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Preliminary Research on Gas Hydrate Reservoir in Qilian Mountain Permafrost with AVO Forward Modeling Technique

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1 Geological setting

The Qilian Mountain permafrost is located in the northern margin of the Tibetan Plateau, and the permafrost area is about 10×10^4 km^2(Zou Youwu et al., 2000). In recent years, the gas hydrate samples were obtained firstly by drilling in the Juhugeng mining of the Muli coal field (Lu Zhengquan et al., 2000). The drilling area is tectonically situated in the western Middle Qilian block formed in Caledonian Movement, adjacent to the South Qilian structural zone. Except for quaternary system, the exposure strata mainly include Jiangcang Formation(J2j) and Muli Formation(J2m) of middle Jurassic. The lithology of the drilling formation is mainly mudstone, siltstone, fine sandstone, medium sandstone and coarse sandstone. Drilling test wells of DK-1, DK-2, Dk-3, DK-4, DK-5, DK-6, DK-7 and DK-8 were carried out, and the gas hydrate was acquired in multiple layers of the wells of DK-1, DK-2 and DK-3. Gas hydrate mainly lied in the Jiangcang Formation of middle Jurassic, and occurred within intervals of about 133-396mbs (meter below surface) below permafrost in the drilling area. There are two types of gas hydrate occurrence in drilling area. One type is foliated, flaky or crumbly gas hydrate was appeared in fissures of the siltstone, mudstone and oily shale etc. The other type is disseminated gas hydrate was filled in pores of the fine siltstone (Zhu Youhai et al., 2010).

2 Basic principle of AVO forward modeling

AVO analysis is based on the basic idea of the rules of the amplitude coefficient changing with of incident Angle (AVA) are related to the formation lithology. It can be used for hydrocarbon detection and reservoir description etc. AVO technique has obtained good effect in marine gas hydrate research. As geologic and geophysical conditions of the gas hydrate in permafrost are more complex, the related research of gas hydrate in permafrost is relative behind. The theory basis of AVO forward modeling is the theory of reflection and transmission of seismic wave. The essence of above problem is the relationship between the reflectivity and the incident angle, and the core is the Zoeppritz equations. The mathematical expressions can be written as:

$$\begin{bmatrix} \sin\alpha & \cos\beta & -\sin\alpha' & \cos\beta' \\ \cos\alpha & -\sin\beta & \cos\alpha' & \sin\beta' \\ \sin 2\alpha & \frac{v_{P1}}{v_{S1}}\cos 2\beta & \frac{v_{P1}}{v_{P2}}\frac{v_{S2}^2}{v_{S1}^2}\frac{\rho_2}{\rho_1}\sin 2\alpha' & -\frac{\rho_2}{\rho_1}\frac{v_{P1}v_{S2}}{v_{S1}^2}\cos 2\beta' \\ \cos 2\beta & -\frac{v_{S1}}{v_{P1}}\sin 2\beta & -\frac{\rho_2}{\rho_1}\frac{v_{P2}}{v_{P1}}\cos 2\beta' & -\frac{\rho_2}{\rho_1}\frac{v_{S2}}{v_{P1}}\sin 2\beta' \end{bmatrix} \begin{bmatrix} R_{PP} \\ R_{PS} \\ T_{PP} \\ T_{PS} \end{bmatrix} = \begin{bmatrix} -\sin\alpha \\ \cos\alpha \\ \sin 2\alpha \\ -\cos 2\beta \end{bmatrix}$$

$$R_{PP} = \frac{B_2}{B_1} = \frac{A_2}{A_1}\cdot\frac{v_{P1}}{v_{P1}} \qquad R_{PS} = \frac{B_3}{B_1} = \frac{A_3}{A_1}\cdot\frac{v_{P1}}{v_{S1}}$$

$$T_{PP} = \frac{B_4}{B_1} = \frac{A_4}{A_1}\cdot\frac{v_{P1}}{v_{P2}} \qquad T_{PS} = \frac{B_5}{B_1} = \frac{A_5}{A_1}\cdot\frac{v_{P1}}{v_{S2}}$$

Where the four parameters are reflection coefficients and transmission coefficients of the reflected P wave, reflected SV wave, transmitted P wave and transmitted SV wave. From B1 to B5 represent amplitude of above different waves., , , , and are physical parameters of different formation. , are the incident angle and reflection angle, and , are transmission angle.

3 Rock physics model

The permafrost thickness is about 95 m in thickness in drilling area of the Qilian Mountain permafrost, but the depths of gas hydrate acquired are below 133m (Zhu Youhai et al., 2010). Based on this fact, the rock physical model for gas hydrate reservoir under the permafrost was established (figure 1). The solid skeleton part is composed of quartz, calcareous and clay, and fluid part is formed by bound water, free water and gas hydrate.

Existence of gas hydrate in pore of the sediment has different microstructures, so the influence of sediment physical properties must be different as the different ways. When gas hydrate is suspended in the pore and regarded as

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a part of the pore fluid, the gas hydrate only has an effect on the bulk modulus of the rock (model A). When gas hydrate is a part of the rock skeleton, the sediment porosity can be reduced, so it has an impact on the bulk modulus of the solid skeleton (model B). When gas hydrate saturation is nearly zero, the gas hydrate is suspended in the pore fluid, and its microscopic structure is close to model A. While gas hydrate saturation is nearly one, gas hydrate must be contacted surrounding sediment particles, so its microscopic structure is close to model B. Therefore, the general model of gas hydrate sediments should be between model A and model B. In order to study conveniently, we establish the velocity model of gas hydrate sediments by use of a simple linear relationship in the study area (model X). The formula can be expressed as:

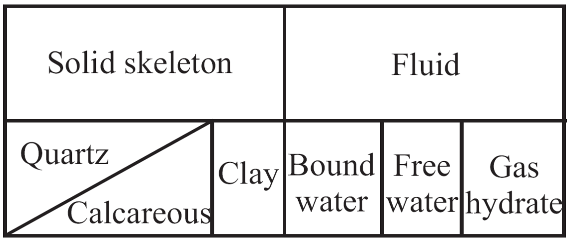

Figure 1 Rock physics model of gas hydrate under the permafrost

$$Vsx = (1 - Sh) \times Vsa + Sh \times Vsb$$
$$Vpx = (1 - Sh) \times Vpa + Sh \times Vpb$$

Where Vpa, Vpb and are the P wave velocity of model A, B and X. , and are S wave velocity of model A, B and X. is gas hydrate saturation.

4 Forward modeling preliminary results and analysis

The lithology of gas hydrate reservoir is mainly sandstone and mudstone in study area, and gas hydrate occurred in fracture for mudstone reservoir (Wang Kangping et al., 2011). Therefore, the lithology of gas hydrate reservoir is selected as sandstone in this study. Assuming sandstone porosity is Φ,the percent of quartz , calcareous and clay are selected as 75（1-Φ）, 15（1-Φ） and 10（1-Φ）according to the general sandstone components. Using Helgerud' s (1999) gas hydrate velocity model, which based on the effective medium theory, P wave velocity, S wave velocity, density and other elastic parameters of model A and B can be acquired. So the corresponding parameters can be calculated by model X.

The P wave velocities, S wave velocities, densities of gas hydrate reservoir and surrounding rock can be calculated by changing formation parameters such as the rock porosity, formation thickness, gas hydrate saturation, free gas saturation, etc. Therefore, different formation models of gas hydrate reservoir can be established by use of these parameters. The sandstone porosities of gas hydrate reservoir in Qilian Mountain permafrost are less than 15%, and gas hydrate saturations are 30~80% Guo Xingwang et al., 2011). In this study, we established eight formation models of two layers that were consist of gas hydrate reservoir and underlying formation (Table 1). The formation porosities are selected as 5% and 15%, and gas hydrate saturations are selected as 30% and 80% based on actual formation situation.

The AVO forward modeling of gas hydrate used Zoeppritz equation and zero phase Ricker wavelet in study area. Considering the maximum incident angle can reach 40 degree in actual exploration for gas hydrate, so the incident angles of AVO forward modeling were selected from 0 to 45 degree. In table 1, the simulated AVO response of the first four formation models were shown in figure 4. The other four formation models are similar, so the modeling results were not listed. When gas hydrate saturations are constant and free gas saturations increase, reflection amplitudes of layer interface increase. This feature can be used to detect the formation of free methane gas. When free gas saturations of underlying formation are constant, the reflection amplitude of layer interface is the weakest with incident angle is zero degree and gas hydrate saturation is low, then it increases as incident angle increases. However, the reflection amplitude of layer interface is the strongest when incident angle is zero degree and gas hydrate saturation is high, then it decreases as incident angle increases. These amplitude characteristics can be used to detect the content of gas hydrate reservoir.

Figure 5 is reflection coefficients of different formation models according to different incident angles synthetizing seismic records. When gas hydrate saturations are constant, but free gas saturations increase, absolute values of reflection coefficients of layer interface increase. This is mainly due to presence of free gas of underlying formation makes the wave impedance of this layer

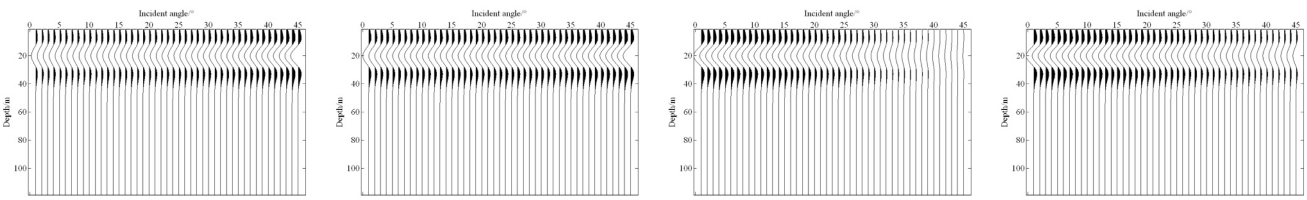

Figure 4 The simulated AVO response of different gas hydrate formation models
(a) Formation model 1 ; (b) Formation model 2 ; (c) Formation model 3; (d) Formation model 4

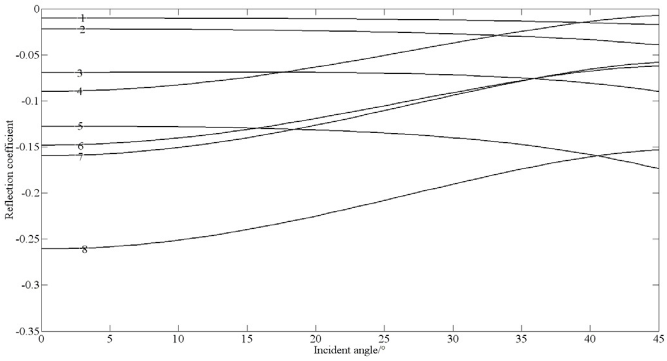

Figure 5 Reflection coefficients of layer interface by the different formation models
(The line 1is the model 1, the line 3 is the model 2, the line 4 is the model 3, the line 6 is the model 4, the line 2 is the model 5, the line 5 is model 6, the line 7 is model 7, the line 8 is model 8.)

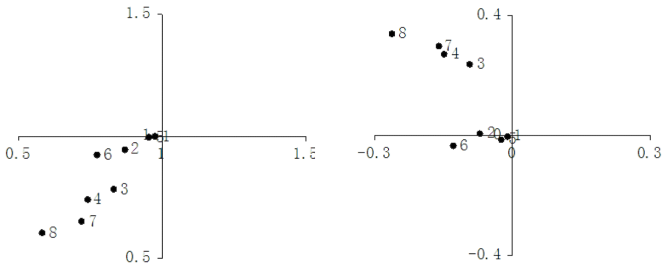

Figure 6 Crossplot of different seismic attribute parameters
(a) Crossplot of P wave velocity ratio and S wave velocity ratio (b) Crossplot of intercept and gradient (Figure 6(a): the horizontal axis is the P wave velocity ratio (Vp2/Vp1), and the vertical axis is S wave velocity ratio (Vs2/Vs1). Figure 6(b): the horizontal axis is intercept(I), and the vertical axis is gradient (G))

declined. When free gas saturations are constant, but gas hydrate saturations increase, absolute value of reflection coefficient of layer interface is the biggest with incident angle is zero degree, then it decreases as incident angle increases. When incident angle is greater than 40 degree, absolute values of reflection coefficients decrease with gas hydrate saturations increase.

According to P wave velocity and S wave velocity of above eight formation models, the corresponding P wave velocity ratio and S wave velocity ratio can be calculated (Figure 6(a)). When gas hydrate reservoir contains gas hydrate, the velocity is in the third quadrant (P wave velocity ratio and S wave velocity ratio are smaller than 1). When gas hydrate saturations and free gas saturations are constant, velocity ratios decrease with formation porosities increase. When formation porosities and gas hydrate saturations are constant, velocity ratios decrease with free gas saturations of underlying formation increase. When formation porosities and free gas saturations are constant, velocity ratios decrease with gas hydrate saturations increase.

According to P wave velocity, S wave velocity and densities of above eight formation models, the corresponding intercept and gradient can be calculated (Figure 6(b)). When gas hydrate reservoir contains gas hydrate, the intercept and gradient are located in the second and third quadrant. When gas hydrate saturations and free gas saturations are constant, the gradients through the origin decrease with formation porosities increase. When formation porosities and gas hydrate saturations are constant, the gradients through the origin decrease with free gas saturations of underlying formation increase. When formation porosities and free gas saturations are constant, the gradients through the origin increase with gas hydrate saturations of gas hydrate reservoir increase.

5 Conclusions

(1)According to the occurrence characteristics of gas hydrate of the drilling area in Qilian Mountain permafrost, rock physics model and velocity model of gas hydrate sediment are preliminary proposed.

(2)The AVO forward modeling technique is preliminary presented in the drilling area. It can be used to forward modeling seismic attribute parameters. The formation porosities, gas hydrate saturations and free gas saturations which affect seismic attribute parameters can be analyzed. It also can lay the foundation for the actual seismic data processing and interpretation.

Key words: Qilian Mountain permafrost, gas hydrate, AVO, forward modeling, seismic attributes

Table 1 The parameter values of formation model for the AVO forward modeling

model	formation	thickness(m)	V_p(m/s)	V_s(m/s)	ρ (kg/m^3)
1	$\phi=5\%$, $Sh=30\%$	20	4117.5	2226.5	2567.9
	$\phi=5\%$, $Sw=100\%$	200	4031.9	2215.2	2569.4
2	$\phi=5\%$, $Sh=30\%$	20	4117.5	2226.5	2567.9
	$\phi=5\%$, $Sg=10\%$	200	3587	2099.4	2565.5
3	$\phi=5\%$, $Sh=80\%$	20	4833.5	2844.9	2565.4
	$\phi=5\%$, $Sw=100\%$	200	4031.9	2215.2	2569.4
4	$\phi=5\%$, $Sh=80\%$	20	4833.5	2844.9	2565.4
	$\phi=5\%$, $Sg=10\%$	200	3587	2099.4	2565.5
5	$\phi=15\%$, $Sh=30\%$	20	3058.5	1441.4	2399.7
	$\phi=15\%$, $Sw=100\%$	200	2921.9	1427.7	2404.2
6	$\phi=15\%$, $Sh=30\%$	20	3058.5	1441.4	2399.7
	$\phi=15\%$, $Sg=10\%$	200	2374.6	1325.2	2392.7
7	$\phi=15\%$, $Sh=80\%$	20	4051.4	2199.2	2392.2
	$\phi=15\%$, $Sw=100\%$	200	2921.9	1427.7	2404.2
8	$\phi=15\%$, $Sh=80\%$	20	4051.4	2199.2	2392.2
	$\phi=15\%$, $Sg=10\%$	200	2374.6	1325.2	2392.7