Raypath-dependent statics

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ABSTRACT

The region of the earth which usually has the greatest effect on the quality of seismic reflection data is that between the surface and the first competent "bedrock" interface, which can occur at a depth of anywhere from zero to a few hundred metres. When the material in this region is much softer than the rocks beneath the bedrock boundary, seismic reflection energy travels along near-vertical paths to and from surface locations, and simple time shifts can be used as effective corrections for seismic traces. The application of these simple "static" time shifts to each trace is often sufficient to correct for velocity and/or thickness variations in the surface layer. When the near-surface material is harder than deeper material, however, as often occurs in arctic permafrost areas and in regions covered with volcanic surface flows or overthrust carbonate layers, the assumption of near-vertical raypaths is no longer valid. Each reflection raypath connecting one surface location to any other surface location has its own unique raypath segments through the near-surface material. This implies a separate static correction for each near-surface raypath segment, rather than a single average correction for all raypaths sharing a single surface location.

We hypothesize how such statics would appear on field data, then seek evidence for their existence on a set of arctic field data.

The Snell ray radial trace transform is used to map seismic trace gathers into the domain of common injection angles (or common reception angles). Common-angle Snell ray trace panels are analyzed for differential statics using static distribution functions. Arctic data analyzed in this way show consistent evidence of small statics that vary slowly with raypath angle. An early attempt to correct these data by applying match filters derived from the angle-dependent static functions have yielded interesting results that appear to verify the existence of raypath-dependent statics and to show that they can be corrected.

INTRODUCTION

Time picks vs static distribution functions

Correcting seismic reflection traces for the effects of propagation through the near-surface region of the earth is a significant ongoing problem for seismic data processors. Most often, data redundancy and favourable near-surface conditions allow the constraint of surface-consistency to be imposed in order to derive appropriate discrete "static" time shifts to apply to correct individual seismic traces. In a significant fraction of cases, however, especially in areas where the surface layer of the earth is significantly higher in velocity than underlying layers, surface-consistency is clearly violated, and some other constraint or condition must be used to assist in solving the "statics" problem. The violation of surface-consistency, the statistical uncertainty of discrete event arrival times, and the possibility of multi-path phenomena are among the near-surface seismic propagation issues which led to a proposal to pose the near-surface correction problem as a deconvolution problem in which a “distribution” of shifts would be determined for each trace and the distribution function removed from the trace via a match filter deconvolution approach (Henley 2004).

The use of a “static distribution function” to describe near-surface effects has some obvious attractions, including the capability of handling multi-path arrivals (even short-period multiples), as well as embodying in a natural way the concept of uncertainty for event arrival times. Furthermore, by adapting the processing architecture of time-varying deconvolution, we can hypothetically apply a static distribution which varies with time, as well, allowing it to accommodate not only near-surface transmission effects, but deeper transmission path variations as well—a full tomographic approach. As with many seismic processing problems, the difficulty with this approach is not with the application, but with the determination of robust static distribution functions from the data in the first place.

For conventional static corrections, it is normally assumed that the near-surface of the earth can be idealized by a model such as that shown in Figure 1. Since all the raypaths which begin or end at a particular surface location follow nearly the same steep trajectory through the surface layer, it is assumed that any static delay attributable to that surface location will be the same for all raypaths. This is the so-called “surface-consistency” constraint which is used by many statics derivation techniques to average sets of raw event time picks into sets of static time shifts. It can be seen from Figure 2, however, that when the surface layer has a significantly higher velocity than the underlying material, Snell’s Law dictates that raypaths terminating at a given surface location will have widely differing transmission angles and path lengths, the deeper the raypath penetration, the shallower the angle of the near-surface raypath segment. Clearly, surface-consistency is violated, so we can’t use the same averaging techniques that are used to derive conventional statics.

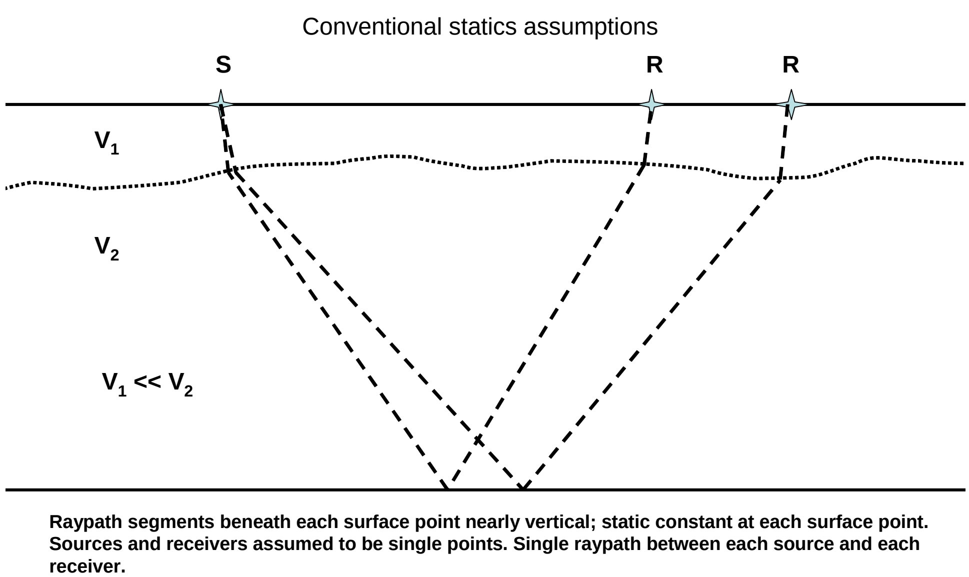

FIG. 1. Schematic showing the assumptions involved in the conventional statics model, which lead to the “surface-consistent” approach.

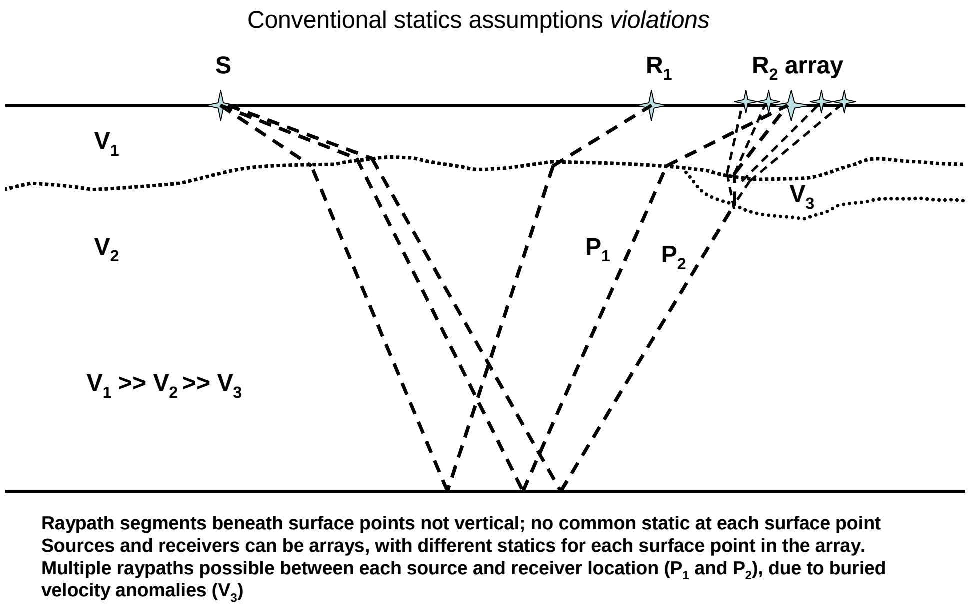

FIG. 2. Schematic showing some of the conditions which violate conventional statics assumptions.

In conventional statics, individual time picks, with their associated picking errors, are the input data; and the averaging techniques used in the solution algorithms are used to increase the statistical robustness of the statics estimates. In our proposed deconvolution approach, however, event "picks" are replaced with "statics distribution functions", which contain not only a pick time or times, but also information about the error associated with these picks related to the width of the function—the wider the function, the less certain the effective pick time (Henley 2004). The best way to estimate these distribution functions is still under active investigation (Henley and Haase 2005), but an early approach used the cross-correlation function between an input trace and either a pilot trace or one of its near neighbours, then applied some ad hoc "conditioning" to make the function more distribution-like.

While distribution functions can be averaged in a surface-consistent manner, just like individual time picks, then used to derive match filters to remove surface-consistent statics effects from shot and receiver gathers, we envision a more general approach. In our general approach we propose either deriving match filters for every static distribution function, for every raypath angle, and applying them explicitly to all pertinent input traces; or, instead, averaging the static distribution functions corresponding to common positions on each of several "focal depth" planes and deriving match filters to apply to "focal depth trace gathers", each of whose trace raypaths traverse a common point on a focal depth plane. In this report, we begin to pursue the first option, which, however, requires robust estimates of statics distribution functions. The second approach, to be investigated in the future, would incorporate averaging of less robust statics distribution functions. However, it requires a systematic way in which to construct "focal depth gathers", of which shot gathers, receiver gathers, and CDP gathers are special cases.

Geometric considerations

For the standard surface-consistent approach, static distribution functions can be estimated by cross-correlating event windows on neighbouring traces on surface-consistent trace gathers (shot and receiver gathers), and these functions are assumed to be largely independent of offset (or near-surface raypath angle). If the near-surface is as shown in Figure 2, however, this is not the case. It thus makes more intuitive sense to correlate neighbouring traces on gathers whose traces share a common raypath angle instead of a common surface location. Common offset gathers could be used for such a purpose, but their angular sampling is very coarse and non-uniform for the geometry in Figure 2, and we choose instead to use the radial trace transform, or its cousin, the Snell ray transform (Henley 2000) to create a set of gathers with finer and more uniform angular sampling. The Snell ray transform, in particular, is attractive because it attempts to map trace samples along a single raypath whose bends are determined by the local velocity and Snell's Law. Sorting the traces in these gathers by angle and surface location then yields common-angle gathers, whose neighbouring traces can be cross-correlated to give static distribution functions as a function of surface location.

EXPECTATIONS AND CONFIRMATION

Model study

Intuitively, we expect a model like that shown in the Figure 2 schematic to exhibit statics which vary slowly but systematically with raypath angle in the following way: we expect that a pattern of static shifts observed on one angle gather should closely resemble the pattern on a gather at a neighbouring angle, but should be shifted to slightly different surface locations due to the changed near-surface ray angle. Also, we would expect the statics to change in magnitude with angle due to the different pathlengths—smaller statics for more nearly vertical raypaths, larger statics for more oblique raypaths. In order to verify this, A. Haase is constructing a synthetic model based on the arctic permafrost layer, which is typically much higher in velocity than the under-consolidated layer immediately beneath. The purpose of the model is to determine the thickness of permafrost and the magnitude of the thickness variations that would be expected to lead to significantly angle-dependent statics. When completed, results from the model should also help confirm the pattern of statics to be expected on field data. The study will be presented in detail in a future report.

Field data

The Hansen Harbour 2-D 3-C survey was selected to examine for evidence of angle-dependent statics because of the known existence of surface permafrost on the line, and because of the wide range of offsets in the dataset. This extended offset range means that there are data with a wide range of raypath angles through the surface layer, thus enhancing our chance of observing angle-dependent statics. The receiver spread for this survey was only 50 stations in length; while the source line was over 200 stations long, extending well beyond both ends of the geophone spread. For this reason, we chose to analyze receiver gathers, each of which thus characterizes the surface variations for the entire line, rather than just those for the receiver spread.

The diagnostic technique that we developed for the Hansen Harbour data is as follows:

- NMO correct each receiver gather with a velocity function based on curve-fitting in the Trace Display ProMAX module. The large offset range in each receiver gather should assist in obtaining accurate velocities.

- Create a Snell ray transform for each receiver gather using a velocity profile based on the Hansen Harbour stacking velocities. Include enough traces in the transform to allow for eventual inversion of the Snell ray transform.

- Sort the Snell ray transform gathers by velocity (value stored in the OFFSET trace header) and receiver surface location to form constant raypath angle gathers.

- Cross-correlate adjacent traces in all constant angle gathers, using a window that includes all likely reflection energy on each trace. The traces with near-vertical angles will see many more reflections because of their depth of penetration than the traces with shallow angles.

- Condition the constant-angle cross-correlation gathers to make the functions look more like static distribution functions (Henley 2004).

- Create colour contour displays of the distribution function angle gathers.

Figure 3 shows a typical Hansen Harbour receiver gather, in which the geophone location is on the inland side of the shoreline, while Figure 4 displays its Snell ray transform. Note that the long traces of this transform, with small apparent velocities, correspond to traces with near-vertical near-surface raypath segments, while the short traces with larger apparent velocities correspond to shallow raypath angles whose associated seismic energy does not penetrate very deeply into the earth. Figure 5 illustrates a common-angle gather for a single value of injection/emergence (raypath) angle. To assess the similarity of statics patterns between such gathers, we computed statics distribution functions between adjacent traces in each of the gathers, seeking trace-to-trace shifts, or "differential" statics.

Note the prominent vertical pattern of statics outlined on Figure 3. The same pattern appears on the Snell ray gather in Figure 4, except that the pattern is not vertical, indicating that the statics are *not consistent* in the angle dimension. Since they *are* vertically aligned on the original gather, this means that they are surface-consistent and should *not* greatly influence statics on constant-angle gathers.

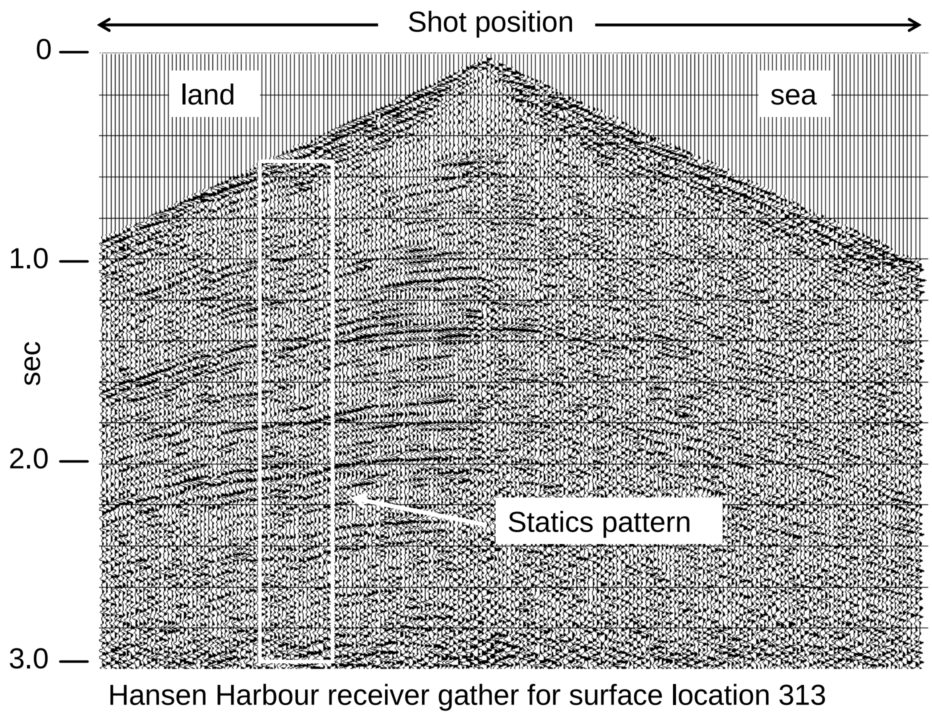

FIG. 3. A receiver gather from the Hansen Harbour 2D 3-C seismic survey. Data quality is much better on the portion of the gather where the shots were located on land rather than on floating ice. Note the pattern of static shifts outlined by the box.

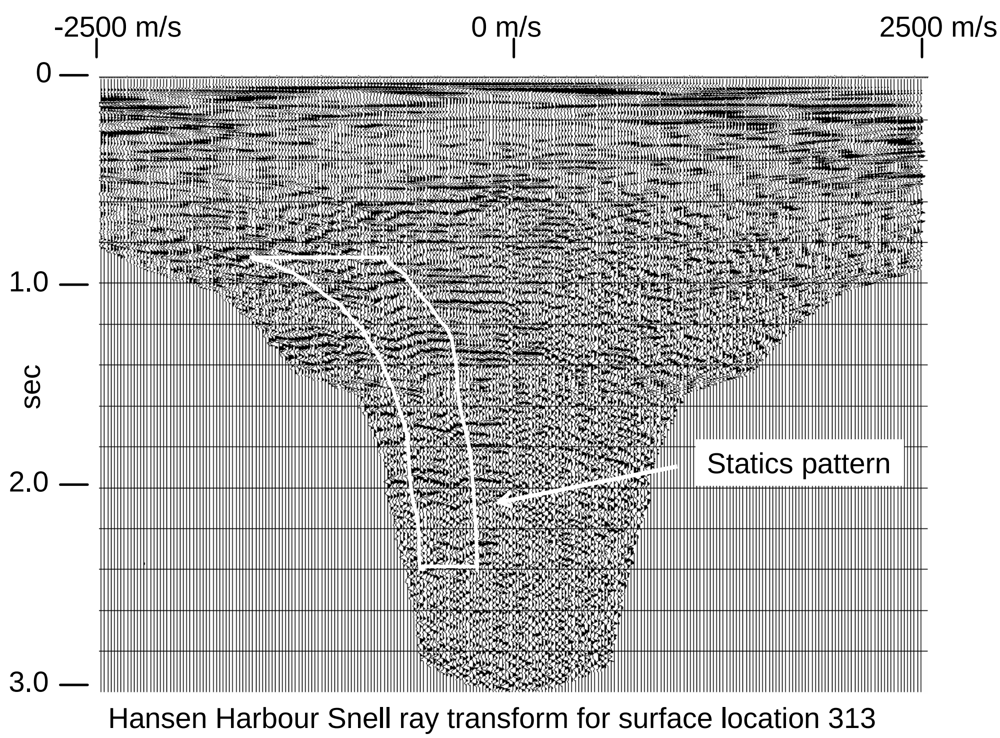

FIG. 4. Snell ray transform of the receiver gather shown in Figure 3. Each trace corresponds to seismic energy arriving at a single emergence angle at the surface.

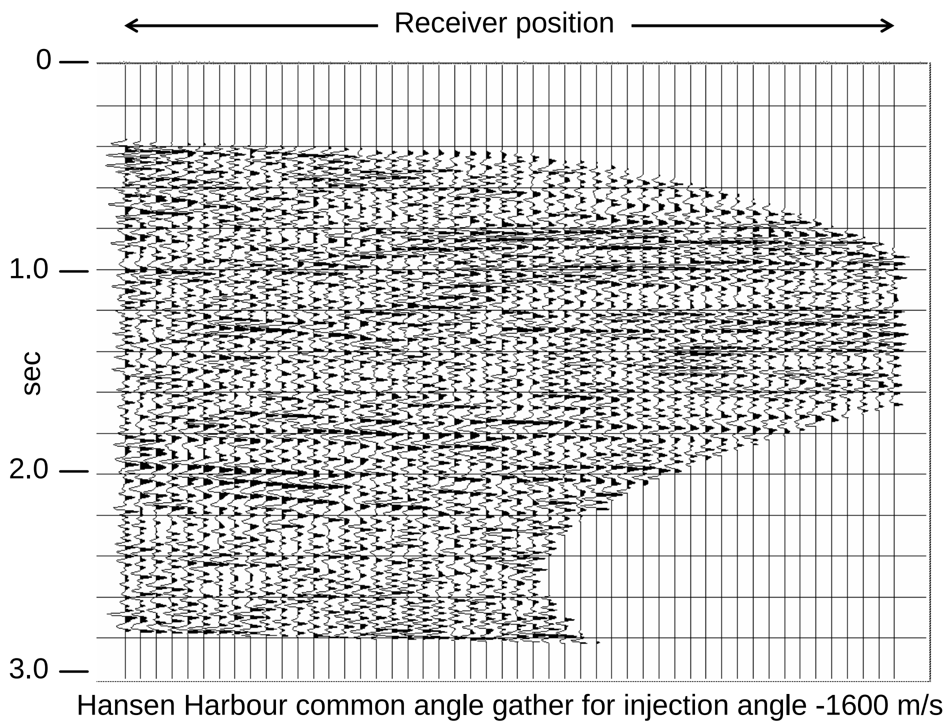

FIG. 5. A gather of Snell ray traces for which the emergence/injection angle is -1600 m/s. No large trace-to-trace statics are visible, but small ones can be seen.

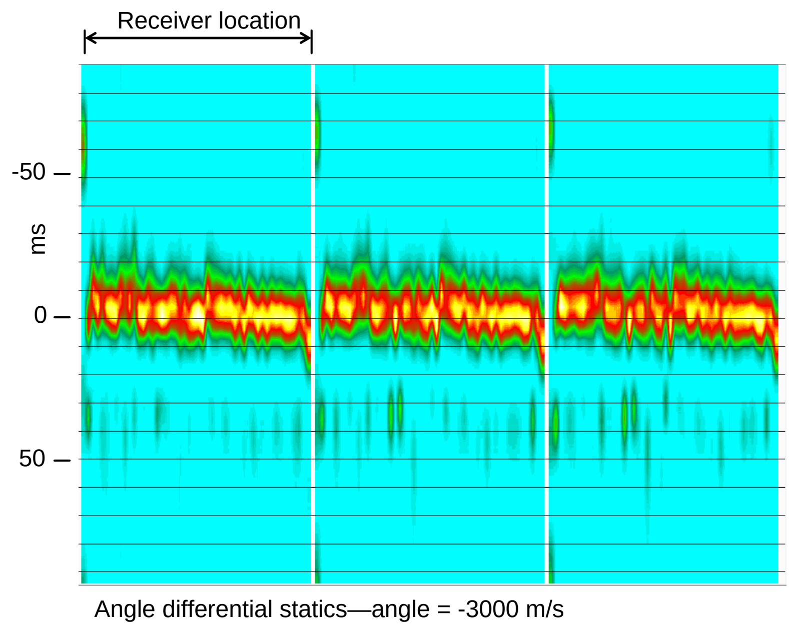

FIG. 6. Statics distribution functions computed for three consecutive common-angle gathers centred on -3000 m/s. These indicate differential statics shifts, from trace to trace, rather than absolute static shifts with respect to a pilot trace.

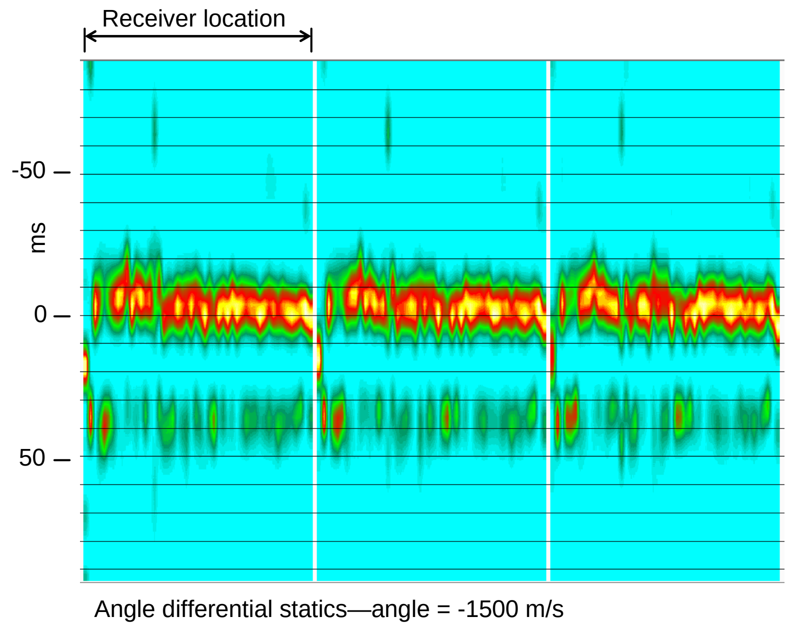

FIG. 7. Statics distribution functions for three consecutive common-angle gathers centred on -1500 m/s.

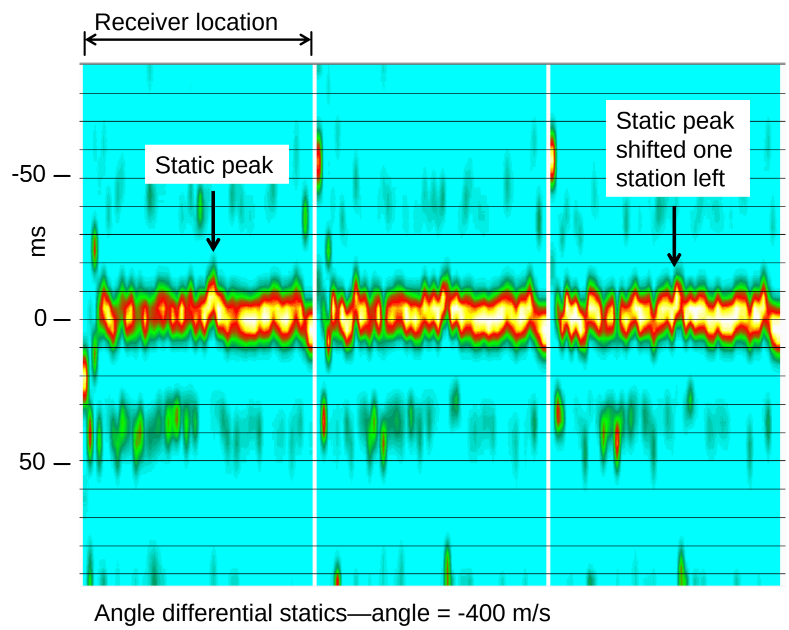

FIG. 8. Statics distribution functions for three consecutive common-angle gathers centred on -400 m/s. The prominent differential static flagged by the arrow in the left panel has shifted one station to the left on the right panel due to changed raypath angle between the two gathers.

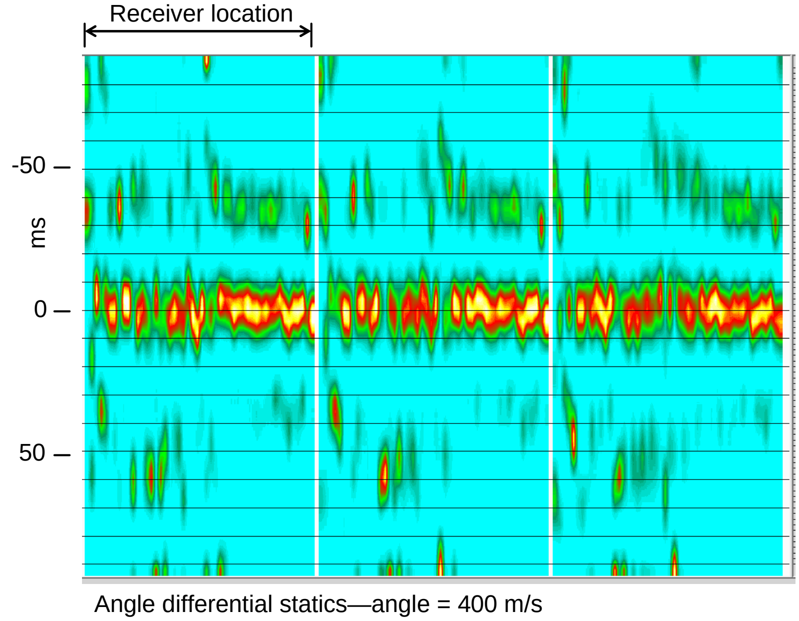

FIG. 9. Statics distribution functions for three common-angle gathers centred at 400 m/s.

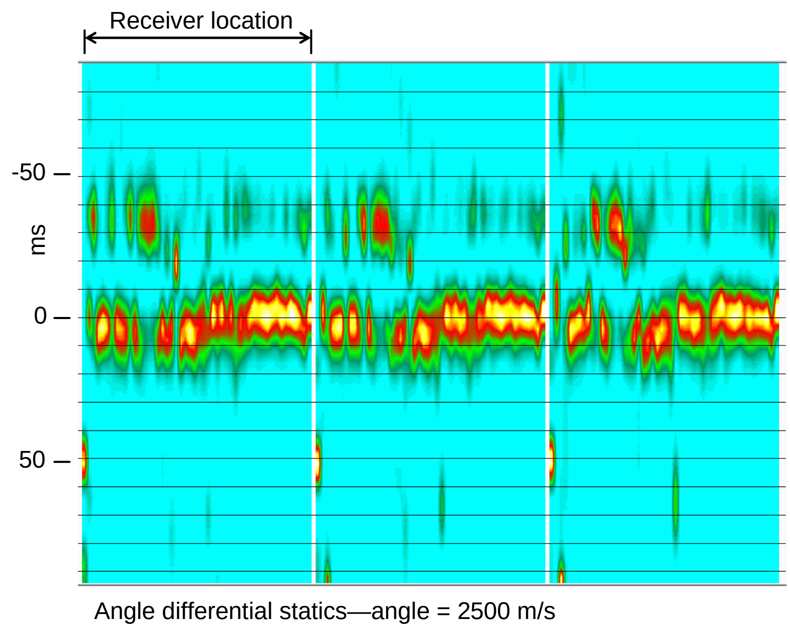

FIG. 10. Statics distribution functions for three common-angle gathers centred at 2500 m/s.

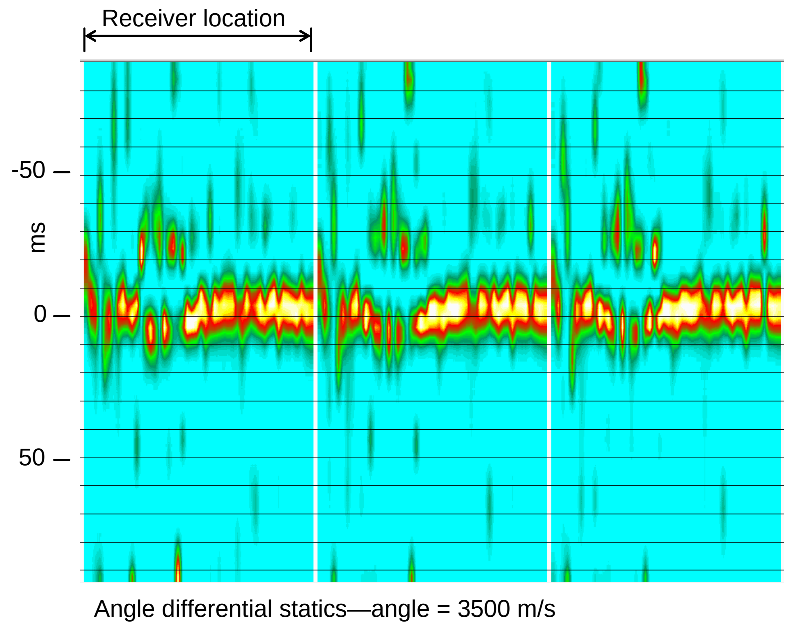

FIG. 11. Statics distribution functions for three common-angle gathers centred at 3500 m/s.

In Figures 6 through 11 we show the contoured statics distribution functions computed from the angle gather cross-correlations for six groups of three successive angle gathers. We make the following observations about these displays:

- They are not all alike—significant differences are evident for each distinct angle gather.
- Statics patterns are very similar for adjacent angle gathers, but *not* identical.
- Statics patterns sometimes appear slightly shifted laterally between neighboring angle gathers.
- Differential statics patterns corresponding to angle gathers more widely separated in angle show fewer similarities than those corresponding to near neighbor angle gathers; hence variation is consistent and systematic.
- Some of the statics distribution functions appear to have subsidiary peaks—possible evidence of multi-path or multiple reflection phenomena.

In combination, these observations are consistent with our expectations for the appearance of angle-dependent statics. When the model study is complete, we expect to see similar diagnostic patterns emerging as confirmation. Independent confirmation would be to successfully use the angle-dependent paradigm to construct a processing sequence which improved the seismic imaging of the Hansen Harbour data.

CORRECTING ANGLE-DEPENDENT STATICS

By definition, angle-dependent statics cannot be corrected by applying two time shifts to a seismic trace: one for source and one for receiver, since each shot and receiver has a set of statics associated with it, one for each angle. Furthermore, we have generated static distribution functions, not single static “picks”, one function for each propagation angle at each surface location. For this situation, it only makes sense to remove statics by deconvolution (Henley 2004). An additional complication is that the distribution functions generated in this study are for differential statics—that is, they characterize relative shifts between neighboring traces, not absolute shifts to some datum. To get the latter, we would need to cross-correlate all input traces with “pilot” traces tied somehow to a datum.

Differential statics can, in fact, be applied; but they must be applied in succession (or integrated from the beginning of a line if they are single shift times). Thus if we derive match filters between each distribution function and a spike centred at zero time, we would need to apply the match filter for the first distribution function to the second trace of the gather and all succeeding traces. The second match filter would then be applied to the third trace and all succeeding traces in the gather, and so on. The nth trace of a gather would thus have n-1 match filters applied to it, and numerical instability would almost certainly manifest itself at some point. Full integration of differential statics is necessary only if the full bandwidth of statics is required, however. If we seek mainly the short wavelength statics that contribute most to degradation of the CDP stack, we can shorten the integration length to perhaps two or three surface locations. This would mean that to correct a given trace by deconvolution, we would need to apply only two or three match filters in succession, the one correcting the current trace relative to its nearest preceding trace, and the one or two match filters immediately preceding. So to correct trace n of a gather, we would need to apply match filters n-3, n-2, and n-1, for example. In fact, if we are interested in only the very shortest wavelength statics, we could simply apply match filter n-1 as a first approximation.

Since the input data have already been expanded into a detailed set of angle gathers in order to estimate static distribution functions, it seems straightforward to simply apply match filters derived from the static distribution functions to the traces in the angle gathers to remove the differential shifts revealed by the distribution functions. The corrected angle gathers could then be sorted back into Snell ray gathers. Since each trace in a Snell ray gather would have been independently corrected within its own angle gather, it is likely that differential statics would exist within the Snell ray gathers. These could be addressed by correlating trace neighbors in the Snell ray gathers, finding match filters for the resulting statics distribution functions, and applying the match filters to correct the differential statics within each gather. At this point, the Snell ray gathers could be inverted to XT domain shot gathers and hence formed into a CDP stack.

A recent first attempt to apply angle-dependent statics adopted a slightly different approach than that outlined above:

- Instead of correlating trace pairs to get differential statics, each constant-angle gather was smoothed with a long trace mix to create a slowly varying pilot trace angle gather. This smoothing also served to limit differential statics between consecutive angles.

- The individual traces of each angle gather were correlated with their corresponding pilot traces and the correlations conditioned to form statics distribution function gathers.
- Constant-angle gathers of match filters were derived between the statics distribution gathers and a bandlimited spike posted at time zero.
- The match filter gathers were convolved with their corresponding constant angle trace gathers.
- The resulting corrected angle gathers were sorted to Snell ray transforms.
- The Snell ray transforms were inverted to XT domain receiver gathers.
- The receiver gathers were inverse NMO corrected.

To provide a seismic image for judging the success of the above approach, the original receiver gathers were NMO corrected and stacked, with no static correction applied. A portion of the resulting seismic image is shown in Figure 12.

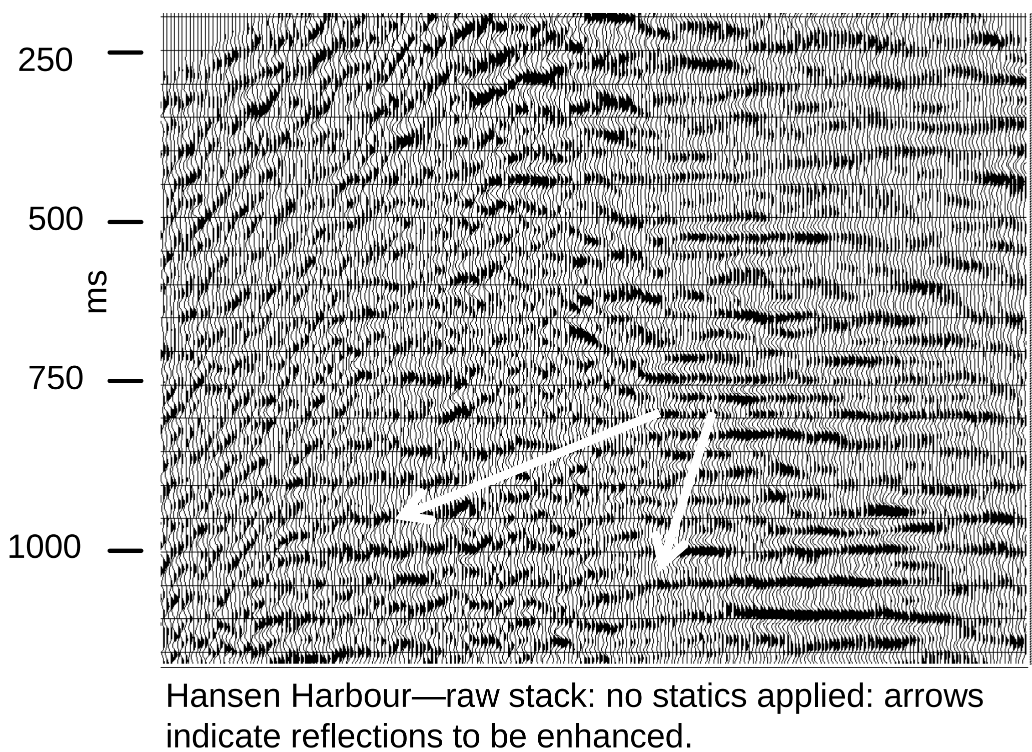

Fig. 12. A portion of the brute stack image for Hansen Harbour. No statics have been applied.

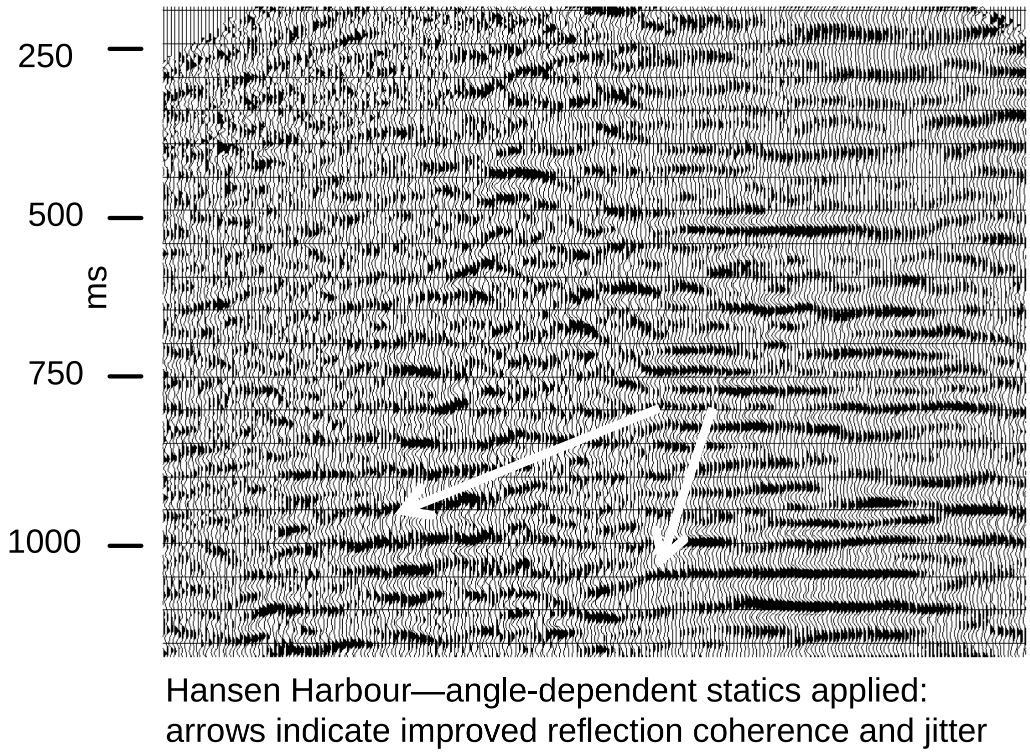

Fig. 13. Hansen Harbour stack after the application of angle-dependent statics.

The comparable stack after application of angle-dependent statics as described above is shown in Figure 13. Small, but significant improvements in event flatness and coherence are visible in several parts of the image, two of them indicated by arrows. Similar improvements can be found over the entire seismic image.

The results shown above are considered promising but not definitive, since the increased event coherence and flatness can conceivably be related to other aspects of the processing stream which we haven't definitely ruled out.

OUTSTANDING ISSUES

Although the cross-correlation function is universally recognized as a robust detector of correlations between events embedded in time series, it suffers from serious band limitation, which reduces its utility in constructing detailed static distribution functions. Elsewhere in this report, efforts are described in which we seek a correlation tool having greater bandwidth/resolution than the cross-correlation (Henley and Haase 2005). It is still unclear how best to derive and apply static distribution functions that are not surface-consistent; but the first attempt will likely follow the scheme outlined above for removing statics which conform to the angle-dependent model. These are some of the issues requiring further attention:

- The permafrost model will be studied extensively for similarity to our field data example.

- The Hansen Harbour data diagnostics are *suggestive* of angle-dependent statics, but do not definitively confirm them; so we will seek other field data sets where this phenomenon may occur.

- Derivation of reliable statics distribution functions remains an important research topic.

- Because of the large variability of the robustness of the static distribution functions we derive, a means needs to be found whereby traces corrected by match filters corresponding to less robust distribution functions are given less weight in the CDP stack.

- Methods for building robust pilot traces need to be explored, since differential statics are more problematic to apply than absolute statics.

CONCLUSIONS

In this chapter, we have hypothesized the existence of non-surface-consistent static shifts which depend on the angle of the raypath in the surface layer. We have proposed a credible model for circumstances which would lead to such statics—a near-surface layer whose velocity is significantly higher than the layers immediately beneath and which has significant thickness variations. A synthetic model is under construction to verify the expected effects of such conditions on seismic event arrival times. A set of seismic field data from the Hansen Harbour survey was investigated to look for these effects. The diagnostics obtained from these data are suggestive of the expected angle-dependent phenomenon, but not definitive. We have constructed a processing sequence by which angle-dependent statics functions should be detectable, and have explored a continuation of the process by which they should also be correctable. Future work will be aimed at testing variations of this sequence. Several technical problems exist, the greatest of these likely being finding a reliable method for actually detecting embedded static distribution functions without excessive bandlimiting.

ACKNOWLEDGEMENTS

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