An interactive solution for resolving mid-wavelength statics anomalies

VITALY KOZYREV, ALEXANDER ZHUKOV, ILYA KOROTKOV, and ARTEM ZHUKOV, Geophysical Data Systems, Moscow, Russia

Automatic methods used in conventional seismic data processing to make statics corrections work well with short-wavelength anomalies but regularly fail to resolve mid-wavelength near-surface anomalies. Calculation of correct static time delays caused by near-surface heterogeneities is especially difficult when the heterogeneities extend from half of a spread length to 2-3 times the source-receiver offset.

In this case, obtaining information about surface conditions, the near surface, and the shape of reflectors should be done prior to making static corrections because it is necessary to eliminate any uncertainty regarding those portions of the data that need to be processed with static corrections and those aspects that represent mid-wavelength anomalies. When only limited a priori information is available, some assumptions about near-surface structure and reflector shape are usually made. For this reason, an essential part of many methods to calculate mid-wavelength statics is direct intervention by an interpreting geophysicist, who can accurately assess various sources of information and make relevant assumptions about the near-surface model.

In the method described in this article, the geophysicist delineates zones of near-surface heterogeneities and interactively determines time shifts within their bounds. No assumptions about the near-surface model are made. A model of time shifts, which adequately reflects near-surface heterogeneities, is generated as the result of the correction. The advantage of this approach is obvious—building the time delays model requires less a priori information than the construction of near-surface model.

Delineation of the near-surface heterogeneity zones. The correction starts with reviewing the early arrivals of the recorded seismic wavefield. In many cases, when quantitative interpretation of first breaks is difficult, it is still possible to delineate areas of the near surface which have anomalous characteristics (and therefore will require statics corrections on the data) by examining common-offset sections—a process we call "on-the-fly reviewing" of the data.

Figure 1a shows a common-offset section (900 m) for a "receiver" line from a 3D survey and a first arrivals time map for this offset derived from the entire set of 3D survey lines. The survey is from Western Siberia in an area characterized by heterogeneous near-surface permafrost, a type of environment in which conventional statics corrections often fail.

Figure 1b shows a corresponding "source" line and first arrivals map. The time decrease of the first arrivals indicates significant velocity heterogeneity. In this case, the heterogeneity and velocity inversion with depth would make it practically impossible to build a reliable near-surface model by quantitative interpretation of first breaks even if the acquisition had finer spatial sampling.

However, determination of the boundaries of the anomaly is still possible. When a 2D seismic line crosses a heterogeneity, the trace that first touches the near boundary will show a time anomaly and, thus, determine one edge of the anomaly. The other boundary will be fixed by a time anomaly on the last trace that goes through the anomaly.

Even more accurate estimation of the boundaries is achieved by simultaneous analysis of common-offset sections from different offset ranges.

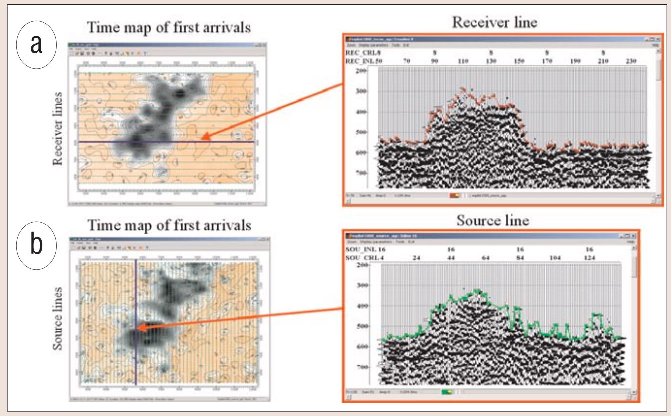

Figure 1. Common-offset sections (right) and first breaks time maps (left) derived from first breaks analysis over all receiver (a) and source (b) lines.

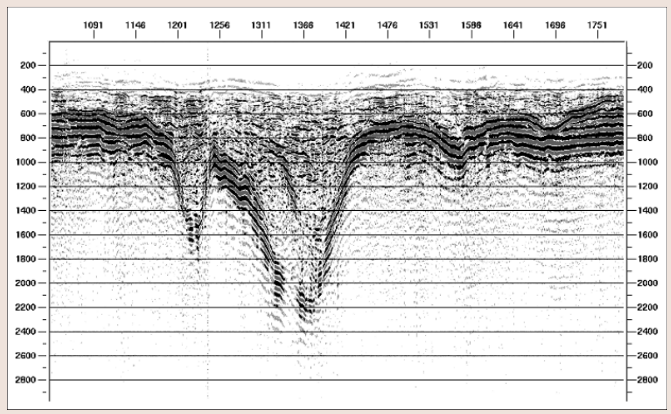

Figure 2. Example of the appearance of surface anomaly on a common-offset time section.

Another key to determining the shape of an anomaly is that, quite often, changes in the parameters of near-surface layers are more obvious on records of surface waves than on first breaks of refracted waves. Thus, on the common-offset section in Figure 2, the areas of intensive oscillation correspond to the surface wave and changes of surface-wave velocity are one indicator of a heterogeneity zone.

This type of initial analysis leads to what we call "qualitative" interpretation of local heterogeneity. Other types of information about the near surface can (and should if available) be used to complement the conventional seismic data. This can include data from wells drilled through the shallow heterogeneous layers, specific targeting of suspected surface layers using refracted or reflected waves, refraction tomography, data from different geophysical methods (such as potential fields), and a detailed description of surface conditions. Even vegetation type can be informative.

Determination of time shifts within heterogeneity zones. The main tools for determination of time shifts within such qualitatively delineated heterogeneous zones are surface-consistent common-source point (CSP) and common-receiver point (CRP) time sections. Selection of the surface-consistent stacking parameters—stacking fold and offset ranges—is based on both preprocessed shot gathers and the results of test CSP and CRP stacking in different ranges. In the case of

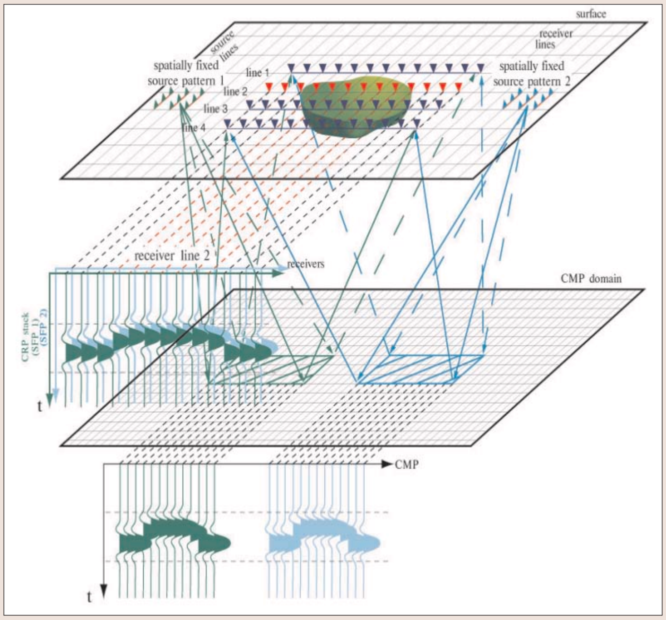

Figure 3. *Example of how two spatially fixed source patterns "illuminate" a near-surface heterogeneity.*

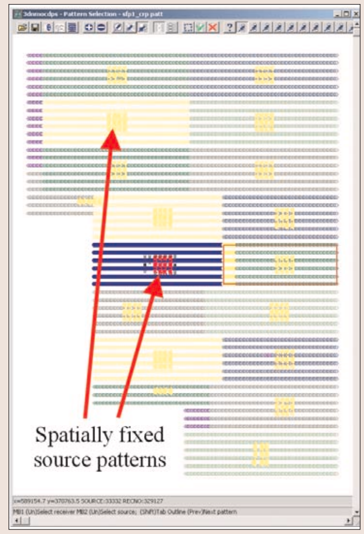

Figure 4. *A survey map of spatially fixed source groups. Receiver groups, illuminated from differently fixed source groups are shown in different colors.*

a 2D off-end spread, this frequently includes three sections: a full-fold stack that covers the offset range selected for analysis, and two partial stacks (the near half and far half of this range). In the case of a split spread, similar partial stacks can be generated for the left and right ends of the spread.

The major complexity behind delineation of mid-wavelength anomalies is that the anomaly pattern will appear on receivers during CSP stacking and on sources during CRP stacking—i.e., the anomaly pattern "couples" on these surface-consistent stacks. Thus, when different offset ranges of each type are stacked, the only anomaly pattern which is consistent on all stacks indicates a surface anomaly.

To avoid this complexity, a special stacking technique called a spatially fixed pattern (SFP) stack is used. In traditional CSP and CRP stacking, the offset range is fixed and the spatial positions of sources and receivers change along the line (in the 2D case). SFP stacking, on the other hand, fixes the spatial position of the receiver or source groups within a particular acquisition spread and the offset range varies.

The principle of surface-consistent stacking for a 3D survey is shown in Figure 3. During CRP stacking, records are stacked for each receiver within the analysis area. First, gathers are stacked, which were acquired from a fixed group of sources on the left and then on the right of the surface heterogeneity. By illuminating the heterogeneity from different directions, all invariant time delays can be identified and removed by appropriate statics calculations. Sections of the resulting CRP cubes along line 2 are shown in the lower left of Figure 3. Surface anomaly patterns on both stacks, derived from different source groups, are similar in appearance. As stated above, this means they are caused by surface conditions (and thus need to be removed by statics corrections); any patterns from actual depth anomalies on these stacks would not be similar because reflecting areas are different for each stack.

Since one such spatially fixed pattern involves only a small fragment of a seismic line or cube, it is necessary to design a set of spatially fixed patterns to provide continuous CSP or CRP stacking for all source and receiver points. Figure 4 is an example of an SFP set designed for 3D CRP stacking. Contour and color show the active receivers area and corresponding sources. Two sets of spatially fixed patterns are usually designed and two sections or cubes of each type (CSP and CRP) are generated for delineation of heterogeneities using the surface-consistent principle.

Interpreting CSP and CRP offset-limited sections in cases of continuous heterogeneity differs from conventional short-wavelength statics correction because of the necessity to discriminate between surface and depth anomalies, and exclude offset-dependent time shifts caused by "coupling." The main problem is identification of surface consistent mid-wavelength anomalies. The problem is solved by analyzing surface-consistent near-, mid-, and far-offsets or spatially fixed CSP and CRP sections by individually matching them, one after another, to the qualitative interpretation of the surface and depth factors at their surface or CMP positions. Surface anomalies match in the first case and diverge in the second. Figures 5 and 6 are examples of such matching.

At this stage, it is important to include additional information about surface and depth conditions and especially the results of the previously conducted wavefield and first arrivals analysis. Figure 5 compares CRP sections derived from two sets of different fixed source patterns and the early times on a common-offset section. All sections are matched by their receiver positions. The observed time anomaly is unambiguously obvious as a surface anomaly.

In the case of a dipping horizon, when the horizon time increment within offset-limited surface-consistent gathers approaches one wavelength, corrections for dip are required. A structure term using initial CDP, CSP, CRP sections is estimated prior to such corrections.

Figure 7a shows how the presence of mid-wavelength surface anomalies is verified on near- and far-offset CMP stacks. The different shapes on the partial-offset stacks indicate the near-surface nature of the heterogeneities. Figure 8 shows horizon velocity anomalies typical of local heterogeneities: the combination of three extrema of different signs with a velocity decrease in the middle of the high-velocity heterogeneity and a velocity increase on the low-velocity one. In the 3D case, comparing partial-offset CMP stacks can be performed with both time sections and time slices where discrepancies related to small magnitude anomalies are often more visible (Figure 9).

Estimation of statics anomalies is conducted on a combination of offset-limited CSP or CRP stacks by shifting reflected events to lines, which interpolates horizon behavior between neighboring zones outside of the anomaly. It is more reliable to use, as a guideline, an estimated structure (which is obtained from combined analysis of CDP, CSP, CRP stacks and a priori information about fixed key points outside zones influenced by heterogeneities). Structural determination is essentially interpretive. The initial estimate is very preliminary, but it should be refined after delineation of the surface components of any time delays.

The structural estimate should not have mis-ties at seis-

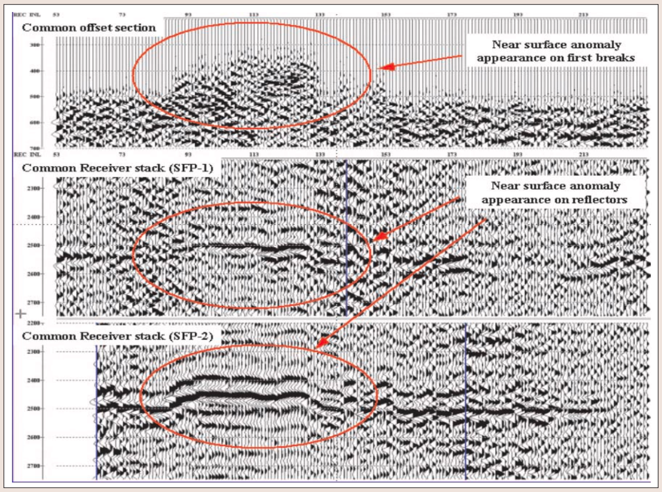

Figure 5. Multipanel display of three sections: common-offset (top), CRP SFP set 1 (middle) and CRP SFP set 2 (bottom). The surface-consistent sections are positioned by receivers. The anomaly image remains stationary.

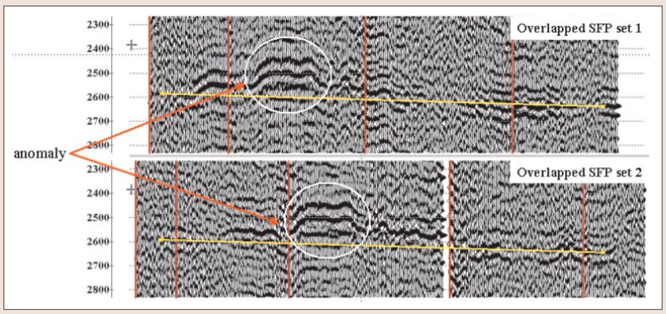

Figure 6. CMP-matching. CRP SFP set 1 (top) and CRP SFP set 2 (bottom). Stacks are positioned by CMPs. The anomaly image shifts on the surface consistent stacks.

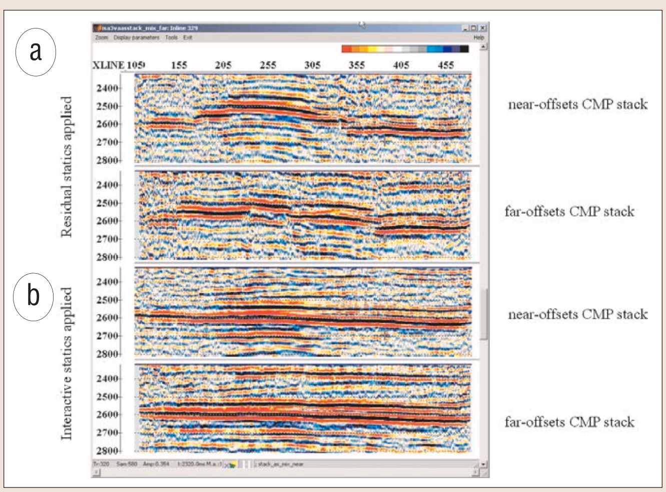

Figure 7. Comparison between CMP partial-offset stacks after autostatics (a) and after interactive statics (b).

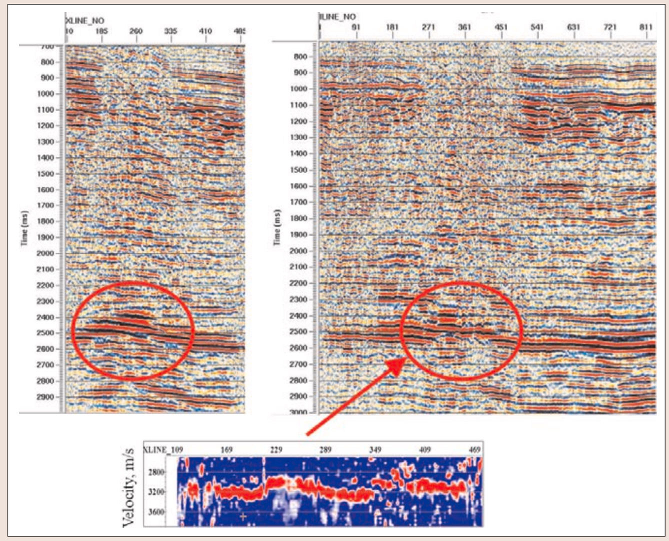

Figure 8. Two perpendicular vertical sections (above) and the horizon velocity analysis panel (below). Automatic statics applied.

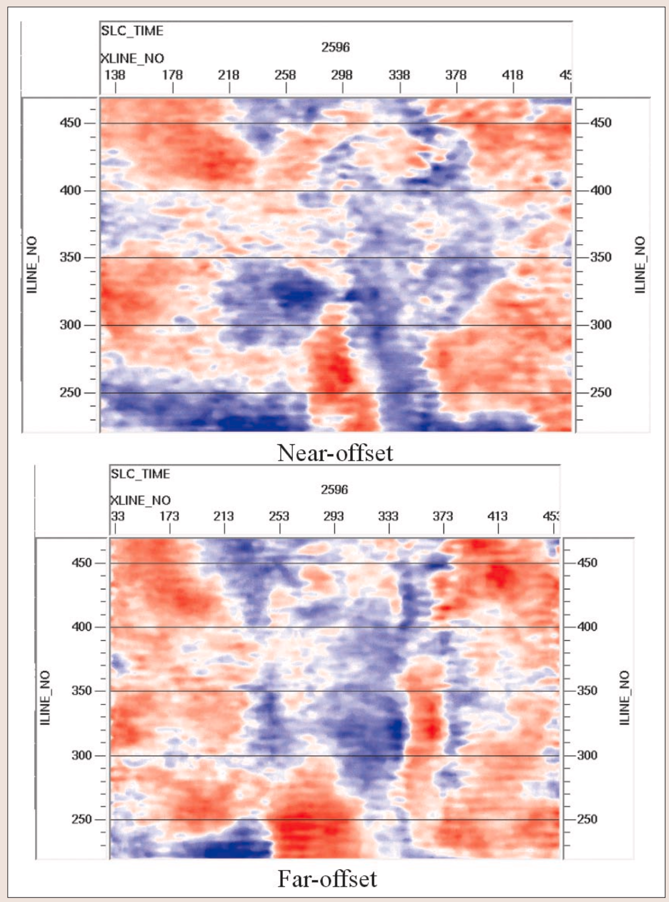

Figure 9. Amplitude time slice at 2596 ms. Near-offset (above) and far-offset (below).

mic line intersections. The mis-ties are dealt with during the next iteration of statics correction. In the 3D case, estimation of the structure is performed on a selected grid of vertical sections and then generalized over the whole area by forming a map that can be displayed on surface-consistent stacks of source or receiver lines.

Interactive analyses of time shifts is performed simultaneously on all stacks. This helps separate regular shifts from random ones and aids in selecting the optimal shifts. During the interactive shifting, the selected horizon is analyzed and it is also determined how "regular" are reflectors within the recorded time interval.

Figure 10 shows vertical cross-sections from two CRP cubes, along a receiver line in area characterized by near-surface heterogeneous permafrost, before and after interactive statics. The sections in Figure 10a show that application of automatic residual statics cannot resolve the anomaly. Figure 11 shows the conventional residual statics (a) and the interactive statics (b) corrections. The iterative approach is the key to the method. The goal of the first iteration when dealing with a complex near surface is delineation of the main heterogeneous zones or blocks by rough estimation of their boundaries and time delays within their limits.

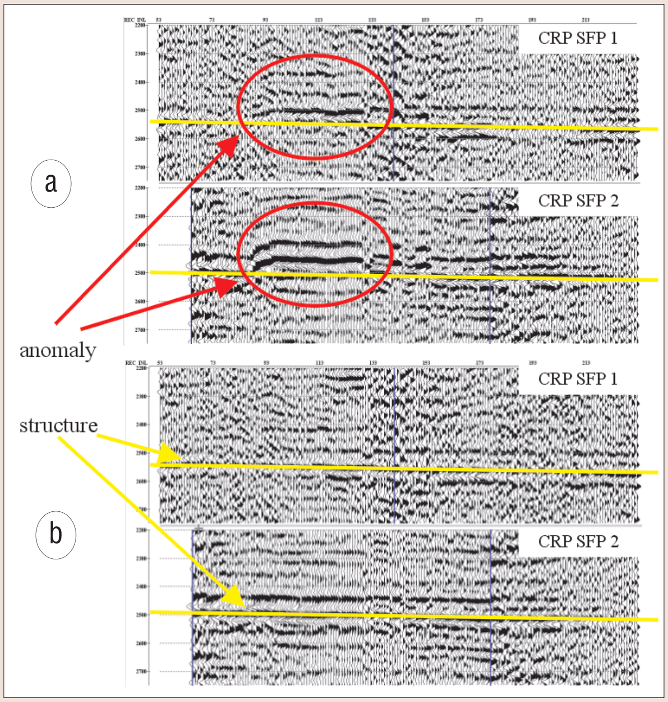

Figure 10. Two CRP sections with residual statics applied (a) and interactive and residual statics applied (b).

During subsequent iterations, the model of the time delays caused by near-surface heterogenities is refined. After one or two iterations of the interactive statics analysis, the time delays approach those assumed in residual autostatics algorithms. Therefore, during the final stage of statics correction, automatic residual statics methods can be implemented for resolving short-wavelength and low magnitude mid-wavelength statics components.

Interactive statics QC. QC of mid-wavelength statics uses partial-offset CMP stacks and the horizontal velocity spectra or vertical velocity field. When horizon times on different partial-offset stacks are similar and local rms velocity anomalies are absent, the statics correction is considered satisfactory.

Figure 7b shows vertical cross-sections of partial-offset CMP cubes along a line crossing permafrost heterogeneity zone. Before interactive statics, the near- and far-offset stacks differ; but after the final iteration of statics corrections, they are identical. Note in Figure 12, after interactive statics, that horizontal velocity spectra align, and anomalies on CSP or CRP stacks are removed. The conformity of delineated anomalies with a priori data is also controlled. Those smooth components, which cannot be delineated by the criteria mentioned above during data processing, should be accounted for during geologic model building and creation of depth sections during the interpretation stage.

Since most standard industry processing software systems don't have the ability to perform the interactive statics described above, a special standalone PC-based interpretation system was developed.

The system prepares the seismic data for interactive correction, designs stacking charts, generates surface consistent stacks, does vertical and horizon velocity analysis, compares/analyzes various stacks and gathers, displays them for matching in different domains (particularly in surface-consistent and CMP domains), performs horizon interpretation, and ultimately shifts single traces and blocks of traces.

Seismic data examples. Figure 13 shows two vertical cross-sections with an interpreted horizon time surface from a 3D cube from Western Siberia. Standard residual statics were applied in Figure 13a and interactive statics in Figure 13b. The latter, which agrees with the geologic model and well data, provides more reliable analysis of dynamic data attributes regarding hydrocarbon prediction in the target reservoir zone.

Figure 14 shows CMP time sections along a line crossing permafrost heterogeneity in another area of Western Siberia. The time section after standard processing (i.e., without accounting for mid-wavelength surface anomalies) shows small structure features that are similar in appearance through all recorded times and don't agree with well data. Interactive analysis indicates anomalies and application of the interactive statics results in a section (Figure 14b) which agrees with formation tops and local geology. It is obvious, that the section in Figure 14b is more suitable for analysis of dynamic attributes.

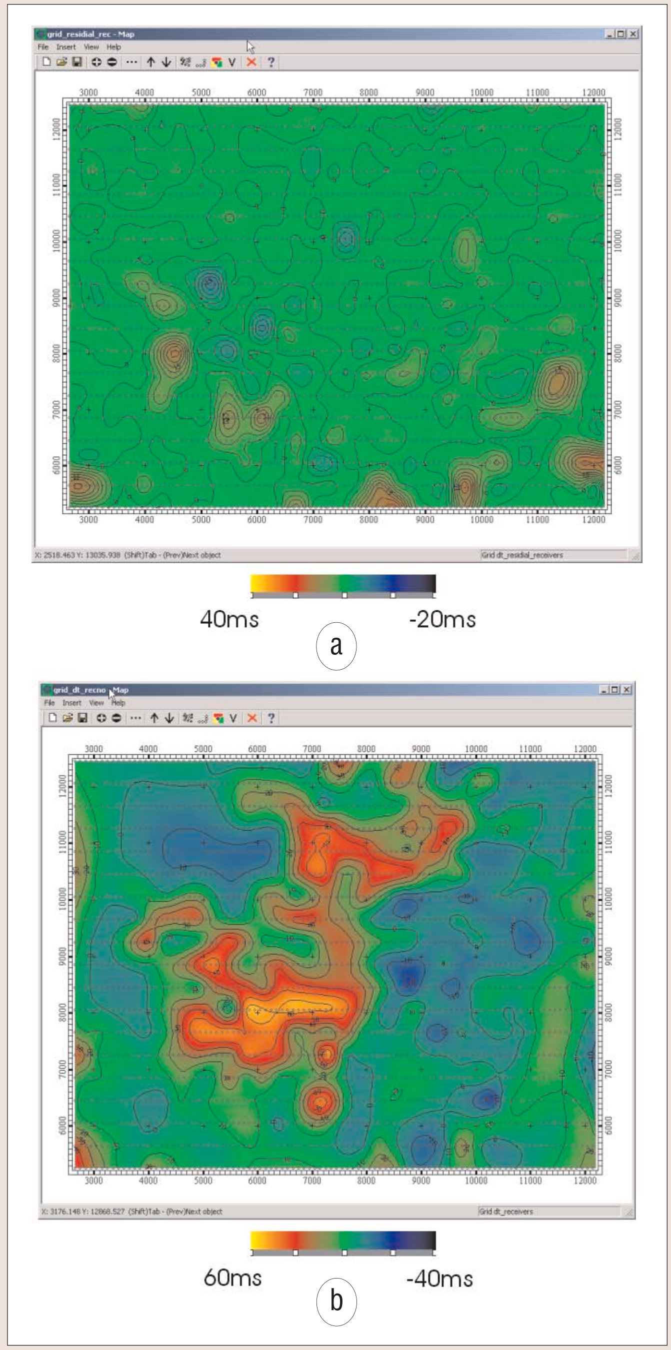

Figure 11. Receiver statics time delays after residual statics (a) and interactive statics (b).

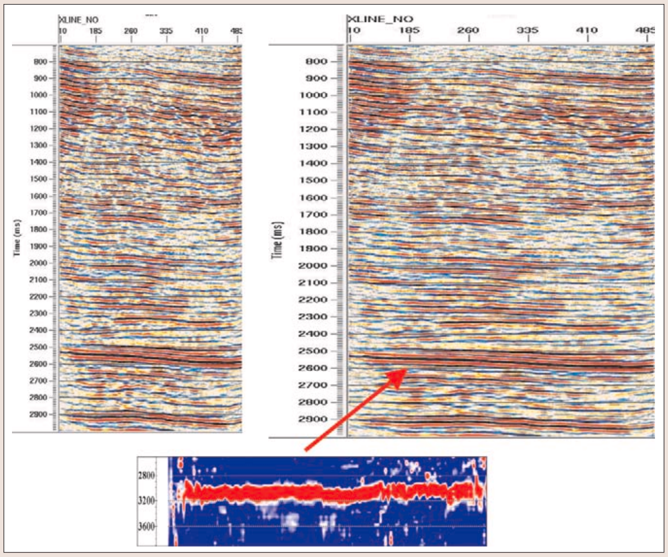

Figure 12. *Same data as in Figure 8 after interactive statics.*

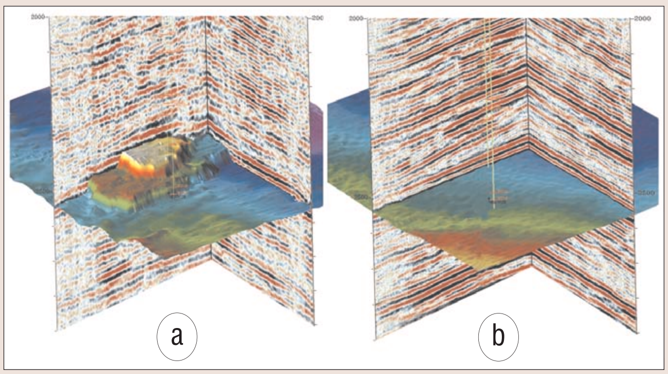

Figure 13. *3D data example of heterogeneous permafrost. Two perpendicular cross sections and horizon time surface. Residual statics applied (a) and interactive statics applied (b).*

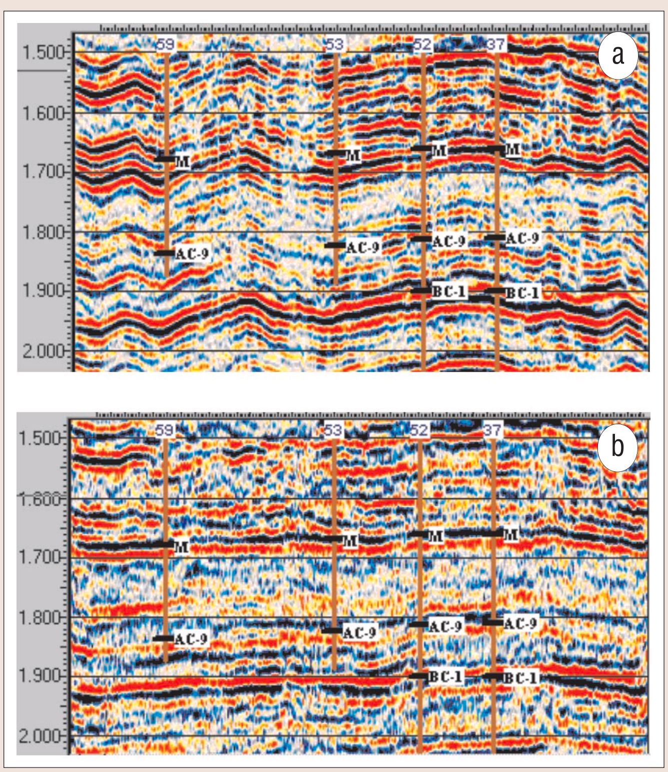

Figure 14. *2D data example of heterogeneous permafrost. Before (a) and after (b) interactive statics.*

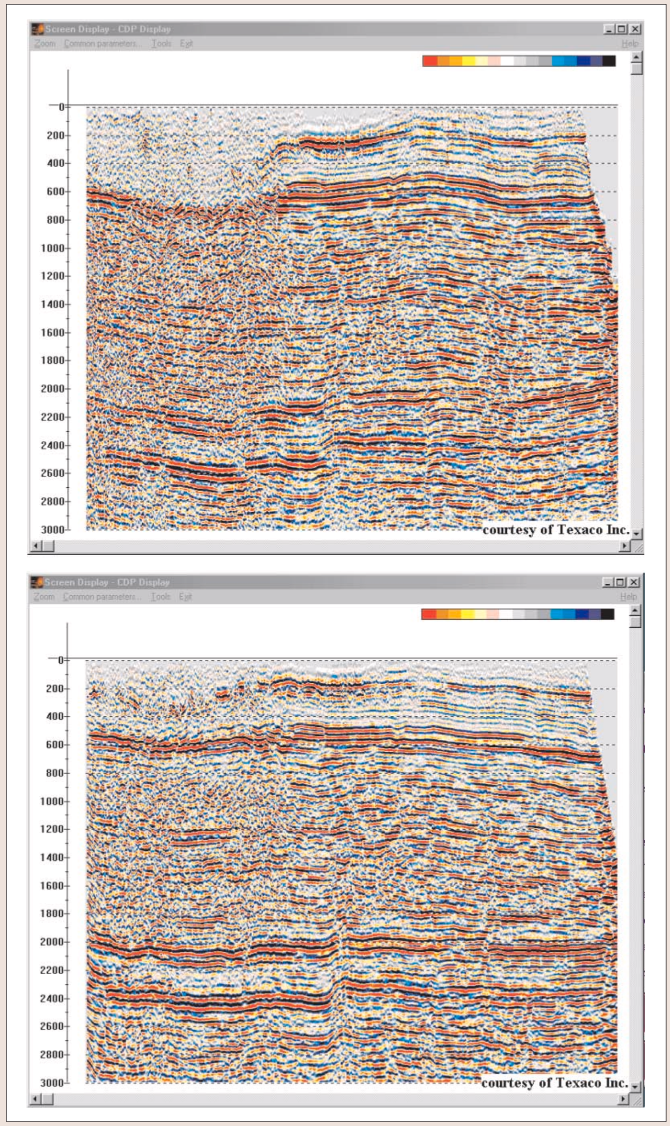

Figure 15. *2D data example of near-surface caliches. Before (above) and after (below) interactive statics.*

Areas in which the interactive statics technology has been successfully applied are characterized by the presence of sharp continuous heterogeneities. These include permafrost regions of Western Siberia, Yakutiya, the north of European Russia, and regions in Eastern Siberia with trapped igneous intrusions regions. Figure 15 shows a 2D example of how application of interactive statics improved the data in and area with near-surface caliches (Delaware Basin, U.S.).

Suggested reading. "Interactive technology of corrections for overburden inhomogeneities in seismic exploration" by Kozyrev et al. (EAGE *Extended Abstracts*, 1995). "Spatially fixed patterns illuminate unresolved static anomalies" by Pecholcs et al. (*SEG 2001 Expanded Abstracts*). "An interactive 3D method for resolving of statics anomalies caused by heterogeneous permafrost" by Korotkov et al. (EAGE *Extended Abstracts*, 2003). TLE

Acknowledgments: The authors thank Gazprom, Ritek, and Texaco for permission to publish the work.

Corresponding author: ilya@gds.ru