3D Seismic Anelastic Waveform Modelling of Intrinsic and Scattering Attenuation Effects

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Summary

The seismic attenuation we observed from previous studies at various sites suggested the complexity of imaging in a hardrock environment. Firstly, the attenuation effect is extremely strong from VSP measurements. It causes the loss of unconformity images along distinct sections. Secondly, the strong attenuation is highly localized. Observation from the surface 3D seismic datasets indicated that the low Q structures occur vertically with specific elongated shapes. We conduct a 3D full waveform viscoelastic modelling using Finite-Difference (FD) software package SOFI3D to illustrate this type of complexity. The 3D model consists of vertical low-Q-low-Vp and high-Q-high-Vp zones. Thus, both of the intrinsic and scattering attenuation effects are embedded. The result implies the surface observed seismic amplitude can exhibit azimuthal variations under the influence of both of these two effects. The local amplitude fast decaying direction may not align with the true low Q or high velocity directions.

Introduction

Modern seismic imaging techniques take advantages of multi-parameter information from the waveform for either enhancing weak images or quantitatively defining subsurface features. However, the attenuation mechanism, which has significant effect on received amplitudes, is still not fully understood especially in 3D. The situation influences less the results from on-land data, as the environment rarely is reported to have intrinsic Q lower than 100. A special case exists in the Athabasca Basin (Shi, 2016), where local Q measured from VSP datasets through various methods confirmed that it can be lower than 10 at multiple sites. Moreover, analysis of the surface seismic amplitude suggests an azimuthal effect. The amplitude decays along fast and slow directions, and it is not associated with any near surface structures present. We hypothesize previously that the deep low Q values relate to faults and fractures and fault-associated alterations. In this study, a 3D model is generalized to demonstrate this 3D azimuthal amplitude and velocity phenomenon can be explained by a mixture of intrinsic and scattering attenuation.

The two components of seismic attenuation, intrinsic and scattering, are independent events from each other. When referring to the intrinsic attenuation, the anelasticity is the precondition. The wave energy transfers to heat through the micro friction mechanism. Loose molecular combination of fluid and gas makes the energy transformation more significant than solids, which explains the direct relationship between the porosity and attenuation observed in sediments (Klimentos, 1990). On the contrary, scattering attenuation refers to the energy loss caused by elastic effects of the material. This includes heterogeneities of velocity and density. Simplest case is the geometrical spreading that can occur in even homogenous environment. When introduced with a layered heterogeneity, the wave energy loses through reflection and transmission along interfaces. The transmission can be signified when wavefront is travelling along thin-high-velocity layers, which is known as the “leaky mode” scattering (Zanoth, 2007). Geologically, small localized heterogeneities are the most common cause of the scattering wave energy loss.

The seismic attenuation quality factor, Q, is defined as the wave energy loss per cycle. In a forward modelling context, the Q is often considering intrinsic attenuation, as the scattering effect is already explained with the elastic component of the wave equation. The model with Q is computed with Maxwell bodies (i.e. relaxation mechanisms) added to the generalized standard linear solid (GSLS) model (Bolhen, 2002). However, common processing and inversion strategies would not separate the two attenuation mechanism by purpose, for the received amplitude is a composite result.

Theory and Method

The intrinsic and scattering attenuation can result in similar seismic amplitude. We demonstrate this by the 2D model in Figure 1. It compares "leaky mode" attenuation with an intrinsic attenuation. The amplitude at the middle of the model attenuate similarly. Thus, the amplitude cannot differentiate the two opposite situations (considering high velocity implies a hard material, while low Q implies soft).

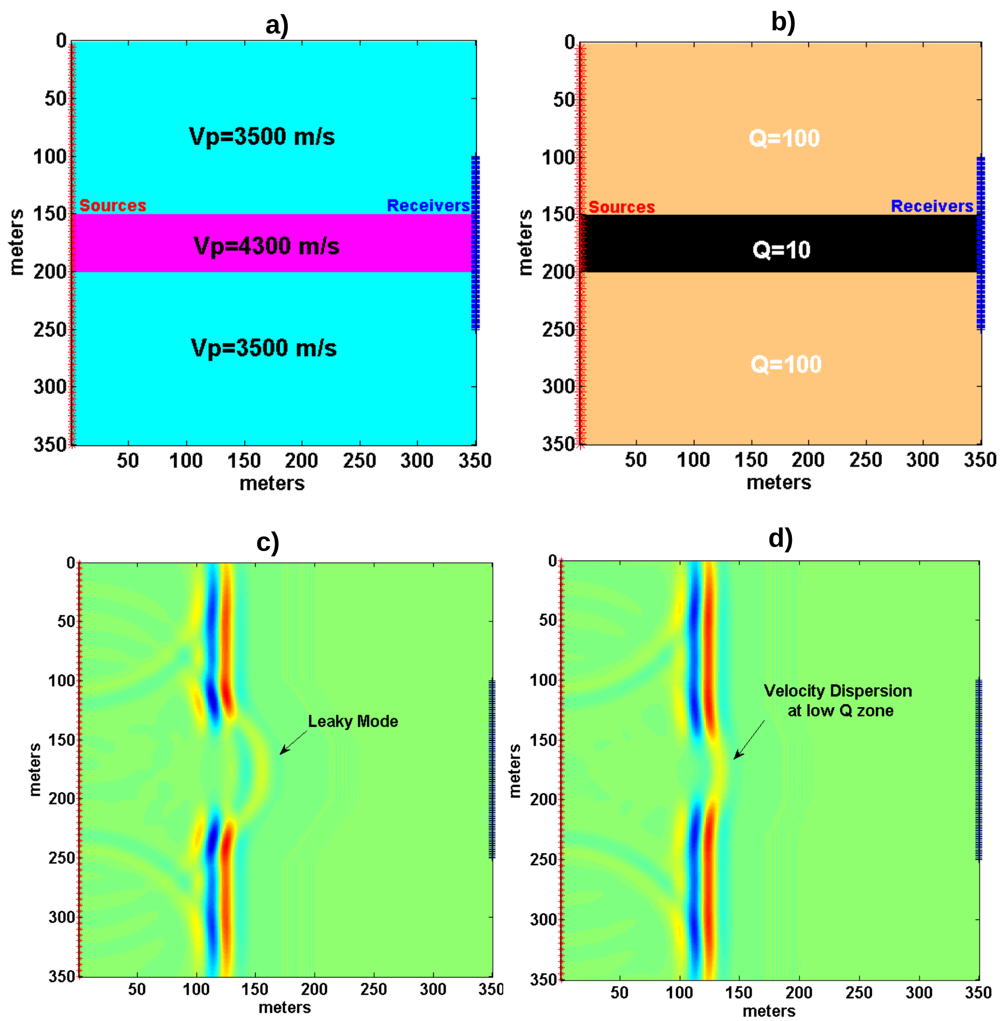

Figure 1. a) A "leaky mode" velocity model with high velocity layer in the middle. The model is elastic, with a constant Vp/Vs ratio of 1.75 b) A Low-Q layer viscoelastic model in a normal high-Q background. The velocity is the same as the background velocities from the model in a) (Vp=3500 m/s, Vp/Vs=1.75) c) Snapshot of the plan wave wavefield of the model in a) d) Snapshot of the plan wave wavefield of the model in b). The attenuation effect of both of the "leaky mode" and intrinsic show similar amplitudes. Both models contains a plan wave source simulated by a small spacing source line from the left.

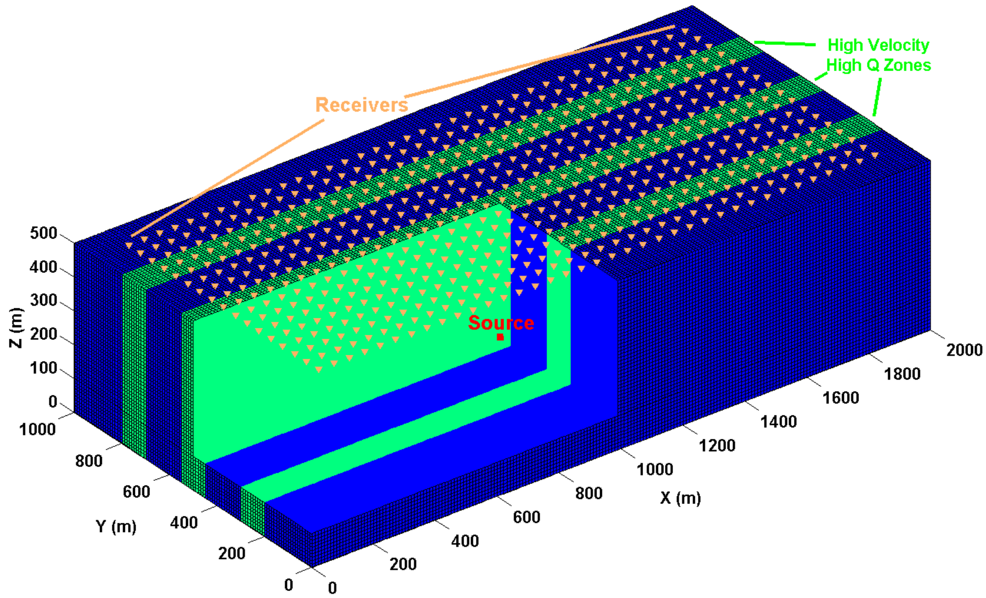

Figure 2. The 3D viscoelastic model created to show an effect of both intrinsic and scattering attenuation. The background (blue zones), low Vp (3500 m/s), density (2200 g/cm^3) and Qp (20) are given. The high-velocity-high-Q stripes (green), high Vp (4200 m/s), density (2300 g/cm^3) and Qp (100) are given. Source is located at 1000m(X)-500m(Y)-400m(D) of the model. Receiver spacing is 50m on both X and Y directions.

The 3D model created is shown in Figure 2. The background (blue) represents low Vp, Vs, density and Q. Three stripes of vertical high-velocity-high-Q zones are added to the background. A non-reflecting absorbing boundary condition (Cerjan, 1985) is used in the SOFI3D waveform modelling package to avoid reflection from edges. The seismic wavefield is recorded by 629 receivers at 50m spacing on both X and Y directions. Source locates at 400m deep at the middle of the model.

Examples

Two snapshots of the divergent components (p-wave) of the wavefield at 101ms and 151ms, respectively, are shown in Figure 3. To illustrate the effect of intrinsic and scattering on received seismographs, the direct wave (first break) amplitude and time are shown in Figure 4.

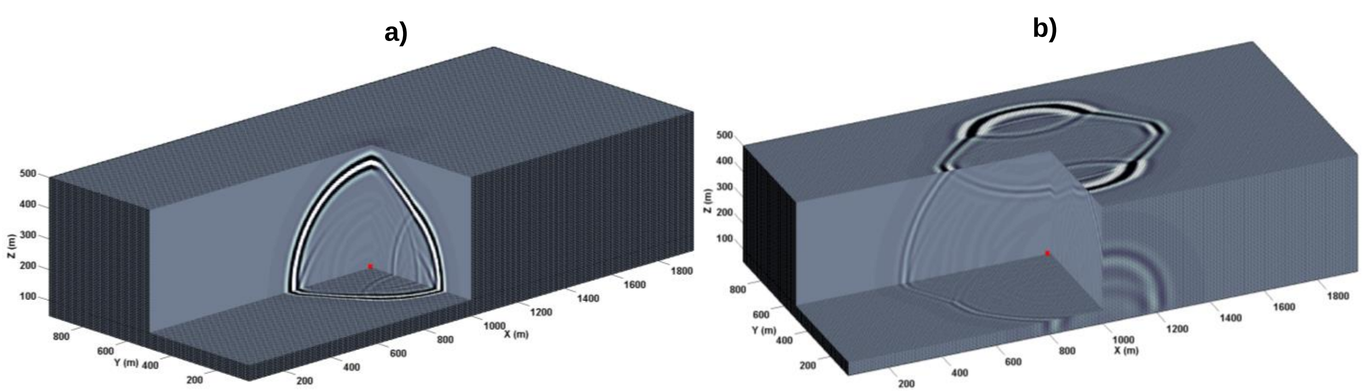

Figure 3. a) A snapshot of the divergence (p-wave) of the wave field at 101 ms. b) A snapshot of the divergence of the wave field at 151 ms.

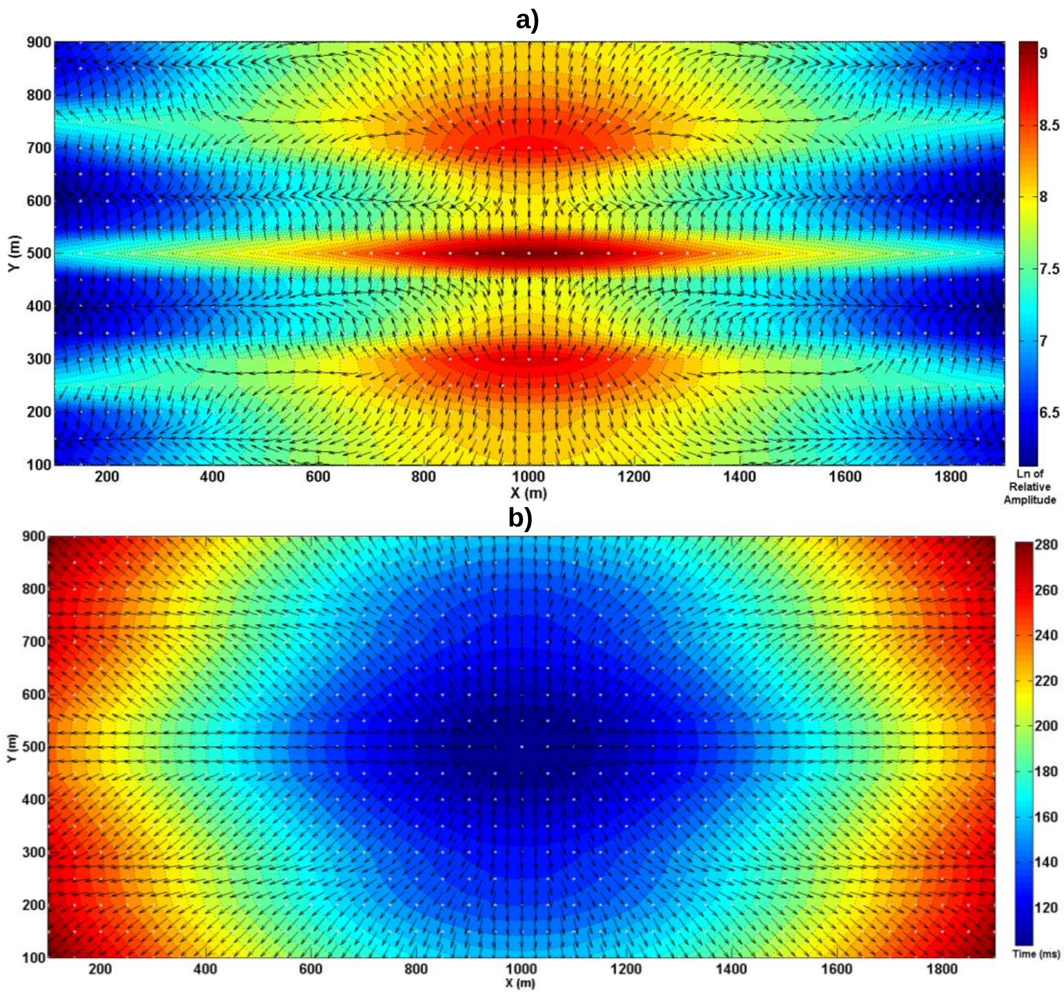

Figure 4. a) A map (plan view) of extracted first arrival root-mean-square amplitude displayed in a logarithm scale. White dots represent receiver locations. Black arrows represent the local amplitude fast decaying direction by computing of the gradient of the amplitude field. b) A map of extracted first arrival time. Black arrows represent the local apparent velocity direction.

The first arrival time displays the pattern that can reflect the fast and slow directions of the 3D model. Apparent velocity aligned to the fast direction (X) in the three high velocity stripes, while it points radial with respect to the source in the low velocity zones. In contrast, the amplitude decaying direction varies even within the high or low Q zones.

Conclusions

We conduct 3D waveform modelling to illustrate the effect of vertically occurring intrinsic and scattering attenuation. With the composite of both attenuation components, the received amplitude will exhibit an azimuthal variation. If the model contains only globally homogeneous Q, amplitude fast decaying directions would be identical to the apparent velocity directions. However, that direction can vary not necessarily corresponding to low Q zones. This explains the misalignment of the velocity and amplitude fast decaying direction observed in the seismic data set at the Athabasca basin site.

Acknowledgements

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References

Best, A. I., McCann, C., & Sothcott, J. (1994). The relationships between the velocities, attenuations and petrophysical properties of reservoir sedimentary rocks. *Geophysical Prospecting*, *42*(2), 151-178.

Bohlen, T. (2002). Parallel 3-D viscoelastic finite difference seismic modelling. *Computers & Geosciences*, *28*(8), 887-899.

Cerjan, C., Kosloff, D., Kosloff, R., & Reshef, M. (1985). A nonreflecting boundary condition for discrete acoustic and elastic wave equations.Geophysics, 50(4), 705-708.

Huang, J. W., Bellefleur, G., & Milkereit, B. (2012). Application of conditional simulation of heterogeneous rock properties to seismic scattering and attenuation analysis in gas hydrate reservoirs. *Journal of Applied Geophysics*, *77*, 83-96.

Klimentos, T., & McCann, C. (1990). Relationships among compressional wave attenuation, porosity, clay content, and permeability in sandstones. *Geophysics*, *55*(8), 998-1014.

Shi, D., Sun, L. F., & Milkereit, B. (2016, June). Seismic Detection and Delineation of a Low Q Structure. In *78th EAGE Conference and Exhibition 2016*. DOI: 10.3997/2214-4609.201601397

Zanoth, S. R., Saenger, E. H., Krüger, O. S., & Shapiro, S. A. (2007). Leaky mode: A mechanism of horizontal seismic attenuation in a gas-hydrate-bearing sediment. *Geophysics*, *72*(5), E159-E163.