

Seismic Wave Attenuation due to Scattering and Leaky Mode Mechanisms in Heterogeneous Reservoirs

Jun-Wei Huang*,

jhuang@physics.utoronto.ca

University of Toronto, 60 St. George Street, Toronto ON, M5S1A7

Gilles Bellefleur

Geological Survey of Canada, 615 Booth Street, Ottawa ON, K1A0E9

and

Bernd Milkereit

University of Toronto, 60 St. George Street, Toronto ON, M5S1A7

Summary

Multi-dimensional and multi-variable heterogeneous petrophysical reservoir models were constructed based on stochastic analysis of well logs. With a full wave form visco-elastic finite difference modeling software, a numerical experiment (cross borehole survey) was conducted to study the impact of P- and S-wave scattering, wave mode conversion, leaky mode mechanism and their integration on the apparent energy loss observed in the various field data. The analysis on the synthetic seismic data from pure elastic models indicates that in a heterogeneous situation both scattering and leaky mode mechanisms contribute to the observed apparent energy loss. The scattering mechanism due to small scale heterogeneity cannot be ruled out when studying the attenuation observed in the field data. In regions with locally continuous large scale heterogeneities, scattering attenuation may become less severe, and the leaky mode mechanism plays the leading role in the apparent energy loss.

Introduction

Wave attenuation is an important seismic attribute that contains significant information about physical rock properties. As observed from field data, the attenuation behavior of waves is too complicated to be explained by a single model or mechanism. One mechanism is the elastic scattering losses due to various scales of heterogeneities (e.g., Aki and Wu, 1988) whereas the other one is concerning the physics process converting energy to heat (e.g., Johnston and Toksöz, 1981). This paper deals with the study of elastic scattering due to the occurrence of gas hydrates in permafrost region.

In the Mallik area, located in the Northwest Territory of Canada, the high velocities due to hydrate formation are physically difficult to reconcile with the strong seismic attenuation obtained from sonic logs (Guerin et al., 2005), cross-well survey (Pratt, et al., 2005) and zero-offset Vertical Seismic Profiling (VSP) (Milkereit et al., 2005) in hydrate-bearing zones. Guerin et al. (2005) explained the acoustic wave dissipation in sonic logs as friction between solid phases and squirt flow. On a macroscopic perspective, Dvorkin and Uden (2004) attributed the attenuation in hydrated sediment to self-induced elastic heterogeneity which caused macroscopic squirt flow and scattering attenuation. Zanoth et al. (2007) used a simple 2D layered acoustic model to demonstrate the significance of leaky mode to the energy loss in the

cross borehole seismic survey. Huang's (2006) deterministic model demonstrated the weak backward scattering and explained the weak seismic expressions of hydrates on the surface seismic data. Here, we further study the scattering attenuation of gas hydrates including the effect of the leaky mode mechanism by using the multi-dimensional and multi-variant heterogeneous model (Huang et al., 2008). We demonstrate that scattering attenuation in elastic and visco-elastic heterogeneous gas hydrate reservoirs can be significant. In addition, leaky mode as another mechanism of energy loss in gas-hydrate bearing sediments (Zanoth, et al., 2007) may play a leading role in areas with local large scale heterogeneity.

Methodology and Results

1. Leaky Mode

The idea of leaky modes in seismology stems from the Rosenbaum's paper (1960), in which a modal method was studied to investigate long-time response of a layered medium. Rosenbaum deformed the integration path of frequency and wave number from real to complex plane and obtained oscillatory motions in addition to the normal modes. Snieder (2004) pointed out that a complex wave number mathematically results in an exponential decay factor in the wave equation that make waves decay in the same direction as propagation. Physically, the exponential decay is due to the fact that as seismic wave propagates along a high velocity zone, the wave energy refracts (i.e. leaks) into the surrounding low velocity zones. The leaky mode is frequently observed in borehole acoustic logging where the fluid filled borehole serves as a waveguide (Paillet and Cheng, 1991). In the numerical experiment of the cross borehole seismic survey, Zanoth et al. (2007) demonstrated that seismic wave were propagating in a hydrate-bearing layer as a guided wave and radiated energy to the surrounding low velocity layers. Taking the advantage of the heterogeneous model and the current computation power, we demonstrate that leaky modes that have been studied in layered media for decades can also be observed in laterally heterogeneous medium and contribute to apparent energy loss in addition to scattering.

2. Models and Results

A high resolution 2D heterogeneous model with 5 cm grid interval and 10 m horizontal characteristic scale (see P-wave model in Figure 1a) was constructed and a cross borehole seismic survey was simulated on it. An Ormsby wavelet (Figure 1b) was used with the similar frequency range from 100-2000 Hz as the real cross borehole seismic survey (Bauer et al., 2005). In figure 1a, two homogeneous layers were added to the top and the bottom of the model and the two red lines denote the location of two boreholes where explosive sources (star) and receivers (triangles) were placed. Two horizontally oriented receiver array (red and blue diamond) at depth of 1040 m and 1070 m respectively, were also introduced to quantify the leaky modes in two regions where sporadic and continuous local distribution of gas hydrates can be identified. Two synthetic borehole logs are displayed on each side of the model. Note that sources were assigned to every grid point to simulate a plane wave front and all boundaries of the model (including the top one) are assigned damping factors to eliminate the artificial reflections (e.g. absorbing boundaries).

Figure 2a shows snapshots of wave propagation, where scattering and diffraction can be observed in small scale heterogeneity regions (e.g., marked by arrow A) and a significant coda wave after the wave front. In a region with large scale heterogeneity (e.g., marked by B and C), certain amount of energy 'leaks' to the surrounding slow formations leaving weak energy in the first arrivals. The energy loss due to leaky mechanism can also be observed in the receivers along the borehole (Figure 2b), where the fast arrivals have significantly smaller amplitude than the later ones. We used the equation of Knopoff (1963), but converted the independent variable from offset to arrival time and the dominant wavelength to dominant frequency:

$$A(t) = A(t_0) \exp\left(\frac{-t f_{dom} \pi}{Q}\right) \quad (1)$$

where f_{dom} is the dominant frequency and t is the arrival time of peak amplitude. For the two horizontal receiver arrays, we obtained a Q value of 22 in the high velocity region compared to a Q of 61 in the region with no obvious leaky modes (Figure 3). Given that a plane wave front was simulated in the model, the geometrical spreading can be ignored. In our heterogeneous model, we found that the leaky modes had severe impact on the first arrival amplitude as long as the wave encounters with a certain amount of locally continuous high velocity structures. The amount of continuous high velocity structures in our model is controlled by the correlation length of the reservoir. We thus predict that the effects of leaky modes to the energy loss increase to the maximum as the correlation length approaches infinity, which is the case of a layered medium (Zanoth et al., 2007). In the heterogeneous earth, the leaky mechanism can be the leading factor in a locally continuous structure along the wave path, and scattering becomes significant in locations with discontinuous small scale heterogeneities.

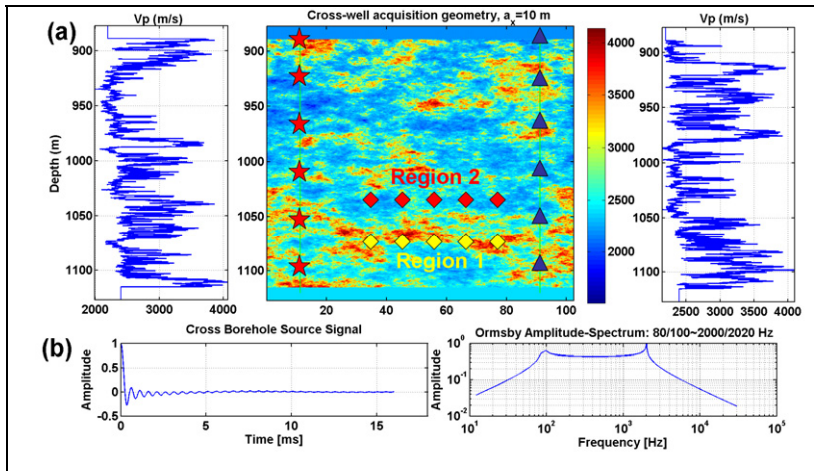


Figure 1: A high resolution 2D elastic heterogeneous model with cross borehole acquisition geometry and the wavelet. (a) In the V_p model with 5 cm grid interval, two vertical boreholes are separated by 80 m. Two synthetic well logs of P-wave velocity are listed beside the borehole. Stars denote the sources and others are receivers. In reality, we can only deploy receivers in the borehole (triangles). To quantify the leaky mode, we put two horizontal receiver arrays inside the model. (b) Ormsby wavelet in the time and frequency domain with the parameters listed in the graph.

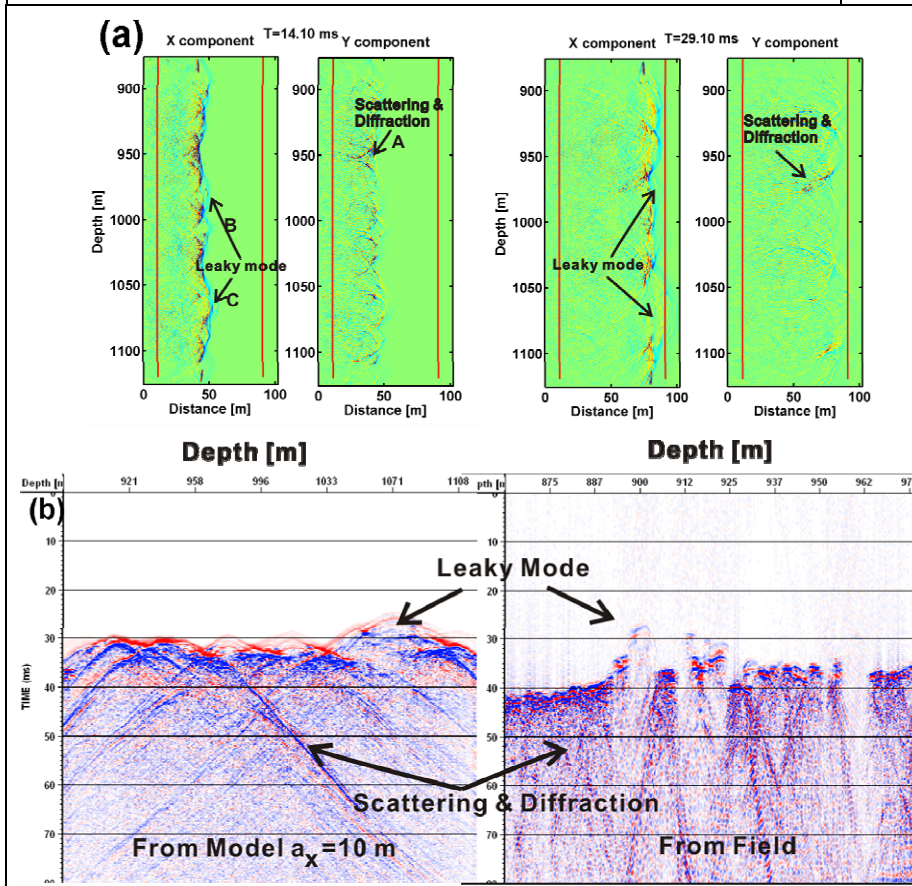


Figure 2: (a) Two snapshots of plane wave propagation through the heterogeneous medium ($t=14.1$, and 29.1 ms). Both scattering and leaky mode were observed in the figure. X-component is the horizontal component in parallel to the wave propagation direction, and Y-component measured the oscillations along vertical direction. (b) The comparison of cross borehole synthetic zero offset seismic data (left) with zero offset field data (right). The energy loss observed in the field data can be attributed to leaky mechanism as well.

We assigned a constant $Q_{int}=50$ and $Q_{int}=10$ into the heterogeneous model using a single relaxation mechanism approximation (Blanch et al., 1995) so that we can simulate intrinsic and scattering attenuation simultaneously. The attenuation Q_{int}^{-1} was shown with the source spectrum in figure 4. The same calculation using equation (1) gave Q_{appt} a value of 22 and 14 in region 1 and 48 and 34 in region 2, for $Q_{int}=50$ and $Q_{int}=10$, respectively. The seismogram and the least square fitting were shown in figure 3 and the comprehensive results were list in table 1.

Conclusions

Energy loss due to scattering and leaky modes was studied in a numerical experiment: 2D cross borehole seismic survey. It implies that the scattering mechanism due to small scale heterogeneity cannot be ruled out in the study of the attenuation observed in the field data. In regions with locally continuous large scale heterogeneities, scattering attenuation may become less severe, and the leaky mode mechanism plays the leading role of the apparent energy loss. The synthetic seismogram from our heterogeneous model indicated that apparent energy loss measured by Q factor is not consistent with the simple linear hypothesis: $Q_{appt}^{-1} \approx Q_{sc}^{-1} + Q_{leaky}^{-1} + Q_{int}^{-1}$, where *appt* represents apparent attenuation, *sc* scattering attenuation, and *int* the intrinsic attenuation (Richards and Menke, 1983 and Zanoth et al. 2007).

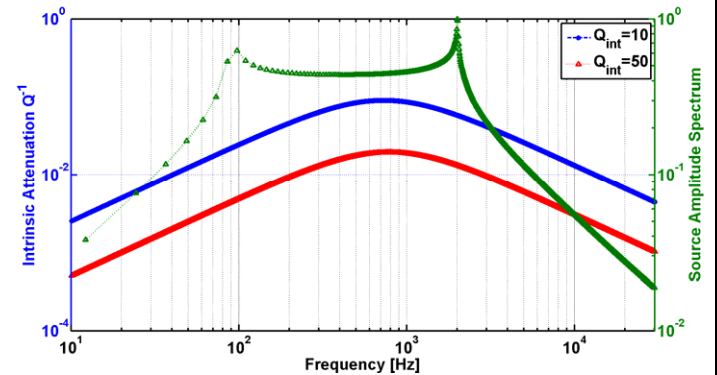
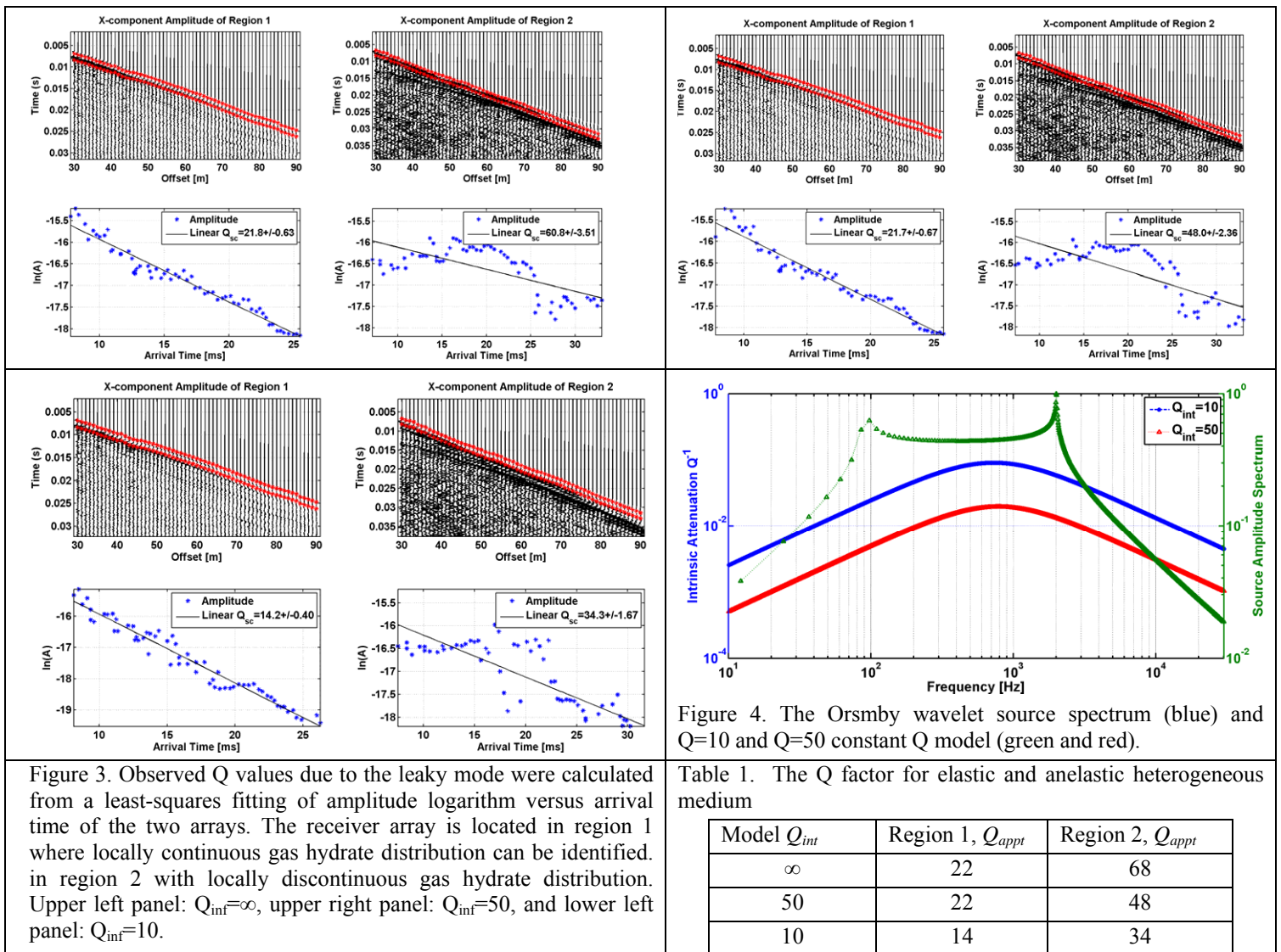


Figure 4. The Ormsby wavelet source spectrum (blue) and $Q=10$ and $Q=50$ constant Q model (green and red).

Table 1. The Q factor for elastic and anelastic heterogeneous medium

Model Q_{int}	Region 1, Q_{appt}	Region 2, Q_{appt}
∞	22	68
50	22	48
10	14	34

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