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Resolution enhancement in tilted coordinates

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ABSTRACT

Deconvolution is applied to remove source wavelet effects from seismograms. The results are resolution enhancement that enables detection of thin layers. Following enhancement of resolution, low frequency and high angle reflectors, particularly at great depth, appear as low amplitude and semi-invisible reflectors that are difficult to track and pick. A new approach to enhance resolution is introduced that estimates a derivative using continuous wavelet transform in tilted coordinates. The results are compared with sparse spike deconvolution, curvelet deconvolution and inverse quality filtering in wavelet domain. The positive consequence of the new method is to increase sampling of high dip features by changing the coordinate system from Cartesian to tilted. To compare those methods a complex data set was chosen that includes high angle faults and chaotic mass transport complex. Image enhancement using curvelet deconvolution shows a chaotic system as a non-chaotic one. The results show that sparse spike deconvolution and inverse quality filtering in wavelet domain are able to enhance resolution more than curvelet deconvolution especially at great depth but it is impossible to follow steep dip reflectors after resolution enhancement using these methods, especially when their apparent dips are more than 45°. By estimating derivatives in a continuous wavelet transform from tilted data sets similar resolution enhancement as the other deconvolution methods is achieved but additionally steep dipping reflectors are imaged much better than others. Subtracted results of the enhanced resolution data set using new method and the other introduced methods show that steeply dipping reflectors are highlighted as a particular ability of the new method. The results show that high frequency recovery in Cartesian co-ordinate is accompanied by inability to image steeply dipping reflectors especially at great depths. Conversely recovery of high frequency data and imaging of the data both at shallow and great depth are an ability of resolution enhancement in tilted co-ordinates.

1. Introduction

Seismic signals are convolutions of source wavelet and reflection series. A wavelet is frequency band limited and during propagation through the subsurface its energy decreases due to absorption in an inelastic media, and processing must cope with time variant data where the amplitude of signal decreases exponentially. Since the objective of measuring seismic data is to imaging subsurface features it is essential to compensate the lost energy, which requires many processing steps. To recover absorbed frequency, resolution enhancement (RE) is necessary. Seismic resolution is conducted in both horizontal and vertical directions and migration is applied to decrease Fresnel zone radius, in order to enhance horizontal or spatial resolution. Changing the coordinate system from Cartesian to another one is a robust approach to enhance horizontal resolution by imaging steep dip reflectors (SDRs) using wide angle and turning waves (Sava and Fomel, 2005; Shragge, 2006; Shan and Biondi, 2008; Shragge and Shan, 2008; Naghadeh and Riahi, 2013a, 2013b). The purpose of this paper is to discuss a method for changing the vertical resolution of migrated post stack data. Many previous approaches have been introduced to address this issue. Deconvolution is an approach based on eliminating the source wavelet effects from a seismogram, which can improve resolution (Berkhout, 1977; Levy and Oldenburg, 1982; Walden, 1985; Debeye and van Riel, 1990; Sacchi et al., 1994; Sacchi, 1997; Kaaresen and Taxt, 1998; Porsani and Ursin, 2000; Margrave et al., 2003; Velis, 2008; van der Baan and Pham, 2008; Margrave et al., 2011). To eliminate non-stationary characteristics caused by attenuation during wave propagation through the inelastic subsurface, inverse quality (Q) filtering is the most well-known step which by correcting dispersion and attenuation tries to improve bandwidth (Bath, 1974; Kjartansson, 1979; Hale, 1981; Tonn, 1991; Zhang and Ulrych, 2002; Montana and Margrave, 2004).

In this paper the second derivative in continuous wavelet transform (CWT) domain is calculated and applied to tilted seismic data in order to enhance vertical resolution. To clarify high angle faults and SDRs using tilted coordinate system is essential because SDRs will appear as low dip structures, which enable the number of samples from these reflectors to increase and after RE the SDRs will be better imaged. To compare RE results which are obtained using different methods, we have to review and extend some old methods in subsections.

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2. Inverse Q filtering

To eliminate non-stationary characteristics caused by attenuation during propagation of waves through the inelastic subsurface, inverse Q filtering is the most common method. Seismic wave propagation clearly depends on Q quantity and phase velocity (Kjartansson, 1979). The Q factor is independent of frequency (Kjartansson, 1979) and is equal to the ratio between the energy stored and the energy lost during a cycle (Montana and Margrave, 2004). To explain source wave field propagation in an attenuating medium, it is better to use a simple Q model that supports linearity, frequency-independent, and frequency-dependent velocity (Montana and Margrave, 2004). Since seismic signals are non-stationary so to compensate attenuation it is best to estimate the time variant Q matrix then calculate the inverse of this matrix mathematically. To conduct this analysis the quantity of Q can be estimated based on the spectral ratio (Bath, 1974) from vertical seismic profiling data (Tonn, 1991), stacked data and common mid-point gathers (Zhang and Ulrych, 2002). To estimate Q factor from stacked data, the seismic section should be divided to many windows with equal length and assume that for each window the quantity of Q factor is constant. Based on Eq. (1), it is possible to estimate Q for each window (Kjartansson, 1979).

$$A(z_2, w) = A(z_1, w)\exp\left(\frac{-w\Delta z}{2V(w)Q}\right) \tag{1}$$

where, $A(z_2,w)$ is the amplitude spectrum of recorded data at depth z_2, $A(z_1,w)$ is the amplitude spectrum of recorded data at depth z_1, w is angular frequency, $V(w)$ is frequency-dependent velocity. Since $\Delta z = V(w)\Delta t$ and $w = 2\pi f$, Eq. (1) will be as follows

$$A(z_2, w) = A(z_1, w)\exp\left(\frac{-\pi f\Delta t}{Q}\right). \tag{2}$$

Finally Q factor can be estimated by Eq. (3)

$$Q = \frac{-\pi f\Delta t}{\ln\left(\frac{A(z_2, w)}{A(z_1, w)}\right)} \tag{3}$$

Then the Q matrix is obtained and an inverse filter can be applied using an equivalent Q matrix (Hale, 1981) or non-stationary inverse Q filter (Margrave, 1998).

In the next subsections, it is essential to introduce some steps to do enhancement in non-Cartesian co-ordinate.

3. Continuous-wavelet-transform (CWT)

The CWT provides a different approach to time–frequency analysis. Instead of producing a time–frequency spectrum, it estimates a time-scale map called a scalogram (Rioul and Vetterli, 1991). The CWT of a signal $x(t)$ with the wavelet ψ is defined as

$$X_w(s, T) = \prec x(t), \psi_{s,T}(t) \succ = \int_{-\infty}^{+\infty} x(t).\frac{1}{\sqrt{s}}\psi\left(\frac{T-t}{s}\right)dt \tag{4}$$

where, s is scale value, T is translation value, and $X_w(s,T)$ is the time scale map (Sinha et al., 2005). Also it can be interpreted as the correlation of the time series with a time-reversed version of ψ rescaled by a factor of s (Munoz et al., 2002). For a 1-D input signal, the result is a 2-D description of the signal with respect to time T and scale s. The scale s is inversely proportional to the central frequency of the rescaled wavelet $\psi_s(t) = \psi(\frac{t}{s})$ which is typically a band pass function, t represents the time location at which we analyze the signal. The larger the scale s, the wider the analyzing function ψ_s, and hence smaller the corresponding analyzed frequency. The output value is maximized when the frequency of the signal matches that of the corresponding dilated wavelet (Munoz et al., 2002).

4. First derivative (FD) in CWT domain

In this part a complex Gaussian wavelet is used to calculate the FD of a time series. The Gaussian wavelet function is as follows:

$$Gw = C_1.\exp(-t^2)\exp(-it) \tag{5}$$

where, C_1 is such that the 2-norm of the FD of Gw is equal to 1. The FD of the mother wavelet will be:

$$\frac{\partial Gw}{\partial t} = G = C_1.\exp(-t^2)\exp(-it)(-i-2t). \tag{6}$$

To calculate the FD of time series $f(t)$ in the CWT domain the wavelet coefficients must be calculated using Eq. (7).

$$F_w(s, T) = \prec f(t), G_{s,T}(t) \succ = \int_{-\infty}^{+\infty} f(t).\frac{1}{\sqrt{s}}G\left(\frac{T-t}{s}\right)dt \tag{7}$$

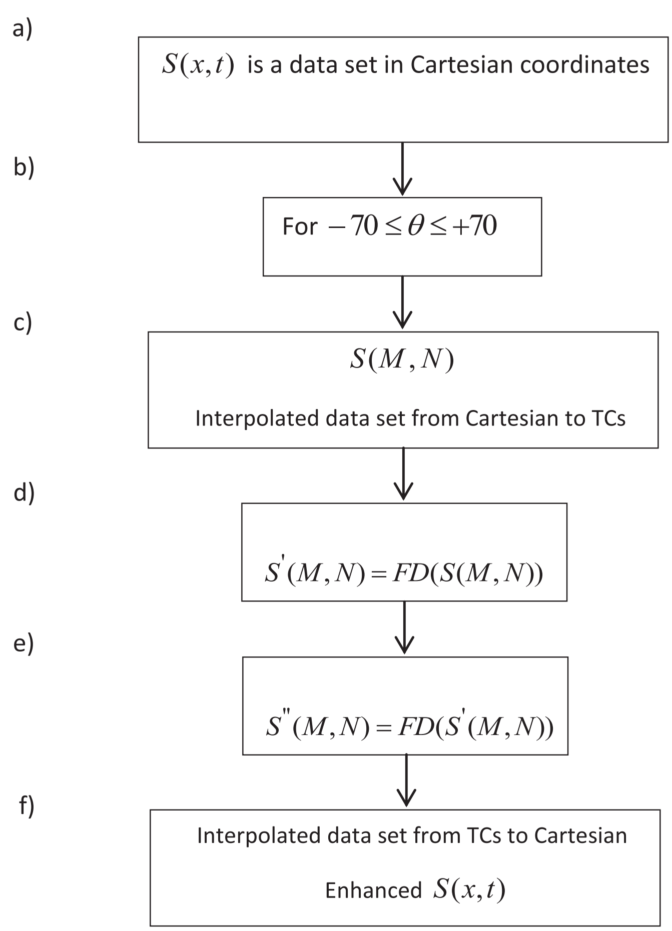

Fig. 1. Flowchart of temporal RE in TCs, (a) a time series $S(x,t)$ in Cartesian coordinate; (b) the maximum and minimum tilting angles based on the maximum absolute apparent dip, which is 70° and based on the horizontal reflectors equals to 0°, are chosen; (c) 2D interpolation is applied to interpolate the data set from Cartesian to tilted coordinates using Eq. (8); (d) $S'(M,N)$ is the first derivative of interpolated data from Cartesian to tilted coordinates, using Eq. (7); (e) $S''(M,N)$ is a second derivative of $S(M,N)$; (f) the output of step (e) is the enhanced data in tilted coordinates. When these data are interpolated to Cartesian coordinate the result will be enhanced $S(x,t)$.