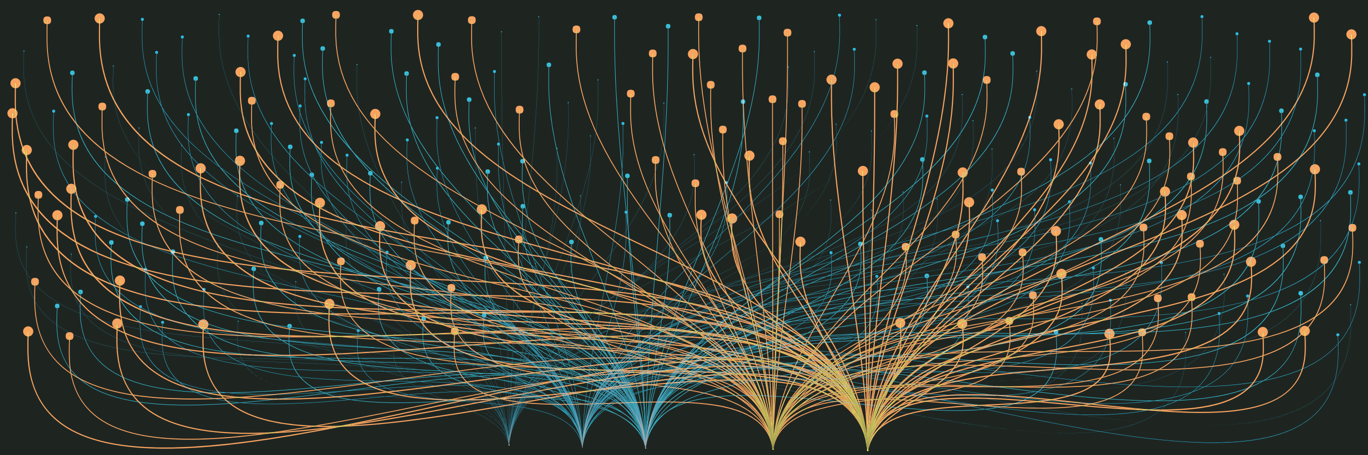
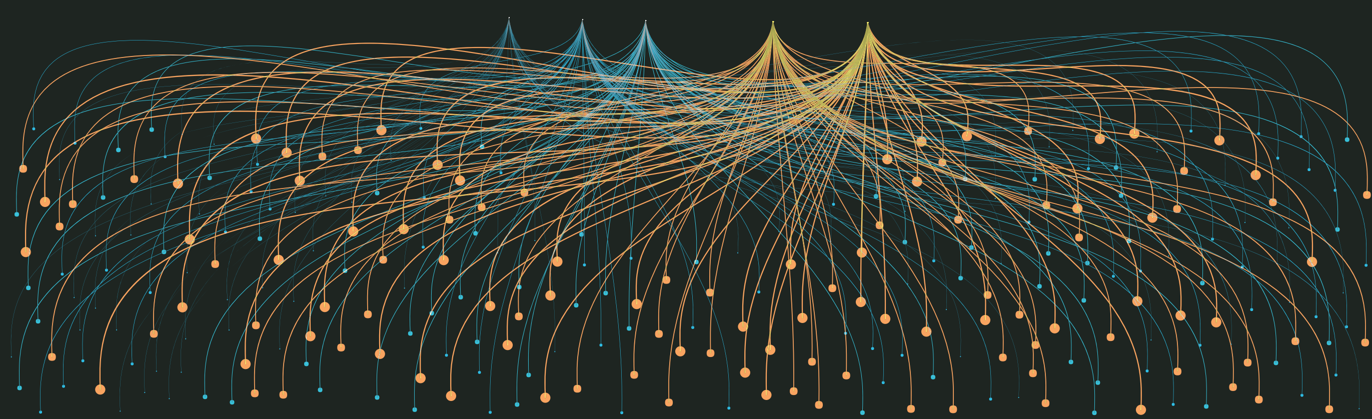


High-Fidelity Visualization and Analysis of Full-Azimuth Seismic

BIG DATA JUST GOT BIGGER

Sharp Reflections uses Big Data technologies to deliver fast, interactive analysis of 3D pre-stack seismic datasets. Its Pre-Stack Pro software utilizes highly parallel, in-memory computing to visualize, process, and interpret amplitudes direct from terrabyte-size gather volumes. The new Pre-Stack Pro Azimuthal module takes pre-stack analysis to the next dimension, with a rich new offering for long-offset, full-azimuth gathers. The new software dramatically improves the resolution of fracture prediction workflows for unconventional reservoirs, while at the same time reducing analysis times from weeks to days.



Advances in seismic acquisition technology are driving growth in high-density, high-fold data with full-azimuth coverage. Offshore, full-azimuth data improves imaging of complex structures by boosting signal-to-noise and enhancing target illumination. On land, azimuthal seismic data is increasingly used to identify anisotropic velocity and amplitude effects that can be used, to predict stress fields and fracture distribution in tight, unconventional reservoirs.

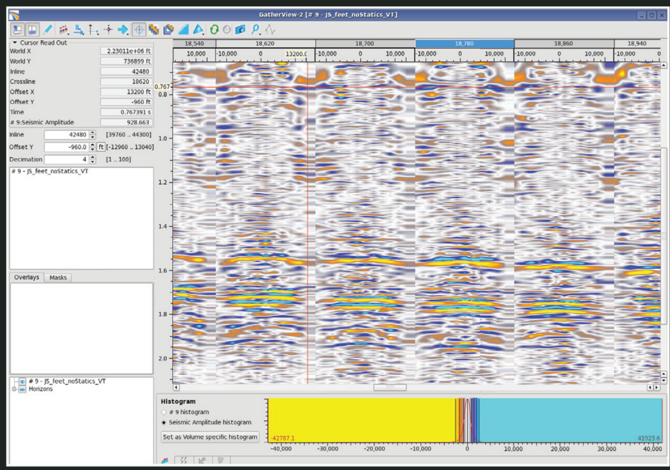
Full-azimuth data are now routinely processed as Common Offset Vectors (COV), also known as Offset Vector Tiles (OVT), with a regular distribution of inline and crossline offsets arranged in a rectilinear pattern. Analysis of COV/OVT data represents a significant computing challenge, as gather volumes routinely contain hundreds or even thousands of traces for each CDP location.

Beginning in 2014, Sharp Reflections partnered with Fraunhofer ITWM to adapt Pre-Stack Pro to full-azimuth data, and deliver tools for fast, interactive gather analysis of these “5D” pre-stack volumes.

The Full-Azimuth Development Blueprint

Cartesian COV/OVT gathers are ideal for creating full or weighted-offset volumes for structural interpretation. After migration, azimuth-sectored offset or angle gathers are required for velocity refinement, amplitude-versus-azimuth analysis, or selective stacking of specific angle and azimuth ranges. For these purposes, COV data are transformed to Common-Offset, Common-Azimuth (COCA) gathers in polar coordinates.

Pre-Stack Pro’s gather data model was extended to support import and storage of both common formats, which can be sorted and viewed in any of the existing data viewers. Figures 1 shows examples of COV gathers displayed in gather (Figure 1A) and stack (Figure 1B) viewers, respectively.



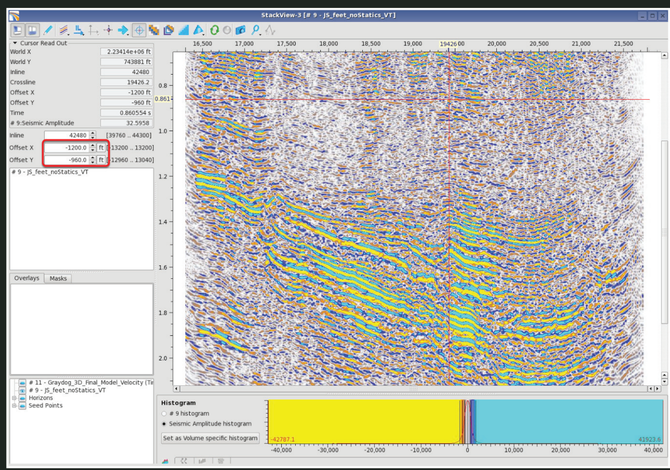


Figure 1. COV gather data displayed in gather (A) and stack (B) Viewer. Data can be viewed for any combination of offset X and offset Y values, and resorted interactively.

Interactive polar sectoring was introduced, to transform COV data to COCA. Nearly all existing processing and interpretation tools (including horizon tracking) have been adapted to seamlessly handle 5D gathers. Finally, new, dedicated modules were developed to characterize and map velocity and amplitude anisotropy directly from pre-stack, full-azimuth data.

Interactive Sectoring and Stacking

Sectoring can be carried out with or without trace interpolation, with the choice guided by data density and type of data analysis workflow. The COCA sectoring module provides diagnostics to guide the choice of sector sorting, by showing trace counts and highlighting locations of empty bins that will be filled by 5D interpolation. Figure 2 illustrates typical sectoring results for coarse COV data, with offset spacing greater than 2000 feet in both Cartesian directions. Sectors are created every 30 degrees with offset spacing of 1200 feet, to generate 120 fold COCA gathers.

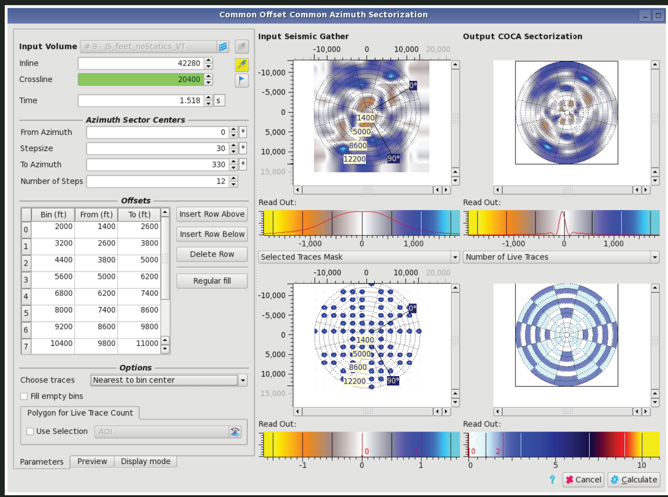
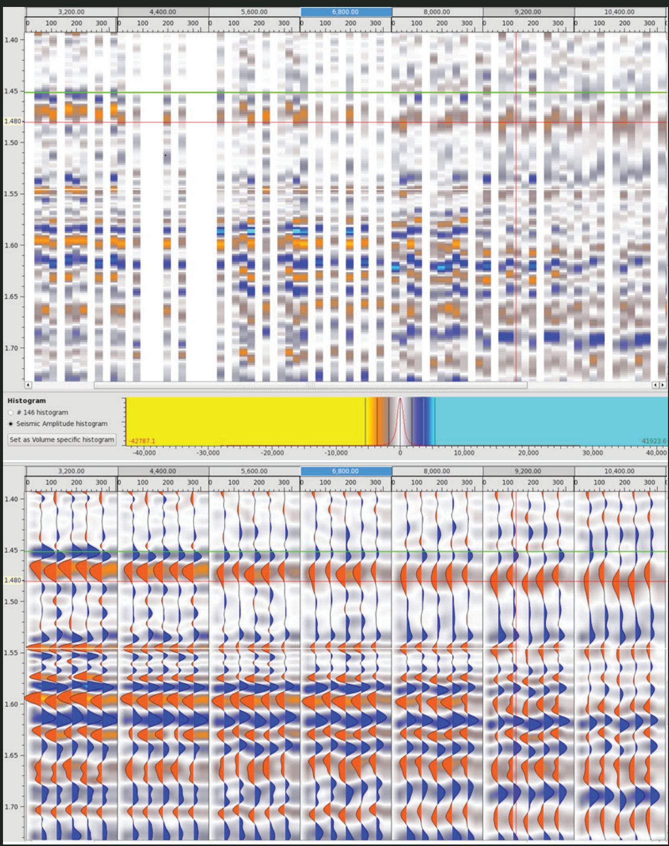


Figure 2. Sectoring of Cartesian gather data is carried out interactively, using user-specified azimuth and offset sector ranges. QC displays guide the selection of sector parameters, and show the resulting trace distribution for any sector geometry. The module generates Common-Offset, Common-Azimuth (COCA) gathers, with or without trace interpolation.



Without interpolation, many short-offset sectors are blank. Figure X compares the COCA-sectored result for a single cdp location, with and without COCA interpolation. Pre-Stack Pro now supports advanced workflows that minimize interpolation trace positioning errors by "losslessly" removing azimuthal moveout and then reapplying to the COCA-sectored gathers. Current R&D work aims to compute all anisotropy analytics direct from COV data, thereby eliminating the need for constructing COCA gathers.

Figure 3. Single COCA gather without (A) and with (B) offset trace interpolation. Near offsets contain many missing traces, which must be filled by 5D interpolation.

Once COCA sectored are generated, users can interactively generate partial stacks for any angle and azimuth sector range, and optimize images for specific reservoir targets. A weighted stack option is available for further customization. 3D horizon tracking can be run on virtual volumes in "interactive stack" mode, to assess the effect of different stack ranges on interpretation. These options are especially useful for sub-salt plays, where targets are often illuminated from only a limited number of angles and azimuths.

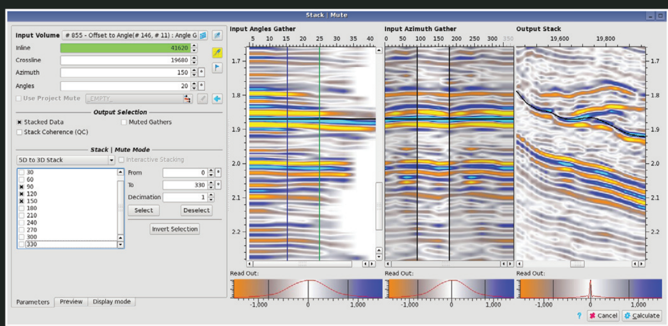


Figure 4. Interactive Stack/Mute module used to create partial stacks with any range of angle and azimuth.

Application to Naturally-Fractured Reservoirs

Formations cut by swarms of natural fractures with a dominant preferred orientation often exhibit azimuthal velocity anisotropy. Seismic P-waves generally travel faster parallel to the fracture planes, which open in the direction of minimum horizontal principal stress. In seismic migrated with isotropic horizontal velocities, azimuthal anisotropy effects commonly manifest themselves as variations in travel times on far-offset COCA gathers. Far-offset seismic raypaths have a large horizontal velocity component, and fast and slow velocity directions can be identified by azimuth sectors with under-corrected and over-corrected offset gathers.

Velocity-Versus-Azimuth (VVAZ) Analysis

Velocity anisotropy effects can be identified and mapped using new “5D” horizon picking methods, and provide a useful quick-look QC to quantify azimuthal moveout on migrated gathers. Event picking algorithms are used to fit multi-dimensional horizons to COV or COCA gathers, and pick times for all pre-stack traces are stored in a 5D horizon object.

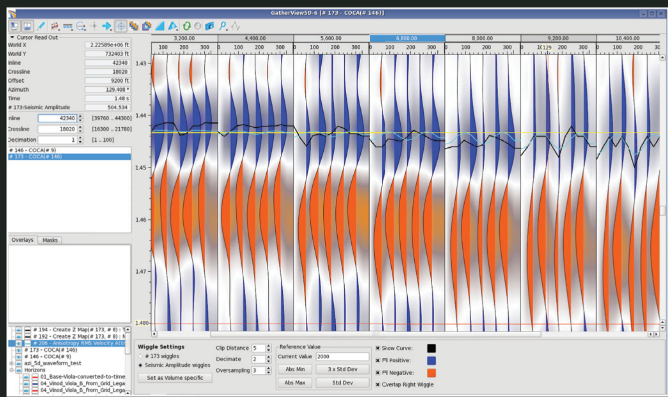
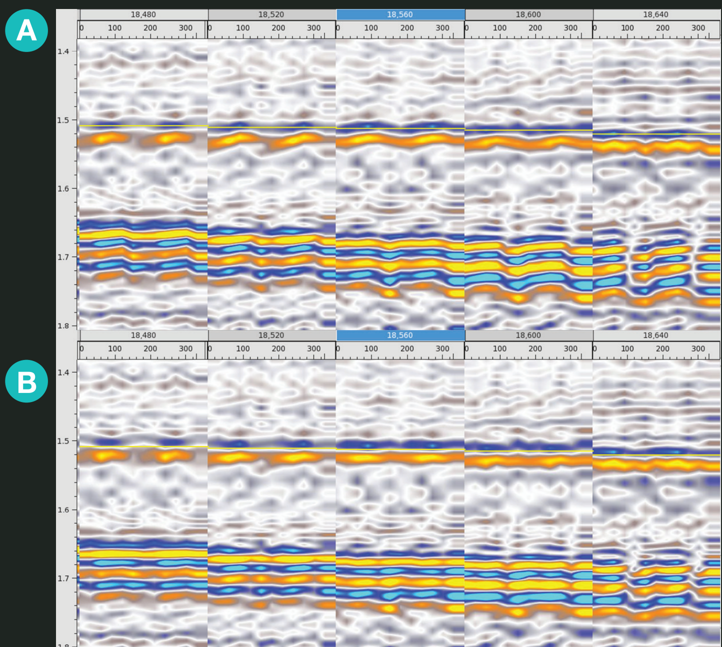


Figure 5. Result of horizon picking and modelling azimuthal travel time variation for a single HTI half-layer. Original 3D horizon pick (yellow) is first snapped to the peak event (black) to produce travel-time picks on every gather trace. These picks are then fit using a single HTI model (blue) with sinusoidal amplitude increasing at large offsets.



Travel time picks can be fit to a model that predicts travel time variation for a horizontal transverse isotropic (HTI) layer, which can be used to assess how well data are explained by this simple theoretical model. 5D travel times for two horizons with robust model fits can be used to estimate azimuthal velocity anisotropy of the intervening layer, but generally require extremely accurate horizon picks on strong, reliable events.

Volumetric velocity estimation methods provide more reliable results in noisier data, though they come at a much higher computational cost. Pre-Stack Pro’s new Azimuthal Residual Moveout Analysis (A-RMO) algorithm loops over a 3D COCA gather volume, removing the azimuthal moveout variations and the estimating the RMS velocity volume for each sector.

Figure 6. Results of full-azimuth RMO. Input gathers (A) show strong azimuthal variations in two-way travel time, which are minimized by the RMO algorithm (B). Azimuthally-varying velocities are subsequently fit to an HTI model to yield Vfast, Vslow, and direction of Vfast for the entire data volume.

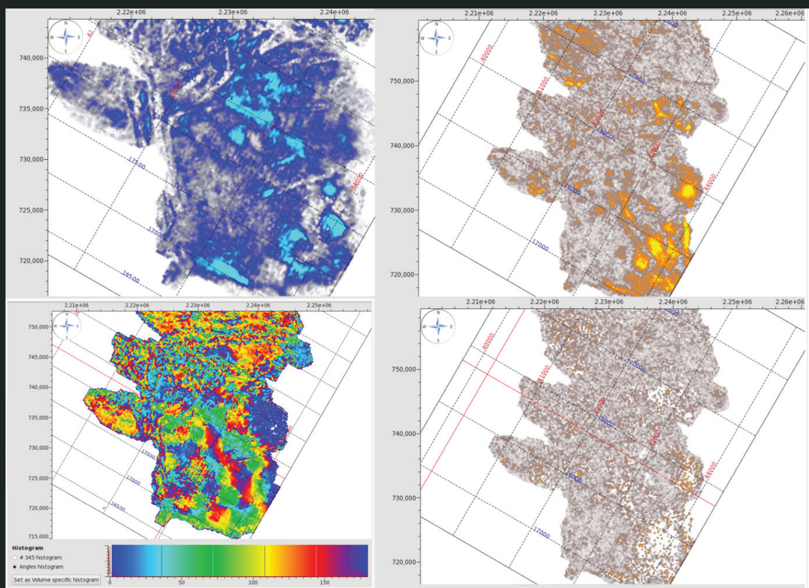
The algorithm fits an elliptical velocity function to the resulting sectored velocities to estimate fast and slow effective velocities, and the azimuth of the fast velocity at each survey sample location. Interval velocities can be readily estimated for seismically-imaged layers using computed Vfast, Vslow, and azimuth of Vfast values on top and base layer horizons. Maps showing the strength of anisotropy (Vfast minus Vslow) and fast velocity direction can be used to predict fracture swarm densities and orientations, and integrated with measurements from wells, core, and microseismic data.

Amplitude-Versus-Azimuth (AVAZ) Analysis

Seismic reflections across fractured interfaces also commonly exhibit amplitude anisotropy, with azimuthal variations in seismic amplitude. Amplitude-Versus-Azimuth (AVAZ) techniques are commonly used to characterize this rock fabric. Pre-Stack horizon interpretation techniques can dramatically accelerate the derivation of AVAZ maps. Instantaneous amplitude maps are extracted from these “5D” horizons, yielding an amplitude value for each azimuth and angle-of-incidence (AOI). This information can be used to quickly map azimuthal variation in amplitude at all incidence angles, and to compute the variation in AVO/AVA intercept and gradient.

Ruger (1996) modelled the seismic amplitude as a function of azimuth for an isotropic half-space overlying a half-space with azimuthal anisotropy, and derived an equation predicting sinusoidal azimuthal variations in amplitude for any non-normal angle of incidence. Pre-Stack Pro’s AVAZ calculator can be used to fit this response to 5-dimensional amplitude surfaces, to derive the P-wave intercept, isotropic gradient, anisotropic gradient, and isotropy plane azimuth for any horizon. These results can be used to predict likely orientations of fracture strike and fracture swarm intensity throughout the 3D survey. The AVAZ algorithm also calculate the “goodness-of-fit” between actual and modelled amplitudes at all CDP locations. Such quantitative error analyses are essential for land surveys, where amplitude variation can be caused by various forms of coherent and random noise. Figure X shows measured anisotropic gradients at the top of a naturally-fractured reservoir. Misfit analysis shows that areas with steep azimuthal gradients tend to show the poorest fits. Misfit values may be co-rendered on top of AVAZ results, or used to filter points considered to be unreliable due to a poor goodness-of-fit.

Figure 7. Maps showing the results of AVAZ analysis at the top of thick, naturally fractured reservoir. Amplitude maps are calculated for each angle and azimuth (A), and used to calculate AVAZ attributes. Direction of steepest AVO gradient (B), along with the anisotropic gradient Bani (C). High Bani areas show poor fits to theoretical AVAZ response, and may be removed for quality assurance (D).



Conclusions and Acknowledgements

Sharp Reflections is setting a new standard for full-fidelity interpretation of azimuthal pre-stack datasets. The new Pre-Stack Pro Azimuthal module makes a strong addition to a growing family of integrated analysis modules that share a common Big Data platform. With new cloud computing delivery options, companies can scale their server backbone up or down to match computational requirements and dataset sizes, to extract more information from full-azimuth surveys.

We kindly acknowledge the tremendous contributions of our R&D partners at Fraunhofer Institute for Industrial Mathematics (ITWM), and in particular the work of Dr. Norman Ettrich. Dr Heloise Lynn (Lynn Incorporated) has been an invaluable source of insight and inspiration, and graciously provided the data examples shown in this article.