

Seismic Wave Propagation and Imaging in Heterogeneous Media

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Summary

The main objective of the study is to investigate the effect of scale parameters and dip on wave propagation in inhomogeneous media. The propagation of the seismic wave is studied using different background velocity models with different scale lengths. As the degree of scale length in the P-wave velocity increases, stronger local distortion of amplitude and arrival times of the direct waves are observed, provided certain conditions of the velocity perturbations are met. This result is different from the elliptical shape of direct waves often defined by effective anisotropic parameters used for layered media.

Introduction

When using seismic waves to probe the earth's subsurface, the information obtained is limited by the quality of the acquired data as well as the processing strategy adopted. It is understood that a real 3D earth model is heterogeneous. By heterogeneity, we mean that geologic and physical rock properties change from one position to another (Figure 1a&b). According to Wu (1989), the spatial scales over which these properties vary have a direct effect on the wave propagation. The characteristics of the resulting wavefield are subject to the relative ratio of the scale lengths (a_x/a_z) to the seismic wavelength, source frequency, strength of fluctuations in physical rock properties, as well as the propagation distance between the source location and the receiver locations. Heterogeneity that is characterized by layering is a common case for transverse isotropy. Thompsen (1986) showed that anisotropy parameters can be used to come up with an equivalent homogeneous anisotropic model that explains the shape of the wavefront at different spatial locations from the source. For example, in elliptical anisotropy ($\epsilon = \delta$, Thompsen, 1986), the P wavefront is elliptic (fast and slow direction), hence the phase velocity and group velocity are different in these circumstances. In addition, anisotropy causes nonhyperbolic moveout of the P-wave fields and consequently causes imaging problems (Alkhalifah and Tsvankin, 1995; Tsvankin, 1995; Greckha and Tsvankin, 1998).

Most of the research on wave propagation in heterogeneous media has been restricted to cases where there is little or no lateral variation in the physical rock properties ($a_x \gg a_z$) over the scale lengths comparable to the acquisition geometry. This is the basis for modeling studies that use homogeneous petrophysical parameters to characterize the host rocks in order to investigate the characteristics of the scattered wavefields from an ore target (Bohlen et al., 2003). However, assessing these scattered fields becomes more difficult when propagating in geologic settings where significant lateral variations exist over variable scale lengths. This is

especially the case in hardrock environments. Understanding the implications for wavefront shape, propagation (e.g. leaky mode effects, Huang et al., 2009), as well as processing requires full modeling of the wavefield within such media. If the effects cause significant deviation of the wavefields from hyperbolic moveouts, this will definitely lead to erroneous velocity models and stacked images that are often produced by using an isotropic velocity model. The isotropic velocity model is typically the mean velocity value derived from a collection of lab measurements or from existing logs (Figure 1a&b). This is the case with the imaging of the Matagami ore body (Figure 1c, Adam et al., 2003). This paper focuses on the modeling that investigates the effects of the background heterogeneity on the overall moveout characteristics of the body waves (e.g. P waves).

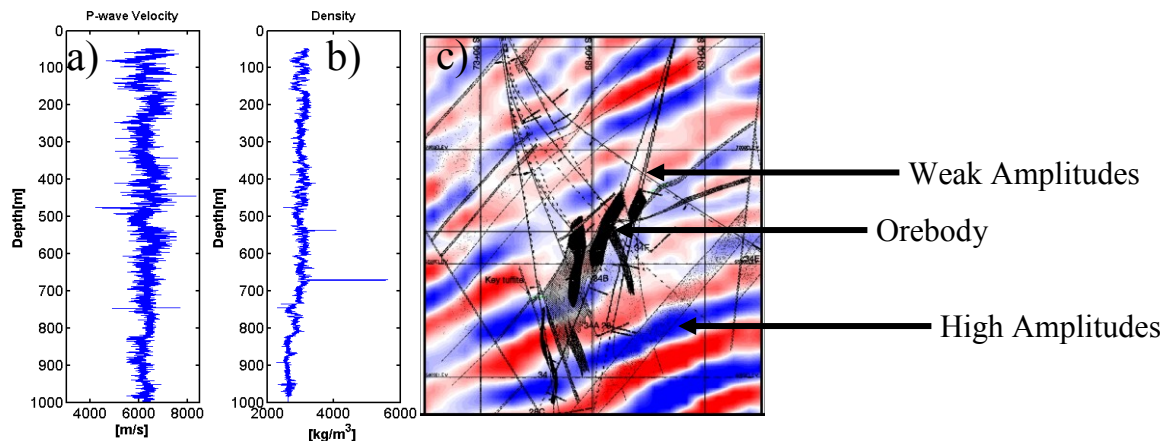


Figure 1: Petrophysical logs from Matagami Mine (Hole 33f, a & b) ; Seismic section coincident with the Bell Allard orebody in the Matagami Mine (c). Note the relative displacement between the strong seismic amplitude location and the orebody location. The dips of the seismic events are correlated to the dip of the background geology.

Method and Results

This research studies the moveout characteristics of wavefields propagating in heterogeneous media with anisotropic scale lengths. The study was conducted using 2-D finite difference elastic wave modeling methods (Bohlen, 2002). The building of the background velocity models was done using statistical methods (Goff and Jordan, 1988) which take into account data from petrophysical logs of the Matagami project (figure 1a&b). To examine the effects of the anisotropy in the medium on the wave, seismic wave propagation was modeled for different heterogeneous models with each having different scale length parameters. The scale length notations are $a_{//}$ in the dip direction and a_{\perp} in the direction perpendicular to the dip direction. The study used two sets of receiver arrangements, and one shot location. A graphical representation of a sample model as well as the receiver configurations is shown in Figure 2a. Figure 2d depicts a heterogeneous background velocity model that can also be classified as an effective anisotropic model. This is due to the anisotropy of the characteristics scale lengths ($a_{//}=6000\text{m}$, $a_{\perp}=20\text{m}$). The dip angle is the angle between direction of the dip and the horizontal level. The scale length characterizes the heterogeneity of the background velocity model. Heterogeneity in the earth (e.g. P-wave velocity) may result in directional dependence of wave propagation; hence rock can be described as being anisotropic.

In the circular receiver configuration (Figure 2a), a total of 360 receivers are uniformly distributed on a circle with 900m radius from the source location. As the wave propagates in each radial direction, each circular receiver records the seismogram at a fixed distance, which can be resolved in the radial, vertical and horizontal displacement of the wavefield. Figure 2a also shows another arrangement of receivers at the model near surface. There are 1000 receivers on the horizontal range of 1500m to 3500m with receiver intervals of 2m. The surface receivers at 10m depth are symmetrical about the source location.

Figure 3a shows seismograms of the radial component of the wave amplitudes in a homogeneous background model with circular configuration of receivers. The vertical axis is time from $t=0$, and the horizontal axis represent the angle of the receivers with respect to the source position. As expected, the plot shows uniform seismogram amplitudes at all directions. On the other hand, Figure 3b shows that the moveout of the wavefield as recorded by the surface receivers has a perfect parabolic shape.

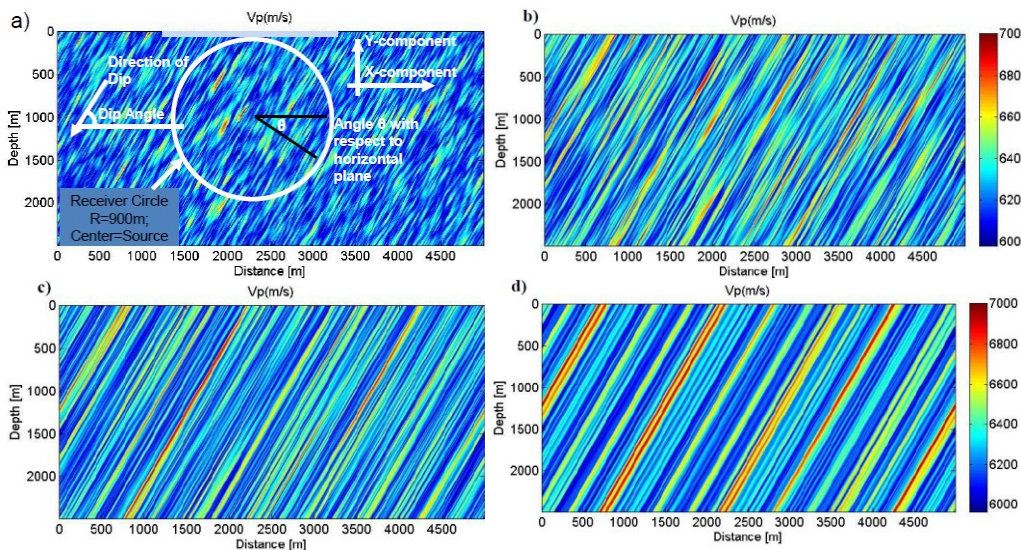


Figure 2. Anisotropic background velocity models at 4 different scale lengths. Model a) has scale lengths of 100m ($a_{//}$), 10m (a_{\perp}). b) has scale lengths of 400m, 10m. c) has scale length of 1000m, 10m. d) has scale length of 6000m, 20m.

The Source is located at the distance of 2500 m and the depth of 1000 m.

The dip angle is 60° .

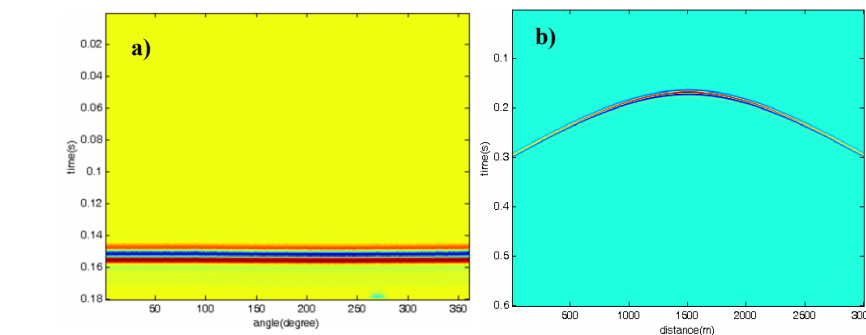


Figure 3. a) Radial component record from circular geometry
b) V- Component surface record

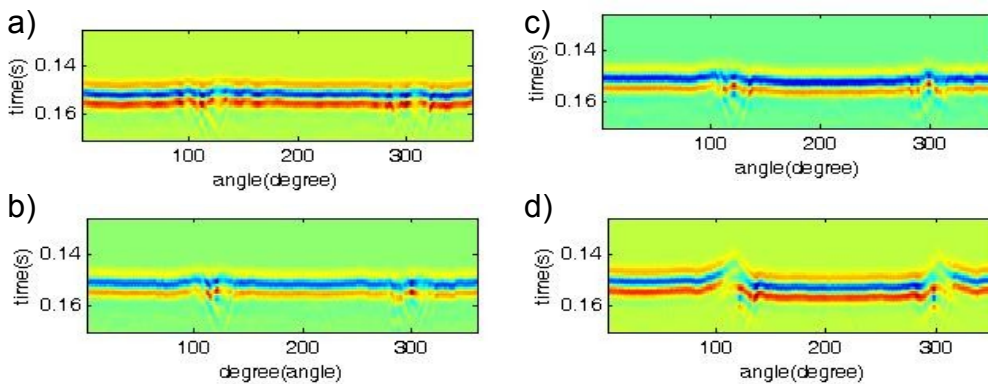


Figure 4. The diagrams show the recorded wavefield of the receivers in the circular geometry; a) uses the model with scale length of 100m (parallel to the dip direction), 10m (perpendicular to the dip direction). b) uses the model with scale length of 400m, 10m. c) uses the model with scale length of 1000m, 10m. d) uses the model with scale length of 6000m, 20m.

The heterogeneous models considered in this study are shown in figure 2 where the dip is 60° . The main differences between these models are based in the characteristic scale lengths. As $a_{//}$ increases toward the size of the spatial domain while a_{\perp} remains fixed, the model gradually approaches a layered model. In figure 2d, the scale length is 6000m in the dip direction and can thus be viewed as a layered model. The strength of the acoustic velocity perturbation in the models is $\sim 3\%$. Figure 4 shows the wavefields recorded by the circular acquisition geometry in the respective models. Since the scale lengths in figure 2a are small compared to the other three models, the net effect on the directional dependence of wave propagation may

not be observed over large propagation distances from source (figure 4a). As the scale length increases, the heterogeneous background (with anisotropic scale length parameters) has increasing scattering effects on the recorded seismograms. In figure 4d the graph shows strong local amplitude and traveling time distortions from 100° to 140° and from 280° to 320° . This can be explained by the fact that the local distribution of fast formations influences the wave propagation. As the wave travels at a different speed in each layer, the wavefront of the propagating wave is thus distorted.

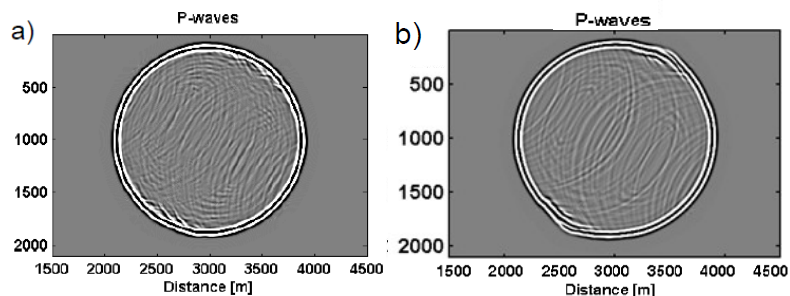


Figure 5. Snapshots of the propagating waves at 1s after source was triggered; a) uses the model with scale length of 100m (parallel to the dip direction), 10m (perpendicular to the dip direction); b) uses the model with scale length of 6000m, 20m.

The response of the propagating waves in the heterogeneous velocity models can be further examined by snapshots of the propagating wavefield (figure 5). The darker lines represent peaks and white lines represent troughs of the propagating waves. The direct wave travels faster along the dip direction (within local fast velocity formation(s), Figure 5b). The shape of the direct wave deviates from regular smooth curve (circular/ellipsoid) at the dip direction within $\pm 20^\circ$. The effect is local, which means the model of fast direction and slow direction (velocity with two parameters) would not apply for such layered model.

Conclusions and Outlook

In this work, the effect of anisotropy due to heterogeneities in elastic rock properties has been examined using 2-D finite difference elastic wave modeling. The result shows that for models with velocity perturbations of $\sim 3\%$, wave propagation in the layered model has strong local distortions in amplitude and time in the dip direction. Such local distortions in the wavefield moveout suggest that equivalent homogenous models with effective anisotropic parameters may fall short to characterize wave propagation effects in such layered media. Consequently, this may result in poor results from NMO and migration routines as well as microseismic imaging routines. Future work will focus on investigating the wave propagation effects of these heterogeneities on wavefield migration routines such as reverse time migration (RTM).

Acknowledgements

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