Analysis of the seismic response of an anisotropic viscoelastic reservoir

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Summary

In this paper, anisotropic viscoelastic media are used to model hydrocarbon reservoirs and to simulate reservoir features such as aligned fractures, fine-layered structures, and fluid saturation. Full wavefield seismic modeling is carried out, based on the Fourier pseudospectral method for the computation of spatial derivatives. We model a common shot reflection survey over anisotropic viscoelastic reservoirs and the reservoirs' structure, anisotropy and attenuation considerably affect the seismic responses. For visco-fluid saturated reservoirs the modeling results show that the converted and reflected S-wave has a reasonable strength, but the energy of the reflected P-wave from the interface below the reservoir is too weak to be detected. The seismic response of a Q interface is also analyzed, where the impedance contrast is very weak but the contrast in attenuation is significant. The boundary between the elastic background and the viscoelastic reservoir forms a Q interface, and the waves reflected from this Q interface have significant amplitudes.

Introduction

Hydrocarbon reservoirs can be represented by anisotropic viscoelastic media. Carcione (1990, 1993) investigated attenuation in such media, and developed the corresponding wave equations, where the numerical problem was solved by using a time integration technique. Ruud and Hestholm (2005) simulate seismic waves in orthorhombic viscoelastic media by a finite differences method. Sinha (2007) uses a layer matrix approach to generate full waveform synthetics in horizontally multilayered anisotropic attenuating media and analyzes seismograms using a spectral decomposition method. Based on the theory of Carcione, this study simulates the seismic responses of a highly dissipative reservoir, and analyzes the effect of anisotropy and attenuation on reflected and transmitted P- and S-waves. A geologic model is designed to simulate reservoirs, including anisotropic attenuating regions with specific configuration and structure. The model can describe reservoir features such as aligned fractures, fine-layered structures, and fluid saturation. The seismic response of a Q interface is also considered, where the impedance contrast is very weak but the contrast in attenuation is significant across the boundary between the elastic and viscoelastic media. Full wavefield seismic modelling in this study is based on the Fourier pseudospectral method for the computation of spatial derivatives (Kosloff and Baysal,1982; Carcione, 1993).

Theory

The wave equations developed by Carcione(1990) for seismic wave propagation in anisotropic viscoelastic media are formulated in a velocity-stress scheme, where memory variables are introduced to model the relaxation mechanism. Full waveform simulation in this study uses the Fourier pseudospectral method to compute spatial derivatives, and a finite difference method to calculate temporal derivations. For example, the calculation of the spatial first-order differential for wavefield φ along the *x*-direction is performed using a basic principle of the Fourier transform

$$D_1\varphi = \sum_{k_1=0}^{k_1(N)} ik_1\tilde{\varphi}(k_1)exp(ik_1x) \tag{1}$$

Where $\tilde{\varphi}$ is the Fourier transform of φ and $k_1(N)$ is the Nyquist wave-number. The factor ik_1 is multiplied in the frequency domain, which corresponds to the derivative in the time domain.

Modeling studies

The geologic model is designed as shown in Figure 1. The corresponding material properties are indicated in Table 1. The model consists of 5 regions. Regions 1 and 2 are isotropic elastic media with different impedances. Regions 3, 4, and 5 represent reservoirs embedded in the isotropic media. Two types of reservoirs are considered in the model. Region 3 represents a sandstone reservoir which has vertical aligned fractures saturated with fluids, and can therefore be described as a viscoelastic HTI medium. Region 4 and 5 are reservoirs consisting of sand/shale fine layer structures and can be modelled as viscoelastic VTI media. Region 3, which is located at the depth range between 500m and 1000m, is lens-shaped with a lateral extent of 1000m. Regions 4 and 5 are relatively thin, with a lateral extent of 2000m.

The model is discretized on a numerical mesh for simulation, with vertical and horizontal grid spacing of 10m, and 256×1024 grid points. Absorbing zones are placed at the four boundaries to eliminate wraparound. The source is an explosive force generating a Ricker-wavelet with a dominant frequency of 40Hz, and is located at the 5000m position. This type of split spread is deployed for surface seismic recording. The maximum offset is 4000m on each side of the source and the spacing between geophones is 10m.

A snapshot of the x-component at a travel time of 1000ms is also shown in Figure 1 to demonstrate wave propagation through anisotropic viscoelastic reservoirs.

Figure 2 represents synthetic seismograms of z- and x-components corresponding to the geometry in Figure 1. For comparison, the case of an elastic reservoir which has infinite quality factor Q is also calculated. Figures 2(a) and (b) represent the case of z-component for viscoelastic and elastic reservoirs, respectively. Figure 2(c) is the difference of Figures 2(a) and (b), and therefore indicates the effect of attenuation on the reflected P- and S-waves. Figures 2(d), (e) and (f) are the corresponding synthetic seismograms for the x-components. In Figure 2(a), the events denoted by numbers 1 and 2 are the reflected P-waves from the top and bottom of reservoir 4, respectively. In Figure 2(c), as denoted by the red circle, the effect of attenuation on the P-wave reflected from the reservoir bottom is significant. The effects of reservoirs 3 and 5 are significant at far offset. In figure 2(d), the events indicated by numbers 3, 4 and 5 are the converted reflected S-waves from the top and bottom of reservoir 4, and from the interface under reservoir 4, respectively. The red circle in figure 2(f) indicates the effect of attenuation on the converted P-S reflection from the bottom of reservoir 4. More interestingly, for both elastic and viscoelastic cases, no obvious reflected P-wave energy from the interface under reservoir 4 can be observed. This may result from the large impedance contrast between medium 1 and reservoir 4, so that most of the energy has been reflected. This can be seen in the reflection coefficients of Figure 3(a), where the colors black, blue and green correspond to P-P reflections from the top and bottom of reservoir, and the reflection from the interface between medium 1 and 2, respectively. However, as denoted by event 5 in Figure 2(d), the converted P-S reflection from the interface under reservoir 4 has a detectable energy in spite of the presence of anisotropy and attenuation in the reservoir. Figure 3(b) shows the corresponding converted P-S reflection coefficients.

In the second example, we consider a more complex geological model in order to test the flexibility and adaptability of our modeling method. The property distributions of the media which may have horizontal or vertical variations are illustrated in Figure 4. In Figure 4 (a)-(d), the properties of isotropic medium 1 are Vp=2600m/s, Vs=1200m/s, Qp=20, Qs=15, and the values of Vp, Vs, Qp, and Qs increase vertically according to the depth. The isotropic media 2 and 5 in Figure 4 have the same properties as medium 1 in Table 1, except for a vertical variation of attenuation in this example, as illustrated by Qp and Qs in Figure 4(c) and (d). Medium 3 presents viscoelastic VTI media as shown in Table 1 and anisotropy parameters ε and δ increase with depth, which are demonstrated in Figure 4 (e) and (f). P- and S-wave velocities of isotropic medium 4 in Figure 4 have both vertical and horizontal variations, as well as its quality factors Qp and Qs as shown in Figures (a)-(d). Figure 4(g) is the density distribution.

The vertical vibration is excited at the location denoted by red stars in Figure 5, and red solid circles represent receivers. Propagating waves and events of seismic events are clear in the snapshots of x- and z-components in Figures 5 (a) and (b), and corresponding synthetic seismograms of x- and z-components shown in Figures 6 (a) and (b).

Conclusions

Modelling results show that the attenuation of anisotropic reservoirs has a significant effect on seismograms. The study also indicates the advantage of converted P-S imaging at a lower layer in the presence of an anisotropic and viscoelastic reservoir above it. A test using wavefields simulation for a complex model with vertically and horizontally varying media properties shows the flexibility and adaptability of our modeling method. The anisotropic viscoelastic wavefield modeling method provides a more realistic simulation of propagating seismic waves. Possible applications may include modeling seismic time-lapsed response due to the variation of reservoir attenuation, or providing a more accurate simulation method for inverse time migration.

Acknowledgements

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Table 1. Material properties

Medium	Style	v11(m/s)	v33(m/s)	v44(m/s)	v13(m/s)	ρ(kg/m^3)	Qp	Qs
1	Isotropy	3600	3600	1900	2396	2700	∞	∞
2	Isotropy	4100	4100	2500	2076	2800	∞	∞
3	HTI	2500	2850	1728	1143	2200	20	15
4	VTI	2355	2150	1240	1538	2100	30	20
5	VTI	2355	2150	1240	1538	2100	30	20

Where, v11,v33,v44, and v13 are Thomson anisotropic velocities for TI media. ρ is density. Qp and Qs are P- and S-wave quality factors, respectively.

Analysis of anisotropic viscoelastic seismic response

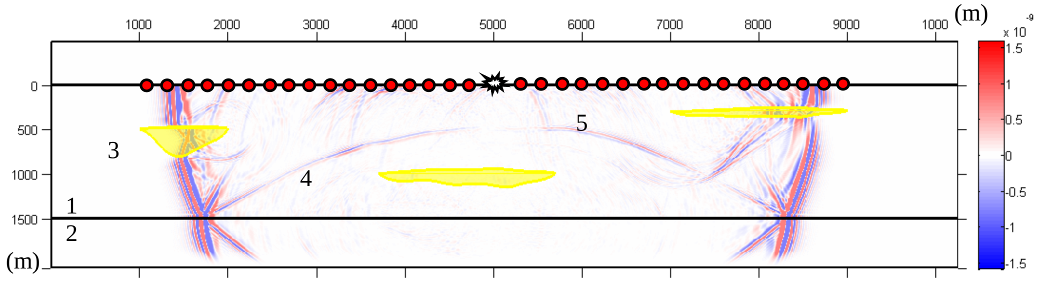

Figure 1: Geologic model and snapshots of x-component demonstrating wave propagation at 1000ms. Regions 1 and 2 are isotropic elastic media. Regions 3, 4 and 5 marked in yellow indicate reservoirs. Region 3 is a viscoelastic HTI medium and regions 4 and 5 represent viscoelastic VTI media. An explosive source is located at the position 5000m, with a maximum offset of 4000m on each side.

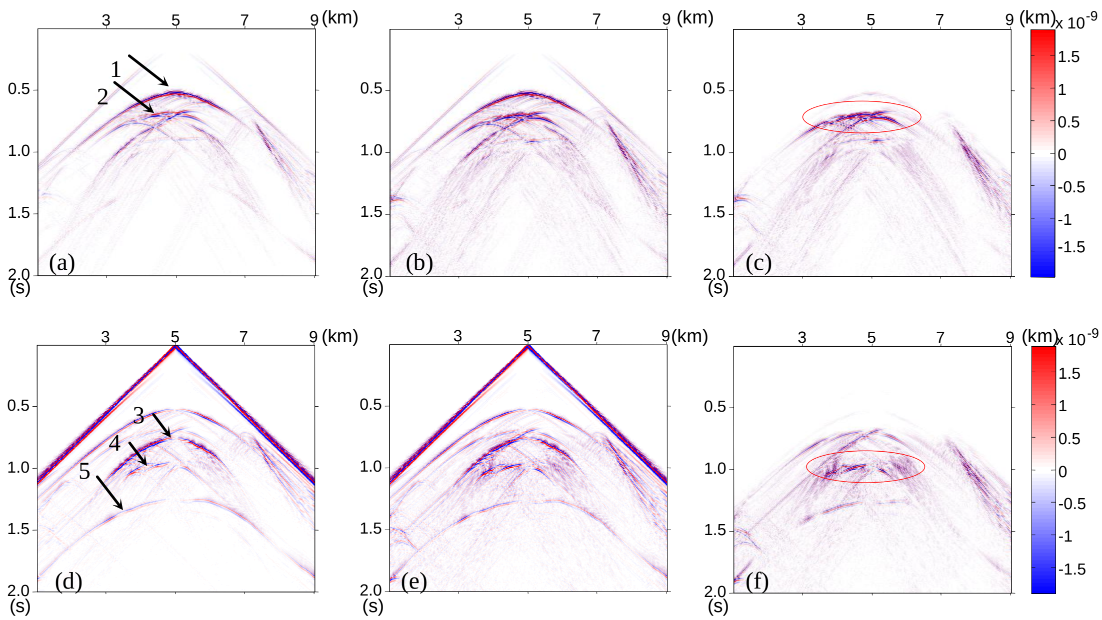

Figure 2: Synthetic seismograms corresponding to the model in Figure 1. (a) and (b) represent the x-component of the viscoelastic and elastic reservoir, respectively. (c) shows the difference between them. (d), (e) and (f) are the corresponding seismograms for the z-component.

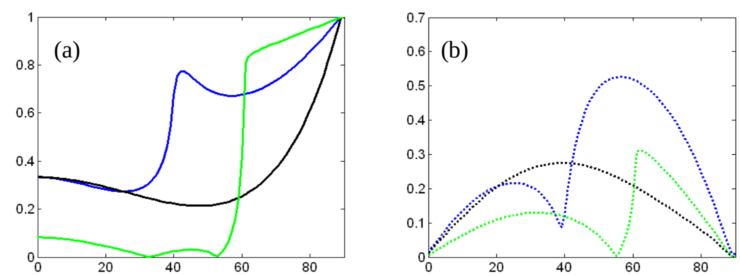

Figure 3: Reflection coefficients of (a) P-P waves in solid lines and (b) converted P-S waves in dashed lines. Black and blue curves correspond to the reflection coefficients of the top and bottom boundaries of reservoir 4. Green curves indicate the reflection coefficients for the interface between medium 1 and 2.

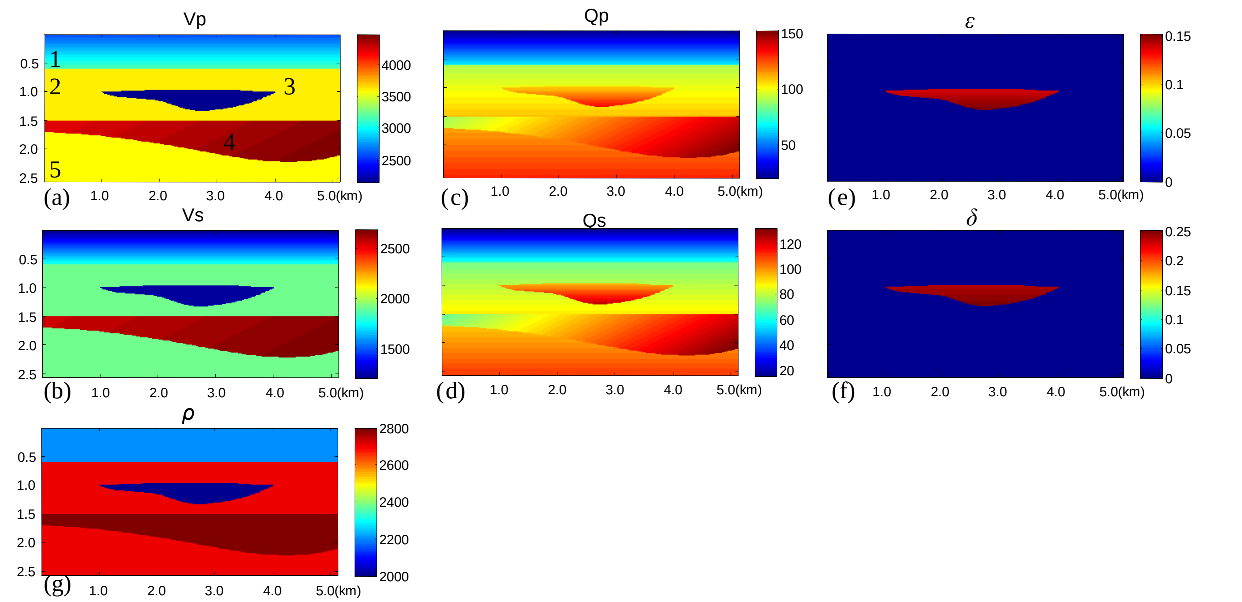

Figure 4: Properties of the model for simulation. Figure (a)-(g) correspond to the distribution of Vp, Vs, ε, δ, Qp, Qs, and ρ, respectively.

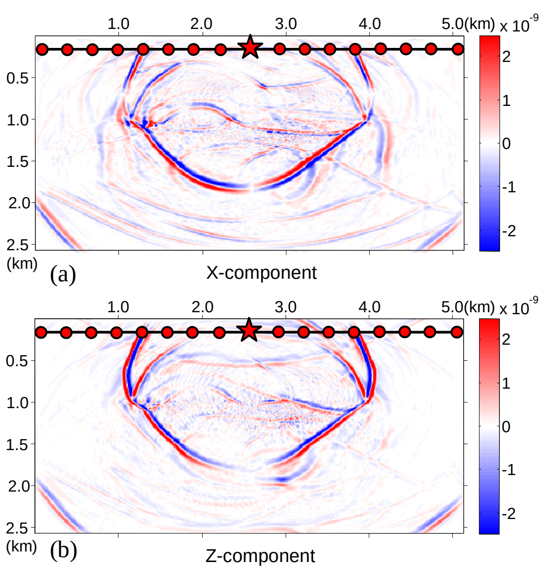

Figure 5: Snapshots at 0.8s calculated according to the model in Figure 4. (a) corresponds to x-compnent and (b) z-component.

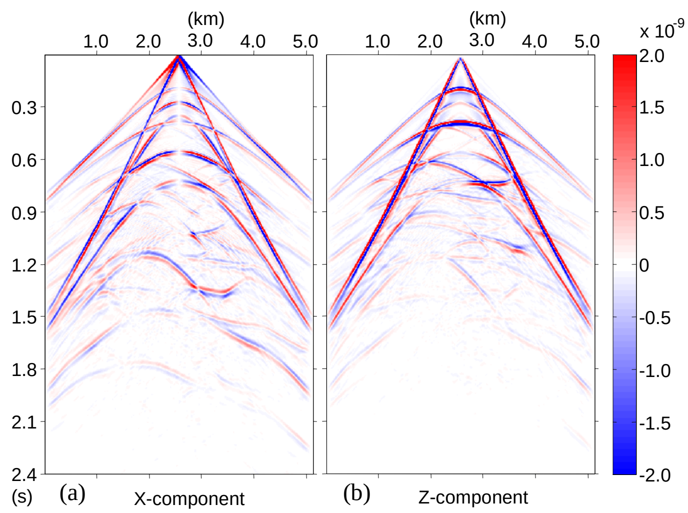

Figure 6: Synthetic seismograms according to the model in Figure 4. Source is placed at the position of 2560m. (a) corresponds to x-component and (b) z-component.