Tectonic forces bend and tilt the earth’s crust and thereby create many of the structures under which we find hydrocarbons. However, the bending and tilting also present a challenge to attribute computation and automated interpretation of the seismic data. Nevertheless, local dip information is a crucial element in seismic stratigraphic internal reflection configuration [1]. Hence, a robust seismic attribute should be able to handle dipping layers in a consistent way. For example, the traditional approach of extracting attributes along vertical traces, irrespective of any dipping nature of the data, clearly imposes a risk of introducing artifacts. This kind of artifacts may not be apparent on horizon or time-slice views of the attributes, but do still impose risks of poor mapping and displacements. In order to avoid such artifacts, the attribute computation should in general either explicitly capture or be invariant to dip and azimuth effects. Furthermore, proper dip and azimuth estimates also enable layer-consistent smoothing and edge enhancement of the seismic data.

In this paper, we will first briefly review the dip/azimuth estimation approach introduced in [2], [3], and then we will describe approaches using this estimate for signal smoothing (both with and without edge enhancement) and for guiding attribute computation.

Dip and azimuth estimation

The approach we introduced in [2], [3] to dip and azimuth estimation consists of three steps: (1) Gradient vector estimation, (2) local gradient covariance matrix estimation, and (3) principal component analysis. The approach is for completeness summarized briefly below.

Gradient vector estimation: The first element of the dip/azimuth estimation is to compute the gradient \( \nabla x(t_1,t_2,t_3) \) of the 3D seismic signal \( x(t_1,t_2,t_3) \). Several discrete approximations of the gradient are available in the literature.

Local gradient covariance matrix estimation and principal component analysis: The three-dimensional gradient vector represents the fine-scale local dip and azimuth of the data, but might be contaminated by noise and other artifacts. Hence smoothing is necessary. However, due to vector wraparound effects, this smoothing is non-trivial. This is solved by estimating the covariance matrix, \( \mathbf{C} \), of the gradient vectors and determining the dominating dip and azimuth as the direction of the principal eigenvector, \( \mathbf{v}_1 \), of this matrix. A localized estimate of \( \mathbf{C} \), \( \mathbf{C}(t_1,t_2,t_3) \), is obtained by replacing the global covariance estimate (low-pass filtered) local estimate, thus also making the eigenvectors local; \( \mathbf{v}_1(t_1,t_2,t_3) \). The window size is adjustable, allowing easy noise vs. resolution (i.e. scale-space [4]) tuning.

Dip/azimuth confidence measure: There will be three eigenvectors of each \( \mathbf{C} \)-matrix, each associated with one eigenvalue, \( \lambda_i \). The larger the difference between the dominating \( \lambda_1 \) and the two other \( \lambda_i \)'s, the more reliable the dip and azimuth estimate is. This relation can easily be captured in a local confidence measure, \( c(t_1,t_2,t_3) \), of the estimated dip and azimuth, also referred to as the chaos seismic texture attribute [3].

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1 The angles -180° and +180° are the same, but averaging two neighbors with these values gives the angle 0°.
Layer-parallel smoothing

The noise level of seismic data varies tremendously and noise is a significant problem in many data sets. One way to suppress noise is smoothing. Furthermore, using the principles of scale-space theory [4], detection of geological features at different resolutions may also take advantage of smoothing; large smoothing leaves primarily the major features, etc. In this section, we present two variants of seismic data smoothing, differing in the preservation of “features of interest”.

By knowing the locally dominating strata orientation in the seismic data (the dip and azimuth), it is possible to do any kind of filtering parallel or orthogonal to the strata [2]. One incarnation of this general concept is smoothing parallel to the layers, while not applying smoothing orthogonally. With such a filter, the “vertical” resolution is preserved, but lateral continuity is enhanced. A 2D Gaussian low-pass filter, known for its joint optimum resolution in time and frequency, is applied. We obtain computational efficiency by utilizing the filter’s separability. The unit pulse response of the filter is

\[ h_c(k) = \frac{1}{\sqrt{2\pi\sigma}}\exp\left(-\frac{k^2}{2\sigma^2}\right) \]  

in each dimension. In each dimension, the filtering is performed along lines respecting the local dip/azimuth of the data [2], [5]. We note that this is essentially the same type of filtering elsewhere referred to as “structure oriented filter” [6]. Results can be seen in Figure 1(b).

Practical experiments have proved that the layer-parallel smoothing is a very powerful noise suppressing technique [7], but with the commonly undesired effect of blurring features such as faults. However, the confidence measure \( c(t_1,t_2,t_3) \) introduced earlier provides an efficient means for steering the filtering according to edges. To obtain this, we replace the symmetric Gaussian filter of Equation (1) with an asymmetric one that filters only to the side of largest accumulated \( c(t_1,t_2,t_3) \). Results using this filtering scheme can be seen in Figure 1(c). Better resolution at the faults, while still maintaining the smoothing can be observed by careful inspection. The effects on an arbitrary fault attribute are observed in Figure 1(d-f).

Dip/azimuth derived seismic stratigraphic texture attributes, e.g. 3D flatness texture attribute

Given that we have a proper orientation estimate for the 3D data cube, deriving measures of several of the (stratigraphic) internal reflection configurations of Vail and Mitchum [1] is a matter of computing statistics of the orientation field. A measure for the 3D flatness texture attribute (parallel, even reflection configuration [1]) for example will then be the local orientation variance, Figure 2(b). This attribute played a major role in identification of karst features, not possible to map without good 3D attributes and classification tools – see [8] for a further description of these classification experiments.
Figure 2. Parallel even seismic texture attribute (b) of the seismic in (a). The detected anomaly corresponds to a possible collapse feature related to karstification. The flatness attribute played an instrumental role in making a 3D classification (c) of the karst feature. See [8] for further details on the karst classification in (c).

Dip/azimuth guided seismic attributes and Gabor frequency spectral decomposition

The dip/azimuth estimates may also be used for conditioning in attribute calculation. To appreciate the importance of this, consider Figure 3, where a comparison between a non-conditioned and a conditioned fault attribute is illustrated. The conditioning also applies to facies type of attributes, such as frequency. Gabor filter banks have proven very useful in frequency domain image texture analysis [9]. The Gabor filter is a (frequency) band-pass filter constructed by a cosine modulated Gaussian. We apply a bank of one-dimensional Gabor filters along dip/azimuth guided layer-orthogonal traces. The filters are followed by a local energy computation [9] and finally the overall amplitude for all frequency bands is normalized. In Figure 4 we can see some examples of the Gabor attribute cubes, with good identification of stratigraphical and fluid features. Further results using these attributes as an essential element can be found in [10].

Figure 3 The effect of dip/azimuth conditioned attribute computation. (a) Input seismic, (b) fault attribute without dip/azimuth guiding, and (c) fault attribute with guiding. We can clearly see how the unguided attribute picks up the dipping layers as well as the fault response. (The illustration is optimized for highlighting this effect, and not representing optimal settings for fault mapping.)

Summary

In this paper, we have demonstrated how the local dip/azimuth estimate of a seismic volume is a strong input for increasing the lateral connectivity of the seismic signal, and how we can use elements of it even for edge enhancement within the smoothing step. Furthermore, we have shown how the orientation estimates give rise to powerful attribute computation useful for identification of stratigraphic features, exemplified by detection of a karst feature. We have demonstrated how we may use the orientation estimate to condition attribute computation in structurally complex areas. Finally, we have described a seismic frequency attribute based on the Gabor filter bank, commonly used in the image processing literature, also using the orientation estimate for preconditioning.

References


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Figure 4 Seismic cube (a) and two of its Gabor attribute cubes (b-c). We can see how the different facies generate different attribute signatures. These attributes have proven instrumental in facies and fluid classification (d-e) [10].