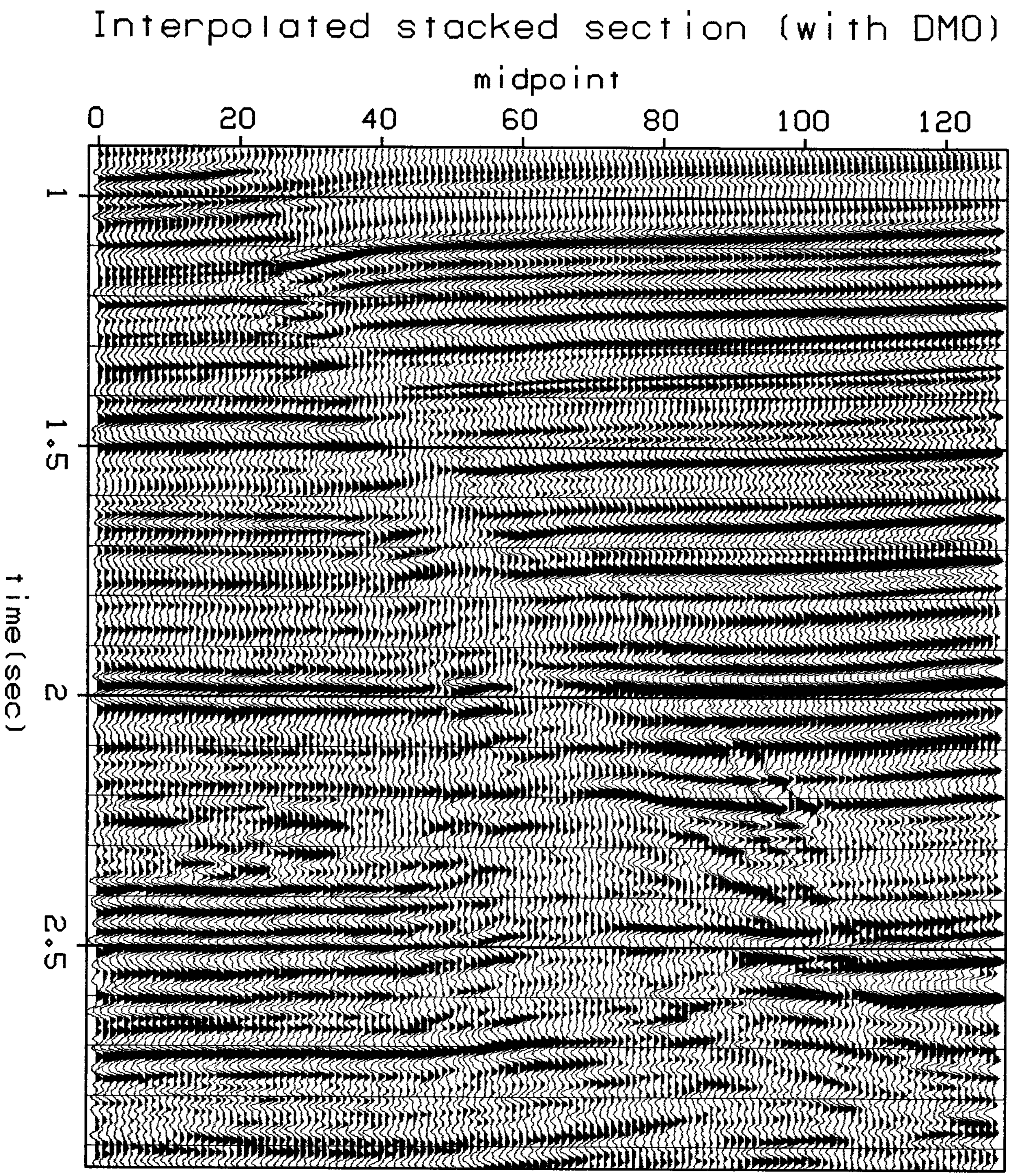

FIG. 9. Stacked section extracted by interpolation after dip moveout correction.

Each constant velocity (y,t) plane may be considered an image of a zero-offset section, albeit a crude one. More accurately, each such plane after DMO contains a reasonable image of those events or regions of the earth which have an RMS velocity close to the specified stacking velocity and elsewhere it presents a poorer image. This suggests that it is at least approximately correct to perform a constant velocity Stolt migration of each velocity panel at the velocity defined by its respective stacking velocity. Note that we are performing a two-dimensional Fourier transform already, so after the DMO correction it is possible to perform a Stolt regridding before we transform back, and pay only a very minimal computational cost for adding the migration step. Thus we can add another possible step to the algorithm suggested above:

iii) (a) Stolt migration of each constant velocity
stacked section: $q(k_y, v_{DMO}, \omega) \rightarrow q(k_y, v_{DMO}, k_\tau)$

Figure 2c shows the constant velocity profile of figure 2b after Stolt migration of each constant velocity panel was added to the algorithm. The visible improvements are slight. The major changes can be seen when we look at the migrated stacked sections. Figure 10 shows the section of figures 3 and 7 after migration at the stacking velocity (2220 m/s). The fault plane has moved to a location in accordance with the visible bed truncations, as expected. Figure 11 shows the final interpolated, migrated and DMO corrected section. For comparison, see figure 1.8a of Hale (1983). The improvement over figure 5 is dramatic; the improvement over figure 9 is also apparent. The correct positioning of the fault plane reflection and the successful collapse of diffractive tails indicates that out choice of velocity function was a good one for most of the section. The region below 2 seconds still retains some ambiguities near the fault zone; this is the region where our velocity function had greatest lateral variation, and would be a good candidate for interactive adjustment of the velocity function to try to better image it, were the software to do so existing.

Discussion and conclusions

Dip moveout has been shown to take a particularly simple form when expressed in a velocity space formed by constant velocity stacking over a range of velocities. It has been demonstrated that implementation of this algorithm is feasible, and can improve the quality of constant velocity profiles and stacks used for velocity analysis. High quality sections corresponding to variable velocity functions can be extracted from the constant velocity stacks by rapid interpolation. Both DMO and migration can be accomplished before a particular velocity function has been selected, and the improvement of the resulting stacked section can be used as an aid in the velocity analysis.

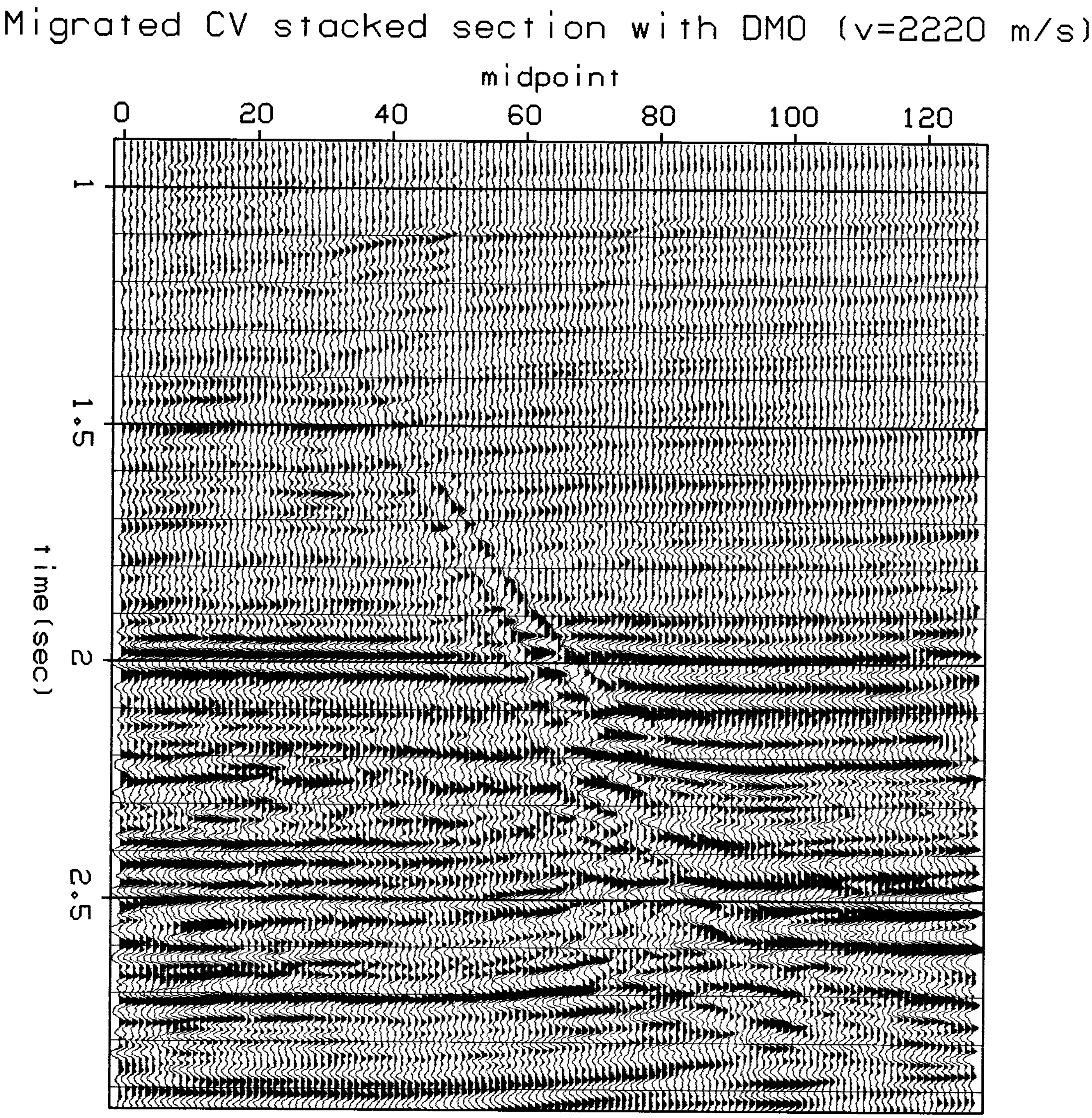

FIG. 10. Constant velocity stacked section of figures 3 and 7 after Stolt migration at the stacking velocity (2220 m/s).

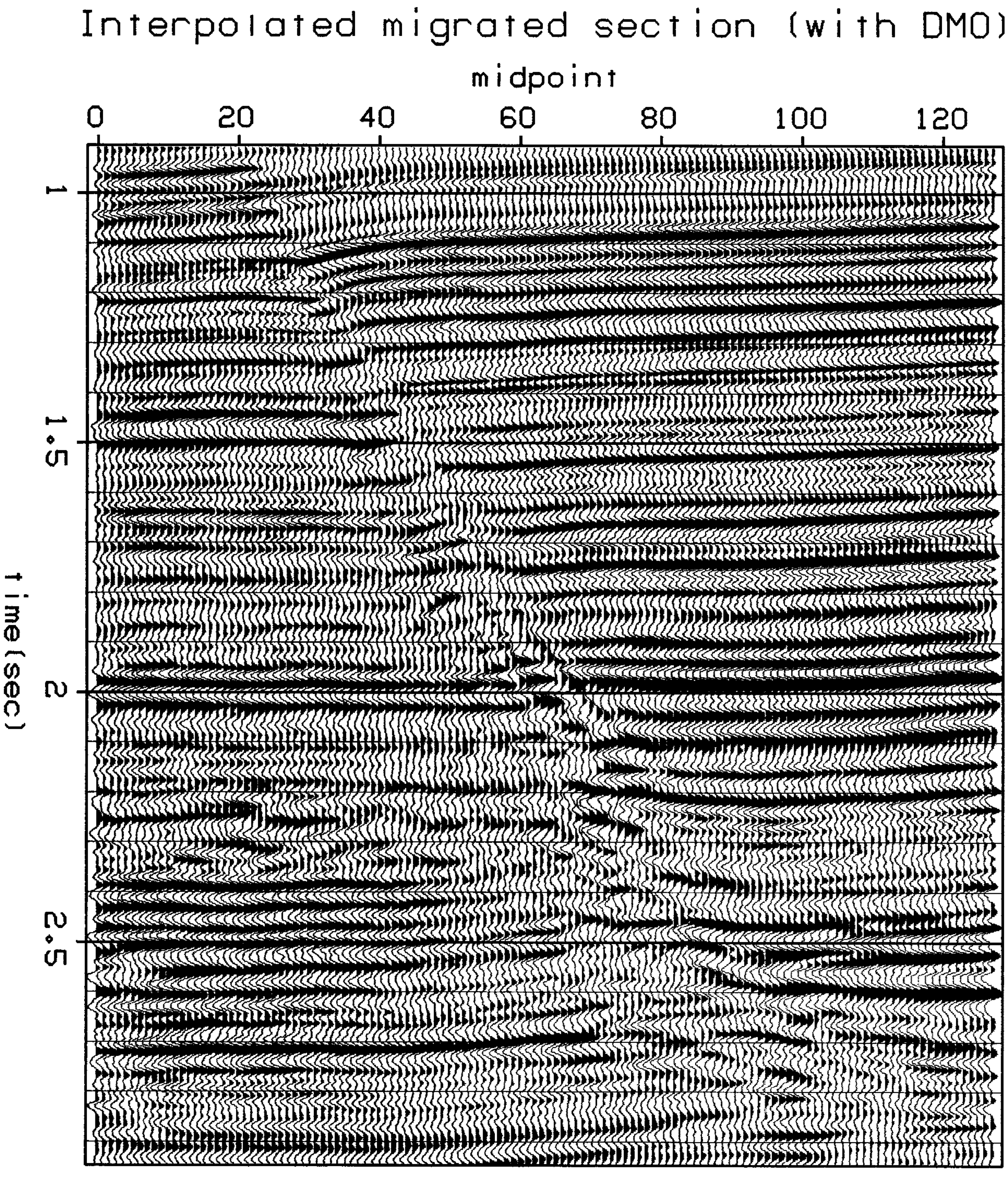

FIG. 11. Stacked section extracted by interpolation after DMO and migration have been applied to constant velocity stacks.

For many data, the computational costs might not justify the use of this algorithm. Results comparable to those of by Hale's implementation of DMO (Hale, 1983) can be achieved by the method described here, but the computational cost of this algorithm is not small. The principal advantage of this algorithm is not that it produces final sections that are intrinsically superior to those which can be obtained by other variations on stacking, DMO, and migration. Rather, the improvements gained by using this process are the ability to postpone detailed velocity analysis until after the DMO and migration processes, which can improve the quality of the velocity analysis, and the ability to rapidly examine the effects on the stack of perturbing the velocity function chosen. A possible role for the process described here might be in locations where precise definition of fault or stratigraphic traps was desired, and fairly subtle changes in imaging due to changes in the velocity model might prove important. Under these conditions, interactive adjustment of velocity functions to improve the imaging of specific features could be very useful.

A practical question which has not yet been answered is how finely velocity should be sampled, and what errors are introduced by using a velocity interval between successive stacks which is too large. This issue is important, since overly fine sampling in v can make the algorithm slower and the velocity space data sets cumbersomely large. The data examples shown in this paper used a velocity interval of 30 m/s between stacks; this was deliberately a finer sampling than was probably necessary. Also, it is not clear yet how severe the restriction on lateral velocity variation will have to be in practice. Note that in the presence of dip this will imply a limitation on the vertical velocity gradient as well. An important practical question is what difference there will be between considering narrow windows each with a fixed velocity function, and allowing a broader window together with a velocity function which changes slowly laterally.

ACKNOWLEDGMENTS

I thank Western Geophysical for the data used in this paper. I also wish to acknowledge the assistance of many individuals. Jeff Thorson got me thinking about constant velocity stack space, and played midwife to many of these ideas. What understanding I have of the relations between dip moveout, normal moveout, and dip filtering owes much to Dave Hale and Helmut Jakubowicz; any misconceptions are probably of my own creation. Discussions with Francis Muir and John Toldi clarified for me the nature of the lateral velocity variation limitation. Dan Rothman patiently reviewed many drafts of this paper. I thank them all.

REFERENCES

Bolondi, G., Loinger, E., and Rocca, F., 1982, Offset continuation of seismic sections, Geophysical Prospecting, v.30, p. 813-828

Hale, I.D., 1983, Dip-moveout by Fourier transform, Ph.D. dissertation, Stanford University, also SEP-36

Judson, D.R., Schultz, P.S., and Sherwood, J.W.C., 1978, Equalizing the stacking velocities of dipping events via Devilish, talk presented at the 48th annual SEG meeting in San Francisco.

Rothman, D., 1983, A short note on constant velocity migrations, SEP-35.

Rothman, D., Levin, S., and Rocca, F., 1983, Residual Migration, SEP-35.

Thorson, J., and Yedlin, M., 1980, Wave equation moveout, SEP-25.

Yilmaz, O. and Claerbout, J.F., 1980, Prestack partial migration, Geophysics, v.45, p. 1753-1779