Enhanced coherence attribute imaging by structurally oriented filtering

Christoph Georg Eichkitz,[1*] Johannes Amtmann[1] and Marcellus Gregor Schreilechner[1] investigate the application and limitations of seismic attributes starting with the building of a unique database.

In commercially available software packages there are numerous seismic attributes available designed to help the interpreter identify certain geologic or textural features. Often attribute work can seem like a black box, where we insert our seismic amplitude cube on one side and receive an attribute cube on the other side. These results are then judged empirically on their applicability and correlation with what is known. But are these results really the best that we can get from our input data? Can we do more?

The aim of our research project has been to investigate in detail the application and limitations of seismic attributes. As an initial state of our research project we did the usual literature search. Over time, the number of papers became increasingly large and we decided to build a database, using a keywords system. With this database we can quickly sort papers by attribute categories, by the principal application of the attributes, and by availability of attributes in various software packages.

The knowledge gained from this database is applied to two different data sets focusing on channel and fault detection, as well as suppression of acquisition footprints. To accomplish this we use semblance coherence after data filtering and steering.

Attribute database

Seismic attributes are becoming more and more an integral part of seismic interpretation, with numerous attributes packages available on the market. In many cases the very same attribute is available under several different names. In the last decades hundreds of papers have been written on this topic. In the course of this research project we accumulated and read many of these papers, but due to the volume alone we lost track of various aspects of each over time. As a consequence we developed the idea of building a database that contained most of these papers with reference to key information. The database needed to be a helpful tool, capable of sorting papers into special topics, a certain geological situation, a seismic attribute category, or sub category. In addition the database had to contain and cross reference the names under which seismic attributes are listed in common software packages.

The database is Microsoft Access based. We have collected approximately 750 papers, reaching as far back as 1973. The topics of the papers range from geology, geophysics, and pattern recognition to medical sciences. All in all about 65 different journals and about 55 conferences are listed in the database. For ease of use it was essential that the database defined keywords, which were critical to obtaining useful outputs. We decided to use twelve main attribute groups (e.g. coherence, dip and azimuth, structural oriented filtering). These 12 main attribute categories are divided further into minor attributes. All in all we have split our 12 main attributes into 152 minor attributes in our database (e.g., eigenstructure-based coherence, semblance-based coherence, discrete scan-based dip and azimuth estimation, median filter, principal component filter).

In addition to the main and minor attribute groups each entry in the database contains information about author(s), year of release, journal, conference, and also the abstract of the paper. In Figure 1, a summary of all input parameters and categories is shown. As output from the database you can get a standardized list of the papers dealing with the reference attribute and the name(s) under which the attribute is listed in commercially available software packages.

Seismic attribute calculation

Today, software packages offer a large assortment of seismic attributes. It is easy for a seismic interpreter to generate and evaluate these post stack attributes. The simplest way to proceed would be to insert the seismic amplitude cube, choose an attribute, and then press the calculation button. Seismic attributes are often impracticable for interpretation when calculated this way. They are contaminated with a lot of noise and artifacts associated with the calculation process. An important step prior to calculating attributes for a volume is the conditioning of our seismic data. This conditioning process includes filtering the original data, as well as attribute calculations along the dip of reflectors. The dip of reflectors can be described by the vector dip. The first part of this paper will deal with the estimation of vector dip, the second part will

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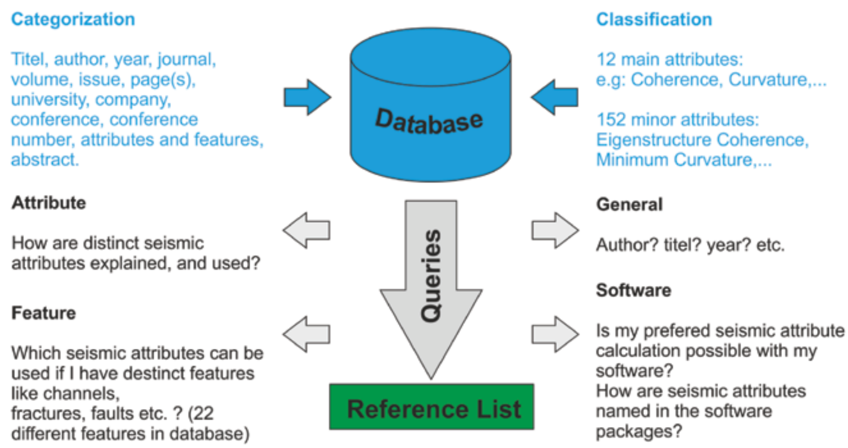

Figure 1 The seismic attribute database contains at the moment about 750 papers. Inside the database for each paper all relevant data like author(s), journal, year of publication, conference, and the abstract is stored. To classify these papers we came up with twelve main attribute categories and 152 minor seismic attribute categories. Each of the papers within the database is classified by these keywords, whereas a paper can get multiple keywords. For the user it is now possible to create queries for attributes, software, application of attributes, keywords in abstracts, or combinations of these issues. The user then receives a reference list, which can be formatted in different standards.

deal with filtering, and in the third part we will focus on coherence calculations.

The estimation of vector dip (vector representation of dip θ and azimuth Φ) can in principal be done using any of three methods; complex trace analysis, discrete scan, and gradient structure tensor.

Vector dip estimation based on a complex trace analysis uses the analytic trace attributes to estimate the apparent angle dips for both inline and crossline directions (Luo et al., 1996 and Barnes, 1996)). The first step in the calculation of dip and azimuth with this method is to calculate the instantaneous frequency ω (Taner et al., 1979) and the instantaneous wavenumbers kx and ky. The instantaneous time dip for both in inline and crossline direction is given by the ratio of kx and ky to ω. Vector dip estimations based on this method are often very noisy and produce somewhat random anomalous patches. To overcome this problem and produce a smoother subsurface image (but at the cost of resolution), Barnes (2000) advises summing many adjacent traces as part of this calculation.

The second method for vector dip estimation is based on a discrete scan of the seismic data. For each sample point in our seismic data the coherence within an analysis window along a discrete number of dips is calculated (Figure 2). The dip with the maximum coherence defines the instantaneous dip for that sample point. This is repeated for all sample points in inline and crossline direction. This general method was proposed by Marfurt et al. (1998), who specifically used the semblance-based coherence calculation for the estimation of dip and azimuth. In place of the semblance coherence method other coherence calculation methods can be used, such as the eigen-structure coherence (Gersztenkorn and Marfurt, 1999) or the least-squares-based coherence calculation by Bednar (1998). The discrete scan method is computationally faster than the complex trace analysis method, but due to the discretization of dip angles, this method might miss subtle features in our data.

The third method for vector dip estimation is based on the gradient structure tensor described by Bakker et al. (2002), and Höcker and Fehmers (2002). Within a defined analysis window the direction is defined in which our seismic data varies the greatest (Figure 3). The dip of our data is defined as the vector perpendicular to the direction of greatest variability. Vector dip estimations using the gradient structure tensor based method is fast, but the resulting steering data can be very noisy. Therefore, it is necessary to apply filtering to this steering cube prior to its use for further attribute calculations.

Seismic data used in the calculation of attributes is often noisy. This noise includes acquisition footprints and processing artifacts resulting from pre-processing steps and migration. Various filters can be applied to reduce this noise. These filters act to enhance our seismic data by improving the signal-to-noise ratio but they might also smear short-wavelength

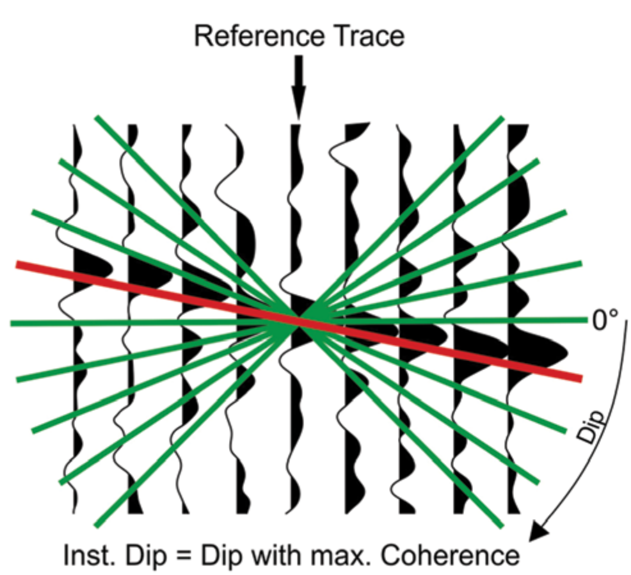

Figure 2 Schematic for the estimation of vector dip using the discrete scan method. In this method the coherence is calculated along a discrete number of dips. The number of adjacent traces, as well as the vertical range used in the estimation can be varied. The coherence algorithm used can be semblance, variance, eigenstructure or least-squares based. The dip with the maximum coherence defines the instantaneous dip. This method is faster in computation than the complex trace analysis method, but due to the discretization of the dips subtle features can be missed.

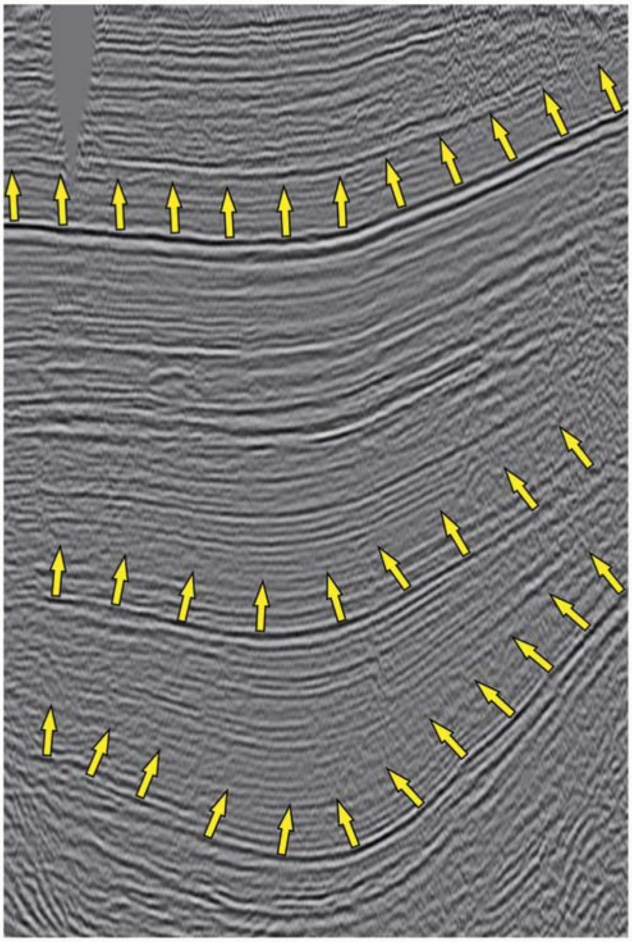

Figure 3 The gradient structure tensor based estimation of vector dip calculates in which direction the seismic data varies the most. This direction (shown as yellow arrows) is perpendicular to the dip of the reflectors. The vector dip estimation by gradient structure tensor based methods is very fast, but has the disadvantage that the resulting steering data tends to be noisy. Therefore, it is necessary to apply filters on this steering cube prior to use it for coherence calculations.

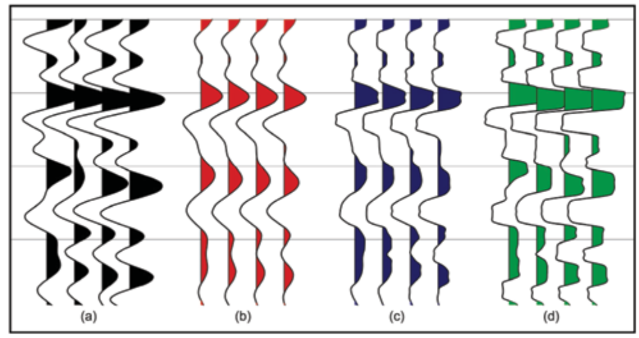

Figure 4 Schematic showing the effect of filters applied on seismic amplitude traces (a). All filters are calculated using a 3x3 search window. The simplest filter is the low-pass (mean) filter (b). It simply averages the data and by that suppresses random noise, but it also smears short wavelength events. The median filter (c) replaces each sample by the median of the samples within the analysis window. By that, it suppresses noise but preserves sharp discontinuities. The edge preserving smoothing filter (d) avoids smearing of discontinuities by using multiple overlapping windows. The algorithm calculates for each of these overlapping windows the variance. Then the samples falling into the window with the lowest variance are smoothed by a mean or median filter.

features (Figure 4). The variety of possible filters is numerous and for the purposes of this paper we will focus only on three basic filtering methods. An expanded discussion of filtering can be found in the work by Al-Dossary and Marfurt (2007).

The simplest filter is the mean (low-pass) filter. In principal, this filter operates as a running window averaging all data samples within the search window. This method suppresses out of range noise, but can blur the data.

In contrast to the mean filter, the median filter is a non-linear filter. This filter replaces the sample in the centre of the search window by the median of the samples within this window. With the median filter, sharp discontinuities are preserved and random noise is suppressed. However, it is not possible to preserve thin lineaments with this filter. A combination of the mean filter and the median filter is the α-trimmed mean filter. The factor α varies between 0 (mean filter) and 0.5 (median filter). The α-trimmed mean filter might be a better compromise than the median filter, but similar to the median filter, it is not capable of preserving thin elements.

The edge preserving smoothing filter (EPS), first described by Luo et al. (2002), is in principal an adaption of the Kuwahara (1976) filter. For each sample point in our seismic data multiple overlapping search windows are activated. The variance is calculated for each of these search windows. Then, for the window with the lowest variance the average sample is determined and substituted as the new value for the sample point. With this method a smoothing operator is applied on windows that do not span discontinuities. Therefore, the edge preserving smoothing is capable of suppressing noise without smearing major discontinuities

Coherence as used in signal processing represents the relationship between two values or groups of values. For seismic interpretation coherence is a representation of the similarity between seismic waveforms of neighbouring traces. Rapid changes in seismic waveform result in low coherence events. These low coherence events can then be correlated with faults, fractures or channel edges. Coherence can be calculated using several methods. These include cross-correlation-based coherence (Bahorich and Farmer, 1995), semblance-based coherence (Marfurt, 1998), eigenstructure-based coherence (Gersztenkorn and Marfurt, 1999), gradient structure tensor-based coherence (Bakker, 2002), least-squares-based coherence (Bednar, 1998), higher-order statistics-based coherence (Lu et al, 2005), and entropy measurement-based coherence (Cohen & Coifman, 2002). Another possibility for calculating coherence is variance-based methods, where the variance is in principal one minus the semblance. For all coherence estimations in this paper the semblance-based coherence was used.

The principal work steps for semblance-based coherency calculations are shown in Figure 5. The semblance-based

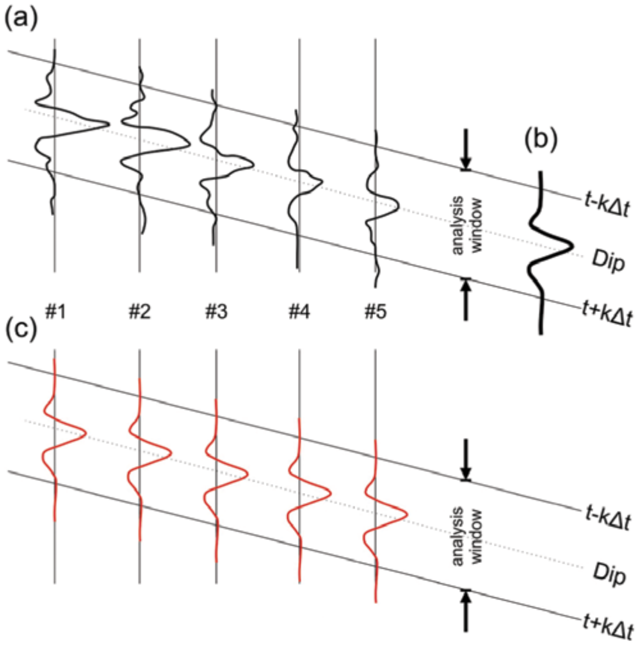

Figure 5 *Schematics for the calculation of a semblance-based coherence. The search window for the calculation follows the estimated vector dip. The first step in the algorithm is to calculate an average wavelet (b) from the input traces within the search window. Then all input traces are replaced by the average wavelet (c). Finally, we calculate the semblance coherence by building the ratio between the energy of the average traces to the energy of the input traces. (Modified after Chopra & Marfurt, 2007).*

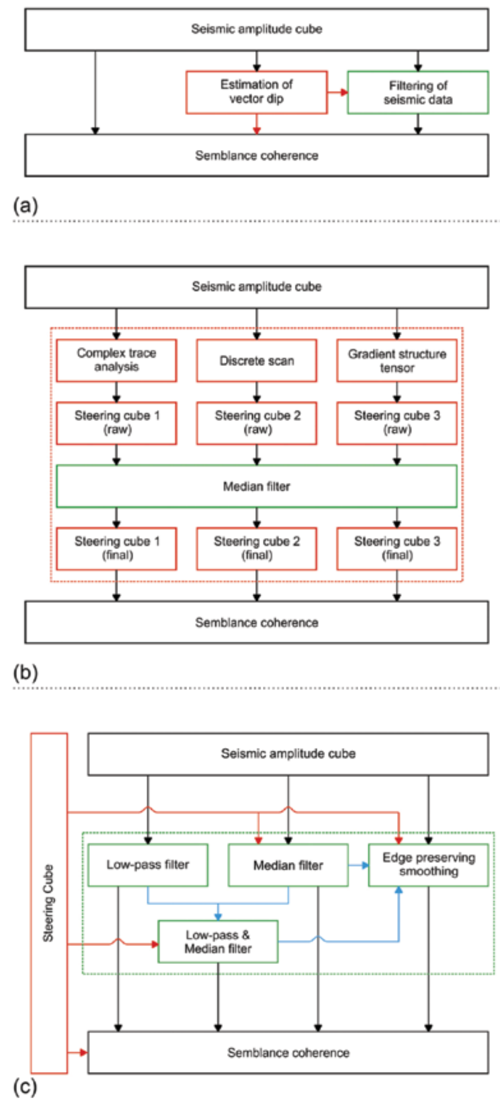

Figure 6 *Flowchart showing the general workflow used for the calculation of semblance-based coherence (a). The process consists of three work steps, the estimation of vector dip (red box), the application of filters on the seismic amplitude cube (green box), and the calculation of semblance-based coherence. The estimation of the vector dip can be done by three different approaches (b). The vector dip can be either calculated using a complex trace analysis, by discrete scan, or by gradient structure tensor. The initial results of these estimation methods are raw steering cubes. A semblance-based coherence calculation using these raw steering cubes yields in low quality results that contain a lot of noise. Therefore, it is advisable to apply a median filter onto these raw steering cubes (green box). From this we get final steering cubes, which can be used for further calculation steps. To enhance the results in coherence calculation, we apply filtering onto our seismic amplitude cube (c). The filters used were basically the mean (low-pass) filter, the median filter, and an edge preserving smoothing. After each filter applied we calculate the semblance-based coherence and compared the results. The first step is to apply only one filter onto the seismic data. The median filter and the edge preserving smoothing can also be dip guided by the steering cube (see red arrows) to improve the quality of the resulting coherence. The next step is to combine all three filter methods (see blue arrows). By using multiple filters the signal-to-noise ratio increases. Especially, suppression of acquisition footprints is much better. The optimal workflow using these methods is to use the median filtered discrete scan based vector dip estimation in combination with a low-pass filter, followed by a steered median filter, and finally followed by a steered edge preserving smoothing.*

coherence calculation takes into account several traces (whereas the cross-correlation-based method only considers two adjacent traces). First, we calculate an average wavelet from our input traces. Then we replace all our input traces by this average wavelet. And finally, we calculate the semblance-based coherence by dividing the energy of the average traces over the energy of the input traces. For the semblance-based coherence calculation it is necessary to define dip and azimuth prior to calculation to avoid low coherence values related to bedding effects. The results of the semblance-based coherence can be predominantly noise if the calculation is performed close to zero crossings. To avoid that problem the semblance-based coherence is usually calculated as an average semblance over a defined vertical search window (Chopra and Marfurt, 2007).

Workflow

The aim of this study is to find an optimal workflow for generating coherence cubes. To this end, we use one small seismic cube (250 x 250 lines) for training purposes and then apply the knowledge gained to a second cube, which is about four times the size (530 x 400 lines) of the training cube. We use the software package OpendTect (dGB Earth Sciences) and the semblance-based coherency algorithm for attribute performing the necessary calculations. The principal workflow (Figure 6) consists of establishing volumetric dip and azimuth cubes (steering cubes), apply filtering, and compute a coherence cube after each work step. These coherence cubes are then contrasted with each other.

The first step in the workflow is to create volumetric dip and azimuth cubes for a cropped volume. In OpendTect dip and azimuth cubes can be calculated using the complex trace analysis method (FFT steering), the discrete scan method (event steering), or the gradient structure tensor-based method (BG fast steering). These steering cubes are used for calculating dip guided coherence cubes. Coherence cubes calculated with these raw steering cubes tend to be noisy. The results of the coherence calculation can be improved (reduction in noise) by prior filtering of the steering cubes. We use a median filter for enhancement of the steering cubes. The new steering cubes can be used to calculate a new set of dip guided coherence cubes. In general, filtering of the steering cubes improves the quality of the coherence cubes (Figure 7). Especially noticeable is the reduction in the acquisition footprints evident in our raw data. The steering cubes calculated by the complex trace analysis and the discrete scan method show the best results. The calculation of the discrete scan cube is much faster than the complex trace analysis cube. Therefore we choose to calculate the discrete scan cube for the whole cube and to use this steering algorithm for further calculations in our workflow.

After finding an optimum steering cube for our data, we tested different filters on our original seismic data. The purpose of the filters was suppression of the acquisition footprints and enhancement of signal-to-noise ratios. We have tested a mean filter, a median filter, and an edge preserving smoothing filter. As the first step in the workflow each of these filters is applied directly to the seismic amplitude cube. After that, we calculate a semblance-based coherence cube for each resulting cube.

The next step is to combine the various filters. We apply a median filter to a mean filtered cube and a mean filter to a

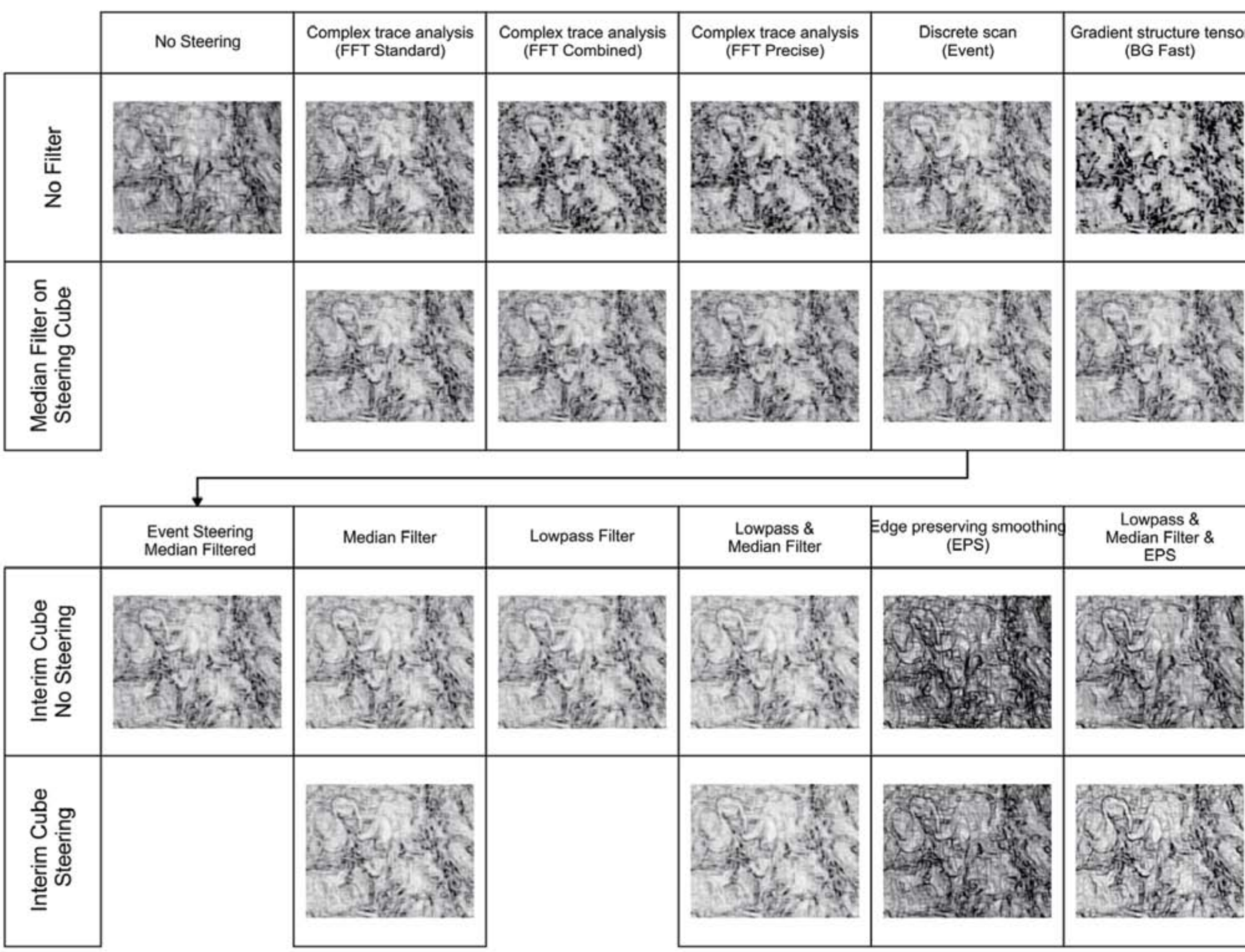

***Figure 7** Summary of the applied workflow. The upper two rows show the testing of the different methods for vector dip estimation. In the first row no filter is applied on the steering cubes, whereas the second row shows the results if we apply a median filter on the steering cubes. The lower two rows show results for different filter algorithms. In the third row the filters are applied onto the data without dip guidance. For the results in row four also the filters are dip guided and thus improve the coherence calculation. The best results are achieved by combination of a low-pass filter, with a steered median filter, and a steered edge preserving smoothing.*

median filtered cube. What we notice, is that there is almost no observable difference in the results of these two workflows, in spite of the fact the mean filter is a linear filter and the median filter is a non-linear filter. In addition we test the combination of edge preserving smoothing with the mean and with the median filter. For this combination the edge preserving smoothing is always the final procedure in the workflow. All of the filters are either directly applied or if possible (only for median filter and edge preserving smoothing) the filters are dip guided. The final workflow applies a mean filter on the original seismic amplitude cube, then a dip guided (discrete scan steering) median filter to the mean filtered cube, and finally, a dip guided edge preserving smoothing to the median filtered cube. With this workflow we are able to definitely enhance the semblance-based coherence calculation. Most noteworthy is how much sharper the geologic channels appear and how well the acquisition footprints are suppressed (see Figure 8).

After establishing an optimum workflow for the first seismic cube, we apply this workflow to the second seismic cube. As in the first case, we initially test the difference steering algorithms with and without median filtering. The results for these tests are similar to the ones from the first example. Also the complex trace analysis and the discrete scan provide the best results and are therefore used for vector dip estimation. This decision was based on the quality of the steering cubes and on computation time. Then we apply the same filtering work steps to the seismic amplitude cube as in the previous case. The original seismic amplitude cube is very noisy with significant acquisition footprints. With this workflow we can once again suppress the acquisition footprints. At the same time we have preserved the geological features of interest and even enhanced the appearance of these features in the coherence cube. In Figure 9 the comparison is shown between a simple press the button

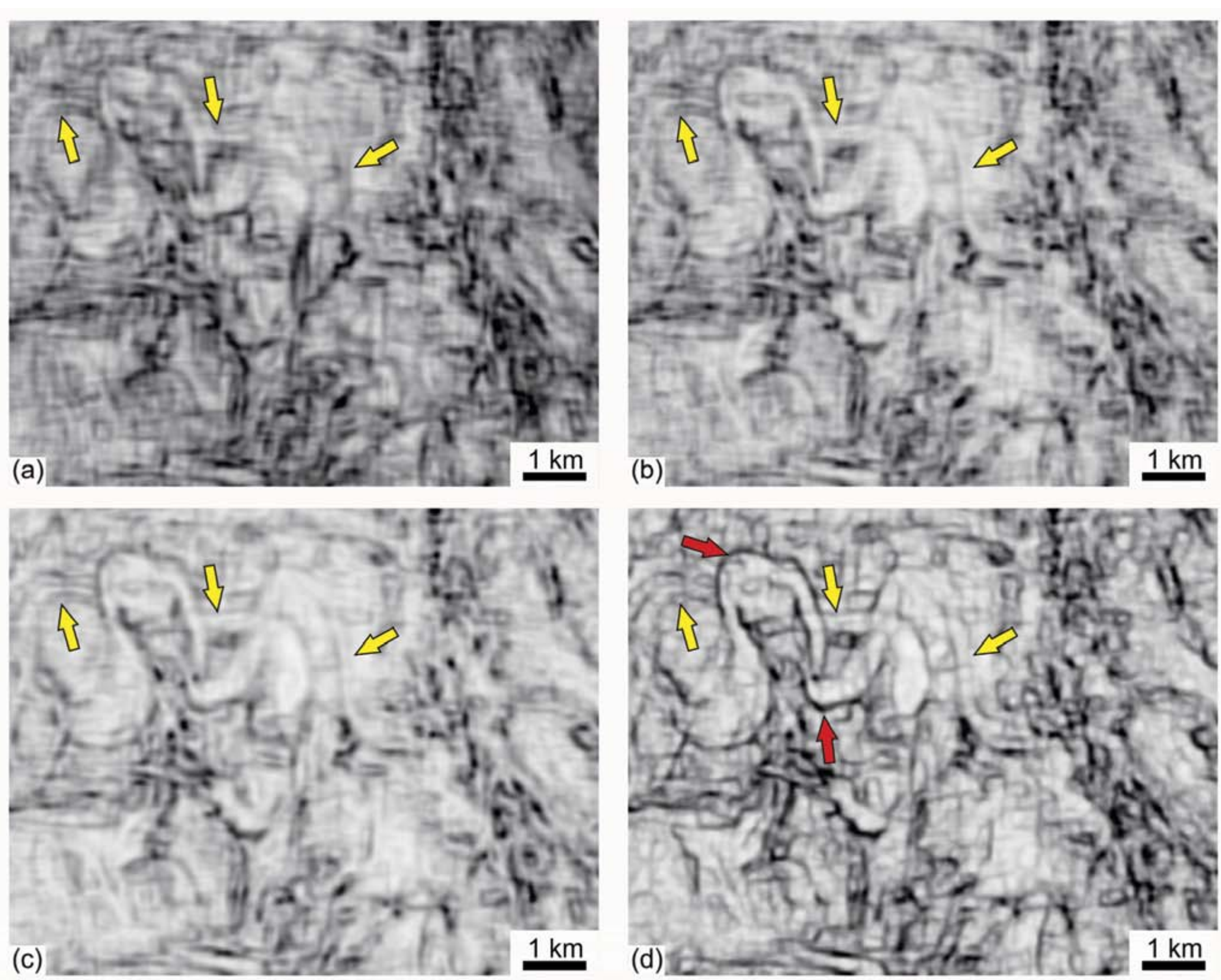

Figure 8 Depth-slice for the first case study, showing the semblance coherence for touch of a button (a), low-pass filter (b), combination of low-pass filter and steered median filter (c) and the combination of low-pass filter, steered median filter and steered edge preserving smoothing (d). The channel system becomes sharper (red arrows) and clearer to identify from (a) to (d). Some of the features cannot or can only hardly be seen on the touch of a button picture (see yellow arrows).

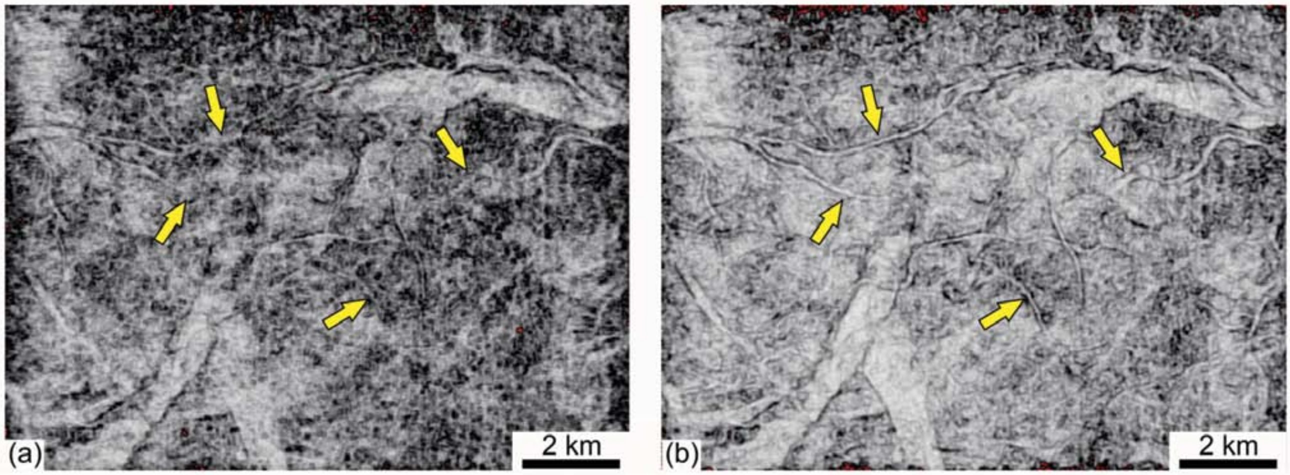

***Figure 9** Time-slice for the second case study. The left picture (a) shows the semblance coherence calculated without any filtering and steering of data. The right picture (b) shows the same time-slice, but in this case the data is filtered and steering is used according to the workflow described before. The yellow arrows indicate some channels where a clear improvement of the semblance coherence can be observed. Some of these channels – especially at the two arrows at the top left – cannot be seen if we interpret a simple touch of a button coherence (a).*

coherence cube (default values, without steering), and the coherence cube calculated after applying all work steps in our workflow. Channel features not seen in figure 9a can now be clearly seen and blurry channel features in the default coherence operation are now depicted as sharp events.

Conclusion

Attribute analysis is a useful seismic interpretation tool. But the number of attributes and synonyms for any one attribute is enormous. With the help of the access database we developed it is possible to establish order and save time evaluating viable approaches. The database is a useful tool to quickly get information on attributes, their application on given geological problems, and their various names in different software routines. Based on the knowledge gained from the database, we developed a workflow for coherence calculation that increased the quality of our coherence cubes. With the help of this workflow we greatly suppressed acquisition footprints without smearing the geological features of interest. This is especially true, for channel systems and faults.

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