High-precision frequency attenuation analysis and its application*

Xiong Xiao-Jun¹, He Xi-Lei¹, Pu Yong², He Zhen-Hua¹, and Lin Kai¹

Abstract: Based on seismic attenuation theory in a fluid-filled porous medium, we improve conventional methods of low-frequency shadow analysis (LFSA) and energy absorption analysis (EAA) and propose a high-precision frequency attenuation analysis technology. First, we introduce the method of three-parameter wavelet transform and the time-frequency focused criterion and develop a high-precision time-frequency analysis method based on an adaptive three-parameter wavelet transform, which has high time-frequency resolution with benefit to LFSA and can obtain a single-peaked spectrum with narrow side-lobes with benefit to EAA. Second, we correctly compute absorption coefficient by curve fitting based on the nonlinear Nelder-Mead algorithm and effectively improve EAA precision. Practical application results show that the proposed frequency attenuation analysis technology integrated with LFSA and EAA can effectively predict favorable zones of carbonate oolitic reservoir. Furthermore, reservoir prediction results based on LFSA correspond with EAA. The new technology can effectively improve reservoir prediction reliability and reduce exploration risk.

Keywords: attenuation analysis, low-frequency shadow, energy absorption analysis, time-frequency analysis

Introduction

Subsurface rocks usually form a porous medium filled with fluid, such as oil, gas, or water. Many petrophysical experiment results (Winker, 1979; Murphy, 1982; Klimentos, 1995; Xi, 1997; Codoret, 1998) have proved that there are seismic wavefield variations caused by fluid, such as velocity, attenuation, and etc. Especially, Korneev et al. (2004) revealed high-frequency energy absorption and phase distortion of seismic reflections from dry and fluid-saturated layers by a series of laboratory ultrasonic experiments. Wang et al. (2006) revealed the relationship between fluid content and wave attenuation: the higher the gas saturation, the stronger the wave attenuation. In the field of practical seismic data processing, we always use quality factor (Q) as a direct hydrocarbon indicator and sometimes can obtain good results (Quan, 1997; Haase, 2005). Moreover, Dialy et al. (1995) documented an empirical relation between partial gas saturation and attenuation at seismic frequencies in a 3D time-lapse steam flood study. In conclusion, both petrophysical experiments and practical seismic data processing have effectively revealed seismic attenuation caused by fluid-filled porous media, which is important for its application...
to fluid identification. These days, how to make use of seismic attenuation to predict hydrocarbon reservoirs is an important research task and the related methods and principles can be classified as: (1) Methods based on low-frequency information. When a seismic wave moves through a fluid-filled porous medium, it may produce high-frequency energy loss and only conserve strong low-frequency energy. Thus, we can predict hydrocarbon reservoirs based on low-frequency information, such as the method of low-frequency shadow analysis (LFSA) (Castagna et al., 2003) designed to directly indicate hydrocarbons. The low-frequency section analysis method was used to image reservoirs in a Western Siberia oil field (Goloshubin et al., 2006). (2) Methods based on frequency attenuation attributes. Based on the high-frequency energy loss principle, we can extract characteristic parameters of high-frequency energy absorption to detect hydrocarbon reservoirs, such as the method of energy absorption analysis (EAA) (Mitchell et al., 1996). (3) Methods based on quality factor Q. Q is a direct fluid indicator, measured by methods such as the spectral ratio method (Rainer, 1991). Because these methods are all involved in seismic wave frequency attenuation, they can be unified as frequency attenuation analysis technology and LFSA and EAA are two main methods.

The definition of a low-frequency shadow is “High energy below reservoir at low frequency” in Sheriff (1999). Taner et al. (1979) first discovered low-frequency shadows from practical seismic sections but they could not get a reasonable explanation because it was just an empirical analysis with multiple solutions. In the following twenty years, LFSA research was non-existent. Castagna et al. (2003) introduced a time-frequency analysis method based on the wavelet transform (WT) to the LFSA field and improved hydrocarbon identification application to a new level. Compared with short-time Fourier transform (STFT), WT can obtain better time-frequency resolution by adjusting the window size. Thus, the development of time-frequency analysis technology gives LFSA technology new life. Recently, many Chinese scholars (Huang, 2008; Yin, 2008.) have done similar LFSA studies based on time-frequency analysis research. However, developing a high-precision time-frequency analysis method for seismic data is still a hot issue.

In order to effectively utilize high-frequency attenuation information, Mitchell et al. (1996) proposed the EAA method by computing the absorption coefficient parameter to determine the amount of absorbed high frequency energy. The energy absorption analysis method uses the exponential attenuation function exp (-ao) where a is the attenuation gradient or absorption coefficient. The EAA key is the correct computation of a. In recent years, EAA has been widely used (Martin et al., 1998). However, the regular EAA method employs the method of two-point slope or linear fitting and can be well used only for high S/N seismic data or in cases with a well-behaved spectrum.

Method and principle of high-precision frequency attenuation analysis

In order to conquer the difficulties of LFSA and EAA, we propose a new high-precision frequency attenuation analysis technology based on high-precision time-frequency analysis and nonlinear curve fitting methods.

High-precision time-frequency analysis method based on adaptive WT

Gao et al (2006) proposed the high-precision three-parameter WT and its continuous wavelet transform definition is

$$w_f(a,b) = \left[ a \right]^{1/2} \int_{-\infty}^{+\infty} f(t) \varphi_{a,b}(t-b/a) dt,$$

(1)

$$\varphi(t) = e^{-\pi t^2} \left\{ p(\Lambda) \left[ \cos(\sigma t) - k(\Lambda) + iq(\Lambda) \sin(\sigma t) \right] \right\},$$

(2)

$$k(\Lambda) = e^{-\pi^2/4t} \cos(\beta \sigma) + 1,$$

(3)

$$p(\Lambda) = \int_{2\pi}^{2\pi} \left\{ 4 \left[ e^{\sigma^2 - \pi \sigma^2} \cos^{2}(\beta \sigma) + 1 - e^{-\sigma^2/2t} \right] \right\}^{1/2},$$

(4)

$$q(\Lambda) = \int_{2\pi}^{2\pi} \left\{ 4 \left[ e^{\sigma^2 - \pi \sigma^2} \sin^{2}(\beta \sigma) + 1 - e^{-\sigma^2/2t} \right] \right\}^{1/2},$$

(5)

where f(t) is an energy-limited or square-integrateable signal, a is the scale factor, b is the displacement factor, \( \varphi(t) \) is the wavelet function (its parameters are \( \sigma, \tau, \) and \( \beta \)), a is the wavelet modulate coefficient, \( \tau \) is the wavelet energy attenuation coefficient, and \( \beta \) is the wavelet energy delay time.