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Seismic Inverse Q Filtering for Carbonate Reservoir Characterization

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Abstract: The Ordovician fractured-vuggy carbonate reservoirs in China's Tarim Basin are characterized by ultra-deep burial (>5000 m) and significant vertical-lateral heterogeneity. Such geological complexity severely degrades seismic data quality, manifesting as low signal-to-noise ratios (S/N) and limited resolution, thereby challenging accurate reservoir characterization. Aiming at these problems, here we use a stabilized inverse-Q filter to process 3D seismic data, conducting seismic amplitude compensation and waveform phase correction, simultaneously. Comparing the inverse-Q filtered result directly with the raw seismic data in terms of seismic profiling, interior information within the reservoir, characterization of faults and fracture-vuggies, we demonstrate the advantages of stabilized inverse-Q filtering in enhancing seismic resolution, strengthening weak signals, and improving lateral continuity of reflections, and reveal that this method can improve the accuracy of fracture-vuggy characterization in the Ordovician carbonate reservoirs.

Keywords: Carbonate Reservoir; Seismic Inverse Q Filtering; Strong Heterogeneity.

1. Introduction

During subsurface propagation, seismic waves experience energy attenuation and phase distortion due to the earth's intrinsic Q-effect. This phenomenon, primarily caused by high-frequency energy loss and velocity dispersion, significantly reduces both data S/N ratios and resolution. Inverse Q filtering attempts to remove the earth Q-effect by performing amplitude compensation and phase correction simultaneously (Wang, 2008a).

Inverse Q filtering has been successfully applied to seismic data of clastic reservoirs, for the sand body description and the hydrocarbon prediction. In this paper, we apply the inverse Q filter to the three-dimensional (3D) seismic data, for improving the characterization of a carbonate reservoir, which is featured by fracture-vuggies.

The Ordovician carbonate reservoir in Tarim basin, China, is buried very deep with a depth being larger than 5000 m. The target formation has extremely strong heterogeneity in both the vertical and horizontal direction. The feature leads to low S/N and low resolution of the seismic reflection data. Aiming at these two problems, we use a stabilized inverse Q filter to process the 3D seismic data in Tarim basin. We will show that inverse Q filtering can improve seismic resolution, by strengthening weak signals and improving lateral continuity of reflections, and in turn can enhance the accuracy of lithologic prediction and reservoir characterization.

2. Stabilized Inverse Q Filtering

Futterman (1962) introduced a frequency-dependent Q model expressed as:

$$Q(\omega) = \frac{|\omega|}{2\alpha(\omega)v(\omega)} \tag{1}$$

where ω , $\alpha(\omega)$ and $v(\omega)$ denote angular frequency, attenuation coefficient, and phase velocity, respectively. Hence, $Q(\omega)$ is frequency dependent. In seismic analysis, as the seismic data are generally recorded as real values, we need to consider only the positive frequency ω . Wang (2008a) point out that Equation 1 is an approximated expression for low-attenuation cases, and can be applied to the exploration seismology where Q >>1 effectively. Different mathematical models in geophysical literature differ only in the definition of the attenuation coefficient and the phase velocity. The modified Kolsky model proposed by Wang & Guo (2004a) makes it comparable to any other Q models. In the field of seismic exploration, because of its low frequency and a narrow band, we can ignore the frequency-dependency and use a so-called constant Q model (Kjartansson, 1979). However, we can see from Equation 1 that the dependence on the frequency still exists in the attenuation coefficient and the phase velocity. On the one hand, this frequency dependence can be exploited to estimate the Q value from seismic data. On the other hand, it causes great difficulty for inverse Q filtering.

Seismic inverse-Q filtering can be regarded as the reversal procedure of wave propagation. Robinson (1979) pointed out that the algorithm of inverse Q filtering is similar to that of seismic deconvolution. In seismic wave propagation, both the amplitude attenuation and the phase distortion are the exponential functions of the frequency and the travelling time. Since the exponent of phase distortion is in imaginary, the exponent of phase correction is still in imaginary, and its numerical implementation is unconditionally stable. Hargreaves & Calvert (1991) proposed an inverse Q filter for phase correction through Fourier transform, which is suitable for a constant Q model. Bano (1996) applied the phase-only inverse Q filter to a layered Q model, with a constant Q value in each layer.

However, because the exponent in the amplitude attenuation function is really valued, the exponent in the amplitude compensation function is also in real, and being positive as well. Hence, the numerical implementation of amplitude compensation is extremely unstable, which will greatly boost the noise of seismic data, and sharply decrease the S/N ratio of seismic data. Wang (2002) for the first time proposed a stabilized inverse Q filter to realize the amplitude compensation. The method adopts the stabilization solution of a mathematical inverse problem into seismic data processing (Wang, 2006). This method even can be used to realize seismic migration with inverse Q filtering (Wang & Guo, 2004b; Wang, 2008b; Bai et al., 2016).

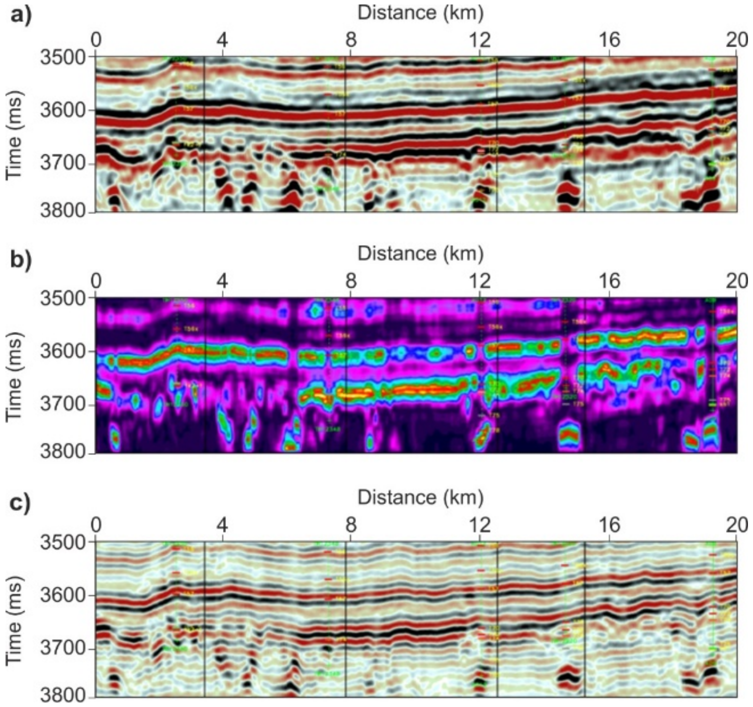

Figure 1. 3D seismic data, attenuation coefficients, and inverse Q filtered seismic data. (a) Seismic profile arbitrarily extracted from 3D seismic data cube; (b) The attenuation profile corresponding to the arbitrary seismic profile; (c) The corresponding seismic profile after inverse Q filtering.

In this paper, we will apply the stabilized inverse Q filter to 3D seismic data of a carbonate reservoir. Figure 1 illustrates the workflow, by displaying a field seismic data example, consisting of Q estimation from 3D seismic data, and applying this Q model for inverse Q filtering. Seismic inverse Q filtering obviously improves the seismic resolution. In the next section, we will carefully analyze the seismic data before and after inverse Q filtering, and the details of reservoir characterization.

3. Application to a Carbonate Reservoir

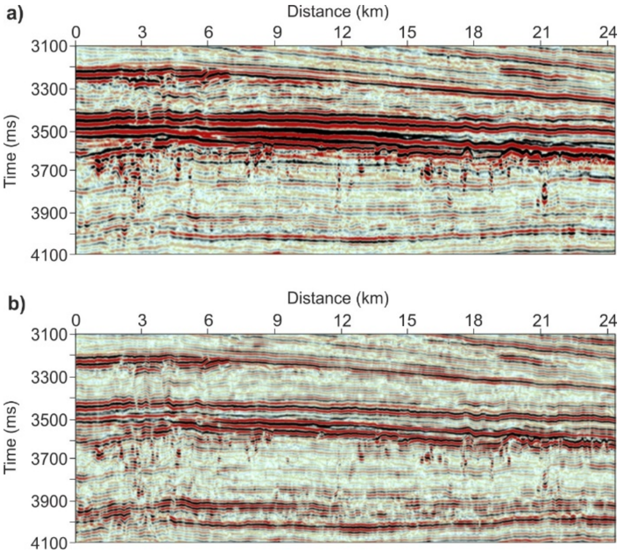

Figure 2. 3D seismic data within the target window of receivers. (a) Seismic profile before inverse Q filtering. (b) Seismic profile after inverse Q filtering. The target of the Ordovician carbonate reservoir is within a time window between 3480 and 3900 ms.

The Tarim basin is a large composite sedimentary basin developed on the top of the Pre-Simian metamorphic rock, and is formed by the Paleozoic craton and the Mesozoic-Cenozoic foreland basin. Influenced by regional tectonic activity and sea-level change, it was formed within three depositional periods: Sinian-Devonian marine sedimentary, Carboniferous-Permian in the land and sea sedimentary, and Triassic-Quaternary continental sedimentary. Our study area is located in the middle of the Tarim basin. The stratigraphic system consists of Triassic continental clastic sedimentary, the Carboniferous clastic folded limestone, and Ordovician carbonate rock. Among them, Ordovician carbonate layer exhibits the low-amplitude erosional residual mound formed by weathering and denudation, with the development of fissure and dissolution holes. Hence, the reservoir has a strong heterogeneity. This paper will demonstrate the effectiveness of stabilized inverse-Q filtering in the field 3D seismic data of carbonate reservoir, in the characterization of the target Ordovician reservoir.

The target reservoir in this area is the carbonate rock formation in Ordovician in the 3480 ms in Figure 2. The stabilized inverse Q filtering technique demonstrates superior performance in three key aspects: (1) enhanced delineation of faults and breakpoints; (2) improved visibility of secondary monadnocks and karst valleys; (3) increased continuity and S/N ratios for reflections from the Ordovician weathered layer, accompanied by strengthened energy responses; the energy of the Ordovician interior reflections are enhanced; and the "string-bead" reflection becomes more focused.

The "string-bead" reflection, caused by a fracture-vuggy, is an important characteristics of the Ordovician carbonate reservoir in the study area. Figure 2 demonstrates that, because the spatial resolution of the seismic data is significantly improved, more "string-bead" reflections can be identified after inverse-Q filtering. Meanwhile, we can see that the internal details of the unconformity layer atop of the Ordovician are clearly presented.

Using dipping-angle attribute (Figure 3), we can identify the disturbance, fold, bulge, differential pressure, and so on. These features are not traceable not only in conventional interpretation but also in seismic coherence attribute. The dipping angles calculated from 3D seismic data cube after inverse Q filtering can show both the main branch fractures and the secondary fractures.

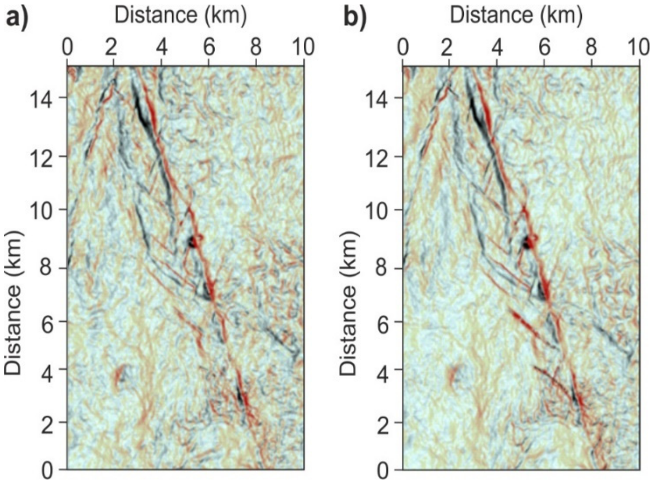

Figure 3. Dipping-angle attributes derived from 3D seismic data. (a) Dipping-angle attribute extracted from seismic data before inverse-Q filtering; (b) Dipping-angle attributes extracted from inverse-Q filtered seismic data

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4. Conclusion

The Ordovician carbonate reservoir is featured by fracture-vuggies, and extremely strong heterogeneity in both the vertical and horizontal directions. These features lead to low S/N ratio and low resolution of the seismic data. Application of the stabilized inverse-Q filter to 3D seismic data effectively enhances profile resolution and provides higher fidelity in reservoir characterization, particularly for complex Ordovician carbonate formations.

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