Statics solutions in seismic data processing: the next generation

T.E. Galikeev,[1*] A.P. Zhukov[2] and V.S. Kozyrev[2] present interactive statics technology (IST) as a method to refine the statics solution in seismic data processing, notable for not being dependent upon the exact velocity model, the velocity field, or the first breaks.

A statics solution, in the case of a complex near surface, is seldom resolved in an early stage of processing and is often compensated for with velocity manipulation, imaging techniques, and cosmetic algorithms later in the processing flow. This approach often leads to the wrong representation of geology and distorted interpretation. Accurately resolving a statics solution early in processing is essential for portraying a seismic image reflecting true subsurface structure while minimizing velocity errors. We present a different method to refining the statics solution, where the exact velocity model, the velocity field, and first breaks are not needed. Our method uses interactive statics technology (IST). Analysis is performed on reflected waves and the statics solution is delivered as time shifts. Application of the suggested method is extended beyond normal exploration and is applied to time-lapse and 4D exploitation projects, where seasonal changes in the overburden can influence the time-lapse anomaly delineation. IST has also been applied to multi-component projects (3C and 9C).

Methodology

Near surface heterogeneities, often expressed geologically as buried paleochannels, karsts, sedimentary collapses (caliche), sand dunes, igneous intrusions, and permafrost can cause abrupt lateral velocity change and introduce large-magnitude time delays. Often, the quality of first breaks deteriorates, leading to an unreliable refraction static solution. Optimization algorithms, such as residual statics, are purely mathematical and in pursuing their goal can overcorrect and mix near-surface anomaly with the actual geological structure, which leads to a distorted image of the subsurface. Velocity-based algorithms, such as refraction statics and tomography statics, can fail in the presence of high velocity contrasts, which are expressed by very high statics correction values. For example, static corrections due to heterogeneous permafrost can be as high as 300–500 ms. Conventional velocity-based methods often require a smooth velocity field and may not converge to the right solution in case of high-magnitude or laterally large inhomogeneities (long wavelength statics).

Static corrections are usually classified into three groups relative to the field acquisition spread length:

- Short wavelength – up to half of spread length;
- Medium wavelength statics – up to two spread lengths;
- Long wavelength statics – anomalies are larger than two acquisition spread length

IST helps to correctly solve for large magnitude short wavelength statics and mid to long wavelength statics (Figure 1). IST starts with analyzing data and if possible finding where near-surface related anomalies are located. Usually this is done with first break analysis, but very often in complex near-

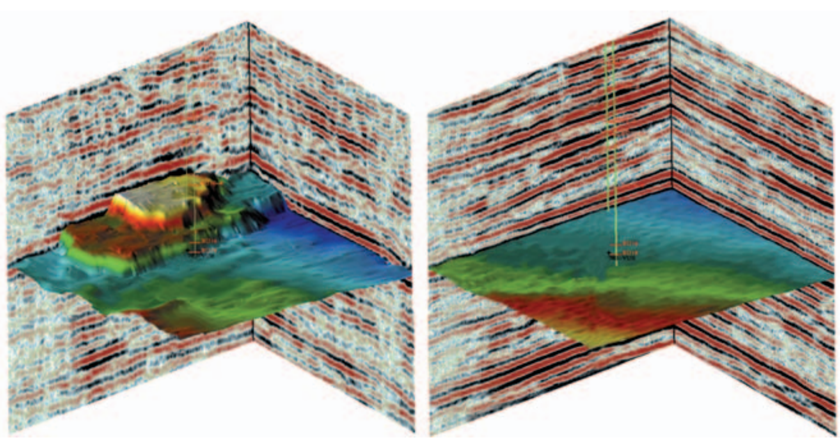

Figure 1 Conventional statics solution (left) vs Interactive Statics Technology (right). IST was able to remove false structure due to large near-surface velocity anomaly.

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surface areas, this is difficult to realize. In this case analysis of common-offset sections is performed (Figure 2). With all a priori statics, applied common-offset sections are formed and analyzed for heterogeneities in the near surface. Anomalous near-surface areas manifest themselves by inconsistent first-break energy times and distortion in surface noise signature. This analysis is performed both on source and receiver lines and maps of first break arrival times are built. Maps are then used to create spatially fixed patterns (SFPs) to start analyzing anomalies and create time shifts (static corrections). SFPs are the most efficient way to analyze near-surface anomalies, since we can 'x-ray' the anomaly from different angles. These patterns are nothing else but the data stacking schemas, which mainly take into account anomaly size and signal-to-noise ratio in the dataset. The SFP for a 2D case is illustrated in Figure 3. SFP allows decoupling of source and receiver statics, as well as placing them in the exact surface-consistent location.

IST is based on a physical understanding of the statics problem allowing the reliable separation of near-surface anomalies from subsurface geology. Our approach uses multiple forward and reverse partial-offset stack displays in the common receiver point (CRP), common source point (CSP), and common midpoint (CMP) domains to delineate and estimate surface-consistent source as well as receiver statics. Since it is only possible to decouple source and receiver statics when the offset distance is greater than the anomaly size, IST uses a special stacking technique – variable-offset SFP – to eliminate source and receiver statics coupling, which has proven to be the only reliable surface-consistent stacking method for 3D.

In order to reliably identify the near-surface related anomaly, several other domains of seismic data are analyzed primarily to make sure that the anomaly is surface-consistent and does not represent the true depth feature, i.e., not CMP (or depth) consistent. These domains are:

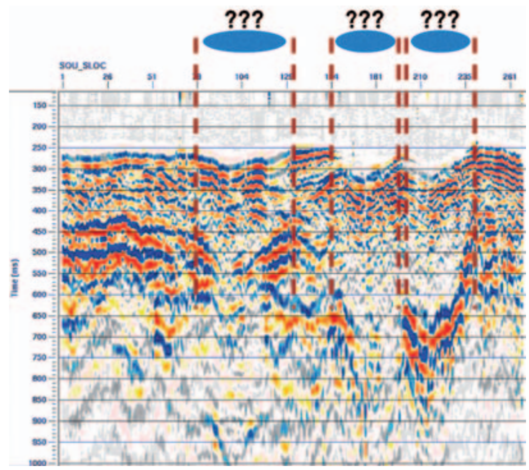

***Figure 2** Common-offset section with all a priori statics applied. Undulations in first break energy and change in surface noise signature denote near-surface related anomalies.*

- Common offset time sections
- Common midpoint (CMP) partial stacks
- Stacking velocities
- Common receiver (CRP) stacks
- Common source (CSP) stacks
- SFP stacks

Figure 4 shows SFP patterns before and after static corrections were applied. Corrections are applied between elements of the SFP patterns to eliminate block shifts and have continuous seismic horizons as well as corrections within the element by moving traces to remove residual statics left in the data by conventional velocity-based methods (a priori statics solution). Corrections are calculated by analyzing multiple data domains at the same time in order to verify the surface-consistent manner of the solution and separation of near-surface anomalies from the true depth structure.

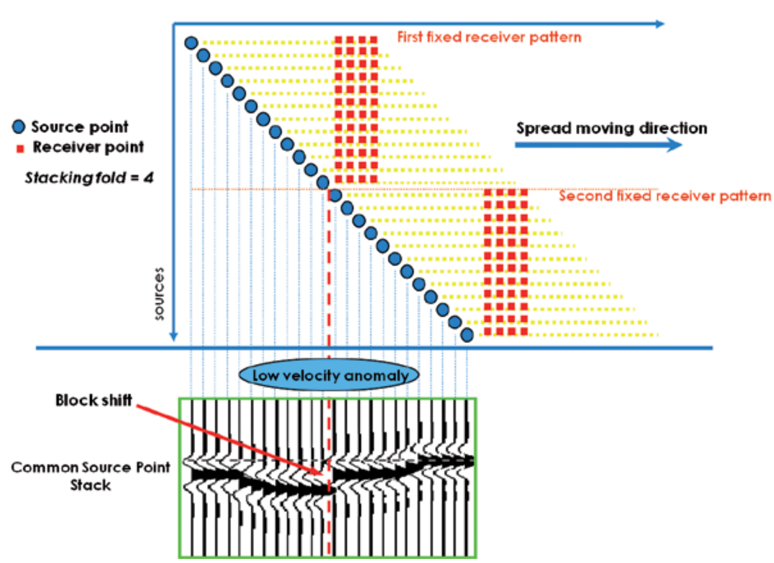

***Figure 3** Spatially fixed pattern in 2D case. Note the block shift between the elements of the pattern due to near surface anomaly.*

The use of SFPs decouples source and receiver statics and allows for analysis of the near surface anomaly from different angles, therefore overcoming the limits of the orthogonal system imposed on the data by assigning traditional processing geometry. SFPs are created based on the size of the anomaly and at least four SFPs are used (two for sources and two for receivers). Several iterations of dynamic statics with velocity analysis and signal processing are required to fully resolve the statics, velocity, and anisotropy components present in a dataset. Analyses in the shot and receiver domains are essential to differentiating a seismic feature caused by a near-subsurface heterogeneity.

After IST analysis, which is an iterative approach and is done along with velocity analysis, seismic anisotropy corrections, residual statics, and signal processing if required, we obtain a seismic image which has correct statics corrections applied, and the three main parameters, which control the structural component of the seismic image (statics, velocity, and anisotropy), are completely decoupled. During subsequent iterations, statics, velocity, and seismic anisotropy parameters are refined. Figure 5 illustrates how correct statics corrections make velocity analysis cleaner and easier to pick.

QC of the statics solution

Next step is quality control to verify that the statics solution is an appropriate one. Two main components are analyzed: partial offset stacks (near and far offsets) as well as the horizontal velocity spectra. These components test the structural component of the final dataset: in the case of a correct statics/velocity solution seismic reflections should be at the same times on partial-offset CMP stacks, and horizontal velocity spectra should have clean signature (Figures 6 and 7). Figure 6 shows that the correct statics solution preserves the same structures on far- and near-offset sections, while incorrect velocity-based statics correction gives two completely different images. Figure 7 illustrates how horizon velocity analysis (HVA) could indicate problems in statics solution for the dataset. Both artifacts with conventional statics solution are created due to the fact velocity analysis was used to compensate for poor statics. In the case of IST (Figures 6–7) statics and velocity models were decoupled, which leads to the right representation of the subsurface.

Application to multi-component (9C) dataset

A 3D–9C dataset was acquired in the panhandle of Oklahoma, northern part of Texas County. The Postle study area is located on the northwest shelf margin of the Anadarko basin. The primary exploration target is the Morrow A sandstone, which is considered to be the incised-valley filled deposit (Wiley, 2009). Thickness of the Morrow A sandstone varies from 0–95 ft throughout the unit and the measured depth of the reservoir is at around 6200 ft. The reservoir is compartmentalized based on the production analysis. Under the circumstances, obtaining a seismic image of the reservoir

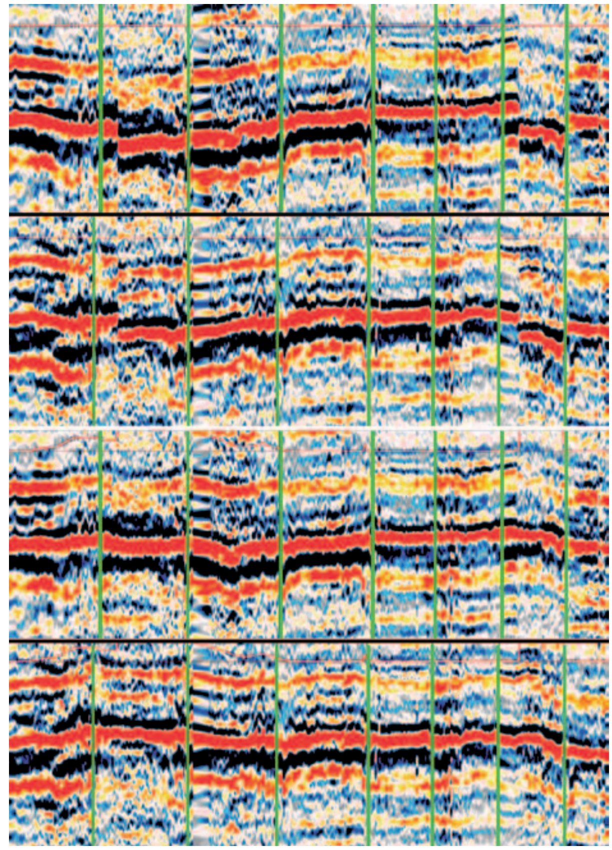

Figure 4 *Spatially fixed patterns before (top) and after (bottom) statics corrections applied.*

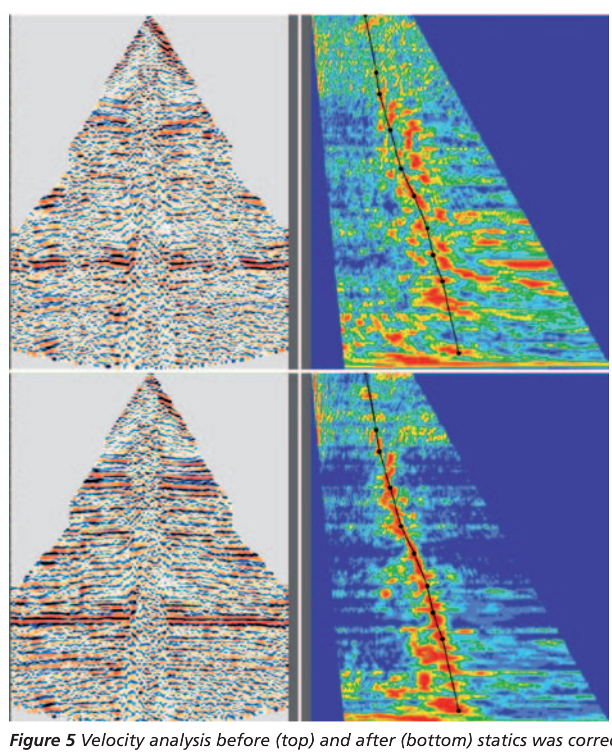

Figure 5 *Velocity analysis before (top) and after (bottom) statics was correctly resolved.*

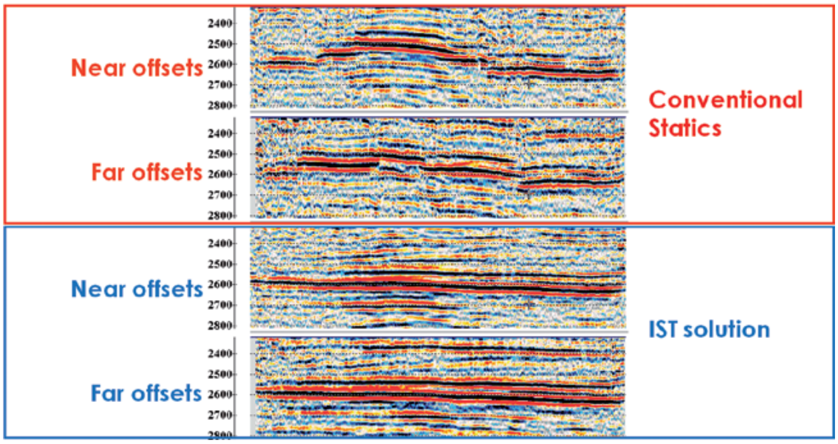

Figure 6 *QC of the statics solution. Conventional velocity-based (top) shows a different geological structure on near and far offset stacks. Correct statics solution (bottom) obtained with IST shows the same structure on both offset ranges.*

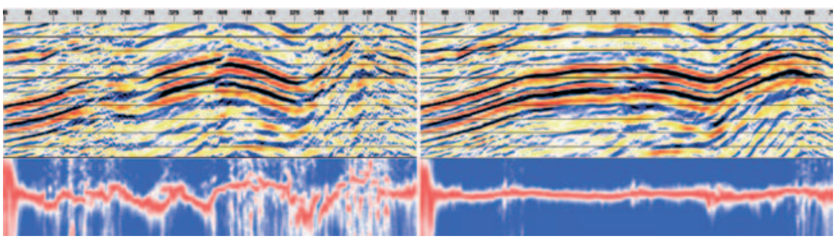

Figure 7 *Horizon Velocity Analysis comparison between conventional (left) and Interactive Statics Technology (right).*

reflecting the true structure and dynamics was very important for further data analysis through seismic attributes and seismic data inversions to delineate Morrow A.

The area under the study has a long production history: the field was discovered and put into production in 1962. Natural depletion was followed by a water flood in 1974. The CO_2 flood programme started in 2008. Close to 1.5 million metric tons (mmt) of oil has been produced so far.

The decision was made to acquire a 9C dataset, since the Vp/Vs ratio is a good indicator of the quality of Morrow A sandstone (Figure 8). Morrow sandstones, according to the well log plots in Figure 8, have a much lower Vp/Vs ratio than the surrounding rock. The reservoir in the illustration is bounded by two horizontal lines on the left panel of Figure 8 and is located at a depth of 6160–6220 ft. The right portion of the figure shows lower values for Vp/Vs at the reservoir level.

Three seismic 3D–9C surveys with repeatable geometry were acquired as part of the 4D reservoir study by the Reservoir Characterization Project. Baseline survey was acquired before the CO_2 flood started in March of 2008 and was followed by two more monitor surveys. The focus of this paper is the first monitor survey, which was acquired in December of 2008. Time-lapse analysis of the datasets is a separate topic and will not be entertained here. The seismic survey covered around 16 km^2, an area complicated by the presence of intensive agricultural activities where laying out the source and receiver lines was a challenge, but the resulting nominal fold was around 100–120. Data were recorded with the three-component digital accelerometers using two universal multi-component vibrators.

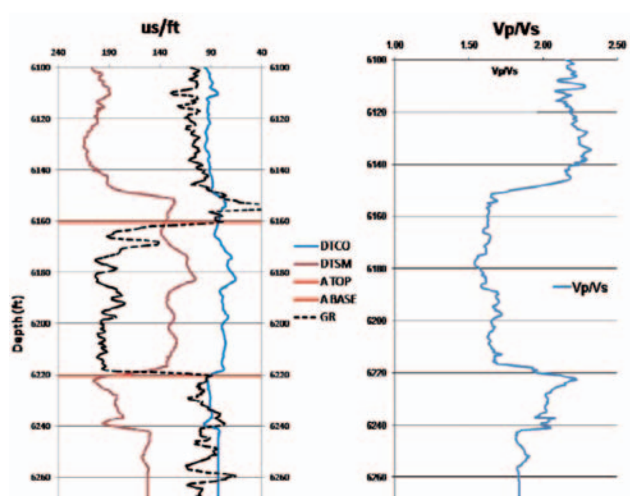

Figure 8 *Vp/Vs ratio in the Morrow A sandstone is a differentiating factor. (From Davis et al., 2010).*

Field data acquisition parameters (Davis et al., 2010):

- Static layout of 1920 single point 3C accelerometers
- 16 receiver lines, spacing at 268 m and receiver spacing at 33.5 m within the line
- 16 source line, spacing at 268 m and source spacing at 33.5 within the line, 5760 total SPs
- P-wave sweep 6–100 Hz, 8 s, four sweeps/VP
- S-wave sweep 4–60 Hz, 8 s, four sweeps/VP

Before ISP was applied to the dataset it was treated to conventional processing by a different contractor, so the comparison is made by two completely independent approaches to the same dataset. Signal-to-noise ratio is poor in the recorded dataset and previous processing was done on the 33.5 x 33.5 m CMP grid in order to boost signal characteristics. IST processing flow preserved the original bin grid at 16.75 x 16.75 m.

Data were processed in the following order: monotype P-wave (PP volume), monotype S-wave (S11), and C-wave image (PS) was obtained 'automatically' by using a velocity and statics solution for sources from the PP processing, and velocity and statics corrections were taken from the S11 processing for geophones. The PP statics solution obtained by applying IST methodology was used as a guiding solution for resolving statics on the horizontal component, so that the spatial distribution of S-wave statics is similar to that of the P-wave statics. The resulting PP and S11 images (Figure 9 and 10) compare favourably with the original processing (different contractor) with refraction statics.

P-wave processing flow was carried through pre-stack time migration and included the following conceptual steps:

- Geometry assignment, edits, QC
- Refraction statics
- Pre-processing
- Dynamic statics flow (four iterations)
  - Velocity analysis
  - IST
  - Residual statics
  - VTI (non-hyperbolic) correction
  - Data enhancements (X-spread and OVT filtering)
- Post-processing
- PSTM and RMO

Figure 9 shows improvements over the conventional processing in the upper section with strong anhydrites imaged above 500 ms. Lateral resolution is more detailed and preserved with the original bin size at 16.75 x 16.75 m without sacrificing signal-to-noise ratio and overall appearance of the image.

Pure mode S-wave processing was challenging due to the low signal-to-noise ratio in the recorded dataset, but the processing has been preserved at 16.75 x 16.75 m bin size. Advantage of the IST approach is that the corrections are made using reflected energy, which are easier to work under low data quality conditions. Due to lower velocities on S-wave data, time shifts between the elements of the SFPs related to the near-surface velocity anomalies have larger magnitude and are better pronounced, so delineating surface consistent static anomalies becomes less ambiguous.

In order to maximize the signal on the S-wave data we have employed the 'hybrid' rotational scheme on the data, where we rotated data to radial in the upper part of the section (0–1400 ms) and used a constant rotational angle in the lower part of the section (below 1400 ms). Rotational analysis for the lower part of the data indicated the angle of rotation at 108°, which corresponded well to the angle of regional stress obtained from the log data analysis.

Processes, which had the largest impact on the data quality when processing pure mode S-wave are:

- IST: Used previously derived statics solution for P-waves as a guide when solving for S-waves
- Hybrid rotation
- VTI correction
- Trim statics encompassing all data

Figure 10 shows incremental improvement from the initial stack to the final. Both S-wave and C-wave data-sets had post-stack migration only as the final processing step.

C-wave processing was used as a QC tool for P-wave and S-wave velocity and statics solutions. P-wave statics and velocities have been applied to the source component of the data and S-wave statics and velocities have been used for the upgoing (receiver) component. Both solutions were used at

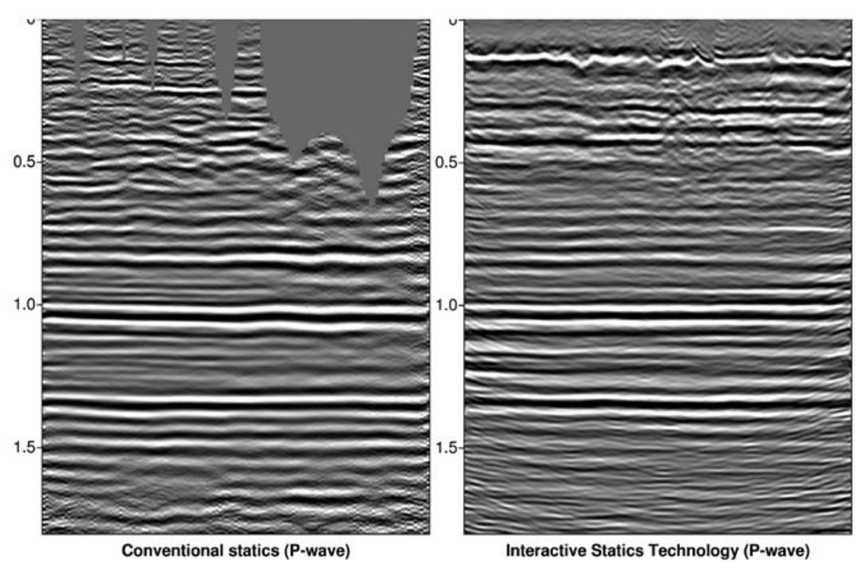

Figure 9 *Conventional (left) and Interactive Statics Technology (right). Note improvements in the shallow section. Reservoir is around 1 s.*

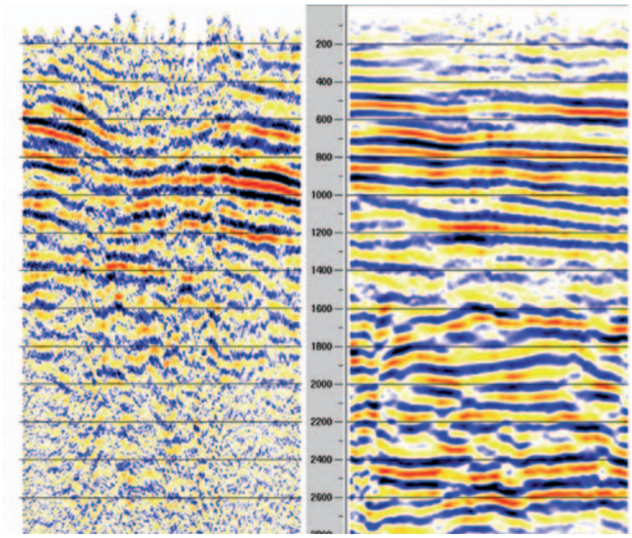

Figure 10 *Initial (left) and final (right) stacks for mono type S-wave dataset.*

face value without any modification. A final C-wave image (which was never obtained in conventional processing) has been delivered and verified the solution for pure mode P- and S-wave datasets (Figure 11).

Conclusions

IST has been applied around the world to a multitude of datasets characterized by a complex overburden and has proved to deliver superior results when compared to a conventional velocity-based statics solution. Analysis does not require the knowledge of the velocity field to deliver the statics solution and uses reflected energy.

A dynamic statics approach with IST as its foundation was applied to a 3D–9C dataset and was able to decouple statics and velocity parameters better than the conventional processing flow utilizing a refraction statics approach. Data processing was maintained at the 16.75 x 16.75 m bin (vs 33.5 x 33.5 m previous processing) resulting in more realistic dynamics for the section as well as better event coherency and lateral resolution. The study area is characterized by near surface complexities which express themselves as sags on the seismic data. The dynamic statics methodology helped to image shallow anhydrite layers. The C-wave image, which was obtained ‘automatically’ corroborates the correct velocity and statics solution for monotype P- and S-wave volumes. An accurate statics solution for time-lapse and 4D surveys is especially crucial since velocity anomalies under investigation might be overwhelmed by seasonal changes in the overburden and influence interpretation of important time-lapse anomalies.

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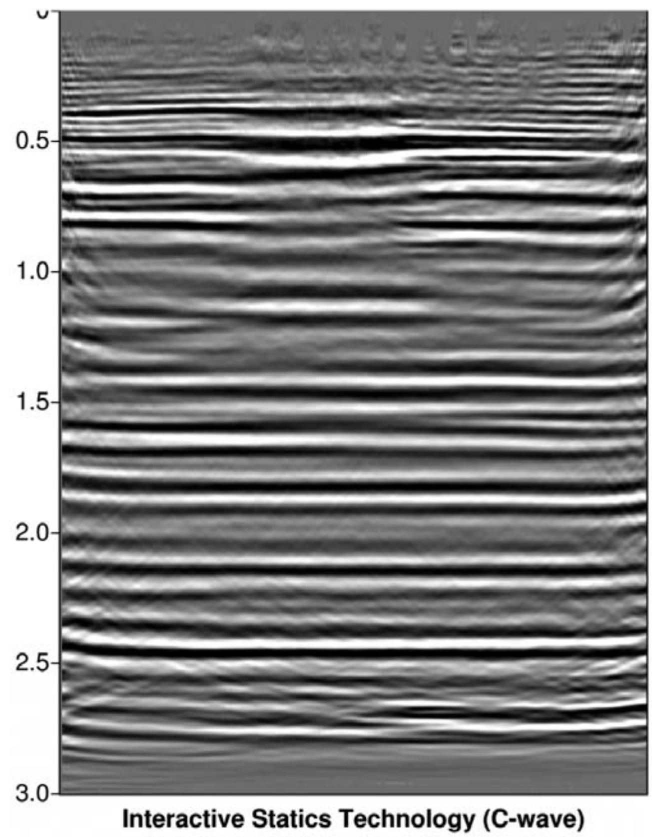

Figure 11 *C-wave results.*

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