3-D Local Radon power Spectra for seismic Attribute Extraction

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Summary

In this paper we discuss a method for volume attribute extraction that is based on a new type of local Radon power spectrum. The new algorithm results in robust and geologically meaningful volume attributes, such as volume dip and azimuth. Seismic volume attribute analysis greatly facilitates the interpretation of large 3-D seismic data volumes. However, horizon attribute maps are generally more easy to interpret than volume attribute images, which are usually time slices or cross-sections. We show that, for dip estimation, the volume attribute image is very similar to the horizon dip map.

Introduction

The demand for more detailed, but less time-consuming, interpretation of 3-D seismic data volumes has incited an effort to develop more effective methods for attribute extraction and analysis. Volume attribute analysis has been very succesfully applied to provide the larger-scale structural and stratigraphic framework before actual 3-D seismic interpretation. (Bahorich and Farmer 1995; Hoogenboom *et al.* 1997). However, seismic attributes are also applied for the detection and analysis of subtle features in a conventional 3-D seismic interpretation. Horizon attribute maps, such as dip and azimuth maps, have proven to be very effective to find and interpret structures that are less easily detected in the original data (see e.g. Hoetz and Watters 1991).

Techniques that are rooted in image processing, such as volume attribute analysis, have some advantages over horizon based analysis methods. Volume attribute extraction is performed off-line, without the need of horizon picking. This can save a considerable amount of time for a 'quick-look' structural interpretation. However, using horizon surfaces as attribute generators, instead of the signal itself, has the advantage that the geological significance of the attributes is more easily inferred. In this paper we will describe a technique for extracting geometrical attributes such as volume dip and azimuth directly from 3-D seismic data. The dip and azimuth is extracted from a local Radon spectrum of a small volume of data. The procedure results in a dip and azimuth estimate at every subsurface sample point (see Figs. 1 and 2). We can compare the resulting attribute estimates with the results that are obtained by horizon attribute extraction (see Figs. 3 and 4).

Attribute extraction procedure

In the last decade tremendous progress has been made in non-stationary spectrum estimation. An example is the development of the wavelet transform. The wavelet transform has received considerable attention from geophysicists, mainly for data compression, but also for data analysis and processing. In time-frequency data analysis, the wavelet transform often gives better results than classical techniques, such as sliding-window Fourier analysis or complex-trace analysis. Wavelet and Fourier representations are obtained by linear transformations, which is clearly an advantage in data processing applications. However, if the application is data analysis, non-linear representations may be far more effective, because of their better resolution compared to linear transforms. The spectrogram (the square of the sliding window Fourier transformation) and the Wigner distribution are two non-linear (quadratic) representations that belong to a much larger class of representations (Cohen 1995). This class of quadratic local frequency representations is a very effective tool for seismic signal analysis (Steeghs 1995b) and seismic attribute extraction (Steeghs 1995a). In this paper we describe an attribute extraction procedure that is based on a 3-D local spectrum estimation with a quadratic representation. The method is based on the observation that a 3-D local Radon representation provides a local dip/azimuth decomposition of the data. Hence, this decomposition can be used to estimate the dip and azimuth of seismic events.

Local Radon power spectra

Our definition of the local power spectrum is based on a generalization of the autocorrelation function to the non-stationary case. The non-stationary power spectrum is defined as the Fourier transform of a local auto-correlation. A 3-D local autocorrelation function of a seismic data set $u(\boldsymbol{x}, t)$ can be defined as

$$R(\boldsymbol{x}, t; \boldsymbol{\xi}, \tau) = u(\boldsymbol{x} + \frac{1}{2}\boldsymbol{\xi}, t + \frac{1}{2}\tau)u^*(\boldsymbol{x} - \frac{1}{2}\boldsymbol{\xi}, t - \frac{1}{2}\tau), \tag{1}$$

where $\boldsymbol{x} = \{x_1, x_2\}$ is the spatial coordinate vector (in-lines and cross-lines), t is the time coordinate and $\boldsymbol{\xi} = \{\xi_1, \xi_2\}$ and τ are space and time shift variables. The non-stationary power spectrum is now defined as the Fourier transformation over the space shifts $\boldsymbol{\xi}$ and time shift τ, i.e.

$$W(\boldsymbol{x}, t; \boldsymbol{k}, f) = \iint \exp(\mathrm{j}2\pi(\boldsymbol{k\xi} - f\tau))R(\boldsymbol{x}, t; \boldsymbol{\xi}, \tau)\mathrm{d}\boldsymbol{\xi}\mathrm{d}\tau, \tag{2}$$

where $\boldsymbol{k} = \{k_1, k_2\}$ is the spatial frequency vector and f is the temporal frequency. This non-stationary power spectrum is known as the Wigner distribution of the signal $u(\boldsymbol{x}, t)$. A local Radon representation can be obtained from the Wigner distribution by setting $\boldsymbol{k} = f\boldsymbol{p}$, where $\boldsymbol{p} = \{p_1, p_2\}$ is a dip (or slowness) vector. The local dip-frequency spectrum $W(\boldsymbol{x}, t; \boldsymbol{p}, f)$ can be obtained by interpolation of the 3-D local frequency spectrum of Eq.(2). The local Radon power spectrum is obtained by inverse Fourier transformation with respect to temporal frequency,

$$S(\boldsymbol{x}, t; \boldsymbol{p}, \tau) = \int_0^\infty \exp(\mathrm{j}2\pi f\tau) W(\boldsymbol{x}, t; \boldsymbol{p}, f) \mathrm{d}f. \quad (3)$$

We can obtain a local dip/azimuth decomposition by setting $\tau = 0$ and the change of variables $|\boldsymbol{p}| = (p_1^2 + p_2^2)^{\frac{1}{2}}$ and $\alpha = \tan^{-1}\{p_1/p_2\}$. The volume dip and azimuth at each subsurface sample point $(\boldsymbol{x}, t)$ is then estimated by computation of the mean $|\boldsymbol{p}|$ and α of the local dip/azimuth spectrum $S(\boldsymbol{x}, t; |\boldsymbol{p}|, \alpha)$.

Results

In Fig. 1 a time slice is depicted from a conventional reflectivity data set from the North Sea. In a stratigrafic sense, the slice is located within the Tertiary and the lithologies comprise sandstones and shales. In the figure below a slice is pictured of the volume dip attribute, calculated in the manner described above, at the same reflection time. The dipvolume was calculated using a small operator, 4 by 4 traces (100 [m] by 100 [m]) and 32 [ms], thus accentuating discontinuities in the dataset. Whereas only major faults are visible on the conventional reflectivity data, minor faults and discontinuities can easily be observed on the slice from the dipvolume. Furthermore some stratigraphic features are visible, such as the channeling systems at the right hand side.

A strong event around 1300 [ms] was picked and autotracked on the reflectivity volume. Next the horizon dip was calculated using a 3 by 3 trace operator in the conventional manner, resulting in the map depicted in Fig. 3. Using the picked times at each CDP, a volume dip calculation was carried out, again using a small operator. The result is depicted in Fig. 4. When comparing the two images, it is clear that the volume attribute map shows more details in a more pronounced manner than the conventional dip map. The shape of the minor faults at the lower left hand is expressed in a more detailed manner by the volume dip map. Furthermore, at the upper part of this map, stratigraphic features are visible which could be interpreted as channelling and/or slumping. Obviously, by its very nature, the the volume dip attribute is more susceptible for random noise than the horizon dip map. At places the volume dip attribute yields a confused image of seemingly high dips. This is caused by aliasing, which in turn is caused by the size of the operator.

These comparisons show that the volume dip attributes provide a fast and reliable estimation of local dips of seismic events.

Discussion

The comparison of Figs. 3 and 4 shows that the volume dip estimation from a local Radon power spectrum provides a robust and meaningful estimation of signal properties. There are many applications in which this strong correspondence between horizon surface properties and volume attributes can be exploited. Volume attribute cubes have the advantage that attributes are available for each subsurface sample point. Hence, they can be used to estimate event dips below and above horizon surfaces, providing information on the internal geometry of stratigraphic units. The most obvious application is the use of volume attributes in autotracking horizons, but also the possibility is opened for automated tracking of faults thanks to its 3-D operator.

References

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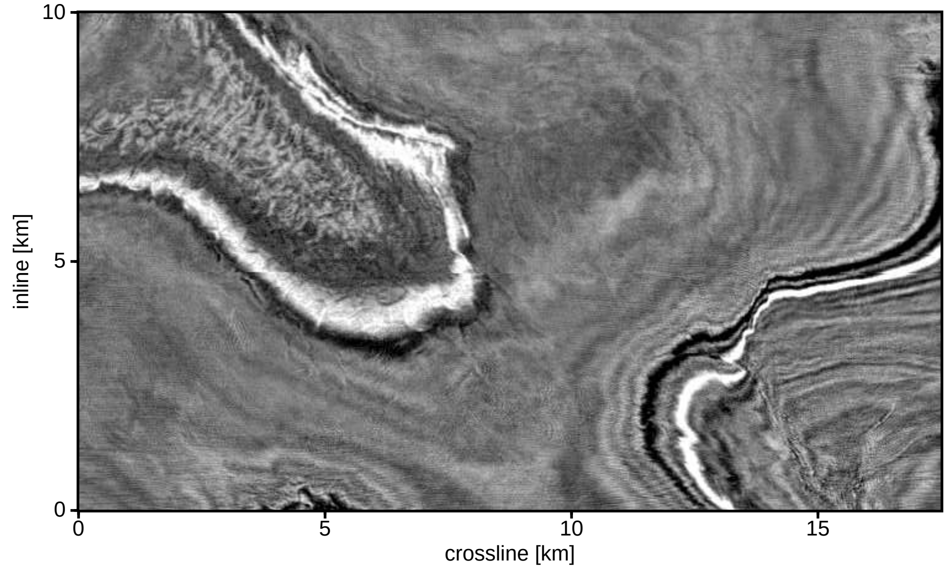

Fig. 1: Time slice at 1.3 [s].

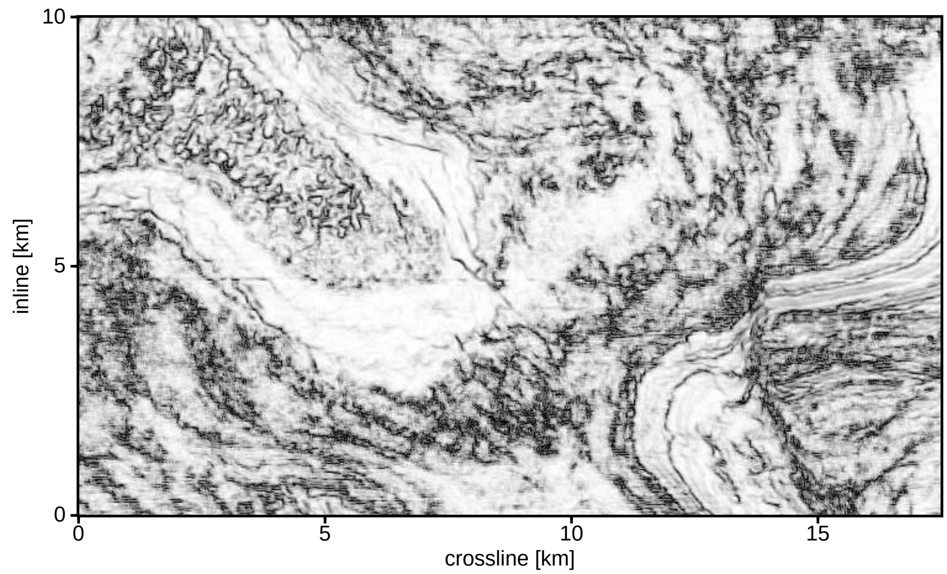

Fig. 2: Volume dip time slice from a 3-D seismic data set. A 4 by 4 by 4 (100 [m] by 100 [m] by 32 ms) operator was used to estimate the dip. Steep dips are given in black, zero local dip is white.

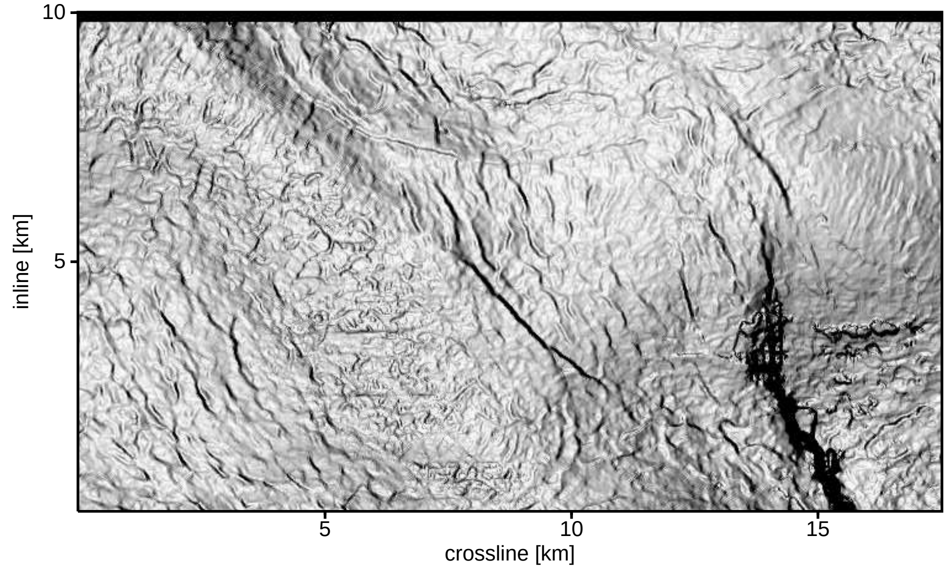

Fig. 3: Horizon dip, computed with a 3 by 3 trace operator in the conventional manner.

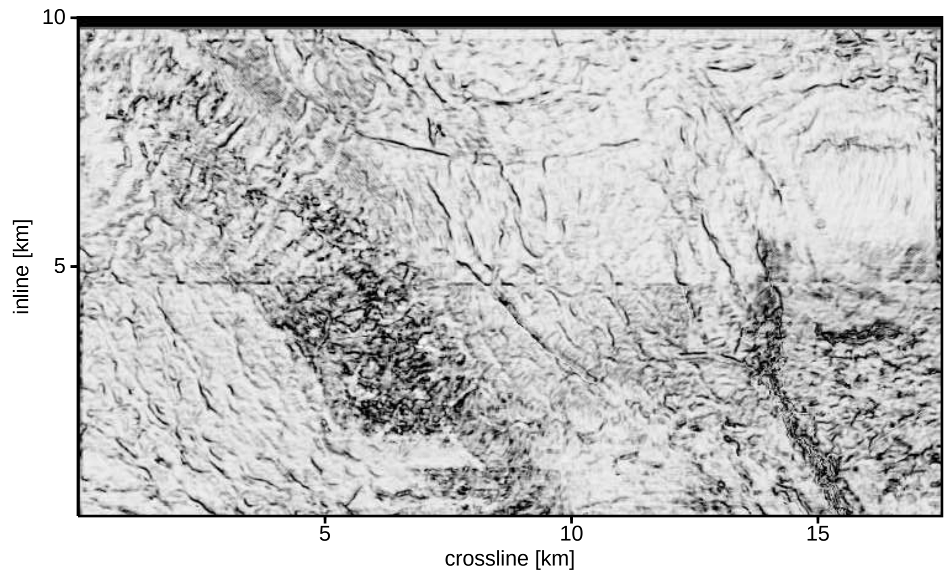

Fig. 4: Volume dip attribute extracted along the same horizon as above.