Abstract

Evidence suggests that hydrocarbon saturated zones exhibit anomalously high values of attenuation, and we are therefore interested to understand this phenomenon. We consider seismic wave propagation through multi-layered models containing one layer which shows strong attenuation. The dominant frequency of the P-wave reflected from the top of this layer is generally shifted with respect to other arrivals, with the shift depending strongly on the AVO class. Reflections from class III gas sand tend to be shifted to lower frequency, while those from class I water sands tend to be higher frequency. Phase shifts can also be seen. The base reflection tends to be stretched in time, with the higher frequencies concentrated at the front and lower frequencies at later times. When an aligned fracture set is introduced, these features are apparent for propagation perpendicular to the fractures but are absent for waves propagating in the fracture strike direction.

Introduction

The variation of the reflection coefficient with both polar and azimuthal angle has provided the basis for interpreting seismic data in terms of lithology, fluid saturation and fracture properties in a range of recent studies. Such applied work often does not explicitly include the phenomenon of attenuation, or may treat it as a complicating feature associated with propagation through the overburden.

Nevertheless, evidence exists that the presence of hydrocarbons is often associated with abnormally high attenuation (see, for example, Klimentos, 1995). In particular, when fractures are present the effect can be seen to vary with direction (Maultzsch et al., 2003; Lynn, 2004; Maultzsch et al., 2005). This attenuation may in general be either intrinsic or apparent, but in either case we expect it to influence the reflection coefficient.

We attempt to capture this situation by considering wave propagation in a layered model in which all layers are purely elastic and isotropic except one, which shows attenuation and frequency dependent properties and may be anisotropic. We demonstrate a range of novel features which may be used to aid interpretation in both the isotropic and anisotropic cases.

Rock physics basis

Precise quantitative attenuation measurements have proven hard to obtain, and we note carefully the comments of Ebrom (2004) concerning processing induced effects which can make reflections from low velocity layers appear to be low frequency. Nevertheless, we believe the evidence, particularly from VSP data, supports the general notion that hydrocarbon saturated zones tend to exhibit higher attenuation than the surrounding rock.

Two plausible explanations which can be given for this are enhanced scattering due to increased heterogeneity in hydrocarbon saturated zones and “squirt” flow. In this paper, we will follow the squirt flow theory, largely because it is easily reconciled with the Gassmann
theory, whose usefulness is generally accepted. The difference between the low frequency “relaxed” moduli and the high frequency “unrelaxed” moduli (e.g. Mavko and Jizba, 1991), a proxy for dispersion and attenuation, depends on the saturating fluid. When we reduce the fluid bulk modulus from that of water to typical values for oil and gas we find a substantial increase in attenuation. Figure 1 gives a generic illustration of the point, calculated using the model of Chapman (2003).

**Reflection coefficient**

Numerous papers have studied the generation of reflected and transmitted waves at the interface between elastic, viscoelastic and poroelastic layers. The advantage of the current formulation is that we model both the existence of non-negligible values of attenuation and dispersion as well as the traditional Gassmann effect. This means that we demonstrate how the dynamic effects are expected to perturb the traditional framework for AVO interpretation.

When attenuation is present the reflection coefficient is in general complex, meaning that we see a frequency dependent phase shift. In the high and low frequency limits, however, attenuation does not exist and the reflection coefficient is real for small angles of incidence. Figure 2 shows a typical example of the variation of the reflection coefficient with angle of incidence for the high and low frequency limits for shale overlying a sandstone saturated with both water and gas. The water saturated case is class I, while the gas saturated case is class III. The difference between the high and low frequency curves is greater in the gas saturated case since there is increased dispersion. In this case, we see that low frequencies are likely to be more reflective in the gas saturated case, but high frequencies will be more reflective in the water saturated case. In a number of cases, we have found that for gas saturation there is class III behaviour at low frequency but class II behaviour for high frequency. This can give rise to a notch in the spectrum of the reflected wave.

**Synthetic Seismograms**

We calculate synthetic seismograms using the reflectivity method with frequency dependent velocities and attenuations supplied by our rock physics model. We consider 10 receivers with a spacing of 50m, and take the depth to the top of the frequency dependent layer to be 300m. The thickness of the frequency dependent layer is taken to be 75 m to avoid the effect of tuning.

Figure 3 shows the wave-train reflected from the top of the attenuating layer for both water and gas saturation. It is clear that the water saturated case shows class I behaviour while gas shows class III, but additionally the reflections in the gas case are lower frequency. This is illustrated in a comparison of the spectra for Receiver Number 5, which confirms the low frequency nature of the gas reflection.

The reflection from the base of the attenuating layer exhibits the effects of dispersion within the attenuating layer. High frequency energy travels faster than the low frequency energy, and this leads to the wavelet being stretched between the two limits (Figure 4). The resulting wavelet has a short, high frequency, head followed by a longer low-frequency tail.

Introducing fractures into the model, we find that the effects associated with the attenuation depend on azimuth. The introduction of gas shifts the frequencies of the top reflection over all azimuths, but a sinusoidal variation of frequency with azimuth is visible. For the reflection from the base of the reservoir, the wavelet stretching demonstrated in Figure 4 occurs for propagation perpendicular to the fractures, while no stretching occurs for propagation in the fracture strike direction. Lynn (2004) has discussed field data which show a similar effect.

**Conclusions**

We have studied seismic wave propagation in multi-layered models containing a single hydrocarbon saturated layer. The properties of this layer are assumed to follow the Gassmann theory (in both the isotropic and anisotropic cases) in the low frequency limit but the low fluid
bulk modulus gives rise to high values of attenuation and dispersion. When this attenuation takes place in the seismic frequency band a range of novel phenomena can occur. In the isotropic case, the reflection from the top of the attenuating layer tends to be shifted to higher frequencies for a class I interface, but to lower frequencies in the class III case. The effects of dispersion can be seen for the base reflection. When we consider dispersion caused by aligned fractures, these dynamic effects are visible for propagation perpendicular to the fractures.

References


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Figure 3: Reflections from the top of the frequency dependent layer, in the water and gas saturated cases (left) and a comparison of the spectra for Receiver Number 5.

Figure 4: Reflections from the base of the frequency dependent layer. In the dispersive case, the wavelet is stretched between the low frequency and high frequency limits.