Seismic Data Preconditioning for Improved Reservoir Characterization (Inversion and Fracture Analysis)*

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Abstract

Advanced seismic techniques such as pre-stack inversion or azimuthal analysis are now routinely adopted for quantitative reservoir characterization of rock properties and fracture indicators, however the quality of the input seismic data is critical to such advanced analyses. Frequency content, random and coherent noise, amplitude-preserving processing and gather flatness must be addressed at the preconditioning stage. Improved results and increased confidence follow from careful well-driven modeling and QCs.

Introduction

The results of pre-stack inversion and fracture analysis are ultimately dependent on the quality of the input seismic data. An optimal result is produced when the seismic data are rich in frequencies (both high and low), relatively noise free, of consistent amplitude, and the signal events are aligned (to the expected AVO modeled response). These properties should be spatially stable, which can be evaluated through map QCs. Care must be taken to not overly process the data, as this may remove signal that contains important information.

To evaluate the suitability of the seismic data, pre-stack modeling at well locations is done. This may be full wave reflectivity modeling (in which primaries, converted waves and multiples are all modeled) or convolutional Zoeppritz-type synthetics (in which only primaries are modeled). Comparing the real seismic to the well synthetic response is the best quality control step. This is usually only practical at the latter stages in processing once the seismic signal is relatively clean and coherent. For this reason the processes described in this discussion are applied after pre-stack migration.

Method

It is recommended to start with a wide range of QCs to analyze the data quality. A series of maps are produced, such as average and dominant frequency content, RMS amplitude over a large window, and AVO cross-correlation correlation. Maps are particularly important since they are diagnostic of the spatial distribution of data properties.

Seismic reservoir characterization assumes the input seismic has an invariant wavelet, frequency and amplitude consistency, and good azimuth distribution across the survey (for anisotropic analysis). Experience has shown that when the seismic does not satisfy these assumptions, preconditioning (with stringent QCs) is helpful. For example, a difference of approximately 20 Hz in the average frequency was observed between two nearby well locations that could not be accounted for by obvious near-surface effects (Figure 1). Preconditioning (spectral balancing, in this case) was done to correct this.

Well logs are used to evaluate the seismic data quality through well ties and phase analysis. Full wave reflectivity and convolutional Zoeppritz synthetics are then compared to the real seismic gather. Reservoir characterization techniques are based on the Zoeppritz equations (or their approximations) as the forward model. If the processed gathers differ too much from the Zoeppritz synthetics, data preconditioning is most likely needed. Full wave synthetics, which include multiples and PS conversions, can help further evaluate what processes should be applied to the gathers. For example, it is possible to assess the influence of the multiple energy by turning on or off multiple generation in the full wave algorithm.

For azimuthal QCs, COCA (Common Offset Common Azimuth) and CACO (Common Azimuth Common Offset) displays are important, and should be reviewed to assess the presence of anisotropy (HTI) in the survey. Spatially, the quality of the azimuth distribution is evaluated using azimuth versus offset cross plots. Synthetic models can also be constructed versus azimuth and QC'd as above (Roure et al., 2011).

Once the evaluation is complete, a preconditioning workflow can be designed and implemented with the above QCs again to verify improvement. With the current computing power, inversion and fracture analysis techniques themselves can now be used as QC steps and be (re)run to evaluate the conditioning processes. It is recommended that at least one fast track inversion should be run on the gathers without preconditioning to set a benchmark.

Conditioning Processes

The importance of data preconditioning can be seen in the difference between Figure 2 and Figure 3, which show density results from pre-stack inversion. Understanding the complex heterogeneity of this oil sands play is essential for successful reservoir development. The resolution (both high and low) has been enhanced through balancing the amplitude spectra. Image quality was also improved through temporal alignment of signal events in the gathers through VTI corrections, and subsequent application of trim statics. Coherent noise was reduced by using a high-resolution Radon transform to attenuate linear and parabolic multiple energy, while random noise was reduced with a 3D FXY projection filter.

Often overlooked is the importance of the information contained in the low frequencies. Model-based inversion schemes use well logs to construct the low frequency model to account for the missing low frequencies in the seismic. When the model has to fill in more frequencies that are missing from the low end of the seismic bandwidth, the inversion result becomes driven more by the wells and less by the seismic. To alleviate this, AVO-friendly broad band spectral balancing (Nagarajappa and Downton, 2009) can be applied. The result will be an increase of high frequency signal for increased resolution, and more low frequency information so that the inversion can be directed by the seismic as opposed to single point location well logs. Also, the amplitude spectra of the seismic is now laterally consistent (cf. Figure 1), hence the assumption of wavelet stability is more valid.

Preconditioning to attenuate random noise may be required. It is not essential to have perfectly noise free seismic data as most inversion schemes model the data, hence random noise (that does not fit the model) is discarded in the residual. Coherent noise is generally attenuated well during conventional processing. If still present, the use of pre-stack noise attenuation schemes such as FXY deconvolution and Radon transform filtering have proven quite effective. Methods and parameters need to be tested, as each seismic dataset is unique. There may be cases where coherent noise is not readily visible on the seismic data, however, and after inversion it can become quite apparent, especially with the rainbow color palettes often used for display.

For fracture characterization azimuthal information needs to be preserved. Processes such as noise attenuation should be done in an AVAz (Amplitude Variation with Azimuth)-friendly manner. Instead of using a two-dimensional filter on a CMP gather, it is recommended to apply a three-dimensional filter to an individual COV (Common Offset Vector) tile gather. For example, 3D F-Kx-Ky filtering can be applied to COV tiles for footprint attenuation. To test parameters, the process must be run for all individual COV tiles (which often number in the hundreds for land 3D geometries) and then sorted back into CMP gathers for QC and stack.

Small-scale alignment of coherent signal events on gathers is generally accomplished through the use of (time-variant) trim statics. However, if VTI or HTI patterns are observed on the seismic data, then additional anisotropy analyses and corrections can be done. Processes such as orthorhombic velocity analysis (Wang and Wilkinson, 2012), high-density bispectral velocity picking, and VVAz (Velocity Variation with Azimuth) investigations provide additional information about the subsurface (for example, estimation of eta field or fracture intensity (Delbecq et al., 2013)). After applying these corrections, any remaining small misalignment can be addressed through a final pass of trim statics.

An additional benefit of reviewing the velocity model is the optimization of offset to angle conversion, since AVO equations are a function of incidence angles. By combining well logs (where present) and seismic velocities (to fill shallow and deep sections) a more accurate velocity model is created. It is also important to note that the offset to angle conversion should be done from a floating datum rather than a flat processing datum. Significant error has been observed when this is not done; underestimating the maximum incidence angle by up to 15 degrees (Figure 4).

Variations in near-surface conditions often result in the loss of amplitude over certain zones. Barring geologic changes, the amplitude of a reflection event should remain relatively consistent across a 3D survey. To correct for these surface-related amplitude changes, the RMS amplitudes are calculated over a large window on the stack, then applied to each gather to normalize the lateral variations. Alternatively, more detailed methods could also be used, such as modeling the expected response from well data (in offset or azimuth), then applying an angle-dependent scaling function to the seismic gathers.

Conclusions

The quality of any seismic reservoir characterization volume is restricted by the quality of the input data. Often, results can be greatly improved by proper preconditioning of the pre-stack seismic data. The method described in this article uses multiple QC products (maps, synthetics, anisotropic analyses and the inversion techniques themselves) to evaluate the seismic prior to the reservoir analysis. The QCs can be used to design a data preconditioning sequence which may include frequency and amplitude balancing, noise attenuation, anisotropic velocity analysis, and signal event alignment. This entire process is non-unique and, if necessary, iterative.

Seismic data QCs and preconditioning provide insight and confidence in the input seismic data and reservoir characterization final results. When properly evaluated and applied, the result is better quantitative reservoir characterization and improved interpretation. This was demonstrated through a density inversion.

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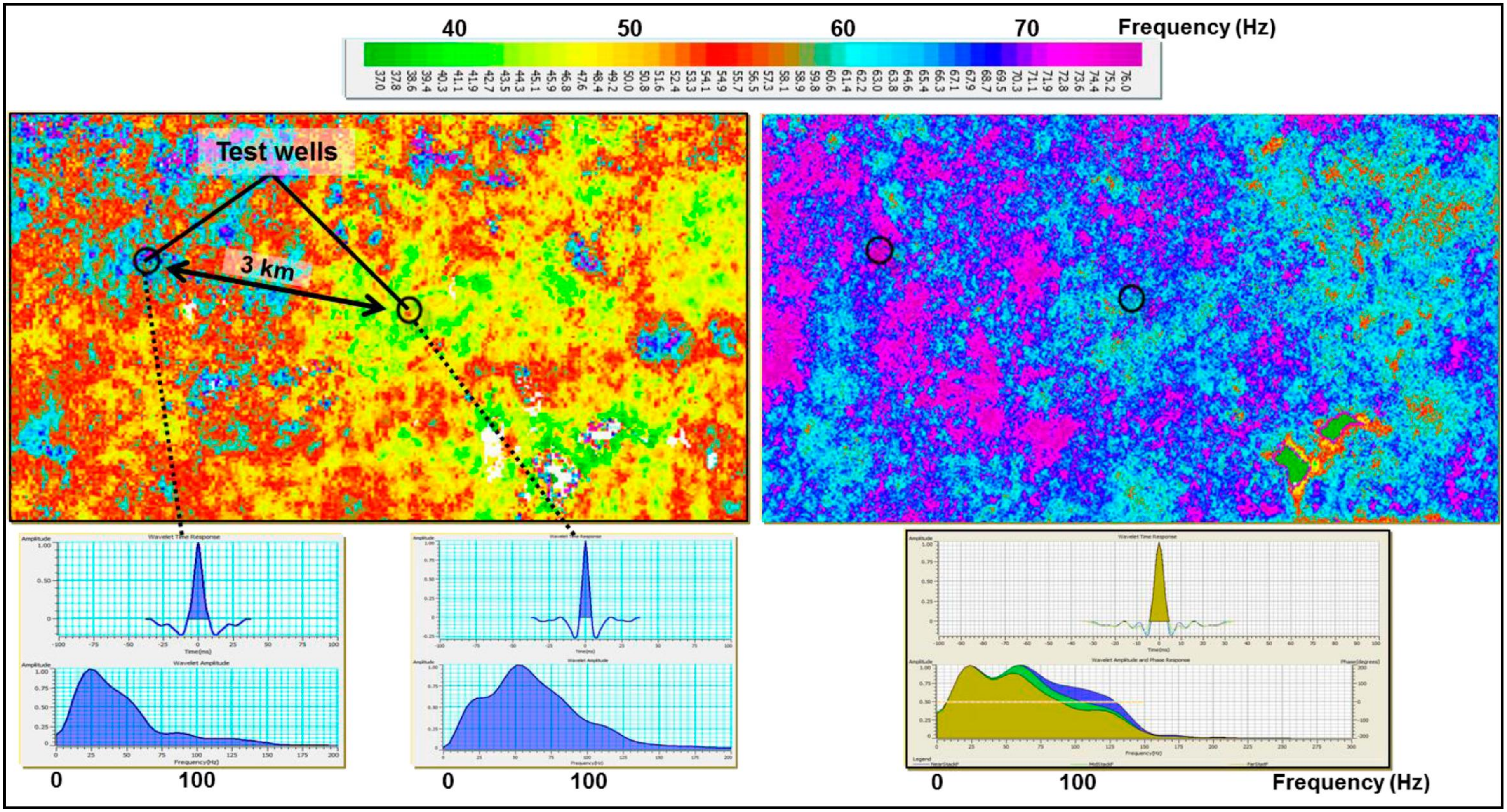

Figure 1. Maps of average frequency before (left) and after (right) preconditioning. Extracted wavelets and amplitude spectra before preconditioning are shown at two well locations (left). The map QC after preconditioning indicates the average frequency is both higher and more laterally consistent (note: the wavelet shown was used for the inversion).

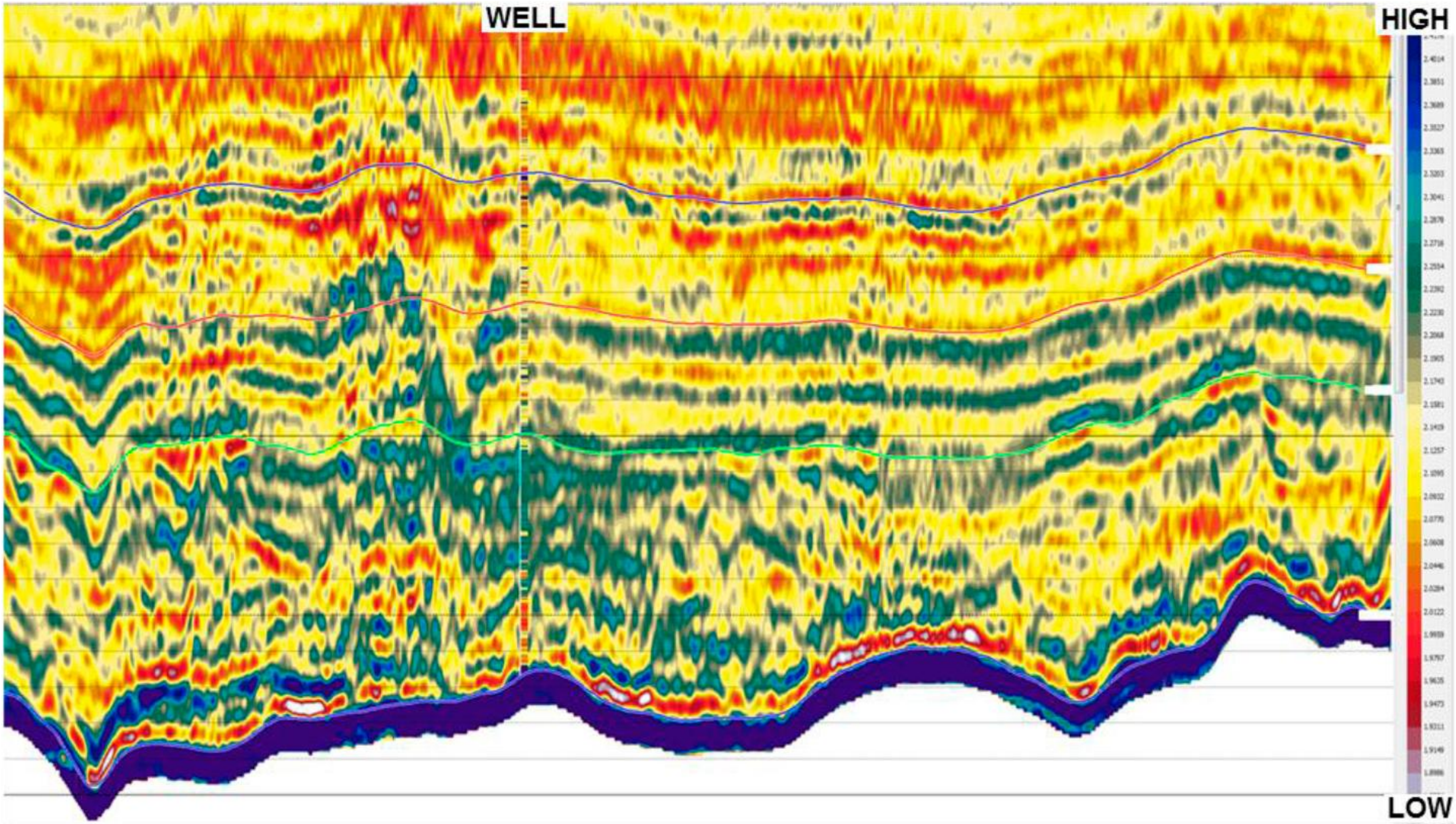

Figure 2. Pre-stack inverted density prior to data preconditioning. The inserted well is a blind control. The survey is from the Kinosis oil sands area (data courtesy of Nexen Inc./CNOOC).

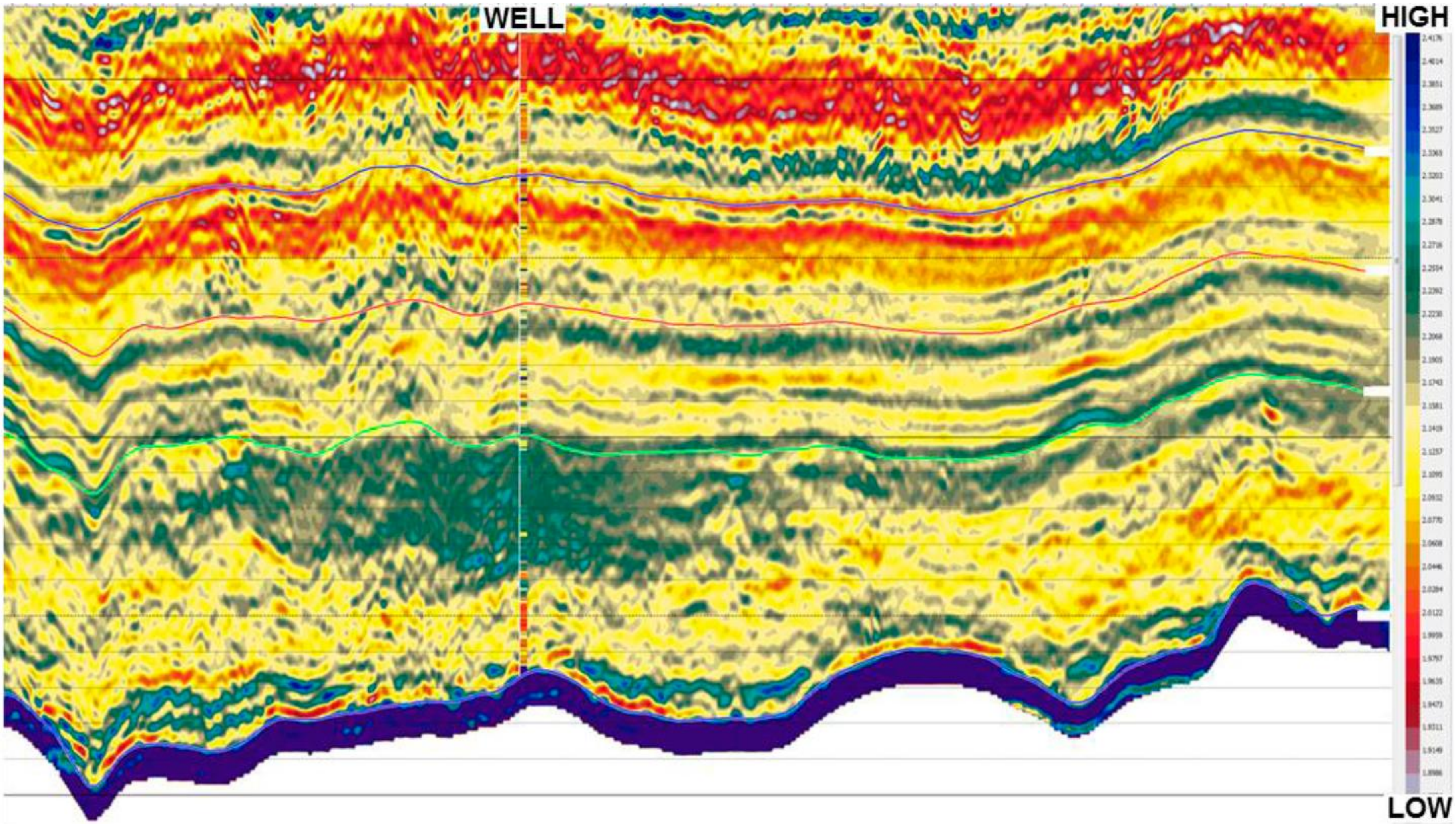

Figure 3. Density from pre-stack inversion of preconditioned seismic. All inversion parameters are the same; the only changes are the input seismic data and the associated offset dependent wavelets.

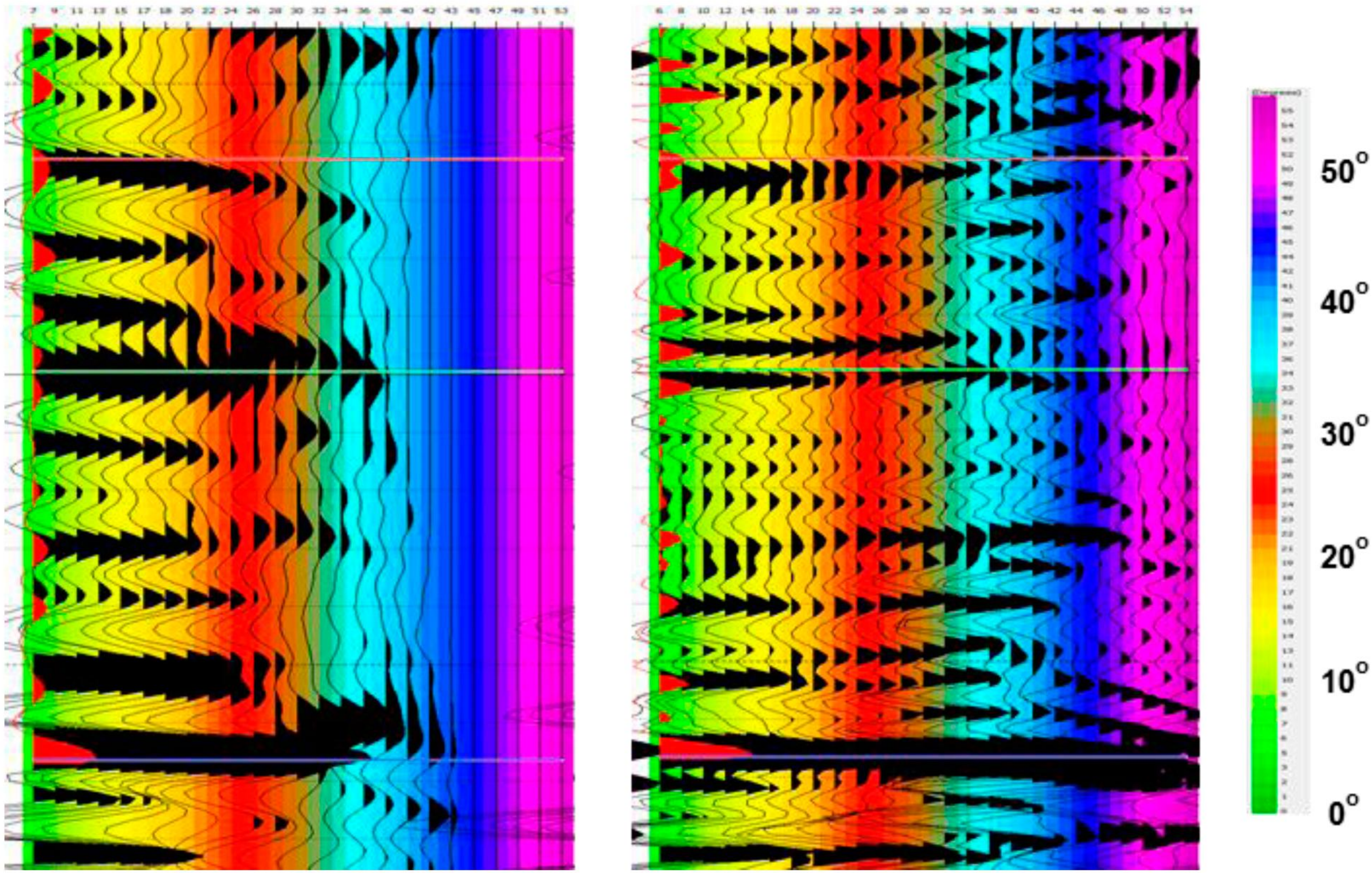

Figure 4. Angle gathers before (left) and after (right) preconditioning. The zero offset synthetics trace from is shown in red. On the left, angles were computed from processing datum. On the right, angles were computed correctly from surface; useable now out to 45 degrees (dark blue). Area is Kinosis oil sands (Nexen/CNOOC).