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Reflections from Thin Layering with Attenuation

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Summary

It is well known that for a layered reservoir, both reflection amplitude and phase vary with frequency. In the presence of attenuation, the phase of reflectivity is also frequency-dependent, which had been suggested as an indicator of inelastic materials such as bitumen-saturated sands. In this paper, we compare the effects of layering and attenuation on the phase of observed reflectivity. The results show an equivalence between phase-shifted reflectivity from ineastic reservoirs and reflections from elastic layering. Reflections from the top of an elastic reservoir followed by weak reflections from its bottom can appear as resulting from low *Q* within or above the reservoir. This apparent *Q* can be frequency-independent or have a frequency dependence corresponding to the pattern of layering. Depending on the pattern of layering, the *Q* interpreted within the reservoir can be positive or negative. Therefore, estimating the *Q* from frequency-dependent reflection amplitudes and phases is an inherently ambiguous problem that can only be resolved by using additional geologic or rock-physics constraints.

Introduction

Seismic reflections are characterized by their arrival times, amplitudes, and phases. Among these characteristics, the times, amplitudes, and spectra of seismic reflections have been used extensively, whereas the phase information is rarely utilized quantitatively. Recently, the attention to the reflection phase was increased because of the interest to seismic attenuation within heavy-oil reservoirs. Lines et al (2008, 2014) observed phase shifts caused by anelastic effects in laboratory experiments, and Morozov (2011) discussed them theoretically. Han et al. (2015) measured phase variations of reflections in recent laboratory experiments by Huang et al (2015) and suggested that reflection phase responds differently to different types of reservoirs. Han et al. (2015) suggested using the reflection-phase response as a complimentary hydrocarbon indicator.

Reflections from the top and bottom of a layer of less than quarter-wavelength thickness are generally inseparable and can be interpreted as a single reflection. The peak frequency of this reflection is generally different from that of the source, the phase shifted, and both the amplitude and phase are frequency-dependent because of the constructive or destructive interference effects. However, in an alternative to interference, all these effects can be interpreted as caused by inelasticity below the reflector (Lines, 2008, 2014; Han et al., 2015). In addition, the attenuation within any medium can also be “elastic” and caused by small-scale layering (White et al., 1975). Thus, there exists a fundamental equivalence between reflection seismic responses of layering and attenuation within the Earth.

In this paper, we investigate this equivalence of the amplitude and phase responses of thin layering and reflectivity from/in an attenuative medium. Approximate quantitative relations between the layer thickness and the apparent *Q* (or conversely, between the *Q* and apparent layer thickness) are obtained. These relations provide some guidance for thin-layer thickness detection and reservoir identification. With certain combinations of observations, it seems possible to distinguish a finely-layered structure from attenuative reflectors, whereas in other cases, they are indistinguishable from reflection observations.

Method

The following analysis is carried out in the frequency domain. Consider a plane wave at frequency f normally incident on either a layered structure or attenuating half-space (Figure 1), as described in the following subsections.

Layered Structure

In the layered model I, two arrangements of three layers are considered, with impedances denoted Z_1, Z_2 and ${}^{1,2}Z_3$ respectively ($Z_1 < Z_2 > {}^1Z_3$ and $Z_1 < Z_2 < {}^2Z_3$; Figure 1). The thickness of the thin layer 2 is denoted Δh. The reflectivity of each boundary equals:

$$r_n = \frac{Z_{n+1} - Z_n}{Z_{n+1} + Z_n} . \quad (1)$$

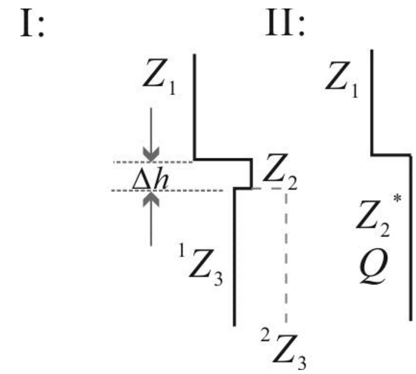

Figure 1. Two types of models considered. Model I (*left*) is elastic, and in Model II, the layer 2 is inelastic. The impedances of the layers are denoted Z_1, Z_2, and Z_3, Two variants $1Z_3$ and ${}^2Z_3$ are considered for layer 3, with $Z_1 < Z_2 > {}^1Z_3$ or $Z_1 < Z_2 < {}^2Z_3$. Δh is the thickness of the second (thin) layer. Q is the quality factor of layer 2 in Model II. Q can also be assigned to layer 1 in Model II.

The arrival time difference between the reflections from the lid and base of the thin layer equals $\Delta t = 2\Delta h/V_2$, where V_2 is its acoustic velocity. Disregarding the internal multiples, the total reflection amplitude above this layer consists of a reflection from the top boundary, with amplitude $r_{top} = r_1$, and a reflection is from the bottom, with amplitude $r_{bottom} = \left(1 - r_1^2\right) r_2$:

$$r(\omega) = r_{top} + r_{bottom} \exp\left(i 2\pi f \Delta t\right) . \quad (2)$$

If layer 2 is thin ($f\Delta t \ll 1$, i.e. $\Delta h \ll \lambda$, where λ is the wavelength) then these two reflections interfere with each other and can be treated as a single phase-shifted reflection. For material parameters shown in Table 1, the amplitude and phase of this interference is shown in Figure 2 as functions of the dimensionless frequency $f\Delta t \equiv \Delta h/\lambda$. The black line indicates the phase variation. When λ is much larger than the thickness of thin layer, the phase approaches zero. The maximum phase shift is determined by the selected model parameters. Note that for low impedance below the thin lid (${}^1Z_3$) , the amplitude increases with frequency, whereas for successively increasing impedances within he reservoir ($2Z_3$), the reflection amplitude decreases with frequency (Figure 2).

Table 1. Physical parameters for the models in Figure 1

Layer	Density ρ (g/cm^3)	Velocity V (km/s)	Q	Thickness Δh (m)
Z_1	2.55	3.14	N/A	N/A
Z_2	2.80	3.5	TBD	20 (Model I)
${}^1Z_3$	2.70	3.4	N/A	N/A
${}^2Z_3$	2.90	3.5	N/A	N/A

Viscoelastic Reflector

The results in Figure 2 can be obtained by a viscoelastic reflector model (Model II), which will be discussed below.

Reflection from a contrast between two viscoelastic media is another potential reason for frequency-dependent amplitudes and phases. We use the standard viscoelastic relation:

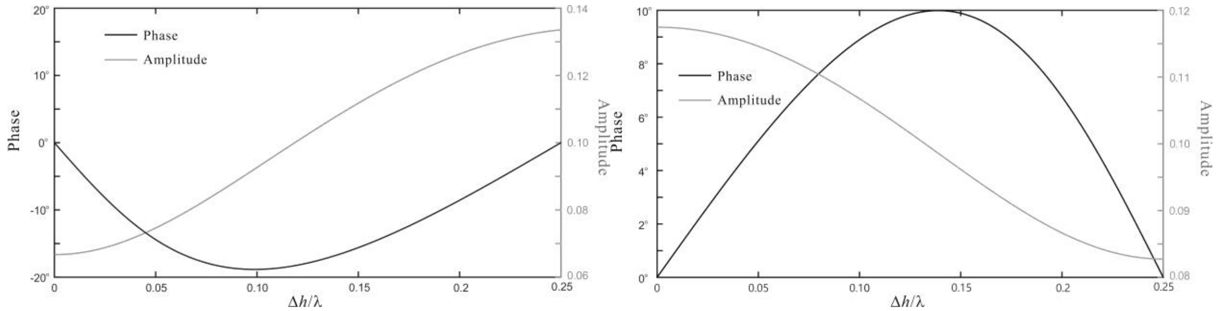

Figure 2. Reflectivity amplitude and phase in Model I (Figure 1) a s function of $\Delta h/\lambda$ of the ratio between the thickness of layer 2 and the wavelength. *Left*: the case of high-impedance reservoir lid, $Z_1 < Z_2 > {}^{1}Z_3$; *right*: progressive increase in the impedance, $Z_1 < Z_2 < {}^{2}Z_3$.

$$Z^* = \rho V(f)\left[1 - \frac{i}{2Q}\right] \tag{3}$$

to derive the reflectivity in a two-layer Model II (Figure 1) by using relation (1). In this relation, ρ is density and $V(f)$ is the phase velocity at frequency f. For a frequency-independent Q, $V(f)$ is given by Kjartansson's (1979) law:

$$Q(f) = \text{const}, \quad \text{and} \qquad V(f) = c_0\left(\frac{f}{f_0}\right)^{\frac{1}{\pi Q}}, \tag{4}$$

where we select the reference frequency f_0 equal 50 Hz.

If the upper layer is elastic and the lower one anelastic with a finite Q, the dependences of the reflection amplitude and phase on frequency are shown in Figure 3. The phase shift equals $\pm\pi$ at $f = 0$ and is practically constant, with a slight decrease with frequency. The absolute value of reflectivity is also near constant, with a noticeable increase for only very low Q values (Q = 5; Figure 3). For such low Q, the dispersion (4) is so strong that it reverses the polarity of reflection at low frequencies (Figure 3).

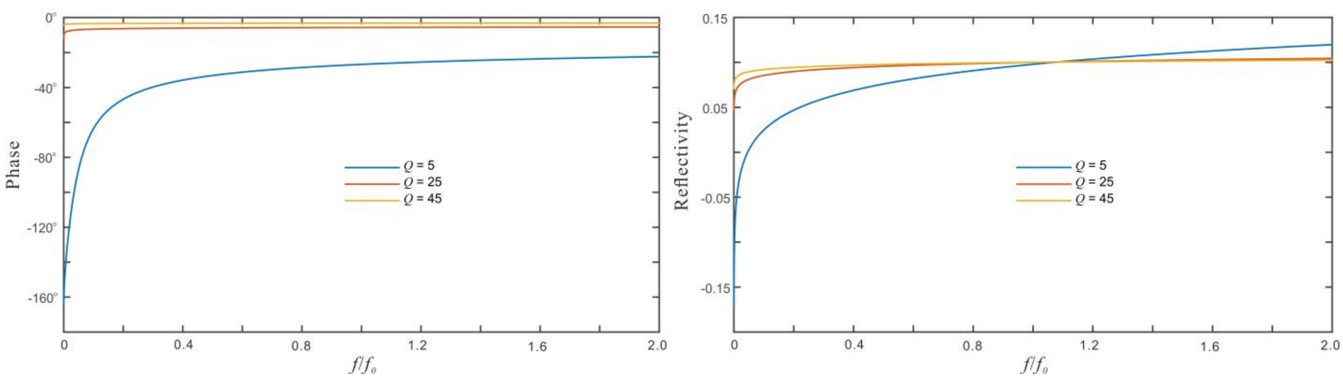

Figure 3. Reflections from an attenuative reflector (Model II in Figure 1). The lower layer is inelastic, the upper layer is elastic. *Left*: phase response; *right*: amplitude response.

Equivalence of layered and inelastic reflectors

Thus, if the velocity dispersion and attenuation laws such as (4) are known, layered reflection sequences and inelastic reflectors produce distinctly different reflection responses (Figures 2 and 3, respectively). With high-fidelity seismic processing and calibration by using acoustic logs, these responses could probably be used to differentiate between Models I and II in Figure 1.

However, in practice, the $Q(f)$ and $V(f)$ laws are hardly known within the exploration-frequency band. If we allow variable $Q(f)$ and $V(f)$, then Model II can produce exactly the same reflection phase and amplitude responses as Model I (Figure 2), From relation (1), to reproduce the $r(f)$ observed in Model I, the complex impedance and the quality factor Q of the lower layer in Model II should equal:

$$Z_2^* = \frac{1+r(f)}{1-r(f)} Z_1 \text{ and } Q = -2\frac{\operatorname{Im} Z_2^*}{\operatorname{Re} Z_2^*}. \quad (5)$$

From these relations, frequency dependences for the phase velocity and Q within the lower layer are shown in Figure 4.

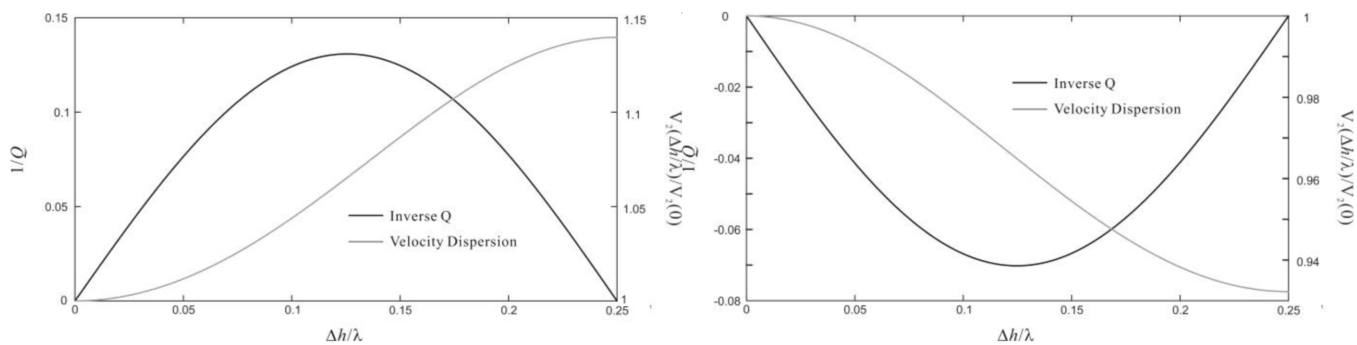

Figure 4. Inverse Q and phase velocity dispersion in model II that would produce reflection response equivalent to that of model I: left plot is for model with ${}^1Z_3$, right plot is for model with ${}^2Z_3$ (Figure 2).

Note that the Q in relations (5) is apparent, *i.e*. only arising from observations of reflectivity from elastic layering and not really related to internal friction within the material. This type of Q was called "fluctuation" Q (which is closely related to scattering Q) by Morozov and Baharvand Ahmadi (2015). This Q can have arbitrary values, and in particular, it can be negative. From Figure 4, in the case of a high-impedance reservoir lid (the case of ${}^2Z_3$), an interpretation using Model II should yield a positive Q and dispersion for its bottom layer. Conversely, for increasing impedances within the reservoir (the case of ${}^1Z_3$), Model II gives a negative Q and velocity dispersion within its bottom layer.

Conclusions

Reflections from thin layered structures can look like viscoelastic reflectors and vice versa. Both models produce frequency-dependent reflection amplitudes and phases, from which the velocity dispersion and Q can be measured. However, these quantities are apparent, and they can be explained by either layering or inelasticity within the reservoir. In particular, the apparent Q is positive (and therefore likely more expected in practice) for a high-impedance lid at the top of the reflecting reservoir. For a stepwise increased of the impedance, the apparent Q will be negative. The attenuation and velocity-dispersion phenomena are concomitant but may not necessary agree with the constant-Q or any other standard relations. Knowledge of such relations from geology, laboratory experiments, or rock physics could allow differentiating between layered and inelastic reservoirs.

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