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Time-lapse Differential AVO: Reflection Coefficient at Fluid-fluid Boundary

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Summary

Time-lapse AVO analysis is used to interpret the amplitude difference and map fluid variation in a reservoir. In terms of elasticity modulus of Zoeppritz equation approximation and based on fluid substitution model, we analyzed the modeled AVO difference between baseline and monitor observations assuming pressure of the reservoir remains the same. We find that formula of differential reflection coefficient is approximated to be a fluid-fluid reflection coefficient, where the fluids represent pore-fluid variations in pre- and post-injection stages. This means that differential AVO between time-lapse observations can be simply expressed as a fluid-fluid reflection coefficient. This fluid-fluid reflection coefficient formula is accurate enough so that it can be used in fluids discrimination in time-lapse seismic observations of a reservoir.

Introduction

AVO analysis has potential to be used in discriminating pore fluids variation and estimating fluids saturation and pressure in time-lapse seismic monitoring (Tura and Lumley, 1999; Landro, 2001;Ma and Morozov, 2010). Similar to conventional 2D and 3D AVO analysis for isotropic media, different approximations (Shuey, 1986; Goodway, et al, 1997) to the Zoeppritz equation can be used in 4D AVO analysis. However, Shuey's approximation or other approximations have a concise physical meaning on 2D and 3D AVO analysis. What does time-lapse seismic amplitude difference mean? Could we use a simple formula to interpret the differential reflection coefficient?

Let us see the approximation of Zoeppritz equation in terms of elasticity modulus (Bortfeld, 1961). The beauty of this formula is that fluid-fluid reflection coefficient is seperated from rigid part of reflection coefficient. This also means that P-wave and S-wave contributions to reflection coefficient are seperated. For the conventional 2D and 3D AVO analysis, we might not easily separate fluid part and rigid part from this formula. It is not easy to understand the physical meaning of fluid-fluid reflection coefficient from this formula when we study 2D or 3D AVO on shale/sand boundary.

In 4D AVO analysis, if we only consider the change of pore fiulds content or saturation and assuming pore pressure is the nature pressure of reservoir, the rigid part of reflection coefficient may change a little and could be neglected. As we know (DOE Annual Report, 2004) that about 10% of reservoir's original oil is primaryly recovered at nature pressure of the reservoir. During injection of water, hot steam or CO_2 for EOR, the pressure of reservoir will be changed. Elasticity modulus will be change with pressure. After the injection, the pressure of reservoir would be recovered to nature pressure of reservoir. Therefore, during pre- and post- injection, the pressure of reservoir could be the same. Even during injection, pressure of reservoir near injection and production wells could be the same between vintages of 4D seismic data. If the pressure of reservoir remains constant, shear modulus does not change when pore fluids saturation change in the reservoir. 4D differential reflection coefficients will be mainly determined by fluid-fluid reflection coefficient part of Bortfeld's approximation. The differential reflection coefficient between two vintages of 4D seismic data can be approximated as a new fluid-fluid reflection coefficient. The accuracy of this new formula is proved in this paper.

Method

In terms of elasticity modulus (Bortfeld, 1961; Wang, 1999; Ma and Morozov, 2004), the approximation of Zoeppritz equation can be expressed as:

$$R(p) \approx R_f(p) - \frac{2\Delta\mu}{\rho} p^2 = R_f(p) - 2\frac{\Delta\mu}{\rho\beta^2}\sin^2\phi \tag{1}$$

Where, μ is shear modulus, p is ray parameter, α is P-wave velocity, β is shear wave velocity and ρ is densit y. φ is P-SV wave reflection angle. $R_f(p)$ is the fluid-fluid reflection coefficient. The second term of rigid pa rt in this equation is mainly related to shear moduli.

The advantage of eq.(1) is that fluid and shear moduli effect on reflection coefficient are separated. According to Gassmann's (1951) theory, shear modulus does not change and shear wave velocity changes little when pore fluids saturation changes in reservoir. The second rigid term changes little which is much smaller than the first term of fluid-fluid reflection coefficient. Rock physics measurements had proved that shear wave velocity (Wang, 1998) could change as large as 1% when pore fluid changes in reservoir, whereas P-wave velocity could change around 10%.

If we compare the differential reflection coefficient during pre- and post- injection and neglect the second term of rigid part supposing pore pressure changed little. The differential reflection coefficient can be simplied as:

$$\begin{aligned}
\Delta R_f'(p) &= R_2'(p) - R_1(p) \approx R_{f2}'(p) - R_{f1}(p) \\
&\approx \frac{1}{2}\ln\left(\frac{\rho_2'\alpha_2'}{\sqrt{1-(\alpha_2' p)^2}} \Big/ \frac{\rho_1\alpha_1}{\sqrt{1-(\alpha_1 p)^2}}\right) - \frac{1}{2}\ln\left(\frac{\rho_2\alpha_2}{\sqrt{1-(\alpha_2 p)^2}} \Big/ \frac{\rho_1\alpha_1}{\sqrt{1-(\alpha_1 p)^2}}\right) \\
&= \frac{1}{2}\ln\left(\frac{\rho_2'\alpha_2'}{\sqrt{1-(\alpha_2' p)^2}} / \frac{\rho_2\alpha_2}{\sqrt{1-(\alpha_2 p)^2}}\right) = \frac{\rho_2'\alpha_2' / \sqrt{1-(\alpha_2' p)^2} - \rho_2\alpha_2 / \sqrt{1-(\alpha_2 p)^2}}{\rho_2'\alpha_2' / \sqrt{1-(\alpha_2' p)^2} + \rho_2\alpha_2 / \sqrt{1-(\alpha_2 p)^2}}
\end{aligned} \tag{2}$$

where p is ray parameter, $R_1(p)$ is reflection coefficient of basline, $R_2'(p)$ is reflection coefficient of monitor data. α_2 and α'_2 represent P-wave velocity of reservoir for baseline and monitor data. ρ_2 and ρ'_2 are density of reservoir for baseline and monitor data. Eq.(2) can be written as a function of incidence angle as well. Where, θ_1 is incidence angle at top of reservoir at different vintages. If the surface condition and geometry of seismic acquisition would be the same for seismic baseline and monitor data, θ_1 would be the same for 4D seismic data. θ_2 and θ'_2 are transmission angles at top of reservoir at different vintages.

It is obvious that differential reflection coefficient $\Delta R_f'(p)$ is a recusive formula. It has the same form as $R_f(p)$ and represents the reflection coefficient at fluid and fluid boundary, where meaning of fluid and fluid boundary here is different from that in 2D and 3D seismic data. We should also note that eq.(2) is functions of ray parameter or incidence angles. It can be interpretated as seismic waves strike at a fluid-fluid boundary (Figure 1). This fluid-fluid boundary here represents fluid variation during pre- and post- injection or production stages. As a recursive formula, eq.(2) may be written as

$$\frac{\rho_2^{'}\alpha_2^{'}}{\sqrt{1-(\alpha_2^{'}p)^2}}=\frac{\rho_2\alpha_2}{\sqrt{1-(\alpha_2 p)^2}}\frac{1+\Delta R_f^{'}(p)}{1-\Delta R_f^{'}(p)}=\frac{\rho_2\alpha_2}{\cos\theta_2}\frac{1+\Delta R_f^{'}(p)}{1-\Delta R_f^{'}(p)} \tag{3}$$

where $\rho\alpha/\cos\theta$ is the impedance of sound waves in the liquid defined by Brekhovskikh (1960). Both $\rho\alpha/\cos\theta$ and $\Delta R_f'(p)$ could be used to measure pore fluid variation in time-lapse observations.

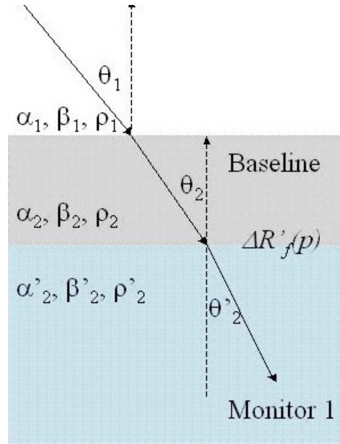

Figure 1: Demonstration of differential reflection coefficient $\Delta R_f'(p)$.

Accuracy of approximation

In order to measure the accuracy of eq. (2), we compared the reflection coefficients by using Zoeppritz equation and eq.(1) (Figure 2) based on fluid substitution model (Table 1). Especially, $R_f(p)$ and rigid part of reflection coefficient of eq.(1) are plotted separately so that we can observe the change of $R_f(p)$ and rigid part. From Figure 2, we note that when pore fluids changes from water to oil or gas, $R_f(p)$ changes a lot and rigid parts are nearly unchanged. If we combine R_f and rigid part reflection coefficient of Figure 2 and Class2, Class3 cases into Figure 3, we see clearly that R_f changes much and rigid parts change little. In Figure 4, the maximum change of rigid part is calculated. The differential of rigid part to differential of fluid-fluid reflection coefficient at larger incidence angle in Class 1 and Class2 cases is maximum 6.9%. In Class 3 cases, the maximum change is within 1.5%.

If we compare the differential reflection coefficients calculated from Zoeppritz equation, we find that $\Delta R_f'(p)$ curve fits other two curves very well within critical angle (Figure 5). This proves that $\Delta R_f'(p)$ of eq.(2) is accurate enough. The comparison of $\Delta R_f'(p)$ at gas/water, oil/water boundary and water/water boundary shows that $\Delta R_f'(p)$ could be used to discriminate pore-fluid variations during injection or production (Figure 5). Compare to $\Delta R_f'(p)$ at water/water boundary which is zero at any incidence angles, $\Delta R_f'(p)$ at oil/water or gas/water boundary increases with incidence angles. From Class 1 cases to Class 3 cases, $\Delta R_f'(p)$ at oil/water and gas/water boundary gradually increases and shows larger difference with $\Delta R_f'(p)$ at water/water boundary. The gradient of $\Delta R_f'(p)$ oil/water and gas/water boundary increases as well (Figure 5). Only in Class 1 cases, the gradient of $\Delta R_f'(p)$ is small and in Class 3 cases is bigger.

Conclusions

If the pore pressure of a reservoir changed little during injection or production, differential reflection coefficient mainly depends on fluid-fluid reflection coefficient in Zoeppritz equation or its approximations, and the rigid part of reflection coefficient is nearly unchanged. Differential reflection coefficient can be expressed as a formula of fluid-fluid reflection coefficient, where fluid-fluid represents fluids in reservoir during pre- and post- injection or production stages. There is no S-wave velocity information in differential reflection coefficient so that we may simply make differential AVO models to interpret and calibrate 4D seismic data in those oil fields without dipole sonic or S-wave velocity logs. As a recursive formula, differential reflection coefficient will inherit all properties from normal incidence reflection coefficient. Differential reflection coefficient and impedance of sound waves in the liquid could be further inverted to rock physics parameters.

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Table 1. Fluid substitution model (Ma and Morozov, 2006).

#		Class 1 (φ = 18%, Sw=30%)			Class 2 (φ = 27%, Sw=30%)			Class 3 (φ = 35%, Sw=30%)		
		Vp (m/s)	Vs (m/s)	Density (g/cm^3)	Vp (m/s)	Vs (m/s)	Density (g/cm^3)	Vp (m/s)	Vs (m/s)	Density (g/cm^3)
1	Shale	3093.0	1514.0	2.40	2642.0	1166.0	2.28	2410.0	988.7	2.2
2	Brine	3814.0	2166.0	2.345	3040.0	1599.0	2.215	2352.0	1095.0	2.078
3	Oil	3731.0	2186.0	2.303	2886.0	1622.0	2.15	2088.0	1117.0	1.994
4	Gas	3713.0	2226.0	2.22	2825.0	1671.0	2.03	1929.0	1165.0	1.835

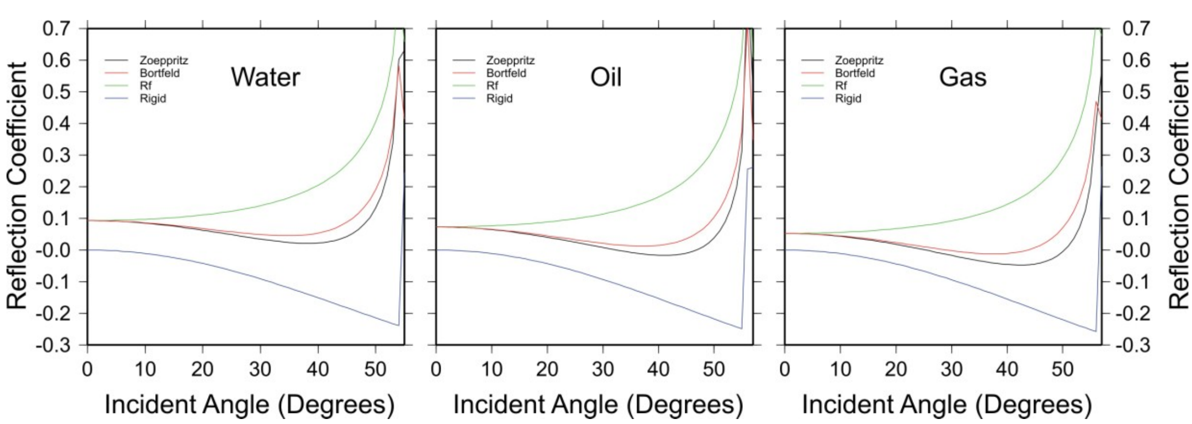

Figure 2. P-wave reflection coefficients in Class 1 cases. Zoeppritz (black) denotes reflection coefficient computed from Zoeppritz equation. Bortfeld (red) denotes reflection coefficient from eq.(1). $R_f(p)$ (green) and Rigid (blue) denote fluid-fluid reflection coefficient and rigid term of eq. (1).

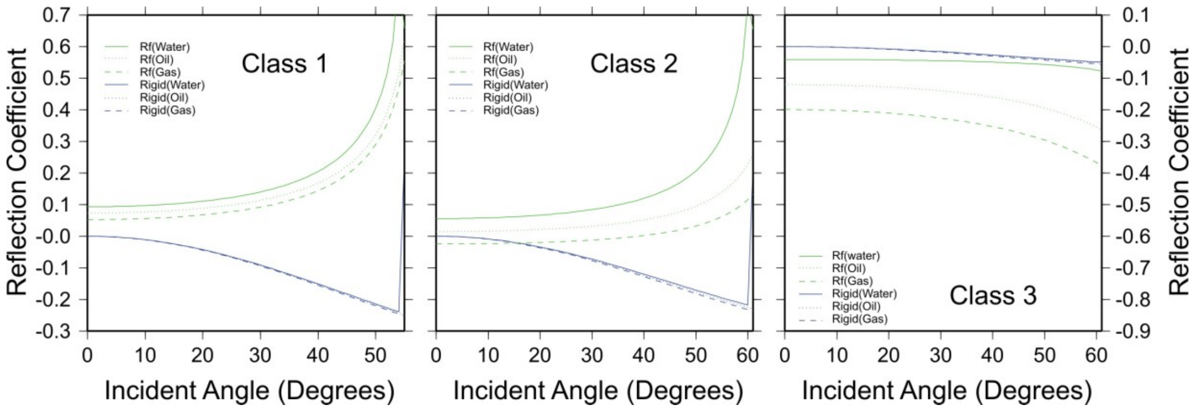

Figure 3. Comparison of fluid-fluid reflection coefficient (green) using $R_f(p)$ and rigid part reflection coefficient (blue).

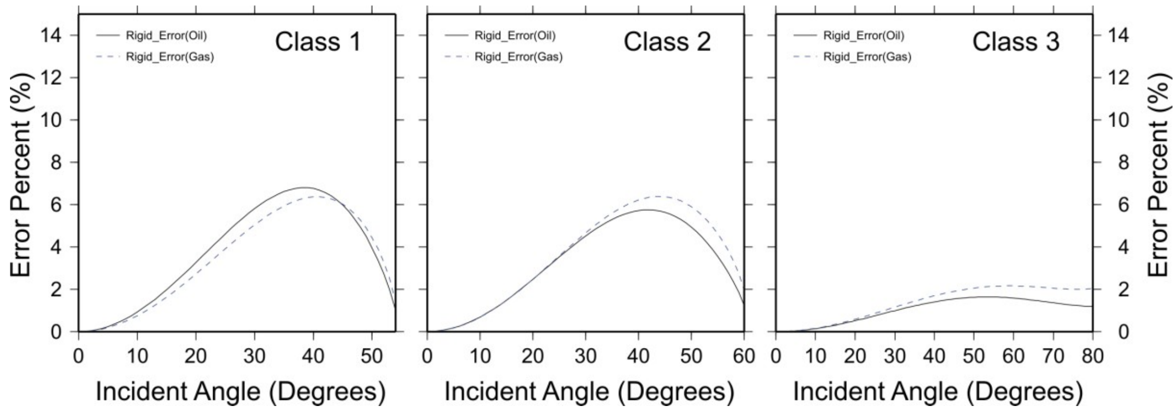

Figure 4. Error percent for rigid part reflection coefficient. Rigid_Error (Oil) is (Rigid(water)-Rigid(oil))/ $\Delta R_f'(p)$, where $\Delta R_f'(p)$ is at Oil/Water boundary. Rigid_Error (Gas) is (Rigid(Water)-Rigid(Oil))/ $\Delta R_f'(p)$,where $\Delta R_f'(p)$ is at Gas/Water boundary.

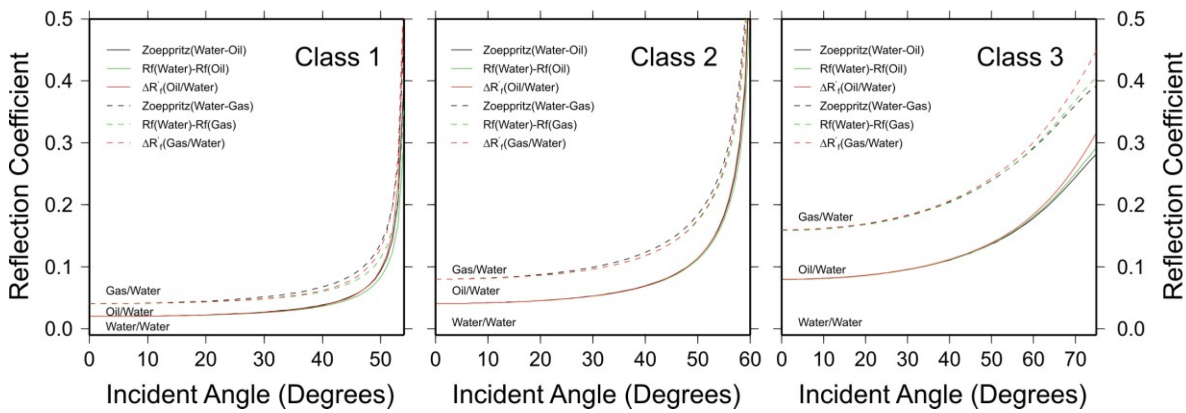

Figure 5. Differential reflection coefficients comparison at three-class sand. Zoeppritz (Water - Oil) denotes differential reflection coefficient calculated from Zoeppritz equation in water-saturated sand minus that in oil sand. R_f(Water) – R_f(Oil) denotes differential reflection coefficient calculated from $R_f(p)$ between water-saturated and oil-saturated sand. $\Delta R'_f$ (Oil/Water) denotes oil-water boundary reflection coefficient which is calculated from eq. (2). Differential reflection coefficients between water and gas are similar as that of water and oil. Differential reflection coefficients between water and water correspond to zero.