Unconventional seismic attributes for fracture characterization

Hardeep Jaglan[1*], Farrukh Qayyum[1] and Hélène Huck[1] **introduce several new geometrical attributes that help in characterizing fault networks, fractures density and their connectivity.**

Faults and fractures are generally represented as discontinuous reflection patterns on seismic data and mostly appear as linear, sub-linear or curvilinear features in three dimensions. In seismic interpretation faults are routinely detected through multi-trace seismic attributes such as coherency, similarity, semblance, variance, curvature, dip, azimuth, etc. These attributes are often grouped as geometrical attributes because they mostly help in defining the geometrical nature of seismic reflections.

The objective of this paper is to introduce several new geometrical attributes that help in characterizing fault networks, fractures density and their connectivity. The proposed attributes are derived after specialized workflows based on a precomputed dip-azimuth volume. These attributes are referred as unconventional fracture attributes because they are new and not routinely applied to fault detection and characterization.

A dip-azimuth volume forms the heart of the workflow (Figure 1). It is computed in a sub-volume level to obtain local dips of seismic reflectors and associated discontinuities. This volume is also known as *SteeringCube* and is computed based on various algorithms. Generally, two types of algorithms are popular in extracting seismic dip and azimuth information. (1) A phase-based dip calculation utilizes seismic phase attribute. (2) A FFT (Fast Fourier Transformation) based algorithm that utilizes seismic frequency and amplitude attributes. We always prefer phase-based dip calculation for structural interpretation and frequency/amplitude based dip calculation for stratigraphic purposes.

Once a SteeringCube is prepared, the conventional attributes can be modified and redefined along the dip and azimuth information. This makes most of the multi-trace seismic attributes dip-steered. The dip-steered attributes always have an advantage over the non-steered attributes because they represent more geological pictures of the subsurface rather than artefacts. The SteeringCube has further applications in data enhancement and in the preparation of dip-steered filters on the seismic data. These filters are applied in a sequential manner to obtain a final cube that is most representative of faults and fractures rather than stratigraphy. Following this, the conventional attributes are recalculated and are further optimized to obtain a fault/fracture cube. The fault cube (such as similarity, curvature and fault likelihood) is then treated through various new fracture attributes (fracture proximity, fracture density, fracture gradient and fracture azimuth) to perform interpretation, which are the core parts of this paper.

Once an end product is prepared, it is further visualized through a voxel connectivity filter to produce the three dimensional nature of the fault network and perform interpretation. This is a crucial part of the proposed workflow that produces an easy to interpret volume with ranked (numbered) geobodies. It opens the ways for interpretation such as fault connectivity vs. permeability, open vs. close fault networks, fracture density, etc. The following sections further define and explain the entire workflow in detail.

Seismic scale faults/fractures

It is important to understand the defining criteria of faults and fractures on the seismic data. A fault is generally defined on seismic data if there is a vertical displacement for a given seismic reflector. Such a vertical displacement can easily be identified through multi-trace correlation. On the other hand, seismic dispersion, scattering, diffraction and other similar noises may impact on such correlations and final results.

It is well-known that the conventional seismic data contains many pitfalls and, due to improper acquisition and/or processing, the imaging of geological faults and their patterns may often not reflect the true picture of the subsurface. Specialized pre-stack processing steps are required to preserve all structural components in the data. For structural interpretation, beam migration in depth domain is considered as an optimum choice compared to the traditional Kirchhoff migration algorithm.

This is especially relevant for cases where multiple arrivals need to be considered in the presence of steeper dips (Ben-Brahim et al., 2009). Such situations routinely occur in subsalt settings at large depths or basement faults. Alai et al. (2014) showed the significance of seis-mic attributes in characterizing basement fracture reservoirs by presenting several case studies. Their work was followed

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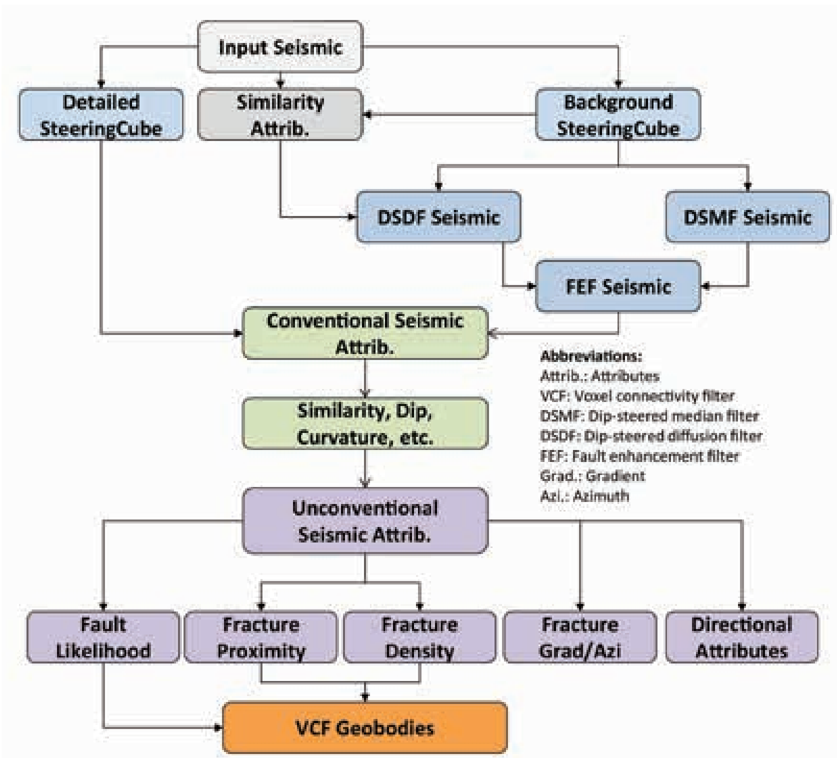

Figure 1 *A flow chart to create the proposed unconventional fracture attributes and eventually 3D fracture geobodies from post-stack seismic data.*

by testing the cases through wells, which was found positive. A relatively modern processing technique of 5D interpolation is also emerging (Trad, 2009) and helps to remove artefacts (e.g., acquisition footprints) caused by suboptimally sampled data during geometrical attribute computations (Chopra and Marfurt, 2007). 5D interpolation also addresses the need of regularly sampled azimuths and offsets required by AVAZ analysis and pre-stack inversion.

In theory, a stress field is defined by three principal stress components, which are oriented perpendicular to each other. The magnitudes and orientations of these three principal stresses are governed by the tectonic regime in the region and by depth, pore pressure and rock properties. These parameters control how stress is transferred and distributed in the sub surface, and consequently the orientation and propagation direction of fractures.

In order to perform quantitative fracture interpretation using seismic data, one has to understand that conventional seismic data do not contain such information unless it is adequately acquired in various azimuth and processed accordingly. Faults and fractures are conceptualized as horizontal transversely isotropic (HTI) media (Sengupta and Bachrach, 2006) which are mathematically expressed by Ruger (1997). Ruger suggested linearized approximations to the Zoeppritz equation for estimating HTI anisotropy parameters from azimuthal seismic P-wave data. This AVAZ (Amplitude vs. Azimuth) analysis eventually enables quantification of fracture density and their orientation.

$$R_{ani}(\theta,\Phi)=A_{iso}+(B_{iso}+B_{ani}\cos^2\Phi)\sin^2\theta + (C_{iso}+C_{ani}\cos^2\Phi)\sin^2\theta\tan^2\theta$$

A_{iso}, B_{iso}, and C_{iso} are isotropic terms;

$$B_{ani}=\frac{1}{2}[\Delta\delta^V+\frac{1}{8}(\frac{V_S}{V_D})^2\Delta\gamma] \text{ and } C_{ani}=\frac{1}{2}[\Delta\delta^V\sin^2\Phi+\Delta\varepsilon^V\cos^2\Phi]$$

are the HTI anisotropy terms;

θ = incidence angle, Φ= azimuth angle, δ^V = Thomsen's δ (delta) parameter relative to vertical, ε^V = Thomsen's ε (epsilon) parameter relative to vertical, γ = Thomsen's gamma parameter

Another sophisticated method requires multi-component seismic data to analyse shear wave polarization that occurs in HTI media. It can be a powerful method of characterizing anisotropy, fracture orientation and intensity (Bale et al., 2009).

In most cases, geoscientists are left with the conventional seismic data, particularly in exploration projects. The requirements of rarely acquired multi-azimuth or multi-component seismic data, limits the usage of the two aforementioned methods. This is where a number of geometrical seismic attributes come into play that can be explored for fault network delineation and fracture analysis.

Data conditioning

Post-stack seismic data is typically a combination of noise and signal. Broadly speaking, the seismic signal may correspond to continuous or discontinuous reflectors; both may or may not reflect geology. In our experience, it is found that conventionally processed seismic data is mostly far less than perfect for seismic interpretation. Hence, mostly a set of data conditioning techniques are used and some of these (also used in this paper) are explained below.

Frequency filtering

Prior to any step, the first goal is to prepare input seismic data such that they do not show frequency related noise. This can be achieved during pre-stack or post-stack seismic processing. A common approach is to apply a frequency (e.g., a band-pass) filter to adjust the bandwidth of the data by minimizing the frequency related noises. Such a filter helps to minimize the noise related to higher frequencies, multiples, or energy dissipation.

In other cases, often the higher frequencies are boosted-up by applying a specialized technique as explained by Blache-Fraser and Neep (2004); and Kazemeini et al. (2008). Such a technique matches the reflectivity spectra obtained from well and seismic data. Only those frequencies are enhanced that lie within the bandwidth of the seismic data. As a result a convolution operator is designed that is convolved with the input seismic data to enhance the frequency contents. This approach often improves the faults definition.

Dip extraction

Dip computation is a crucial part of the workflow as it influences both the post-stack seismic filtering as well as the seismic attribute results. Seismic dips can be computed using various methods: amplitude-based, phase-based, amplitude-frequency based etc. (Tingdahl and de Rooij, 2005; Chopra and Marfurt, 2007).

These methods operate on post-stack seismic data. Phase-based dip computation is used in this paper. The calculation and filtering parameters for the dip estimation are optimized through a series of experiments. The final dip volume is processed in the entire 3D seismic at every sample position.

This volume is used as an input for structural oriented filtering and dip-steered seismic attributes and is hereinafter referred to as the 'SteeringCube'. The tool can be filtered either locally or regionally according to the objective of the study and data quality. A heavily filtered one is informally referred as a background SteeringCube because it helps in defining overall dip trends of seismic reflectors. This volume has more applications in data enhancement and attribute calculation. A mildly filtered one is informally referred to as a detailed SteeringCube because it helps in defining local dips of seismic reflectors. Such a volume is mostly used for detailed attribute analysis and is not recommended for data enhancement.

Structural oriented filtering

It is essential to start with seismic data on which the faults and fracture features can be sharply defined. To obtain such a goal, the seismic data is routinely pre-processed and conditioned. There are three main steps performed to condition the seismic data and produce a final volume for faults and fractures interpretation.

1. The smoothing of seismic reflectors through dip-steered median filtering.
2. The enhancement of fault positions through dip-steered diffusion filtering.
3. The merging of the first two steps through a logical statement to produce a fault enhanced seismic data.

These filters are further described below:

Dip-steered Median Filter (DSMF): This is a statistical filter that is applied on the seismic data using a pre-processed SteeringCube. It uses median statistics on the seismic amplitudes by following the seismic dips. It results in a smoothed seismic volume such that the continuity of seismic reflectors is improved by removing the background random noise. It is often considered as an edge preserving smoothing filter if a fault zone is larger than the median filter size. However, if a fault zone is smaller than the size of a median filter, the data will be smoothed out. Hence, additional filters may be required to sharpen the fault zones as described below.

Dip-steered Diffusion Filter (DSDF): Mostly, the seismic data show diffused character close to a fault zone. If pre-stack processing is not optimized for the faults, a fault zone may not be sharply defined on the seismic data. To improve the sharpness of the faults, one may apply an intermediate filter that is referred to as a DSDF. This filter evaluates the quality of the seismic data in a dip-steered circle. The central amplitude is replaced by the amplitude where the quality is deemed best. In the vicinity of a fault, the effect is such that good quality seismic

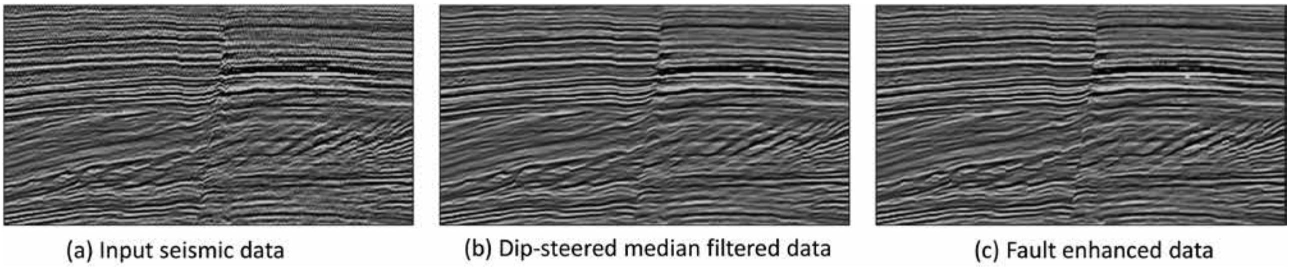

***Figure 2** Inline from F3 block of the Dutch sector of North Sea showing (a) raw seismic data, (b) dip-steered median filtered (DSMF) seismic data and (c) seismic data after application of fault enhancement filter (FEF).*

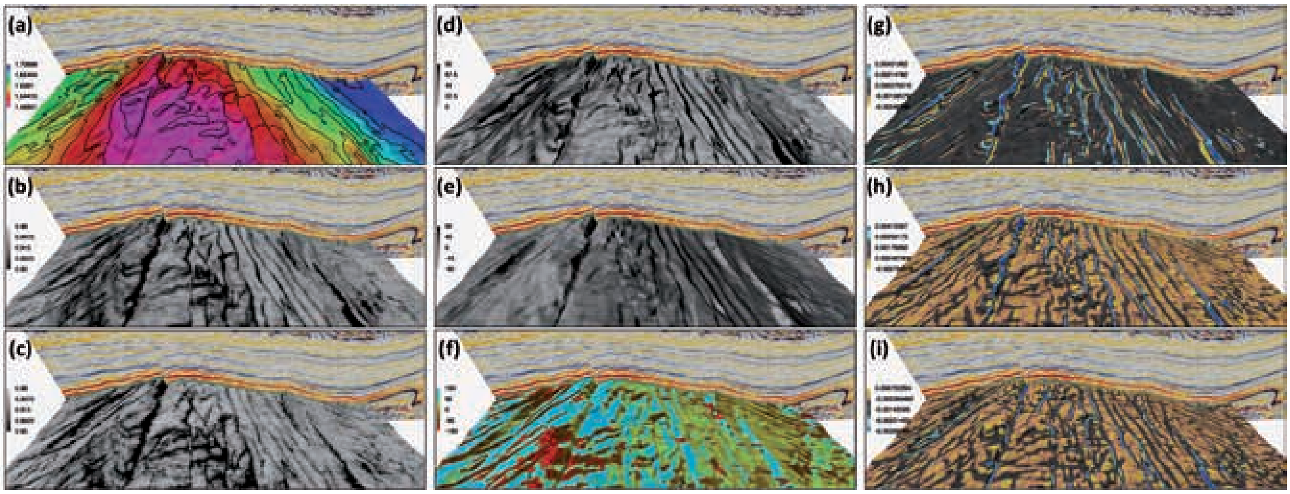

Figure 3 Examples of various conventional fracture attributes are shown using the F3 dataset from North Sea: (a) Base Tertiary horizon with seismic time (ms) contours, (b) similarity computed using raw seismic, (c) similarity computed using FEF seismic data which shows sharp fault patterns. (d) Polar dip, (e) apparent dip along 45 degree azimuthal direction and (f) azimuth attributes are similar to the similarity attribute with an added dip/azimuth information. The curvature attributes such as (g) maximum (h) most positive and (i) most negative curvatures show the sense of fault throw (upthrown and downthrown sides). The maximum curvature attribute has an edge over others and it shows simultaneously both directions with different colours (signs). In our experience, the attributes such as 'c' and 'g' are superior for fracture detection and candidate inputs for unconventional fracture attributes.

data is moved from either side of the fault in the direction of the fault plane, hence the fault becomes sharper.

Fault Enhancement Filter (FEF): This filter is produced by applying a logical expression on the earlier produced volumes (DSMF and DSDF). It also requires a seismic attribute that highlights discontinuities e.g., similarity (recommended) or curvature. Based on a cut-off value, a logical expression is prepared such that shows reflectors and faults in one seismic volume. For instance, if the similarity attribute is used, the values below a cut-off may correspond to discontinuities and above a cut-off may correspond to continuities. The resultant fault enhanced seismic data is thereafter used as an input for seismic attributes. The attribute mostly shows sharper definition of faults and hence improves the visualization and interpretation.

Figure 2 shows the comparisons between raw seismic, DSMF seismic and FEF seismic on an example inline from the F3 block of the Dutch sector of the North Sea. This F3 dataset is used throughout the paper to create various example figures.

Dip steered attributes

Conventional fracture attributes

Similarity and its equivalents:
The lateral correlation between waveforms along a given reflection can be measured by computing the euclidean distance between the amplitude vectors representing the waveform. This operator is often referred to as a similarity measurement. Its computation provides a direct measurement of lateral discontinuities in the waveform. The attribute is very sensitive to phase changes, which makes it very useful when the waveforms are offsets because of vertical offsets due to fault throws. This attribute normally shows correlation strength between a number of waveforms in three dimensions. If the strength is 100%, it suggests that the traces are quite similar in their response. If the strength is below 60%, then the traces do not correlate properly, suggesting dissimilar waveforms, discontinuities or in other words faults and fractures. In our presented workflow, this attribute is also used as a defining criteria to differentiate faults from reflectors (as explained in FEF). Furthermore, it is notable that similarity attribute calculations made from fault enhanced seismic are better than the raw seismic.

Dip-Azimuths:
The seismic dip and azimuth attributes natively represent a SteeringCube.

Polar Dip: This attribute converts extracted inline and crossline dips to a true geological dip. The polar dip is the square root of the sum of (inline dip)^2 and (crossline dip)^2. The polar dip is thus larger or equal to zero. Dips are given in µseconds/metres in time surveys, since they are a ratio between a vertical length and a horizontal distance. Polar dip is a valuable attribute to explain how dipping is a fault plane when transformed in degrees using a seismic velocity volume.

Azimuth: This attribute returns the azimuth of the dip direction of seismic reflectors. It is often represented in degrees ranging from -180 to +180. Azimuth is typically defined relative to the seismic survey geometry/orientation. Positive azimuth is defined from the inline in the direction of increasing crossline numbers. Azimuth = 0 indicates that the seismic reflector at evaluation point is dipping in the direction of increasing cross-line numbers. Azimuth = 90 indicates that the seismic reflector at evaluation point, is dipping in the direction of increasing in-line numbers. Therefore, this attribute becomes useful to explain the orientation of fault networks. It can also be used to fine tune a volume by clipping the fault network to a specific azimuth range when used with logical expressions.

Curvatures:
Curvature analysis has been used for many years in the oil industry to detect geological features from the shape of the seismic reflections. Mathematical calculation of curvature is usually done by the least-square fitting of a quadratic surface:

$$z(x,y) = ax^2 + cxy + by^2 + dx + ey + f$$

A large variety of curvature attributes are described in the literature, e.g. Gaussian curvature, Mean curvature etc. (Roberts, 2001). However, the three most frequently used attributes for fracture detection are described here.

Most Positive Curvature: This attribute returns the most positive curvature at various points along the interpreted horizon, from the infinite number of normal curvatures that exist. The attribute reveals faulting and lineaments. The magnitude of the lineaments is preserved but the shape information is lost. This attribute can be compared to the first derivative-based attributes (e.g., dip, edge, and azimuth). It primarily amplifies anticlines and upthrow side of faults.

$$k_{pos} = (a+b) + [a-b)^2 + c^2]^{\frac{1}{2}}$$

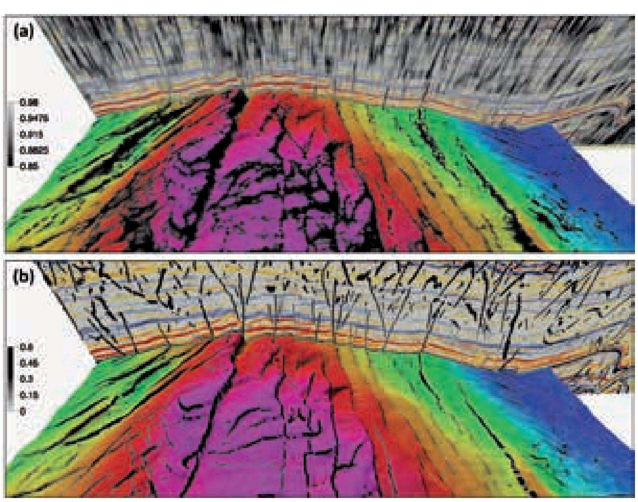

Figure 4 *A comparison of (a) similarity attribute computed using the FEF seismic against the (b) fault likelihood attribute. Clearly the fault likelihood attribute results in sharper and correctly outlined faults identification. Furthermore, note that the dip of the fault plane is also adequately captured by the fault likelihood attribute when compared with the similarity attribute result.*

Most Negative Curvature: This attribute returns the most negative curvature at various points along the interpreted horizon, from the infinite number of Normal Curvatures that exist. Similar to Most Positive Curvature, this attribute also reveals faulting and lineaments. Again, the magnitude of the lineaments is preserved but the shape information is lost. This attribute can also be compared to the first derivative-based attributes (e.g. dip, edge, and azimuth). It primarily amplifies synclines and downthrown side of faults.

$$k_{neg} = (a+b) + [a-b)^2 + c^2]^{\frac{1}{2}}$$

Maximum Curvature: From the infinite number of Normal Curvatures there exists one curve, which defines the largest absolute curvature of the surface. This is called the maximum curvature. The plane in which maximum curvature is calculated is orthogonal to the plane of the Minimum Curvature. This attribute is computed at various points along the interpreted horizon and is very effective at delineating faults and fault geometries. Maximum curvature is derived from Gaussian and mean curvatures. Figure 3 shows the examples of aforementioned attributes.

Unconventional fracture attributes
Fault Likelihood and Sharpness: Hale (2013) defines the fault likelihood as a power (for instance n= 8) of semblance (1–Semblance^n). However, this results into faults that have non-geological dips and strikes. Such information is obtained when the result is scanned for a given range of positive and negative dips to maximize the fault likelihood. This produces faults with true dips and strikes. Further filtering is performed to highlight only the local maxima within the fault likelihood volume to achieve a sharper fault plane. Fault likelihood has a value range from 0 to 1. We believe that Hale's contribution for fault extraction is a great attempt towards unconventional fracture attributes. We illustrate one example as a starting point towards fracture characterization (Figure 4).

Fracture Proximity: This attribute improves the visualization of potential fracture anomalies by revealing the connectivity of fracture networks, as well as the distance between them. It computes the lateral distance (i.e., along a Z-slice) of any trace in consideration from a trace location classified as a fracture. Whether a particular trace can be defined as being part of a potential fracture anomaly, is determined by a user-specified threshold, on various discontinuity attributes such as similarity or curvature. This attribute generally is a measure of a distance of hundreds of metres. For interpretation it is vital to understand the proximity to (and between) fracture zones; the lower attribute values suggest closeness to the centre of the fracture zone.

Fracture Density: This attribute is useful in pinpointing locations of maximum number of fractures within a given radius. This radius can theoretically be linked to a fracking

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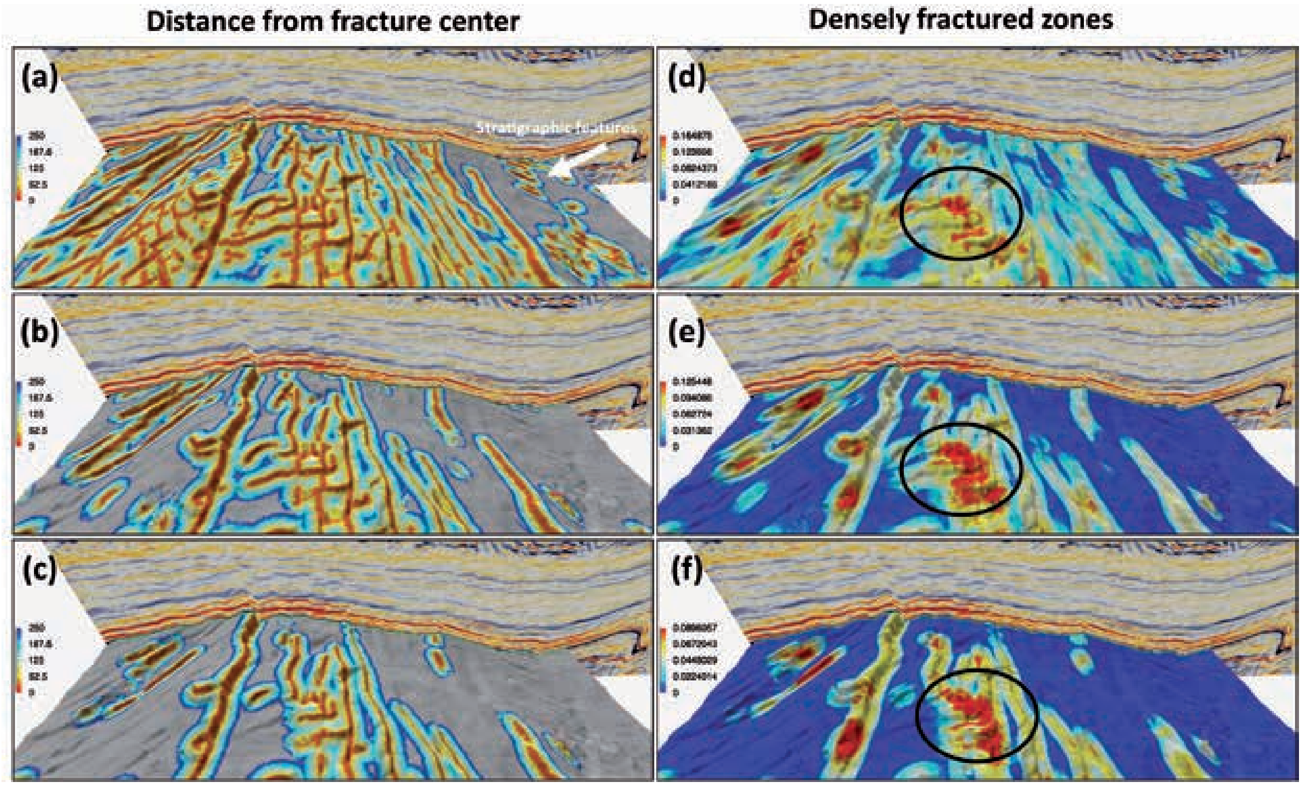

Figure 5 Fracture proximity computed by defining a fracture threshold of 0.2 on fault likelihood attribute in (a), 0.4 in (b) and 0.6 in (c). In addition to these threshold values, a radius of 250 m is used to calculate fracture density in (d), (e) and (f) respectively. Using the higher threshold of 0.6 results in the identification of the strongest fracture patterns while supressing the stratigraphic expressions (arrow).

radius for drilling a fractured reservoir. It computes the ratio of a 'number of seismic traces classified as being fractures' to the 'total number of traces present' in a given radius. This attribute directly highlights the regions with higher fracture density as sweet-spots for drilling. For other cases, such as geothermal energy or hydrocarbon traps, this attribute highlights the regions of higher risk or leakage for drilling. Figure 5 presents examples of fracture proximity and density attributes calculated using different thresholds on fault likelihood.

Fracture Gradient: It is another new dip-steered seismic attribute and is defined as a spatial derivative of fault cube using a SteeringCube. It is computed along all azimuths (i.e., 0 to 360 degrees) and the result is outputted along the direction where it is maximum. It requires a discontinuity attribute e.g., fault cube: dip-steered similarity using FEF data or max curvature as an input. The main advantage of this attribute is that a fault/fracture becomes prominent at the centre of the attribute response.

Fracture Azimuth: It is another dip-steered attribute and outputs the azimuth along the maximum value of a fracture gradient. It is a supplementary result to understand the fracture gradient and its orientation. Figure 6 shows fracture gradient and azimuth attributes applied on similarity from FEF seismic, maximum curvature and fault likelihood cubes.

Directional Attributes: The majority of multi-trace seismic attributes can be treated through a simple equation to obtain a (pseudo)-response in a given azimuthal direction. For such purposes, two gradients are pre-defined. One along the inline direction and the other one along the crossline direction. Once these gradients are extracted, we can use the following formula to derive directional attributes:

$$B\Phi = Attribute\ Gradient_{IL} cos(\Phi) + Attribute\ Gradient_{XL} sin(\Phi),$$

Φ= azimuth angle (referenced from true geographic north).

This technique provides new insights, as directional variations in certain attributes, could in theory, be linked with HTI anisotropy caused by fracture networks. An example of this attribute is presented in Figure 7.

Voxel connectivity filter (VCF)

Fault networks and fracture zones need to be visualized in three dimensions as geobodies. To understand their connectivity in 3D, one has to apply some advanced filters to produce bodies of faults and fractures. Voxel connectivity filter is one such filter. It produces continuous geo-bodies based on a fault cube. A 'voxel' is defined as the small 3D

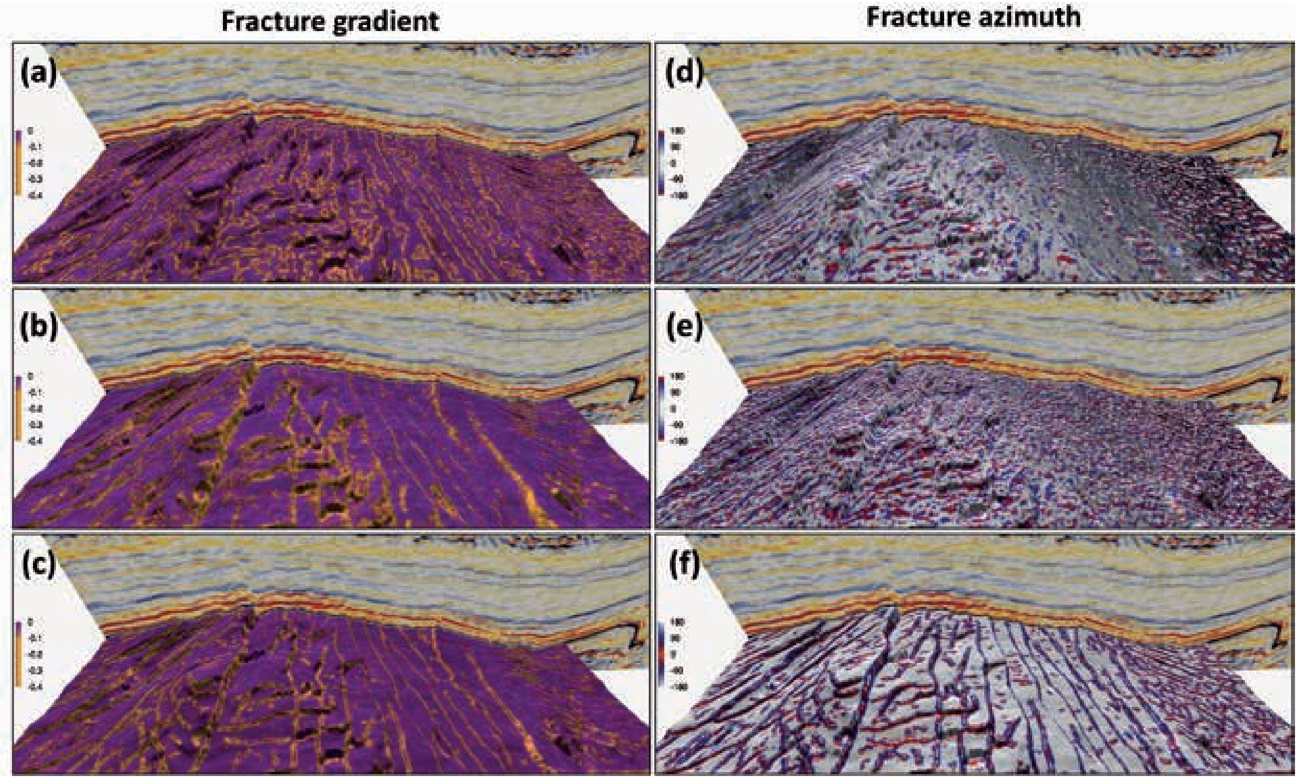

Figure 6 Fracture gradient applied on (a) similarity from FEF seismic, (b) maximum curvature and (c) fault likelihood attributes. Corresponding fracture azimuth results are shown in (d), (e) and (f) respectively. In this example, it is evident that the fracture gradient and azimuth attributes from similarity and curvature are noisier; however, the fault likelihood attribute produces reasonable results.

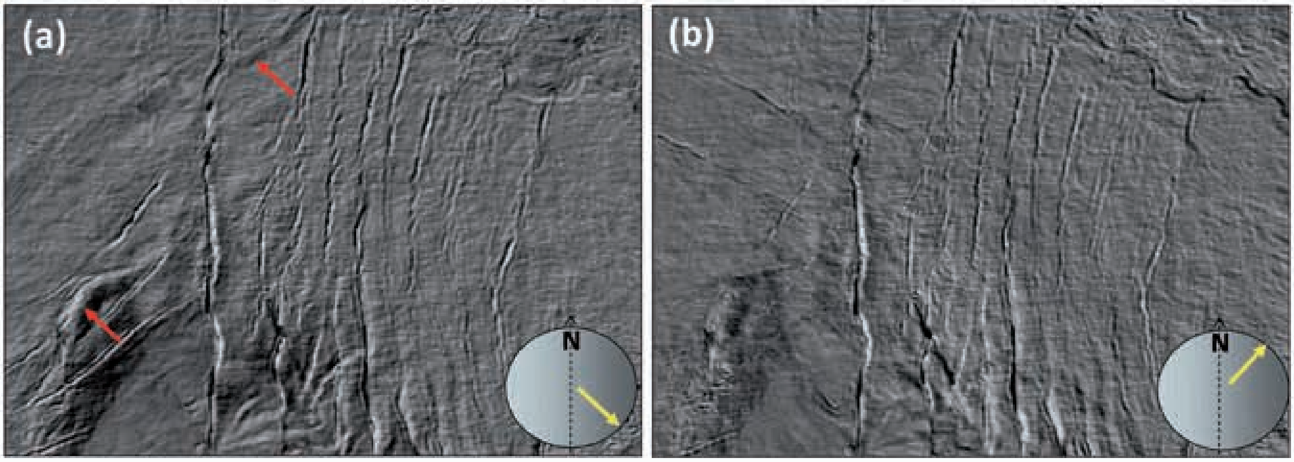

Figure 7 A comparison of directional (amplitude) attributes: (a) along 135 degrees azimuth highlighting stratigraphic features, while (b) along 45 degrees azimuth primarily amplifies fault lineaments.

volume corresponding to one seismic sample, and is thus linked to the bin size and sampling rate of a seismic survey. This filter works as follows:

1. Use the voxel value to make it binary (true or false) based on criteria such as cut-off/threshold.
2. The neighbourhood around each voxel with a 'true' value is searched for other voxels with 'true' values. If such voxels are found, the voxels are joined into one body. The neighbours are searched on the basis of all common faces, or all common faces + edges, or all common points. This can be understood by imagining the voxel in question, at the centre of a 3x3x3 Rubik's cube (Figure 8e). If all the 26 cubes (i.e., voxels) around the central cube are having the 'true' value, it corresponds to all common points. If only those cubes that share faces with the central cube have 'true' value, it corresponds to

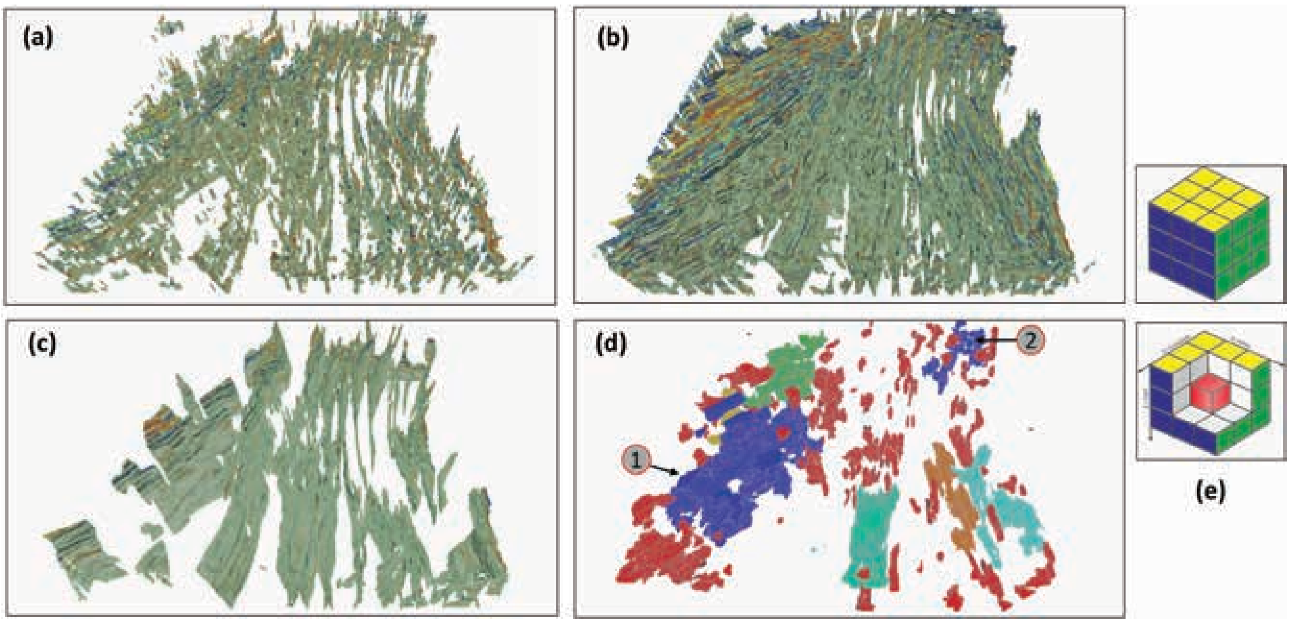

Figure 8 *Voxel connectivity filter applied on (a) similarity attribute from FEF seismic, (b) fault likelihood (0-1) attribute with low connectivity threshold of 0.2 covering more faults, (c) fault likelihood (0-1) attribute with low connectivity threshold of 0.6 covering only the biggest faults and (d) fracture density attribute pinpointing the ranked fractured zones with highest density, e.g. '1' and '2'. Rubik's cube is shown in (e) to understand the neighbourhood searching criteria of the voxel connectivity filter.*

common faces. Finally, if in addition to the faces, the cubes that share edges with the central cube are having a 'true' value, it corresponds to all common faces + edges.

3. Store the connected geo-bodies. At this stage, a seismic attribute volume is written out where the values inside the connected bodies can be either:
   a. The attribute value itself,
   b. The body's size, i.e., number of voxels forming the body (often considered as an important result in faults/fracture studies),
   c. A unique ranking of bodies based on their size.

In this paper, the VCF is applied on various fault attribute volumes: fault likelihood, similarity from FEF seismic and fracture density volume derived from the fault likelihood attribute (Figure 8). Clearly, the extracted geobodies from the fault likelihood attribute provide crucial insights into the 3D fracture patterns and their connectivity. In addition, the ranked (see 3c above) geobody extracted from the fracture density attribute help visualize the best zones for hydrocarbon exploration in 3D.

Conclusions

This paper presents the popular seismic attributes that are routinely applied to perform visualization and interpretation for faults and fracture detection. These attributes become meaningful and useful for interpretation when they are further processed for fracture detection using the proposed unconventional fracture attributes.

Seismic data conditioning is a vital step of the workflow as it aims to clean the data for all unwanted elements and focuses on enhancing faults. The fracture attributes – which are applied on conventional seismic attributes derived from dip-steered and fault enhanced datasets – further enhance the strength, pattern and orientation of fractures.

We identify two promising attributes that can directly characterize the fracture proximity and their density in a given area. These attributes lead to the identification of potential sweet spots. However, fracture gradient/azimuth attributes are found less useful because of their noisier appearance when applied on seismic data. Nevertheless, the directional attributes can alternatively be used for analysing fracture orientation.

The remaining part of the workflow uses the power of visualization to understand fault networks and their connectivity in a three-dimensional space using the voxel connectivity filter. This produces a ranked fracture volume that can be used for hydrocarbon exploration, risk assessments, drilling through unconventional plays and basement fracture zones.

Acknowledgements

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