Seismic Exploration for Tight Gas Sand in Sulige Gasfield

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Summary

Sulige gas field is the largest in China. The main pay zone in Sulige is the braided river sediment of lower–Permian He8 formation and the main reservoir is tight quartzose sandstone. The He8 formation is characterized by thin net pay thickness and strong lateral heterogeneities. In this paper, the key techniques of seismic acquisition, data processing and reservoir characterization applied in Sulige gas field are discussed. And the main methods for reservoir characterization emphasized are the sensitive elastic parameters selecting, PP wave AVO, simultaneous inversion of PP waves and interpretation of multicomponent (MC) seismic data.

Introduction

Because of the complex near–surface and deep geological conditions, there are several challenges in seismic exploration for Sulige gas field. In seismic data acquisition, because the weathering layers are thick and variation roughly, the shooting and receiving conditions are poor, and the resulting quality of raw seismic data is poor. The challenges of data processing are low frequency, strong inconsistent surface conditions, and noisy. In reservoir prediction, the challenges are that the resolution of seismic data is relatively low, that the reservoir is rather thin, and that there are only small differences between the PI (P wave impedance) of the reservoir and adjacent layers.

To deal with these difficulties and obtain better raw seismic data, we have taken the following two important steps in data acquisition: carrying out detailed surveys of weathering layer with uphole and LVL refraction survey, and designing shooting parameters point by point. With the weathering–layer data obtained in this manner, seismic lines can be laid out optimally and shot depths can be varied from point to point by incorporatin satellite remote sensing data in the design process. In addition, long spreads, small geophone intervals, and single digital geophone receivers are used.

In data processing, we follow up with corresponding techniques to ensure the gain in data quality obtained from the improved survey techniques is preserved. Therefore, we have also developed cascaded deconvolution, anisotropy processing and MC seismic data processing techniques.

For applications to reservoir characterization, it is rather difficult to characterize the reservoir properties by P–waves alone because the reservoir is thin (15–35 m) and strongly anisotropic. Based on the geology of the main pay zone, we first conduct a detailed rock physics analysis, then choose the factors and the best AVO attributes that are sensitive to the lithology and fluid. In order to predict the gas–bearing reservoir, we propose the elastic impedance inversion and pre–stack simultaneous inversion. The analysis of full wave attributes and the joint inversion of PP & PS data are also applied. We have obtained favorable results with the help of above techniques.

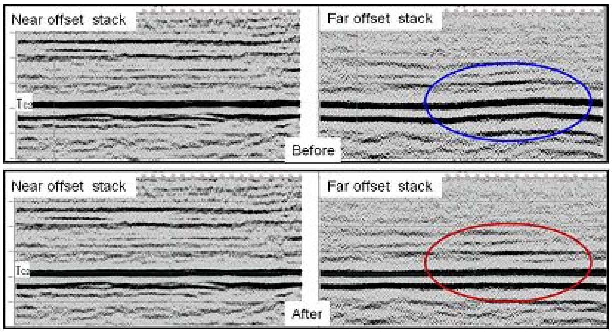

Fig.1 Sections before and after anisotropy processing

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Geometry design

With the weathering-layer data obtained through uphole and LVL refraction surveys, seismic lines can be reasonable arrangement and shot depths can be point-to-point designed with satellite remote sensing data. And also long spread, small geophone interval and single digital geophone receiving are used.

Complete system of PP & PS processing

In case of reasonable S/N (signal to noise ratio) in data, the resolution of seismic data is enhanced progressively by cascaded deconvolution, in which including surface-consistent predictive decon, multichannel statistical spiking decon and zero-phase decon.

In Sulige gas field, a part of seismic data is acquired with long spread. Long offset data cannot be flattened by NMO correction due to anisotropy. Therefore, the AVO analysis and pre-stack inversion are seriously affected. The anisotropic processing is required to solve these problems.

As for converted wave data processing, the static correction based on first break of converted wave, PP and PS wave consistent processing, and PS wave resolution enhancement processing are also applied. To improve the converted wave image, we use better pre-stack time migration.

Optimal selection of sensitive elastic parameters

It´s well known that the velocity of seismic wave (both P-wave and S-wave) can be affected by many of petrophysics parameters, such as density, porosity, water saturation, gas saturation, shaliness and others, and some of them have explicit connection with velocity. The analysis of the relation between lithology and velocity may help select the most sensitive parameters.

Table 1 Physical Properties of H8 Formation

Lithology Parameters	Gas Sand	Sand	Sandy Shale	Shale
Density (g/cm^3)	2.38-2.57	2.55-2.68	2.54-2.7	2.4-2.73
Vp(m/s)	3920-4640	4550-4890	4130-4790	4000-4600
PI (m/s★g/cm^3)	9330-11925	11602-13105	10490-12933	9600-12512
Gr(API)	30-85	45-100	100-140	140-190

The analysis of drilling and well logging data from 36 wells shows that the differences between P-wave impedance (PI) of shale, sand, and gas sand are small (Table 1), so it is difficult to identify the lithology and fluid content with only PI (Zhou et al, 2009). The analysis also shows that Vp is generally inversely proportional to gas saturation, therefore it can be used for gas prediction. Figure 2 shows the cross plots of Vp/Vs, $\lambda\rho$, $\mu\rho$, λ/μ and ρ/μ. From these cross plors, we find that the gas sand can be effectively distinguished from sand and shale by joint interpretation of $\lambda\rho$ and $\mu\rho$, Vp/Vs and $\mu\rho$, and λ/μ and $\mu\rho$.

AVO analysis of PP wave

The appearance of "bright spot" brought about a revolution to hydrocarbob direct indicator (HDI) (Ostrander 1984). With the advancement in exploration, geophysicists realized that there could be many traps in the application of "bright spot". For example, an obvious "bright spot" on stack section might be from two different CDP gathers, one with first kind of AVO anomaly and another with third kind. We have carried out AVO forward modeling for the He8 formation based on typical wells in the prospecting area. Through the analysis of the relationship between amplitude and offsets, and according to AVO classification established by Rutherfold and Williams (1989), we have determined that He8 formation should produce Class III AVO anomalies. From Shuey´s approximation, we obtain tens of attributes such as P&G and the converted attributes from it, all of which have their own applicabilities. Through a great deal of AVO analysis and correlation of known wells with seismic traces, we have found that the P+G, P×G, and Rp-Rs are particularly indicative in the area. In practice, the crossplot interpretation of P&G may reduce ambiguity. It can be seen from Figure 3 that an obvious anomalous area is shown on the target zone of the fluid factor section from one seismic line. It interesting to note that well wa intersects this zone and has a production of $8.14\times10^4 m^3/d$ of commercial gas.

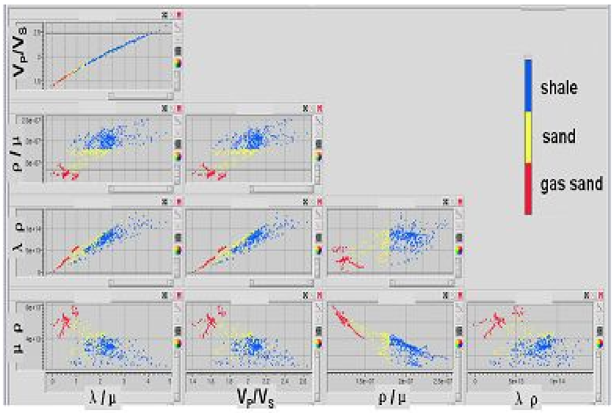

Figure2 Cross plots of five selected elastic parameters. Red refers to gas sand, yellow refers to sand, blue is shale.

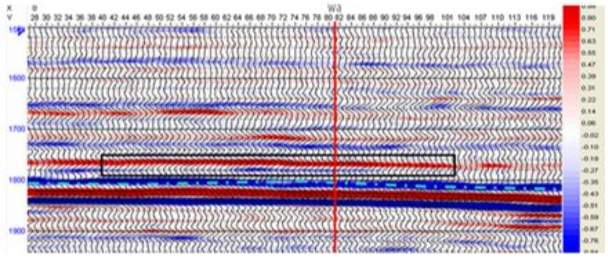

Figure3 AVO Attribute (Fluid Factor)Section

Elastic inversion

Elastic inversion requires high-quality well logging data, high fidelity prestack gathers or partial stack data, correct time-depth (TD) data, and a reasonable AVO wavelet. Unfortunately, the prestack seismic data generally cannot meet these requirements. Faced with the quality difference of data from different areas, the simultaneous inversion based on prestack gathers and partial stacks and elastic impedance inversions are applied in different areas. All the methods mentioned above are utilized to predict the gas reservoir in the entire area.

Elastic impedance inversion

There are many algorithms for calculating elastic impedance, such as Zoeppritz equation, Aki - Richards approximation, or Patrick Connolly approximation (Connolly, 1999), EEI (Whitcombe, 2002), GEI, and others. In this paper, we apply EEI as defined below,

$$EEI(\theta)=V_{p0}\rho_0\left[\left(\frac{Vp}{V_{p0}}\right)^p\left(\frac{Vs}{V_{s0}}\right)^q\left(\frac{\rho}{\rho_0}\right)^r\right]$$

Based on tests, we have established a procedure for elastic impedance inversion. The sensitive EI angle and input seismic data quality are critical. We selected a 27° EI angle. Direct use of stack data is meaningless because of some necessary AVA information is lost. Hence, constrained sparse spike inversion is applied to common-angle stack data to obtain elastic impedance and acoustic impedance data volumes. Following that, interpretation of the crossplot of PI and EI can be carried out.

Simultaneous inversion

Prestack inversion is also called simultaneous inversion because the inversion may output PI, SI, Vp/Vs, density, and other models simultaneously. According to the type of input data, simultaneous inversion may be classified as prestack gather based or partial stack based method. The drawback of the former is that it may output a great deal of data, and its advantage is that more AVO information can be preserved. The method calls for high quality prestack gathers and it is suitable for areas with high signal-to-noise ratio. In contrast, the partial stack based method does not have a stringent requirement on data quality, thus it may be applied to areas within which the data quality is not very high.

To complete the job, poststack data from three different angles and corresponding wavelets should be input, and the vertical changing trend of different data (PI, SI and density) and their lateral constraint limits should be set. Then a group of quality controlled parameters can be obtained. The key aspects for simultaneous inversion are the wavelet extraction and λ selection. Then, a simultaneous inversion with the Aki-Richards AVA model should be carried out to get PI, SI, and density and, through them, more properties such as λρ, μρ, Vp/Vs and Poisson's ratio can be obtained. Figure 4 shows the results of simultaneous inversion based on partial stack. The red part in the sections is the low Vp/Vs area and indicates the favorable zone. Well Ws9 was proposed based on the result of this inversion and proved to be a gas well with high commercial flow. In contrast, an old well (Ws2) is located outside the red area on the same seismic line, but only has some gas show.

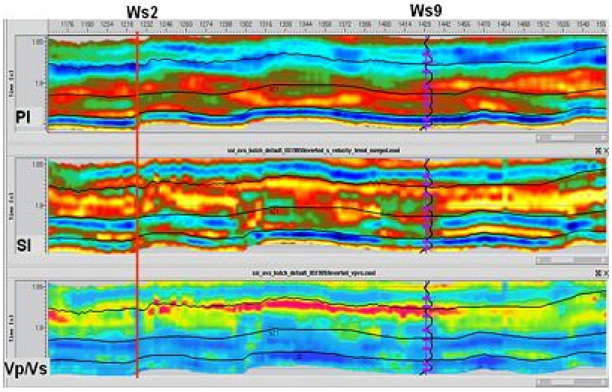

Figure 4 Section of Simultaneous Inversion Based on Partial stacks (Upper: PI, Mid: SI, Bottom: Vp/Vs)

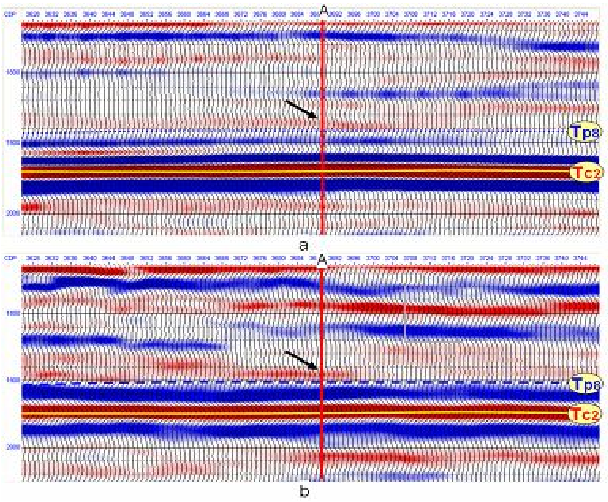

Figure 5 "Bright Spot" Section a) PP Section b) PS Section

Full wave attribute analysis

Compared to the PP wave, MC seismic data can yield much more seismic attributes such as attribute difference, attribute ratio, and ratio of attribute differences and complex components. Comprehensive utilization of these MC attributes can greatly improve success ratio of the interpretation. Field data sets have shown that, AVO analysis, hydrocarbon detection and bright spot identification using MC seismic data have great potentials. "Bright spot" analysis with PP wave has widely used in the Sulige gas field, but the method has been problematic due to the ambiguity. However, when combined with converted wave data, the approach can effectively distinguish between true and false "bright spots." Seismic rock physics analyses and real data comparisons show that a good reservoir reflection has medium to strong amplitude both in PP and PS data. Therefore, simultaneous strong amplitude in PP & PS data is in general an indication of thick sand body, perhaps good favorable gas-bearing sand body. Figure 5 shows a typical true "bright spot" seismic section in Sulige gas field. Both PP (Figure 5 (a)) and PS (Figure 5(b)) have strong amplitudes around well A, which is a high production commercial gas well. Figure 6 shows a false "bright spot" seismic section in the study area. The PP data have strong amplitude (Figure 6 (a)) around well B, Figure 6(b) shows weak amplitude in the PS data, and there is no sand encountered in well B.

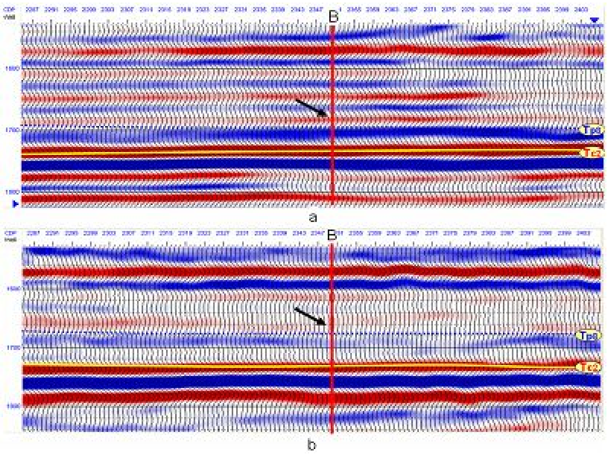

Figure 6 False "Bright Spot" Section
a) PP Section b) PS Section

Joint inversion of PP & PS data

When only P-wave data is available, we can approximately estimate the S-wave attributes from the PP-wave data. Joint inversion of PP and PS data allows us to obtain more accurate S-wave impedance (SI), P-wave impedance (PI), velocity, density, Poisson´s ratio and other elastic parameters. As expected, there is always some uncertainties. The work flow of joint inversion in our study is as follows: 1) converting PS data to the PP time domain; 2) extracting the PP and PS wavelet in the PP time domain; 3) selecting the appropriate PP, PS data and corresponding PP and PS wavelets; 4) solving for the

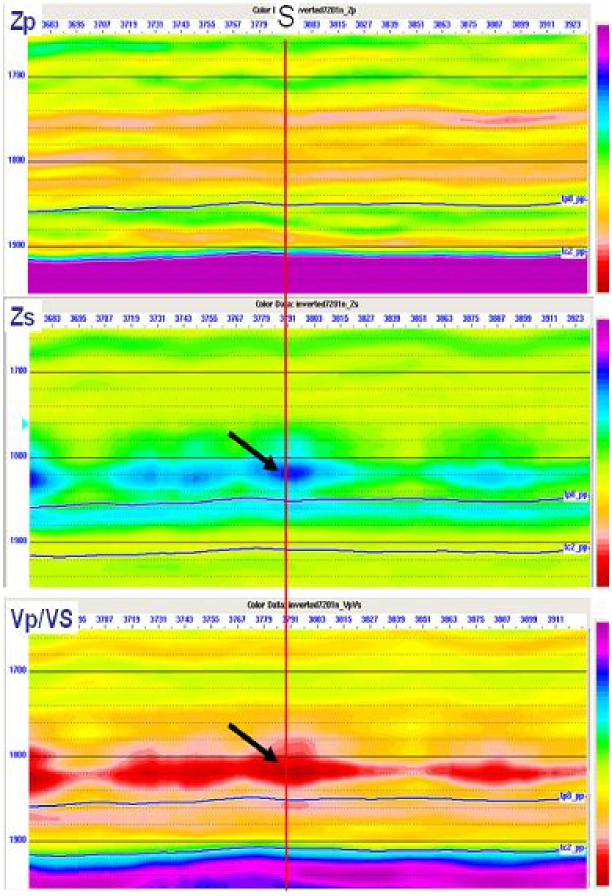

Figure 7 Joint Inversion Section

velocity and density using Aki & Richards approximate equation; 5) Using Fatti´s simplified equation to estimate the relationship between P- & S-wave impedances and density; and 6) obtaining Vp, Vs, Vp/Vs and other selected elastic parameters that are sensitive to lithology and fluid through the joint inversion. Figure 7 shows the PI, SI and Vp/Vs sections (from top to bottom) obtained from joint inversion. For the gas bed, Vp reduces significantly but Vs is less affected and has almost no change. The inversion sections show a low PI, high SI and low Vp/Vs around the well S, which is a high commercial gas production well. This example shows that joint inversion of PP and PS data is more stable and reliable in reservoir characterization than the PP wave inversion.

Conclusions

Detailed analyses of petrophysical properties and selection of sensitive elastic parameters form the foundation for reservoir characterization. The best use of PP and PS seismic data, comprehensive application of multi-wave AVO techniques, and simultaneous inversion are effective means for reservoir characterization in Sulige gas field. For such applications, the stability and reliability of multi-wave method are much better than the method using PP data alone.

The high production gas bearing layer of He8 in the Sulige gas field is discovered by joint inversion. In the study area, nine wells have been proposed based on the MC data analyses, four of which are completed with high production commercial gas flow.

Acknowledgments

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