The Shape of Seismic Interpretation

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Abstract

Seismic interpreters routinely use the shape of an interpreted surface in developing prospects, with the classic hydrocarbon trap being a ridge-shaped anticline. Carbonate buildups may appear as dome-shaped and karst collapse features as bowl-shaped. Differential compaction often results in valley-shapes over shale-filled channels.

The interpretational value of a given shape is dependent on its depositional, diagenetic, and tectonic deformation context. If the channel fill is sand and the surrounding matrix shale, differential compaction can result in an incised valley appearing as a ridge, thereby providing a lithologic indicator. In flat-lying carbonates, joints will often be diagenetically altered and appear as valleys, while fracture intersections will appear as bowls. As always, the interpreter needs to be aware of the seismic data quality. In areas of limited lateral and vertical resolution, diffuse, or poorly-imaged faults may give rise to a recognizable shape anomaly. Care needs to be taken where velocity pull-up may induce deeper ridges and push-down deeper valleys on what might actually be flat structure.

Coupled with coherence, which delineates reflector edges, volumetric shape helps us rapidly recognize structural and stratigraphic style on horizontal and vertical slices. Pop-up blocks may appear as ridges bounded on both sides by low-coherence faults. Listric faults may be associated with a ridge-shaped roll-over anticline. Gas- and water-charged debris flow that can be drilling hazards may appear as high-coherence, dome shaped blocks.

Quantitative measures of reflector shape computed from uninterpreted seismic volumes are a by-product of volumetric curvature. Volumetric curvature is now well-established in the interpretation community, with workflows developed to correlate healed fracture zones to ridges in shale plays to help guide hydraulic fracture stimulation programs. More recently, advances have been made in the volumetric quantification of pinch-outs and unconformities, providing images of both the magnitude and azimuth of reflector convergence. There is no “best” attribute. Rather, one should co-render mathematically independent attributes that are coupled through the underlying geology.

I will illustrate these concepts through application to land data volumes from North America.

Introduction

The shape of a seismic reflector has long played a key role in seismic exploration and production. Perhaps the classic hydrocarbon play is that of an anticline. Carbonate reefs and bioherms are recognized by their dome shape. Bowl-shaped features due to collapse of the Ellenburger in the Fort Worth Basin are avoided in the overlying Barnett Shale since they are filled with water. Similar collapse features in the Edwards limestone of south Texas are sought after since they can lead to thicker pay in the shallower Eagleford Shale. Differential compaction giving rise to a valley-shaped channel can indicate it is shale-filled while a ridge or dome shape can indicate it is sand-filled (e.g. Hertier *et al.*, 1990).

The association of structural shape with faults and fractures is also a key component of seismic interpretation. Rollover anticlines form an excellent target and are commonly associated with the downthrown block of listric faults (Xiao and Suppe, 1992). Natural fractures are associated with flexures and folds.

Increases in computation speed, the development of 3D geometric attributes, and the broad deployment of desktop 3D visualization tools over the past 15 years facilitate workflows to rapidly apply such shape-based workflows to large 3D data volumes. In this tutorial paper, I summarize key technical components, illustrate effective multi-attribute display techniques, and show the value of these workflows through examples.

I begin by reviewing some of the more useful seismic attributes in mapping the morphology, or shape of seismic reflectors, illustrating their use through application to the Ellenburger Limestone and Barnett Shale sequences of the Fort Worth Basin of North Texas. I then extend the application to illustrate tectonic deformation, fluvial systems, carbonate buildups, and progradational systems. Next, I discuss the limitation of these attributes, as well as possible interpretation pitfalls when using seismic data that have not been properly acquired, processed, or converted to depth. I conclude with a summary of the major findings and a vision for the future.

Geometric Attributes

There is a rich (perhaps overwhelming) suite of seismic attributes that can aid interpretation. Some attributes are sensitive to seismic amplitude, others to phase, still others to spectral content. In this paper I will focus on the subset of “geometric” attributes that measure vertical and lateral changes in waveform and vector dip. The word morphology comes from the Greek word for form, which suggests that geometric attributes are well-suited for seismic geomorphological analysis. However, we should be aware that important features such as channels and mass-transport complexes may often be better delineated by attributes such as energy or components of spectral decomposition.

Coherence

Coherence is a measure of the lateral change of the seismic waveform along structural dip. Some coherence implementations, such as those based on cross-correlation, eigenstructure analysis or Kohonen-Loeve (KL) filters, are sensitive to changes in waveform only (e.g. Bahorich and Farmer, 1995; Gersztenkorn and Marfurt, 1999; Marfurt, 2006), and are insensitive to waveforms that have the same shape but exhibit different amplitudes. Other implementations, such as those based on semblance (or equivalently, variance) analysis (e.g. Marfurt *et al.*, 1998), Sobel filters (Luo *et al.*, 1995), and the gradient structure tensor (giving rise to the chaos attribute) (Randen *et al.*, 2000) are sensitive to changes in both waveform and amplitude. In general, the eigenstructure-family of coherence attributes provides better lateral resolution, giving the appearance of sharper edges of faults and relatively thick stratigraphic features. In contrast, the second family of coherence attributes (including semblance) often better delineate thin channels that fall below tuning.

Figure 1 shows a time slice at t=1.2 s through a coherence volume computed by taking the ratio of energy of the KL-filtered version of the data and the energy of the unfiltered data. The circular features (such as the one indicated by the yellow arrow) are collapse features described by Sullivan *et al.* (2006) seen in the Cambro-Ordovician Ellenburger limestone that propagate further up into the section, beyond the Cretaceous-age Caddo limestone. Only a few faults are seen in the time slice, two of which are indicated by the magenta and green arrows. Due to extensive well control, the depth and even the thickness of the overlying Barnett Shale is well known throughout most of the Fort Worth Basin. One of the primary values of 3D seismic is to map, and subsequently design a drilling program to avoid the collapse features, faults, and if possible, joints, that connect the water-filled Ellenburger to the overlying gas-rich shale reservoir.

Curvature

Curvature obtained from well tops and 2D seismic correlated to natural fractures and improved production was perhaps first reported by Murray (1968), who analyzed production from the Bakken formation of North Dakota. While subsequent workers further calibrated the correlation of curvature to fracture prediction, the technology was underutilized until Roberts (2001) applied it to surfaces interpreted from 3D seismic data. The computation begins by approximating each point on an interpreted surface by a local, quadratic surface. At any analysis point, P, a quadratic surface can be defined by two orthogonal principal curvatures, k_1 and k_2, where $k_1 \geq k_2$. Curvature is the reciprocal of the radius of curvature of any circle tangent to the surface. For a quadratic surface, there will be two circles, the two circles that best fit the surface. For a quadratic surface, the tangent circle with the minimum radius and the tangent circle with the maximum radius will be orthogonal to each other and fully define the surface (Figure 2). Historically, workers have used the maximum and minimum curvatures, k_{max} and k_{min}, defined as

$$k_{\max} = \begin{cases} k_1 \ if \ |k_1| \geq |k_2| \\ k_2 \ if \ |k_2| > |k_1| \end{cases}, \text{ and} \tag{1}$$

$$k_{\min} = \begin{cases} k_2 \ \ if \ |k_1| \geq |k_2| \\ k_1 \ if \ |k_2| > |k_1| \end{cases}. \qquad (2)$$

Horizon-based curvature measures are based on the 2nd derivatives of the picked horizon, or alternatively, on the 1st derivatives of reflector inline and crossline apparent dip components. This latter observation lead al-Dossary and Marfurt (2006) to introduce volumetric curvature, which they computed on volumetric estimates of the two apparent dip components. They followed Bergbauer *et al.* (2003) and showed that applying long- or short-wavelength filters to the curvature operator provides curvature measures at different scales, highlighting desired broad or local features.

Careful examination of these measures will show that a major advantage of using the principal curvatures is the ability to track lineaments, such as diagenetically-altered fractures through areas where the feature of interest no longer has the larger absolute value. Figure 3 shows such features which Sullivan *et al.* (2006) interpret as a system of intersecting joints. The reason for these joints appearing as structural lows is still undetermined. They could be actual "valleys" due to diagenetic alteration and dissolution. Alternatively, the diagenesis (or stress release) may have lowered the velocity of the overburden. Whatever the reason, the intersection of these most-negative curvature lineaments correlates very strongly to the location of the collapse features seen on coherence (Figure 4). Note also how accurately the k_2 anomalies track synclinal structures in the two vertical seismic amplitude slices. While faults often give rise to curvature anomalies, they are usually laterally shifted from the discontinuity seen in coherence. In this example, I believe curvature is measuring the effect of antithetic faulting such as that reported by Ferrill and Morris (2008). In softer sediments fault-related curvature anomalies they may correlate to sediment drag and rollover anticlines.

The most-positive principal curvature, k_1, always measures the curvature orthogonal to the most negative principal curvature, k_2. The most-positive principal curvature image corresponding to that shown in Figure 3 is shown in Figure 5. For a collapse feature, the structure approximates a bowl, such that both k_1 and k_2 are synclinal or less than zero. For this reason, the collapse features in Figure 5 appear as blue negative curvature anomalies, surrounded by a ring of red positive curvature anomalies. Figure 6 shows the correlation between these "bowl" shapes and the collapse features by co-rendering the most-positive principal curvature and coherence anomalies. Note the correlation of red "ridges" of the most-positive principal curvature with the structure seen on the vertical slices through the seismic amplitude volume. Using modern 3D visualization software, we can co-render the most-positive and most-negative curvature anomalies with coherence and seismic amplitude to obtain the image shown in Figure 7. In this image, we begin to see how coherence and curvature are mathematically independent and interpretationally complementary attributes. I will better illustrate this value in the subsequent section entitled "Examples".

Be advised that care must be taken in understanding how your software has been implemented. First, there is a sometimes significant difference between the most-positive and negative curvatures, k_{pos} and k_{neg}, and the most-positive and most-negative *principal* curvatures, k_1 and k_2. The first two attributes will exhibit anomalies along the crest and trough of a fold with respect to the vertical time or depth axis. In contrast, the principal curvatures are rotationally invariant and will exhibit anomalies along the tightest synclinal and anticlinal components of a fold, independent of the fold orientation. Second, while most references, including mathematical references on solid geometry, define the maximum and minimum curvatures, k_{max} and k_{min}, using equation 1, other references, and several geoscience interpretation packages simply define k_{max} to be equivalent to k_1 and k_{min} to be equivalent to k_2.

Reflector Shape

At those locations where the value of the most-positive principal is negative (the blue anomalies in Figure 5), we know we have a bowl-shape feature since $k_1 \geq k_2$. In this survey, the Ellenburger limestone is a relatively flat-lying (dip < 2^0) formation that is riddled with collapse features and dissected by joints; there are no structural domes. Nevertheless, since $k_1 \geq k_2$, the red areas (positive values) of the most-negative curvature time slice shown in Figure 3, correspond to erosion remnants that have a dome shape. A more rigorous and general quantification of these relationships is defined by the shape index, s, (e.g. Roberts, 2001; Bergbauer *et al.*, 2003) given by

$$s = -\frac{2}{\pi}\text{ATAN}\left(\frac{k_2 + k_1}{k_2 - k_1}\right), \quad (2)$$

and the curvedness, C,

$$C = \left(k_1^2 + k_2^2\right)^{1/2}, \qquad (3)$$

and displayed graphically in Figure 8. The curvedness, *C*, quantifies the degree of deformation, with a value of *C*=0.0 defining a planar surface and large values of *C* a highly deformed surface. The shape index, *s*, defines the type of deformation, and progresses from a bowl (*s*=-1.0), through a valley (*s*=-0.5), saddle (*s*=0.0), ridge (*s*=+0.5), to a dome (*s*=+1.0), with all the values in between.

Figure 9 displays vertical slices and a time slice at *t*=1.2 s through a volume of the shape index, s, modulated by the curvedness, *C*, using a 2D HLS-based color bar described by Guo *et al.* (2008). Note that the collapse feature indicated by the yellow arrow is blue, indicating that it has a strong bowl shape. The fault indicated by the magenta arrow appears as cyan (a valley) to the North and as yellow (a ridge) to the south of the E-W trending fault. A similar pattern brackets the NE-SW trending fault indicated by the green arrow. By setting values with lower curvedness to be 100% transparent, and values with higher curvedness to be 50% transparent, I can co-render the composite reflector shape attribute with the seismic amplitude on the vertical slices and with coherence on the time slice at *t*=1.2 s (Figure 10). As anticipated, the incoherent anomalies associated with collapse features align nicely with the bowl-shaped (blue) reflector shape anomalies. Note that the valley-ridge pattern associated with the two previously discussed faults bracket the coherence anomaly mapping the fault discontinuity. The valley-discontinuity-ridge triplet is seen on the vertical slice through seismic amplitude on the east side of the image.

Al-Dossary and Marfurt (2006) showed how to design a simple raised cosine filter to construct a volume that quantifies the strength of any given shape component. Figure 11 shows the filter applied to the curvedness, *C*, as a function of the shape index, *s*, to obtain the bowl component of deformation. Figure 12 co-renders this bowl component with vertical seismic section through the seismic amplitude and the time-slice at *t*=1.2 s through the coherence volume. The strong blue-colored bowl shapes correlate to the incoherent collapse features.

Figure 13 shows the same data, but now shown using volume rendering. The bowl-shape features continue up to and through the Cretaceous-age Caddo horizon. These bowls provided accommodation space for sands and gravels in the slightly lower Atoka formation, forming an important hydrocarbon reservoir.

Lineament magnitude and strike

Examination of Figure 3 will show that the curvature lineaments associated with the joints are not random, but appear to be restricted to a relatively small population of azimuths. The theory and field measurements of tectonic deformation show that we commonly encounter major fault orientations and one or more sets of conjugate faults and fractures. Since the horizontal components of stress are often unequal, some of these fracture sets may be open and some may be closed. Nissen *et al.* (2009) interpreted such curvature lineaments associated with fractures in the Mississippian limestone of central Kansas, and found one fracture set to be diagenetically-altered and fill with shale by the overlying sequence, and another fracture set to be open and communicating with the underlying aquifer. Furthermore, by hand-measurement of the distance between each well to the closest lineament corresponding to each fracture set, she was able to show a clear one over distance relationship of 5-year water production to the open fracture set.

In addition to providing the most-positive and most-negative principal curvatures (which are mathematically the eigenvalues of the quadratic surface), curvature analysis provides the azimuth of minimum curvature (or the *eigenvector* corresponding to k_{min} projected onto the horizontal plane). For geologists, we would recognize this measurement to be a strike rather than an azimuth, and note that it will map the strike of the ridges and valleys. By construction, there should be two eigenvectors, which are orthogonal to each other. Rich (2008) pointed out that while the azimuths of minimum and maximum curvature are orthogonal in the dipping plane tangent to analysis point on any surface, they are no longer orthogonal when projected onto the horizontal plane. Indeed for very steep dips, the two azimuths become almost co-linear.

Al-Dossary and Marfurt (2006) and Guo *et al.* (2008) showed how one can co-render the azimuth of minimum curvature and the strength of the ridge or valley component to obtain volumetric images of lineaments. However, a given lineament may start as a valley, intersect another valley and become one of the components comprising a bowl, or intersect a ridge and become the negative component of a saddle. For this reason, I have generalized the concept of azimuths of minimum and maximum curvature to produce images of the strike of the most-positive and most-negative principal curvatures, ψ_{k1} and ψ_{k2}. Using the HLS colorbar defined in Figure 14, I map the strike of the most-negative principal curvature, ψ_{k2}, against hue and strength of the most-negative principal curvature, k_2, against intensity (Figure 15). Note the collapse feature indicated by the yellow arrow occurs at the intersection of a green (NW-SE trending) and magenta (NE-SW trending joint). The lineament on the downthrown side of the E-W trending fault indicated by the magenta arrow appears as yellow, while the NE-SW trending fault indicated by the green arrow appears as magenta.

Figure 16 shows the same image co-rendered with the vertical slices through seismic amplitude and time slice at t=1.2 s through coherence. Following the two faults indicated by arrows to the vertical slice through the seismic amplitude on the east side of the survey, note how the color-coding allows the interpreter to see the strike of the fault on a vertical section. Following Guo *et al.* (2009) we use transparency to volume render the stronger lineaments in 3D (Figure 17). While this latter figure may be pretty, the value of a still volume-rendered image is quite limited; the true value requires interaction on a workstation.

Mai *et al.* (2009) and Guo *et al.* (2010) showed how volumetric measurements of vector data can be displayed as 3D rose diagrams. I display the information displayed in Figure 17 as a rose diagram in Figure 18. In this process, I defined an analysis window (2200 ft by 2200 ft and 10 ms, and then set thresholds as to which k_2 values I wished to count by interactively adjusting the color bar of the image in Figure 3 to obtain an image of what I interpreted to be joints. The values of k_2 are scaled to range between 0 and 1, with the scale directly corresponding to the intensity of the colorbar. The scaled values are then binned into 12 petals (for a total of 24) and added according to their strike. Narhari *et al.* (2009) demonstrated the correlation of such rose diagrams to those of natural fractures measured in image logs, thereby guiding a successful drilling program in Kuwait.

Reflector convergence

One of the major interpretation breakthroughs of the 1970s was the acquisition of very long 2D seismic lines and the subsequent development of seismic stratigraphy. A key component of seismic stratigraphy is the identification of reflector configurations which can be described as concordant, onlapping, downlapping, hummocky, sigmoidal, and chaotic among others (e.g. Macurda and Nelson, 1988). Until recently, such mapping needed to be done by hand. Barnes (2000) developed one of the first algorithms to compute volumetric convergence. More recently, van Hoek *et al.* (2010) have introduced an unconformity attribute based on volumetric estimates of the two apparent dip components.

Marfurt and Rich (2010) define the apparent reflector convergence, **c**, in the inline and crossline direction by taking the curl of the unit vector normal to the reflector in the inline, crossline, and horizontal planes and then taking the crossplot with the normal of the average dip:

$$\begin{aligned} \mathbf{c} = \mathbf{n} \times \boldsymbol{\psi} = \hat{\mathbf{x}} & \left[n_y \left(\frac{\partial n_x}{\partial y} - \frac{\partial n_y}{\partial x} \right) - n_z \left(\frac{\partial n_y}{\partial z} - \frac{\partial n_z}{\partial y} \right) \right] \\ + \hat{\mathbf{y}} & \left[n_z \left(\frac{\partial n_y}{\partial z} - \frac{\partial n_z}{\partial y} \right) - n_x \left(\frac{\partial n_x}{\partial y} - \frac{\partial n_y}{\partial x} \right) \right] . \\ + \hat{\mathbf{z}} & \left[n_x \left(\frac{\partial n_z}{\partial x} - \frac{\partial n_x}{\partial z} \right) - n_y \left(\frac{\partial n_y}{\partial z} - \frac{\partial n_z}{\partial y} \right) \right] \end{aligned} \quad (4)$$

Next, they combine these three components to generate a reflector convergence vector which can be defined by a convergence magnitude and converge azimuth displayed by using a 2D color table. Figure 19 shows a representative vertical slice through the seismic amplitude, vector dip, and vector convergence volumes for a survey acquired over the Central Basin Platform of Texas. Note the convergence of the sediments towards the southwest (in green) on the east side of the tilted fault block and the corresponding convergence towards the northeast (in magenta) on the west side of the reverse fault in Figure 19c. Figure 20 shows the same pattern shows on the time slice at 1.5 s through the three volumes.

Examples

Given the above definitions and display workflows, we can now examine how geometric attributes can be used to enhance geomorphological components present in 3D seismic data.

Structural Deformation

Coherence is routinely used to map faults. However, due to difficulties in seismic acquisition, shallow velocity heterogeneities, or difficult statics, the fault terminations are often smeared, such that coherence is not able to map them. In such situations, the correlation between curvature and coherence on the up- and down-thrown side of the faults can help delineate such features. Mai *et al.* (2009) provide a tutorial on how to integrate these complimentary attributes using a structurally complex data volume acquired in the Chicontepec Basin, Mexico. Figures 21 and 22 show the most-positive and most-negative principal curvatures co-rendered with the seismic amplitude. Note how curvature delineates not only the edges of the pop-up blocks but also the anticlinal and synclinal axes. Figure 23 shows the same vertical slice, but now with the reflector shape co-rendered with the seismic amplitude. Note how the ridge and valley shapes bracket the faults. Figure 24 shows the same vertical line, but now with a time slice at t=1.75 s, showing how one can track shapes associated with faults, synclines, and pop-up features laterally along the time slice.

Channels and differential compaction

One of the primary uses of seismic geomorphology is to couple images of channel, turbidite, and fan systems with an appropriate depositional model in order to predict sand-prone and shale-prone facies. Chopra and Marfurt (2008) present an example from Alberta, Canada of a distributary system that can be seen on coherence (Figure 25a). Differential compaction over this (shale-filled?) channel gives rise to most-negative principal curvature anomalies (Figure 25b). Co-rendering the two images (Figure 25c) adds a degree of confidence in using the most-negative principal curvature to extend our interpretation well beyond the discontinuities seen in the coherence image. The channel has become so thin that any discontinuity falls below the limits of seismic resolution. In contrast, the subtle valley-shaped deformation can still be tracked using most-negative principal curvature.

Figure 26 from Chopra and Marfurt (2010) shows the opposite case. In this image from a different Alberta, Canada survey, coherence again delineates the channel edges, but the channel axis is represented by a most-positive principal curvature anomaly. These structural highs are clearly seen on the vertical slice through the seismic amplitude volume (indicated by block yellow arrows), indicating that the channel fill has undergone less differential compaction than the matrix through which it was cut, an indication that it may be sand- rather than shale-filled.

Carbonate buildups

Carbonate buildups are well-suited to analysis using geometric attributes. The Diamond-M field within the Horseshoe Atoll of west Texas has produced for over 40 years. Even with tight well spacing, adjacent wells often have differing oil/water contacts with new wells sometimes encountering version pressure. One of the objectives is to map compartments within the buildup which is an amalgamation of many small pinnacle reefs. Figure 27 shows a time slice at t=0.910 s through a shape index modulated by curvedness volume. The 2D color bar is identical to that used in previous reflector shape images. A portion of the interpreted surface of the top of the buildup pokes through the time slice. Block arrows indicate selected dome, ridge, and bowl features shown on this time slice.

Figure 28 shows the same data volume and top buildup surface, but now with a time slice at t=0.970 s. Note the excellent correlation between the previously selected arrows and the hand-interpreted surface. Since the reflector shape is a volumetric computation, it is possible to map potential pinnacle reefs (dome-shaped features) internal to the buildup that are not mapped by a single hand-interpreted surface.

Progradation and pinchouts

Moving shallower, above the carbonate buildup, we recognize a progradational wedge westward into the basin. Figure 29 shows vertical slices through the seismic amplitude volume and a time slice at t=0.700 s through the coherence, co-rendered with the reflector convergence attribute described earlier. Reflector convergence is displayed using a 2D color bar, with the azimuth of the convergence plotted against hue, and with the degree of convergence plotted against lightness, with the convergence of parallel reflectors being displayed as white. On the vertical slices, there is strong convergence at t=0.580 s indicated by the yellow dotted line, which will be shown in Figure 30. On the time slice at t=0.700 shown in Figure 29, the convergence is somewhat weaker, and appears to represent sediment flow that is spreading away from (or converging towards) the coherence anomaly which might represent a channel system. The eastern-most vertical slice appears to show a scoured surface at t=0.580 s where the reflector convergence is strongest.

The time slice on Figure 30 cuts very close to the platform edge of the progradational wedge. The coherence measures show that this deposition is quite chaotic, with both horizontal discontinuities, associated with channelization and mounds, and vertical discontinuities, associated with erosional surfaces and pinch outs. The convergence is updip, towards the north-northeast (magenta), southeast (orange) and south (yellow). The color rendition of the convergence is more clearly seen on Figure 31, which is the same image without the co-rendered coherence. On an interactive workstation, one would simply animate between the two images and roll through a suite of vertical lines to better understand the geometries.

Limitations and Pitfalls

Seismic attributes are extremely effective in enhancing subtle features that may not be readily visible in good-quality seismic data volumes. Unfortunately, seismic attributes also exacerbate subtle noise that may be in the seismic data. One of the most common artifacts "enhanced" by seismic attributes is acquisition footprint, illustrated by a conventional picked surface and corresponding azimuth shown in Figure 32. Note the N-S trending lineaments that could mask or misinterpreted as faults or fractures.

Seismic data also suffer from limitations in the signal-to-noise ratio. Care must be taken in seismic processing not to consider any incoherent signal to be "noise". I like to differentiate "seismic noise", which may include backscattered ground roll, multiples, misaligned statics, and operator aliasing, from "geologic noise", which may include mass-transport complexes, collapse features, stacked channels, and carbonate buildups – features that may appear to be "chaotic" to an inexperienced seismic processor. Ideally, the seismic processor would design a workflow that suppresses the seismic noise and preserves the geologic noise.

I like to use multiattribute rendering as a means emphasizing the significance of a given measurement, as illustrated by the weighting of the shape index by the curvedness, or the strike of a given lineament by the strength of that lineament shown in many of the previous figures. Attributes can organize seismic noise. By construction, we compute dip-magnitude, dip-azimuth, and curvature values at every sample in our seismic volume, independent of the seismic amplitude and signal-to-noise ratio. The white block arrows in Figure 33 show several most-positive curvature anomalies that may be interpreted to be meaningful. In Figure 34 I use transparency to co-render the coherence attribute over the same area. This image leads me to have much less confidence in the previous curvature lineaments.

Finally, many of our seismic images have been time-migrated rather than depth-migrated. The well-known fault shadow effect (e.g. Trinchero, 2000) will often result in a doubled coherence discontinuity (Figure 35). Lateral changes in velocity of the overburden will cause artificial time structures that do not exist in depth. Figures 36 and 37 show a representative vertical slice through the seismic amplitude and horizon slices along the basement through the coherence and the most-positive principal curvature volumes computed from pre-stack depth-migrated and pre-stack time-migrated-data volumes of a Fort Worth Basin survey acquired 50 km away from that shown in Figures 1. In the pre-stack depth-migrated images (Figure 36), we note a strong basement high that is well-delineated by the most-positive principal curvature volume. Careful velocity analysis showed that the fast Ellenburger limestone had significant lateral changes in thickness, resulting in velocity pull-up of deeper basement structures that produced a pre-stack time-migrated image that was nearly flat, removing the structural high, resulting in a more subdued positive curvature anomaly and low-coherence anomaly associated with poor imaging (Figure 37).

Conclusions

By enhancing subtle structural and depositional components from 3D seismic volumes, geometric attributes can both facilitate and accelerate the application of seismic geomorphology to a greater number of surveys. Combining mathematically independent attributes sensitive to the same geologic feature through 3D visualization provides a quick, interactive clustering workflow, and allows one to extend the interpretation beyond that of the “best” attribute for a given task.

Seismic attributes are only as good as the seismic data to which they were applied. Improvements in bandwidth, lateral resolution, routine depth migration, and suppression of seismic artifacts will result in improved attribute images.

The use of seismic attributes in seismic geomorphology is still in its infancy. While there are many published examples of the attribute expression of fluvial-deltaic and turbidite systems, karsting, salt and shale diapirism, and complex faulting, a good representation of carbonate buildups, dewatering features, and gas pockmarks, there are few published examples on the attribute expression of injectites, volcanic dikes, fractured basement, buried topography, and gas hydrates. In short, we need to improve our library of examples to facilitate the pattern recognition process.

As we move from exploration to resource plays, the shape of seismic interpretation will continue to expand. I conclude this paper with an example of a gas shale play from the Fort Worth Basin, Texas. Figure 38a shows a phantom horizon through the most-positive principal curvature, k_1, 10 ms above the base of the Barnett Shale reservoir. This reservoir has been extensively hydraulically fractured by several hundred vertical and horizontal wells. The resulting induced fractures, coupled with the resulting horizontal stress regime, give rise to the seismic anisotropy displayed in Figure 38b. Co-rendering these two images, we note that the curvature ridges clearly delineate what we interpret to be fracture compartments. The cause and the economic implications of such a phenomenon is at present unclear. What is clear is that we need to keep our interpretation skills in shape to address such challenging problems.

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Table of Figure Captions

Figure 1. Representative vertical lines through a seismic amplitude volume and a time slice at *t* = 1.2 s at the approximate Ellenburger horizon through a corresponding coherence volume. Low coherence elliptical features such as that indicated by the yellow arrow are collapse features. Linear features are such as those indicated by the magenta and green arrows are faults. (Data courtesy of Devon Energy).

Figure 2. (a) A quadratic surface with the normal, n, defined at point *P*. The circle tangent to the surface whose radius, *R*, is minimum defines the magnitude of the maximum curvature, $|k_{max}| \equiv 1/R_{min}$ (in blue). For a quadratic surface, the plane perpendicular to that containing the previously defined blue circle will contain one whose radius is maximum, which defines the magnitude of the minimum curvature, $|k_{min}| \equiv 1/R_{max}$ (in red). Graphically, the sign of the curvature will be negative if it defines a concave surface and positive if it defines a convex surface. For seismic interpretation, we typically define anticlinal surfaces as being convex up, such that k_{max} has a negative sign and k_{min} has a positive sign in this image. (After Mai et al., 2009).

Figure 3. The same view as shown in Figure 1, but now through the most-negative principal curvature, k_2, volume. Note the network of lineaments seen on the time slice. The arrows are in the exact same location. Note the bright blue (strong negative curvature) anomaly over the collapse features such as that indicated by the yellow, that occur at the intersection of these lineaments. Note the curvature anomaly associated with the E-W trending fault indicated by the magenta arrow is displaced to the North (downdip) from the corresponding coherence anomaly. (Data courtesy of Devon Energy).

Figure 4. Co-rendered vertical slices through most-negative principal curvature and seismic amplitude and the time slice at t = 1.2 s. through most-negative principal curvature and coherence. Note the correlation of the strong negative curvature and low coherence anomalies over the collapse features such as that indicated by the yellow arrow. Note the lateral displacement between the curvature and coherence anomalies along the faults (magenta and green arrows). (Data courtesy of Devon Energy).

Figure 5. The same view as the previous figure, but now through the most-positive principal curvature, k_1, volume. Note the network of lineaments seen on the time slice. The arrows are in the exact same location as in the previous images. The bright blue (strong negative curvature) anomalies correlate to the collapse features, such as that indicated by the yellow arrow, and are surrounded by circular positive curvature anomalies that outline the edges of the collapse features. The curvature anomaly associated

with the NE-SW trending fault indicated by the green arrow is displaced to the North (updip) from the corresponding coherence anomaly. (Data courtesy of Devon Energy).

Figure 6. Co-rendered vertical slices through most-positive principal curvature and seismic amplitude and the time slice at t = 1.2 s. through most-positive principal curvature and coherence. Note the correlation of the strong negative curvature and low coherence anomalies over the collapse features such as that indicated by the yellow arrow. Note the magenta fault lies downdip from a parallel positive curvature anomaly to the south, as seen on the vertical section through the seismic amplitude data. Data courtesy of Devon Energy).

Figure 7. Co-rendered vertical slices through most-positive and most-negative principal curvatures and seismic amplitude and the time slice at t = 1.2 s. through most-positive and most-negative principal curvatures and coherence. Note the correlation of the strong negative curvature and low coherence anomalies over the collapse features such as that indicated by the yellow arrow. Note the faults indicated by the magenta and green arrows are bracketed by curvature anomalies which can be seen on the eastern vertical slice through seismic amplitude. (Data courtesy of Devon Energy).

Figure 8. The definition of 3D quadratic shapes expressed as a function of the most-positive and most-negative principal curvatures, k_1 and k_2, through the shape index, $s=-(2/\pi)ATAN[(k_2+k_1)/(k_2-k_1)]$. By definition, $k_1 \geq k_2$. The curvedness, $C=[k_1^2+k_2^2]^{1/2}$. For values of $k_1=k_2=0$, the curvedness, $C=0$, the shape index, s, is undefined and we have a plane. If the shape index, $s=-1.0$, we have a bowl, if $s = -0.5$, we have a syncline, if $s = 0.0$, we have a saddle, if $s = +0.5$, we have an anticline, and if $s = +1.0$, we have a dome. (Figure modified from Bergbauer et al., 2003; redrafted by Ha Mai).

Figure 9. Multiattribute display of the shape index, *s*, modulated by the curvedness, *C*. Bowl-shape collapse features appear blue (yellow arrow). The fault indicated by the magenta arrow appears as cyan (a valley) juxtaposed to yellow/orange (ridges). (Data courtesy of Devon Energy).

Figure 10. Multiattribute display of the shape index, *s*, modulated by the curvedness, *C*, co-rendered with seismic amplitude on the vertical slices and coherence on the time slice at $t = 1.2$ s. Note the correlation of the reflector shape attribute with the structure seen on the vertical slices through the seismic amplitude. The coherence images are mathematically independent and complementary to the reflector shape attribute , allowing us to make a more confident interpretation. (Data courtesy of Devon Energy).

Figure 11. A raised-cosine filter applied to the shape index, in this case about s=--1.0, allowing one to quantify those structural features that are most like a bowl.

Figure 12. The bowl component of structural shape co-rendered with seismic amplitude on the vertical slices and coherence on the time slice at t=1.2 s. The bowl component has strong values over the collapse features and near zero values elsewhere, allowing them do be used in neural network or geostatistical analysis. (Data courtesy of Devon Energy).

Figure 13. 3D visualization of the bowl component. Note the collapse features at the Ellenburger level continue as bowl-shape features up to the Atoka formation which lies just below the strong Cretaceous Caddo horizon in this image. These bowls formed accommodation space for deposition of sands and and gravels during Atoka time. (Data courtesy of Devon Energy).

Figure 14. Multiattribute display using an HLS color model. (a) Illustration of the strike of most-negative principal curvature, ψ_{k2} . (b) A 2D color table that modulates the value of the strike of the anomaly (plotted against hue) and the strength of the anomaly (plotted against lightness). (Modified after Mai et al., 2009).

Figure 15. Multiattribute display of the strike of the minimum curvature, ψ_{k2}, modulated by the strength of the most-negative principal curvature, k_2, using the color bar shown in Figure 14b. The strength of the minimum curvature is displayed in Figure 3. Note the E-W trending fault indicated by the magenta arrow is displayed as yellow-red, while the NE-SW trending fault (green arrow) appears as magenta. The collapse features occur at the intersection of different joints. (Data courtesy of Devon Energy).

Figure 16. Multiattribute display of the strike of the minimum curvature, ψ_{k2}, modulated by the strength of the most-negative principal curvature, k_2, using the color bar shown in the previous figure, co-rendered with seismic amplitude on the vertical slices and coherence on the time slice at t = 1.2 s. Note the E-W trending fault indicated by the magenta arrow is displayed as yellow-red, while the NE-SW trending fault (green arrow) appears as magenta. The collapse features occur at the intersection of different joints. (Data courtesy of Devon Energy).

Figure 17. Volumetric display (1.0 5 s < t < 1.2 s) of the strike of the most-negative principal curvature, ψ_{k2} , displayed such that the weaker values of k_2 are rendered transparent. (Data courtesy of Devon Energy).

Figure 18. Volumetric display (1.0 5 s < t < 1.2 s) of the rose diagrams generated from data shown in the previous image using a 2200 ft by 2200 ft by 10 ms analysis window. (Data courtesy of Devon Energy).

Figure 19. A representative line through (a) the seismic amplitude volume showing the Delaware Basin on the left, and the Midland Basin towards the right. (b) Vector dip-azimuth, and (c) vector convergence for

the same line co-rendered with the seismic amplitude. Note the excellent correlation between the reflector convergence attribute with the onlap and offlap images seen in the seismic amplitude. (After Marfurt and Rich, 2010; data courtesy of Burlington Resources).

Figure 20. Time slices at *t*=1.5 s through (a) coherence, (b) vector dip-azimuth, and (c) vector convergence. (b) and (c) are co-rendered with coherence. Red arrow indicates an angular unconformity, yellow arrow a reverse fault, green arrow a strike-slip fault, and orange arrows two antithetic faults. Note the convergence of reflectors to the west (green) on the eastern side of the tilted fault block. (After Marfurt and Rich, 2010 ; data courtesy of Burlington Resources).

Figure 21. Images from a survey acquired over the Chicontepec Basin, Mexico. Seismic amplitude co-rendered with most-positive principal curvature, k_1. Strong positive and negative values of k_1 are rendered more opaque, while values closer to zero (representing planar features, are rendered transparent. Note the excellent alignment of the curvature anomalies with flexures seen on the vertical seismic amplitude data. (After Mai et al., 2009; data courtesy of PEMEX).

Figure 22. Seismic amplitude co-rendered with most-negative principal curvature, k_2. Strong positive and negative values of k_2 are rendered more opaque, while values closer to zero (representing planar features, are rendered transparent. Note the excellent alignment of the curvature anomalies with flexures seen on the vertical seismic amplitude data. (After Mai et al., 2009; data courtesy of PEMEX).

Figure 23. Seismic amplitude and coherence plotted against a gray scale co-rendered with the shape index , *s*, plotted against hue and the curvedness, *C* , plotted against lightness using a 2D color bar. All shape values are plotted as 50% opaque while coherence uses the opacity shown in an earlier image. Note the correlation of ridge (yellow-brown) and valley (cyan and blue) features with coherence anomalies allowing us to better map the edges of the diverse fault blocks and the axial planes of the pop-up features. (After Mai et al., 2009; data courtesy of PEMEX).

Figure 24. Same vertical slice and attribute as shown in the previous image, but now with a time slice at *t*=1.75 s. The coherence volumes suffer from artifacts due to difficult acquisition and shallow volcanic intrusives. In contrast, the longer-wavelength curvature images provide an excellent representation of the structural deformation. (After Mai et al., 2009; data courtesy of PEMEX).

Figure 25. Stratal slices through (a) coherence, (b) most-negative principal curvature, and (c) a co-rendered image of the two attributes showing an incised channel in Alberta, Canada. Note how the co-rendered version provides confidence that the most-negative principal curvature is mapping valley-

shaped channel axes, allowing one to map the distributary system into areas where the channels are so thin that they no longer give rise to a lateral discontinuity. (After Chopra and Marfurt, 2008; data courtesy of Arcis).

Figure 26. Stratal slices through (a) coherence, (b) most-positive principal curvature, and (c) a co-rendered image of the two attributes showing an incised channel in Alberta, Canada. Note how the co-rendered version provides confidence that the most-positive principal curvature is mapping ridge-shaped channel axes, allowing one to predict that this channel is sand-filled and appears as a structural high after differential compaction. Block arrows indicate structural highs seen on the vertical slice through the seismic amplitude volume. (After Chopra and Marfurt, 2010; data courtesy of Arcis).

Figure 27. Time slice at t=0.910 s through the shape index modulated by curvedness volume computed for a survey over the Diamond-M field of Horseshoe Atoll, west Texas. Red features indicate local dome features, which are correlated to the location of pinnacle reefs. Arrows indicate some of the computed shapes. White arrow indicates part of a time-structure map showing the interpreted top of the carbonate buildup (Data courtesy of Parallel Petroleum LLC).

Figure 28. Time slice at t=0.970 s through the shape index modulated by curvedness volume shown in the previous figure. Note the strong correlation of the shape shown on the time structure map and the shaded relief map of the interpreted horizon. (Data courtesy of Parallel Petroleum LLC; interpretation by Roderick Perez, OU).

Figure 29. Vertical slices and time slice at *t*=0.700 s through the reflector convergence volume computed for a survey acquired over Diamond M Field, Horseshoe Atoll, Texas. Arrows indicate pinchouts towards the southeast (orange), south (yellow), north-northeast (blue, northeast (purple) and south-southwest (green). North arrow is in the lower right corner of the figure. Note the sediments prograding westward into the basin on the southern vertical slice. The dotted yellow line indicates the level of the time slice at t=0.580 s shown in the following figure. (Data courtesy of Parallel Petroleum LLC).

Figure 30. Vertical slices through seismic amplitude and time slice at *t*=0.580 s through the reflector convergence volume co-rendered with coherence. The coherence overlay shows that much of this sedimentation is episodic, with both lateral and vertical discontinuities. At this level most of the sediments are converging towards the east-northeast (magenta), southeast (orange) and south (yellow) which correlates well with the progradation sequence seen on the south vertical slice through the seismic amplitude volume. (Data courtesy of Parallel Petroleum LLC).

Figure 31. The same image but without co-rendering with coherence to better show the convergence azimuth. At this level most of the sediments are converging towards the east-northeast (magenta), southeast (orange) and south (yellow) which correlates well with the progradation sequence seen on the south vertical slice through the seismic amplitude volume. (Data courtesy of Parallel Petroleum LLC).

Figure 32. (a) A time-structure map of a horizon picked from a "vintage" 3D survey on the shelf of the Gulf of Mexico, and (b) its corresponding azimuth. Note the strong N-S trending footprint associated with narrow-azimuth acquisition and either migration stretch or migration operator aliasing. (Data courtesy of Schlumberger).

Figure 33. Two representative vertical slices and a time slice at t =1.3 s through the seismic amplitude volume co-rendered with the most-positive principle curvature, k_1, for a survey acquired on the shelf of the Gulf of Mexico. White block arrows indicate curvature features that are difficult to interpret. (Data courtesy of PGS).

Figure 34. The same image shown in the previous figure, but now co-rendered with coherence. Note that complex, difficult-to-interpret features indicated by the white block arrows in the previous figure lie within the low-coherence salt diapirs, and are therefore probably due to noise that has leaked through the processing flow. (Data courtesy of PGS).

Figure 35. (a) 3D perspective of vertical slices through a seismic amplitude volume and a time slice at t = 1.5 s through a coherence volume showing the fault shadow effect. (b) The same time slice with the block yellow arrow indicating the fault shadow. (After Lewis, 2008).

Figure 36. Pre-stack depth migrated (a) vertical section through the seismic amplitude volume along line BB' and (b) horizon slices along the basement through the corresponding coherence and k_1 most-positive principal curvature volumes. Yellow arrows indicate the top of the Cretaceous Caddo, Cambro-Ordovician Ellenburger, and Basement horizons. Orange arrows indicate positive curvature anomalies associated with a basement high. This structural high appears as a relatively high coherence zone. (After Aktepe et al., 2008).

Figure 37. Prestack time-migrated (a) vertical section through the seismic amplitude volume along line BB' and (b) horizon slices along the basement through the corresponding coherence and k_1 most-positive principal curvature volumes. Orange arrows indicate the location of the depth-migrated structural high.

In this time-migrated image, the curvature anomaly is muted and a coherence discontinuity appears. (After Aktepe et al., 2008).

Figure 38. Phantom horizon slice 10 ms above the base of the Barnett Shale from a survey acquired in the Fort Worth Basin, Texas through (a) most-positive principal curvature, $_{k1,}$ (b) azimuthal anisotropy measured from the prestack data, and (c) co-rendering of the two images. Note how the structural ridges appear to control the azimuth of fractures (and/or the stress regime) following hydraulic fracturing. (After Zhang et al., 2010; data courtesy of Devon Energy).