Seafloor-consistent multiple suppression

3.1 OVERVIEW

In the last example of the previous chapter, I applied surface-consistent gapped deconvolution to a marine line from the Barents Sea. This comprised an unsuccessful attempt to remove the multiple reverberation trains generated by the large seafloor impedance contrast. In this chapter, I move into deeper waters and investigate deconvolution with spatial constraints imposed directly at the bottom of the sea. To get to and from the ocean bottom I use wave extrapolation rather than vertical time shifts. At the seafloor, I design reverberation reflection operators using linearized methods described in previous chapter. Key features of the method are: truly seafloor-consistent filters; incorporation of the pure seabottom multiple; fitting error minimized at the surface; and simultaneous design using all the recorded data. This process proves quite successful at suppressing strong pegleg trains for that same Barents Sea line.

3.2 INTRODUCTION

Multiple reflections are often a problem in marine seismic exploration. Each shot, of unknown signature, sets up reverberations within the water layer that produce the seafloor multiple and a downgoing, reverberatory waveform below the seafloor. The downgoing wave then reflects from the subsurface, travels up through the seafloor, and again reverberates in the water layer to produce primaries and their seafloor pegleg trains. These multiple trains pose a serious problem in areas where the water bottom has a high impedance contrast – the reverberations are slow to decay and correspondingly less source energy is transmitted through to illuminate the subsurface.

Such water reverberations commonly have two features that help us differentiate them from primary reflections. These are their moveout velocity and their periodicity. CDP stack and moveout filters are two standard tools for multiple attenuation which rely on velocity differences between primary and multiple reflections. Gapped deconvolution is the standard tool which exploits the periodicity of multiples.

The standard tools are often ineffective for attenuating pegleg multiples, i.e., multiples with one primary subsurface reflection and one or more seafloor reflections. Figure 3.1 shows a sample pegleg raypath. Because their arrival times are delayed and a good portion of their travel paths lie in the subsurface, pegleg stacking velocities are often close to primary stacking velocities. Moveout discrimination is poor, making velocity filtering and CDP stack ineffective. Gapped deconvolution is also unreliable because it assumes a flat water bottom and faithful amplitude preservation. Both are rare to find in practice. Furthermore, even when these conditions do hold, the strong, pure water-bottom multiple decays at a different rate than pegleg multiples; pegleg attenuation filters estimated from the data will be degraded.

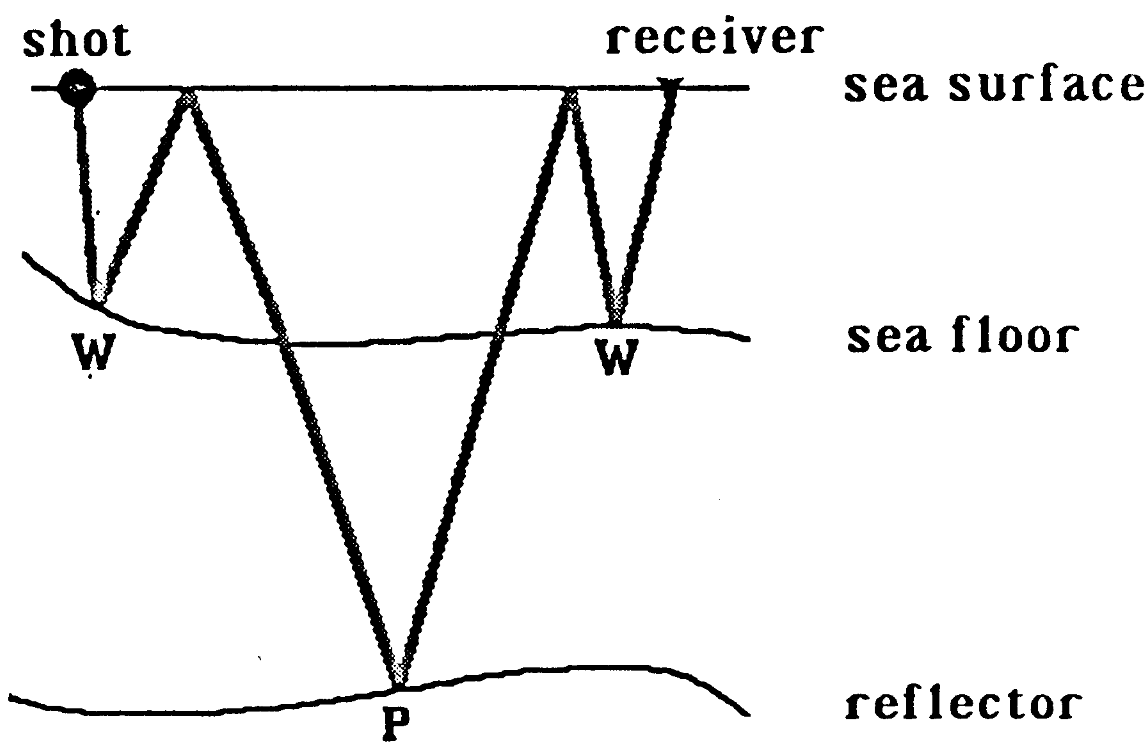

FIG. 3.1. A sample pegleg raypath. Here, the travel path bounces once off the seafloor before illuminating the subsurface reflector. After the subsurface reflection is bounces once again off the seafloor. This **WPW** pegleg arrives at the receiver at nearly the same time as its cousins **WWP** and **PWW**, thereby tripling the recorded reflection amplitude.

Three ways exist to improve discrimination against pegleg multiples: First, we can change field acquisition parameters to better resolve small velocity differences. This can be done by increasing the source bandwidth, shortening the recording sampling interval, lengthening the cable, and/or decreasing the group interval. Second, we can use more precise models of primary and pegleg moveout and more sophisticated moveout filters. Examples of this approach are found in Schneider, Prince, and Giles (1965), Ozdemir (1981) or Hampson (1986). Third, we can use better models of multiple generation, namely those based on wave extrapolation, to improve timing and amplitude estimates of these multiples. Examples of this approach (the approach I use here) appear in Riley and Clærbout (1976), Estevez (1977) and others.

3.3 WAVE-EQUATION PREDICTION-ERROR FILTERING

Improving the predictive suppression of marine multiples requires modeling their timing and amplitude more accurately. This is the rationale for using wave extrapolation instead of simple time delays to predict multiples on the recorded data. The papers of Riley and Clærbout (1976) and Estevez (1977) seem to be the first published applications of wave-equation multiple suppression to seismic field datasets. These researchers work only with plane-wave stacks to make computations manageable. Morley (1982) makes two significant advances: First, he clarifies which multiples are predicted by an additional bounce through the water layer. Second, he demonstrates the importance of working with unstacked data and developed a "seafloor-consistent" theoretical model for wave-equation pegleg prediction. His model is more precisely described as a surface-consistent model applied to seismic data that has been first redatumed to the seafloor by numerical wave extrapolation. Using this model, he then develops gather-by-gather multiple suppression algorithms for several limiting cases.

Morley's model for pegleg multiple suppression is encapsulated in his equation (3.3.9)

$$\Delta_{W.E.} = (1 + \uparrow_s c_s \downarrow_s \nu_s)(1 + \uparrow_g c_g \downarrow_g \nu_g) \quad , \tag{3.3.9}$$

where the boundary operators ν_s, ν_g are 1 for a free surface, c_s, c_g are reflection operators associated with the seafloor, and $\uparrow$ and $\downarrow$ are operators that extrapolate waves from the seafloor to the surface or from the surface to the seafloor.

In recent years, several other geophysicists have applied wave extrapolation to field data. Bernth and Sonneland (1983) use a two-stage adaptive process to tackle both peglegs and pure water bottom multiples. Wiggins (1985) applies Morley's model to field data from the eastern Grand Banks, with careful attention to geometric and statistical detail. Berryhill and Kim (1986) apply Kirchhoff wave-equation datuming to propagate to and from the seafloor in a hybrid approach.

Clærbout (1986), in a related setting, uses wave extrapolation for his simultaneous $t-\tau$ deconvolution. Clærbout's model, leaving out complications of spherical divergence and other weightings, is given by

$$\Delta_{W.E.} = (1 + c_g \uparrow_g \downarrow_g)(1 + c_s) \quad . \tag{3.1}$$

He uses this model to tackle both seafloor multiples and shot signature.

3.4 IMPROVING THE MODEL

In this chapter, I extend Morley's model in two significant ways. First, I incorporate the pure seabottom multiples as well as pegleg multiples. Second, I make the seafloor reflection filters truly seafloor-consistent instead of projecting surface-consistent filters to the seafloor.

Incorporating the pure seabottom multiple

The difference in amplitude behavior between the pure seabottom multiples and pegleg multiples is described by Backus (1959). He shows that the amplitude of the pure seabottom multiple is proportional to R^n, where R is the seafloor reflection coefficient, and n is the number of bounces off the seafloor. At the same time, the amplitude of the pegleg multiples arising from a primary subsurface reflection with reflection coefficient R_1 is proportional to $(1-R^2)(n+1)R_1R^n$ – a decay proportional $(n+1)R^n$.

To appreciate the relative strengths of the two types of multiples, I measured from the marine data in Figure 2.19 a seafloor reflection coefficient of $R \approx 0.25$ and a reflection coefficient $R_1 \approx 0.05$ for the strong subsurface reflector at about 1.5 seconds. With divergence correction proportional to t, the seafloor reflection emerges over five times stronger than the primary reflection. The first seafloor multiple is one third larger than the primary reflection. And the first pegleg multiple is about half of the strength of the primary reflection.

Morley's model does not include the pure seabottom multiples explicitly, and so tries to fit their amplitudes with a sequence decaying proportional to $(n+1)R^n$. The estimate of R obtained by treating the seabottom multiple train as a pegleg sequence is only half the proper value. If we perform a least-squares fit over a window spanning the first two seconds of these data, this incorrect reflection estimate will have 25 times the weight of the strong primary and its pegleg. This will significantly bias the overall estimate of R towards zero.

Two ways exist to deal with this problem: One can suppress or downweight the seabottom multiples in the data during pegleg processing, or one can anticipate them by extending the underlying model for multiples. I will do the latter. Berryhill and Kim attempt the former by adjusting the start times of their processing windows to just after the arrival of a seafloor multiple. Bernth and Sonneland do the latter in their formulation, but do not follow through in their application. Instead, they do two passes over the data. The first pass tries to suppress pure seabottom multiples, trusting that pegleg amplitudes do not bias their reflection coefficient estimates strongly. (Morley also assumed this in his applications.) Next, Bernth and Sonneland mute the seafloor reflection, and do a second pass to predict the peglegs remaining on the data. Wiggins also does a two-step procedure, relying on L^1 norm minimization to further reduce the influence of peglegs during the first pass.

Seafloor-consistency

I improve on Morley's model in a second way by more carefully defining and honoring the idea of seafloor-consistency. His equation (3.3.9) above contains two descriptions of the seafloor: c_s when the source is above it, and c_g when the receiver is above it. These reflection operators are supposed to describe how waves are reflected from the seafloor; this is a physical response that is independent of the location or even existence of any equipment for seismic exploration. For this reason, I constrain c_s and c_g to be identical functions of seafloor position in my model. This notion of seafloor-consistent filtering is the analogue of the midpoint-consistent, or structure, term in the surface-consistent statics model.

Dereverberation model

To suppress water reverberations, I first predict them by extrapolating the recorded data one additional bounce off the seafloor. I then subtract them from the original data. I model seafloor reflectivity with a spatially variable reflection filter with unknown coefficients and adjust these coefficients to minimize the prediction error, i.e. the root-mean-square amplitude after subtraction of the multiple estimates.

In more detail, I first scale the field records by $t^{1/2}$ to convert (approximately) from 3D to 2D amplitude divergence. Then, I extrapolate the shots forward down to the seafloor and up again, so as to predict the multiples due to shot reverberations. This is Morley's $(1 + \uparrow_s c_s \downarrow_s \nu_s)$ dereverberation operator. When I've chosen the right set of seafloor reflection coefficients, the seafloor multiple and its (direct) illumination of subsurface reflectors should vanish. Finally, I predict and remove peglegs from primaries that emerge after subsurface reflection and then reverberate in the water layer before arriving at the geophone. These are predicted by propagating each partially deconvolved common shot gather, with the seafloor primary reflection deleted by muting, one more bounce off the seafloor reflection coefficients, and removing this from the unpropagated gather. By muting, I include the seafloor multiple in the process instead of trying to attenuate it separately by velocity filtering.

Assuming a free surface, i.e. ν=1, this sequence leads to the prediction error model

$$0 \approx (1 + \uparrow_g c \downarrow_g Mute)(1 + \uparrow_s c \downarrow_s)\sqrt{t}\ \ Data \quad . \qquad (3.2)$$

The job is to estimate the c 's.

3.5 ESTIMATION PROCEDURE

To simplify the task of estimating seafloor-consistent multiple suppression operators for the Barents Sea field data I am using, I make the following assumptions:

1. The seafloor is relatively flat and the recording geometry is regular. This simplification lets me conveniently precompute the wave-propagation operators.
2. The water is sufficiently deep that the shot waveform and the seafloor multiples are separated in time. This permits me to debubble (or deghost) at my convenience, either before or after multiple suppression, without having to incorporate the shot waveform into the wave-equation processing.

3. Seafloor reflection operators are not significantly angle-dependent on the gathers being processed. In deep water, and with judicious muting, this is a reasonable assumption which lets me replace seafloor reflection operators with convolutional seafloor reflection filters.

4. The sea surface is the standard –1 free surface reflector. With this assumption, ghosting becomes a constant filter applied to all the traces; it will not interfere with the multiple estimation.

Under these assumptions, I insert $c_o + \Delta c$ into (3.2) to linearize around a reference model c_o. This yields

$$\begin{aligned} -(1 + \uparrow_g c_o \downarrow_g Mute)(1 + \uparrow_s c_o \downarrow_s)\sqrt{t}\ \ Data \ \approx \\ (1 + \uparrow_g c_o \downarrow_g Mute)(\uparrow_s \Delta c \downarrow_s)\sqrt{t}\ \ Data \ + \\ (\uparrow_g \Delta c \downarrow_g Mute)(1 + \uparrow_s c_o \downarrow_s)\sqrt{t}\ \ Data \quad , \end{aligned} \tag{3.3}$$

which must be solved for Δc.

Equation (3.3) has the form

$$y \approx (A + B)\Delta c \tag{3.4}$$

with

$$\begin{aligned} A\ \Delta c &= (1 + \uparrow_g c_o \downarrow_g Mute)\uparrow_s [\downarrow_s \sqrt{t}\ \ Data\ ] * \Delta c \quad , \\ B\ \Delta c &= \uparrow_g [\downarrow_g Mute\ (1 + \uparrow_s c_o \downarrow_s)\sqrt{t}\ \ Data\ ] * \Delta c \quad , \end{aligned} \tag{3.5}$$

and $*$ representing trace-by-trace convolution. I use the conjugate gradient program LSQR (Paige and Saunders, 1982) for the solution. For the conjugate gradient solution, the transpose operations are required as well. These are

$$\begin{aligned} A^T\ x &= [\downarrow_s \sqrt{t}\ \ Data\ ] \circledast \downarrow_s^- (1 + Mute\ \uparrow_g^- c_o^* \downarrow_g^-)\, x \qquad \text{and} \\ B^T\ x &= [\downarrow_g Mute\ (1 + \uparrow_s c_o \downarrow_s)\sqrt{t}\ \ Data\ ] \circledast \downarrow_g^- x \qquad , \end{aligned} \tag{3.6}$$

where $\uparrow^-$ is backward (in time) propagation from the seafloor to the surface and $\circledast$ represents trace-by-trace correlation.

In this chapter I'm now working directly with the overdetermined system (3.3), in contrast to Chapter 2 where I formed normal equations. In Chapter 2, I found that numerical conditioning was not a problem, and there was a distinct computational advantage to using the normal equations. For wave-equation multiple suppression, there is no computational advantage in forming the normal equations. Computational savings come from pretabulating the bracketed terms in (3.5) and (3.6), which depend only upon the input data and the initial filter estimates.

This estimation procedure improves on past applications in one of two ways:

1. Fitting error is measured at the surface. This gives me an advantage over Riley, Estevez, Morley, or Wiggins because they measure fitting error at a seafloor, where data is neither recorded nor processed.
2. Reflection operators are placed at the seafloor. This gives us an advantage over Bernth and Sonneland or Berryhill and Kim who posit a fixed seafloor location, and design adaptive filters at the surface to try to compensate for errors in location, strength, and duration of their seafloor reflection model.

3.6 APPLICATION: BARENTS SEA

In Section 2.6, I applied surface-consistent deconvolution to a marine line from the Barents Sea in an unsuccessful attempt to suppress water-path multiples. Figure 3.2 shows a stack of that line. It features a hard, flat seafloor at 0.4 s, a gently dipping primary at about 1.5 s, and multiple trains following both. The stacking process has attenuated the pure seabottom multiples, but the pegleg stacks in strongly because its moveout is near the primary stacking velocity.

Conventional multiple suppression

From the center of this line, I take a window of 56 CDP gathers, each 48-fold and 4.1 seconds (1 024 samples) long. Figure 3.3 shows a stack and some representative gathers. The pure seabottom multiple beginning at 0.8 s is attenuated by the stacking, but the pegleg multiple at 2 s remains quite strong. As Figures 3.4 through 3.6 show, conventional processing does not successfully remove these multiples. Figure 3.4 is the best result of several runs of F-K multiple attenuation. This process applies a moveout correction intermediate between multiple and primary velocity and applies half-plane filtering to attenuate undercorrected, presumably multiple, events. The moveout correction is then removed. Figure 3.5 is the result of gapped deconvolution before normal moveout. Figure 3.6 is the result of gapped deconvolution after normal moveout. The gap is 380 ms, just above the seafloor arrival; the filter extends 128 ms below that. Even with the intermediate moveout velocity positioned at water velocity, F-K processing attenuates the primary at 1.5 s. The gapped deconvolutions did at least some good in attenuating the pegleg multiple.

Wave-equation multiple suppression

At this point, I turn to wave-equation multiple suppression. Projecting the shot and receiver locations for the data window downward to the seafloor, I specify 156 seafloor stations at which to estimate 128 ms reflection filters. The resulting least-squares problem has 5 184 unknown reflection filter coefficients to be estimated from 2 752 512 equations. The wave operator is precomputed using dip-limited phase shifts (Levin, 1983) to extrapolate between the surface and a datum time of 380 ms, just above the seafloor.

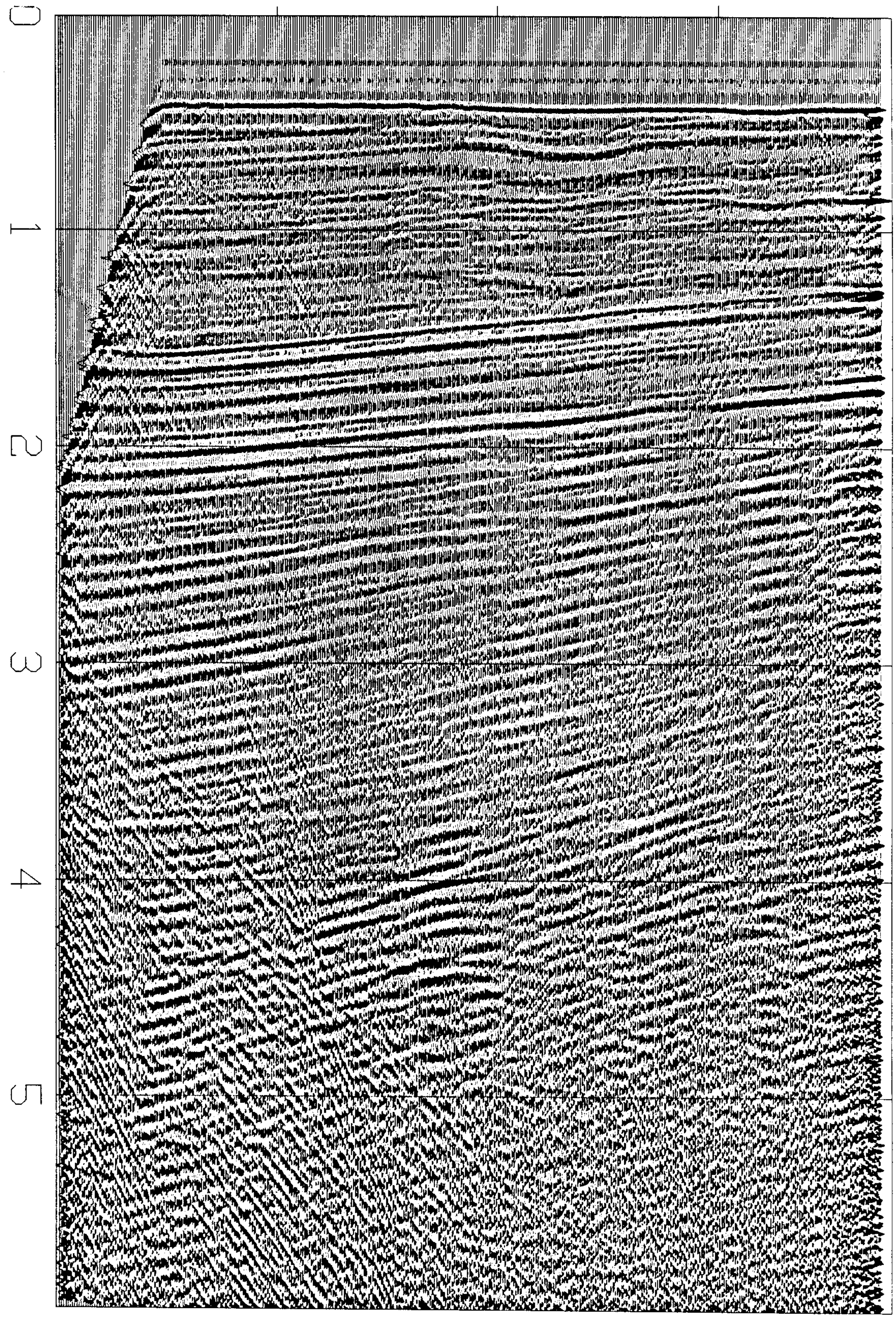

FIG. 3.2. Stack section for marine line from the Barents Sea. Trace spacing is 12.5 m; time sampling interval is 4 ms. The dipping primary at about 1.5 s is followed by a strong pegleg near 2 s.

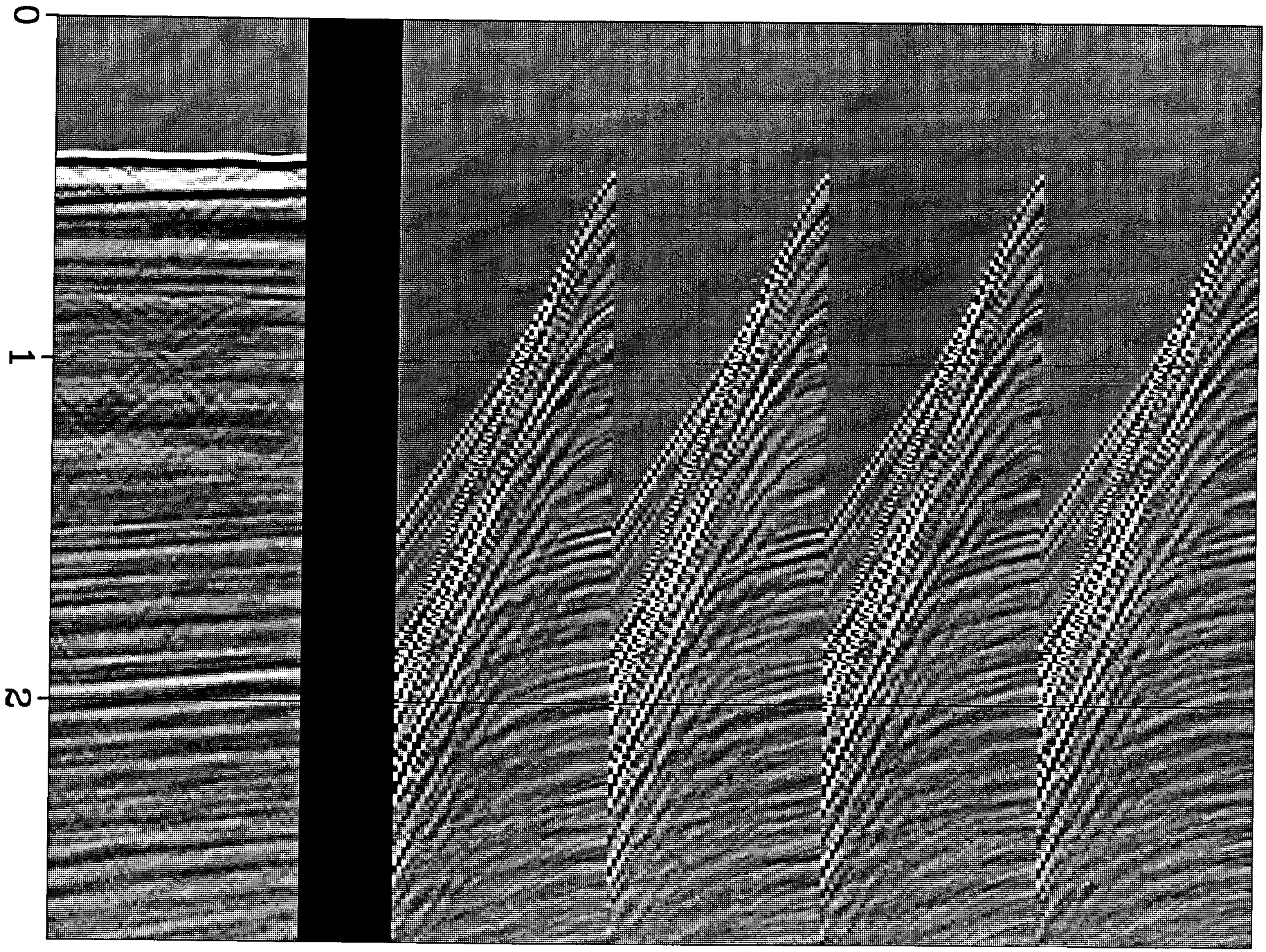

FIG. 3.3. 56 CDP stack and selected CDP gathers from the center of the Barents Sea profile of Figure 3.2. CDP interval is 12.5 m, time sampling interval 4 ms. Gathers are 48-fold with a 25 m trace interval.

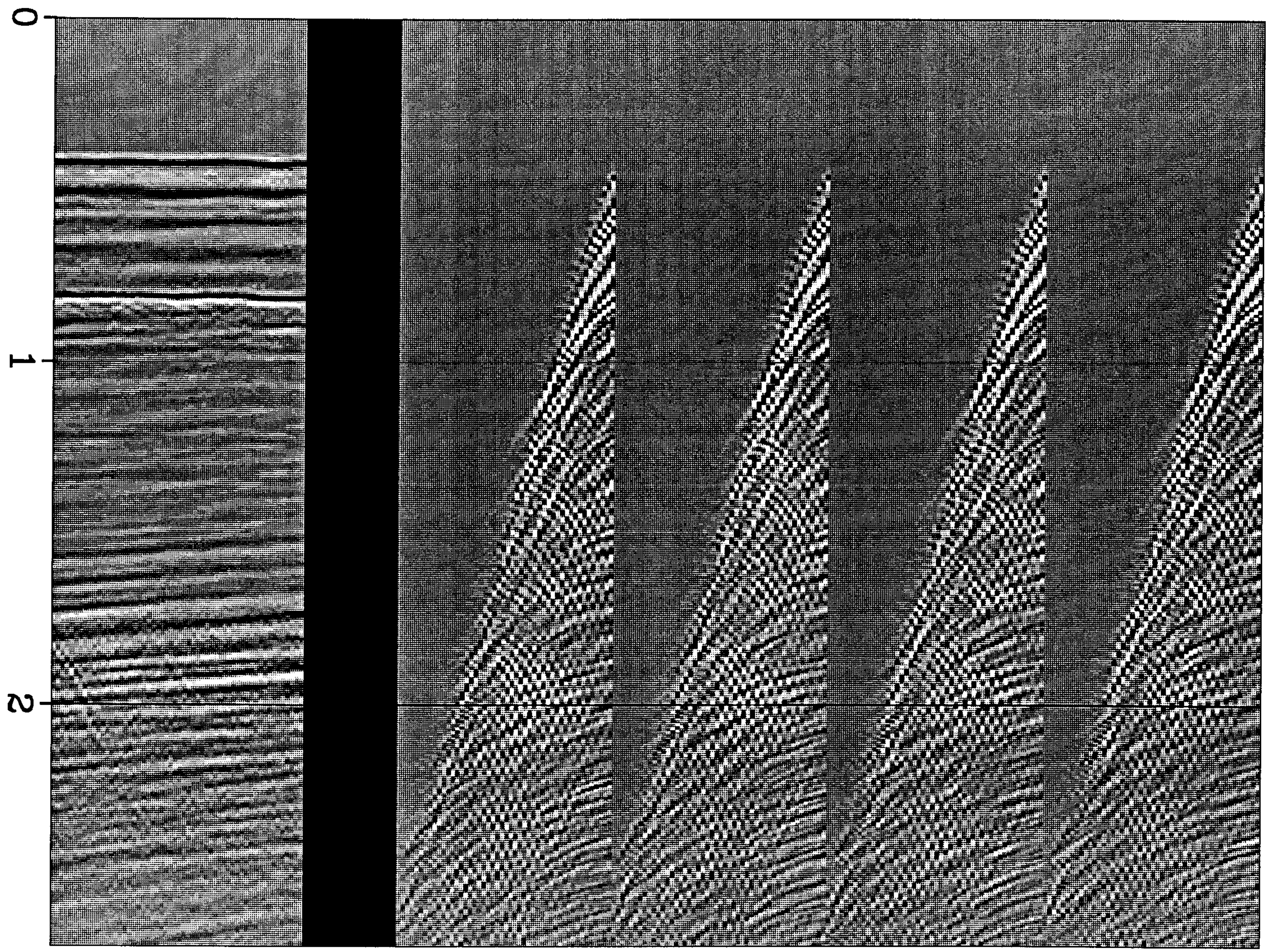

FIG. 3.4. Result of conventional F-K moveout filtering to attenuate multiples. The primary at 1.5 s is undesirably attenuated because its moveout velocity is too close to that of the pegleg at 2 s.

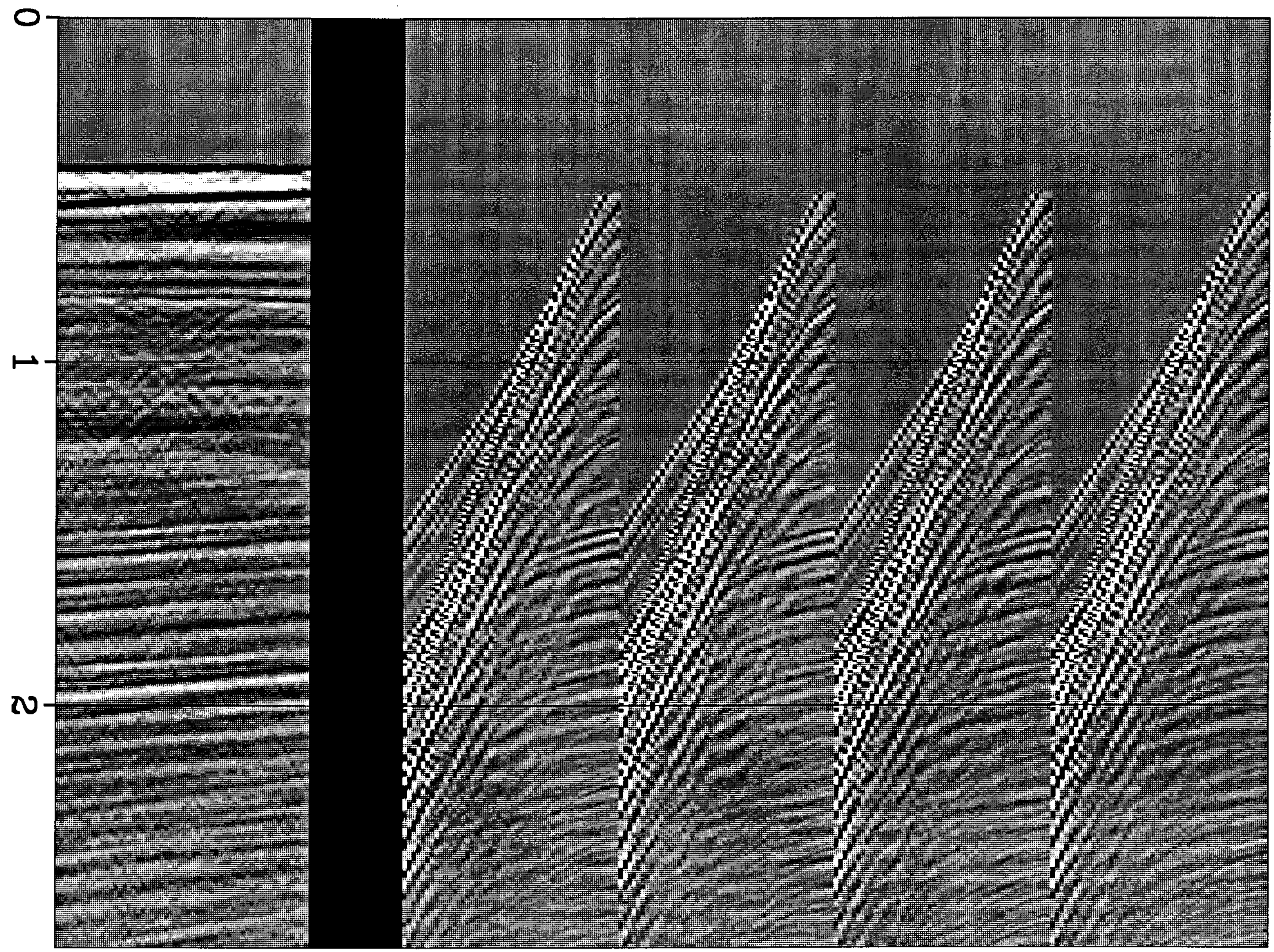

FIG. 3.5. Result of gapped deconvolution before normal moveout correction. The gap is 380 ms, the filter length extends an additional 128 ms. The pegleg at 2 s remains strong on the stack.

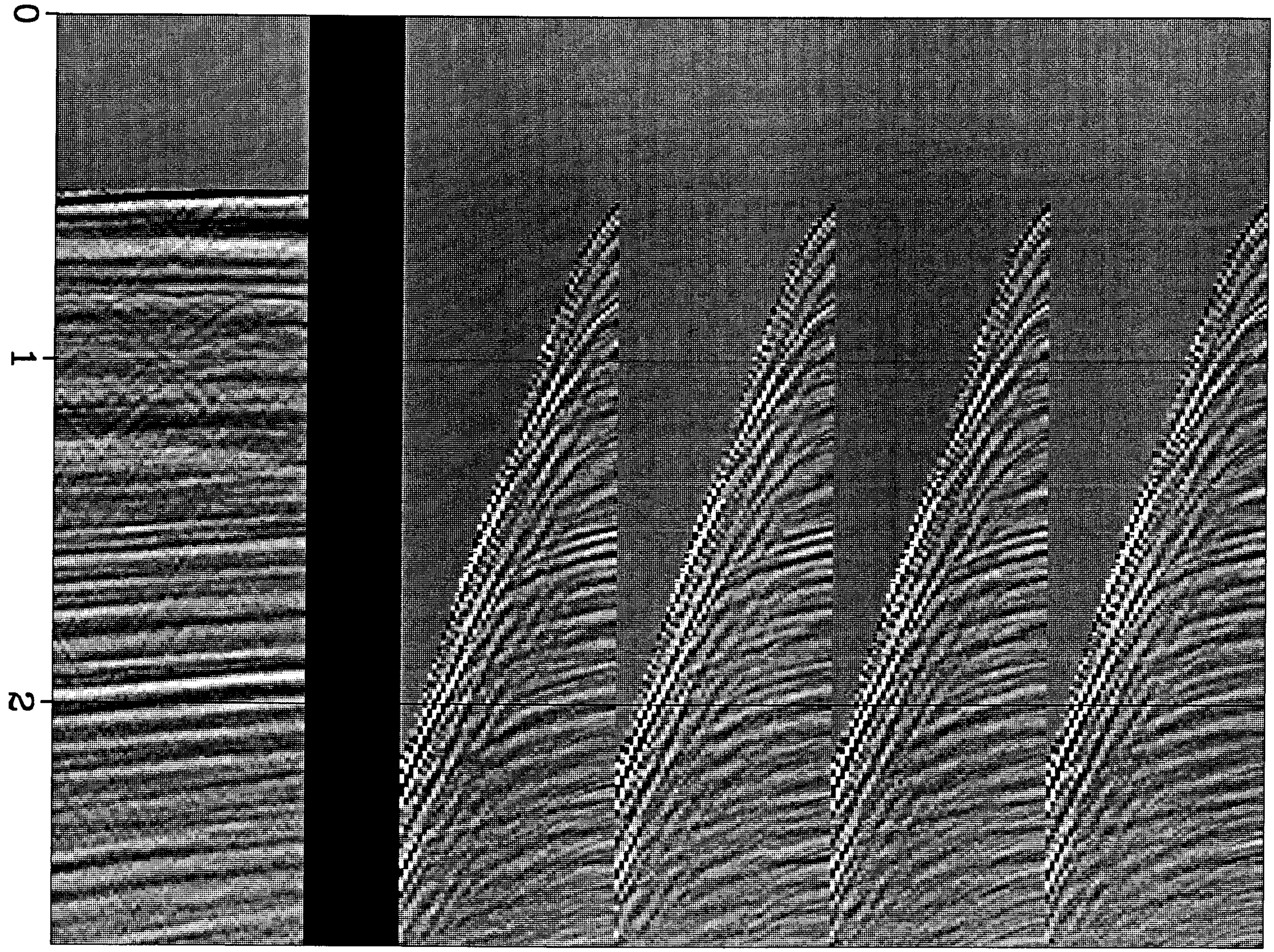

FIG. 3.6. Result of gapped deconvolution after normal moveout correction. Filter parameters are the same as for Figure 3.5. Normal moveout is removed from the CDP gathers before display. Again, the pegleg at 2 s remains strong on the stack.

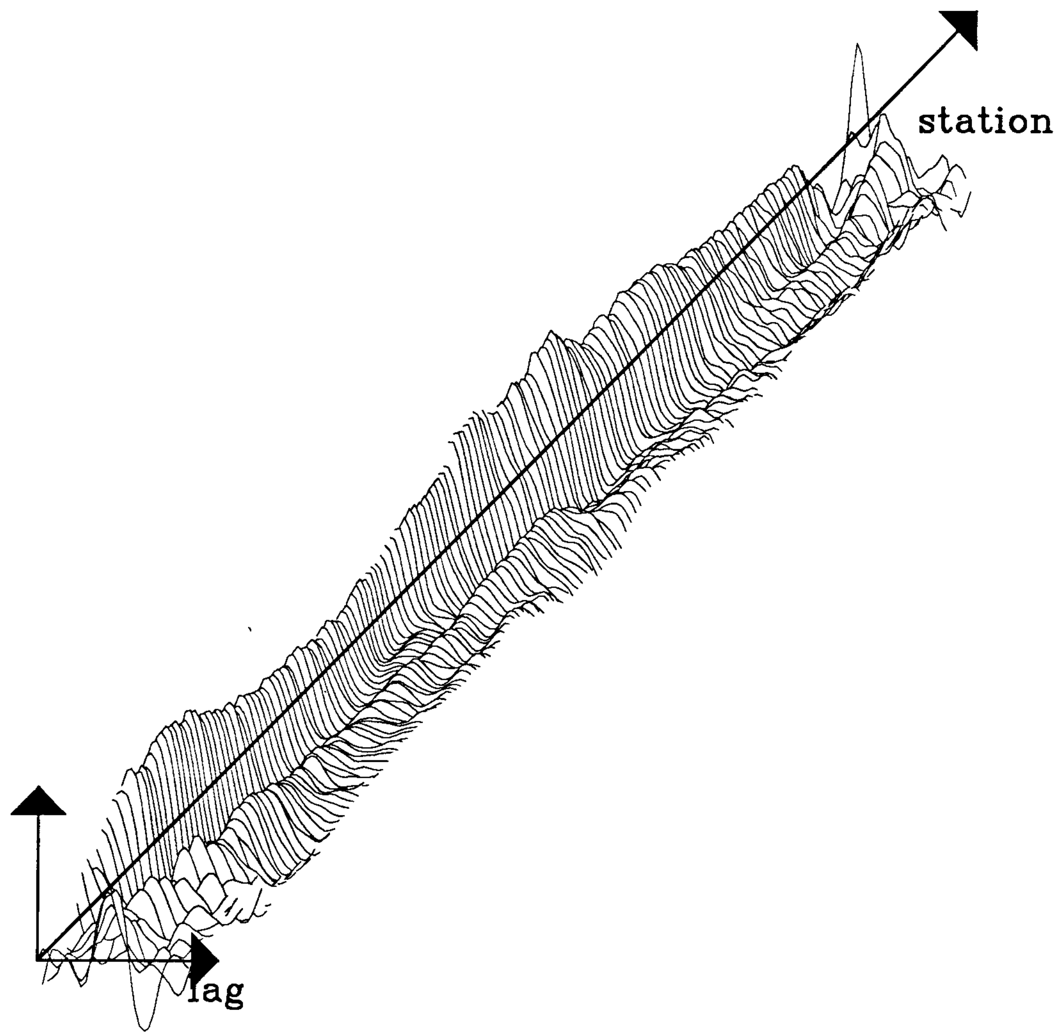

FIG. 3.7. Seafloor reflection operators designed by least-squares. The result of five conjugate-gradient iterations, these filters are convolved with the extrapolated gathers at the seafloor to suppress water-borne multiples.

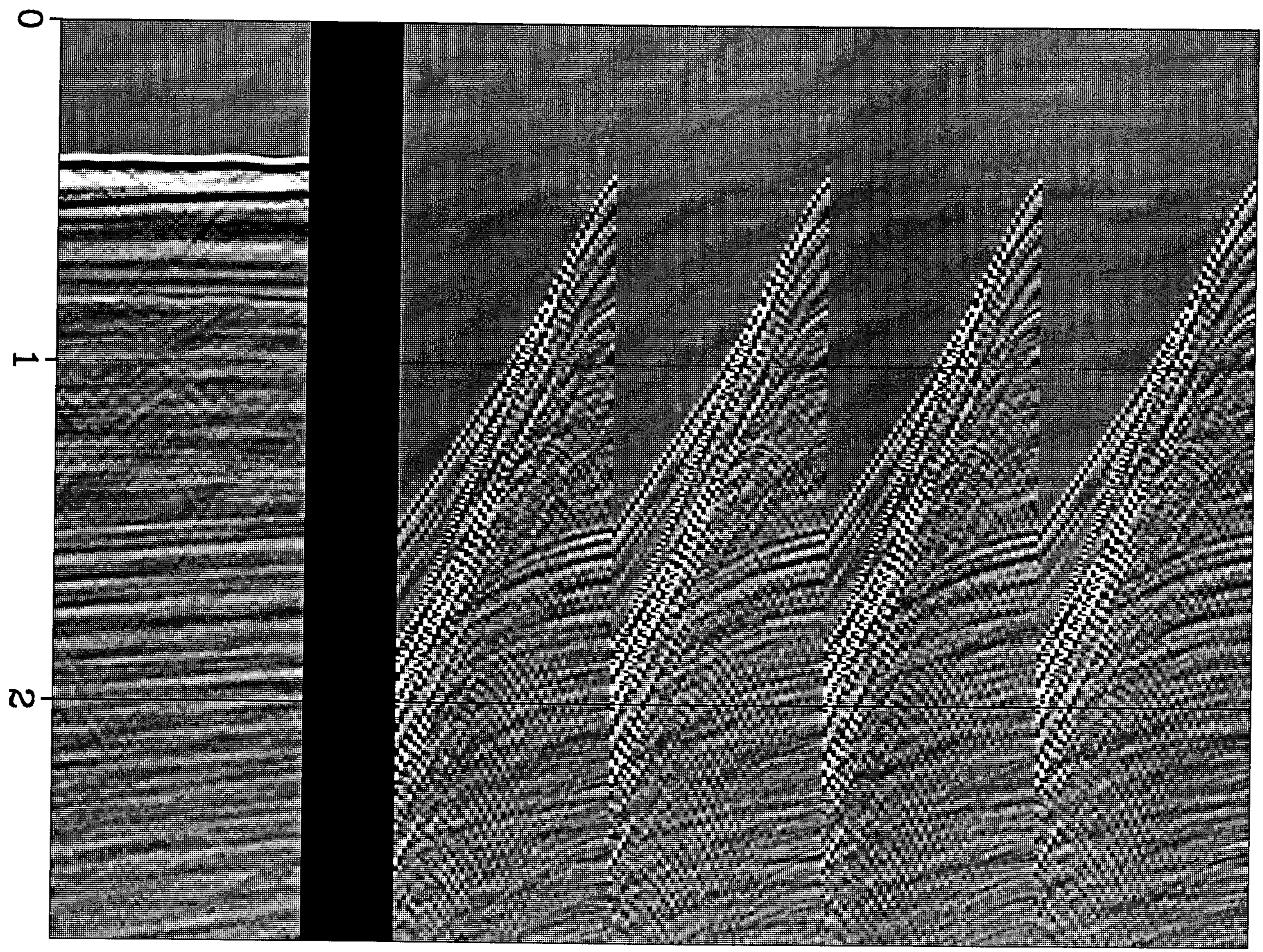

FIG. 3.8. Stack and selected CDP gathers after seafloor-consistent multiple suppression. The pegleg at 2 s is attenuated significantly on both the gathers and the stack. The pure seafloor multiple is attenuated by the stacking, but remains strong on the CDP gathers.

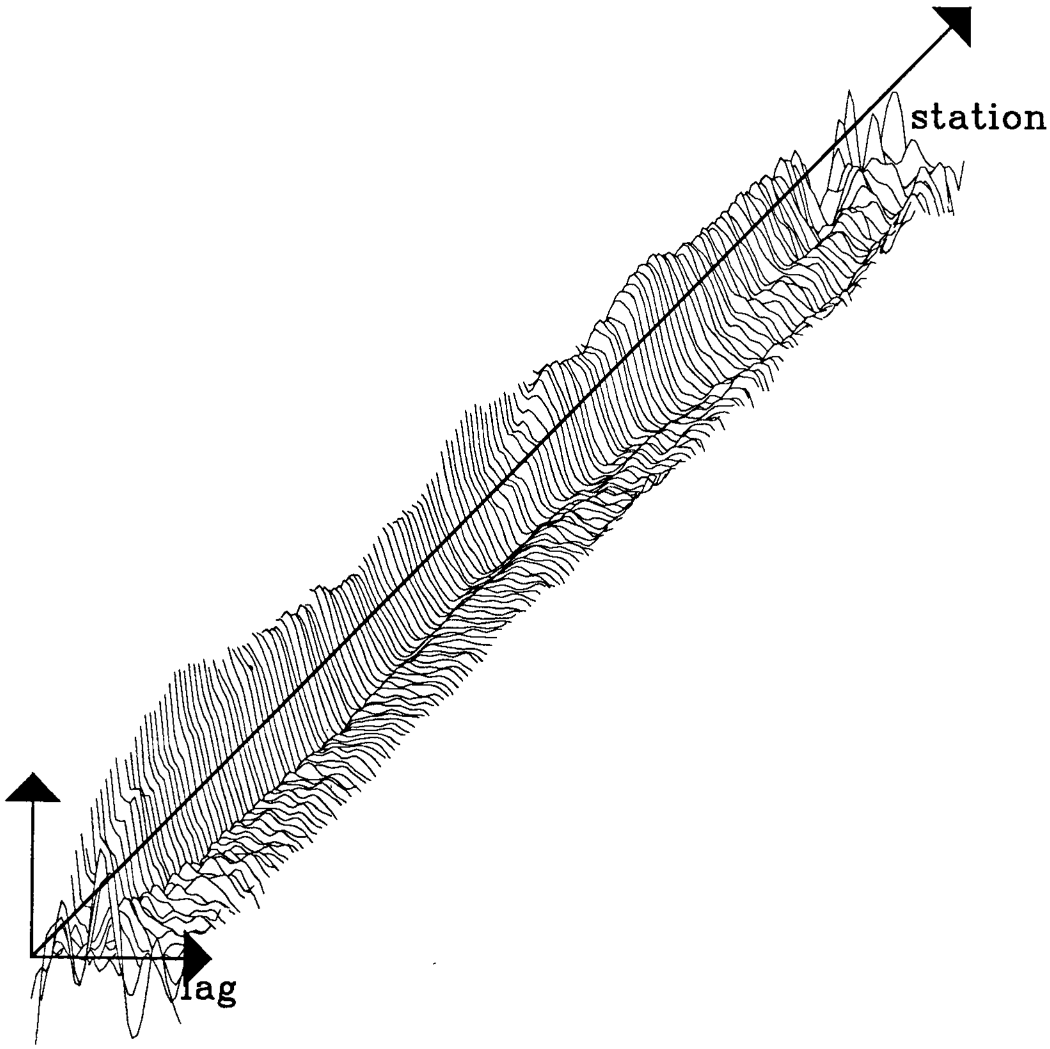

FIG. 3.9. Seafloor reflection operators designed using the filters of Figure 3.7 as a starting point.

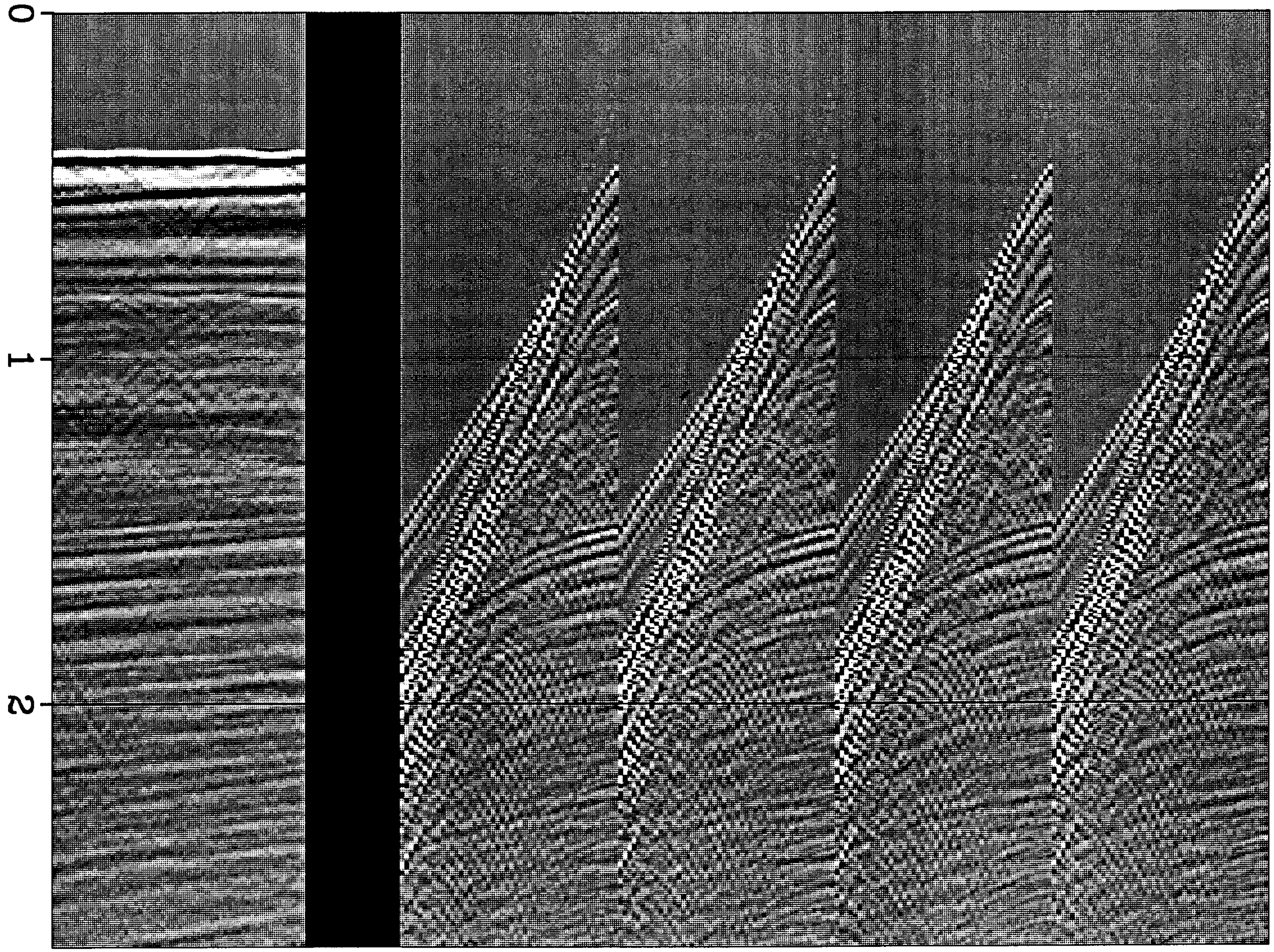

FIG. 3.10. Stack and selected CDP gathers after seafloor-consistent multiple suppression with the filters of Figure 3.9. Comparing with Figure 3.8, we see no visible difference in multiple attenuation.

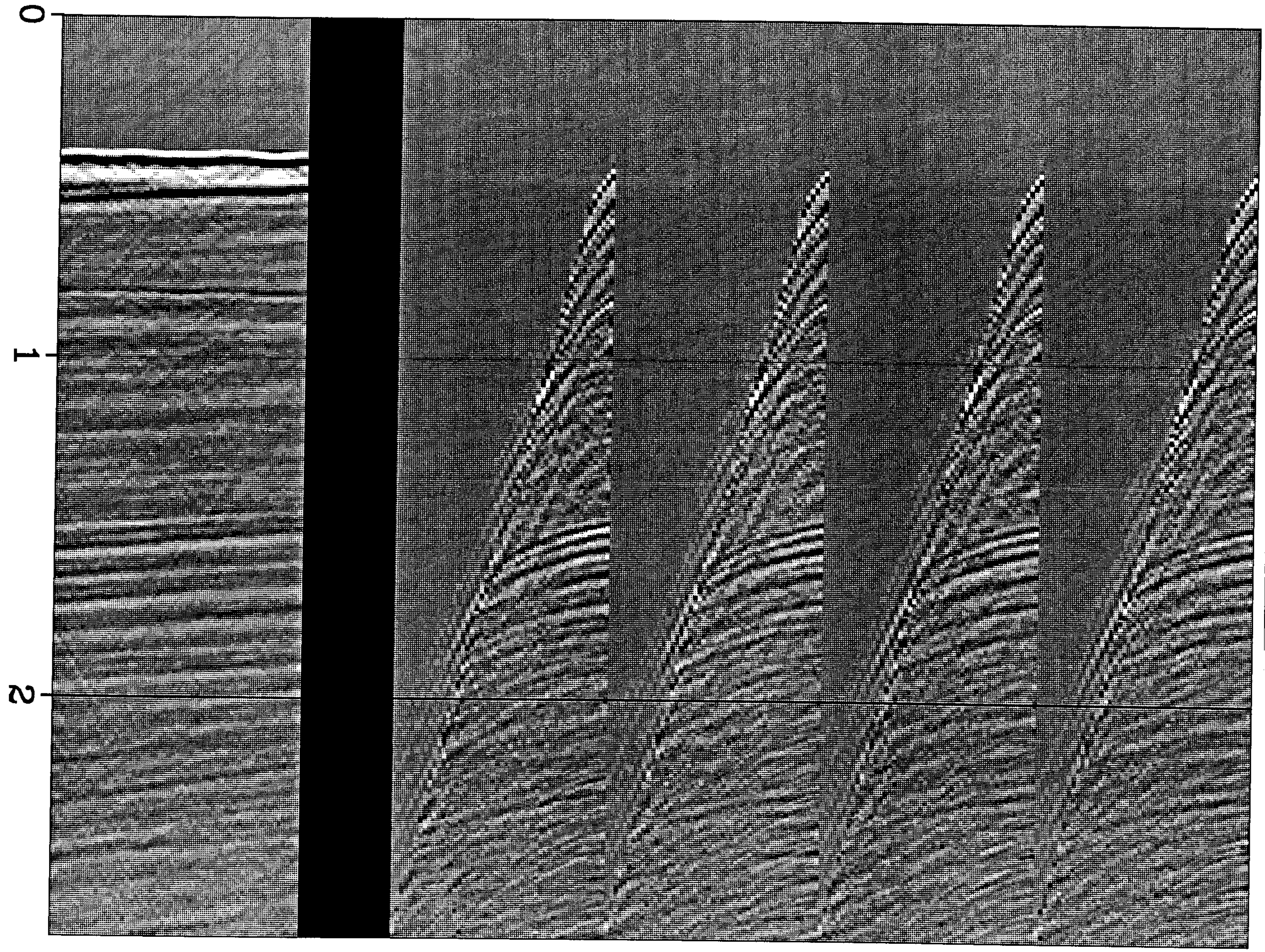

FIG. 3.11. Stack and selected CDP gathers after seafloor-consistent multiple suppression where the wide-angle arrivals have been removed by muting. The mute was applied above a hyperbola with apex at 250 ms and a velocity of 1100 m/s. Multiple attenuation is improved because I have removed aliased events inappropriate to my underlying model for reflection amplitude.

Figure 3.7 shows the seafloor reflection filters resulting from 5 conjugate-gradient iterations to solve equation (3.3). The starting point for the design is $c_0 \equiv 0$. Figure 3.8 shows the corresponding stack and some CDP gathers after this processing. We see a marked improvement in pegleg multiple suppression.

Of course, one may argue, starting with $c_0 \equiv 0$ is an abysmally poor first guess. $c_0 \equiv 0$ means we think the seafloor is transparent. If this were so, we wouldn't be worrying about seafloor multiples. It does have a practical advantage. Half the terms in the matrix-vector products in equations (3.5) and (3.6) go away, thereby saving about the same fraction of computer time. Also no data preprocessing is needed to specify a zero starting model.

Is this shortcut justified? How much better can we do starting with a reasonable first guess? To answer this, I use the filters from Figure 3.7, i.e. the output of the first run, as the starting model for a new filter design. The results, shown in Figures 3.9 and 3.10, are nearly the same as starting from $c_0 \equiv 0$, but cost nearly twice as much to compute. Overall, it would be more cost effective to instead let the $c_0 \equiv 0$ design proceed for twice the number of iterations.

3.7 THE MULTIPLES THAT GOT AWAY

Wave-equation multiple suppression has done a superior, but not a perfect, job of removing water reverberations. On the stack of Fig. 3.10, we still see some residual pegleg at 2 s, and only a little attenuation of the pure water bottom multiple at 0.8 s. If we look at the individual CDP gathers before and after multiple attenuation, we find: a) the pure seabottom multiple is suppressed at all but the near offsets; b) the deeper pegleg is attenuated at all offsets; c) the aliased, steeply-dipping refractions, wide-angle reflections, and multiply-reflected refractions are producing hyperbolic artifacts on the gathers that do not appear on the stack; and d) the multiples of the seafloor diffractions are not attenuated on the stack.

Inner offsets

The shallow seabottom multiple remains on the inner offsets because of the finite recording aperture of the cable – specifically the nonzero inner offset. The direct seafloor reflection needed to predict the first multiple at the inner offsets arrives at the surface at half the inner offset. It is therefore not in the recorded data. Berryhill and Kim (1986) recommend some amount of interpolation into the missing inner offset range to alleviate the problem. This is much less of a problem for deeper events when the raypaths are closer to vertical. This is why we observe good attenuation of the deeper pegleg arrivals at 2 s and 2.4 s, which are more gently sloping at the inner offsets than the water bottom multiple at 0.8 s. Berryhill and Kim also recommend using reciprocity to extend the gathers. This is most useful for processing arrivals from dipping beds and diffractions.

Post-critical arrivals

Because of aliasing, the wide-angle reflections and refractions generate hyperbolic artifacts on the processed gathers. Their influence on the stack is small for two reasons. First, and foremost, they do not line up along primary stacking hyperbolas. They're more nearly perpendicular than parallel. Stacking therefore discriminates against them. Second, the artifacts are spreading the energy on the wide-angle arrivals over a much greater area, giving them correspondingly lower amplitudes. This makes the original linear events (at least those remaining after processing mute) stack in weaker as well.

Even though they stack in weakly, the hyperbolic artifacts do bias the regression for the seafloor derverberation filters. My least-squares design measures the prediction error on the individual traces in the field records, not the output power on the stack. We should endeavor to reduce the level of these artifacts and the weight assigned to them in the least-squares procedure.

Trace interpolation to reduce aliasing is an inappropriate way to remove the hyperbolic artifacts because it will increase the influence of wide-angle arrivals on the seafloor reflection filter estimates. The multiple trains following wide-angle reflections and refractions fit neither the R^n amplitude decay of pure seabottom multiples, nor the $(n+1)R^n$ behavior of near-offset peglegs. These post-critical arrivals are built up from trapped modes and are dispersive, but do not lose energy into the subsurface. In the far-field, they decay with normal spherical divergence $1/r$ (Pekeris, 1948; Officer, 1953.) In the vicinity of critical incidence, the usual case in seismic exploration, the decay is even slower (Hatherly, 1982.) On a far offset trace in Fig. 3.3, I compared the amplitudes of two multiples from the first arrival, a refraction, and found the decay proportional to $1/\sqrt{r}$.

Because they do not fit the multiple model I've used, the wide-angle arrivals degrade the multiple-attenuation process. For Figure 3.11, I muted the near- and post-critical arrivals before wave-equation multiple-attenuation. Comparing this result to Figures 3.8 or 3.10, we see this improves the pegleg attenuation both on the individual gathers and on the stack. The mute has done double duty: it has removed aliased energy and suppressed wide-angle multiples that do not fit the model for multiple amplitudes I've used.

Seafloor diffractions

I cannot say with certainty why diffractions remain attached to the seafloor multiple after processing. Certainly some of this an aperture problem as diffracted energy arrives at the surface at all possible angles. For this, Berryhill and Kim's trick of enlarging the aperture by reciprocity should help. Also, the spherical divergence of diffractions is asymptotically proportional to $1/t^2$, whereas 2D wave extrapolation expects them to decay as $1/t$. Thus the $\sqrt{t}$ correction in equation (3.2) is inappropriate for the diffractions. Adding a seafloor bounce with wave extrapolation should therefore not produce the right amplitude. For this reason it is probably fortunate that the diffractions are weak on the gathers and thus have little influence on the early least-squares filter design iterations. Wiggins (1986), however, shows an example where there was a significant attenuation of these diffraction multiples. Since he uses an L^1 minimization instead of L^2 minimization, this suggests that the filter design method plays a role. However, it could also arise from dip-filtering in his Kirchhoff wave extrapolation operator, as his processed gathers are obtained by extrapolation back to the surface after minimizing the fitting error at the seafloor.

In an attempt to better predict amplitude and phase of the diffracted multiples on the data, I tried 3D wave extrapolation instead of $\sqrt{t}$ scaling and 2D extrapolation in order to more closely model the physical experiment which I am modeling. For this purpose, I used a 2.5D code (3D wave propagation, 2D earth model), courtesy of Norman Bleistein and Paul Docherty at the Center for Wave Phenomena, Colorado School of Mines, to model an impulse response for a point diffractor on the seafloor. I substituted this impulse response (and its transpose) for the operators used to extrapolate to and from the seafloor in equations (3.3), (3.5), and (3.6). The results were poor and got worse as the number of design iterations increased. The problem is a combination of wraparound artifacts and aliasing. The modeling program is simply too good. The high frequency and dip content of the synthetics make them unsuitable as wave extrapolation operators until frequency and dip filtering comparable to those I used in my 2D phase-shift operators is applied. This I leave to future studies.

Further directions

One other possible direction for improved multiple suppression is to incorporate some angle dependence in my model of seafloor reflection. This can be done in several ways. Conceptually, the simplest way is to work in the slant $p-\tau$ domain. There, like Estevez (1977), we can directly specify a model of reflection coefficient, and source directivity, as a function of angle. A similar model can also be incorporated into the phase-shift operators I currently use. One must remember that since these are plane-wave reflection coefficients, they will only be correct for a flat seafloor and will not account for local inhomogeneities at the seafloor. We've seen in Chapter 2 that such inhomogeneities distort the multiple waveform, making it hard to predict. An alternative to plane wave decomposition is to design a 2D convolutional reflection filter at each seafloor station in order to accommodate angular dependence. This approach was suggested by the work of van der Schoot, Wapenaar and Berkhout (1985). Since the number of equations is several hundred times the number of parameters in the 1D filter design, the 2D convolutional filters can safely be allowed to be quite wide.

3.8 SUMMARY

I have developed a new seafloor-consistent method for suppression of marine multiples. I applied it to field data and found it worked well where conventional methods and surface-consistent deconvolution did not. This confirms that wave-equation modeling can do a superior job of predicting the timing and amplitude of water-path multiples. My choice of modeling and filter estimation procedure differs from previous applications in some or all of the following aspects: truly seafloor-consistent filters; incorporation of the pure seabottom multiple; fitting error minimized at the surface; and simultaneous design using all the recorded data.