# An Integrated Workflow to Optimize Discontinuity Attributes for the Imaging of Faults

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## Abstract

In the first part of this paper, we give an introduction in seismic attributes for fault detection to set the context to understand imaging of faults with seismic attributes as an integrated workflow. Several well-known attributes for discontinuity analysis are discussed: coherency, similarity, variance, and semblance. After discussing these attributes and their different representation of the seismic and geological characteristics of a dataset, we focus on the dip-steered similarity attribute.

In the second part of the paper, we describe an integrated workflow to produce optimized discontinuity volumes for fault detection First we discuss several preprocessing options to optimize the data for the application of the discontinuity attribute. Second we show the effects of several parameter settings of the similarity attribute. Finally, we discuss the application of postattribute filters (filters applied to the discontinuity attribute) to demonstrate how the attribute image can be enhanced by improving the completeness, resolution, and contrast of the similarity attribute.

## Introduction

Discontinuity volumes are an important tool, often used by interpreters to assist manual fault interpretation. In addition, discontinuity volumes are increasingly used in automated workflows for seismic interpretation. However, in our experience, there are too many instances where discontinuity attribute analysis yields sub-optimal or disappointing results, especially when applied by non-experts. In our opinion, improvement can be achieved easily by applying a more thoughtful and integrated approach. However, in the available literature, although there are many papers on individual attributes and filters, there is a lack of papers describing a multistep workflow for optimizing discontinuity attributes in a systematic, high-level, holistic manner. In this paper, our aim is to fill that gap and to provide the non-expert user with a guide that:

1. Provides a framework for a systematic workflow using a holistic approach, in which all optimizations are considered with the final application of the discontinuity volume in mind. This includes conditioning the seismic data, optimization of the parameters used to compute the discontinuity attribute, and image enhancement applied post-processing to the discontinuity volume.
2. Provides an overview of typical methods that can be used in the different stages of this workflow.

While we focus on developing a workflow with the similarity attribute, the workflow or structure described can be applied to all attributes in the class of discontinuity attributes, as well as related structural attributes, such as the class of curvature attributes. In addition, while here we focus on fault detection, the same workflow is valid when using discontinuity attributes to target other geological features, such as incised stratigraphic features, certain forms of reefs, or collapse (paleokarst) structures.

## Discontinuity and Other Seismic Attributes for Highlighting Faulting

### Rationale behind using seismic attributes to highlight faulting

A proper interpretation of faults is essential in any seismic interpretation for the purpose of exploration for, or development of, hydrocarbon reservoirs. The conventional workflow for fault interpretation is a manual picking of fault sticks by the seismic interpreter on seismic lines and time slices: see Brown (2004). In the next step, the individual faults sticks are sorted per fault and interpolated to construct fault planes. The main disadvantages of this manual interpretation workflow are:

1. The interpretation is often a low resolution and simplified version of the actual fault (system). First, the actual geologic faults or fault zones are only partially imaged in the seismic data. Then, the interpretation of the seismic fault system is generally a subsampled and simplified representation of the fault system as it is visible in the seismic data. Compounded, this leads to a geologically unrealistic simple model of the subsurface.

2. Manual interpretation is time consuming.
3. Manual interpretation is subjective.
4. In certain orientations of reflector dip, fault dip, and the section or slice through the seismic volume, the discontinuities in the seismic data representing faults are difficult to discern on cyclic seismic images.

Using seismic attributes to highlight faulting in combination with manual fault interpretation mitigates these problems:

1. A proper fault attribute displays the fault structures in nearly the same resolution as the seismic data. Details such as Riedel structures, splinter faults, and fault relay ramps show and are easier to interpret. Such images make it possible to infer secondary geological attributes such as paleostress regimes and vertical conductivity of faults to hydrocarbons and other fluids.
2. The manual interpretation of faults is sped up by using seismic attribute displays. In addition, automated methods can be used to create a model of the faulting, as demonstrated by Pedersen *et al.* (2002), Dorn *et al.* (2005), and Jacquemin and Mallet (2005).
3. A seismic attribute provides an objective translation of seismic data to a geologically meaningful image.
4. Faults that have been obscured due to the cyclic nature of the seismic data become more visible.

Obviously, there are disadvantages and problems using seismic attributes. The most obvious two are:

1. Seismic and geologic artifacts that are highlighted by the same seismic attribute as faults can confuse the interpreter. Examples are surface static effects and stratigraphic incisions that may have discontinuity as an attribute. This is the flip side of working objectively with the measured data, as a human seismic interpreter will subjectively filter such artifacts when manually interpreting faults. Gaining more experience with attributes, a seismic interpreter will learn to apply a similar subjective filter working with seismic attributes. Additionally, there are several techniques to minimize the presence of artifacts discussed later in this paper.

2. Some faults (portions) are obscured even when using seismic attributes. Such obscuring can be caused by several factors. For example, the seismic data may be of poor quality, geologic factors can cause certain attributes to fail (including the fault dip-slip being much lower than seismic resolution), or incidental juxtapositions of similar seismic phase and seismic amplitude on both sides of the fault will locally obscure the fault. Several techniques exist to minimize these problems and will be discussed later in this paper.

The most obvious characteristic of geologic faults is lateral discontinuity of the geologic strata. The equivalent seismic representation is the discontinuity of seismic reflectors. Following this reasoning, multiple seismic attributes highlighting seismic discontinuity, or its inverse, the seismic continuity, have been developed. Examples are: cross-correlation (Bahorich and Farmer, 1995), semblance (Marfurt *et al.*, 1998b), similarity (Tingdahl and de Rooij, 2003), variance (van Bemmel and Pepper, 2000), and eigenstructure (Marfurt *et al.*, 1999). Note that this is not an exhaustive list, and other seismic attributes that highlight seismic discontinuity exist. With the proliferation of attributes to measure seismic discontinuity, it is impossible to provide detail on each method. Below, we will explain dip-steered similarity in detail, and provide a high-level comparison with some of the other discontinuity attributes. In the remainder of the article, we will use dip-steered similarity as the principle discontinuity attribute unless noted otherwise. However, the reader should note that the choice for dip-steered similarity is coincidental with our experience and that other (discontinuity) attributes can be substituted in the workflows described in this article. In our opinion, most discontinuity attributes provide comparable results. For detailed explanations of the other methods, we refer to their principle papers mentioned before.

## *Correcting multitrace (discontinuity) attributes for the seismic reflector dip*

A prerequisite to the creation of multitrace attributes, such as discontinuity attributes, is the knowledge of the dip of the seismic events; if horizontal seismic events are assumed, the attribute will return faulty inaccurate values in the presence of seismic dip. Several discontinuity attributes, for example coherency, calculate the dip instantaneously as the attribute is calculated. Using dip-steered similarity, a dip-steering volume is extracted *a priori* and stored as a separate volume. This has the advantaged that the dips can be validated and conditioned easily. This is discussed later in the paper; we will first explain the basic principles for calculating the dip from the seismic volume.

Mathematically, geological dip is defined as a unit vector in 3D space, normal to the geologic layer plane. One can translate the concept of geological dip to seismic dip, which has its direction thus defined by two numbers, the polar dip and the azimuth. The polar dip is the largest dip of the seismic reflector, measured from the horizontal and increasing down with positive values. The azimuth is the direction of the dip vector, measured from the north. As the seismic data exists only on a 3D grid, the seismic dip is calculated in reference to the seismic survey (inline, crossline, Z), and stored as inline dip and crossline dip, which are equivalent to polar dip and azimuth.

The dip is extracted from the seismic amplitudes using a 3D probe centered at the actual sample location. Several methods have been developed to convert the collected seismic amplitudes into dip values. A first method consists uses a Fourier-Radon transform (Tingdahl and de Groot, 2003). Locally, the seismic amplitudes are transformed from the time domain into the wave number frequency domain and then to the slowness frequency domain. Integrating over the frequency axis and then picking the maximum amplitudes in the transform domain provides the dip from the slowness coordinates of the picked maximum. A second method is the extraction of the dip from the calculation of the amplitude or phase gradient (A. Wilson, personal communication, 2008). This method is based on the strong intrinsic anisotropy of the seismic data: the amplitudes or phases vary much quicker perpendicular to the layer plane than along a layer. Therefore, the estimation of the direction of maximum gradient allows the derivation of the reflector dip. This method is much faster than a Fourier-Radon transform as it requires neither an oversampling of the input seismic nor a costly 3D FFT transformation. A third method of dip calculation used by introduced by Randen *et al.* (2000) to create a dip volume is based on the gradient structure tensor.

## *Creation of discontinuity attributes using dip-steered seismic amplitude extraction*

Discontinuity attributes are nearly always created by performing mathematical operations between lateral trace segments and extracted using local time gates. This applies to variance, coherency, similarity, and semblance-based computations that form one family of discontinuity attributes.

One of properties controlling the output of a discontinuity attribute is the choice of the operator applied to the trace segments, to estimate their dissimilarity. Variance, coherency, similarity, and semblance each use a different operator. The variance is a simple statistical property of the seismic amplitudes. The coherency is based on a dot-product cross-correlation computation. The similarity uses the Euclidian distance, while the semblance computes a squared sum between the trace segments or vectors.

A noticeable difference between them is that while coherency and similarity work between multiple pairs of vectors and then are recombined using another measure, variance and semblance can natively incorporate more than two traces in their computation. For dip-steered similarity, the vector pairs used for computing the attribute are most often the trace segment of the center trace, and a selection of neighboring traces. Note that the vertical location of the trace segments center varies from trace to trace when using a dip-steering correction, illustrated in Figure 1.

### *Similarity attribute parameterization*

Most significant variations between the representations of the similarity attribute are due to three attribute parameters:

1. Choice in statistics: In the similarity attribute, several measurements of similarity in different directions and trace pairs are recombined. The statistic chosen to recombine the different measurements affects the output. Figure 2 shows the difference between the maximum and minimum output in an 8-trace pairs similarity attribute.
2. Handling of the seismic dip: Usually the discontinuity attribute is corrected for the seismic dip. This dip can be conditioned to represent a local dip or a subregional dip. This conditioning will have a major effect on the attribute, as shown in Figure 3.
3. Choice of lateral and vertical analysis windows: The distance between the trace locations that are compared, directionality of the extracted trace locations, and the vertical trace segments that are used around the center point are major factors in the attributes' appearance.

Between the different discontinuity attributes, it is our experience that the choice of attribute (operator) is of lesser importance, and a correct parameterization of the attribute is of greater importance to create the best possible results. The testing of attribute parameter is discussed in more detail later in this paper.

## Other attributes for fault detections

Though discontinuity is the principal attribute for fault detection, there are other attributes, and methods based on multiple attributes to highlight faults. As the workflow presented in this paper is applicable to these alternative attributes and methods, we provide an overview of the main alternatives.

### *Curvature*

Seismic curvature is a measure of the amount of bending in a seismic reflector (Fig. 4). A nice feature of curvature for fault detection is that it uses a seismic property that is mathematically independent of discontinuity. Curvature is especially useful in highlighting faults having a dip-slip that is small compared to the seismic wavelength. These faults often look like flexures of the seismic reflector, are not detected by discontinuity attributes, but can be picked-up by the curvature attribute. A second application of curvature for fault detection arises when the geological strata are folded at the sides of faults due to fault drag, as seen in Figure 4. Note that contrary to the discontinuity attribute, the curvature attribute normally has its extreme values at the sides of the fault plane instead of in the center. So a filter or numerical manipulation should be used to place the strongest response in the center of the fault plane.

### Multiattribute methods

Often, single attributes do not optimally highlight targeted geological features such as faults. In some cases, non-target seismic or geologic features are highlighted leading to confusion. In other cases, the entire target feature is not highlighted, leading to oversights. Often both problems occur at once. A solution is to recombine several parameterizations of an attribute and/or recombine different types of attributes. The different extractions will capture different features of the data and then are recombined in a single, optimized fault volume. Examples are the cross-plotting approach, described by Chopra and Marfurt (2009), and the neural network method described by Tingdahl and de Rooij (2005).

### Choosing the right fault attribute

Proper choice of the principal fault attribute, discontinuity, curvature, or "multiattribute," can be essential for achieving satisfactory results. Therefore, we present in Table 1 a number of criteria that may help the reader to select the proper approach.

## Optimization of Discontinuity Attributes by Applying an Integrated Multistep Workflow

Although many tools for discontinuity attribute analysis exist, the approach of many practitioners consists of choosing one particular attribute and applying it to unconditioned input data using the default attribute parameters. In our experience, this approach often leads to suboptimal, if not disappointing, results. Major improvements over a default “push-button” approach to (discontinuity) attributes will come from optimization applied in three steps:

1. Conditioning of the seismic and steering data.
2. Customization and optimization of the attribute parameterizations.
3. Postprocess image enhancement filters applied to the discontinuity or generalized fault attribute.

The best strategy to create an attribute having optimal fault imaging is to sequence systematically through these steps and if necessary iterate. However, before starting at all, the interpreter should hold back, think the problem through, and design a plan of attack. This strategy implies reconsidering the exact objective of the attribute analysis, identification of problems with the input dataset, and identifying opportunities (A) to solve these problems and (B) to improve further the results in context of the ultimate objectives using the particular "toolbox" the interpreter has available.

## Objectives, present applications, and future applications of discontinuity attributes

To understand the need for optimization, and which method(s) should be applied, it is important to establish the relation between the optimization methods and ultimate objective(s) of the discontinuity attribute. Here, we give an overview of typical objectives and associated considerations for optimization:

- Assisting manual interpretation of faults: The main consideration is to map all faults (completeness of the attribute) and create a visually pleasant output for the interpreter to work with. It is less important to remove all artifacts (uniqueness of the attribute) as the interpreter will be able to recognize many of the artifacts. However, it is preferential to remove artifacts that have a fault-like appearance on time slices, such as linear channels.
- Automated fault extraction using discontinuity attributes: The most important consideration is the removal of noise and artifacts that do not represent faults. Some applications may require numerical connectivity between discontinuity patches representing the same fault. However, a complete representation of all faults by discontinuity voxels would not be necessary as gaps in the fault surfaces would be easily interpolated postextraction.
- Auto-tracking of seismic horizons: The discontinuity volume acts as a boundary to prevent the auto-tracker from continuing through fault planes to an incorrect reflector in another fault block. Figure 5 provides an example of this application. For this purpose continuity of the discontinuity volume is the most important, as a single gap can allow the auto-tracker to break through into a neighboring fault block. Artifacts are less of a consideration, as gaps in horizons due to false positives can easily be addressed in a postauto tracking interpolation.
- Prediction of permeability and vertical connectivity (D. Burch, personal communication, 2008): Discontinuity attributes can be used to predict zones of enhanced permeability both in lateral and vertical direction. Examples are in optimization of well completions in unconventional hydrocarbon reservoirs and predicting water breakthrough in the Barnett shale gas reservoir. In the critical application of reservoir optimization one needs a very accurate imaging of fault-related seismic discontinuities. Thus, one needs to address the conflicting requirements of imaging all faults and avoiding inclusion of noise and artifacts in the discontinuity volume.

## Step 1: Conditioning of the input volumes

Important improvements of discontinuity attributes can be achieved by proper conditioning of the input seismic data. In the case of dip-steered discontinuity attributes, the dip-steering should also be conditioned to achieve optimal results. We will discuss four types of filtering:

1. Improving the seismic data by removing discontinuities not related to geology.
2. Improving the steering cube to correctly represent the sub-regional geological dip.
3. Additional conditioning of the seismic data: frequency enhancement filters and fault enhancement filters.
4. Removing stratigraphically oriented noise

### *Removing artifacts from the seismic data*

Most disturbing to geometric attributes such as discontinuity or curvature are acquisition footprint, coherent noise, and certain processing artifacts, such as “smiles” due to over migration or uncollapsed diffractions.

The challenge is to find a seismic filter that subdues "artifact" discontinuities while leaving discontinuities due to faults unaltered. Note that one does not necessarily need to remove the noise altogether. Once the dynamic range of the fault-related discontinuities has become separable from the dynamic range of the artifacts, then one can isolate the faults by applying a cut-off or visually by adjusting the color bar clipping.

Several filtering methods may be applied to lower noise levels in the seismic data. We apply a method based on a dip-steered statistical filter operator. Alternate approaches are based on a Radon transform type filter (Marfurt, 1998a), on singular value decomposition of the seismic data (Al-Bannagi *et al*., 2005; Guo *et al*., 2009) or on adaptative subtraction algorithms **(**Davogustto *et al*., 2009).

In Figure 6, an example is presented of the removal of the acquisition footprint using a dip-steered median and averaging filter. The filter operator is aligned with the seismic reflectors using the same dip-steering principle as applied to the similarity. First, a median filter is applied to the seismic data. Note that the median operator is a step-preserving operator. Therefore, it will remove outliers but will retain steps in data values as encountered near faults. The median operator, however, may also retain some of the steps or periodic variations encountered in acquisition footprints. In this case, an optional dip-steered averaging filter can be applied in sequence. It is key to keep the operator size of the averaging filter to a minimum, as the averaging operator is not step-preserving and a small operator size minimizes smoothing of the seismic data over faults. The choice whether to apply a final averaging step is best made empirically by comparing test results on slices similar to what is shown on Figure 6.

### *Improving the steering cube*

Described earlier in this paper, many discontinuity attributes use the seismic reflector to correct trace segment extraction at step-out traces of the seismic dip. This can be done *a priori*, such as with the dip-steered similarity, or simultaneously, such as with the dip-scan coherency (Marfurt *et al.*, 1999). The first method has the advantage that the dip-field used can be conditioned for optimal results. The main optimizations that one can apply are removal of noise in the dip field and removing local information of dips in favor of subregional dips. The latter gives a better result as the local dip calculated near a fault may be unreliable, as most calculations of the seismic dip fail near a seismic discontinuity. More important, the local dip, if correct, may adjust the extraction of trace segments at opposite sides of the faults such that the almost identical trace segments are extracted and thus the fault is obscured. This is the case when the fault has a small dip-slip compared to the seismic resolution, or if there is considerable folding of the seismic reflectors near the faults; see Figure 7. Simultaneous dip-scan methods will generally be limited to local dip and may suffer from this drawback. See Figure 3 for an illustration of the effect of using local versus subregional dip-fields.

There are different methods for filtering the dip-field. We generally apply statistical filters, as shown in Figure 8. An alternative approach is to apply a low pass filter in the frequency-wave number domain.

### *Improving the seismic data to emphasize discontinuities*

Contrary to removing noise, one can also apply certain operators to the seismic data in which the objective is to improve the imaging of the faults. In our workflow, we typically apply two steps: optimization of the frequency content using seismic spectral blueing (SSB) and applying a fault enhancement filter to the seismic data.

Often, seismic data are not optimized for the frequency content. If well data and density and P-wave logs are available, one can apply a geologically (well-log) driven optimization of the frequency spectrum in seismic data using SSB. The theoretical justification for this method is given in Velzeboer (1981) and Walden and Hosken (1985) and a practical application is presented in Blache-Fraser *et al.* (2004). In the context of discontinuity attributes, the significance of SSB is that the seismic visibility of faults having small dip-slip will be enhanced. These small faults can have large impact on the production behavior of hydrocarbon reservoirs because of reservoir compartmentalization and/or vertical communication of fluids along the fault plane. Therefore, frequency optimization should be a default step in fault detection for reservoir optimization. Figure 9 provides a comparison of a seismic section before and after optimization, illustrating the improvement in fault visibility.

Once the best frequency content has been established, one can apply a fault enhancement filter to the seismic data. This step is optional and can be beneficial if there is a low seismic data quality in the direct vicinity of the faults. The fault enhancement filter is an adaptive, conditional filter that sharpens discontinuities near suspected faulting and smoothes the seismic reflectors at all other locations. First, a quality volume is processed to tag a certain location as part of (near of) a fault or part of non-faulted seismic data. If the location is near or on a fault, a sharpening filter is applied based on the gradient observed in the similarity. Elsewhere, a smoothing filter is applied to the seismic data. This workflow has the effect that the seismic amplitude data become more continuous everywhere, except at faults where they become strongly discontinuous. A workflow with a similar effect is described in detail by Fehmers and Hoecker (2003).

## Step 2: Optimization of attribute parameters

Once the input data are optimized, the next step is to optimize the discontinuity attribute itself. This is an empirical process, in which one needs to experiment with the parameters of the discontinuity attribute:

- Time gate: The time-gate chosen will determine the vertical localization of the discontinuity attribute. Smaller time gates will result in higher localization and resolution. A drawback of smaller time gates is the enhancement of stratigraphically aligned artifacts, including both seismic and numerical noise due to zero-crossings, low reflectivity zones, and stratigraphically aligned features attributable to geology such as erosional edges and mass transport systems. The second drawback of short time windows is often

### *Removal of stratigraphically oriented artifacts around the seismic zero-crossing*

Often, discontinuity attributes show artifacts aligned with seismic zero-crossing or low amplitude reflectors. This effect is stronger when relatively small time windows are used in the discontinuity attribute. Though often there is no real hindrance, these stratigraphically aligned anomalous zones do not represent faults; thus ideally they should be removed. An improvement can be achieved by using the analytic trace as input instead of the real trace (Chopra and Marfurt, 2007). Figure 10 shows the result of statistically combining dip-steered similarities with Real and Hilbert transformed traces as input to the discontinuity attribute, which minimizes the stratigraphically aligned anomalies. It also shows the result of an alternative statistical filter applied to the discontinuity output, rather than the seismic input. Which filter to use is best determined empirically.

the loss of vertical continuity in the fault image. Larger time windows provide, due to averaging, minimal stratigraphically aligned noise and will provide larger vertical continuity of the faults but will exhibit more vertical smearing. The best time-gate should be determined empirically and is dependent on the characteristics of the dataset and the particular interpretation objective. The best practice to determine this setting is to measure the dominant period of the seismic signal and then define several test time-gates as ratios of the dominant period. In the example of Figure 11, we use 0.5, 1, and 2 times the dominant period T as time gate.

- Geometry and step-out: The most conventional choice for trace pairs would be two perpendicular pairs towards larger inlines and crosslines. Also one can imagine the same setting but in the reverse direction, or looking at the diagonal directions. Figure 12 shows the result of such a discontinuity attribute on vertical and horizontal sections. Such trace position settings generate the most detailed discontinuity attribute, with an effective size of one bin. However, its display may look aliased with an interpolated (non-blocky) display. But the largest drawback can be seen when displaying the discontinuity attribute on top of the seismic (Fig. 13). The actual positions of the maximum of the discontinuity attribute values are not located at the fault location, but laterally shifted next to it. This shift can be compensated during postprocessing; however, this is easy to avoid by setting up another sort of input geometry. Figure 14 presents an example of discontinuity attribute using the four pairs of traces that coincide with the inline and crossline directions. This attribute still features an effective size of 1 bin but with connectivity between the bins. The roughness seen previously decreases a bit, and the peak amplitude actually corresponds now to the location of the fault plane. Although the roughness and interconnectivity are coming from the larger number of pairs (8 instead of 4), the positioning of the response is again directly related to the symmetry of the extraction locations. It is also possible to use the four diagonal pairs in order to capture a network of faults oriented along the survey diagonal directions. Nevertheless, the gain in detection of diagonal faults will have to be balanced with the larger size (+40%) of the extraction array and proportionally lower crispness of the attribute. Lastly, it is also possible to combine the eight pairs of traces around the central location (Fig. 15). This extraction setup provides the optimum continuity of the attribute response but at a subsequently lesser level of detail and more contrast between the discontinuities and the background. In the case where the interpreter wants to focus selectively on one directional fault set, one can limit the trace pairs to lie in certain directions (Fig. 16). The directional quality can even be improved more by certain postprocessing filters.

Generally, it is advantageous to work with the smallest step-out distance for the trace pairs as possible. However, if one has very low dip faults, such as the sole of a growth fault or low angle thrust faults, it may be necessary to use larger step-outs to properly image the faults.

- Output Statistic: In many discontinuity attributes an intermediate result is produced that contains a set of discontinuity measures between many pairs of traces. As the final result should be one measure, this set is often reduced using a statistical operation. In the case of similarity one can choose minimum, maximum, or average. Choosing the maximum similarity will result in a "cleaner" image, which will not detect all faults, as often the maximum pair will not cross the fault but is parallel to the fault. The minimum similarity will provide a more complete image of the faults as it will always take the similarity of a trace pair that crossed the plane of maximum discontinuity (usually a fault). However, it is more sensitive to noise and will deliver a less "crisp" image. See Figure 2 for an example of the effect of the output statistic. Between the statistics options available, it is generally advised to use statistics that selects the trace pair having maximum discontinuity (minimum similarity), as missing fault (segments) are unacceptable.

Finally, the choice of input volume can make import differences. Different volumes, such as prestack versus poststack processed volumes or near versus far stack volumes, do often provide different seismic images of the geologic fault system. In the case that discontinuity attributes have different inputs provide complimentary images of the fault system, one can combine them using one of the multiattribute methods presented in Table 1. Before combining discontinuity attributes from different input volumes, care should be take to align the attributes in temporal and lateral sense.

## Step 3: Postprocessing image enhancement

Once one or more discontinuity attributes have been processed, several techniques are available to reduce any remaining problems, to improve the general quality for interpretation or subsequent workflows, and to create special purpose volumes. The following list summarizes a number of options for image enhancement of discontinuity type attributes. Which method to apply depends on specific problems encountered, the objectives of the discontinuity volume, and if the objective warrants the effort.

- Stratigraphically oriented noise can be minimized using a vertically oriented statistical filter. We use this as a first step when finalizing the discontinuity volumes. The improvement of this step is illustrated in Figure 10 next to an alternative filter that can be applied preprocessing.

- It is not uncommon to arrive at different versions of discontinuity attributes that each have different complimentary images of the fault system. To simplify the interpretation, it is often a consideration to blend them into one volume but with preservation of the optimal characteristics of each volume. The simplest approach is to apply a brute-force merge using an averaging or statistical operator between the volumes. However, more advanced methods are available, as summarized in Table 1.
- To increase resolution and remove remaining noise, a ridge-enhancement filter can be applied, originally developed by de Rooij and Tingdahl (2002). This filter is especially useful in structurally complex areas having dense fault systems and in areas with strong stratigraphically oriented noise. Details of this filter are discussed below.
- The interpreter can separate different fault trends using directional decomposition of the discontinuity attribute. This can be useful in both manual and automated fault interpretation. The method is described in more detail further below.
- The quality of faults can be considerably improved for the purpose of manual and automated interpretation using fault-dip conditional filtering (FCF) and fault-dip oriented statistical filtering (FSF) and. The sequential application of FCF and FSF can address issues as stratigraphically oriented noise, vertical fault continuity, and staircase behavior in one step. This is a powerful workflow that demands more user interaction during parameterization and has more computational intensity. It is most applicable if the discontinuity volume is meant to be used in a subsequent automated workflow, in which there is the need for the volume to be noise free, smooth, and continuous. Donias *et al.* (2007), proposes a similar workflow.
- Other authors have reported good results using techniques from the field of image processing; for example Barnes (2005).

### *Ridge enhancement filter*

We frequently use the ridge-enhancement filter (REF). The filter is applied to a discontinuity attribute or other fault attribute. The filter is an adaptive second-order derivative filter applied in different lateral directions. Between the probed directions, the optimum direction, typically perpendicular to the fault plane, is chosen as output. The advantages of using a second-order derivative are: (1) laterally continuous discontinuity anomalies are obscured, minimizing stratigraphic noise; and (2) the operator is symmetrical and provides a single extreme output at the center of the fault plane, whereas first order derivatives are asymmetrical and result in extreme values of opposite sign at the sides of the fault plane. The advantage over the common Laplacian filter, also based on second order derivatives, is the adaptive selection of the optimal direction of the operator. An example of the effect of the REF is shown in Figures 17C and 17D.

### Directional decomposition of the discontinuity attribute

Often the interpreter wants to separate one distinct fault set at a time for interpretation. Directional decomposition of the fault attribute provides that possibility. The first step of this workflow is often done during attribute optimization, as described in the previous section, by selecting only a directional subset of all available trace pairs in the dip-steered similarity. Then, a final separation can be obtained by applying the ridge-enhancement filter, limited to a subset of its azimuthal probes, followed by an averaging filter in the perpendicular direction. The decomposition of the discontinuity attribute in two directional attributes, each representing one fault set is demonstrated in Figure 16, showing the benefit for interpretation in a structurally complicated setting.

### Fault dip conditional filter and fault dip statistical filter

If there is a need to make very high quality fault volume that can be used in downstream automated data-driven workflows, the fault-dip conditional filter and fault-dip statistical filter are two workflows that can significantly improve the quality of output discontinuity volumes. The complete workflow has the following steps:

1. Calculate a steering volume from the discontinuity data. Typically, the volume will contain the dips of the discontinuities for which the discontinuity attribute is anomalous and will contain the dips of the seismic reflectors (stratigraphic dip) elsewhere. The output of this step is shown in Figure 17.
2. Apply the FCF. Generally, there is a significant difference between minimum fault dip and maximum stratigraphic dip. In this case, one can use the dip-difference to remove stratigraphically oriented discontinuities and only pass steeply dipping discontinuities typically associated with faulting.
3. Apply the FSF. This filter improves the vertical continuity of the faults by filling smaller gaps in the fault plane. In addition, the typical staircase appearance of discontinuity attributes is minimized. which is visually more pleasing and may be useful when building geological models. The filter works by applying a multibin statistical operator typically with a median, average, or minimum operator, at the location of the faults. The fault-dip steering volume is used to align the

filter operator with the fault plane. A typical result of this step is shown in Figure 17.

## Review and iterate through preprocessing, parameter optimization and postprocessing

For benchmarking purposes, Figure 18 shows a detail and the typical characteristics of a good quality discontinuity volume for fault detection. Typical qualities include: (1) no stair case behavior; (2) the discontinuity attribute is nicely centered at the fault plane even if the reflectors are interfingering due to poor seismic data quality; (3) artifacts, particularly with respect to stratigraphic features, are subdued; and (4) for fault positions having an isophase juxtaposition, the fault is still indicated (the complete faults are imaged).

Going through the flow of data preconditioning, attribute parameter optimization, and finally postprocessing, additional insights are gained on how to improve the results, as the initial result is not always the best possible result. Generally after reviewing the initial result, one may want to improve and re-apply earlier steps. Experimentation using key lines and slices, instead of the whole volume, can be time-saving. A systematic approach and note keeping will lead the interpreter to a set of personal best practices that will save time and improve results in future projects.

## Conclusions

Using seismic (discontinuity) attributes for fault imaging has several advantages. Manual fault picking can be executed with greater speed and accuracy. In addition, several methods for automated fault extraction and horizon picking are enabled by good fault attributes.

There exist many seismic attributes for imaging reflector discontinuity for the purpose of mapping faults, as well as many optimization tools to precondition input data and enhance a discontinuity volume postprocessing. The abundance of methods available may be perplexing, and it is helpful to adhere to the following overall workflow:

1. Preprocessing: identify obvious problems of the input seismic data and look for other optimizations that could be applied to the input data. Based on this analysis, design a preprocessing strategy to precondition seismic and steering data and select the most appropriate tools that are available.
2. Empirically optimize the parameter settings for the attribute by on-the-fly testing on key sections and slices. Note that different parts of the seismic

data volume may require different optimizations. One can accommodate for that requirement by using multiattribute methods such as neural networks, or one can merge different attributes mathematically; for example, using stratigraphically derived constraints.

3. Analyze the output of the optimized discontinuity attribute, identifying any remaining problems and possible improvements that can be made. Based on the analysis, design a postprocessing strategy and select again the most appropriate tools available.
4. QC the final result and iterate through the steps if necessary.

Of course, the computer and interpreter time and expenses that needs to be, or can be, devoted to the workflow depends on the final objective and its significance. In addition, it is important that for most steps and problems encountered, multiple tools exist that often provide comparable outcomes. Ultimately, the outcome of the workflow is determined by the interpreter's capability to understand both the complete workflow and its steps in the context of the final objective. True understanding, as opposed to a "push-button" approach, will enable the interpreter to identify problems, possible improvements, and apply the attributes and optimization methods in a proper manner that increases the quality of the final result more than the choice of one particular algorithm over another. This does require that the interpreter invests into achieving a certain knowledge level to understand, create, optimize, enhance, and interpret fault attributes. However, once knowledge and experience have been obtained, fault interpretation workflows can be performed much quicker and provide more important detail about the fault regime at the same time. In addition, a number of novel automated workflows come within reach of the interpreter once he is able to produce a high quality discontinuity volume. This next generation of interpretation tools will ensure the interpreter will spend less time mapping and more time understanding the geology.

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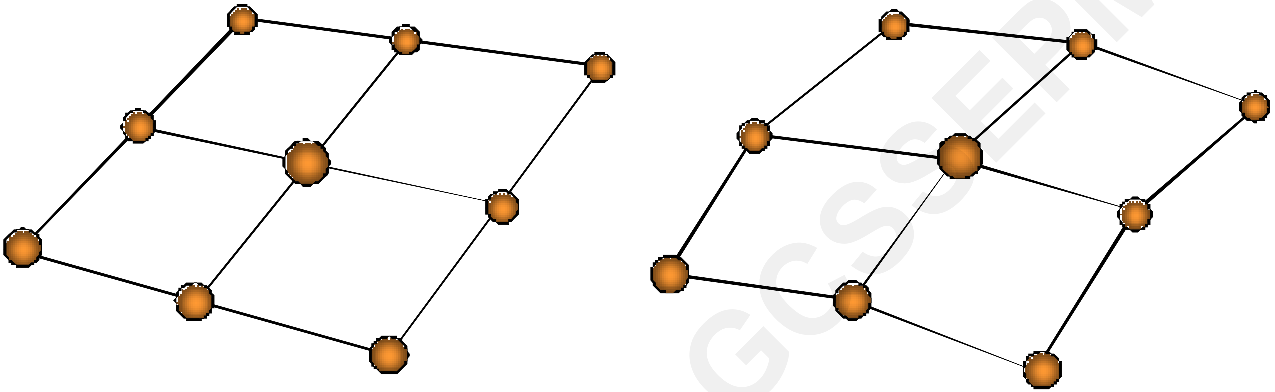
**Table 1. Selection of the best fault imaging methodology.**

| Criterion | Best method |
|---|---|
| Most faults are well defined by discontinuities in the seismic reflector. | Use a discontinuity type attribute. |
| Most faults are defined by seismic reflector flexures or seismic reflector folding at the sides of the faults. | Use a curvature type attribute. |
| The faults are not completely imaged by a single attribute, but the faults are well imaged by a pair of attributes (i.e. discontinuity and curvature) or a single attribute type with two different parameterizations (i.e. short time window and long time window). | Use cross-plotting and/or mathematical recombination to combine the two attributes. |
| The expression of faults in the seismic data is very variable or weak and three or more attributes or attribute parameterizations are needed to adequately image the faulting. | Use an interpreter driven neural network. |



Non-steered: all samples have the same depth

Full-steered: the depth is determined by the dip field

**Figure 1. The concept of dip-steering. 3D-view of the trace segments center location, without (left) and with (right) the use a full-steering correction.**

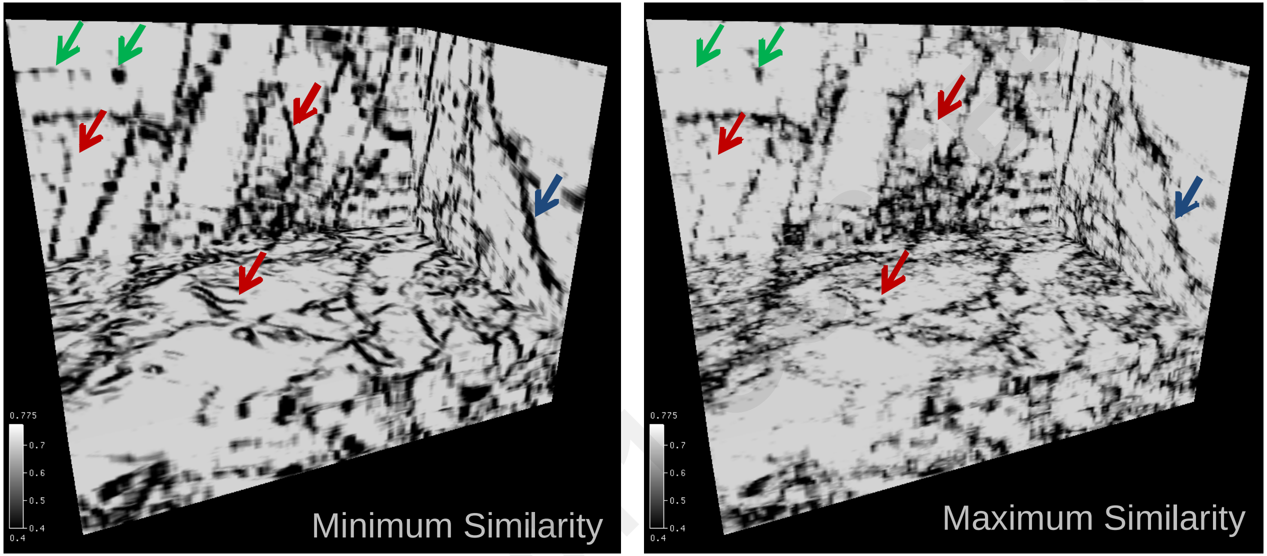


**Figure 2. Side-by-side comparison of the minimum statistic (left) and maximum statistic (right) applied to a set of eight similarity measurements, taken from trace pairs oriented in different directions. It is seen that the “minimum operator” renders a more complete image of the faults (red arrows), while the maximum operator renders an image having high resolution (blue arrow) and less spurious highlights (green arrows).**

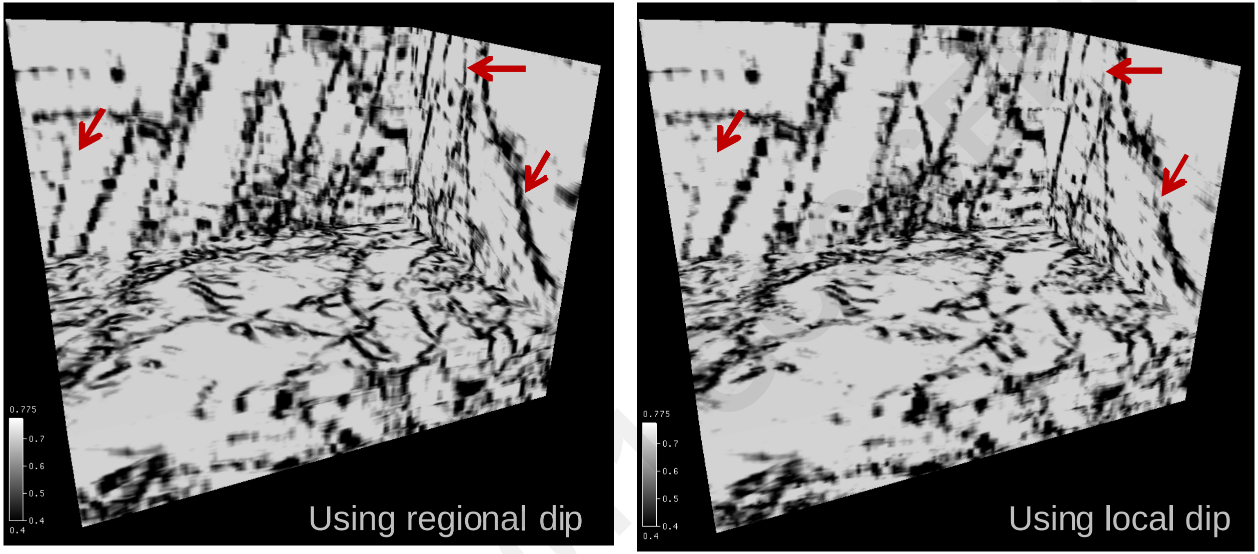


**Figure 3.** Side-by-side comparison of dip-steered similarity using the regional dip field as steering (left) and a dip-steered similarity using the local dip field as steering (right). Close inspection reveals that using the local dip fields leads to a number of faults and fault segments not being imaged (see red arrows).

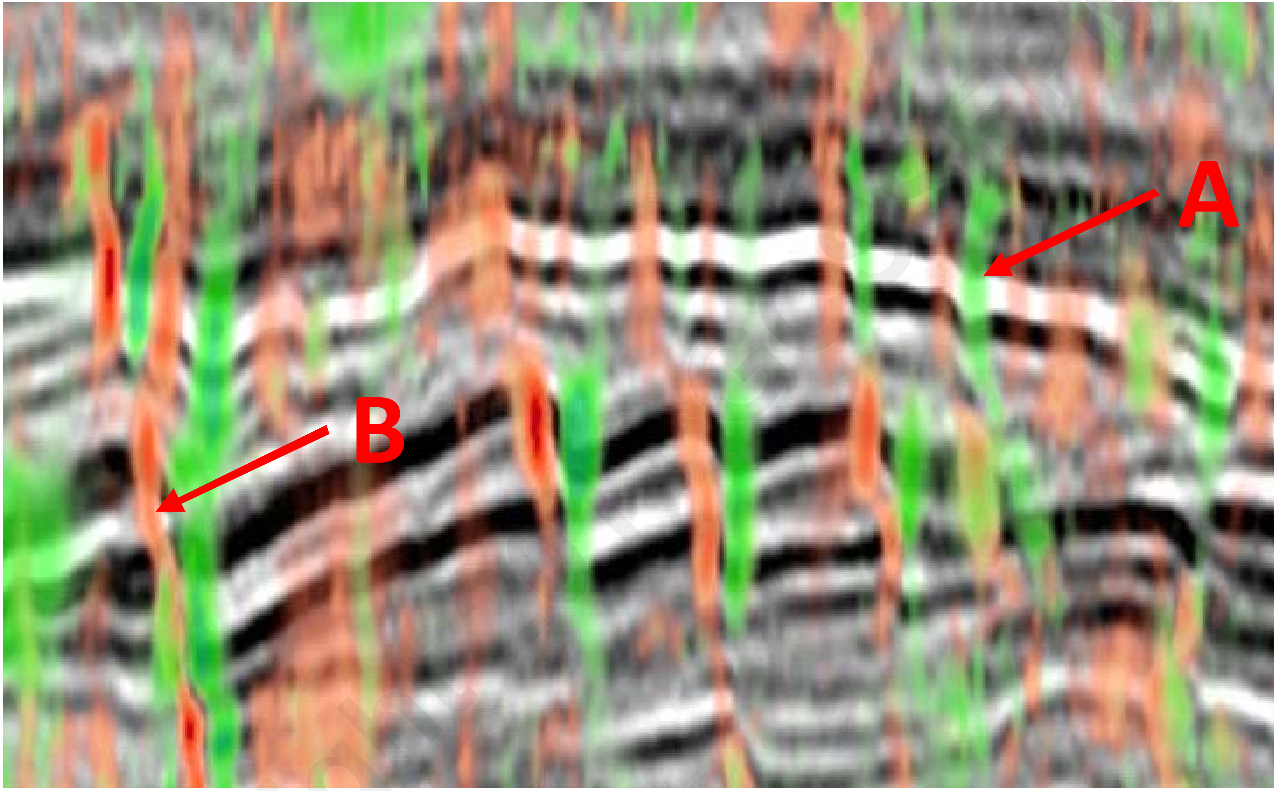


Figure 4. Curvature (red: positive curvature, antiform; green: negative curvature, synform) overlain on seismic section in grey scale. Many faults are characterized by a positive/negative pair of curvature extremes on the side of the fault. This pattern can be caused by sub-resolution fault dip-slip (arrow A) expressed as seismic flexures, geological folding expressed as seismic reflector faults (arrow B) or a combination thereof.

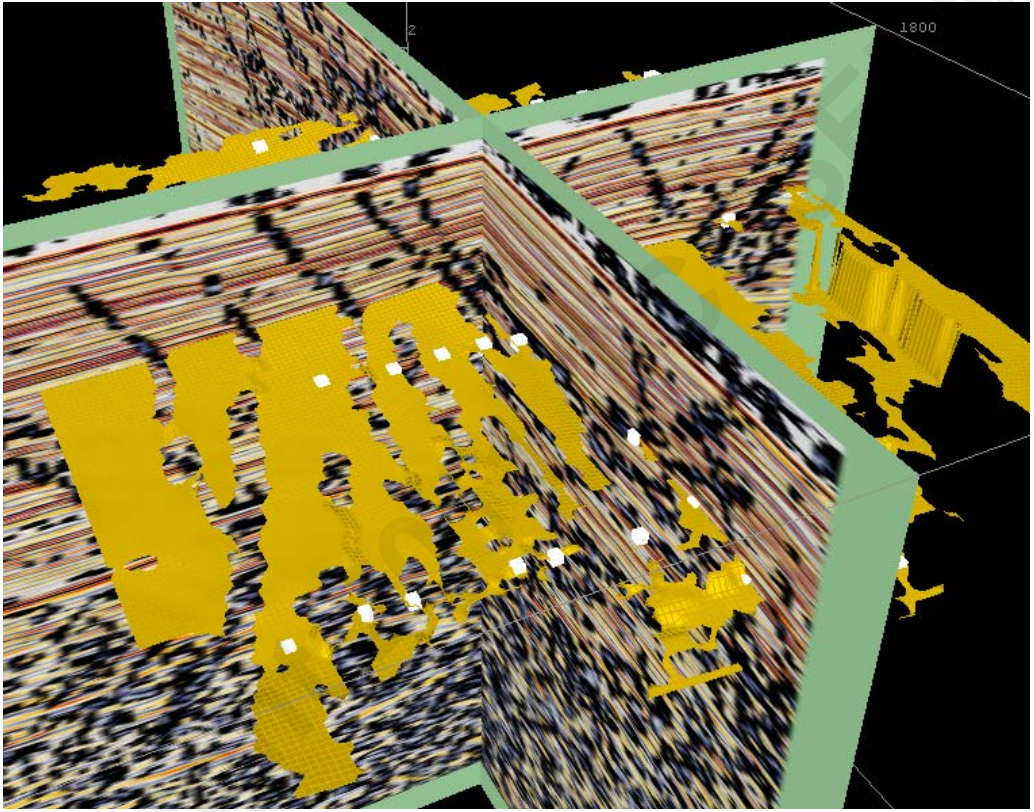


**Figure 5. Automated horizon tracking in the presence of faulting, using a combination of seismic amplitude and discontinuity volumes as input to the horizon tracking algorithm. Each fault block is seeded independently by the discontinuity volume preventing autotracker-tracking through the faults in the absence of an explicitly interpreted fault model.**

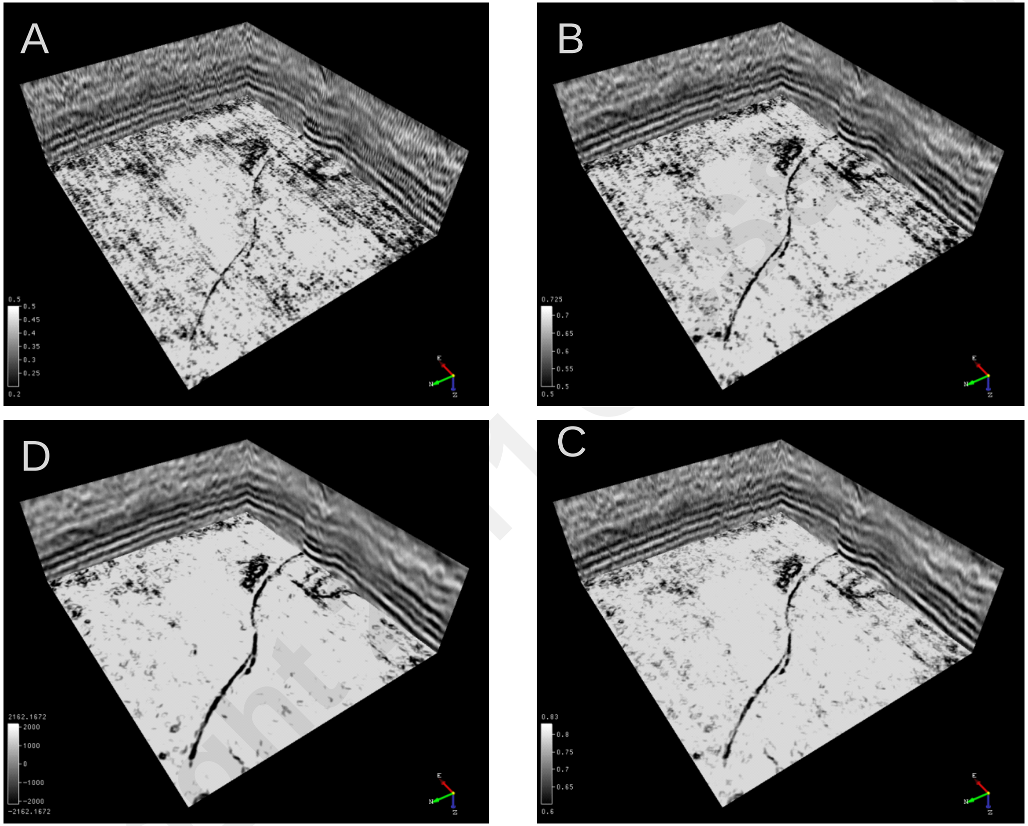


**Figure 6. Removing acquisition footprint, showing dip-steered similarity on the slice and input seismic on the sections. Starting in the left upper corner, clockwise: (A) original seismic amplitude; (B) dip-steered median filter (DSMF), operator size 1; (C) DSMF, operator size 2; (D) DSMF, operator size 2 followed by dip-steered averaging filter, size 1.**

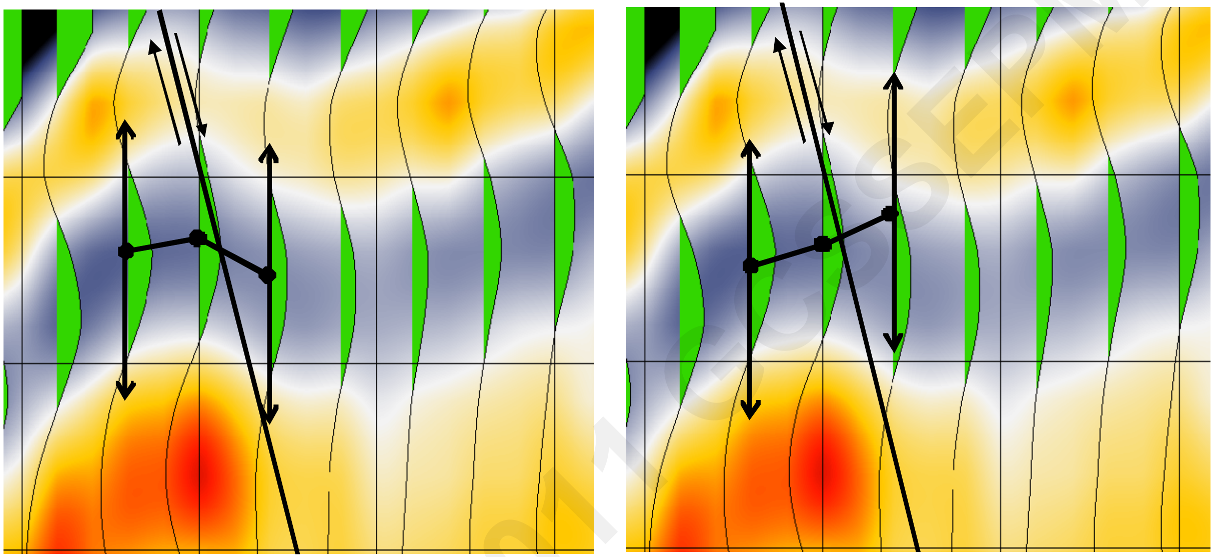


**Figure 7. Seismic data plotted using a variable area with wiggle overlay display. Note how the dip is used to extract trace segments used for the discontinuity measurement over the fault. In the left image the local dip is used. The abnormal dips due to fault drag near the fault plane cause a local correction such that nearly identical trace segments are extracted. As a result the attribute will not yield an indication of discontinuity. Instead, if a subregional dip is used, as in the right image, two very different trace segments are extracted, and the fault will be highlighted by the discontinuity attribute.**

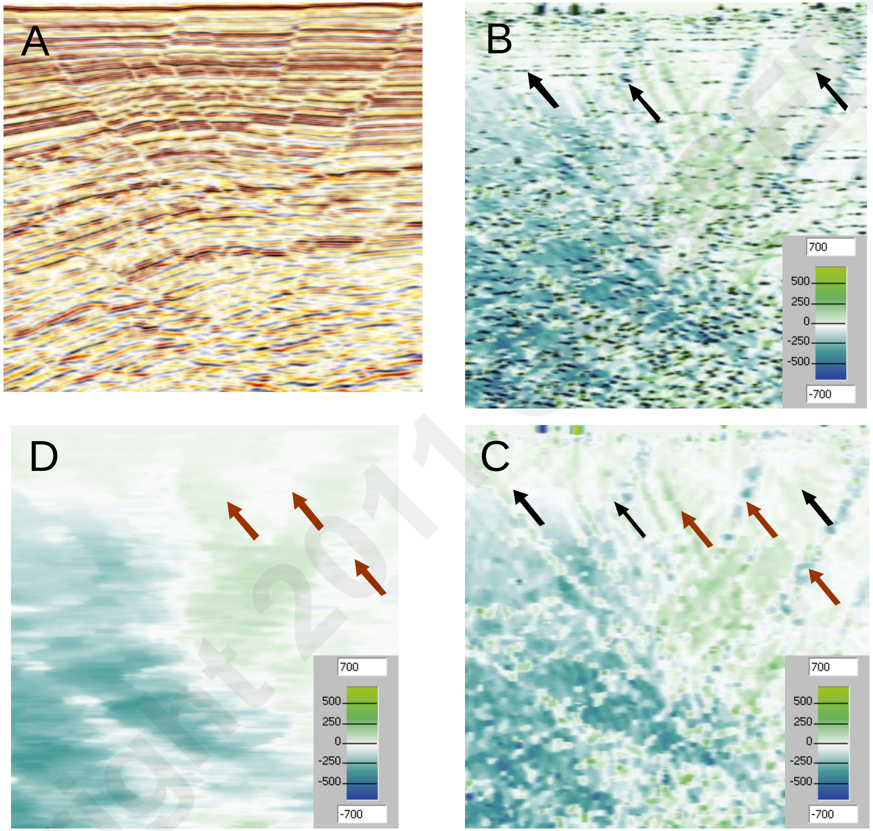


**Figure 8. Conditioning of a dip-field for dip-steering. Starting in left upper corner, clockwise: (A) input seismic data; (B) raw dip-field, noise indicated by black arrows; (C) noise removed by vertically oriented filter, local dips indicated by red arrows; (D) local dip removed by lateral filter.**

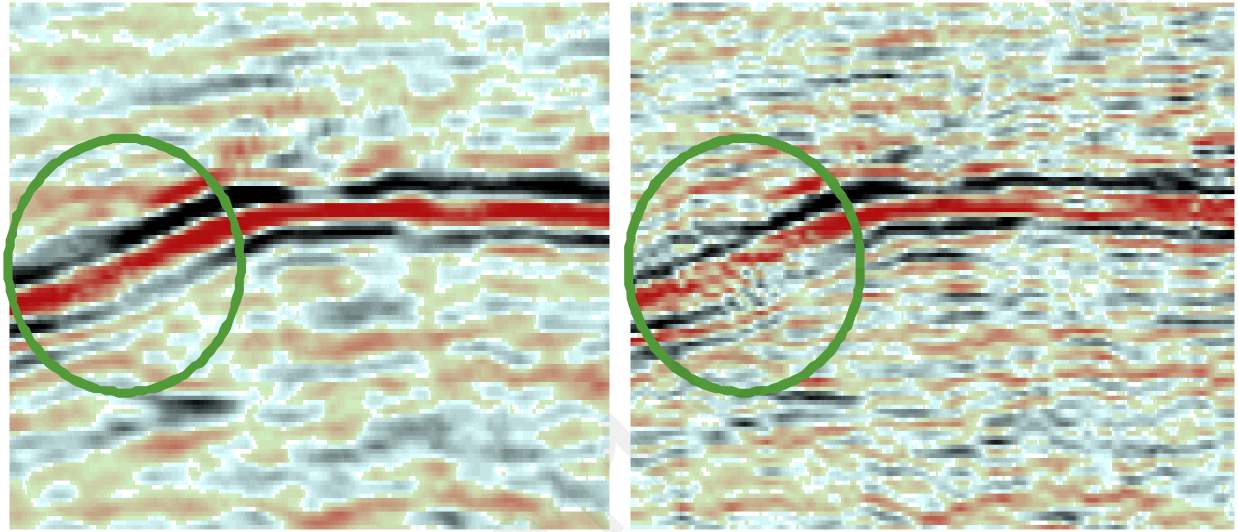


**Figure 9. Frequency enhancement through the Seismic Spectral Blueing enhancing the definition of a series of faults in a reservoir formation.**

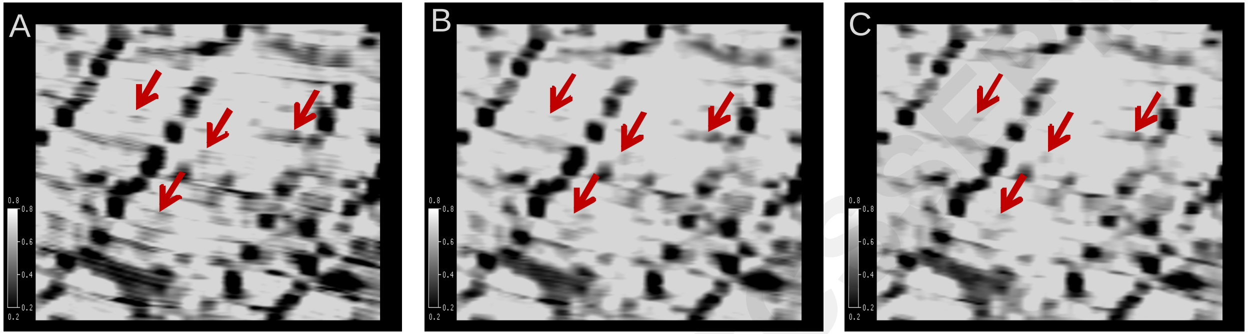


**Figure 10. Comparison of two methods to minimize stratigraphically aligned artifacts. From left to right, (A) depicts the original discontinuity attribute with some stratigraphically aligned artifacts indicated by red arrows. (B) The statistical recombination of two discontinuity attributes, one based on the real seismic volume and one based on the Hilbert transformed seismic volume. (C) Result obtained by applying a vertically-oriented statistical filter to the original discontinuity attribute.**

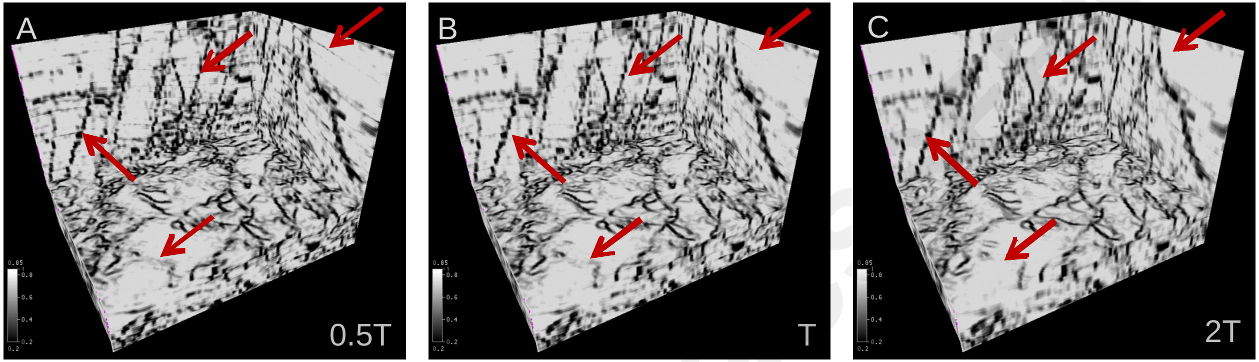


**Figure 11. Effect of the time window on the output of the discontinuity attribute. Time windows are best reference to the dominant period *T* of the seismic data in the interval under consideration. The left to right time gate is 0.5*T* (A), 1T (B) and *2T* (C). Red arrows indicate locations that show artifacts or excessive smearing.**

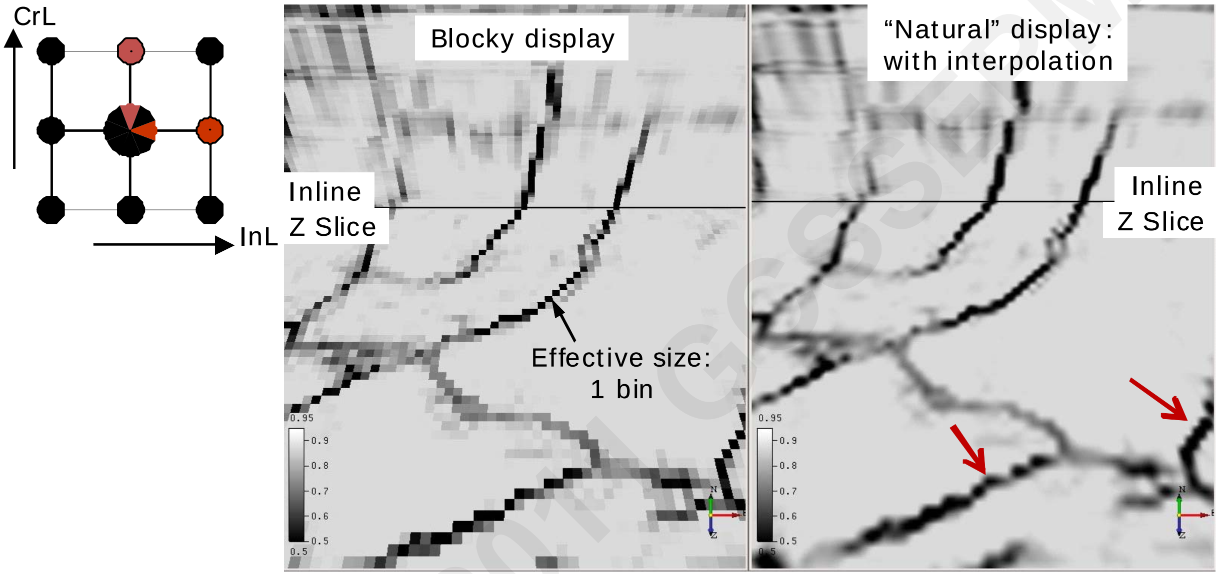
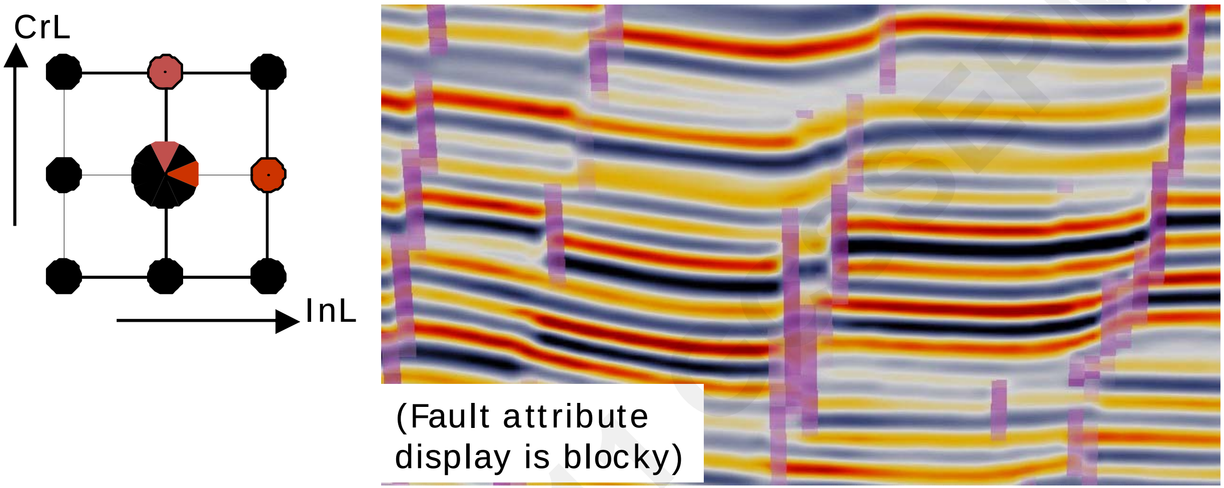


**Figure 12. Dip-steered similarity on an inline and intersecting time slice, with two pairs of perpendicular traces as input. Note the roughness of the interpolated display due to the small bin size (red arrows).**



(Fault attribute display is blocky)

**Figure 13. Dip-steered similarity on a line overlaying seismic data, computed using two pairs of perpendicular traces as input. Note the position of the amplitudes, always on one side of the fault.**

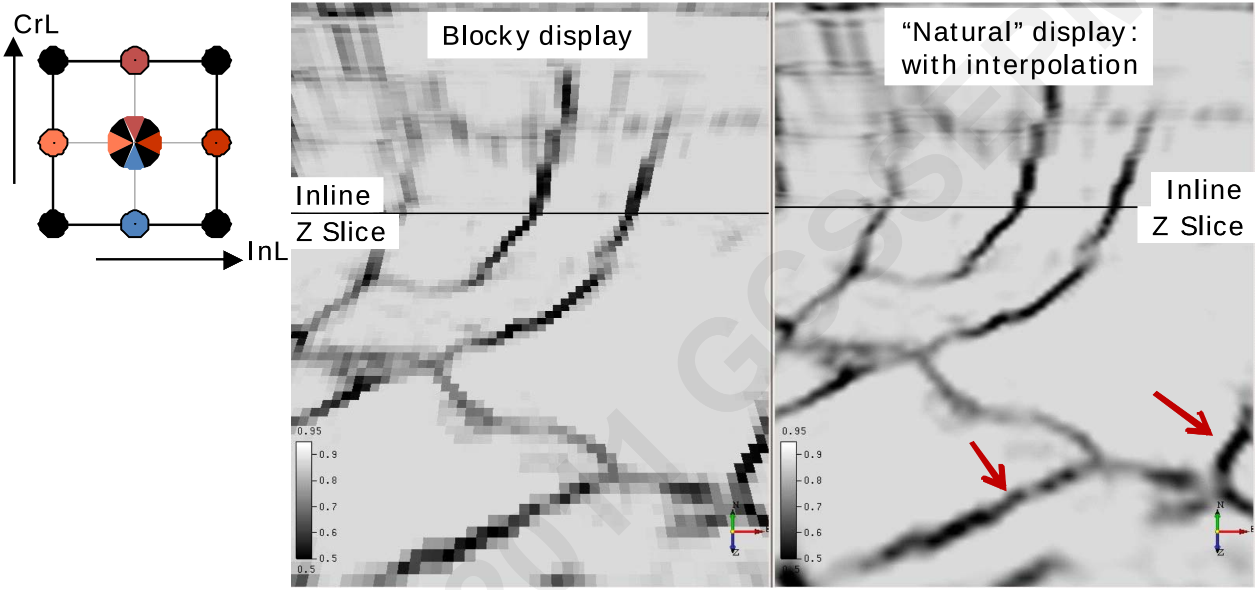


**Figure 14. Dip-steered similarity on an inline and intersecting time slice using four pairs of perpendicular traces as input. Note the reduced roughness compared with Figure 12.**

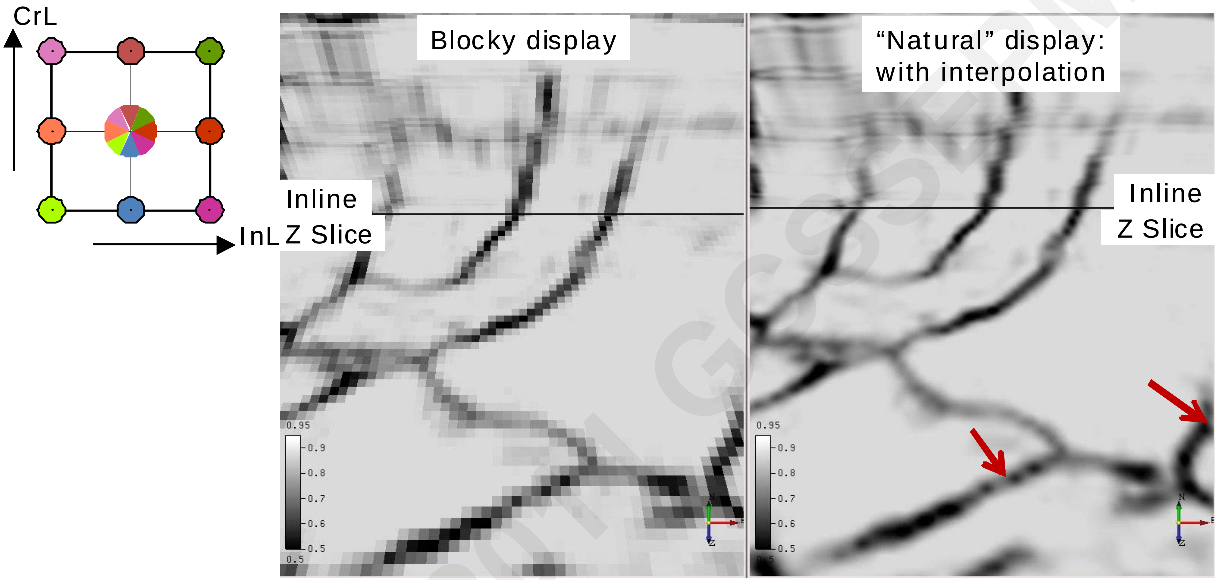


**Figure 15. Dip-steered similarity on an inline and intersecting time slice using eight pairs of traces as input. Note the reduced roughness compared with Figures 12 and 14.**

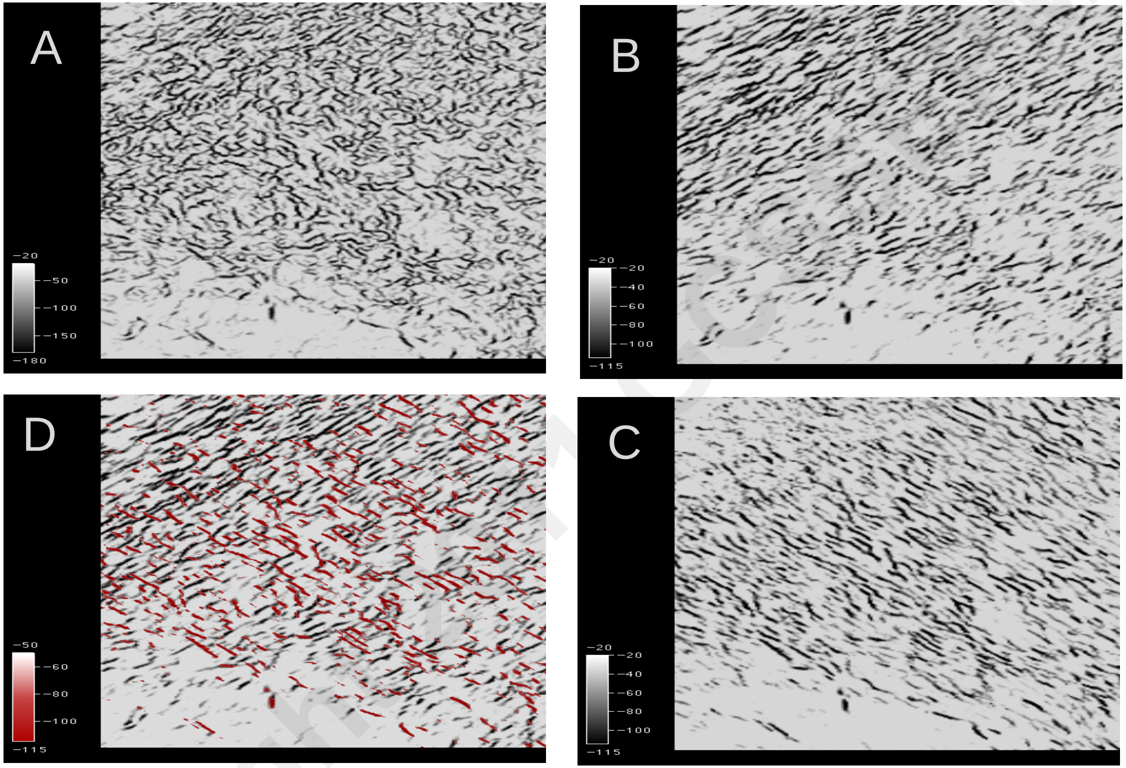


**Figure 16. Directional decomposition of a discontinuity attribute shown on a time slice. Clockwise starting top left. (A) the original discontinuity volume; (B) Northeast-southwest decomposition; (C) Northwest-southeast decomposition; (D) transparent overlay of the two trends showing their interdependency.**

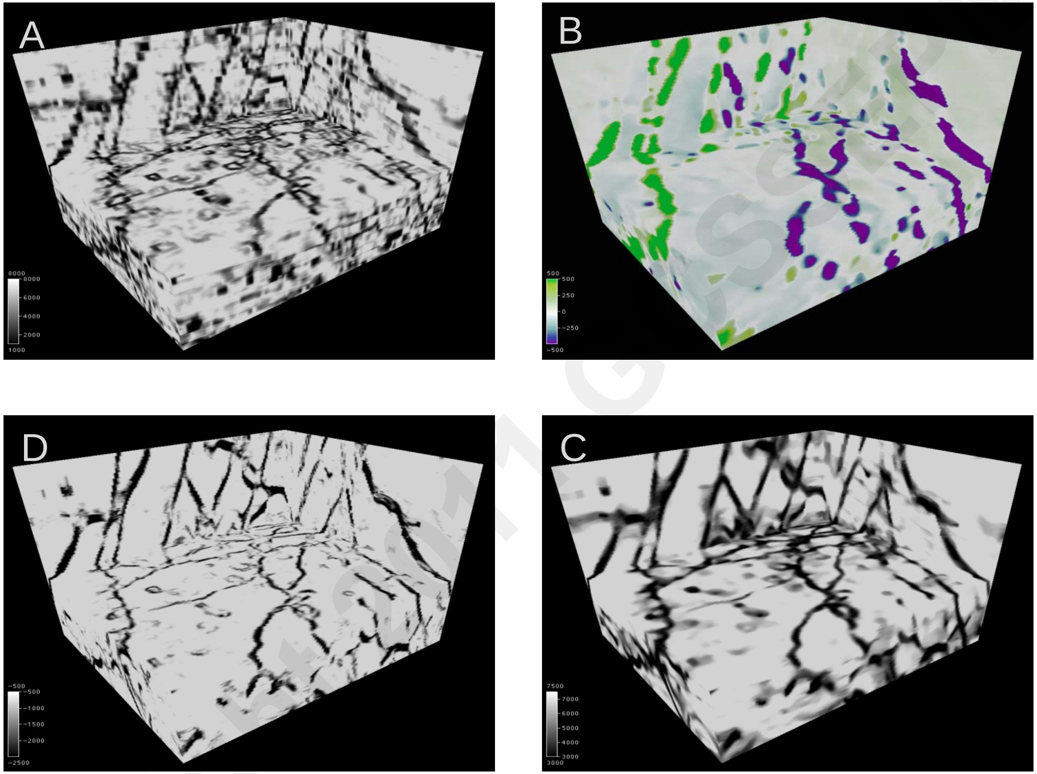


**Figure 17. The result of applying structurally oriented filters using the fault dip. Clockwise from upper left. (A) Discontinuity attribute used as input; (B) Crossline dip component of the dip in the discontinuity volume. (C) The discontinuity volume after application of FCF and FSF. (D) After the additional application of the ridge enhancement filter.**

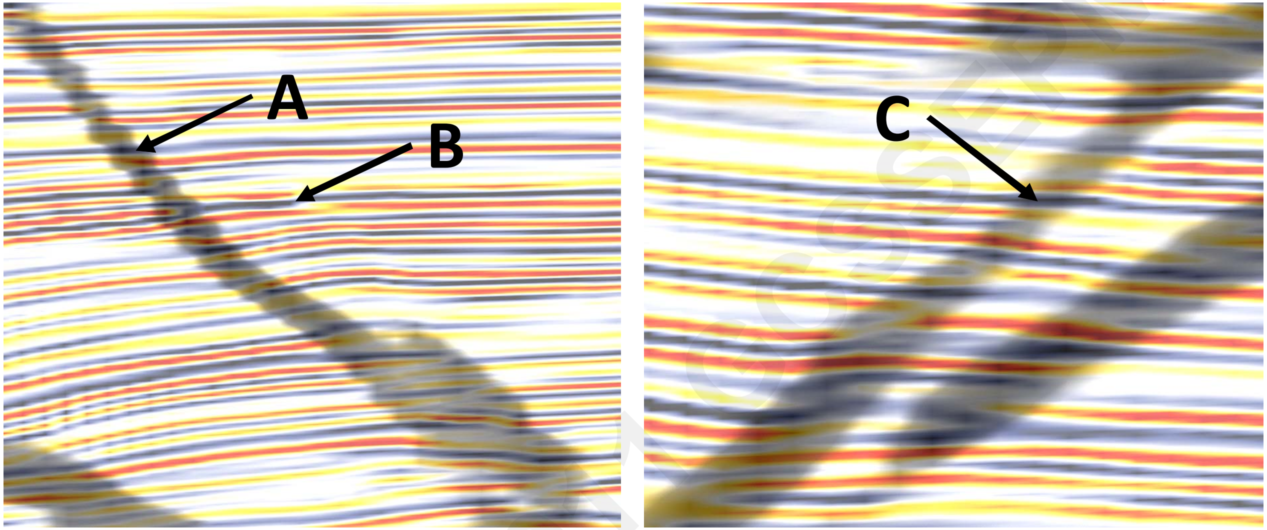


**Figure 18. Illustration of a high-quality discontinuity volume. The volume does not exhibit staircase behavior and is nicely centered about the fault plane, even in the presence of interfingering reflectors (A). Discontinuities not associated with faults are suppressed (B). Even at positions where reflectors show an local apparent continuity (*i.e.*, a numerical continuity, not representing a geological continuity) the discontinuity volume provides a fault indication (C).**