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Reflectivity Color Correction in Gabor Deconvolution

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Abstract

White reflectivity is not a fundamental assumption in the convolutional models. However, the deconvolution algorithms should be modified slightly to honour color in the reflectivity series. This color correction is just possible when enough well-log information is available to build a mathematical model for the regional reflectivity. A method for correcting reflectivity color effects in frequency domain Wiener deconvolution is extended to Gabor deconvolution. The potential advantage of Gabor deconvolution in addressing the color reflectivity issue is the use of a time-frequency mathematical model for the reflectivity, which result in a more accurate compensation especially in areas with strong variations of the local reflectivity frequency spectrum with depth.

Introduction

A generally accepted model for the seismic trace is to consider it as a convolution of the earth seismic response with a source wavelet. In turn, this wavelet can be regarded as the convolution of several effects: source signature, recording filter, earth filter, surface reflections and geophone response (e.g. Robinson, 1985). Deconvolution is the process of removing the wavelet from the seismic trace to estimate the earth seismic response, which is composed of primaries and multiple reflections. The application of deconvolution to seismic processing relies on the fulfillment of a set of assumptions on which the convolutional model is based: stationarity, minimum phase wavelet, white reflectivity and white additive noise.

In presence of inelastic attenuation, the stationary assumption is not valid. A nonstationary convolutional model (e.g. Margrave and Lamoureux, 2002) is formulated using the constant-Q theory and the mathematical operation called nonstationary deconvolution (Margrave, 1998). The Gabor deconvolution method (Margrave et al 2003, Margrave et al. 2004) is a nonstationary extension of the Wiener deconvolution method, based on the nonstationary convolutional model.

Minimum phase, the second assumption of the convolutional model, continues occupying an essential place in Gabor deconvolution. Besides the minimum-phase character associated with the source wavelet generated by an explosive source, the constant-Q theory gives strong arguments to consider that the attenuation earth filter is endowed with a minimum-phase character as well.

The assumption that the reflectivity is a white and stationary time series is not fundamental in the deconvolution methods, but it has to be addressed in order to avoid inaccuracies both in the amplitude and in the phase spectrum of the deconvolved trace. It has been largely reported that earth reflectivity does not have a white spectrum but instead shows considerable spectral color evidenced by a pronounced roll of in power at the low frequencies as seen in the example shown in figure 1. Analysis of well logs in various regions of the world (e.g. Walden and Hosken,

1985) observed that in the majority of cases reflectivity tends to depart from the white noise behaviour by a loss of power at low frequencies, thereby termed blue reflectivity. The assumption of white noise leads to a conventional deconvolution operator that can recover only the white component of reflectivity, thus yielding a distorted representation of the desired output, as pointed out by Sagaff and Robinson, (2000). The diagnostic and correction of these distortions in the application of Gabor deconvolution is the main subject of this work.

Nonstationary Convolutional Model

The constant-Q model (e.g., Kjartansson, 1979) is the underlying theoretical support for the nonstationary convolutional model and the Gabor deconvolution method. Its basic assumptions are linearity, frequency-independent Q and velocity dispersion. A theoretical model for an attenuated trace can be derived from the constant-Q model, which is useful for analyzing the effects of inelastic attenuation and for searching different methods of correcting them. These effects on the signal can be summarized as amplitude decay, due to energy absorption, waveshape modification, due to stronger absorption of higher frequencies, and phase delay, due to dispersion. In contrast with the stationary convolutional model, which can be formulated in a simple way either in the time or the frequency domain, the nonstationary convolutional model is easily depicted in mixed time-frequency domains. A mathematical model for an attenuated seismic trace $S(f)$ is, (e.g. Margrave and Lamoureux, 2002),

$$S(f) = \sigma(f) \int_{-\infty}^{\infty} \alpha_Q(f,\tau) r(\tau) e^{-i2\pi f\tau} d\tau \,, \qquad (1)$$

where f is the frequency, τ is the arrival time, $\sigma(f)$ is the Fourier spectrum of the source signature, $r(\tau)$ is the reflectivity, and

$$\alpha_Q(f,\tau) = \exp\left(-\pi f\tau / Q + iH(f\tau / Q)\right), \qquad (2)$$

where Q is the attenuation parameter and H indicates the Hilbert transform operation. Equation (2) states that the Fourier transform of the seismic trace is equal to the Fourier transform of the wavelet, multiplied by an integral that has the shape of a Fourier transform, but that given the presence of the time-frequency function $\alpha_Q(f, \tau)$, is rather a nonstationary extension of the Fourier concept, known in mathematics as a pseudodifferential operator. The function $\alpha_Q(f,\tau)$ contains the attenuation information and is endowed with minimum phase character as can be observed in the relation between the real and the imaginary part of the exponent, through the Hilbert transform. As written, these simplifications can be removed with a slight complication in the formula.

The theoretical relation between the Gabor transform and the pseudodifferential operators allows a asymptotic factorization of the nonstationary trace model, which can be considered a first order approximation to Equation (1), (Margrave and Lamoureux, 2002, Margrave et al., 2004),

$$Gs(\tau, f) \approx W(f)\alpha_Q(\tau, f)Gr(\tau, f) \,, \qquad (3)$$

which states that the Gabor transform of the seismic trace, Gs(τ , f) , is approximately equal to the product of the Fourier transform of the source wavelet, W(f) , the time-frequency attenuation function, α_Q (τ, f), and the Gabor transform of the reflectivity Gr (τ, f).

Gabor Deconvolution and Color Correction

The Gabor deconvolution is a non-stationary extension of the Wiener deconvolution method in the frequency domain and implies a minimum-phase source wavelet and white reflectivity series, which is not fundamental but should be addressed to avoid miscalculations. The method assumes that |Gr(τ, f)|, the Gabor amplitude spectrum of the seismic trace, is a rapidly varying function in both variables τ and f; |W(f)|. The Fourier amplitude spectrum of the source wavelet is smoothly varying in f; and α_Q (τ, f) is an exponentially decaying function in both variables τ and f, and constant over hyperbolic families of τf = constant. An approximation |θ (τ, f)| of the product |W(f)| | α_Q (τ, f) is obtained by applying a smoothing operator to |Gs(τ , f)|. As θ(τ, f) represents the attenuated source wavelet, its minimum-phase function is estimated from its amplitude spectrum |θ(τ, f)| using the Hilbert transform as:

$$\varphi(\tau, f) = \int_B \frac{\ln|\theta(\tau, f')|}{f - f'} df' \qquad (4)$$

where B denotes the available spectral band. Finally, the Gabor spectrum of the reflectivity is estimated in the Gabor domain as:

$$Gr(\tau, f)_{est} = \frac{Gs(\tau, f)}{\theta(\tau, f)} . \qquad (5)$$

An example of the performance of Gabor deconvolution in the case of white reflectivity is shown in figure 2. Gabor deconvolution makes an excellent correction of the phase shifts and rotations introduced by attenuation. The Gabor deconvolution method, which has the constant Q theory for attenuation among its fundamental elements, compensates intrinsically for the effects of velocity dispersion.

The color correction can be addressed in the time-frequency domain in the following way: if a time-frequency model P(τ, f) for the nonwhite reflectivity is available, the deconvolution operator with color correction is

$$\theta_c(\tau, f) = \frac{P(\tau, f)}{\overline{|Gs(\tau, f)|} + K} e^{i\phi_c(\tau, f)} , \qquad (6)$$

where |Gr(τ, f)| is the smoothed Gabor spectrum of the seismic trace, K is a stability constant and the phase spectrum φ_c(τ, f) is given by the following Hilbert transform, H,

$$\phi_c(\tau,f) = H\left(\ln\left[\frac{P(\tau,f)}{\overline{\left|Gs(\tau,f)\right|}+K}\right]\right). \tag{7}$$

The application of color correction is illustrated in figures 3 and 4. Figure 3 shows what happens when the nonwhite reflectivity character is not taking into account at applying Gabor deconvolution. An overcorrection of the phase shifts and rotations leaves the trace with phase and rotations of the same order as initially.

When the color correction factor is applied to the Gabor deconvolution operator, the phase differences are reduced to a small portion of the phase differences existing before deconvolution, this can be observed in figure 4. However, the effect of color in the reflectivity series on the phase is just one component of the whole phase problem in Gabor deconvolution. Other factors affecting the phase and not considered in this work are noise in the seismic data, inaccuracies in the sonic log recording process, and the difference between the seismic Nyquist frequency and the maximum frequency of the sonic well logging tool. This latter factor is examined in Montana and Margrave, 2005.

Conclusions

Gabor deconvolution is the nonstationary extension of Wiener deconvolution, based on the nonstationary extension of the convolution operation and the convolutional model. Color correction in reflectivity in Wiener deconvolution can be extended to Gabor deconvolution in an analog way. However, this correction should be applied in conjunction with corrections to the other sources of amplitude and phase differences in deconvolution.

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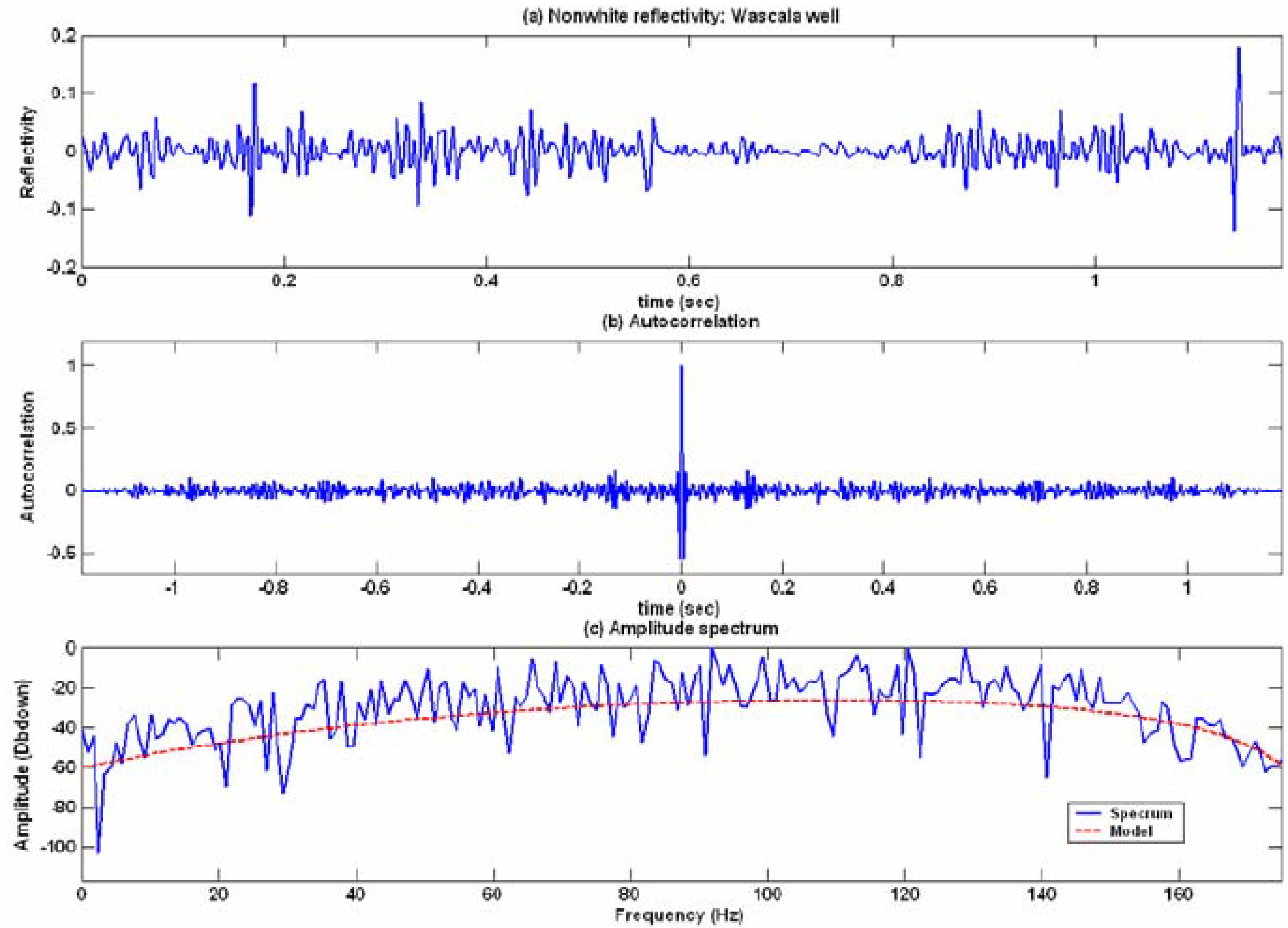

Figure 1. (a) Nonwhite reflectivity calculated from the sonic log of the Wascala well. (b) The autocorrelation shows nonwhite character, evidenced by the presence of significant negative values at small lags. (c): The amplitude spectrum of the reflectivity shows a rolloff from 80 to 0 Hz.

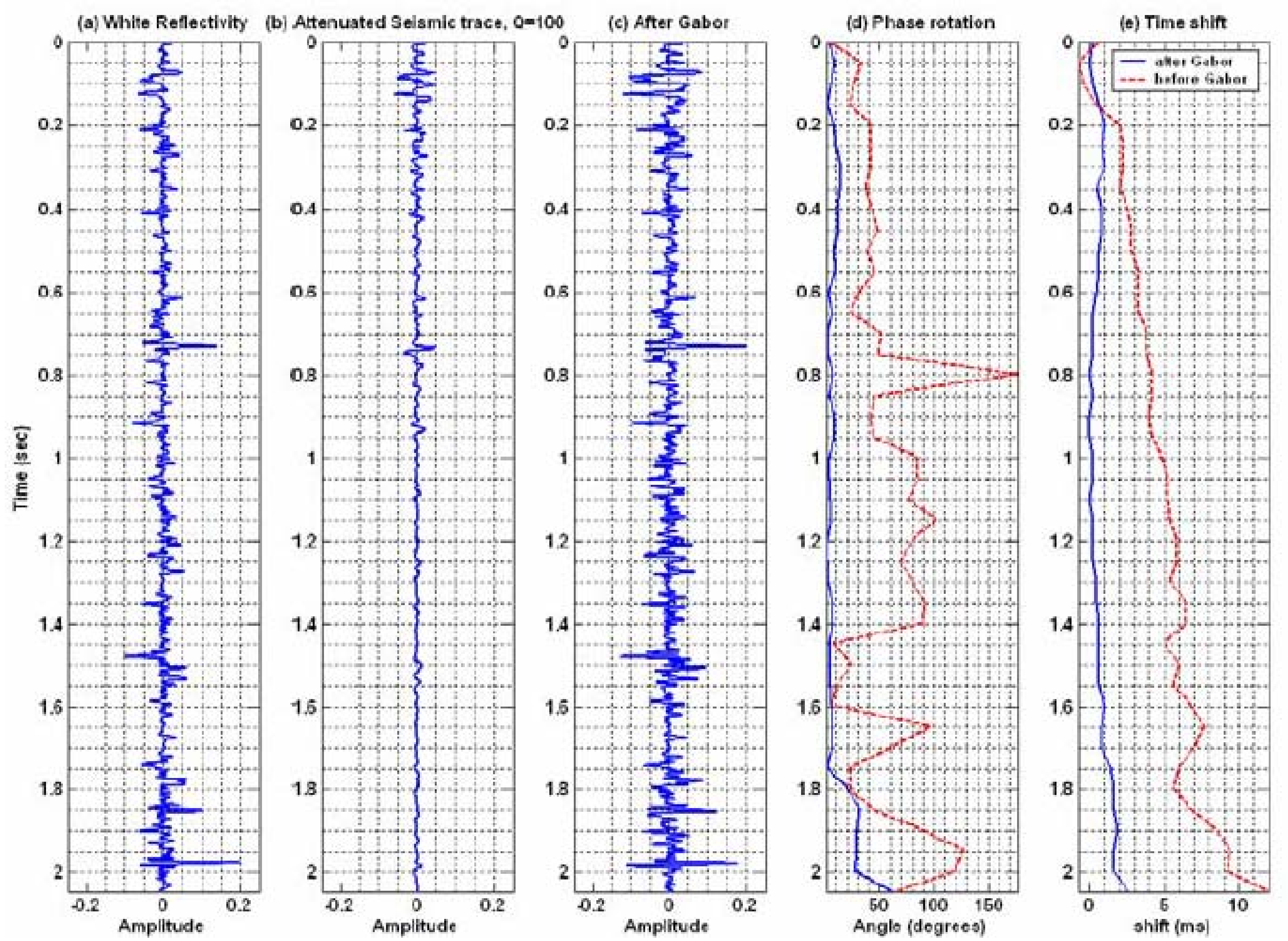

Figure 2. Gabor deconvolution in for white reflectivity. (a): White reflectivity. (b): Attenuated seismic trace (forward Q=100). (c): Gabor deconvolved trace. (d): Time-variant apparent phase rotation before and after Gabor decon. (e): Time-variant phase shift.

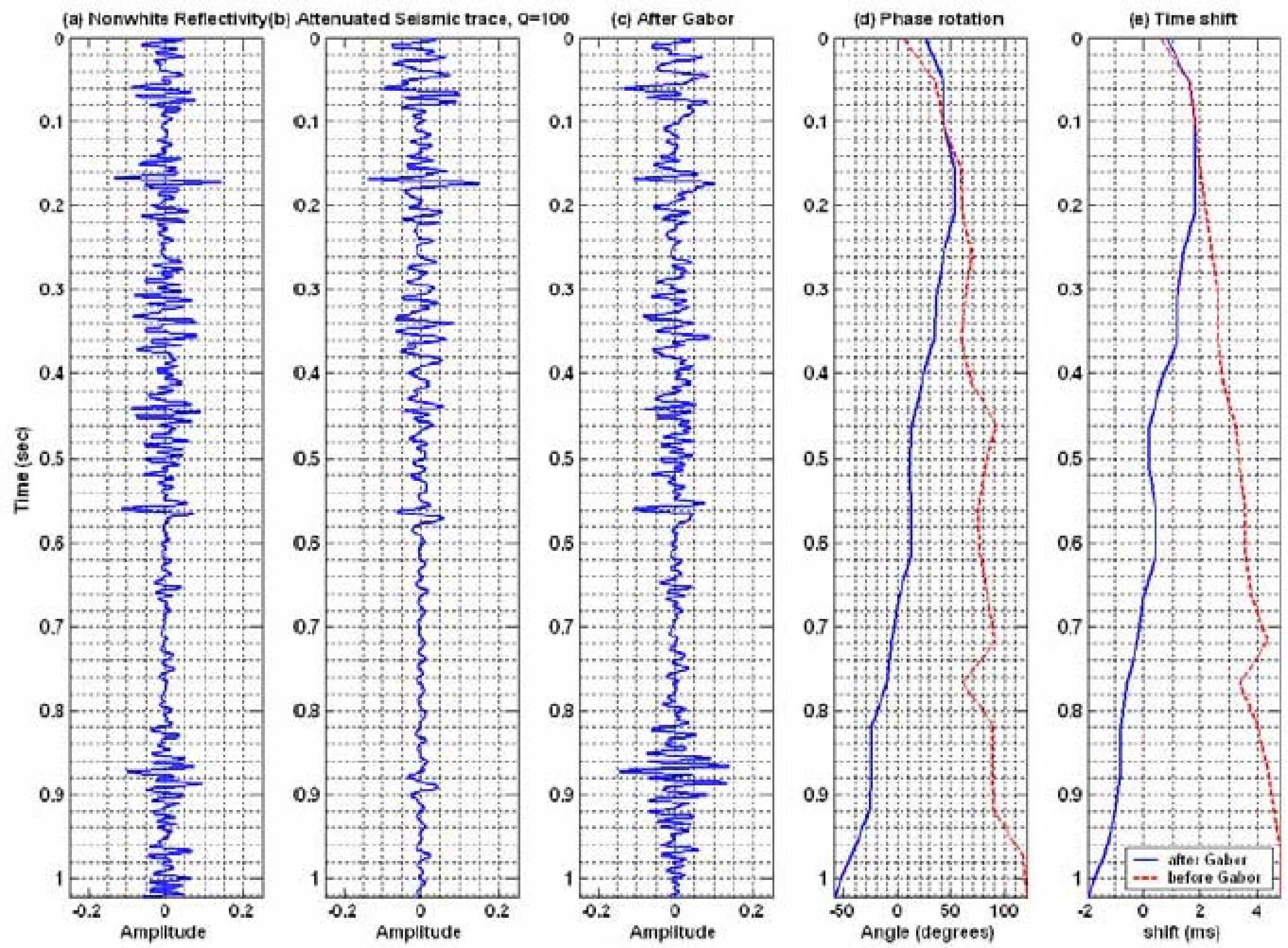

Figure 3. Gabor deconvolution for nonwhite reflectivity. (a): Nonwhite reflectivity. (b): Attenuated seismic trace generated by applying a forward Q=100 filter and convolving the result with a minimum phase wavelet. (c): Gabor deconvolved trace without color correction. (d): Time-variant apparent phase rotation before and after Gabor decon, the phase rotations seem overcorrected. (e): Time-variant phase shift, the times-shifts appear overcorrected.

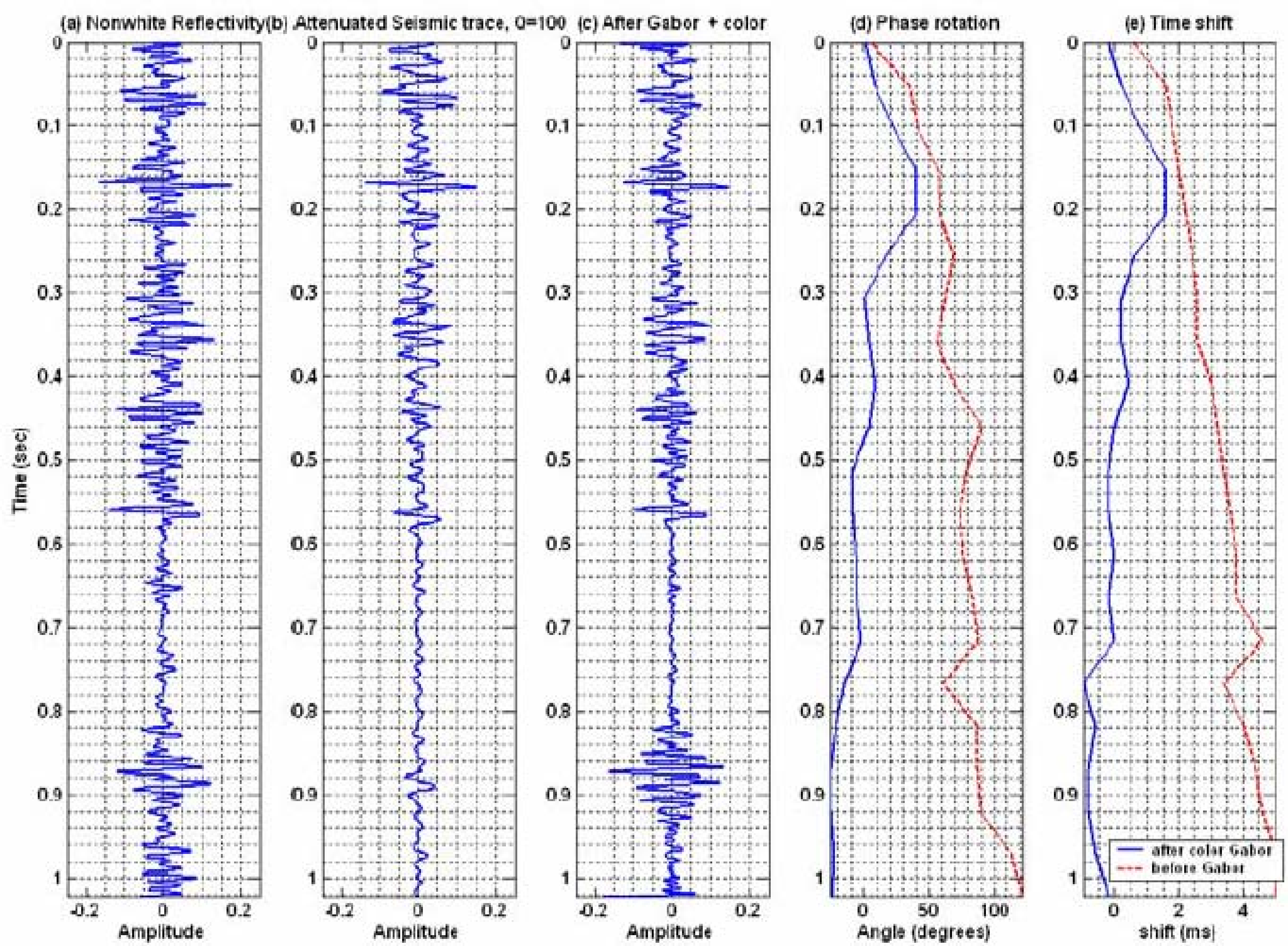

Figure 4. Gabor deconvolution for nonwhite reflectivity. (a): Nonwhite reflectivity. (b): Attenuated seismic trace generated by applying a forward Q=100 filter and then a convolution with a minimum phase wavelet. (c): Gabor deconvolved trace with color correction. (d): Time-variant apparent phase rotation before and after Gabor deconvolution. (e): Time-variant time shift.