Application of raypath-dependent statics to Arctic seismic data

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ABSTRACT

Correcting seismic data for the effects of the earth's near-surface remains a significant problem in seismic processing, especially for data from areas with particularly difficult surface conditions, such as the presence of permafrost. Earlier work has introduced the concept of generalizing statics corrections from simple time shifting of seismic traces to a deconvolution process aimed at removing "statics distribution functions" from the traces. In addition, the notion of raypath angle dependence of near-surface corrections was introduced for those situations when the near-surface velocity exceeds that of deeper bedrock.

This work revisits the raypath-dependent statics concept, illustrates a processing flow for determining the raypath-dependent statics functions and removing them, and discusses the rationale behind the processing. The University of Calgary Hansen Harbour seismic data set, in spite of its relatively small statics, was used earlier to illustrate the process. A second example is shown here, a high resolution data set contributed by Shell. This example provides a more compelling result while also illustrating some of the problems with the technique which remain to be resolved.

INTRODUCTION

The practice of removing the effects of transmission through the earth's near-surface by time shifting seismic traces in order to align corresponding reflection events on the traces is called "static correction", and is applied with varying degrees of success to almost all seismic data acquired on land. There are, however, many parts of the world where static correction either fails or brings little improvement to the seismic data, often because one or more of the assumptions behind the technique has not been satisfied. Among the assumptions that fail most often are the following:

- A seismic reflection wavefront arriving at the surface consists of a single discrete arrival corresponding to a single seismic raypath.
- The velocity of the near-surface is so low compared to that of the underlying bedrock that raypath segments terminating in source points or receiver stations are nearly vertical.

The first of these is violated in any circumstances where multi-path phenomena are likely, including sharp lateral velocity changes in the near-surface, interbed multiples, or inclined wavefronts striking the elements of receiver arrays at slightly different times. Since a single time shift can not properly correct a trace whose reflection events have several discrete arrival times embedded, the concept of static shifts must be expanded to that of "statics distribution functions", which are essentially time histograms of all wavefront arrivals for a given event. If the statics distribution function for each seismic trace can be determined somehow, its effect on the trace can be removed by deriving and applying an inverse filter for it (Henley, 2004a, 2005).

Violation of the second assumption occurs routinely in permafrost areas, as well as in areas whose surface materials consist of hard carbonate overthrusts, or volcanic materials, or other similar “hard” substances. This violation actually has more serious consequences for near-surface correction. Sincee seismic data are inherently noisy, it is difficult to pick reflection events on single seismic traces accurately enough to provide good time shift values for static correction. Thus, most statics correction schemes use redundancy in the data to refine the derived statics—the most common redundancy used being that of surface-consistency, where it is assumed that all raypath segments ending at a surface location are nearly vertical and thus nearly identical. This allows reflection pick times to be averaged over each source or receiver surface location in order to give a more robust estimate of a single static shift for that location. When surface-consistency is lost, however, we are faced with the task of determining individual statics (or statics distribution functions) for each seismic trace.

For seismic data where one or both of the usual statics assumptions are violated, we are developing a method for deriving and removing a statics distribution function from each trace of a seismic data set. Since we abandon the surface-consistency constraint used by most “statics” methods to find solutions, we substitute, instead, a weaker form of data redundancy in the derivation and application of near-surface corrections.

AN ARCTIC DATA SET

We have previously shown an early attempt to apply raypath-dependent statics to an experimental 2D 3C seismic line acquired in the Hansen Harbour area of the MacKenzie Delta (Henley, 2005). In the current work, we show the application of the method to a set of high-resolution seismic data from the MacKenzie Delta, contributed by Shell Canada. These data are unique in that the single receivers were spaced at 5 m increments, allowing the wavefield to be recorded with very high lateral resolution. The line was recorded on the frozen surface in the winter using a vibrator as the source. Because of the surface source, whenever the line crossed a frozen river channel, ice flexural waves were generated in abundance, generally obliterating any evidence of reflections. The objectives for processing these data focused on coherent noise attenuation, particularly removal of the ice wave, and on static correction, particularly in the vicinity of the river channels.

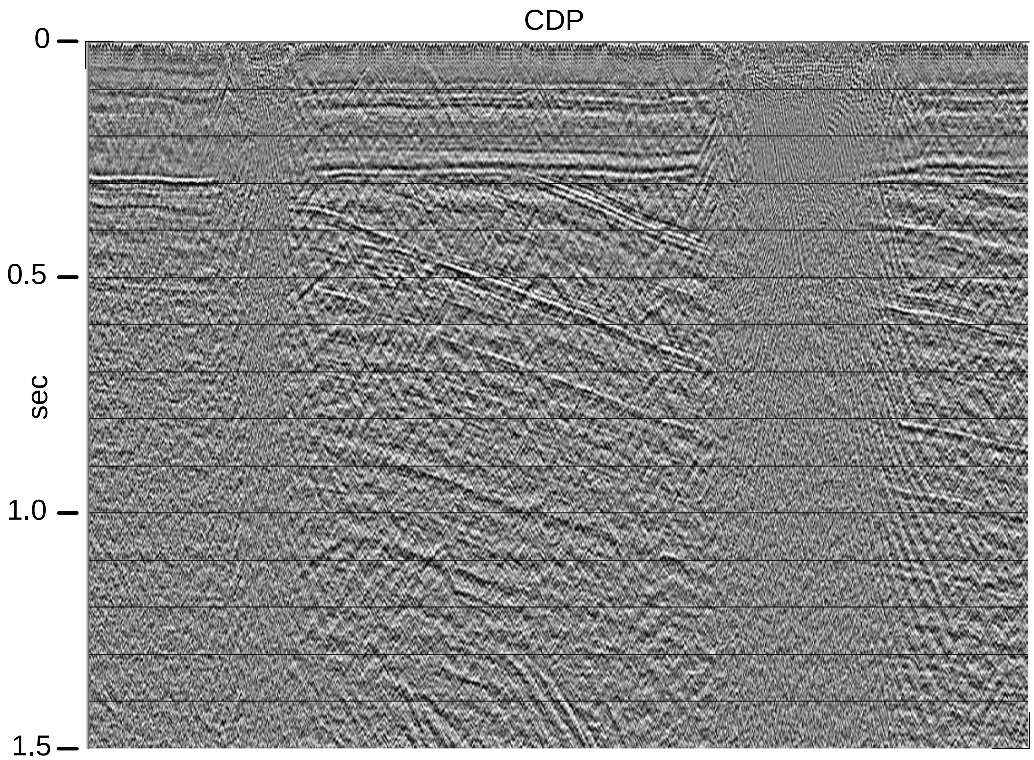


FIG. 1. Brute stack of a portion of an arctic seismic line from Shell Canada showing wipeout of data in the vicinity of river channels, due to large statics and the ice flexural wave.

Figure 1 shows the brute stack of a portion of this line, with no noise attenuation or statics applied. The effects of two river channels are very evident on this image. Even the strong reflection from the shallow Iperk unconformity is totally obscured. Figure 2 shows the same stack after the shot gathers have been subjected to the radial trace domain noise rejection technique described by Henley (2004b). While the noise attenuation has greatly improved the reflections, and more of the Iperk reflection is visible, it is evident that this event is still disturbed and discontinuous in the vicinity of the two river channels. While it is possible that the ice wave noise was so strong that no reflection signal survives beneath it due to acquisition dynamic range, we conjecture that at least some of the reflection disturbance is caused simply by large statics due to the softer, unfrozen material beneath the channels. Because of the low signal to noise ratio in the vicinity of the river channels, traditional residual statics picking and correction schemes fail. In what follows, therefore, we construct and apply a method for finding and removing raypath-dependent statics, hypothesizing that at least part of the static solution difficulties is due to raypath problems in the neighborhood of the channels.

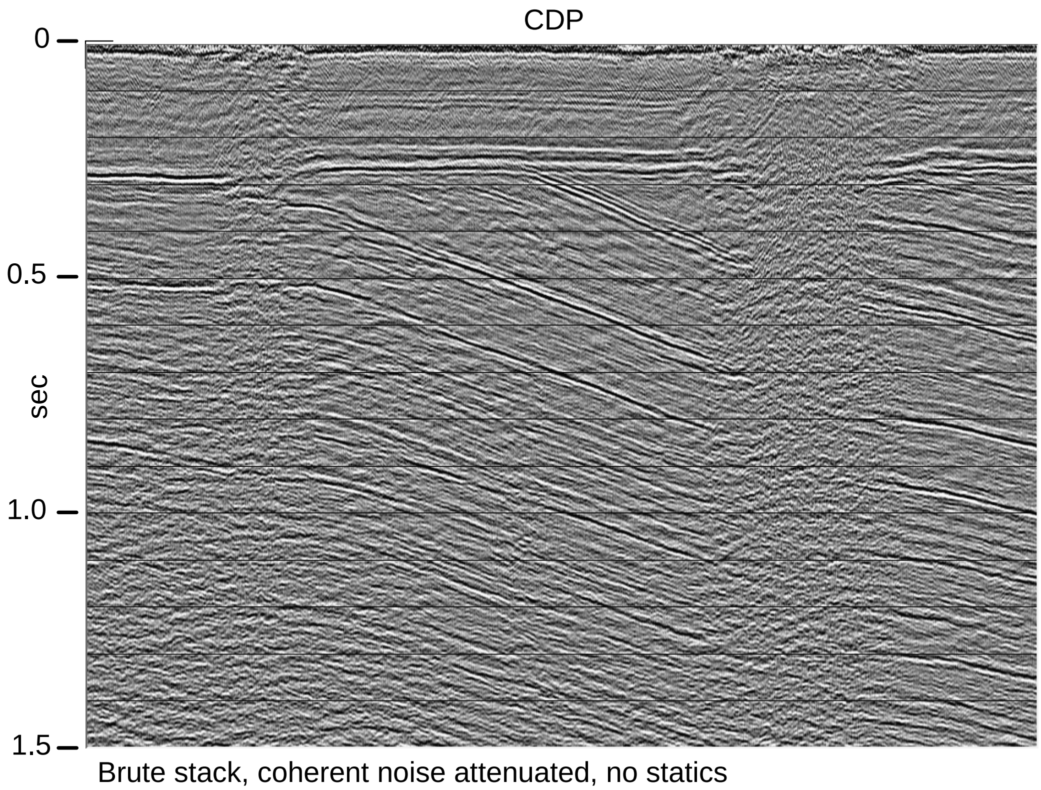
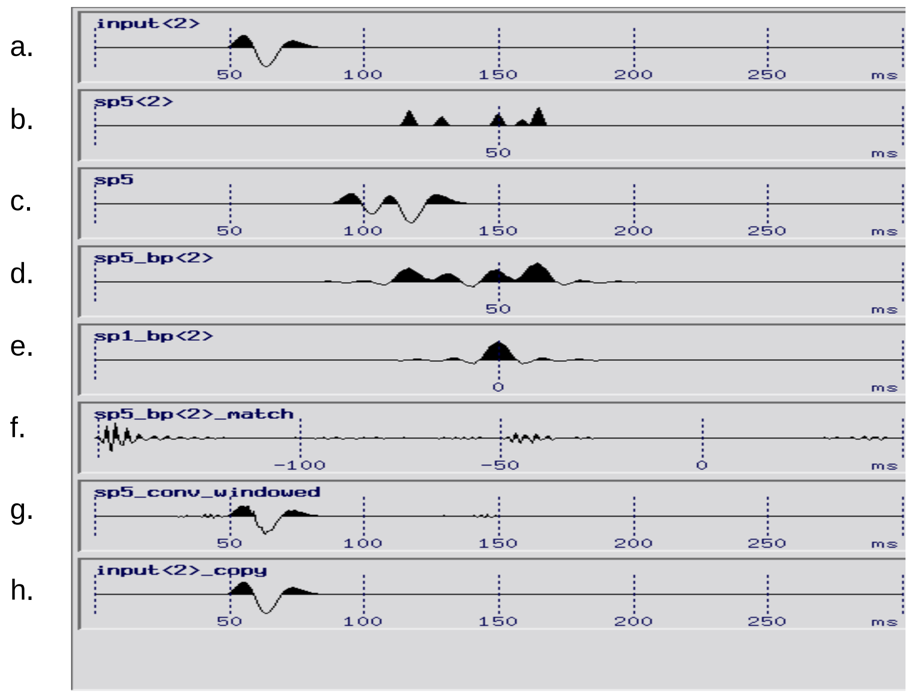


FIG. 2. Brute stack of Shell arctic data after attenuation of coherent noise. Reflections are still discontinuous beneath river channels, probably due to statics issues

RAYPATH-DEPENDENT STATICS

Statics distribution functions

In earlier work (Henley 2004a) we generalized the "statics correction" method by replacing the conventional model of one time shift per seismic trace with the "statics distribution" model, in which it is assumed that a given event on a seismic trace may consist of not just a single energy arrival, but a group or "distribution" of arrivals due to multi-path phenomena in the near-surface. These multi-path phenomena can be as simple as a tilted wavefront impinging on the elements of a receiver array at slightly different times, or raypaths through neighboring parcels of weathered material being delayed by slightly different amounts, or energy scattered in the near-surface arriving slightly later than the direct arrival, or simply interbed multiples. Even if we believe that an event consists of a single wavefront arrival, the distribution function can represent the uncertainty associated with finding the single "best" arrival time. Regardless of the underlying mechanism, by allowing a distribution of arrivals for each event, we can devise a method for removing all the delays simultaneously, rather than a single average or "predominant" delay. That method is simply to estimate the distribution function for each seismic trace, to derive an inverse filter for the distribution function, and to apply the inverse filter to the trace. Deriving and applying an inverse filter is not difficult, but estimating the statics distribution function for each trace is. Our current approach, which is constantly under development, is to create a set of model or “pilot” traces from the input data set itself, to cross-correlate each raw input trace with its corresponding pilot trace, and to let the cross-correlation function represent a bandlimited version of the statics distribution function for each trace. Figure 3 illustrates the concept of deconvolving statics distribution functions from seismic traces. The crucial step here is in obtaining the “estimate” of the actual distribution function embedded in the seismic trace (simulated in Figure 3 by the bandlimited spikes in d.).



The static deconvolution principle

FIG. 3. A model demonstration showing that a distribution of “statics” can be removed from a seismic trace by deconvolution methods. (a)—An ideal seismic trace with one event. (b)—A distribution of 5 static shifts of various strength and time shift (the sum of their amplitudes is unity). (c)—The seismic trace of (a) as affected by the “statics” distribution in (b). The event undergoes a bulk shift as well as smearing in time. (d)—A bandlimited version of the distribution function, as might be obtained by operating on a cross-correlation function between the trace (c) and some “pilot” trace. (e)—A bandlimited spike at the zero shift position. (f)—The match filter between (d) and (e). (g)—The smeared, shifted seismic trace in (c) after application of the match filter (f). (h)—The original seismic trace for comparison.

The creation of pilot traces for automated data correlation is more an art than a science, and there are a number of considerations, including the nature of the seismic data themselves, whether the geology is basically flat or heavily structured, and the level of random and coherent noise in the data. Pilot traces are normally created by mixing or stacking raw traces in some domain—a common method being to laterally mix CDP stacked traces to smooth over minor structural and character changes along the stacked section. Smoothing can also be applied over shot gathers, receiver gathers, common-offset gathers, and other ensembles, to attempt to construct pilot traces which differ from their constituent raw traces only by the embedded statics distributions. Pilot trace creation is one of the more important areas of ongoing statics research.

The most generally accepted method for finding the shifts of an event on individual traces with respect to its corresponding event on a pilot trace is cross-correlation, although the resolution of the cross-correlation function is relatively limited. There may be other detection functions useful for this application (Henley, et al, 2005), but they remain untested. Our current statics distribution function estimation begins with the computation of cross-correlation functions, which are then modified using various ad hoc operations until they resemble the statistical functions we desire. Some of the operations that can be used to alter the correlation functions are spectral whitening, exponentiating the samples, or raising them to a power. All these are aimed at converting the broad-peaked cross-correlation function with its broad sidelobes into a sharply peaked function, which, nevertheless, may have more than one major peak, if significant multi-path phenomena are present.

If we simply choose the time shift of the maximum value of the statics distribution function for the value of a static to be applied to the corresponding trace, we would be ignoring other information potentially contained in the distribution function. Thus, in a significant departure from conventional statics practice, we use the entire distribution function by deriving an inverse filter for it and applying the filter to the corresponding trace. If the distribution function for a trace is basically a single narrow, symmetric peak, the net effect of the inverse filter derivation and application is little more than a time shift. If, however, the distribution function is multimodal or asymmetric, indicating either multipath phenomena or picking uncertainty, the inverse filter approach automatically corrects for the asymmetry.

Abandoning surface-consistency

Surface-consistency is a mathematical constraint adopted by most statics corrections methods to deal with the problem of redundant, but noisy input data in the form of time picks of reflection events on seismic traces. The underlying assumption behind surface-consistency is that the portions of seismic raypaths beginning and ending at specific surface locations are nearly vertical, regardless of the source-receiver offset, due to the velocity structure of the near surface, as shown in Figure 4.

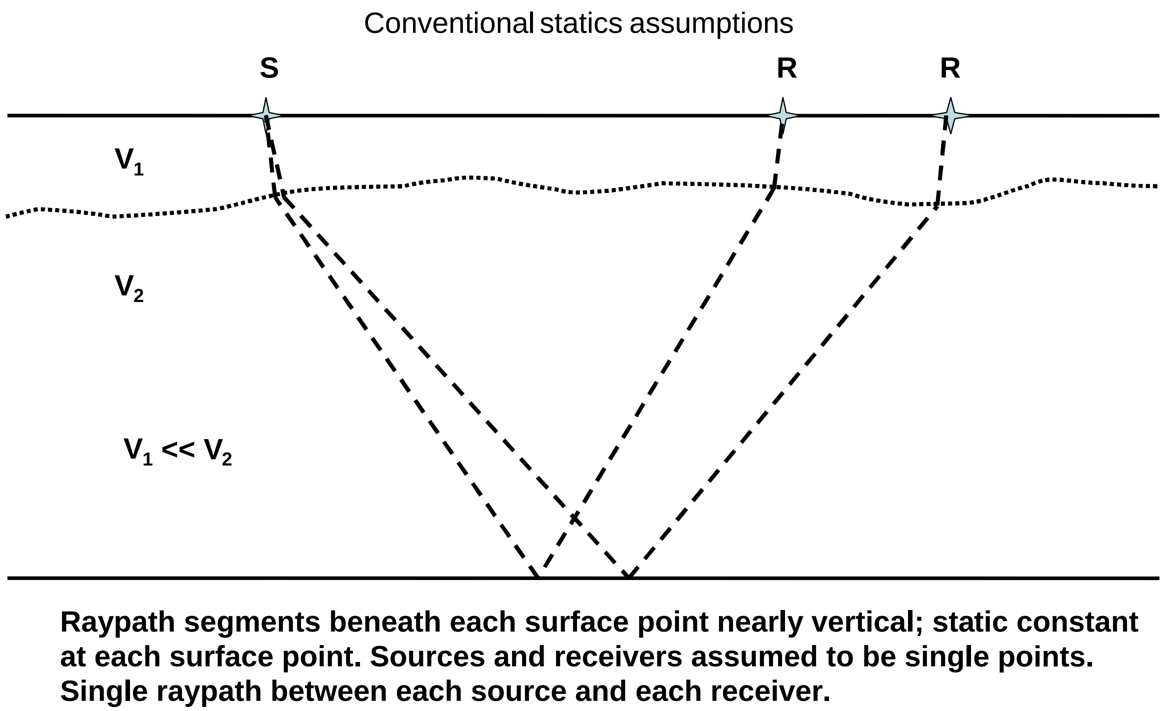


FIG. 4. The approximations and assumptions behind the surface-consistent statics model.

If the raypath segments are nearly vertical, then they can be considered to be in common for each surface location, and the delay along a particular raypath segment can be computed by suitable averaging of input event time picks. When a high velocity surface layer exists, however, the near-surface raypath segments for different offsets are no longer common, as shown in Figure 5. This means that averaging can no longer be used as a tool to determine a particular static delay time associated with a given surface location. In effect, each raypath requires its own static.

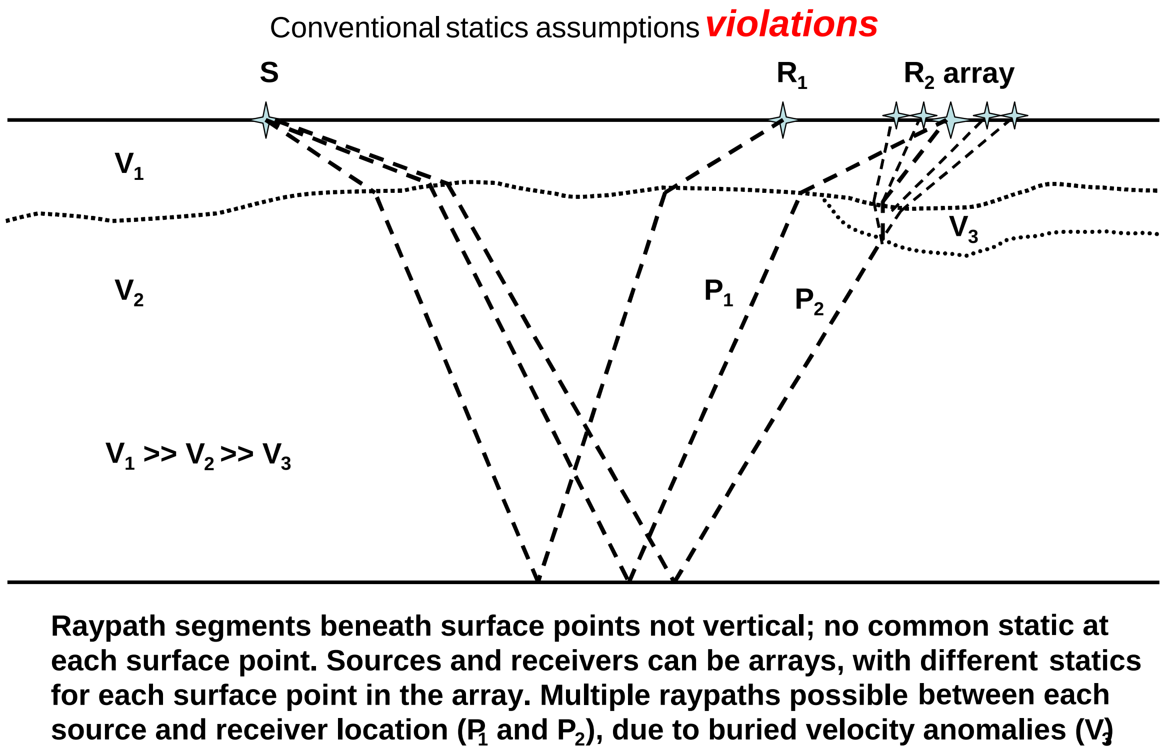


FIG. 5. Ways in which the surface-consistent, single arrival model breaks down.

If seismic data were maximally broadband and noiseless, it would be possible to uniquely determine a static shift for each raypath at each surface location by simply comparing a perfect reflection time pick with its “ideal” or pilot trace pick. Because data never satisfy either of these criteria, however, we introduce the statics distribution function to accommodate both the uncertainty in reflection arrival times due to bandwidth limitations and possible multi-path phenomena, and we introduce the radial trace (RT) transform to provide raypath separation of statics and some weak data redundancy through oversampling. By associating a weighted distribution of event arrival times with each “picked” event, instead of a single arrival time, the statics distribution function removes the necessity of finding a single optimum static time shift for each seismic trace, and hence partially relaxes the need for redundancy in order to obtain solutions.

The RT transform is a remapping of seismic wavefield samples from coordinates of offset and travel time to apparent velocity and travel time, and Figure 6 shows the raypaths that correspond to a trace in both the initial XT domain and the resulting RT domain. Note that all raypaths for a trace in the RT domain share the same descending raypath and hence have both the near-surface raypath location and angle in common. Therefore, to find raypath angle-dependent statics distribution functions, we first transform a set of seismic shot gathers into the RT domain.

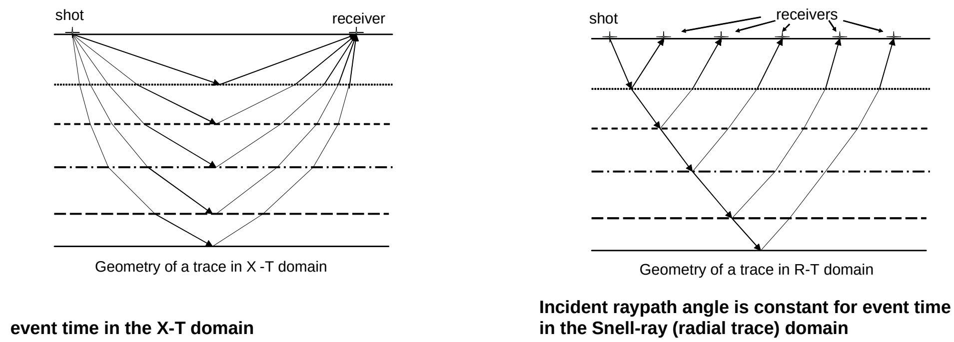


FIG. 6. Raypath geometry for a single trace in the XT domain (left) and a single trace in the RT domain (right). In the RT domain, incident raypath is common for all event arrivals. Emergent ray angle is also common for all event arrivals.

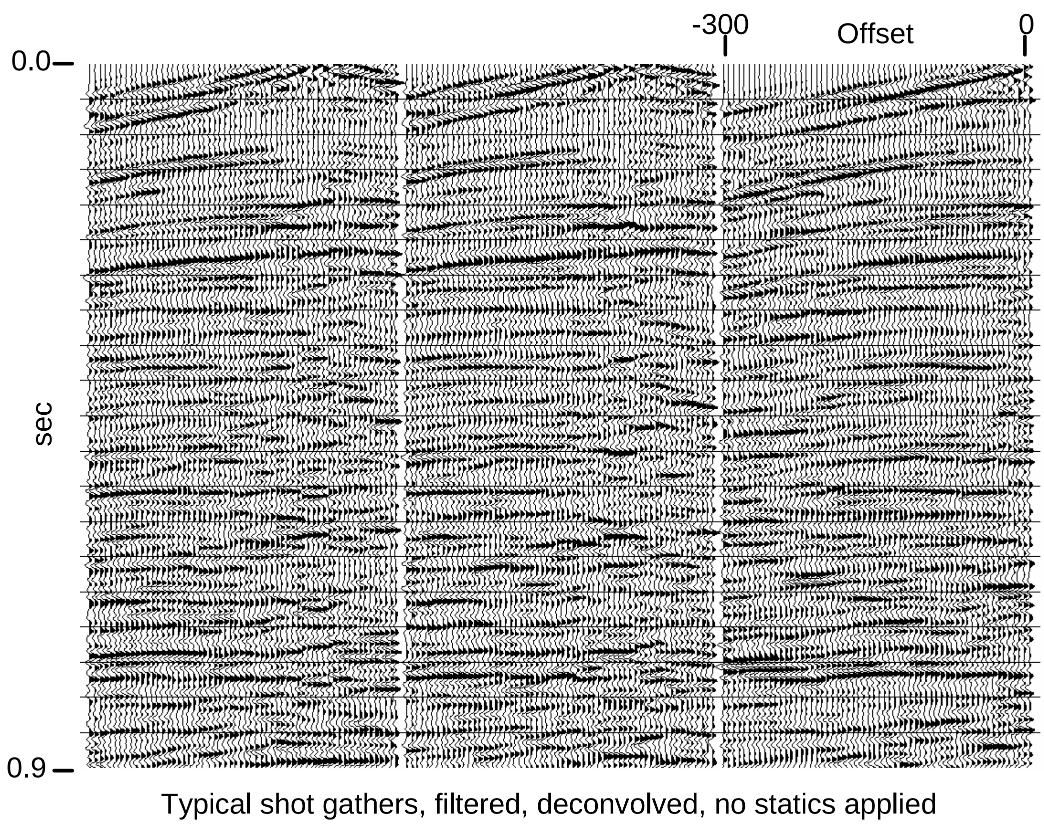


FIG. 7. Three typical shot gathers from the Shell arctic data set, after coherent noise removal and deconvolution.

Figure 7 shows three shot gathers for the Shell high-resolution seismic line from the MacKenzie Delta, after noise attenuation, and Figure 8 shows a radial trace transform corresponding to the central one of the shot gathers. In order to introduce some redundancy into the analysis data, we choose a much larger number of radial traces in the RT domain than the number of traces in the original XT domain. This means that the raypath angles of neighboring radial traces will be very nearly the same. If we then make the reasonable assumption that a statics distribution function probably varies only slowly with raypath angle at a single surface location, we can then find individual, (noisy) statics distribution functions for all the traces at each of many closely spaced angles, and average them over some range of angles to improve the robustness of our solutions. Alternately, we can deconvolve the distribution functions from the traces first, then average the traces over angle before sorting them back into RT transforms and inverting them to XT shot gathers.

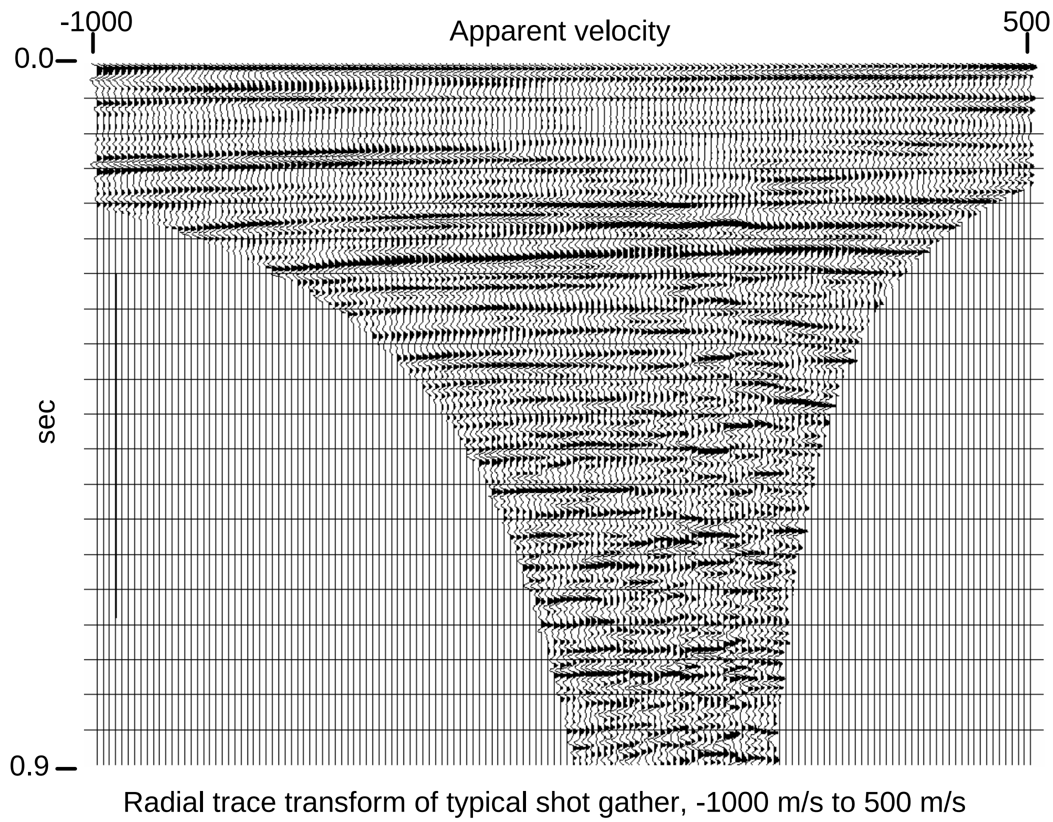


FIG. 8. Radial trace (RT) transform of one of the shot gathers shown in Figure 7.

Detecting and estimating the distribution functions

In order to detect and estimate the relative trace shifts at a constant angle from position to position along the surface of a line, we sort the RT transformed data by apparent velocity (raypath angle) and surface position (shot position) to form a series of constant-angle gathers. Figure 9 shows one example of such a gather. Note the relatively short traces in this gather…an indication that energy propagated at this raypath angle only penetrates to a certain depth in the earth before returning to the surface. Depending upon which reflection events are used for statics distribution function estimation, raypath-dependent statics are also depth-dependent, due to the geometry of the raypaths.

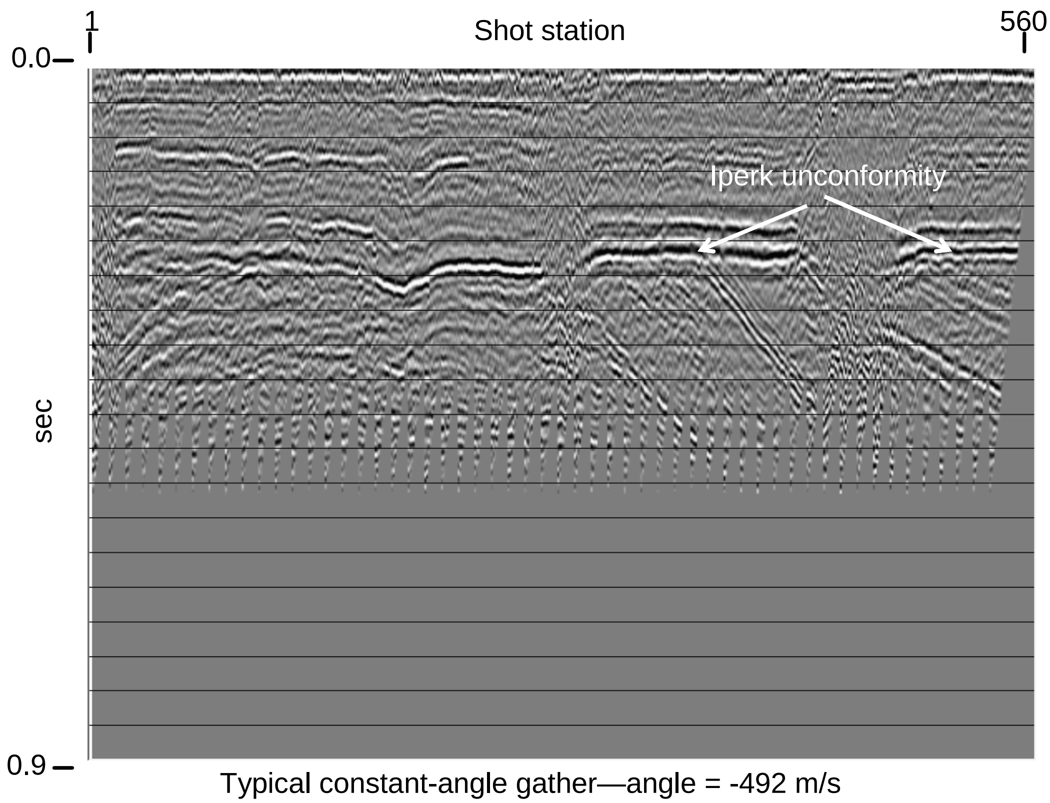


FIG. 9. Example of a constant-angle gather for Shell arctic data. At this particular angle (apparent velocity) some distorted reflection energy is apparent even beneath the river channels.

Examination of a series of consecutive constant angle gathers for two different sets of seismic data convinced us that, indeed, raypath-dependent statics change relatively slowly with raypath angle (Henley, 2005). Interestingly, the quality of the reflections on these gathers varied considerably with angle, as well, sometimes exceeding that of the same reflections on the brute stack. This suggests that if we perform our actual statics correction on these angle gathers, we might preferentially weight the better quality corrected gathers relative to those of poorer quality as we reconstruct the RT shot gathers, then invert to XT shot gathers. We might, by this simple act, further enhance the coherent signal on the shot gathers.

As mentioned earlier, the process of estimating statics distribution functions continues to evolve; but current techniques involve cross-correlating traces either with neighboring traces or with a pilot trace (which seems to be more reliable). As also mentioned before, pilot trace creation is also an active research topic; but we have achieved some success for relatively flat reflection events, by merely mixing the traces of a constant angle gather, using a mixing length that can be adjusted to smooth over static variations of various wavelengths. The constant-angle panel of Figure 9 from the Shell data set was mixed to yield the pilot trace panel shown in Figure 10.

FIG. 10. Pilot trace panel created from the constant-angle panel in Figure 9 and its neighbors at nearby angles.

Each trace in this panel is matched with its corresponding trace in the original angle gather, and the distribution function estimated by first computing the cross-correlations for each trace pair. We currently whiten the correlation functions by raising their samples to some positive exponent (usually between 3 and 9). This suppresses minor side lobes and narrows major peaks so that the correlation functions at least *look* more like distribution functions. Figure 11 shows the functions derived from the pair-wise correlation of Figures 9 and 10. This is a variable-density plot, so the width of the black at each station is indicative of the width of the distribution function for that station.

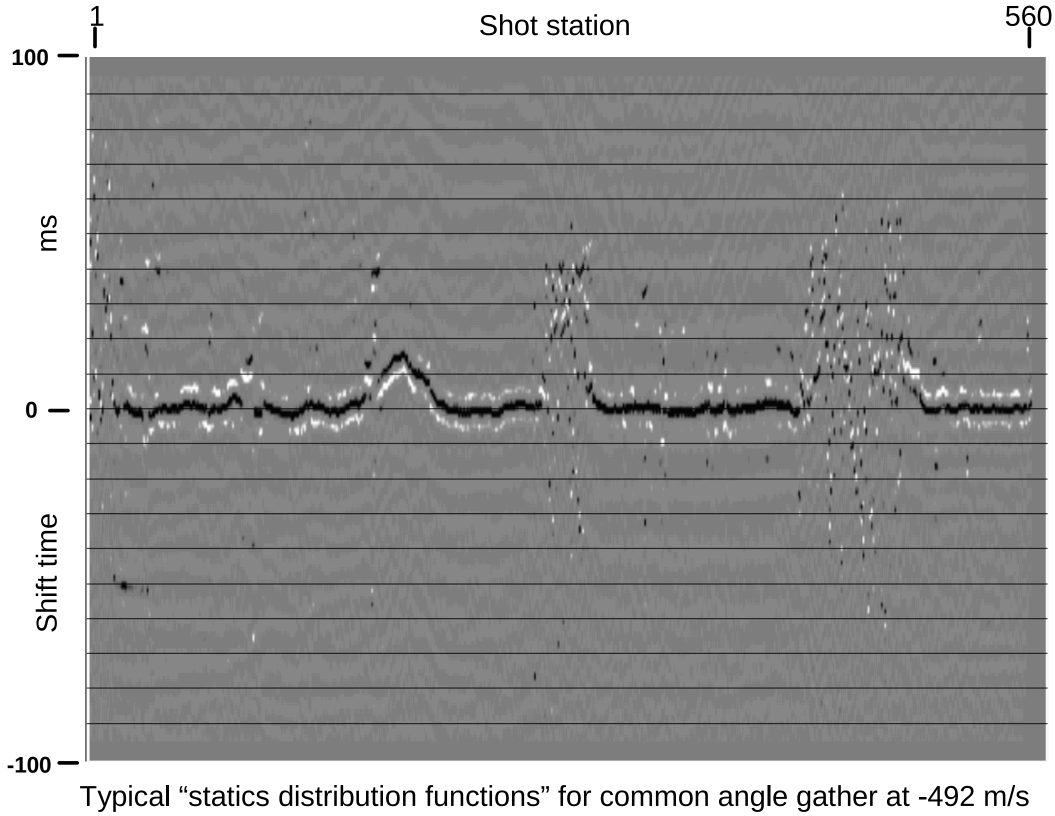


FIG. 11. Statics distribution functions estimated from cross-correlating constant-angle gather traces with their corresponding pilot traces.

Note that while most of the distribution function peaks are positive (black), there are also negative ones (white). Of course, a true statistical distribution function is always positive, but we rationalize these negative peaks as being due to arrivals of wavefronts of reversed polarity or to bandlimited resolution of the distribution function. In some cases, more than one peak can be seen at a single surface location. This can be an indication of multi-path phenomena, or simply of the uncertainty in estimating a particular function. Three river channels with their thawed subsurface environments are easily seen in this figure as the large positive deflections of the plotted distribution functions. The very weak reflection energy beneath these channels contributes to the chaotic pattern of distribution functions beneath two of the channels, since correlations for these traces are very weak. This figure shows only one set of distribution functions; a similar set is computed for each of the constant-angle gathers, typically 500-2000 gathers per line, depending upon the number of angles (traces) chosen for the radial trace transform.

Applying raypath-dependent statics

Having a set of statics distribution functions like those in Figure 11 for each of a set of constant-angle gathers, we can use one of a number of possible algorithms to derive an inverse or match filter for each of the distribution functions. If we then apply all the inverse (or match) filters to their respective constant-angle gather traces, we obtain results like those shown in Figure 12 (compare to Figure 9) for each of the constant-angle gathers.

FIG. 12. Common-angle gather from Figure 9 after being corrected by inverse filters for the statics distribution functions shown in Figure 11. The Iperk event at 300 ms is now nearly continuous across the river channels.

We also note at this point which of the constant-angle gathers shows the most improvement, so that we can weight them during the reconstruction of the original data set. The correlation window for these data was centered on the prominent flat Iperk event near 300 ms, a well-known major unconformity in this region, so it is no surprise that this event shows the most improvement in coherence. Also, the correlation function includes shifts as large as +/- 100 ms, to allow for any eventuality such as large pockets of soft, slow material.

After applying the inverse (match) filters, we can actually start another iteration of the process by using the corrected constant-angle gathers to create improved pilot trace panels. To reconstruct the original data set for imaging, however, we first re-sort the traces in the corrected constant-angle gathers by shot location and apparent velocity into their original RT gathers. It is at this point that the data redundancy that we forced by our oversampling in the RT domain can be utilized to improve the robustness of the solution. To average statics solutions over a range of angles, we can use a simple weighted trace mix in the RT domain. To guide the reconstruction more toward the raypath angles with the most robust statics solutions, we simply apply trace weights to each trace in the RT gathers before inverting the RT transforms. Figure 13 shows one of the RT transforms after statics correction, and Figure 14 shows the same three shot gathers as Figure 7 after statics correction.

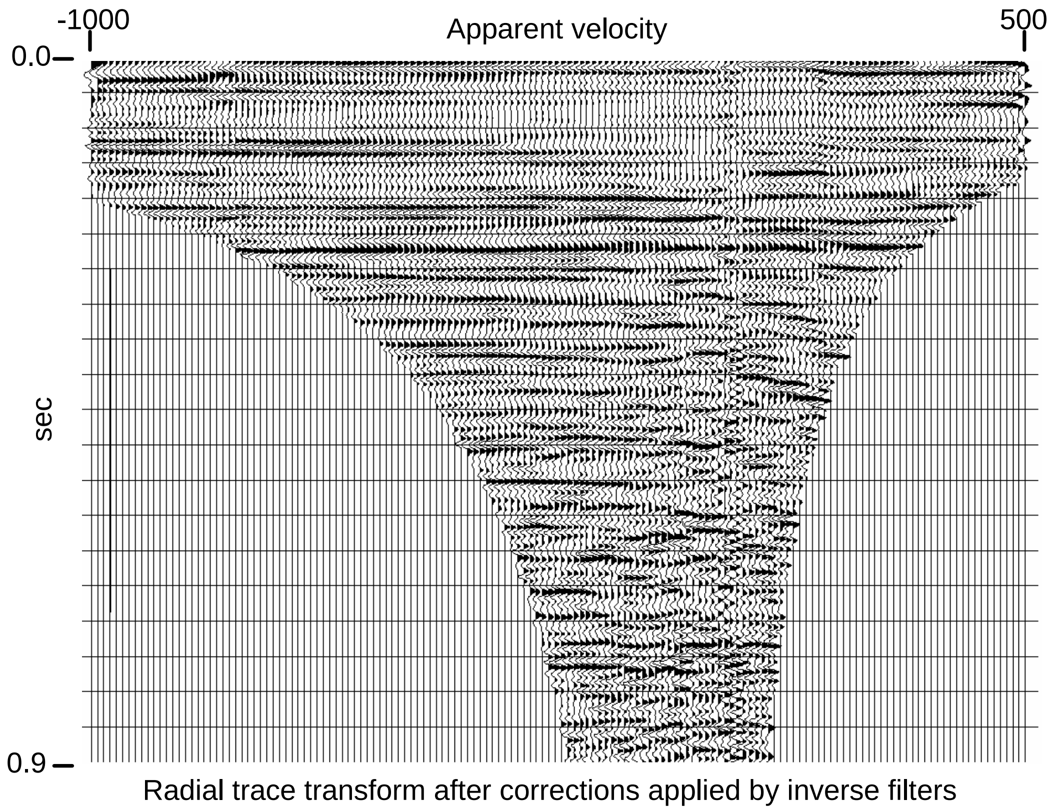


FIG. 13. Radial trace transform from Figure 8 after raypath-dependent statics corrections. Events down to and including the Iperk event are flatter and more continuous.

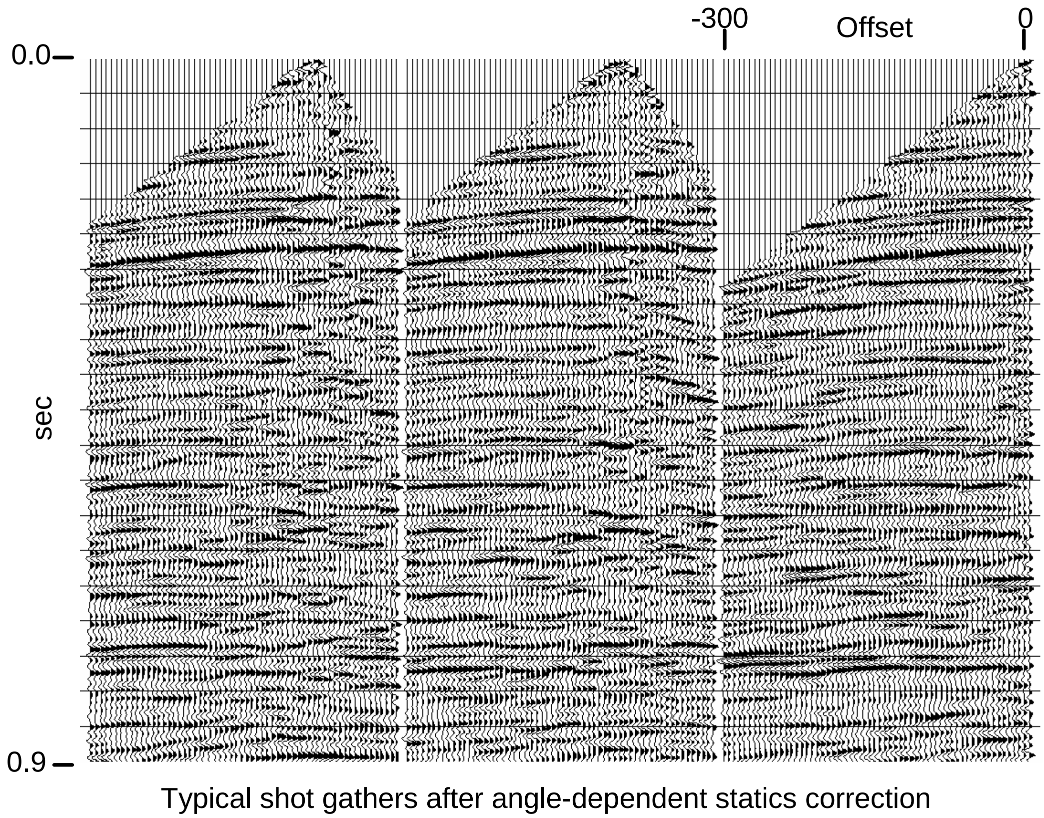


FIG. 14. Shot gathers from Figure 7 after raypath-dependent statics correction. The early parts of the records are truncated along constant velocity trajectories, due to the choice of RT velocity range.

Stack results

The brute stack of the high resolution Shell line, with only noise attenuation applied, is shown in Figure 15, where the effects of the three river channels can be easily seen. While the noise attenuation has successfully reduced the noise level, the noise was originally so strong that acquisition system dynamic range limitations precluded the recording of much reflection signal beneath the level of the unconformity.

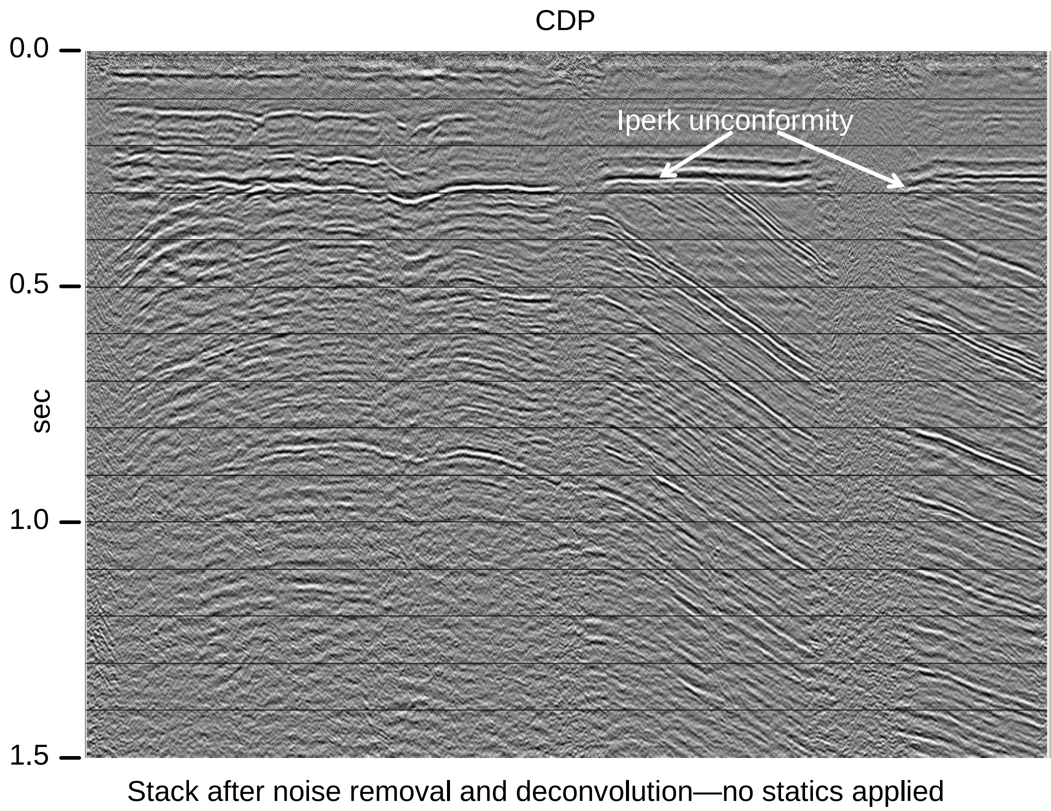


FIG. 15. The entire Shell line after noise attenuation and deconvolution.

Derivation and application of raypath-dependent statics functions leads to the stack shown in Figure 16. As can be seen, the unconformity event is quite coherent and flat, and some of the dipping reflections beneath have improved as well. The result shown in this figure is due to a single pass of the procedure described, using a very wide mixing length to derive pilot traces. Figures 17 and 18, however, show the result of a "bootstrap" method, where we use a much shorter mixing length for pilot traces and hence correct relatively short wavelength statics in the first pass, then apply progressively longer mixing lengths for successive pilot trace estimation for each of several passes. The result of 4 iterations is shown in Figure 17 and 6 iterations in Figure 18. The big difference between these figures and Figure 16 is that the unconformity event is not nearly as flat or continuous, but its coherence does improve slightly with each pass, and in the vicinity of the largest channel on the right end of the line, some of the steeply dipping reflectors beneath the unconformity appear to be becoming more coherent. We continue to investigate this approach, as well as the one-pass method, since neither technique appears to provide the "best" solution.

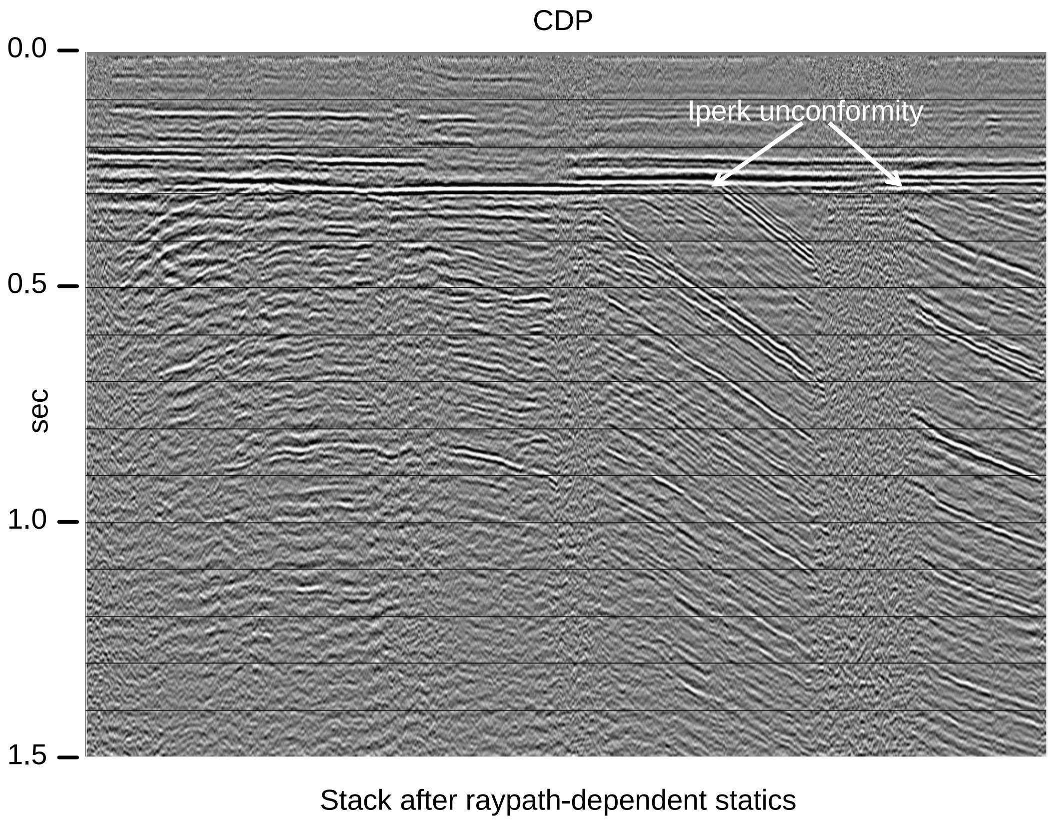


FIG. 16. Shell arctic line after one pass of long-wavelength raypath-dependent statics.

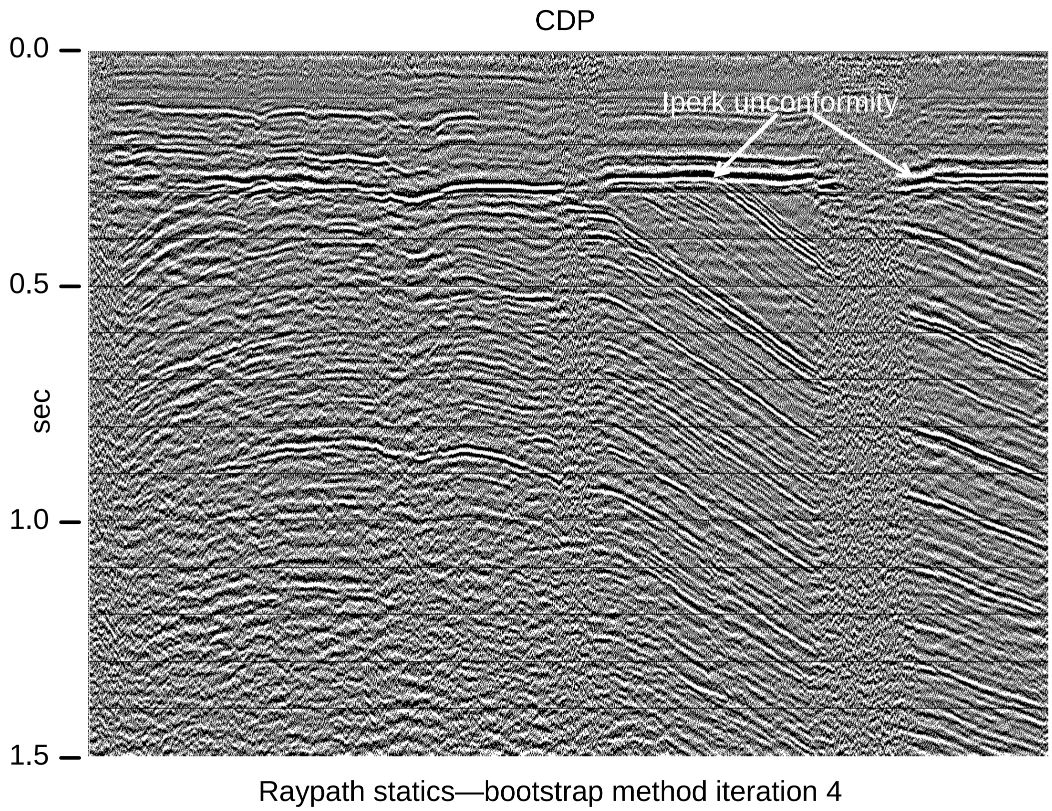


FIG. 17. Stack after 4 iterations of the “bootstrap” method, where short wavelength statics are corrected first. The Iperk reflection is not flat, but some coherence begins to appear in deeper reflections.

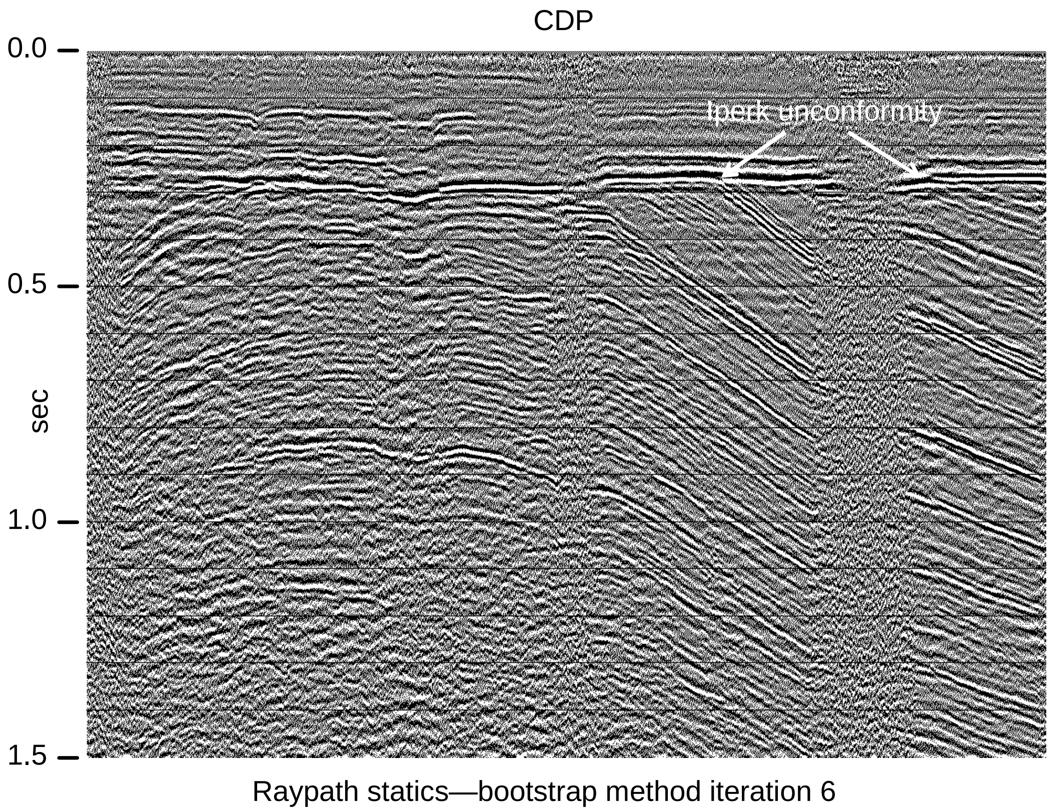


FIG. 18. Stack after 6 iterations of "bootstrap" raypath-dependent statics. The coherence of the Iperk reflection increased slightly over Figure 17.

DISCUSSION

We have so far applied our ideas for raypath-dependent statics to two different sets of data from the Arctic, where we expect the frozen surface to lead to the failure of the surface-consistent assumption used for conventional statics solutions. As yet, we have no ray-traced model results to help confirm that the phenomena we are addressing are actually statics that vary with raypath angle; but we see, particularly on the present data from Shell, diagnostic results that are consistent with raypath-dependence (statics patterns that vary slowly from one constant-angle gather to the next, for example). Furthermore, we observe very significant improvement of reflection coherence (and flatness, in the case of the Iperk unconformity) when applying our technique. At the very least, by allowing us to find a multitude of almost-redundant statics solutions, one for each raypath angle, some of those solutions over certain ranges of angles are quite robust and contribute to an overall improvement in the stack image, unlike more conventional statics approaches, which totally fail in the vicinity of the river channels.

Two aspects of the method which clearly need more work are the construction of pilot traces and the reshaping of the correlation functions into statics distribution functions. In addition, some scheme to allow the distribution functions derived for one angle gather to influence those being estimated at a neighboring gather might lead to greater robustness. At some point, it will be useful to ray-trace an arctic model, forcing it to exhibit raypath-dependent statics, so that the method can be more convincingly confirmed.

ACKNOWLEDGEMENTS

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