Introduction

Ostrander (1982, 1984) deduced the reflection coefficients at non-normal angles of incidence, and proposed to identify gas sands using the increasing reflection coefficients with incident angle. Since then, there has been rapid development for AVO technology over past 30 years. This method has been widely applied in oil & gas exploration, and has become an effective tool for hydrocarbon detection based on numerous studies (Rutherford and Williams, 1989; Castagna and Backus, 1993; Fatti et al., 1994, Foster et al., 2010).

However, due to special environment and formation mechanism, heavy oil has a density which is close to that of brine, making it difficult to distinguish heavy oil sands from brine sands using AVO technology. Therefore, few researches have been reported about AVO characteristics of heavy oil reservoirs.

In this paper, the theoretical basis of AVO technology-Zoeppritz equation is discussed firstly, which points out that the factors influencing amplitude-versus-offset include Vp, Vs and density of the target layer. These three parameters are then deduced as functions of oil saturation and porosity according to Biot-Gassmann theory (Lee, 2002). Subsequently, fluid substitution and porosity substitution are conducted on a simplified heavy oil model to compute the Vp, Vs and density under different oil saturations and porosities. Then, Zoeppritz equation based AVO forward modeling is applied with above parameters to analyse the impact of oil saturation and porosity on AVO responses for heavy oil reservoirs when assuming the lithology unchanged. Porosity is proved to be the main influencing factor of AVO responses for heavy oil sands, while the impact of oil saturation is negligible. A new method is therefore proposed to predict petrophysical property of heavy oil reservoirs according to the variation of AVO responses. Finally, the method is applied and validated in JZ heavy oil field, northern Bohai Bay Basin, China.

Sensitivity factors study of AVO responses for heavy oil reservoirs

Zoeppritz equation is the theoretical basis of AVO technology, which describes the relationship of reflection coefficient and incident angle. This equation shows that the variation of reflection coefficient with incident angle is affected by Vp, Vs and density. While the Vp and Vs of saturated rocks can be written as the function of bulk modulus, shear modulus and density:

\[ V_p = \sqrt{\frac{K_{sat} + 4\mu_{sat}}{\rho_{sat}}} \quad V_s = \sqrt{\frac{\mu_{sat}}{\rho_{sat}}} \]  

(1)

In which \( K_{sat} \) and \( \mu_{sat} \) are bulk and shear modulus of saturated rocks. From Biot-Gassmann Equation, we have:

\[ K_{sat} = K_{dry} + \frac{\phi}{K_m} \left(1 - \phi\right) \left(\frac{1}{K_w} - \frac{1}{K_{dry}}\right) \quad \mu_{sat} = \mu_{dry} \]  

(2)

While the density \( \rho_{sat} \) can be expressed as:

\[ \rho_{sat} = \rho_m(1 - \phi) + \rho_s\phi + \rho_o(1 - \phi)\phi \]  

(3)

In which \( K_{dry}, K_m, K_w \) and \( \mu_{dry} \) are bulk modulus of dry rocks, matrix and pore fluids respectively; \( K_m \) is the shear modulus of dry rocks; \( \rho_m, \rho_s, \rho_o \) are density of matrix, brine and oil respectively, \( \phi \) is porosity and \( s_o \) is water saturation. For pore fluids composed of brine and oil, \( K_o \) can be written as:

\[ \frac{1}{K_o} = \frac{s_o}{K_o} + \frac{1 - s_o}{K_w} \]  

(4)

In which \( K_o, K_w \) are bulk modulus of brine and oil respectively, the typical values of which are given by Batzle and Wang (1992) through large number of statistics and experiments. Then Vp and Vs can be expressed in the following form by bringing equation (2) (3) (4) into equation (1):
It can be seen clearly that for given rock type and pore fluid, all the parameters in equation (3) and (5) are known except for $\phi$ and $S_w$. That is to say, petrophysical property (porosity) and hydrocarbon saturation are two main factors influencing $Vp$, $Vs$ and density, which will further affect the AVO characteristics.

In order to study the sensitivity factors of AVO characteristics for heavy oil reservoirs, a simplified three-layered model is constructed. The top and base layers of model are both mudstone, with a sand layer in the middle, which is 50m in thickness (larger than a quarter of wavelength, factors such as thickness are not considered in this paper). The sand layer has an original porosity of 20% and oil saturation of 50%, with pore fluid composed of heavy oil and brine. The density of heavy oil and brine are 0.95g/cm$^3$ and 1.05g/cm$^3$ respectively. The original velocity and density of model are shown in figure 1.

Bulk and shear modulus of the original model are computed according to equation (1), then $K_{dry}$ and $\mu_{dry}$ can be obtained using equation (2). Fluid substitution and porosity substitution are then conducted to compute $Vp$, $Vs$ and density at different oil saturations and porosities. As shown in Figure 2, when oil saturation increases from 0 to 100%, $Vp$ and density nearly remain unchanged. However, both of them decrease dramatically when porosity changes from 0 to 35% (Figure 3). Therefore, the variation of porosity has a greater impact on the elastic parameters of rocks bearing heavy oil.

\[
V_p = \frac{K_{dry} + \left(1 - \frac{s_w}{K_{dry}}\right)\frac{\phi}{K_n}\left(1 - S_w\right)}{\rho_n(1 - \phi) + \rho_o S_w \phi + \rho_w (1 - S_w) \phi} \left(1 - \frac{K_{dry}}{K_n}\right)^2 + 4 \frac{K_{dry}}{3 \rho_{dry}}
\]

\[
V_s = \sqrt{\frac{\mu_{dry}}{\rho_{dry}(1 - \phi) + \rho_o S_w \phi + \rho_w (1 - S_w) \phi}}
\]
Subsequently, parameters after fluid substitution and porosity substitution are respectively used to conduct AVO forward modeling according to the exact Zoeppritz equation. A zero-phase Ricker wavelet with dominant frequency of 30Hz is adopted. Then AVO analysis is performed on the seismic gather corresponding to the top of sand layer. Comparison of AVO curves with different oil saturations and porosities shows that, when oil saturation ranges from 0 to 100%, the AVO responses almost remain unchanged (Figure 4a), especially within the angle of 0 to 40 degree (the general range of seismic data). However, obvious differences can be seen among AVO curves at different porosities (Figure 4b). The AVO intercept (P) gradually decreases when the porosity increases from 0 to 35%, while the gradient (G) nearly remains constant. Therefore, it can be concluded that porosity is the sensitivity factor of AVO responses for heavy oil reservoirs.

Based on the above analysis, a new method is proposed to conduct petrophysical property prediction for heavy oil reservoirs according to the variation of AVO responses.

**Figure 4** AVO curves of models with different oil saturations (a) and porosities (b).

**Example**

JZ oilfield is a large heavy oil field located in the northern Bohai Bay Basin, China. The density of crude oil is 0.972g/cm³, which is close to that of water. The depth of main oil layer, Guantao Formation in Neocene, is about 1000m, and is characterized by the universal existence of gravel within the whole work area. Therefore, the petrophysical property of target layer is poor in local areas, which further influences the hydrocarbon abundance. However, statistics of drilling shows that area with high porosity is positively correlated with the area with high oil in place. Prediction of areas with preferable petrophysical property is therefore of great importance.

Drilling results show that the thickness, lithology and buried depth of target layer are relatively consistent within the whole work area. Therefore, possible influencing factors of AVO responses include oil saturation and porosity. On the basis of fluid substitution and porosity substitution, AVO forward modeling is then conducted on parameters with oil saturation of 0, 20%, 50%, 80%, 100% and original porosity ±5%, ±10% and ±15% respectively, to verify the quality of logging data. Result shows that porosity dominates the influence on AVO responses (Figure 5), which further confirms the viewpoint above. In addition, AVO responses of original seismic gather and forward modeling are compared to conduct feasibility analysis of seismic data (Figure 6). As shown in the figure, the trend of AVO curves for sand top and base both match very well. Based on the above analysis, it can be concluded that the method proposed in this paper is suitable for this area.

**Figure 5** AVO analysis on models after fluid and porosity substitution on actual data.
Figure 6 AVO curves of original seismic gather and forward modeling.

Then, the P*G attribute of target layer within the angle of 0 to 30 degree is extracted in the following map (Figure 7). Red color corresponds to small value of intercept-times-gradient, which means relative large porosity, and green color represents small porosity. It can be seen that well J1 and J7 are in the middle of the red area, which indicates relatively large porosity; well J3 and J5 are on the edge of red area which means medium porosity; well J2 and J6 in the green area indicates relatively poor porosity. The lateral variation of porosity within the whole area reflected on AVO attribute is well validated by the drilling outcomes, and the method proposed in this paper is therefore proved to be effective, which provides references for the following exploration and development.

Figure 7 AVO attribute of target layer within JZ oilfield.

Conclusions

Although it’s generally known that AVO technology can’t be used for the detection of heavy oil, the research in this paper shows that it has great potential in petrophysical property prediction for heavy oil reservoirs. The application result of the method in this paper is consistent with the drilling outcomes, which validate the effectiveness of this method. However, the study is conducted assuming that the influence of thickness, lithology and oil saturation can be neglected, which still needs further in-depth studies.

References