Ensemble-based deconvolution: when and why

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ABSTRACT

Techniques for deconvolving seismic data often use the statistical properties of the data themselves in designing operators to apply to the seismic traces. In the early stages of seismic processing, individual seismic traces are usually members of one or more ensembles like shot gathers or receiver gathers, and their statistical properties are related not only to their own intrinsic character, but also to that of neighbouring traces within the ensemble. We demonstrate that seismic traces contaminated primarily by bands of coherent noise are often best deconvolved singly by a non-stationary algorithm like Gabor deconvolution, but traces uniformly contaminated by varying levels of random noise are better deconvolved by estimating an average operator for all the traces in an ensemble.

INTRODUCTION

The problem

Gabor deconvolution, introduced by Margrave et al. (2001, 2002a, 2002b, 2003), is a non-stationary process which adapts to time-varying characteristics of a seismic trace in order to provide the optimum deconvolution. As such, it adapts readily to seismic traces which are contaminated by short bursts of interfering coherent noise, during deconvolution operator construction. A short noise burst typically does not affect more than one or two time windows of the Gabor transform, and the noise will therefore only minimally influence wavelet determination. Random noise, like wind noise on a geophone, however, poses quite a different challenge, since it may persist for the entire length of a seismic trace. The net effect of this is to limit the signal bandwidth available for whitening by the Gabor operator in all time windows. For zero phase whitening, this is not a severe problem; but if the desired result is minimum phase, the phase computation, and therefore event timing, is directly affected by the bandwidth. Low noise traces with broader signal bandwidth will yield deconvolved events whose minimum phase peak amplitudes occur slightly earlier in time than those on high noise traces with less bandwidth. The phase of an event on a stack trace will thus depend on the specific blend of low-noise and high noise input traces contributing to it. Since this mixture will typically vary from one CDP to the next, the result is apparent lateral phase instability or event splitting along a stacked reflection.

A solution

One way to alleviate this problem is to average the Gabor transform used for operator design over an ensemble, when the traces within the ensemble exhibit varying levels of contaminating random noise. The result of applying this average operator to all the traces in the ensemble will be deconvolved traces whose bandwidth may not be as large as that of the best traces in the ensemble, but whose event phase will be consistent across the ensemble. In effect, an ensemble with S/N varying with each trace exhibits non-stationarity not only in time, but in offset. An ensemble average of the Gabor transform is an approximate way to counter this. The most obvious ensemble to use with this approach is the shot gather, since the wavelet should be more consistent than for other ensembles, but receiver gathers may also be appropriate.

The future

Ultimately, it might be desirable to implement an algorithm which would accommodate non-stationarity in the offset dimension with overlapping windows of weighted traces, similar to what is currently done in the time dimension in the current algorithm. Doing this rigorously would mean defining a three dimensional Gabor transform in which the third dimension would be offset. Offset would be windowed using overlapping weighted windows (perhaps Lamoureaux windows, as in the time domain). The additional dimension would also provide new opportunities for averaging to determine the time-and-offset dependent wavelet characteristics.

DEMONSTRATION

The problem illustrated

The issue of event phase stability after deconvolution has been raised by Mike Perz, among others, when he compared our current version of Gabor deconvolution with the more traditional surface-consistent approach (Perz et al., 2005). Specifically, a synthetic data set created by Mike for testing deconvolution exhibited lateral phase instability for several of the weaker events in the stacked section, when processed in a conventional fashion using Gabor deconvolution in its single-trace derive and apply mode. The model created by Mike from a well log was deliberately contaminated with relatively high levels of both coherent and random noise. While the coherent noise strength was constant across any particular shot gather, the random noise, simulating wind on geophones, varied greatly in strength from trace to trace within each shot gather, and from shot to shot. Figure 1 shows a shot gather of synthetic traces with no attenuation and no noise added, the so-called “ideal” data set. Figure 2, on the other hand, shows the same gather with Q-filter (a minimum phase operation which asymmetrically broadens and delays reflection events) applied to simulate earth attenuation, and contaminated with additive random noise whose amplitude varies dramatically with offset in the gather. Figure 3 shows yet another gather with the additional complication that simulated ground roll has been added to the gather after Q-filtering and wind noise addition. In all cases, a single synthetic trace was repeated to form a shot gather, forward moveout applied to the gather traces, Q filtering applied, and the simulated noise added to the traces (Montana et al, 2006). In figures 1-3, moveout has been removed for clarity (some trace timing irregularities visible on the plots may be due to the forward NMO/Q-filter/inverse NMO sequence). The synthetic model whose shots include both wind noise and ground roll will be used for the current demonstration.

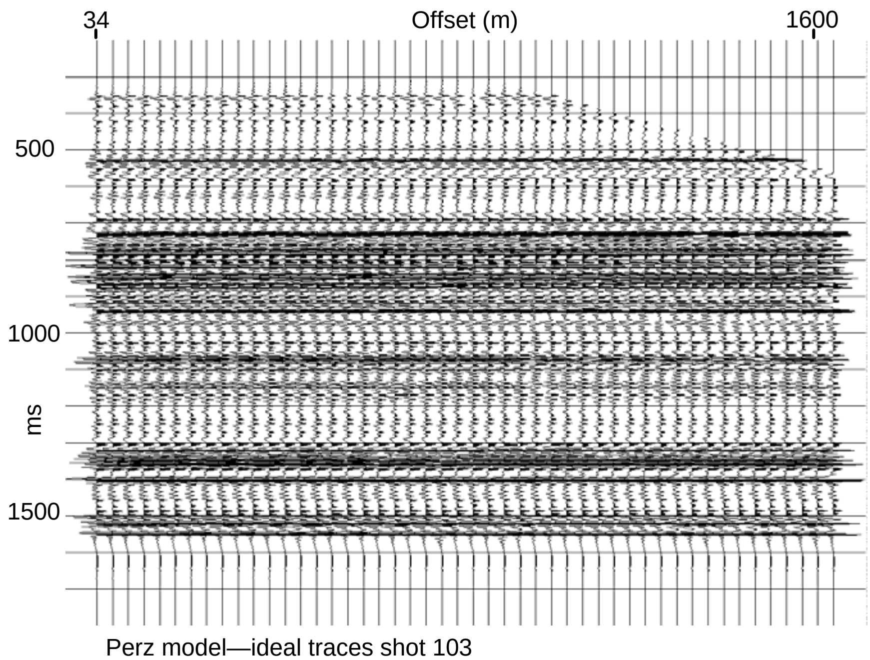

FIG. 1. One shot gather of a model line created by Mike Perz for testing deconvolution methods. The model is based on a well log and consists of 80 shot gathers, covering 446 CDPs. Shown above is the noise-free, full bandwidth “ideal” shot gather. NMO has been removed.

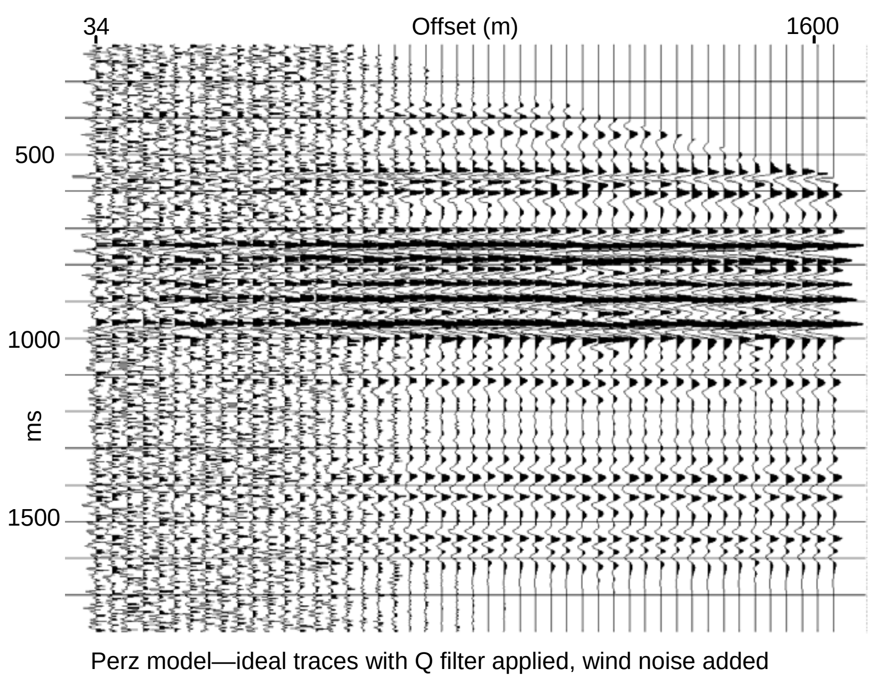

FIG. 2. Perz model shot gather after application of Q filter and addition of random noise with varying amplitude. Note the time lag of later events, compared to Figure 1, caused by the Q filter. A successful deconvolution will restore these events to their “ideal” positions. NMO has been removed.

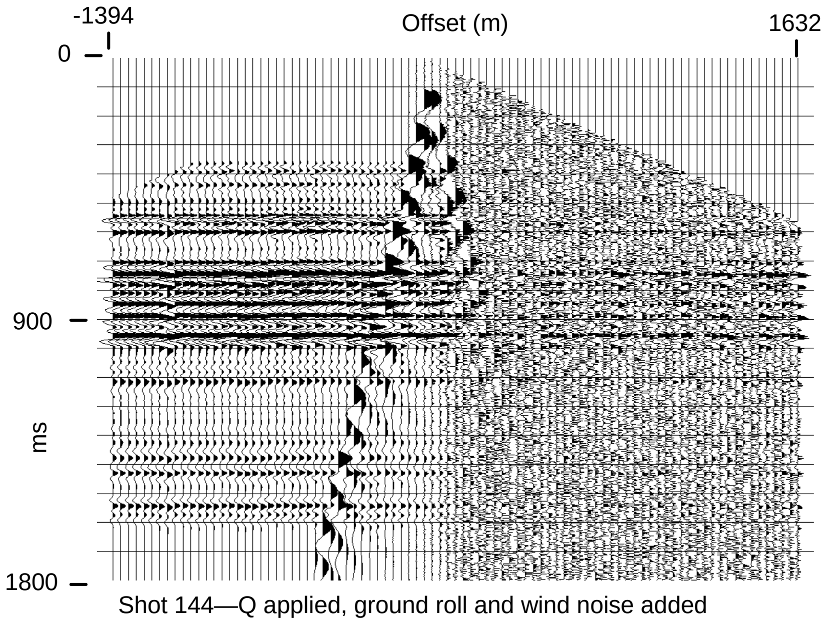

FIG. 3. Perz model shot gather with Q filter applied and with both simulated ground roll and offset-varying wind noise added. NMO has been removed.

The baseline standard for all following comparisons will be the noiseless, full bandwidth “ideal” data set. A portion of the stack of the 80-shot line is shown in Figure 4 for comparison to all other stacks presented. The ideal data have been zero-phase bandlimited to 8-12-55-70 Hz to make the comparisons more visually compelling. To illustrate the phase instability problem, we applied Gabor deconvolution in its single trace derive and apply mode to the noisy shot gathers, using a very low stability factor in order to force the Gabor algorithm to whiten the data as much as possible. The deconvolved traces were then NMO corrected and stacked, with the result shown in Figure 5. While the stronger and shallower events are flat and have consistent phase, some of the deeper, weaker events show peak splitting, time shifting, and other evidence of phase instability that varies with CDP.

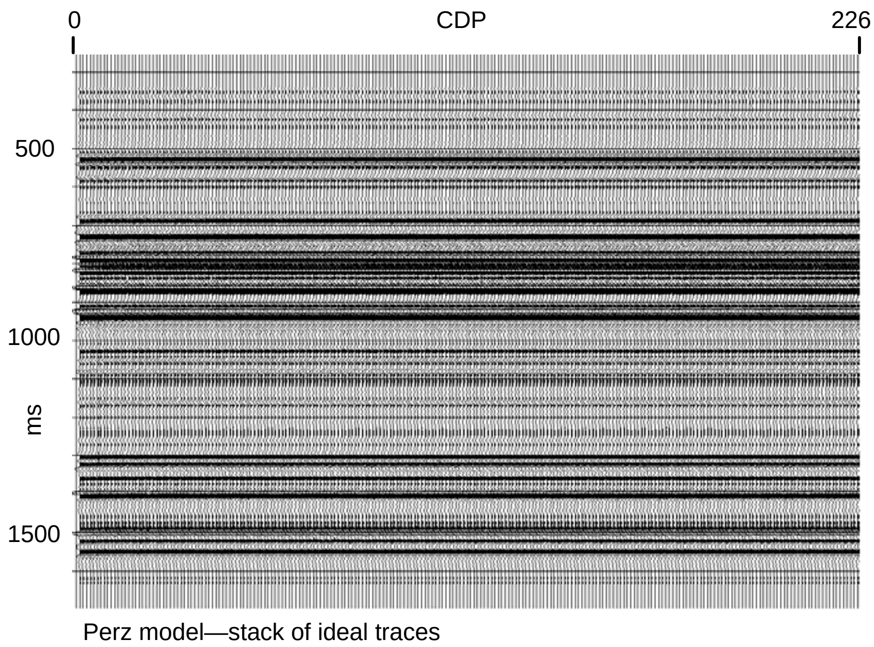

FIG. 4. Stack of noise-free "ideal" traces

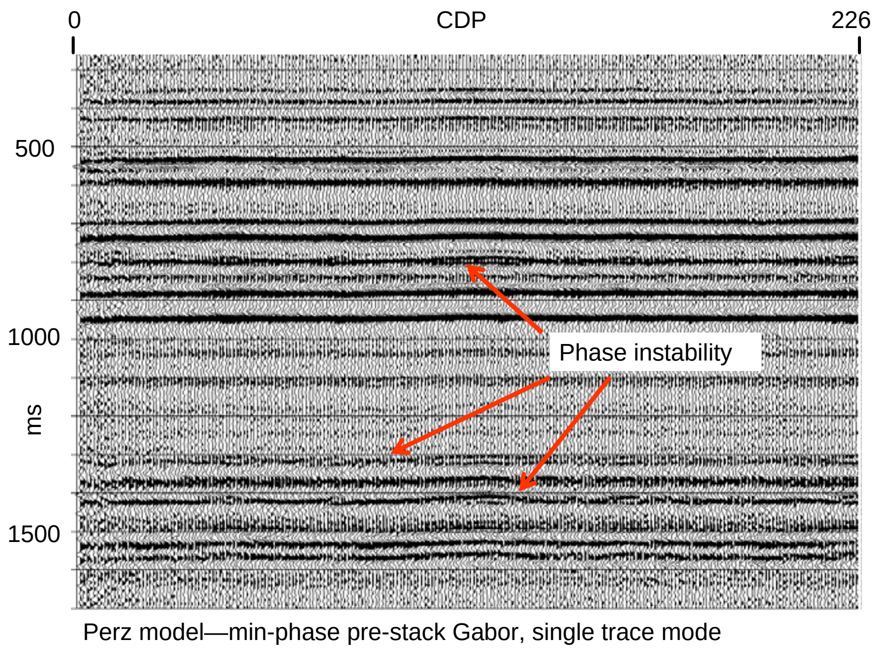

FIG. 5. The problem—phase instability in the stack

The cause illustrated

We select shot 144 from Mike Perz' data set to illustrate the phase instability problem with the Gabor deconvolution single trace mode, since this shot has both additive coherent noise and additive random white noise whose intensity varies with offset. Figure 6 shows the ideal shot with no Q or additive noise, while Figure 7 shows the same traces with Q applied (notice, in particular, that application of a Q factor leads to delays of the reflection event peaks that are proportional to transit time, as we expect). A successful deconvolution algorithm should be able to whiten the spectrum and to restore the reflection events to their proper transit times. We first apply Gabor deconvolution in its single trace derive and apply mode and ask for zero phase output. The stability factor is very small (0.00001) in order to force the algorithm to whiten as much as possible. The gather in Figure 8 is the result. It is obvious here that the traces have been considerably whitened, but that event timing is unchanged (compare with Figure 7), since Q has not been removed properly (Q is a minimum phase effect). When Gabor deconvolution in its single trace mode is constrained to produce a minimum phase result, as in Figure 9, however, not only are the events whitened, but they are also collapsed towards their inception time, making them approach their ideal positions (compare with Figure 6).

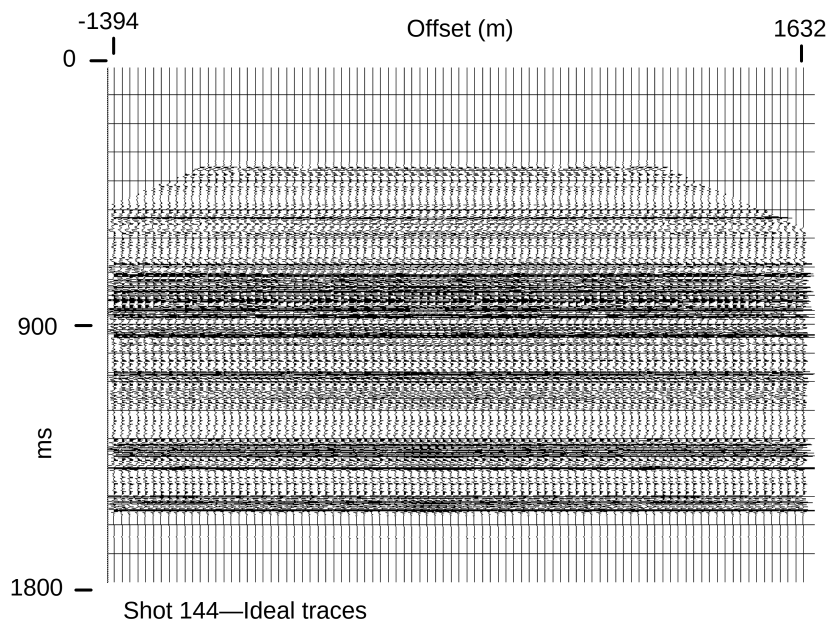

FIG. 6. Perz model shot 144 ideal traces, no Q applied, no additive noise, NMO removed

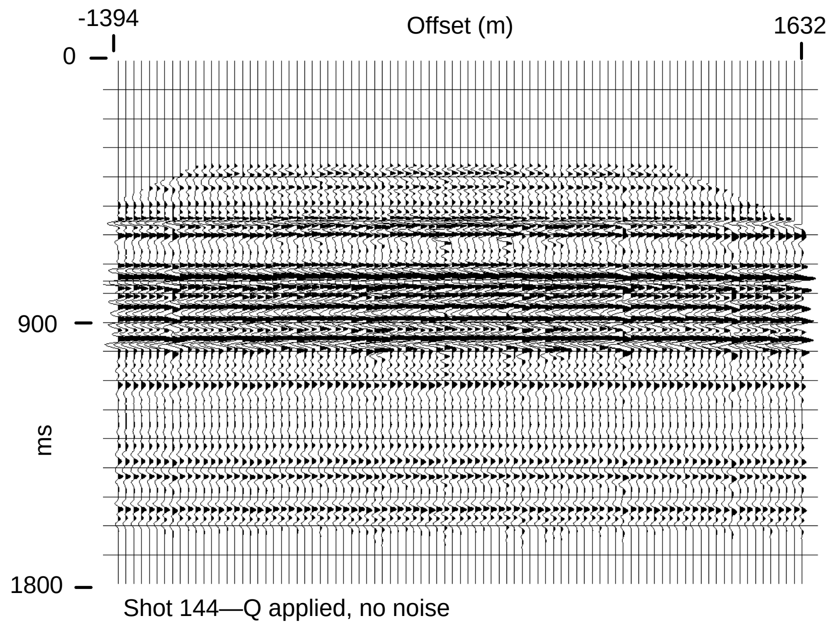

FIG. 7. Perz model shot 144 with Q applied, NMO removed

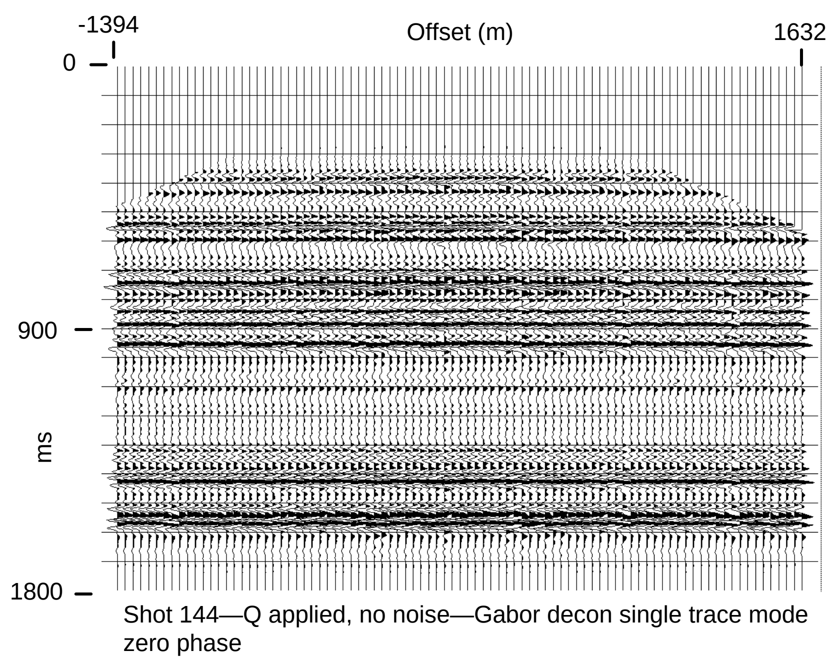

FIG. 8. Perz model shot 144 with Gabor deconvolution in single trace mode, zero phase, NMO removed

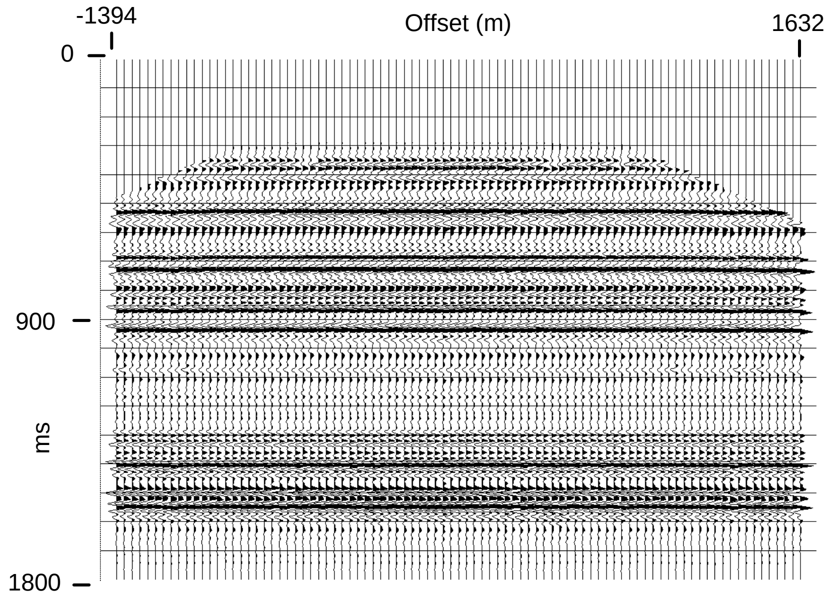

FIG. 9. Perz model shot 144 with Gabor deconvolution in single trace mode, minimum phase, NMO removed

The situation changes, however, when we add coherent noise as well as varying levels of random noise to the gather after applying Q, as in Figure 10. The use of the zero phase option of Gabor deconvolution in single trace mode results in the gather shown in Figure 11. The coherent noise obviously has little effect, and we also see no variation in event timing in the presence of varying levels of random noise on this gather. Nevertheless, the zero phase result gives the wrong event timing relative to the ideal data. The minimum phase option of single-trace mode Gabor deconvolution leads to the results in Figure 12, however, where the effects of varying levels of random noise are quite evident. As with the zero phase mode, the coherent noise does not significantly affect the deconvolution; but in this case the varying level of random noise directly affects the phase of the deconvolved events. As the level of random noise increases, the deconvolution is able to see less signal bandwidth, and the whitened spectrum is more representative of the additive noise than the underlying signal. The minimum phase constraint means that the phase for each frequency is computed uniquely from the amplitude (magnitude) spectrum. Since the random noise spectrum is broad and is not affected by Q, minimum phase computed from it will differ very little from zero phase. This is, indeed, the effect we see in Figure 12. As the reflection signal is increasingly masked by noise (moving from left to right on the gather), there is less signal bandwidth with which to detect the Q effects, and the noise increasingly controls the phase computation. This means that events which are properly collapsed forward into their proper inception times on the noise-free traces on the left end of the gather fall increasingly close to their zero phase positions as the noise increases toward the right. Hence, when deconvolved traces from relatively noise-free parts of a shot gather are gathered by CDP with other deconvolved traces from noisy parts of other shot gathers, it is evident that the phase of stacked events will depend upon the relative proportion of noise-free and noisy traces, as well as the amplitudes of the events.

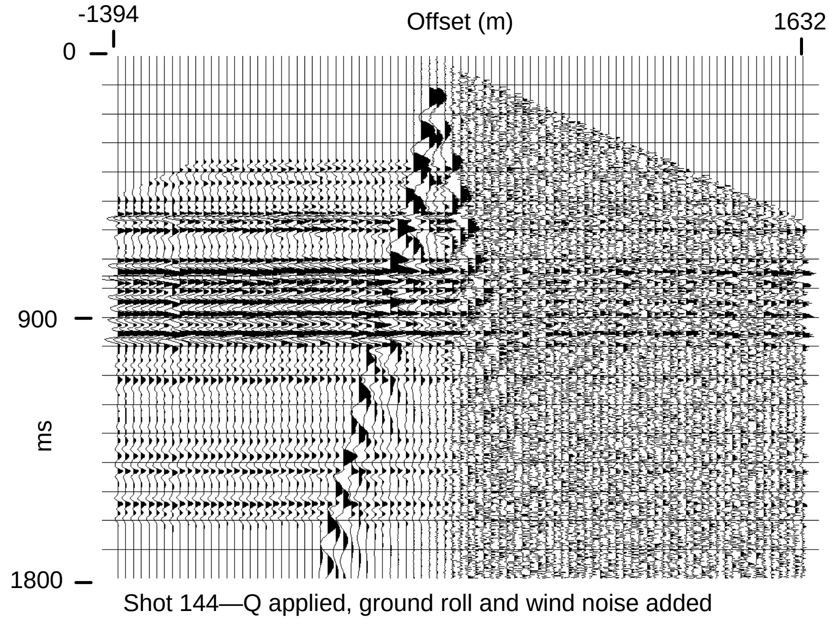

FIG 10. Perz model shot 144 with Q applied, ground roll and simulated wind noise added. NMO removed

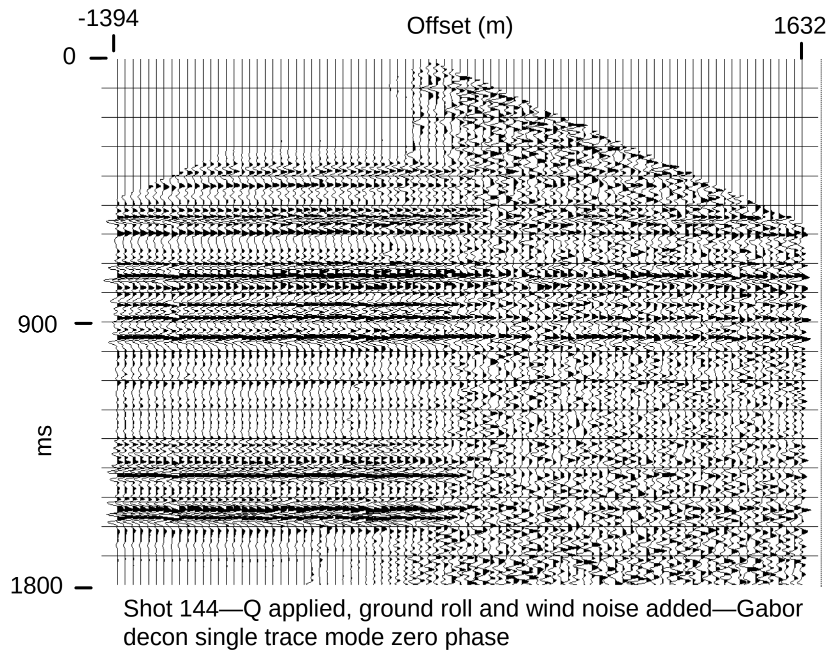

FIG. 11. Perz model shot 144 with Gabor deconvolution in single trace mode, zero phase, NMO removed

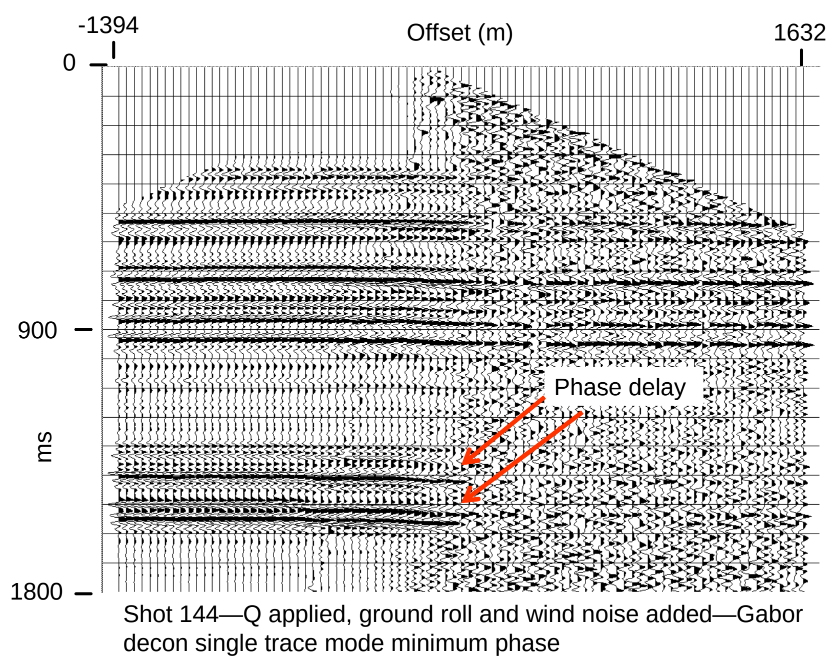

FIG. 12. Perz model shot 144 with Gabor deconvolution in single trace mode, minimum phase, NMO removed

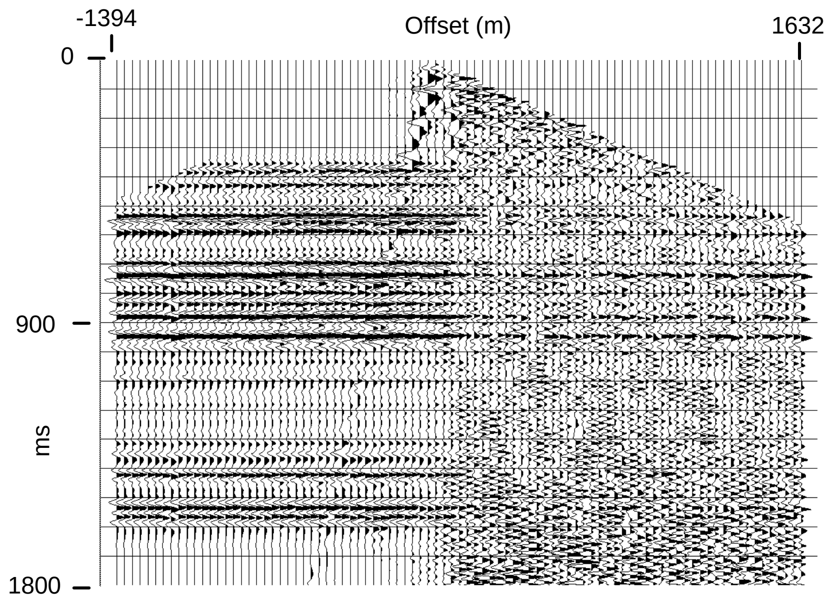

FIG. 13. Perz model shot 144 with Gabor deconvolution ensemble mode minimum phase. Note that the ground roll is not handled as well in this mode. NMO removed.

A remedy illustrated

If we can force the phase of an event on a shot gather to be consistent regardless of the level of additive noise, we can fix the phase stability problem on the stack. One way to do that is to invoke one of the options of the current version of Gabor deconvolution: the ensemble derive/apply mode. In this mode, the Gabor transforms of all the traces in an ensemble are computed and stacked. This summed transform is then used to derive a deconvolution operator that is then applied to each trace in the ensemble. In this mode, the deconvolution operator will not be optimum for any single trace in the gather, but the phase will be the same for all traces. Figure 13 shows the result of applying this mode to the noisy gather. We can observe the following effects: the phase is consistent across the gather; the clean traces on the left are whitened somewhat less than they were in single-trace mode (compare with the left-most traces on Figure 12); the phase adjustment, while moving the events closer to their ideal positions, does not do as complete a job on the clean trace events, leaving more of a residual mismatch with the ideal trace events. Furthermore, the ground roll, since it is captured by more Gabor time windows in the ensemble than on any single trace, is not as easily averaged out, and is therefore not as well removed in ensemble mode as in single trace mode.

To see what effect this has on the stack, we observe Figure 14 and compare it with the ideal stack in Figure 4 and the zero-phase stack in Figure 15. It is evident that event phase stability is no longer a problem when we apply the ensemble mode Gabor deconvolution before stack. On the other hand, the phase correction does not completely remove the reflection event time lags compared to the ideal stack. The zero phase stack events are even less well matched to the ideal stack events in time (since zero-phase deconvolution cannot compensate the minimum phase Q effects), but it does display more bandwidth than the minimum-phase ensemble mode result. Some of the traces on Figure 5 (minimum-phase single trace mode) appear to match the phase of the ideal section closely; presumably these correspond to CDPs for which the S/N ratio of all the constituent traces is high.

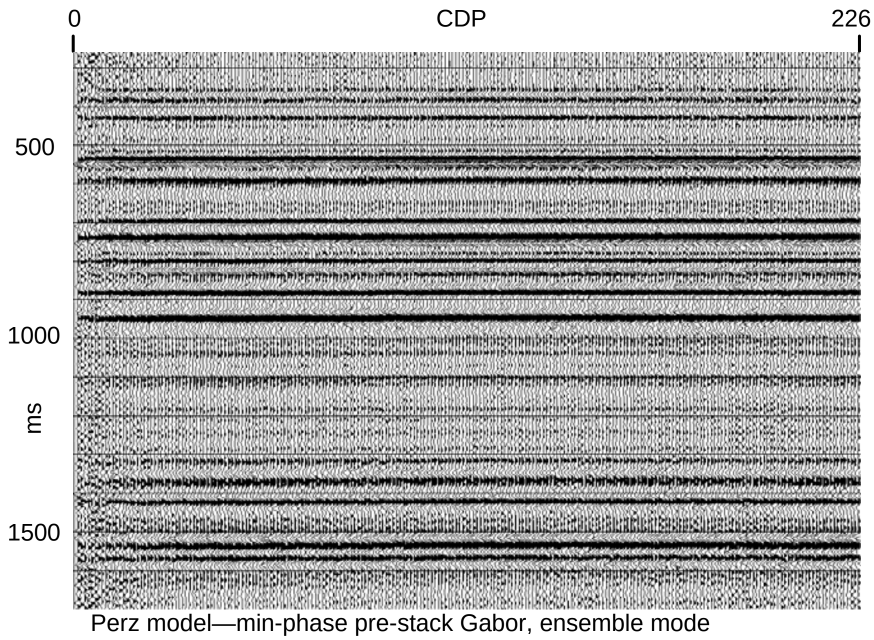

FIG. 14. Perz model stack after Gabor deconvolution in ensemble mode, minimum phase

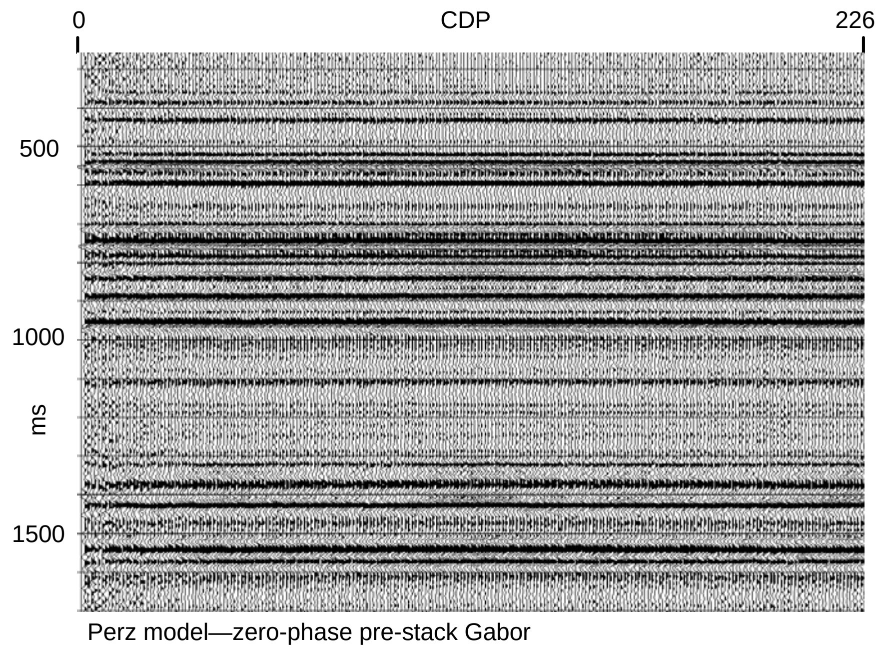

FIG. 15. Perz model stack after Gabor deconvolution in single trace mode, zero phase

DISCUSSION

We thus have three versions of a stack, all of which compare favourably to the ideal stack in some way, but less favourably in others. If we use zero phase Gabor deconvolution in single trace mode, we get a stable, broadband result, but the transit times of events show a time-increasing mismatch with the events of the ideal section, since the phase delay of Q on the input data is not compensated by zero phase deconvolution. If we use minimum phase Gabor deconvolution in single trace mode, those CDPs whose constituent traces are relatively noise-free exhibit broadband events with nearly correct timing. For CDP's having more noisy constituent traces, however, the incorrect phase leads to event timing errors that show up as phase instability and event splitting in the stack. The application of Gabor deconvolution in the ensemble mode appears to be a compromise solution, in which event phase and timing is stable, if not quite correct, and bandwidth is somewhat lower than with the zero phase single trace mode.

THE REAL WORLD—AN EXAMPLE

We consider the Perz model to be a severe test of deconvolution strategies because of its greatly varying levels of random noise contamination; the shot gathers in most field surveys will exhibit far higher levels of coherent noise and far less random noise than those in this model. In the previous section, it was shown that the most desirable deconvolution results are obtained using Gabor deconvolution in single trace, minimum phase mode, since this provides the most whitening and the most accurate phase correction…except when varying levels of random noise are present. This implies that ensemble mode deconvolution is not always justified, and in fact, should be applied only when particular field circumstances dictate. As it happens, CREWES has access to a data set which seems to satisfy the criteria for invoking ensemble-average deconvolution.

The Okotoks field school experiment

In 2003, the field school run by the Department of Geology and Geophysics recorded a seismic line near the town of Okotoks. The source was a weight drop, and the quality of the recorded data was very poor. Most shots were contaminated with both coherent and random noise, the levels of both types of noise varying considerably with channel. Figure 16 shows two of the shot gathers from this line, on which we can see ground roll, repeated first arrivals, 60 Hz power line pickup, and bandlimited random noise, with traces at the longest offsets being most affected. Because of the trace to trace noise variation, we decided to test the ensemble mode of Gabor deconvolution on these data in order to try to improve on earlier processing results.

These data were originally processed by applying spectral clipping (Henley, 2001) to attenuate 60 Hz, then several cascaded passes of radial trace filtering (Henley, 2003) to attenuate coherent noise. Next, Gabor deconvolution was applied in single trace mode before stack. The gathers in Figure 16 are shown in Figure 17 as they appear after filtering and deconvolution. Stacking the data results in Figure 18, the best image obtained for those data at the time.

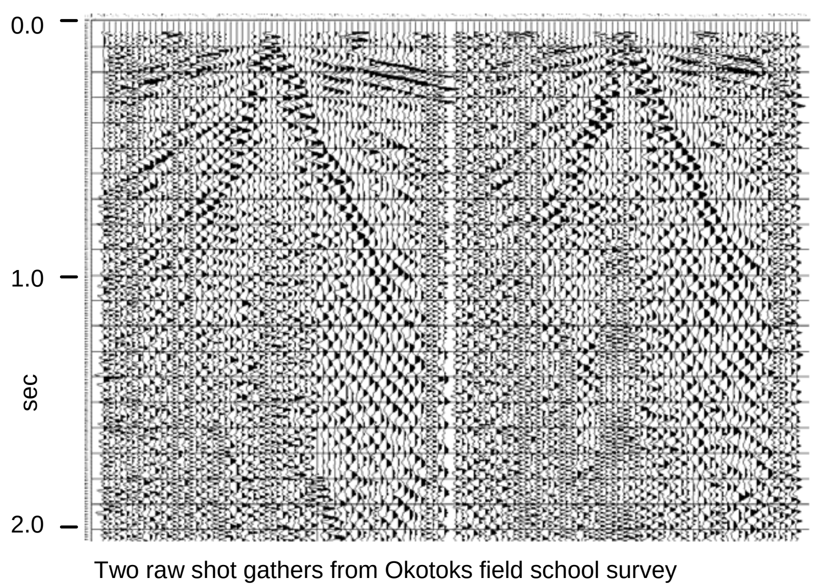

FIG. 16. Two typical shot gathers from the 2003 Okotoks field school survey. Levels of both coherent and random noise vary from trace to trace—a candidate for ensemble mode deconvolution?

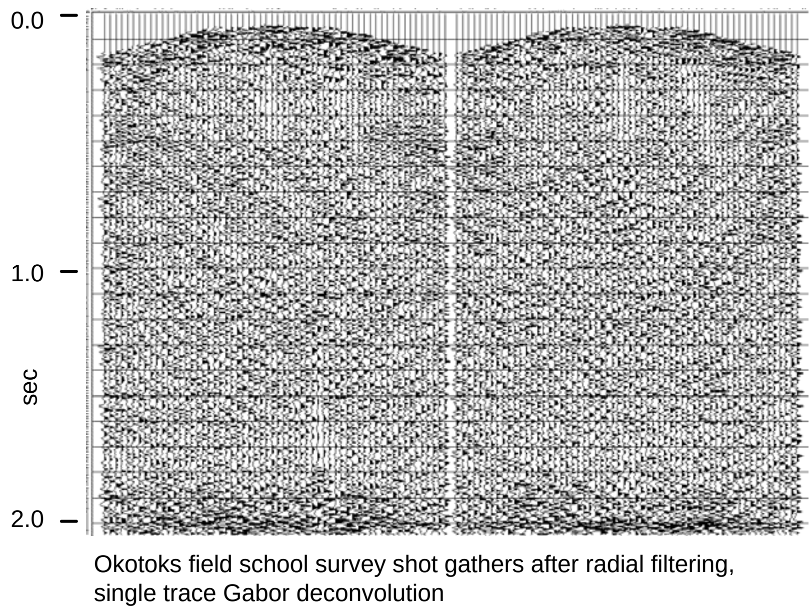

FIG. 17. Okotoks field school shot gathers after extensive spectral clipping, radial trace filtering, and single trace mode Gabor deconvolution. Coherent noise is mostly gone—but where are the reflections?

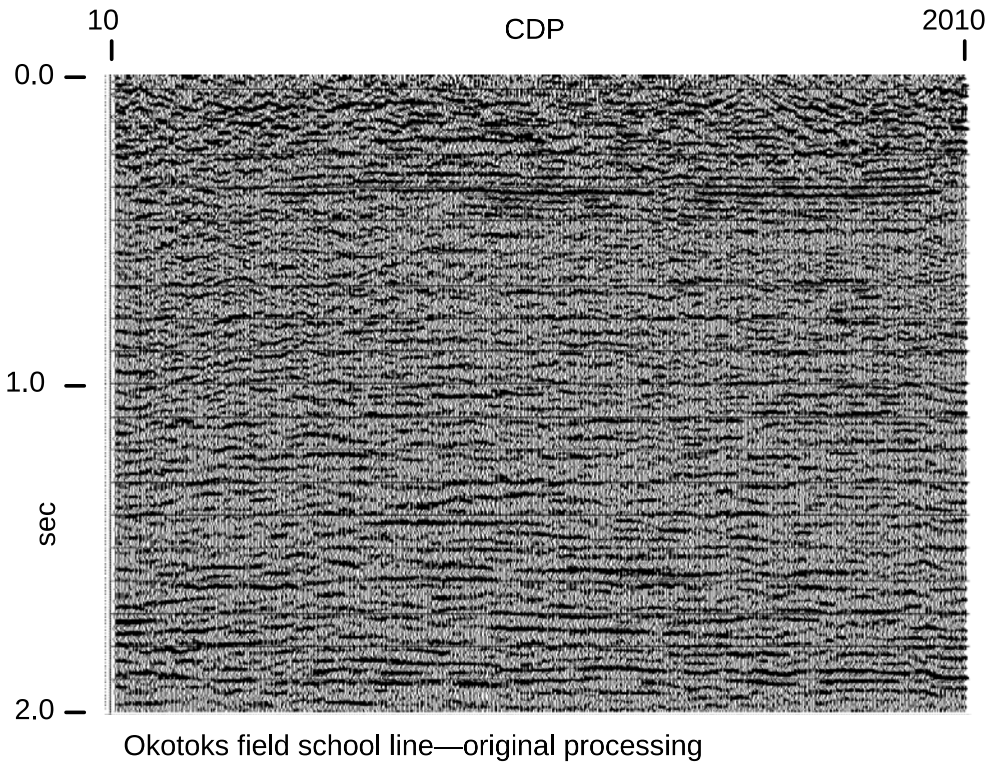

FIG. 18. Stack of Okotoks field school data with single trace mode Gabor deconvolution

To test ensemble mode Gabor deconvolution, we started with the shot gathers after spectral clipping and radial trace filtering. We then applied Gabor deconvolution in ensemble mode to the shot gathers, then sorted the data to receiver gathers, applied Gabor deconvolution in the ensemble mode to these gathers as well, then re-sorted to shot gathers. The results are seen in Figure 19 on shot gathers and in Figure 20, on the stack. The shot gathers show some obvious improvement, since reflection fragments are visible in Figure 19 and not in Figure 17. Comparing Figures 18 and 20, we conclude that the stack image in Figure 20 has slightly more bandwidth than that in Figure 18, and considerably more event continuity for deeper events. Furthermore, the shallow portion of the section appears to be better imaged (although it has not been migrated), since the events appear to make more geological "sense".

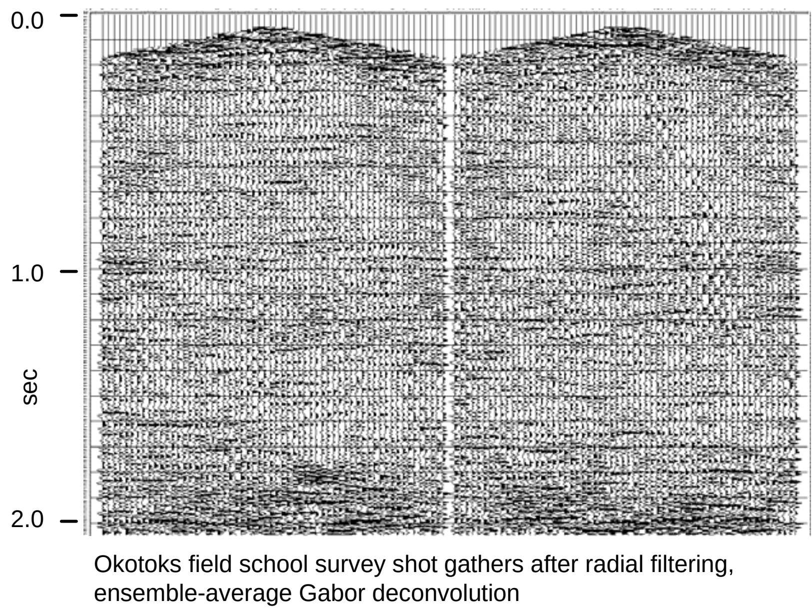

FIG. 19. Okotoks field school survey after noise reduction and ensemble mode Gabor deconvolution. Reflections are now visible.

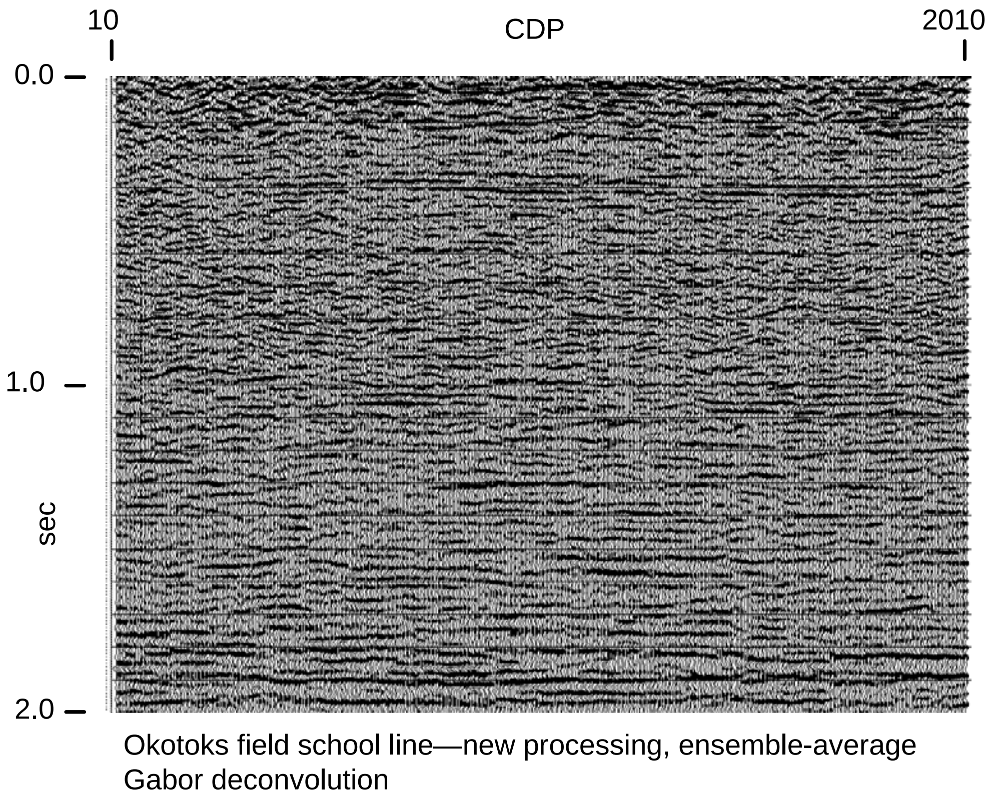

FIG. 20. Stack of Okotoks field school data after ensemble mode Gabor deconvolution in shot and receiver domains. All other processing is identical to that for Figure 18. The image has slightly greater bandwidth, more continuity of deeper events, and a better shallow image.

CONCLUSIONS

While not a definitive test of ensemble mode Gabor deconvolution, the test on the Okotoks field school data is intended as a demonstration of conditions for which it might be appropriate to apply this mode, and of what possible benefits there might be. On this data set, the results are visible, but not dramatic. On other data sets, where noise variability on a gather is not an issue, we have seen little, if any benefit from ensemble mode deconvolution. In fact, the cleaner the data, the less benefit to be obtained, apparently.

While we currently have the ability to partially emulate surface-consistent deconvolution with ensemble mode Gabor deconvolution applied first to shot, then receiver gathers, a new Gabor algorithm which also does a CDP-consistent Q compensation has been implemented, and is being tested by Montana et al. (2006). Since this algorithm derives a single operator for each trace, it should be more consistent and efficient for deconvolving a broad range of seismic data of varying quality.

ACKNOWLEDGEMENTS

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