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SEISMIC COHERENCE MEASURE IN PRESENCE OF RESIDUAL TRACE-TO-TRACE TIME DELAY VARIATIONS

В работе после сопоставительного анализа меры когерентности и предполагаемой модели сейсмической записи предложен новый метод оценки когерентности. Метод обеспечивает большую чувствительность когерентности в присутствии остаточных временных сдвигов после учета локального наклона в окне анализа. Он основан на более реалистичной модели сейсмической записи, которая допускает произвольные вариации амплитуды сигнала, дисперсии помехи и остаточных временных сдвигов. Новый метод апробирован на теоретических и реальных данных.

В роботі після порівнювального аналізу міри когерентності та передбачуваної моделі сейсмічного запису запропоновано новий метод оцінки когерентності. Метод забезпечує більшу чутливість когерентності у присутності залишкових часових зсувів після врахування локального нахилу у вікні аналізу. Він ґрунтується на більш реалістичній моделі сейсмічного запису, яка допускає довільні варіації амплітуди сигналу, дисперсії завади та залишкових часових зсувів. Новій метод апробовано на теоретичних та реальних даних.

In the paper after analyzing the relation of coherence to the supposed mathematical model of seismic data, a new method is presented. It makes coherence more sensitive to the presence of residual time delay fluctuations of the signal after removal of its average local dip in the analysis window. The method is based on a more realistic data model that permits arbitrary trace-to-trace variations in signal amplitude, signal time delay and noise variance. The novel method is tested and compared with conventional approaches on synthetic and field data sets.

Introduction. Analysis of seismic attributes is a key element in interpretation of reflection data for various geoscience applications. Attributes used for qualitative and quantitative characterization of wavefields and the objects they represent are increasingly growing in number and variety as advanced computing facilities allow ever more rapid computation and sophisticated visualization. Research in this line develops either by using new attributes or by making simultaneous use of multiple or composite (hybrid) attributes combined through geostatistics or other multiattribute analysis tools. The choice of attributes depends on the target. For instance, reflector dip and azimuth, curvature, and coherence are used to identify and image lateral formation variations and stratigraphic features such as buried river channels, pinch-out, faults and fractures, etc. The choice of attributes depends on the target. For instance, reflector dip and azimuth, curvature, and coherence are used to identify and image lateral formation variations and stratigraphic features such as buried river channels, pinch-out, faults and fractures, etc.

The coherence measure was first suggested by Norbert Wiener in 1930, and since then its theoretical background has been developed and applied to many fields of knowledge, including seismic exploration. Coherence has been largely and successfully used in seismic interpretation. The measure is a useful tool intended for improving images of discontinuities caused by spatial variations in geology, such as structure, stratigraphy, lithology, porosity, and the presence of hydrocarbons. Low-coherence zones associated with small-scale faulting, fracturing, pinch-out, and buried channels result from destructive interference of reflected and diffracted waves. For several reasons, this effect eludes attenuation by migration which, among other purposes aims at removing diffraction. Thus, discontinuities appear as local lows of seismic amplitude, signal-to-noise (S/N) ratio, and coherence.

Various methods have been devised to measure coherence. They utilize a normalized crosscorrelation between adjacent traces, a multitrace semblance measure, an eigendecomposition of the data covariance matrix, a local structural entropy, higher-order-statistics and supertraces, dip-scanning eigenstructure analysis and supertraces, predictive painting [1-4]. In order to improve the technology, we analyzed the relation of this attribute to the supposed mathematical model of seismic data and presented a new method for calculating coherence [5]. It is based on a more realistic data model that permits arbitrary trace-to-trace variations of signal amplitudes and noise variances.

In the present paper, in order to further improve this method, we generalize the data model by introducing into consideration residual trace-to-trace signal time delay fluctuations within the analysis window. We describe how these time delay fluctuations can be calculated and taken into account when computing coherence. The advanced method is then tested and compared with conventional approaches on synthetic and field data sets.

Purpose. Improvement of coherence measure by development of the modified method which is based on more realistic model of seismic data and is included residual time-delay correction.

Generalized data model. Most if not all of the above methods define coherence as the ratio of the signal energy to the total energy. This implies either direct or indirect signal evaluations and therefore requires a proper mathematical data model to be formulated. Let the data in a sliding window wherein coherence is calculated be given as

$$x_{ik} = a_i s_{k-\tau_i} + n_{ik}\,, \tag{1}$$

where a_i, τ_i ($i = 1, \ldots, M$) and s_k ($k = 1, \ldots, N$) are, respectively, the trace-dependent amplitudes, the residual (after removal an average local dip) trace-to-trace variations of time delays and the trace-independent waveform of a signal; M and N are, respectively, the number of traces and the number of samples per trace in the window; n_{ik} is additive noise. The signal is thus assumed to have an identical waveform on each trace, with arbitrary trace-dependent amplitudes and residual time delays. Also, we suppose that n_{ik} is independent of the signal and between channels stationary Gaussian random noise with a zero mean and identical to within a scale factor, the variance σ_i^2, autocorrelations on different traces. The presence of coherent noise is thus neglected because it is supposed to be pre-subtracted.

Dependence of seismic coherence definition on a prespecified data model. Let us start with the conventional case when the signal time delay variations τ_i are neglected. Depending on the model assumptions, various methods for computing coherence may be appropriate. Consider some of them (Table 1).

If both a_i and σ_i^2 are trace independent, the best (in a least-squares sense) approximation of the signal is the mean of traces, which entails the coherence measure known as semblance [1].

If all a_i are permitted to vary in an arbitrary manner across the traces, which is more geologically meaningful, provided that all σ_i^2 are trace independent, this entails the eigenstructure-based coherence measure [2].

In order to improve the coherence measures still further, we introduced a more realistic data model that permitted arbitrary trace-to-trace variations of both a_i and σ_i^2. The corresponding method was called generalized (Table 1) and successfully tested on synthetic and field data sets [5,6].

Table 1

Dependence of seismic coherence definition on a prespecified data model

Signal amplitude	Signal time delay	Noise variance	Method
constant	constant	constant	Semblance (Marfurt et al., 1998)
variable	constant	constant	Eigenstructure-based (Gersztenkorn and Marfurt, 1999)
variable	constant	variable	Generalized (Tyapkin and Mendrii, 2012)
variable	variable	variable	Further generalized (in the present paper)

Figure 1 borrowed from [2] compares horizontal slices through coherency cubes generated by two algorithms (semblance and eigenstructure-based) for a salt dome in the Gulf of Mexico. Sediments around the stock are heavily faulted and fractured. The image of the features obtained using a more complex record model and, correspondingly, eigenstructure-based method instead of semblance-based method, is of a superior quality in terms of noise and resolution. Therefore, it is reasonable to make the record model for coherence computation more sophisticated and realistic.

Theory and method. Since deviations from local planar behavior can be crucial in unraveling complex fault patterns, improving interpretations, and delineating reservoir extent [1,2], it is beneficial to progress to the more general case when the signal time delay variations $\tau(i)$ are considered. To optimally estimate the unknown vectors $\mathbf{a} = (a_1, ..., a_M)^{\mathrm{T}}$, $\boldsymbol{\tau} = (\tau_1, ..., \tau_M)^{\mathrm{T}}$ and $\mathbf{s} = (s_1, ..., s_N)^{\mathrm{T}}$ of equation (1) from the data X, where T denotes transposition, we adopt the theoretical basis from Tyapkin [7]. He presents statistically and deterministically regularized iterative solutions to the problem. The first of them, which takes into account statistical information about the sought-for quantities, is a maximum a posteriori probability estimate. Since a, $\boldsymbol{\tau}$ and s are supposed independent random variables, this solution satisfies the criterion

$$\max_{a,\tau,s} \{P(\mathbf{X} \mid \mathbf{a}, \boldsymbol{\tau}, \mathbf{s}) P(\mathbf{a}) P(\boldsymbol{\tau}) P(\mathbf{s})\}, \qquad (2)$$

where $P(\mathbf{X} \mid \mathbf{a}, \boldsymbol{\tau}, \mathbf{s})$ is the likelihood function, whereas $P(\mathbf{a}), P(\boldsymbol{\tau})$ and $P(\mathbf{s})$ are density functions of $\mathbf{a}, \boldsymbol{\tau}$ and $\mathbf{s}$, respectively.

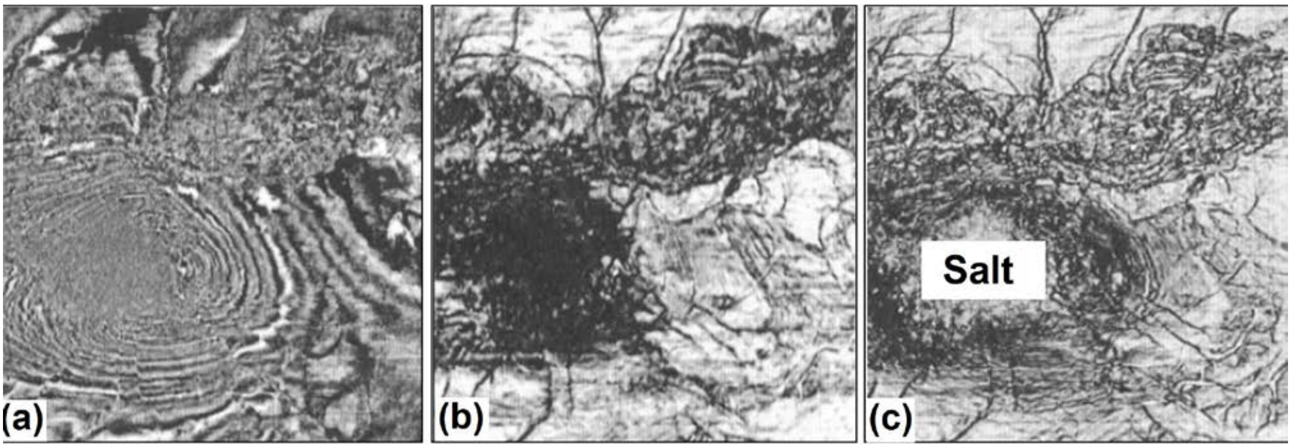

Fig. 1. Horizontal slices through seismic (a) and respective coherence cubes calculated by semblance (b) and eigenstructure-based (c) algorithms borrowed from [2]

It is, however, more convenient for us to use the deterministically regularized solution. It is a maximum likelihood estimator that introduces a priori information about $\mathbf{a}, \boldsymbol{\tau}$ and $\mathbf{s}$ via the technique of convex projections.

Once $\mathbf{a}, \boldsymbol{\tau}$ and $\mathbf{s}$, have been calculated, any coherence measure from Table 1 can be further improved. This can be done via introducing an additional factor that accounts for the presence of the time delays τ_i. For this purpose, we make use of the ratio of the signal energy after out-of-phase summation ($\tau_i \neq 0$) to that after in-phase summation ($\tau_i = 0$):

$$\left\{\left[\sum_i a_i \cos(\omega_\mathrm{m}\tau_i)\right]^2 + \left[\sum_i a_i \sin(\omega_\mathrm{m}\tau_i)\right]^2\right\} \Big/ \left\{\sum_i a_i\right\}^2, \tag{3}$$

where ω_m is the most energetic frequency. Note this implies that the signal is of narrow band.

For semblance, which implies that a_i are trace independent, expression (3) turns into

$$M^{-2}\left\{\left[\sum_i \cos(\omega_\mathrm{m}\tau_i)\right]^2 + \left[\sum_i \sin(\omega_\mathrm{m}\tau_i)\right]^2\right\}. \tag{4}$$

Hereafter, these coherence measures are referred to as *modified*. Note that when the additional factor equals unity, i.e. τ_i are neglected, the modified attributes turn into conventional ones.

Synthetic data experiments. To demonstrate the merits of the new method, one of the simplest coherence measures, semblance, is chosen for comparing with its modified analogue. In the first experiment, the results of which are shown in Figure 2, we create a synthetic seismic image of 31 traces and a 1 ms sampling rate. The signal waveform is chosen identical for all the traces and modeled as a zero-mean stochastic process convolved with a 20 Hz Ricker wavelet. The signal is aligned all over the image except for the central 10 traces delayed in time in a saw-like manner (± 7 ms) (Fig. 2a). For simplicity, no random noise is added to the signal. In this test, a sliding window of M = 5 and N = 100 is used. Figure 2b shows that modified semblance reacts much more intensely and abruptly to the presence of the anomalous interval than conventional semblance does.

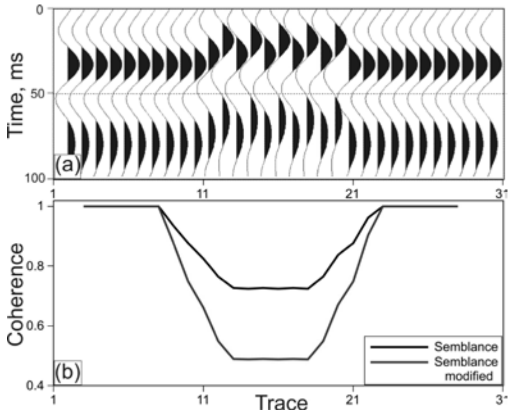

Fig. 2. Synthetic seismic image (a)and comparison between semblance and modified semblance determined from this image (b)

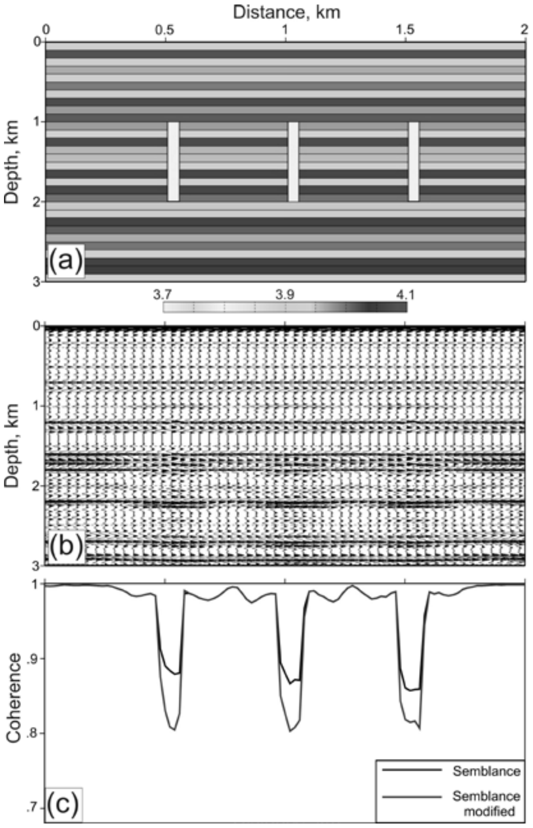

Fig. 3. Depth-velocity model with a color velocity scale in km/s at the bottom(a), depthmigrated image (b), and comparison between semblance and modified semblance determined from this image (c)

The merits of the modified coherence measure are also demonstrated in Figure 3 on a synthetic data set obtained using 2-D finite-difference modeling software of Tesseral Technology Inc. We run the software with the depth-velocity model shown in Figure 3a. This model consists of horizontal layers with random velocities evenly distributed between 3.9 and 4.1 km/s. Also, one can see three vertical zones mimicking fracture corridors of height 1 km, width 50 m and velocity 3.7 km/s. After depth migration, the image from Figure 3b was obtained. To derive semblance and modified semblance shown in Figure 3c, a sliding window of $M = 5$ and $N = 100$ centered at the image middle is used. Both types of coherence demonstrate three intervals of relatively low values, which coincide reasonably well with the low-velocity vertical zones in Figure 3a. However, as well as in the previous test, the response of modified semblance to the presence of the anomalous zones is much more intense and abrupt than that of conventional semblance.

Field data experiment. The new (further generalized) method was compared with its precursor (Table 1) on 3-D seismic data from the Krasnolimanska coalfield in the Donets Basin. Both coherence cubes were derived with pre-compensation for reflector dip. Figures 4a and 4b present portions of stratigraphic slices through both cubes at the level of the l_3 coal seam, currently the most productive seam of the Krasnolimanska coalmine. This mine is among the most dangerous in Ukraine due to methane concentrations which can lead to explosions. On May 23, 2008, a disaster caused by a methane explosion happened when mining the l_3 coal seam. The location of this fatal accident, marked with a star, coincides with a NW-SE trending zone of low-coherence lineations. This zone can be associated with a set of subtle strike-slip faults parallel to the zone trend and show in Figure 4. This strike-slip faulting can be considered a concentrator of fractures, which are possible Riedel shears, containing methane. One of such fracture swarms is encountered in the mine just at the accident point. A careful review of both coherence slices shows that en echelon structure of discontinuities, most pronounced on the curvature slice (Fig. 4d), is highlighted and more easily recognized after using the modified coherence measure. The explanation lies in this attribute being 'strengthened' by accounting for residual time delay variations (Fig. 4c). Interesting anomalies highlighted by the modified attribute are seen at the upper right corner. This feature is worthy of further investigation.

Conclusions. We have presented a new method for improving seismic coherence measures that makes them more sensitive to the presence of residual time delay fluctuations of the signal after removal of its average dip in the analysis window. The method is based on a more realistic mathematical model of seismic data that permits arbitrary trace-to-trace variations in signal amplitude, signal time delay and noise variance. The new method has been tested on synthetic and field data sets.

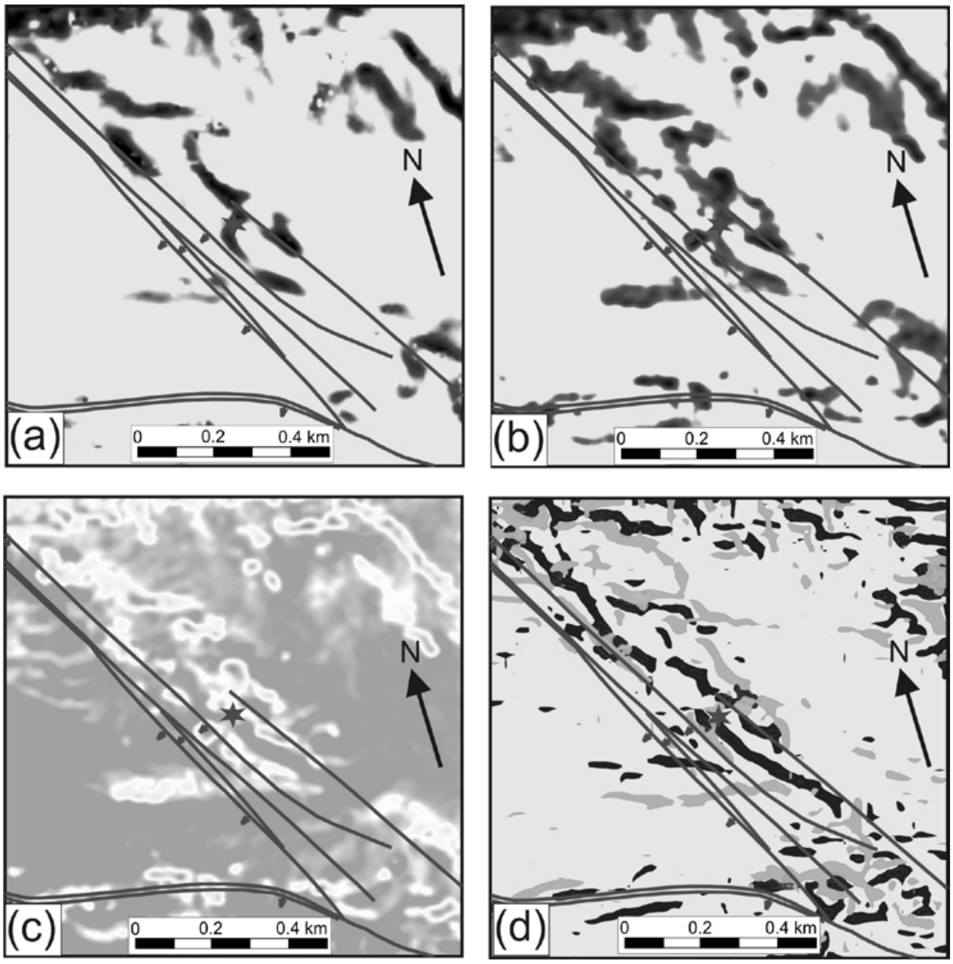

Fig. 4. Stratigraphic slices through cubes of coherence (a), modified coherence (b), factor that accounts for time delay variations (c) and curvature (d) at the level of the l_3 coalseam in the Krasnolimanska coalfield. The last slice depicts most negative curva-

tures in black and most positive curvatures in grey. Subtle strike-slip faults outlined after mining and drilling are shown as lines

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ОСОБЕННОСТИ И ЗАКОНОМЕРНОСТИ ИЗМЕНЕНИЯ ВОССТАНОВЛЕНОСТИ УГЛЕЙ БАШКИРСКОГО ЯРУСА ЗАПАДНОГО ДОНБАССА

В статье приведена детальная петрографическая характеристика углей башкирского яруса Западного Донбасса. Проведена классификация по восстановлености в соответствии с петрографическими типами. Установлены стратиграфические и площадные закономерности изменения степени восстановлености

У статті наведена детальна петрографічна характеристика вугілля башкирського ярусу Західного Донбасу. Проведена класифікація відновленості, згідно з петрографічними типами. Встановлені стратиграфічні та просторові закономірності зміни ступеню відновленості.

The article gives detailed petrographic characteristics of coal of Bashkirian formation of Western Donbas. The classifications for recovery in accordance with petrographic types are given. The stratigraphic and areal patterns of change in the degree of recovery are established.

Вступление. В Украине запасы высококачественного угля на относительно незначительных глубинах практически исчерпаны. К отработке постепенно будут привлекаются поля шахт с более низкосортным углем. Возможность расширения сырьевой базы Украины возможно за счет ввода в эксплуатацию угля Лозовского района.

На сегодняшний день, приобретает актуальное значение всестороннее комплексное изучение и системное обобщение показателей состава и качества угля Лозовского района, установление их генетических особенностей, определения стратиграфических и латеральных закономерностей их изменения, с по-