Raypath statics revisited: new images

David C. Henley

ABSTRACT

In previous work, we have shown that near-surface effects, principally static shifts, can be largely removed from seismic data using two novel concepts: finding and deconvolving ‘statics distribution functions’ from the traces; and transforming the input data to the radial trace domain, where near-surface effects can be separated by their dependence upon raypath angle. We have demonstrated our techniques via several procedures implemented in ProMAX, using two data sets from the Canadian arctic, one of which manifests very large near-surface effects due to river channels. For the latter data set we were able to improve the coherence and continuity of the near-surface layers on the seismic image; but not that of deeper, more structured layers. In this report, we describe an extension of the technique, for which we can improve the continuity, not only of the shallow layers, but the deeper structure, as well. We also issue a warning about a possible pitfall of this technique.

INTRODUCTION

The degrading effects of the earth’s near-surface layers on the seismic reflections from deeper layers are well known, and many techniques have been devised to compensate for them. Among the most serious effects are differential arrival time delays and waveform phase disturbances, since these cause misalignment of reflection events common to gathers seismic traces, leading to decreased event coherence and bandwidth in reflection images. Near-surface effects on seismic traces are most often attacked with techniques which can be loosely categorized as “deconvolution”, or “static correction”, or both. The technique described in this chapter incorporates elements of both kinds of methods.

In previous work (Henley 2004, 2005, 2006) we have described in detail the motivation behind the concepts of “statics deconvolution” and “raypath statics” and have illustrated both concepts with real data examples. Recently, we have begun to explore the common elements between “statics deconvolution” and the currently flourishing field of seismic interferometry (Henley and Daley 2007). Briefly, the method which we developed for estimating and removing the “statics distribution function” from each seismic reflection trace shares a key element with interferometric methods in that it uses cross-correlation functions between individual seismic traces to derive match filters or inverse filters to remove the ‘statics distribution function’ from each input trace by deconvolution.

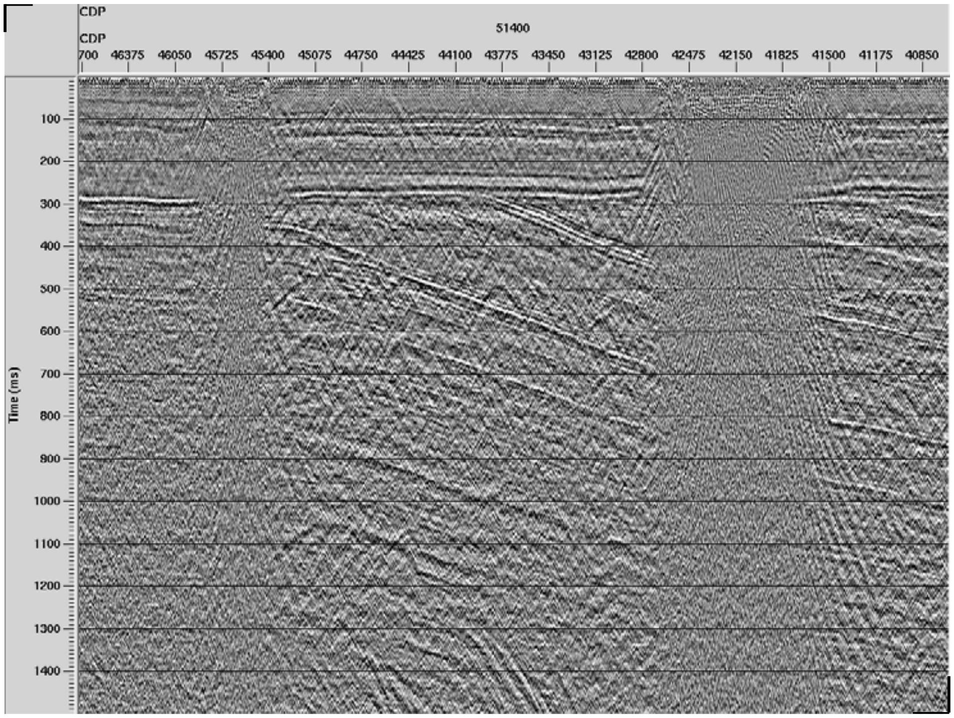
Most procedures to remove near-surface effects from seismic traces assume that near-surface layers have much lower seismic velocity than deeper layers, and that raypaths through these layers will be nearly vertical. When these conditions are met, corrections for near-surface effects will be surface-consistent…that is, seismic traces recorded at one surface location will suffer the same degradation at the receiver, regardless of the location of the source point. Likewise, seismic traces sharing a single source point will suffer a common degradation at the source, regardless of the location of the receiver. The surface-consistent assumption is at the heart of many techniques which rely on averaging to obtain estimates of near-surface effects from noisy data. In certain environments, however, like the arctic, high near-surface velocities ensure that raypaths will deviate considerably from vertical, weakening the surface-consistent assumption considerably. In cases like this, we have shown (Henley 2005) that the input data can be remapped into a domain (radial trace domain) in which the near-surface effects are separated by surface location and raypath angle. While we lose the power of surface-consistent averaging for finding surface-correction operators, we partly compensate by over-sampling in angle, correcting the individual angle gathers, and smoothing over angle as we re-constitute the original input gathers from the radial trace domain.

Efforts to develop the method of raypath statics has focused on two areas: improving methods for estimating statics distribution functions from cross-correlation functions, and improving methods for creating “pilot traces” to guide the cross-correlations. To date, the greatest improvements have resulted from improved pilot trace estimations; and we show here the application of our latest technique to the Shell MacKenzie Delta data set first shown in 2006 (Henley).

THE MACKENZIE DELTA DATA SET

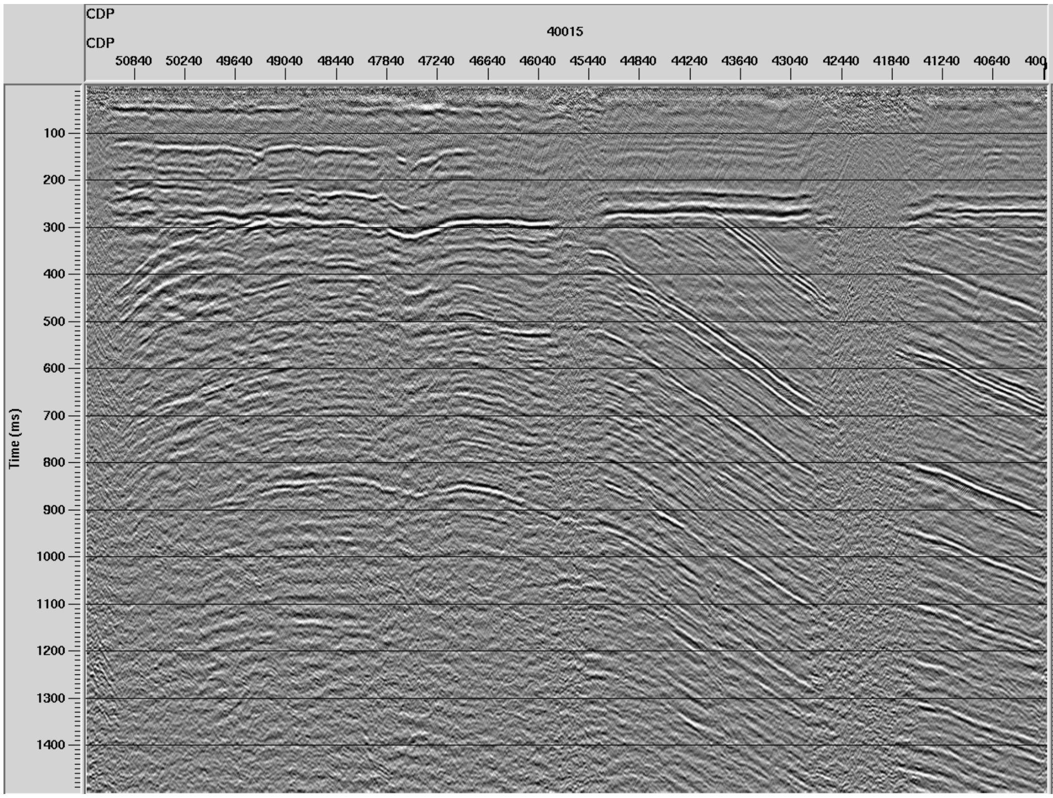
In 2003, Shell Canada Ltd. graciously loaned us an experimental high-resolution seismic data set acquired in the MacKenzie Delta in the early 1990’s. This data set is unique in that the receiver spacing was an unprecedented 5m, in an era when receiver arrays were the norm and station spacing was rarely less than 20m. Early images created from these data showed great promise as well as serious problems. The promise was that very high resolution, wide band seismic reflection images could be obtained with the technique; but the problems were manifested as very large statics associated with melted permafrost pockets and very strong coherent noise associated with ice-covered river channels. Because both high quality and poor quality data exist on the same seismic line, the data set is ideal for developing and testing algorithms for both coherent noise attenuation and unconventional statics correction.

Our first processing efforts on this line focused on attenuating the powerful ice flexural wave using methods outlined by Henley (2004). While successful, largely because the 5m station spacing allowed the ice wave to be recorded with little aliasing, the resulting stack images indicated that the untreated statics problems prevented the data from imaging properly. Figure 1 shows a portion of the line encompassing two river channels, with no noise attenuation or statics applied. Attenuating the coherent noise using radial trace filtering techniques, but attempting no statics corrections resulted in the image in Figure 2, showing the entire line, in which it is clear that statics are crucial to the proper imaging of these data.



No radial filter, no statics, post-stack Gabor decon only

FIG. 1. A close-up portion of the brute stack of Shell high-resolution line showing the data wipeout caused by strong ice wave noise and large statics associated with ice-covered river channels.



Stack after noise removal and deconvolution—no statics applied

FIG. 2. The Shell high-resolution line after attenuation of the severe ice wave noise. Reflection event strength and continuity are greatly improved, but "statics" are obviously still an issue.

RAYPATH STATICS METHOD

Though details of the raypath statics method are described in earlier work (Henley 2004, 2005, 2006), we will reiterate here, briefly, the key assumptions and steps in the method.

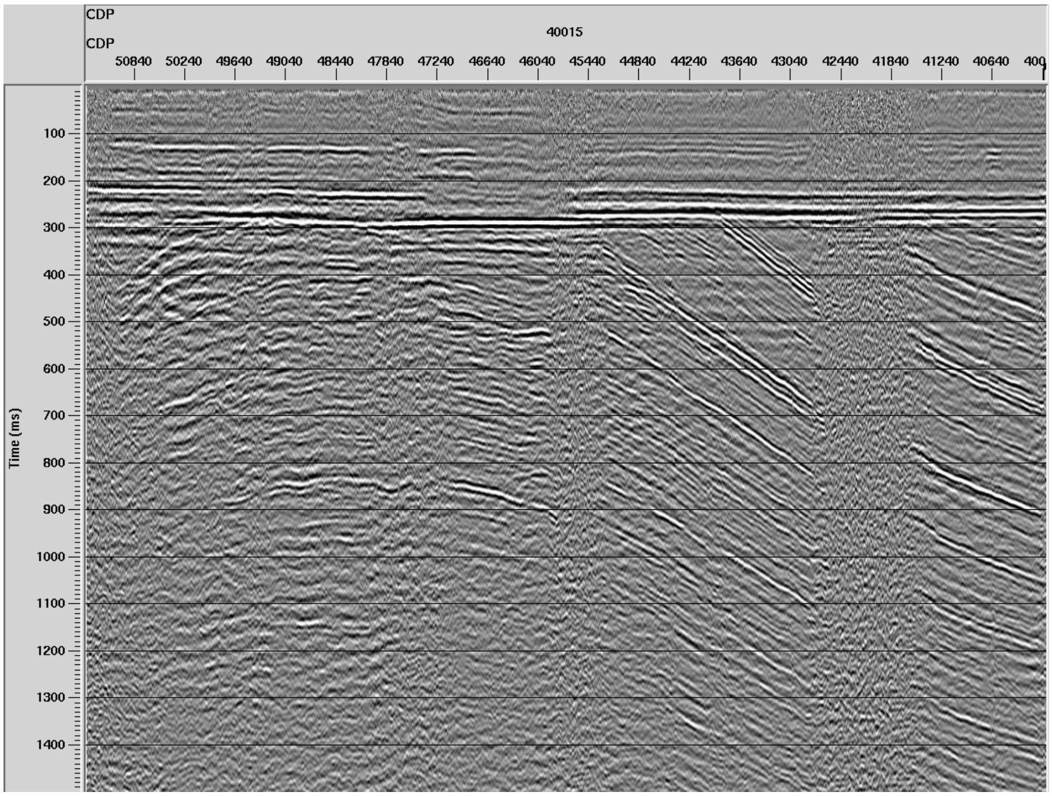
First, we broaden the conventional statics correction model. We recognize that assuming that a simple time shift of a seismic trace will correct the trace for near-surface effects is always an approximation. Therefore, we make the less restrictive assumption that near-surface effects can be characterized by a "statics distribution function", which is intrinsically convolved with the reflection response embedded in a seismic trace. This function can be considered to be a histogram of all the wavefront arrivals for a given single event, where the arrivals are due to direct transmission as well as local scattering in the vicinity of the source (receiver) associated with the seismic trace. In many cases, the statics distribution function will closely approximate a single spike, thus justifying the single static shift approximation; but often, a function will be bimodal, indicating possible multi-pathing, or diffuse, indicating near-surface scattering. In these cases, a single shift cannot correct a trace for the effects, but applying a match filter or inverse filter derived from the statics distribution function can correct the trace. When posed in this fashion, the statics correction problem becomes one, not of finding the optimum time shift for each trace, but of finding the statics distribution function for each trace.

Whereas conventional statics methods start with cross-correlation functions of traces either with their neighbors, or with pilot traces, and use only the picked positions of the correlation maxima, we use each function in its entirety as a bandlimited estimate of the statics distribution function. In the case of correlation of individual raw traces with pilot traces, we attribute the estimated statics distribution function to the individual trace, assuming that the pilot traces have no net remnant statics distribution functions of their own (since they are usually formed by stacking raw traces, thus averaging out the statics). To whiten the estimated distribution functions without introducing extra spikes, the samples of each correlation function are raised to a power. This makes the functions more 'spiky'. Deriving an inverse filter for each function and applying it to the corresponding input trace then removes the near-surface effects, including net time shifts, embedded in each trace. The success of the method relies on getting good pilot traces, each of which, in a sense, is an estimate of the desired final reflection image. Pilot traces are most often created by stacking raw traces over some common attribute (like source, receiver, CDP, or surface location), or sometimes over more than one attribute (mixing CDP stacked traces, for example). The ideal for each pilot trace is to represent each reflection event with sufficient amplitude, in its unshifted position, so that correlating it, over any event window, with any raw trace from its stack group, will yield a good estimate of the particular statics distribution function for that raw trace.

The statics deconvolution method outlined above can be used on any data set, including those for which surface-consistency holds. In that case, trace mixing of shot and receiver gathers can provide pilot traces for correlating with the individual traces of the gathers themselves. In case surface-consistency fails, however, we can recast the problem into the raypath domain by taking the radial fan transform of each input gather (either shot or receiver domain works for this), then sorting the traces into common-raypath-angle gathers (analogous to common-offset gathers in the X-T domain). In earlier work, we found that applying trace mixing to these common-angle gathers created pilot trace panels which proved effective in correlating with the raw input common angle traces. The correlation functions for each common angle panel are converted to distribution functions and inverse filters derived for each function. The application of these inverse filters to each trace, still in the common angle domain, constitutes the statics correction procedure. Re-sorting the traces back to radial trace gathers, then inverting the radial trace transform for each gather completes the procedure. Gathers corrected by this procedure can then be NMO corrected and stacked.

PREVIOUS RESULTS

Using the method described above, creating pilot traces by simple trace mixing of common-raypath-angle gathers, it was found that only the relatively horizontal events provided reliable correlation functions for statics deconvolution of the Shell data set. Any attempt to widen the correlation window to include the steeply dipping events below the Iperk Unconformity led to less successful static deconvolution. An example of the application of raypath statics to these data is shown in Figure 3, where it can be seen that the horizontal events above and including the Iperk Unconformity are strong and continuous, while the deeper structure still shows gaps where the shallow statics functions are inadequate for correcting deeper events. A closer look at the shallow part of the section indicates a possible problem here, as well. At the edge of the channel near the centre of the section, the Iperk event appears to have a loop skip mis-tie, as well. Both these problems convinced us that further improvements were needed for creating pilot traces for these data, since horizontal trace mixing was clearly inadequate for characterizing reflection images with any structure or lateral irregularities.



Stack after raypath-dependent statics

FIG. 3. Shell high-resolution line after noise attenuation and application of the raypath-dependent statics technique using pilot traces based on horizontal events only. The continuity of shallow events has greatly improved, but there is a lateral character change along the obvious (Iperk) unconformity that may signal a loop skip in the statics solution.

PILOT TRACES REVISITED

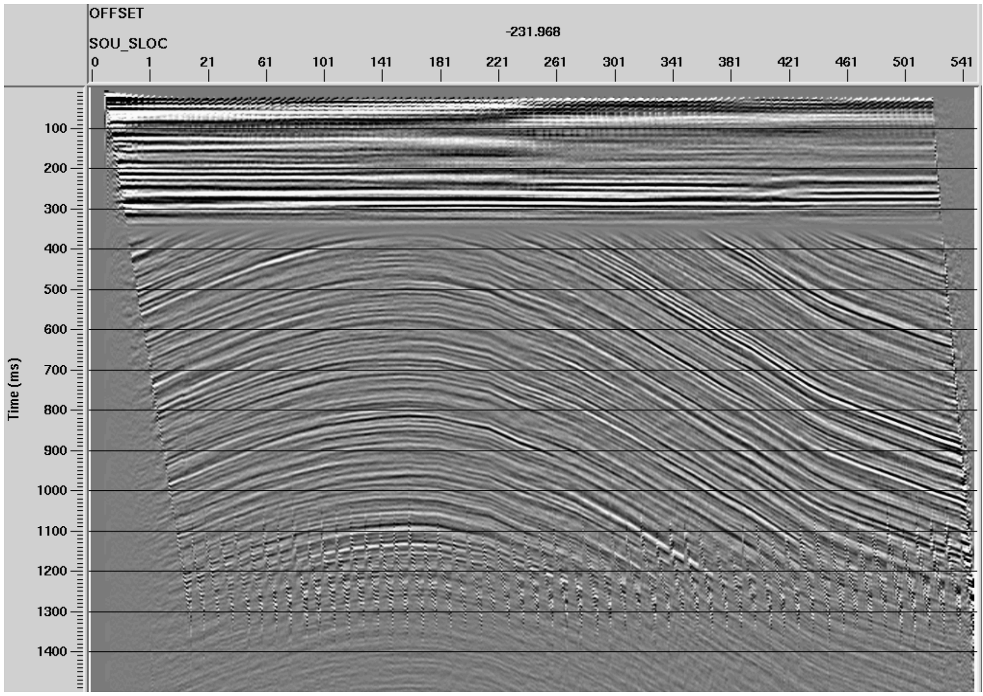
It was clear from earlier results that simple horizontal trace mixing is not appropriate for creating pilot traces for statics procedures for structured seismic sections. Since the approach provided some promising results, however, we decided to attempt to improve it by forcing the mixing to follow the geological structure. A relatively straightforward way of doing this was to display a brute stack section, then hand-pick a reflection horizon on the section. The horizon picks can then be used to flatten any group of traces to the horizon pick times. We found that picking the Iperk event as if it were a smooth, continuous reflection horizon (ignoring obvious channel sags), then applying horizon flattening to the common-raypath-angle gathers before trace mixing yielded superior pilot traces. When we removed the horizon flattening from the pilot traces and used them for deriving the statics functions, we obtained a stack image similar to Figure 3, except that the loop skip near the central channel was gone.

This encouraging result led us to experiment with horizon picking for the deeper events in the section, as well. We found that we could, indeed, pick a smooth horizon corresponding to the anticline beneath the unconformity, flatten the common-angle gathers to that horizon, apply trace mixing to get pilot traces, remove the horizon flattening, and use the "structured" pilot traces to correlate the common angle gather traces. This yielded statics functions whose inverses corrected the deep structural part of the stacked section, but destroyed the coherence of the Iperk event.

This result created a dilemma: it seemed that we could correct the shallow part of the section, or the deep structure, but not both simultaneously. A review of the suite of common-angle gathers in each case soon resolved the dilemma, however. In the raypath statics format, we had noticed earlier that common-angle gathers over certain relatively narrow ranges of angle seemed to capture certain events with much higher S/N than over other angular ranges. In particular, the Iperk event was much more strongly represented on those common angle gathers whose angles corresponded to apparent velocities of 300-600 m/s, and was weaker on the more nearly vertical raypaths. Furthermore, because of the raypath angles, the deeper structured events aren't even captured by common-angle gathers on which the Iperk event is strongest. The deep events, however, are more prominent on the more vertical common-angle gathers whose angles correspond to velocities less than 100 m/s. This means that when we use pilot traces based on a flattened Iperk event, the bulk of the corrections which affect the imaging are actually applied over a limited range of angle gathers which don't even capture the deeper reflections. Conversely, when we use pilot traces based on a flattened anticline structure, the bulk of the corrections are applied over an angular range which doesn't strongly represent the Iperk event: the two geological realms are partially decoupled by the angle-gather representation, just as they are by the actual physical unconformity.

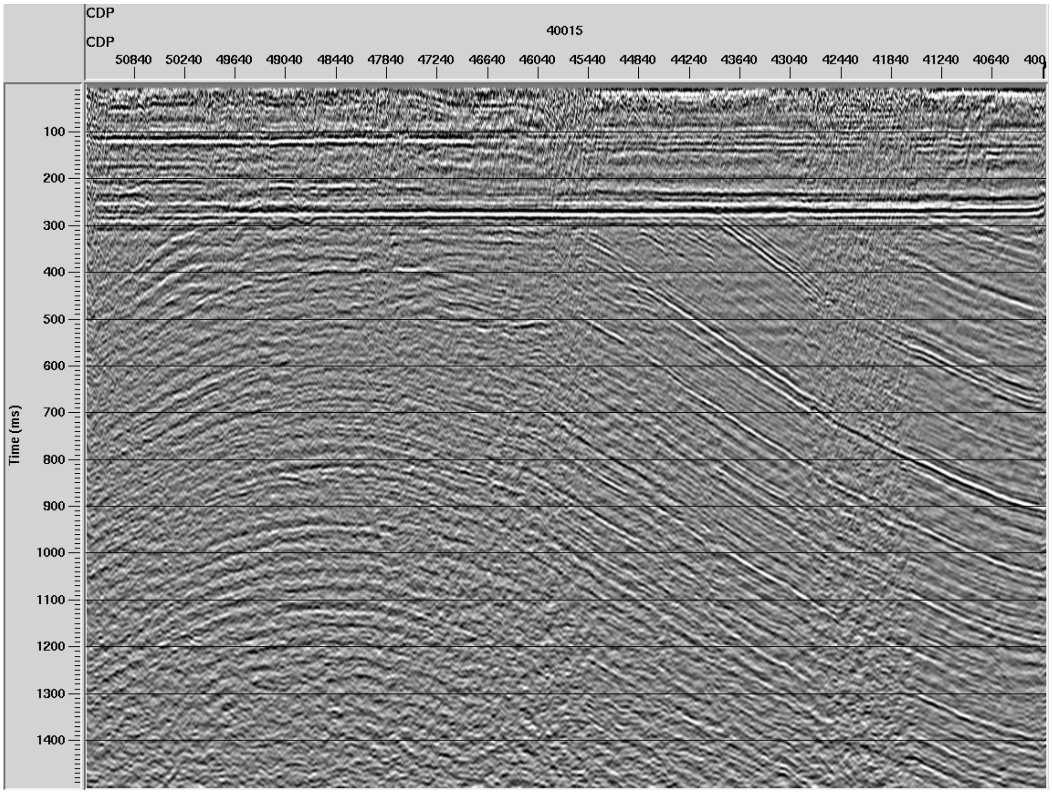
Since the static correction procedure is actually applied in the common-angle domain before the data are inverse-transformed back to the X-T domain of shot/receiver gathers, and since the shallow and deep corrections seemed to be coming from different angular ranges, it seemed appropriate to try to combine the two solutions in order to obtain a single image with improved coherency both shallow and deep. The first attempt consisted of computing two complete sets of statics distribution functions, one for the shallow pilot traces, and the other for the structural pilot traces. Two methods were tried for applying these functions: deriving inverses for both shallow and deep functions and applying them in succession to the traces; and summing the functions, then deriving and applying a single inverse for each trace. Neither of these methods worked particularly well, however.

The technique which ultimately proved most robust was to generate both sets of pilot traces, then to sum the pilot traces for each input trace. Figure 4 shows a typical common-angle panel of these summed pilot traces. Correlating these pilot traces with their corresponding common-angle gather traces over a wide correlation window that included both the shallow, near-horizontal events and the deeper anticline led to statics functions whose inverses applied to the raw traces led to the image in Figure 5. Here, it can be seen that the Iperk and events above it are nicely coherent and continuous, while the deeper anticline is also well-imaged (though with some small imaging problems beneath the channels where reflection strength is weak due to the former ice wave contamination).



Composite pilot traces—shallow and structural

FIG. 4. A set of pilot traces for one angle gather based on a composite of shallow, horizontal events, as well as deeper, structured events.



Stack after raypath-dependent statics; structural model pilot traces

FIG. 5. Stack of Shell high-resolution line after application of statics functions derived using the composite pilot trace model. While image S/N has decreased slightly, all events are now continuous, both shallow and deep. Furthermore, no shallow loop skips are evident.

DISCUSSION

Although very empirical, the method described above for creating pilot traces to help find and remove statics functions makes intuitive sense, at least. Transforming these data to the common-angle domain provides a partial separation of shallow events from deeper ones, so pilot traces created only from shallow events will be unable to help correct deeper ones, and vice versa. By summing the two sets of pilot traces, however, we create new pilot traces which will interact with the shallow data in their range of angles, the deeper data over their range, and will interact with both in the range over which they overlap.

One possible danger associated with this technique is the possibility of "creating data" from random events (Ursenbach et al, 2000). For this reason, it is advisable to be very careful in picking the event horizons which guide the creation of the pilot traces. Events should not be 'phantom picked' through noise zones in which they are not visible, unless it is certain that the events are continuous, and not faulted; and the noise zone is relatively short. For the data set shown in this report, it is known that the Iperk event is continuous over a wide geographic area; and the deeper structure shows no evidence of discontinuity outside the noise zones, suggesting that it is continuous through these zones as well.

Figure 5 is probably the best image yet of this line, in terms of interpretability; but it isn't perfect. There remains some image ambiguity on the flank of the anticline beneath the channels, and the overall bandwidth and S/N of the section is less than that of some pre-statics versions.

CONCLUSIONS

We have demonstrated an extension of the raypath statics technique which seems able to remove the near-surface effects on a difficult seismic line, on which the most serious problems occur in exactly the same location where S/N is lowest due to contamination by strong coherent noise. This extension involves an "interpretive" step in which the processor must "pick" an event shallow in the section to help create pilot traces for low raypath angle seismic data, as well as a deeper event to help create pilot traces for seismic data with higher raypath angles. It is the angular separation of the seismic data via the radial trace transform that provides the key to the success of this technique—a similar method attempted in the X-T domain is less successful, since the statics distribution function for the shallow part of a given trace is different than that for the deeper part. In a very real sense, the method we describe is one manifestation of time-dependent "statics" correction (or "dynamics" correction?). While the overall interpretability of an image is greatly improved, there is an apparent tradeoff in terms of a slight decrease in image bandwidth and S/N.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the continuing financial support of CREWES sponsors and ongoing technical assistance from CREWES staff. Shell Canada is also gratefully acknowledged for the use of their data, as well as permission to show these results.

REFERENCES

Henley, D.C., 2004a, A statistical approach to residual statics removal: CREWES 2004 research report, **16**.

Henley, D.C., 2004b, Attenuating the ice flexural wave on arctic seismic data: CREWES 2004 research report, **16**.

Henley, D.C., 2005, Raypath-dependent statics: CREWES 2005 research report, **17**.

Henley, D.C., 2006, Application of raypath-dependent statics to Arctic seismic data: CREWES 2006 research report, **18**.

Henley, D.C., and Daley, P.F., 2007, Connecting statics deconvolution and seismic interferometry: CREWES 2007 research report, **19**.

Ursenbach, C.P., and Bancroft, J.C., 2000, Noise alignment in trim statics: CREWES 2000 research report, **12**.