Tech Trends

Attributes Improve 3-D Interpretation

Advanced volumetric attributes such as reflector convergence and reflector rotation about the normal to the reflector dip hold promise in interpreting angular unconformities and determining the rotation of fault blocks across wrench faults and other discontinuities. Such attributes can facilitate and quantify applying seismic stratigraphic workflows to large 3-D seismic volumes.

By Satinder Chopra and Kurt J. Marfurt

CALGARY–Coherence, curvature and other geometric attributes are useful for delineating a subset of seismic stratigraphic features such as shale dewatering polygons, injectites, collapse features, mass transport complexes and overbank deposits, but they have limited value in imaging classic seismic stratigraphy features such as onlap, progradation and erosional truncation.

In this context, advanced volumetric attributes such as reflector convergence and reflector rotation about the normal to the reflector dip seem to hold promise. While the reflector convergence attribute is useful in interpreting angular unconformities, the reflector rotation about the normal attribute determines the rotation of fault blocks across wrench faults and other discontinuities. Such attributes can facilitate and quantify using seismic stratigraphic workflows to large 3-D seismic volumes.

Another attribute that is useful in interpreting seismic data is the Euler curvature. This attribute is helpful in interpreting lineament features in desired azimuthal directions. It can be run on the final migrated stacked volume to obtain the attributes in different azimuthal directions and does not require azimuth-limited prestack migration.

FIGURE 1

Possible Rotations of Fault Blocks

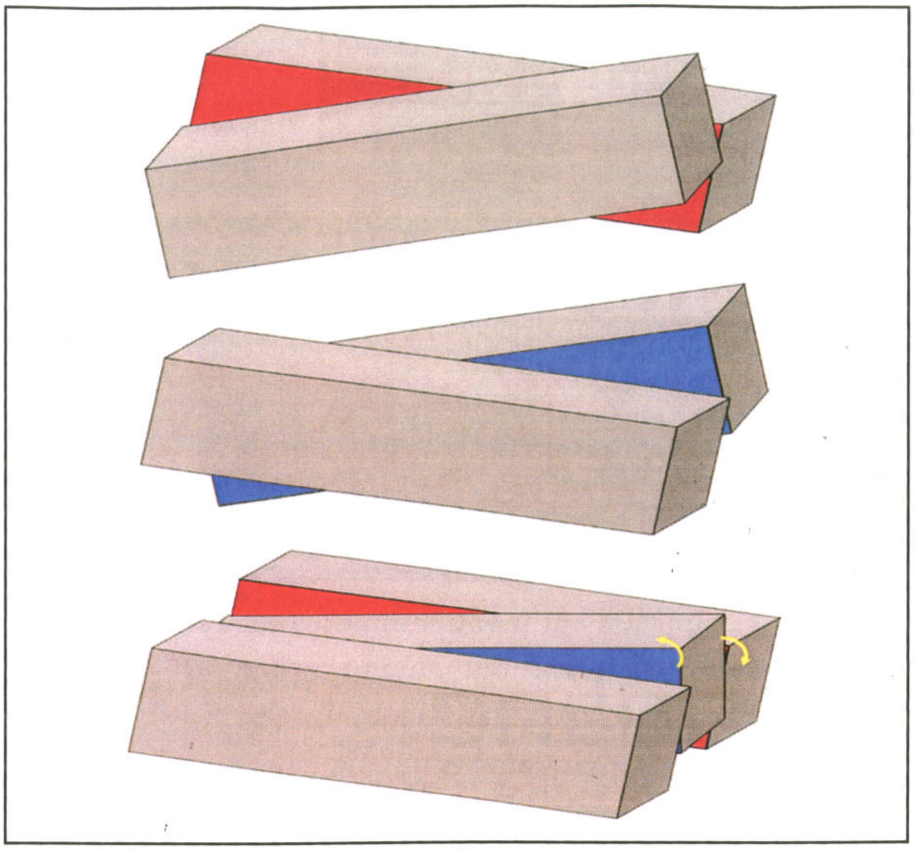
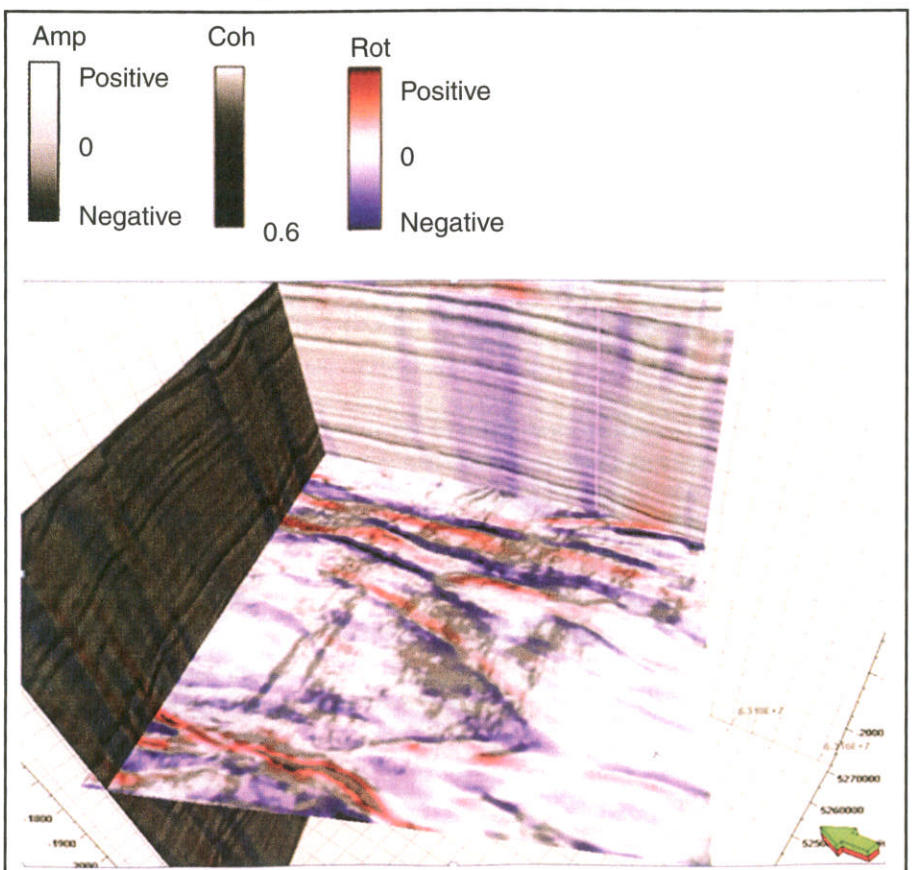


FIGURE 2

Time Slice Through Rotation About the Average Reflector Normal



Seismic stratigraphic analysis refers to analyzing the configuration and termination of seismic reflection events, packages of which are then interpreted as stratigraphic patterns. These packages then are correlated to well known patterns, including top lap, onlap, down lap, erosional truncation and so forth, which in turn, provide architectural elements of a depositional environment. Through well control as well as modern and paleo analogues, a probability map of lithofacies then can be produced.

Geometric attributes such as coherence and curvature are commonly used to map structural deformation and depositional environments. Coherence is useful in identifying faults, channel edges, reef edges and collapse features, while curvature images folds, flexures, subseismic conjugate faults that appear as drag or folds adjacent to faults, roll-over anticlines, diagenetically altered fractures, karst, and differential compaction over channels.

Although coherence and curvature are excellent at delineating a subset of seismic stratigraphic features, they have only limited value in imaging classic seismic stratigraphy features such as onlap, progradation and erosional truncation. This is where the newer volumetric attributes come in, facilitating stratigraphic analysis in large 3-D data sets.

Reflector Convergence

Because of the distinct change in reflector dip and/or terminations, erosional unconformities and angular unconformities in particular are relatively easy to recognize on vertical seismic sections. Although there often is a low-coherence anomaly where reflectors of conflicting dip intersect, these anomalies take considerable skill to interpret. Early innovations first computed volumetric estimates of vector dip, after which the mean and standard deviations were calculated in a local window. Those reflections that exhibit parallelism have a smaller standard deviation, while nonparallel events such as angular unconformities have a higher standard deviation.

Another early innovation was to compute convergence/divergence of reflections by computing a vertical derivative of apparent dip at a user-defined azimuth. We expand on this previous methodology by taking the curl of the volumetric vector dip, thereby generating a 3-D reflector convergence azimuth and magnitude estimates.

Reflector Rotation

Compressive deformation and wrench

faulting often cause fault blocks to rotate, with such rotation observed in laboratory clay models and outcrop. The extent of rotation depends on the size, the comprising lithology and the stress levels. Figure 1 shows how such a rotation could happen in a block faulting environment. As the individual fault blocks undergo rotation, the edges are expected to experience higher stresses and undergo fracturing.

In this example, the block at the top has a positive rotation (in red) and rotates down to the right across the fault. The block in the middle has a negative rotation (in blue), rotating up to the right across the fault. At the bottom, a graben rotates between two horst blocks, giving rise to both positive (red) and negative (blue) rotations.

Natural fractures account for much of the strain associated with fault block rotation. Fault block rotation also can control depositional processes by providing increased accommodation space in subsiding areas and accelerating erosional processes in uplifted areas. Besides the reflector convergence attribute, we therefore introduce another attribute that can be calculated to determine the rotation about the normal to the reflector dip and provide a measure of the reflector rotation across a discontinuity such as a wrench fault.

As the first step, the in-line and cross-line components of dip are determined at every sample in the 3-D volume using a semblance search or other vector dip computation method. After defining the three components of the unit normal, its rotation is computed by mathematically measuring rotations about the average normal within an analysis window to determine conflicting dips across wrench faults. Similarly, the cross product of the calculation measures the rotation along axes perpendicular to the average normal, providing a measure of reflector convergence.

Figure 2 is a 3-D chair display with the vertical in-line, cross-line and an arbitrary line showing reflector rotation co-rendered with seismic amplitude on the vertical sections and coherence on the time slice. The alternating red and blue patterns on the time slice through rotation about the average reflector normal indicate the rotation of down-dropped fault blocks.

A time slice at t=1.6 seconds is shown

FIGURE 3

Time Slice Through Reflector Convergence Co-Rendered with Coherence

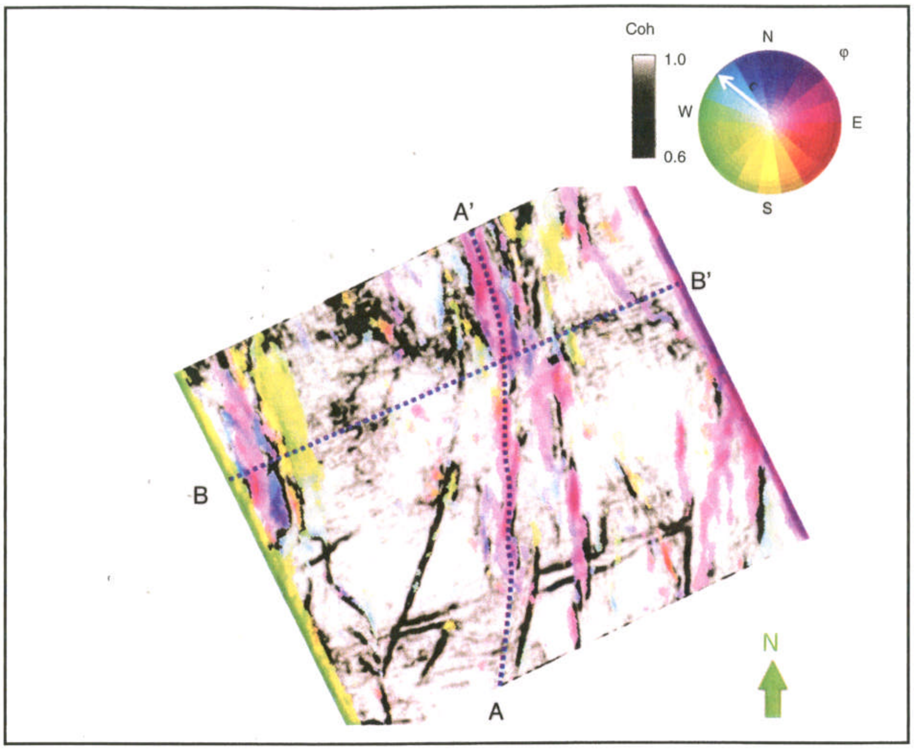
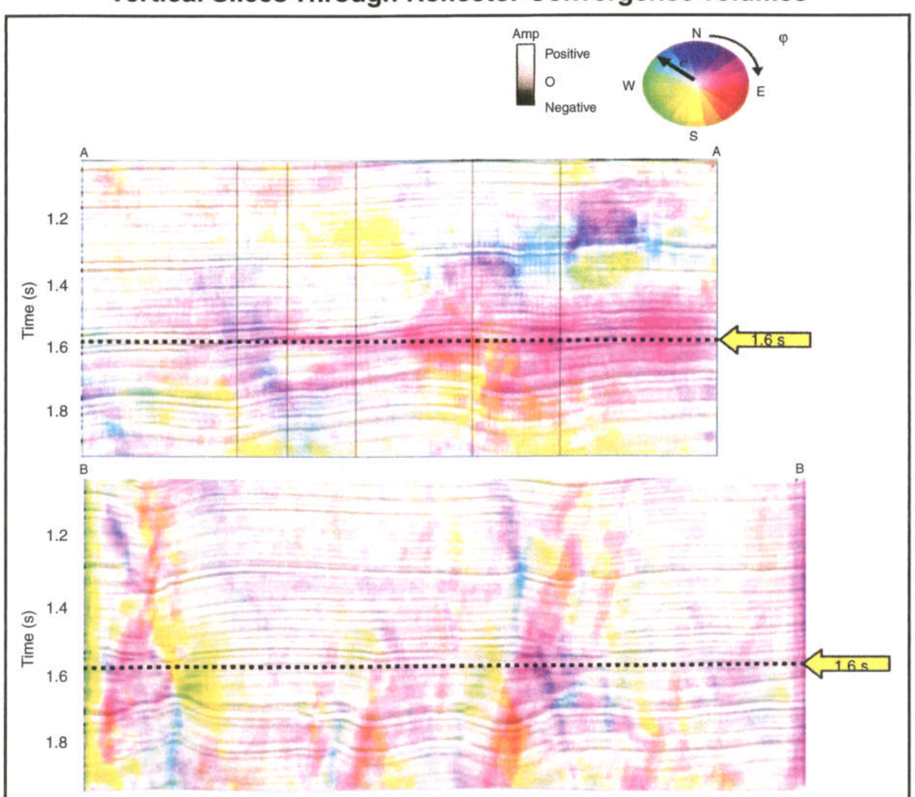


FIGURE 4

Vertical Slices Through Reflector Convergence Volumes

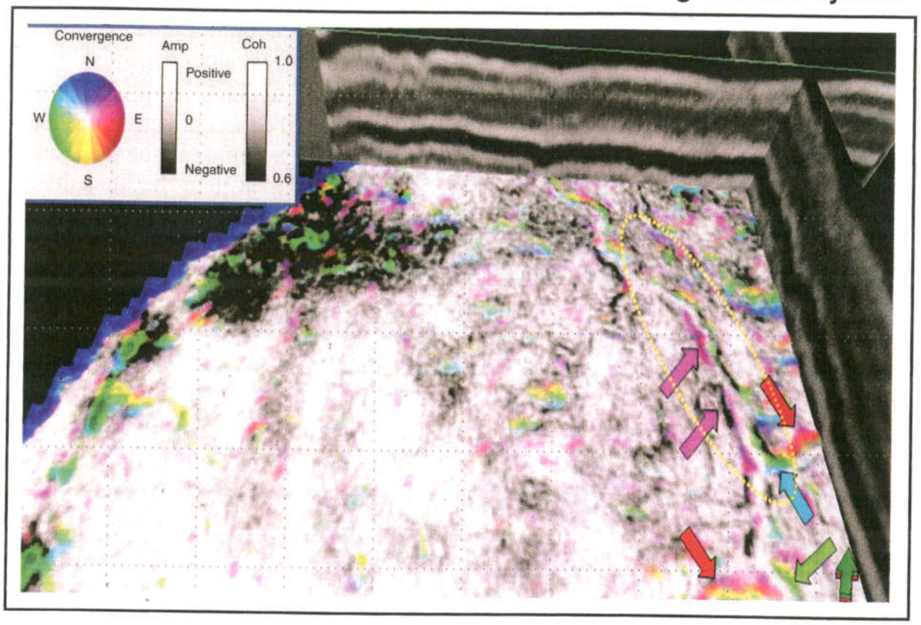


in Figure 3 through a coherence attribute in gray scale co-rendered with the reflector convergence displayed against a 2-D color wheel. Vector convergence azimuth is plotted against hue, while its magnitude is plotted against lightness to produce the color wheel. Sediments that are converging toward the southwest are colored green while those converging toward the northeast are shown in magenta. By integrating this image with Figure 2 (showing rotation), the patterns can be interpreted to indicate syntectonic deposition as the grabens rotated, forming greater accommodation space in a given direction.

Figure 4 displays two arbitrary lines (AA' and BB') through the same volume, showing the infill of grabens. The change in color is related to changes in accommodation space provided by the block rotations. Sediments that have low convergence magnitude or that are nearly parallel have been rendered transparent.

FIGURE 6

Coherence Time Slice as Horizontal Section Showing Channel System



Clastic Depositional System

A second example is of a clastic depositional system with minimal structural deformation. Figure 5 illustrates the use of reflector convergence in analyzing stratigraphic relationships within a channel with or without levee/overbank deposits in terms of four cases:

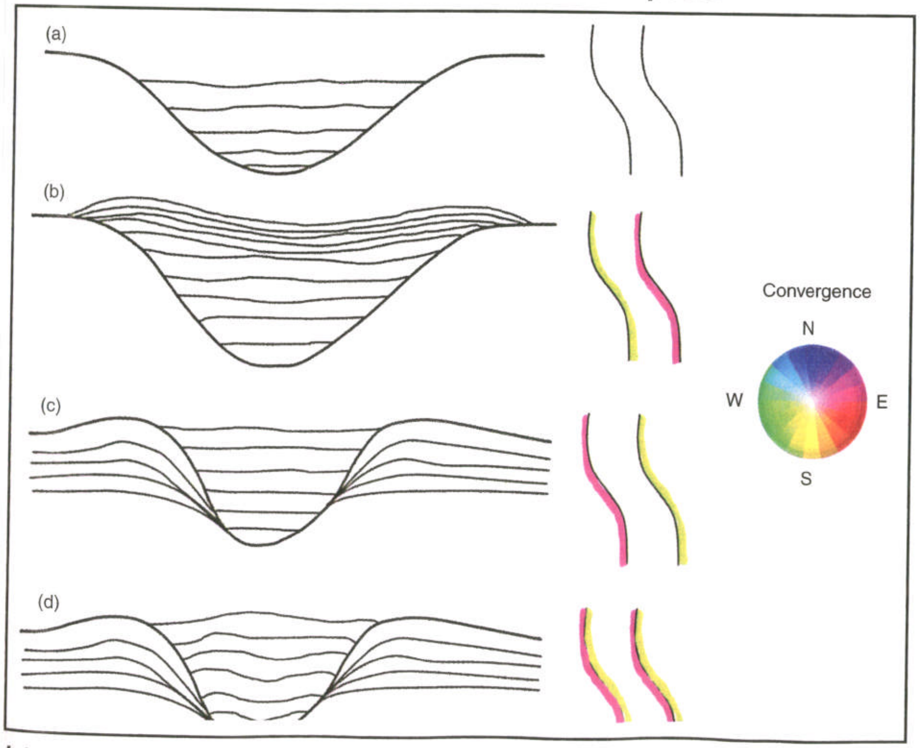
- Case A, where the deposition within the channel shows no significant convergence;
- Case B, where the deposition within the channel is such that the west channel margin is converging toward the west and the east channel margin is converging toward the east (displayed in color to the right with the help of a 2-D color wheel);
- Case C, where the deposited sediments within the channel are not converging at the margins, but the levee/overbank deposits converge toward the channel (west deposits converge toward the east and vice versa); and
- Case D, where both the strata within the channel and levee/overbank deposits are converging (this appears to be a combination of the B and C cases).

Note how the convergence shows up in color using the 2-D color wheel as displayed to the right in cyan and magenta colors along the channel edges.

The computation of reflector convergence and the rotation about the normal to the reflector dip attributes were carried out for a suite of 3-D seismic volumes from Alberta. Figure 6 depicts a 3-D chair view with a coherence time slice exhibiting a channel system, co-rendered with reflector convergence attribute using a 2-D color wheel. Within the area highlighted by the yellow, dotted-line ellipse, an interpretation has been made keeping

FIGURE 5

Convergence within a Channel With or without Levee/Overbank Deposits



Interpretation courtesy of Supratik Sarkar, University of Oklahoma in mind the cases shown in Figure 5. Apparently, the levee/overbank deposit is converging toward the channel margin, generating the magenta and green colors with respect to reflector convergence.

Euler Curvature

Euler curvature can be thought of as apparent curvature along a given strike direction. Since reflector dip magnitude and azimuth can vary considerably across a seismic survey, it is useful to equally sample Euler curvature azimuths on the horizontal X-Y plane and project these lines onto the local dipping plane of the reflector before implementing Euler curvature calculations.

Mapping the intensity of a given fracture set has been a major objective of reflection seismologists. The most successful work has used attributes computed by azimuthally limited prestack data volumes. Coherence attributes computed from azimuthally restricted seismic volumes can enhance subtle features hidden or blurred in the all-azimuth volume. Vector-tile and other migration-sorting techniques are now the method of choice for both conventional P-wave and converted-wave prestack imaging, allowing interpreters to predict both fracture strike and intensity.

Curvature, acoustic impedance and coherence are the most effective attributes for predicting fractures in the post-stack world. Rather than map the intensity of the strongest attribute lineaments, an image-processing ("ant tracking") algorithm can be applied to enhance curvature and coherence lineaments that were parallel to the strike of open fractures at an angle of some 45 degrees to the strike of the strongest lineaments.

Related technology has been used to azimuthally filter lineaments in the Eagle Ford Shale formation in South Texas, and then compute root mean square maps of each azimuthally limited volume that can be correlated to production. It has been theorized that each azimuthally limited attribute volume computed from the magnitude and strike of the most-positive principal curvatures corresponds to open fractures. Each volume can be correlated to production to either validate or reject the hypothesis.

Example Data Displays

Euler curvature has been applied to two 3-D seismic volumes from Northeast British Columbia. We propose an interactive workflow, as is used to generate a suite of shaded-relief maps to display apparent dip rather than apparent (Euler) curvature. Figure 7 shows 3-D chair view displays for Euler curvature run at 0, 45, 90 and 135 degree azimuths. The left column is the long-wavelength version, with the short-wavelength version in the right column.

For 0 degrees azimuth (north), lineaments in the east-to-west direction seem to stand out. For 45 degrees, the lineaments that are almost northwest-to-southeast are pronounced. Similarly for 90 degrees, the roughly north-to-south events stand out. For 135 degrees, the events that are slightly inclined to the vertical are better defined. The same description applies to

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Kurt J. Marfurt joined the University of Oklahoma in 2007, where he serves as the Frank and Henrietta Schultz Professor of Geophysics in the ConocoPhillips School of Geology & Geophysics. He began his career as an assistant professor at Columbia University, followed by 18 years in Amoco's Tulsa Research Center, and eight years teaching at the University of Houston. Marfurt was the 2006 European Association of Geoscientists & Engineers/Society of Exploration Geophysicists distinguished short course instructor, lecturing on seismic attributes. In addition to teaching, he leads a research consortium at OU on seismic attributes. Marfurt holds an M.S. and a Ph.D. in applied geophysics from Columbia University.

the short-wavelength displays that show more lineament detail and resolution than the long-wavelength displays.

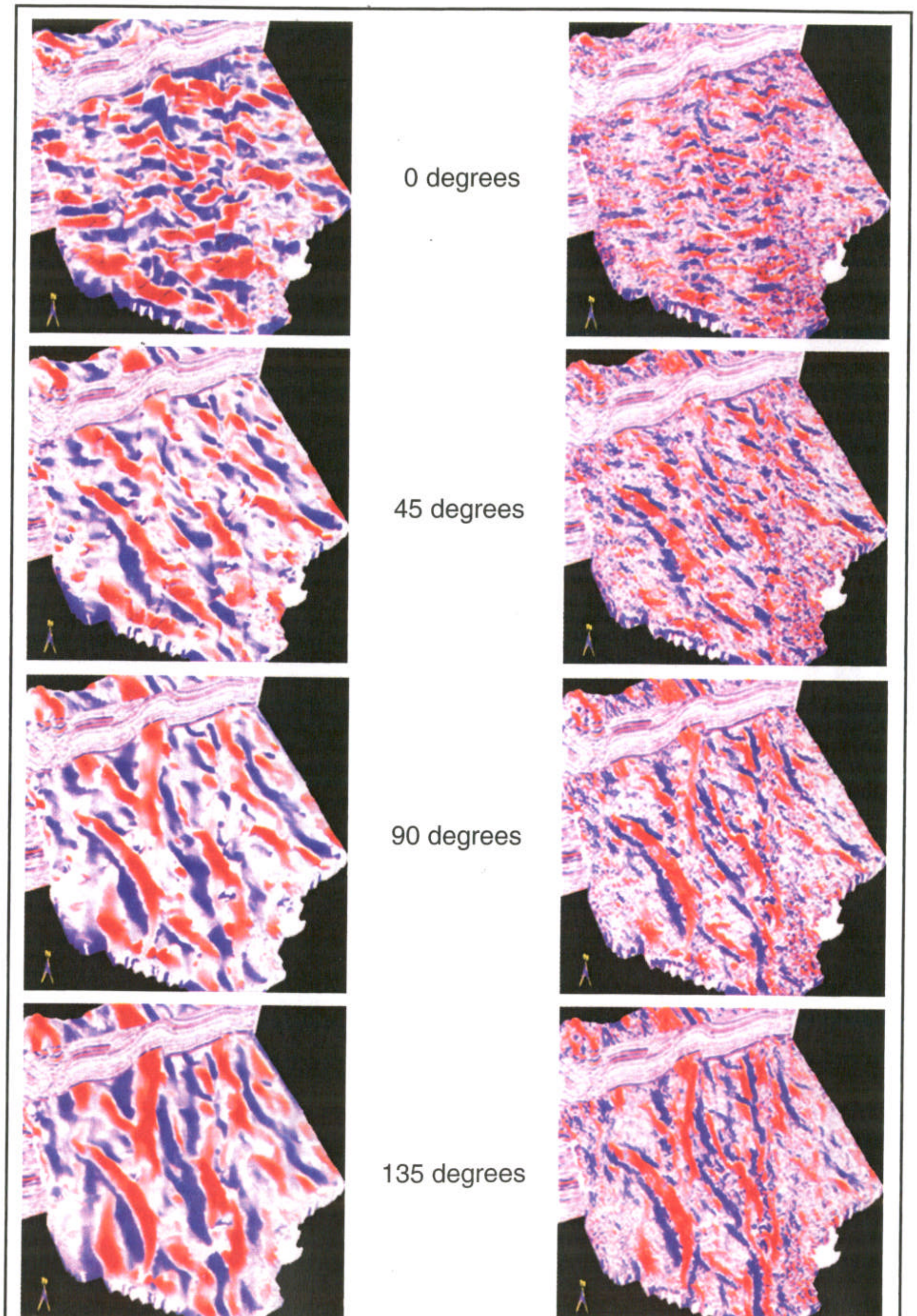
There are obvious advantages to running Euler curvature on post-stack seismic volumes in that azimuth directions can be chosen carefully to highlight the lineaments in the directions known through image logs or production data to better correlate to open fractures. This does not entail processing azimuth-restricted volumes (usually three or four) all the way to migration and then passing them through coherence/curvature computation.

As shown on two 3-D seismic volumes, applying the reflector convergence and the rotation about the normal to the reflector dip attributes has proven very useful. Reflector convergence gives the magnitude and direction of thickening and thinning of reflections on uninterpreted seismic volumes, while reflector rotation about faults is clearly evident and has a valuable application in mapping wrench faults. Such attributes yield convincing results on data sets that have good quality.

Euler curvatures run in desired azimuthal directions exhibit a more well-defined set of lineaments that may be of interest. Both the long- or short-wavelength computations can be of value to the interpreter, depending on the desired level of detail. The short-wavelength Euler curvature is more beneficial for observing fracture lineaments. This work is ongoing and we hope to calibrate the observed lineaments with the image logs in terms of rose diagram matching to enhance the interpreter's level of confidence. ❐

FIGURE 7

Correlation of an In-Line with Euler Curvature Attribute Volumes at Different Angles (Left: Long Wavelength; Right: Short Wavelength)



Enbridge Energy Expands Bakken Transport Ability

HOUSTON–Enbridge Energy Partners says it will spend another $145 million to add a rail car loading facility to its Berthold, N.D., terminal, raising the expected capacity of its Berthold rail project to 80,000 barrels of oil a day.

Enbridge explains that its Berthold rail project complements its Bakken expansion program, and integrates the crude oil gathering system in western North Dakota and eastern Montana, created by the company's Bakken access program.

The Bakken expansion program, Enbridge notes, was announced in August 2010. It will provide 145,000 bbl/d of take-away capacity–25,000 bbl/d of which already is available–for production in Montana, North Dakota and Southeast Saskatchewan by early 2013. The Bakken access program, Enbridge continues, involves increasing gathering pipeline capacities, constructing additional storage tanks and adding truck access facilities at multiple locations in western North Dakota. It is expected to be in service prior to the startup of the Bakken expansion program.

The Berthold rail project, which entails constructing a double-loop unit train facility, crude oil tankage and other terminal facilities, according to Enbridge, will have the ability to stage three unit trains at any time. After an initial 10,000 bbl/d startup in July 2012, Enbridge says, the full 80,000 bbl/d of rail export capacity is scheduled to be in service in early 2013. ❐

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