JOURNAL OF SEISMIC EXPLORATION **20**, 45-55 (2011)

STUDY AND APPLICATION OF SEISMIC ATTENUATION BASED ON THE ONE-WAY WAVE EQUATION

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(Received September 19, 2010; revised version accepted December 16, 2010)

ABSTRACT

Bai, X.Y., Liang, K., Chen, Y.B. and He, B.H., 2011. Study and application of seismic attenuation based on the one-way wave equation. *Journal of Seismic Exploration*, 20: 45-55.

Characteristics of seismic attenuation can effectively reveal the impact of rock absorption on seismic waves in heterogeneous viscoacoustic media. In this paper, based on the one-way wave equation, seismic attenuation is simulated successfully in a nonzero-offset viscoacoustic medium by combining the quality factor Q with the Split-Step Fourier (SSF) wave extrapolation method through the Futterman dispersion equation. In addition, the use of the reflection wave forward propagation theory greatly improves the computation efficiency. Numerical experiments are given to show that the one-way wave method is efficient and can generate a clear and simple wave-field, easing the way of further analysis and the construction of reverse algorithms. Besides, the simulation results also reveal the influence of quality factor Q on the seismic wave, such as the wave's shape, energy, frequency, etc. Finally, applying this numerical tool to weak seismic response records of an actual reservoir covered by a high-speed gypsum-salt layer, the reservoir is identified effectively by using complete analysis of attenuation characteristics.

KEY WORDS: one-way wave numerical simulation, seismic wave attenuation, Q value,
reservoir prediction.

0963-0651/11/$5.00

INTRODUCTION

Recently, seismic attenuation, as one important kind of seismic attribution, has been widely used to directly predict the hydrocarbon and its migration (Sun, 2000; Ma, 2005). In this paper, a new numerical method of seismic attenuation is proposed by using the one-way wave equation (Bai, 2008; Xiong, 2007) as the fundamental formula and the wave-field forward propagation as the extrapolation direction, which greatly enhance the calculation efficiency. Additionally, by establishing a model of weak seismic response in an actual reservoir covered by a high-speed gypsum-salt layer, we thoroughly analyze the influence of Q on seismic propagation and study the relationship between them. Furthermore, for the weak seismic response data, we analyze the seismic attenuation carefully and complete reservoir identification by using a layer absorption parameter. Finally, the perfect results show the efficiency of the method and provide a good practice guide.

THEORY

One-way numerical simulation operator with Q

In order to improve the applicability of the one-way wave equation method to the lateral velocity variation when using it to extend the wavefield, Stoffa proposed the SSF method based on Phase-Shift Migration. The basic conception of this method is velocity field split, i.e., dividing the whole velocity field into two parts: constant velocity background and velocity perturbation. For an acoustic medium, the SSF method consists of two steps:

$$\begin{aligned} P_1(x,z_{i+1},\omega) &\approx P(x,z_i,\omega)\exp(-iA_1\Delta z_i) \ , \\ P(x,z_{i+1},\omega) &\approx P_1(x,z_{i+1},\omega)\exp(-iA_2\Delta z_i) \ , \end{aligned} \tag{1}$$

$$\begin{aligned} A_1 &= \sqrt{\{(\omega^2/c^2) + (\partial^2/\partial x^2)\}} = \mathrm{sqrt}(\omega^2 s_0^2 - k_x^2) = \sqrt{\{k_a^2(\omega) - k_x^2\}} \ , \\ A_2 &= (\omega/v) - (\omega/c) = \omega\Delta s(x,z) \ . \end{aligned} \tag{2}$$

A_1 and A_2 are the first and second phase shift, frequency-wave-number and frequency-space domains, respectively.

The equations above are all valid for acoustic media, where the velocity is independent of frequency. While real earth media are usually viscoelastic, so the wave (refers to phase surface) velocity is no longer the case, it is not only the function of frequency but also having a complex form (Carcione, 1988), caused by the phase perturbation due to the frequency-dependent attenuation and dispersion. According to the assumption of the Futterman model, that Q is independent of frequency, as well as the dispersion formulation of phase velocity, while $\omega < \omega_c$, he one-way wave wavefield extension method in a viscoacoustic medium can be written as:

$$\bar{P}(k_x,z_{i+1},\omega) = \bar{P}(k_x,z_i,\omega)\exp(-iA\Delta z) \ , \qquad (3)$$

$$A = \sqrt{\{K\omega^2 - k_x^2\}}$$

$$= \sqrt{[\{(\omega^2/v^2)[1+i(1/2Q)]^2[1+(1/\pi Q)\ln(\omega/\omega_c)]^{-1}\}^2 - k_x^2]} \ , \qquad (4)$$

expanding A according to the Taylor formula, and make phase velocity meet the Futterman dispersion relations we have:

$$A_1 = \sqrt{\{(\omega^2/c^2)[1+i(1/2Q_a)]^2 - k_x^2\}} \ ,$$

Let:

$$A_2 = [\omega/v(\omega) - \omega/c] + i\{[\omega/v(\omega)](1/2Q) - (\omega/c)(1/2Q_a)\}$$

$$A_3 = -(k_x^2/2\omega)\{v[1 + i(1/2Q)]^{-1} - c[1 + i(1/2Q_a)]^{-1}\} \ . \qquad (5)$$

Where c ? Q_a is velocity and Q of the background, respectively, and $v(\omega_c)$ is velocity when $\omega = \omega_c$. Then we get:

$$\bar{P}(k_x,z_{i+1},\omega) = \bar{P}(k_x,z_i,\omega)\exp[-iA\Delta z]$$

$$= \bar{P}(k_x,z_i,\omega)\exp[-i(A_1 + A_2 + A_3)\Delta z] \ , \qquad (6)$$

Eq. (6) is exactly the one-way wave forward extension operator with Q.
At normal incidence, P-wave impedance in an absorptive medium is:

$$Z = \rho v[1 + i(1/2Q)] \ . \qquad (7)$$

Thus, the familiar formula for the reflection coefficient from a boundary of two layers:

$$R = (Z_2 - Z_1)/(Z_2 + Z_1) \ ,$$

and then the reflection in a viscoacoustic medium can be obtained in the frequency domain:

$$\bar{P}_R(\omega) = R\bar{P}(\omega) \ , \qquad (8)$$

where $\bar{P},\bar{P}_R$ is the incidence wave and the reflected wave.

S-transform technology

Stockwell (1996) proposed a new time-frequency analysis method called S-transform based on the previous studies of the time-frequency analysis method. S-transform is a reversible time-frequency analysis tool. It is the combination of short-time window Fourier transform and wavelet transform.

One-dimensional S-transform is defined as follows

$$S(\omega,f) = \int_{-\infty}^{\infty} h(t)[|f|/\surd(2\pi)]\exp[-f^2(\omega - t)^2/2]\exp(-i2\pi ft)dt \quad , \tag{9}$$

where f is the frequency, τ is the center of the time window function, which controls the location of the Gauss window function in the time axis.

Continuous inverse transform is

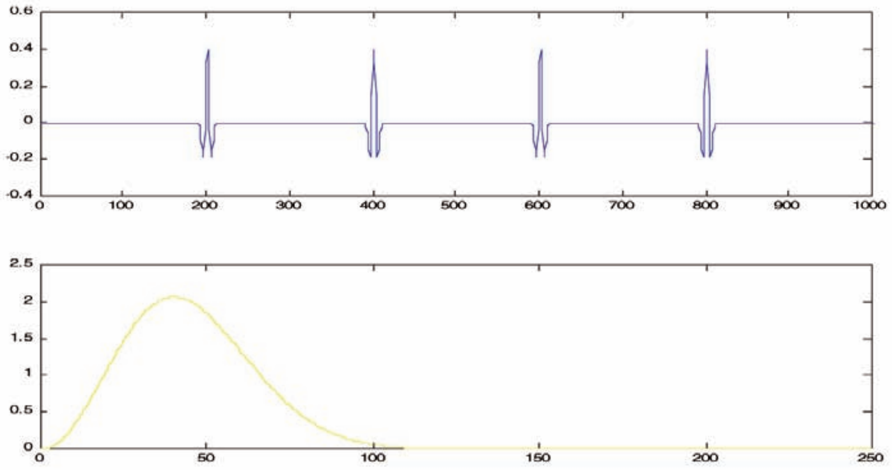
$$h(t) = \int_{-\infty}^{\infty} [\int_{-\infty}^{\infty} S(\omega f)d\omega]\exp(i2\pi ft)dt \quad , \tag{10}$$

The S-transform has more superior properties than the Fourier transform and the wavelet transform. In the time-frequency domain, we can comprehensively consider the information of energy, frequency and bandwidth.

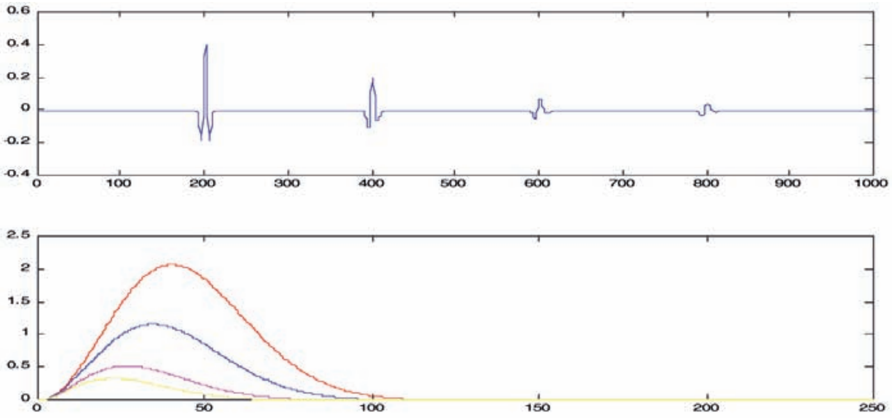
EXAMPLES

We designed a five-level layered model to show the only difference caused by Q: the four interface reflection coefficient of the acoustic and viscoacoustic medium both equal to 0.4, the only difference is that the former with Q = 1000, the latter with Q = 1000,40,60,80,100 in five layers. The record is shown in Fig. 1, which shows the amplitude decrease and the domain frequency shift to lower frequency in a viscoacoustic medium.

In order to study the variation of the reflection wave along with the decreasing Q, i.e., the enhancing seismic attenuation, of weak seismic response of a gas reservoir covered by the high-speed gypsum-salt layer, a simple three-layer horizontal model is designed in this research. In this model, gas fills in the second layer, that is in the middle, and Q varies from 5 up to 155 with a gradual increase of 10 (Table 1). The velocity and density shown in Table 1 are used to calculate the reflection coefficient for the reflected wave. The one-way wave equation is used to form the seismograms using a Ricker wavelet,



(a) Acoustic medium

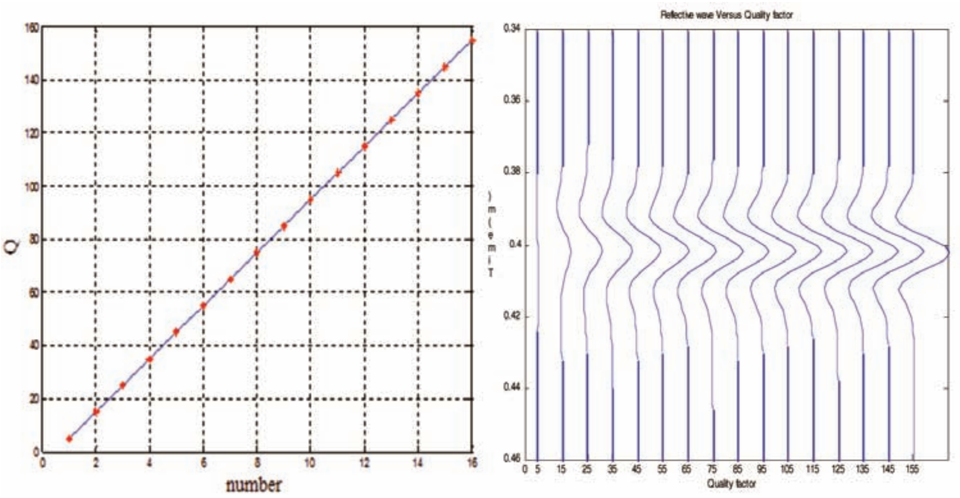


(b) Viscoacoustic medium

Fig. 1. Difference caused by Q in record.

Table 1. Parameters of Model.

Layer	V_P (m/s)	Q	Density
First	4600	10000.0	2.58
Second	4400	5:10:155	2.48
Third	5000	10000.0	2.6

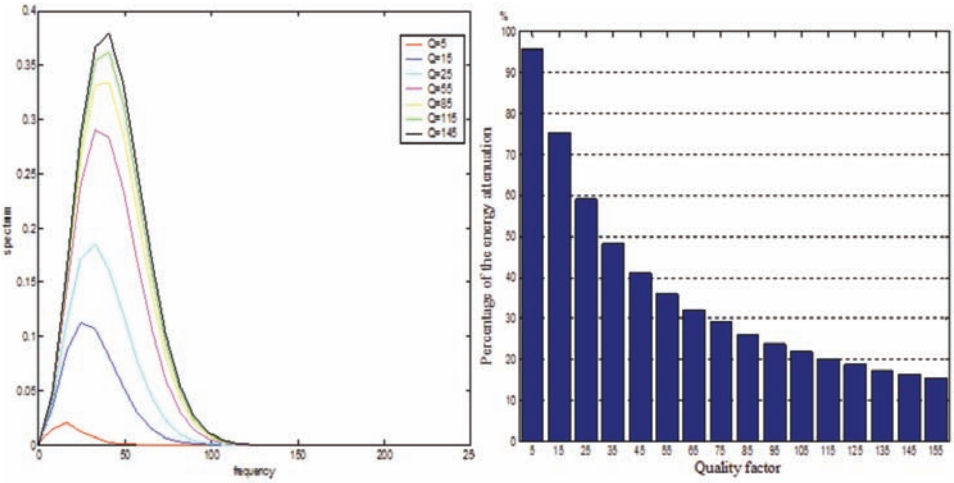


(a) (b)

Fig. 2. Q trend and seismography in a gas layer.

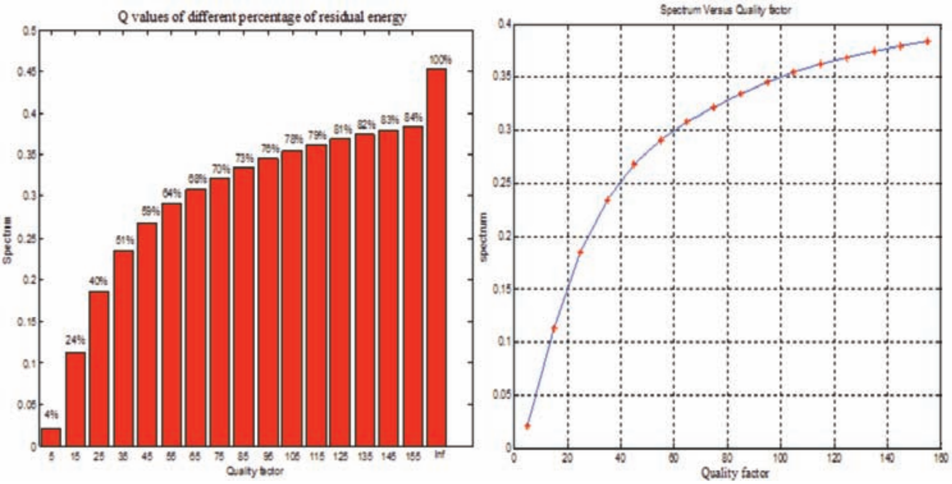
and then the one for gas layer is selected [Fig. 2(b)]. Finally, a variety of information, such as amplitude, peak frequency, and center frequency, varying with Q are analyzed and shown in Fig. 3.

Fig. 2(b) is the modeling post-stack seismic record of the middle gas layer, which shows that the amplitude of the reflection wave increases with rising Q from left to right in Fig. 2(a), implying smaller Q leading to weaker attenuation. Spectrum analysis are shown in Fig. 3(a), revealing the significant influence of decreasing Q on the seismic wave spectrum, that is weaker amplitude, smaller main frequency and narrower bandwidth. From the attenuation analysis of amplitude [Figs. 3(b) and 3(c)], we can see that along with the declining Q, the attenuation gradient rises gradually, i.e., the seismic wave energy loses faster with smaller Q. Especially, when Q is around 10, the amplitude energy can reduce more than 90%. Figs. 3(d), 3(e) and 3(f) are changing curves of amplitude, peak frequency (the frequency corresponding to the maximum amplitude) and centroid frequency (the frequency corresponding to the centroid of the amplitude spectrum) with Q. It seems likely that all of them are brought down with decreasing Q and have greater decline gradients in lower Q. In Fig. 3(e), there are three apparent attenuation steps of peak frequency, which is the frequency of the maximum amplitude, corresponding to three Q regimes which are really the domain of gas, oil and water referred to, therefore, it provides good theoretical support for the later application researches. A comparison of high and low energy of picked seismic wave is analyzed in Figs. 3(g) and 3(h). There is little difference when Q is large, but as Q drops gradually, the difference becomes large because high energy decreases faster than low, although they both decrease, which offers a great conception of evaluating layer absorbing parameter for the following study.



(a) Spectrum analysis

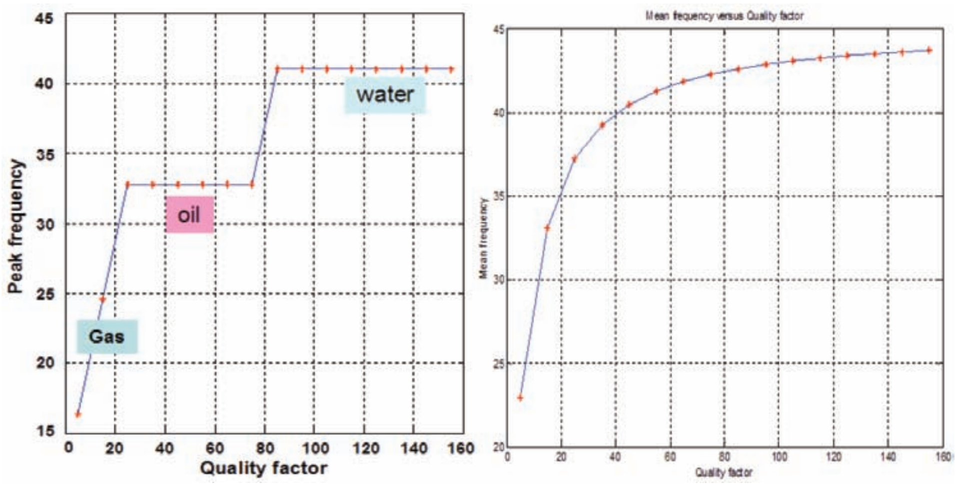
(b) Amplitude attenuation



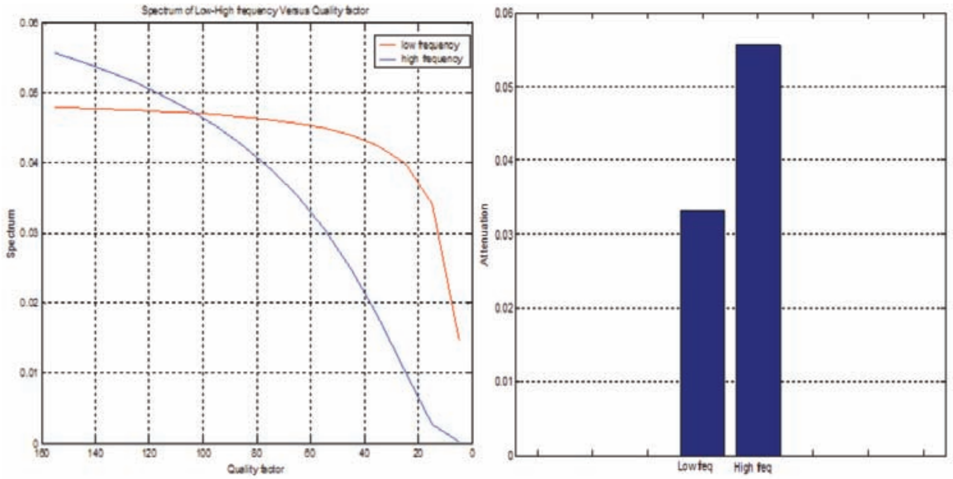
(c) Residual amplitude

(d) Amplitude variation with Q

Fig. 3. Analysis on the influence of quality factor Q.



(e) Peak frequency (f) Centre frequency



(g) Comparison of high and low energy

(h) Attenuation of high and low energy (Q = 5)

Fig. 3. Analysis on the influence of quality factor Q.

Application of attenuation characteristics

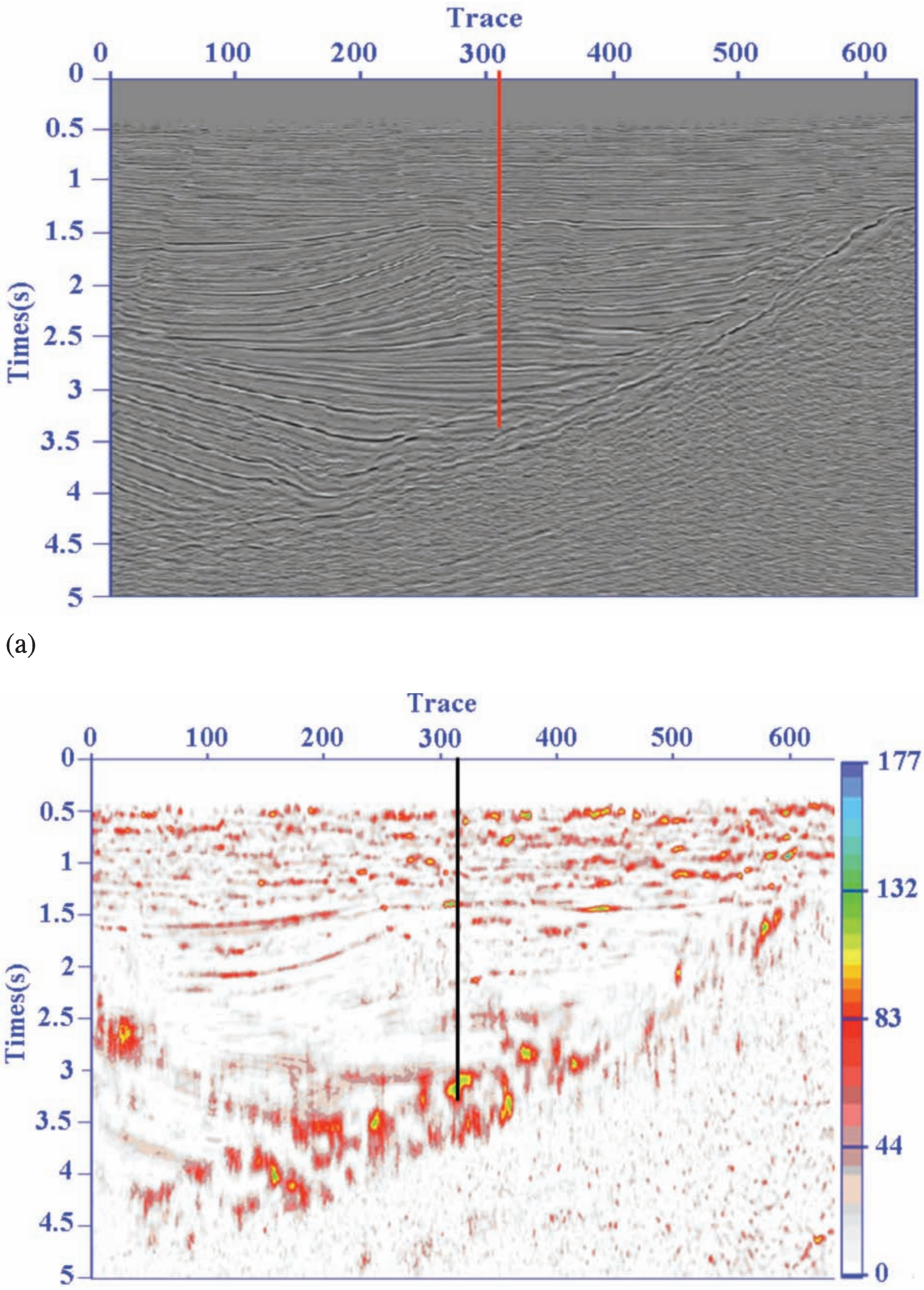
Weak seismic amplitude response can always be found in reservoir covered by a high-speed gypsum-salt layer, so it is really difficult to identify this kind of layer and therefore good method is needed to deal with this problem. Here, an effective approach is proposed, which is achieved by dismissing the shielding effect of gypsum-salt layer via layer attenuation analysis technology and then using attenuation characteristics, after consideration of the anomalies of amplitude, frequency and phase, to finally predict the hydrocarbon-bearing characteristics and range from weak signals (Rainer Tonn, 1991; Dasgupta, 1998; Sun, 2000). Furthermore, according to the relationship between layer absorption and seismic response (in part II), three methods, i.e., the relationship between peak frequency and Q, the relationship between the gradient and intercept of 2D spectral frequency after the high frequency attenuation in the S-domain, and the regional anomaly absorbing attribute of balancing the spectrum variation, are established by a S-transform time-frequency analysis technology, and then the layer absorption integrated parameter is obtained using principal component analysis method. Eventually, we get perfect reservoir identification results in application to actual seismic data.

The gas reservoir in the test block is a deep basin gas trap, located around a big steep slope zone. The difficulties of reservoir prediction here lies in the very weak seismic response due to the surprisingly strong reflection of the covering gypsum-salt layer, and the great identification disturbance caused by complex sedimentary of the steep slope zone and the indistinct sedimentary process.

Fig. 4(a) is the original seismic data. It is a prestack time migrated section. Fig. 4(b) is the section of layer absorption integrated parameter which is a dimensionless parameter extracted from in-lines passing by log 1. The absorption anomaly of gravel rock reservoir along the deep slope zone is strong with a strongest bright spot in gas layer of log 1 [Fig. 4(b)]. Besides, the effect of surrounding strong absorption on gas reserve prediction vanishes.

CONCLUSIONS

A new one-way wave simulation method is proposed in this paper because of its advantages of multi-reflection controlled, and kinetic characteristics of seismic wave contained. To deal with some complex problems, like weak seismic response and hard prediction of the hydrocarbon-bearing characteristics, of reservoir covered by a high-speed gypsum-salt layer, the one-way wave simulation method is used in the paper. The seismogram recorded by using this



(a)

(b)

Fig. 4. Attenuation integrated parameter section of Inline 3680. The profile in (a) is original seismic data, (b) are attenuation integrated parameters.

one-way wave simulation method is simple and clear, so the analysis can be done accurately and inversion algorithm can also be reliable to be developed. From the analysis of model forward simulation, we can get some useful information: (1) in a gas layer, i.e., when the layer has strong absorption, the energy of seismic wave decreases, the main frequency drops and the bandwidth becomes narrower than other layers [Fig. 3(a)]; (2) the seismic wave energy declines more than 60%, and the speed is even faster as Q decreases; (3) peak and centre frequency decrease apparently with increasing Q, and the declining gradients both rise in gas area; (4) high frequency energy weakens much faster than that of low frequency. According to these rules, three different ways are formed by introducing S-transform technology, and then the method of layer absorption integrated parameter is used to predict the weak seismic response reservoir covered by high-speed gypsum-salt layer. In the actual data test, the fault of other hydrocarbon prediction means that fail to resolve the problem of strong amplitude affect caused by gypsum-salt layer is overcome by this method, so perfect identification results are obtained, which is really useful to the actual exploration of hydrocarbon reservoir.

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