Geophysical Research Progress On Tight Sandstone Reservoir In Sulige Gas Field

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Abstract

The tight sandstone reservoir in the cooperation block of Sulige gas field is characterized by thin gas-bearing sand, large variation laterally, and strong heterogeneity. Due to the complex surface conditions, and particularly the thick weathered zone, the 3D seismic data presented limited frequency bandwidth. Both processing and reservoir prediction did not achieve expectation. To enhance the reliability of predicted results, the reprocessing data with better quality were obtained in the pilot area by using the prestack data processing procedure with wider frequency, higher fidelity and preserved amplitude from its cores. Compared to the previous results, the reprocessing data exhibits wider bandwidth, higher resolution and better consistency. The seismic forward modelling shows that the data can be used to discriminate over 10 m single sandbody or sand group, and over 5m gas-bearing sand. Using cross-plot interpretation of selected sensitive parameters, the thickness of reservoir and effective sandstone can be estimated quantitatively. Obvious enhancements were obtained for the well-seismic match of AVO features and prestack seismic inversion. The research findings in the pilot area will have an important guidance to the development of international cooperation block in Sulige gas field.

Introduction

Sulige gas field lies in the northeast of Ordos Basin， and its regional structure is subordinate to Shanbei Slope. The two major gas-bearing intervals are Shanxi Group and Lower Shihezi Group, both with fluvial sedimentation. It belongs to tight sandstone gas reservoir with lower permeability, lower pressure, lower production, lower abundance, and stronger heterogeneity (Ding et al 2007).

The target zone in this study is He8 formation within Lower Shihezi Group. The Upper He8 formation belongs to meandering river deposition, and braided river deposition for Lower He8 formation. He8 reservoir is characterized by small scale single sandbody with lenticular shape mostly, and large scale compounded sandbody with multistage stacked layers vertically and quick change horizontally. The effective reservoir shows great transverse variation with isolated or small area continuous distribution, and there is not specific correlation with sandstone thickness. In addition, the geologic structure has no control on the gas sand distribution (Li et al. 2009).

The joint development of Sulige gas field between CNPC and TOTAL began in 2006. The cooperation block is located in the south of middle area of the gas field, in which over 1000km^2 full fold 3D seismic data was available (**Figure 1**).

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The main geophysical problems in the cooperation block are presented as complex surface conditions with large LVL thickness (mean 104m), limited frequency bandwidth (10-33Hz) and lower resolution for the previous seismic data processing, unable to estimate He8 sandstone thickness accurately due to the lower precision of prestack seismic inversion results, and poor effect of the reservoir prediction.

So, it is necessary to select a typical 3D seismic pilot area in the cooperation block to conduct the data reprocessing and interpretation techniques research to improve the data quality, and finally to enhance the reliability of reservoir prediction results. This study will provide an important guidance with the development of the whole cooperation block.

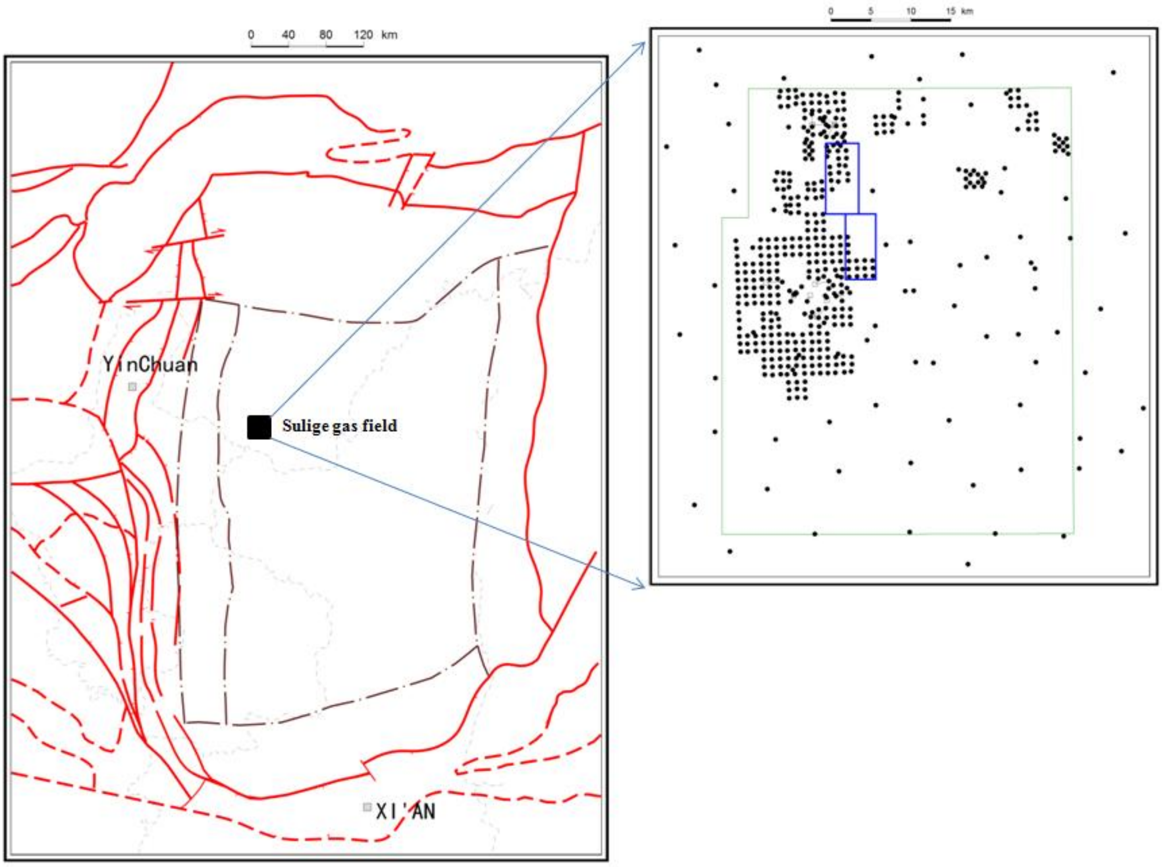


Figure 1—Sulige gas field (green rectangle: cooperation block, blue rectangle: pilot area).

Previous Seismic Data Analysis in the Pilot Area

The selected 3D seismic pilot area covers a full fold area of 86km^2 with 33 drilled wells. The surface conditions are complex, which basically consist of sand, alkaline land and grass land, and with a large variation of LVL thickness (60-190m) (**Figure 2**).

The quality of 3D seismic raw data is mainly affected by LVL thickness. As a result of this affection, the noises in the data including stronger refraction, stronger energy at near shots, and so on, are developed. For the target zone, effective frequency bandwidth is 5-30Hz, and primary frequency of effective reflection is 15Hz. The main problems from the previous data processing as follows:

1. The surface consistency problem was failed to be effectively resolved, that resulted in stronger energy on the near offset seismic traces and weaker energy on the far offset seismic traces. The maximum amplitude analysis along horizon (**Figure 3a**) shows that there is a bigger amplitude strength difference among the five angle stacks.

2. The primary frequency of target zone is about 15Hz, and gradually reduces along with the increasing incidence (**Figure 3b**).
3. The substack data failed to reserve prestack AVO components from the raw data (**Figure 3c**). Through the characteristics contrast analyses of target zone in 33 wells between AVO forward modelling and corresponding substack data, only 14 wells exhibit good match.

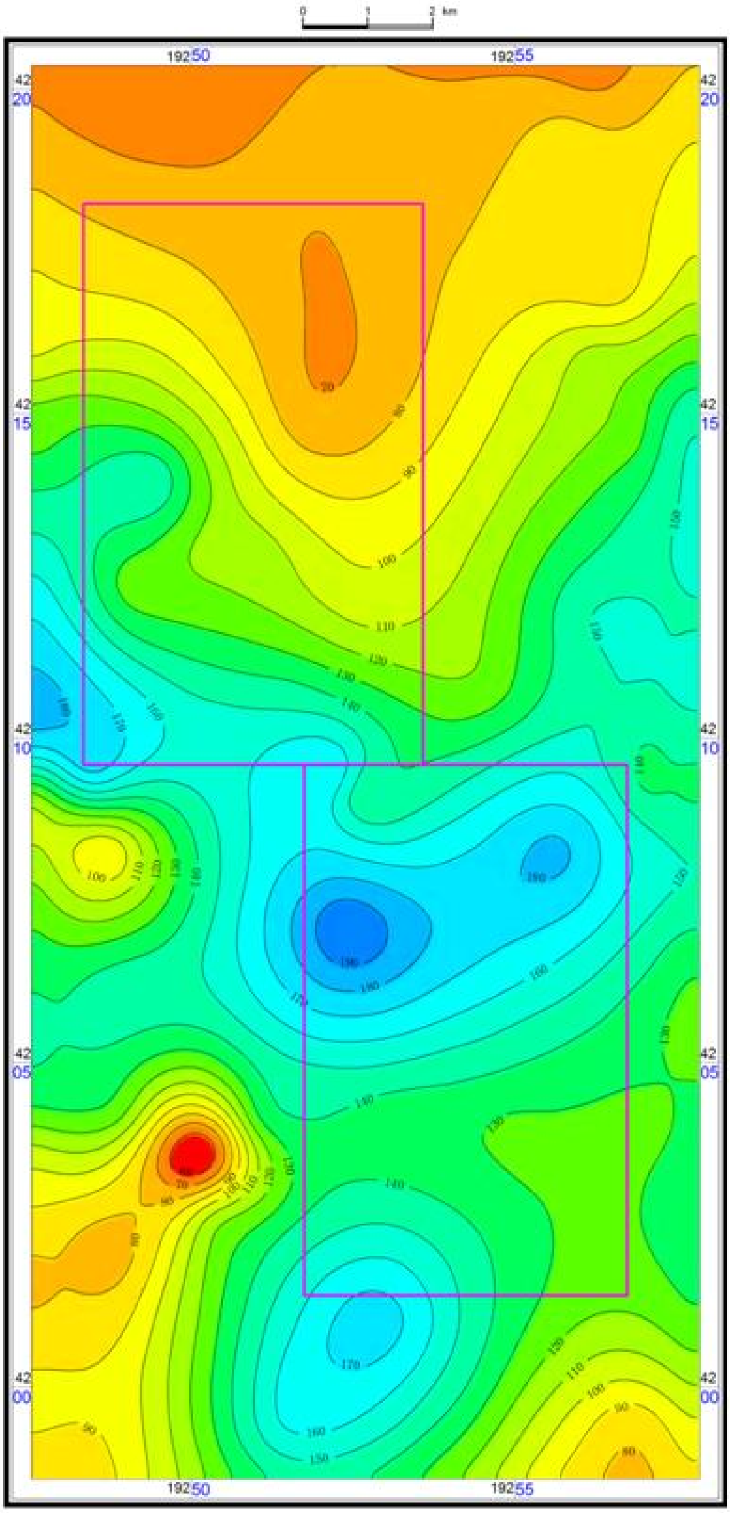
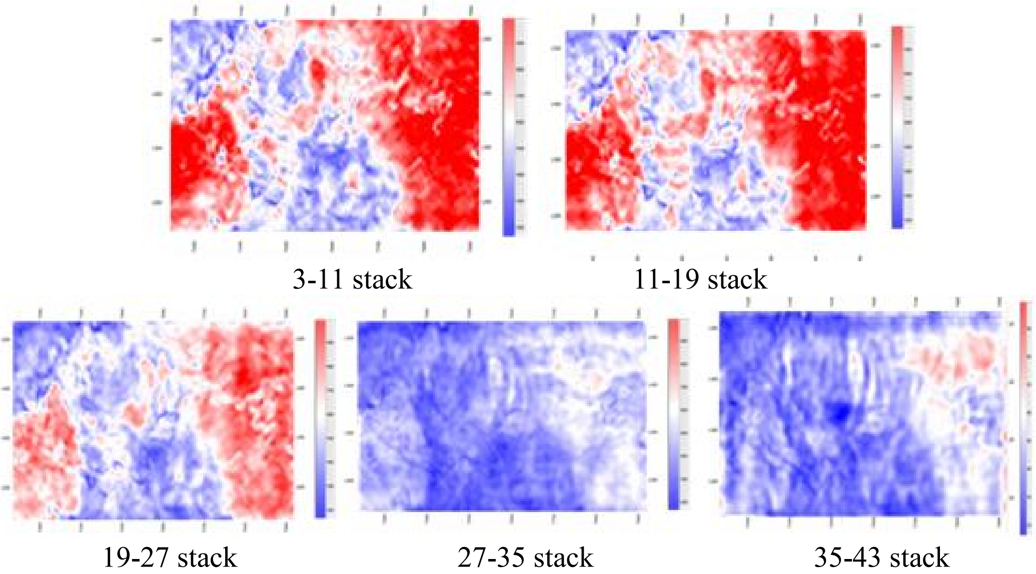
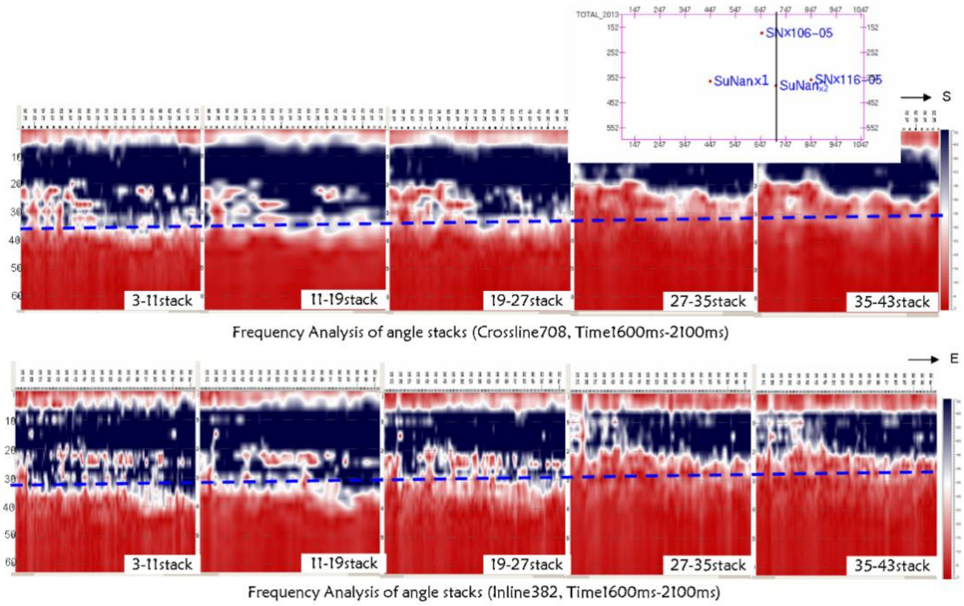


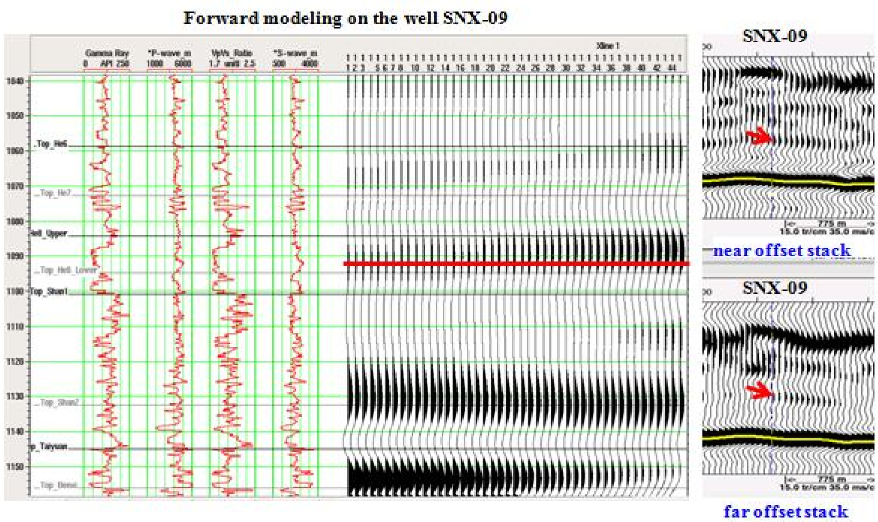
Figure 2—Map of LVL thickness in the pilot area.



(a)



(b)



(c)

Figure 3—Main problems from the previous data processing. (a) Maximum amplitude analysis along horizon from the previous angle stacks. (b) Frequency analysis from the previous angle stacks. (c) AVO forward modeling and substack sections through the well SNX-09.

Seismic Data Reprocessing Techniques

Considering the features of raw data in the pilot area, and existing problems in the previous data processing, to make the need of seismic reservoir prediction, the goal of seismic data reprocessing is to take amplitude and fidelity reserved as precondition, to remove the surface impacts on the data, and to improve S/N (signal to noise ratio) and resolution of the data. The key reprocessing techniques include 3D statics, 3D prestack signal-noise separation, high resolution processing with keeping relative amplitude, and OVT (offset vector tile) prestack time migration.

3D Statics. The application of conventional elevation or refraction statics could not resolve the static correction problem in the work area. By using tomostatics, we can get more accurate near surface model, and thus to improve the accuracy of statics and get better processing effect.

3D Prestack Signal-noise Separation. The main interferences existing in the raw data include linear noise, strong energy noise at near shots, and wide frequency refraction noise. 3D cross banding cone filter was applied to remove linear noise, and multi domain frequency decomposition was applied to remove strong energy noise at near shots and wide frequency refraction noise.

High Resolution Processing with Relative Amplitude Reserved. The primary frequency of target zone in the better data quality area is about 20Hz, and it is about 15Hz in the medium data quality area. Based on the significant quality difference, to meet the need of reservoir prediction, the well control processing technique was applied to enhance seismic data resolution and keep the relative relationship of amplitude.

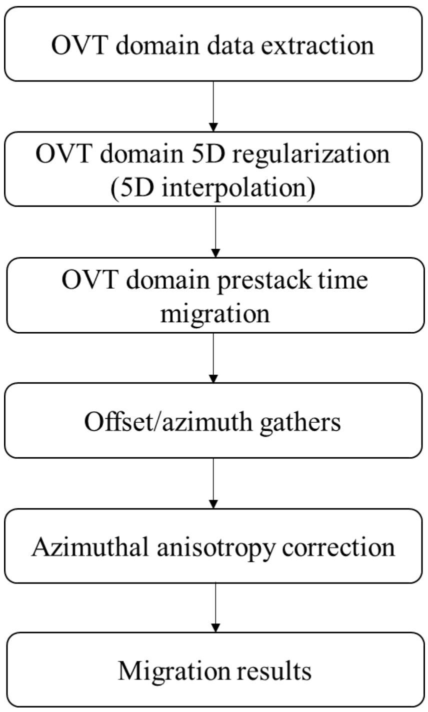


Figure 4—Workflow of OVT domain processing.

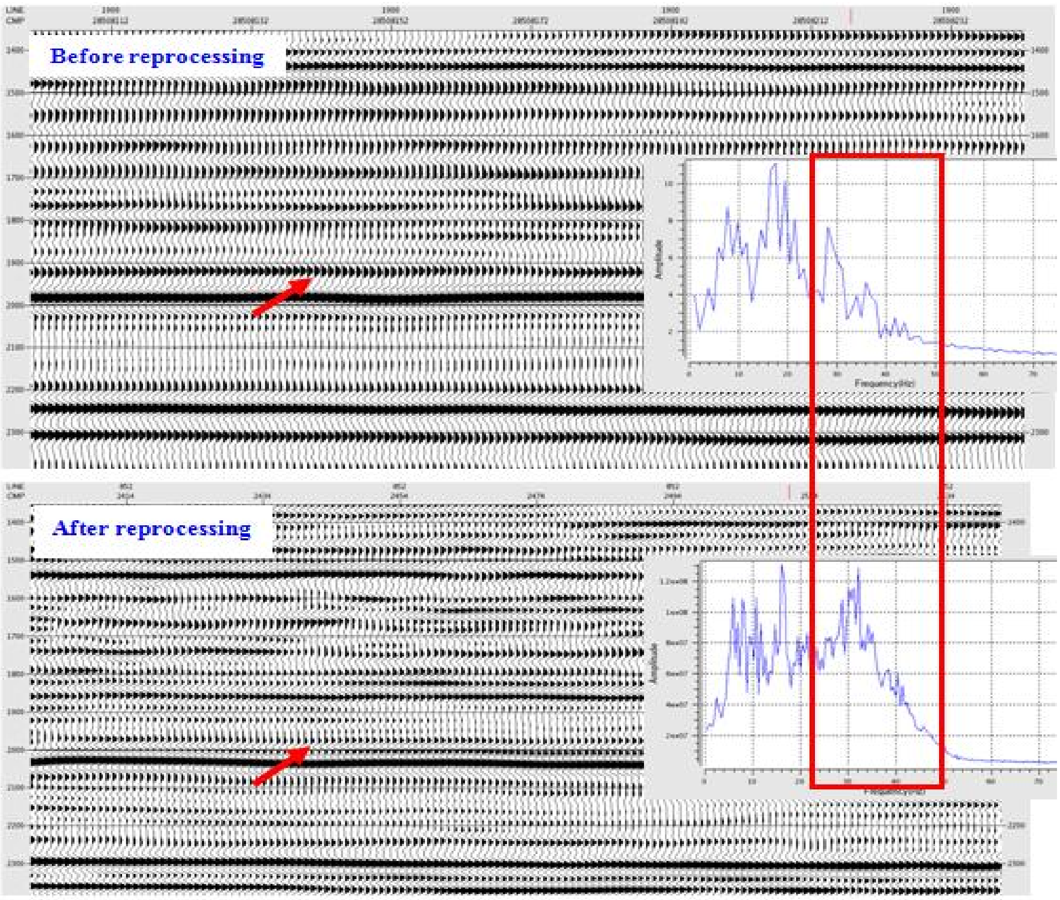
OVT Domain Processing. OVT (offset vector tile) processing is carried out in the subdividing cross spread domain. This method can keep more accurate azimuth and offset information. It is not only used to improve full azimuth imaging accuracy, but also used to extract attribute vs relating to the azimuth and detect fractures. The processing workflow (**Figure 4**) mainly includes four key steps, namely OVT partition and gathers data preparation, OVT domain data regularization, OVT prestack time migration, and migrated gather processing (Schapper et al. 2009; Stein et al. 2010; Li 2008; Duan et al. 2013).

Seismic Data Reprocessing Effect Analysis

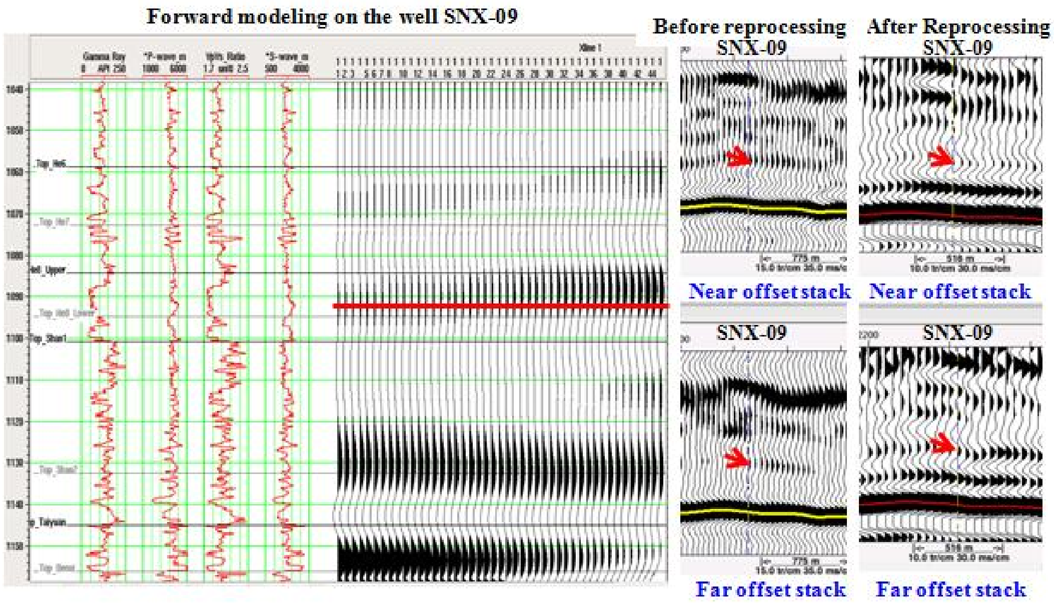
After reprocessing, 3D seismic data in the pilot area are characterized as follows:

1. Compared with previous processing results, the data show wider frequency bandwidth, higher resolution, and better coherency (**Figure 5a**).
2. The acquired substack data are of higher fidelity, and exhibit reasonable frequency, phase and amplitude features on the near and far offset stack sections, respectively. Compared with the previous processing results, there is a better match between AVO features on the seismic sections and AVO forward modelling results from wells. So, the reprocessed data are able to meet the needs of AVO analysis and prestack seismic inversion (**Figure 5b**).
3. By comparing the seismic section through a well with its synthetic seismogram, we find out that the features of amplitude and phase within the marker bed and target zone are of good match with well synthetics. It illustrates that the seismic data reprocessing techniques, workflow and parameters are reasonable, and the reprocessed data are of higher fidelity (**Figure 5c**).

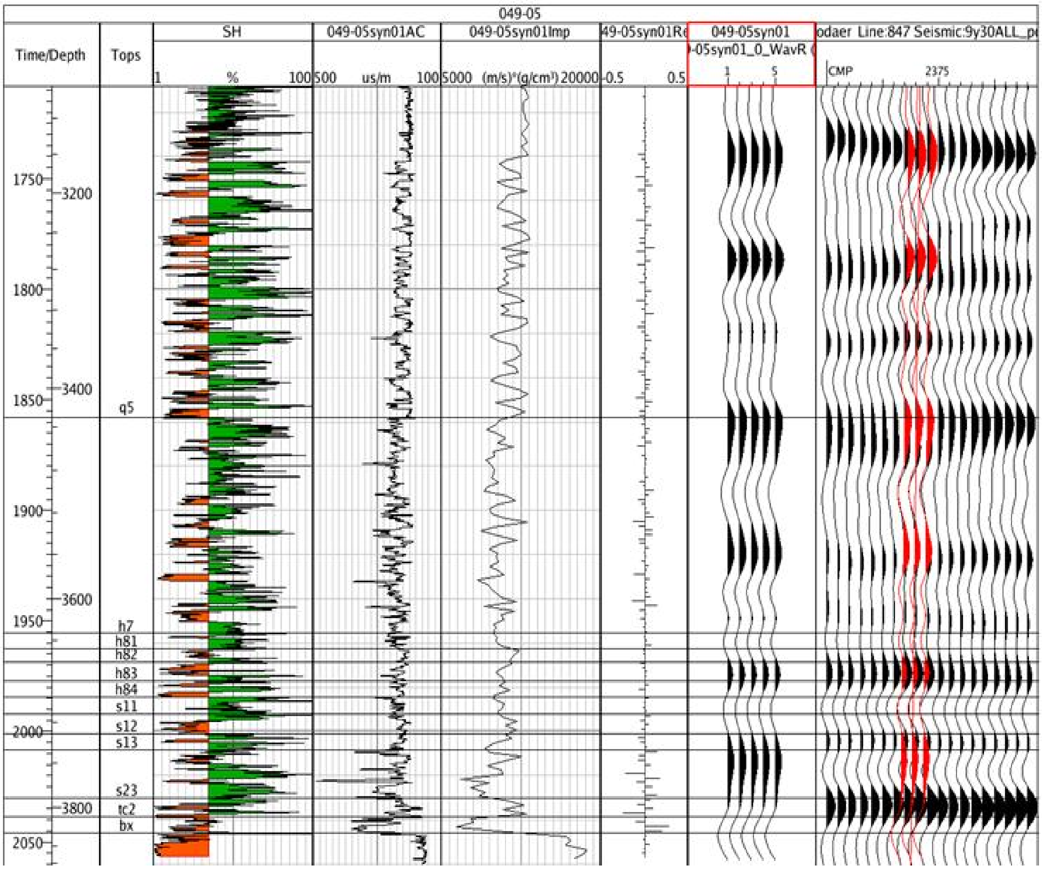
By reprocessing, the impact of LVL on the data was removed effectively. From **Figure 5d**, we find out that there is no similarity between the RMS amplitude distributions extracted from 150ms and 15ms time window near horizon T_{c2}, respectively. Meanwhile, there is also no similarity between RMS amplitude distribution mentioned above and that of LVL thickness.



(a)


Forward modeling on the well SNX-09
Before reprocessing
After Reprocessing
SNX-09
Near offset stack
Near offset stack
Far offset stack
Far offset stack

(b)


049-05
Time/Depth
Tops
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049-05syn01AC
049-05syn01Imp
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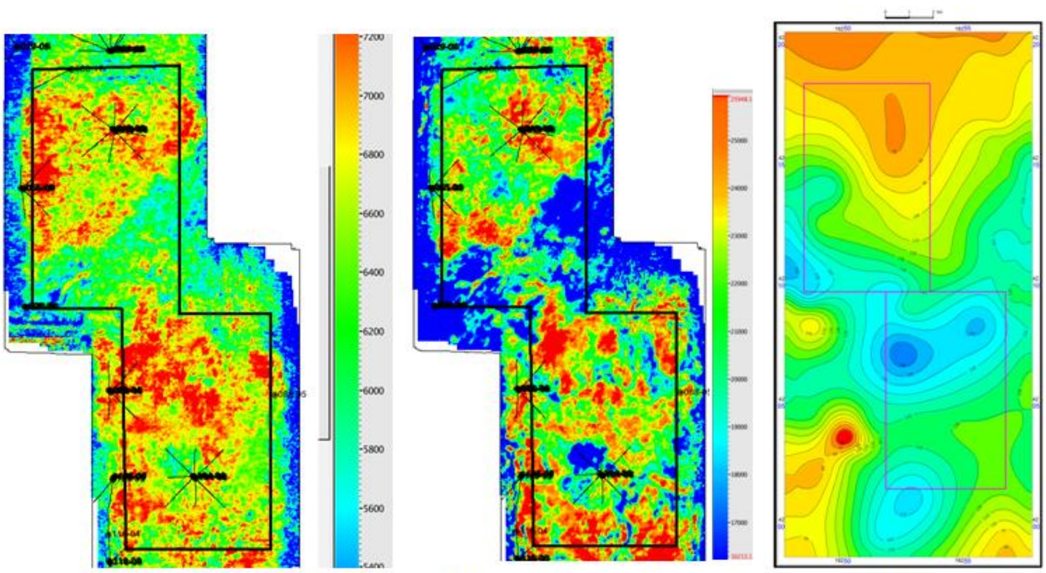
(c)



RMS amplitude of 150ms time window near horizon Tc2

RMS amplitude of 15ms time window near horizon Tc2

Map of LVL thickness in the pilot area

(d)

Figure 5—Characterization of the pilot area from 3D seismic data. (a) Comparison of the data processing results (section, frequency spectrum). (b) Comparison of AVO features and forward modelling on the well SNX-09. (c) Seismic and geology synthetic calibration on the well SNX-05. (d) Correlation analysis between RMS amplitude near horizon T_{c2} and LVL thickness.

Seismic Reservoir Prediction Research in the Pilot Area

The research approach is to focus on the effective reservoir forecasting, select the sensitive seismic attributes and parameters to the reservoir, finely carry out prestack simultaneous inversion， and predict the horizontal distribution of He8 sandbody and gas-bearing sand in the pilot area.

Optimization of Sensitive Seismic Attributes and Parameters to the Reservoir. Aimed at He8 target zone, 11 amplitude attributes, 7 frequency attributes, 9 statistics attributes, 6 energy spectrum attributes, and 5 single frequency attributes are extracted. According to the information from drilled wells, we select the sensitive attributes and parameters to the reservoir by combining automatic optimization with expert evaluation. Based on AVO forward models, reservoir forward modelling results, and rock physics analyses, we conclude that the amplitude attribute is of good correlativity with sandstone thickness, AVO attribute is of good correlativity with gas-bearing sand, and Vp/Vs ratio is the most sensitive parameter to He8 reservoir. Meanwhile, we can predict the reservoir quantitatively via the crossplot interpretation between Vp/Vs ratio and prestack parameter such as P-impedance or S-impedance.

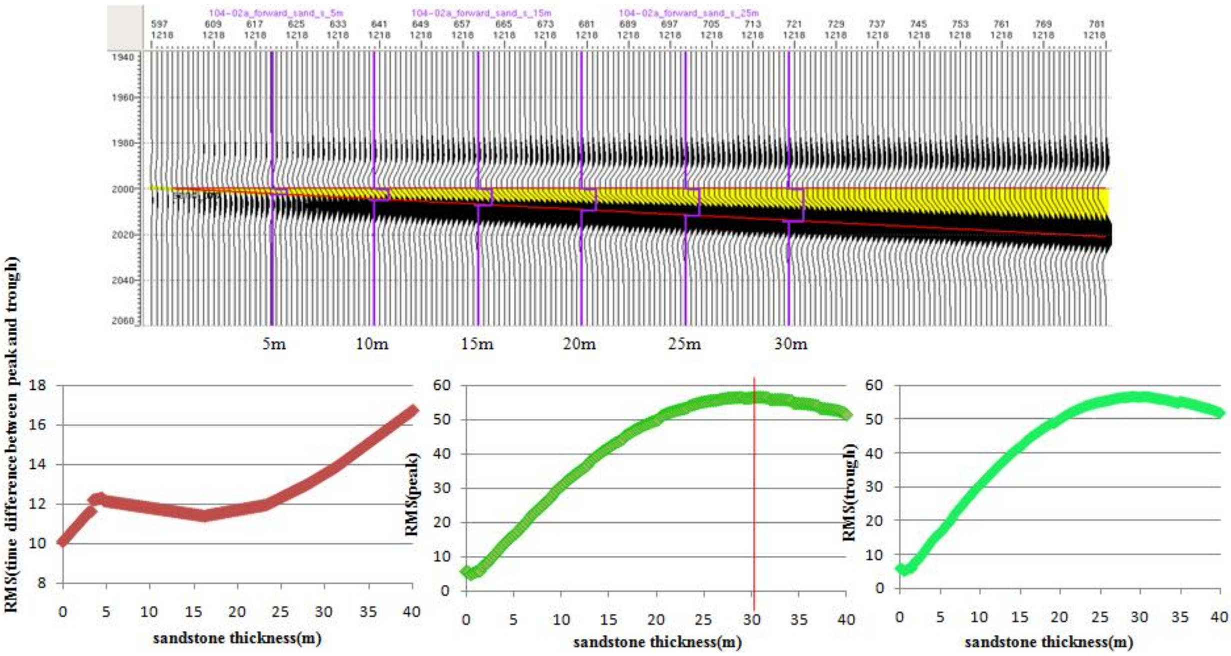
RMS(Root-Mean-Square) Amplitude Attribute. The thickness of He8 formation is 60-80m, and that of the single sand-body is 5-15m.On the seismic sections, He8 formation mainly shows mid-strong wave peak reflections, which are synthetical seismic response to multistage stacked sandbodies.

The seismic response characteristics of wedged sandstone forward modelling show (**Figure 6a**) that the relationship between reflection amplitude strength and sandstone thickness is of a positive correlation when sandstone thickness is less than 30m. By means of building the relationship between amplitude attribute and sandstone thickness, we are able to predict He8 sandstone thickness. According to the wedged sandstone forward models (**Figure 6b**), well data analysis results，and combined with reprocessed seismic data resolution (6-40Hz of frequency band), we think that 10m above single sand-body or sand group can be identified by using RMS amplitude attribute.

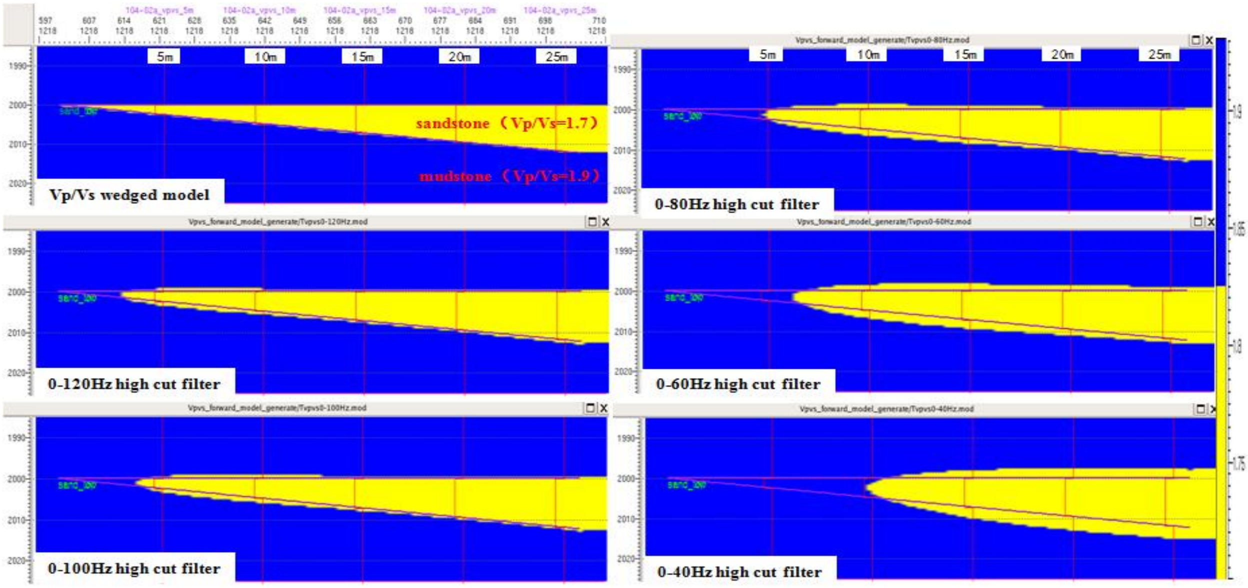
***AVO Attribute*.** AVO forward modelling results of target zone in the work area show: He8 gas-bearing sand exhibits class Ⅲ AVO response characteristics (Zou et al. 2005), which means as the incidence increases (or offset increases), the amplitude energy gradually enhances (**Figure 7**). Through comparative analysis between AVO forward modelling results of target zone from 33 drilled wells and corresponding amplitude features on the substack data, the coincidence rate of wells with good match is 73% (previous one is 42%). Thus we can predict the gas-bearing reservoir qualitatively by using AVO attribute analysis.

***Vp/Vs Ratio*.** The rock physics analysis of He8 reservoir in the work area (**Figure 8a**) shows: The Vp/Vs ratio is of higher sensitivity and discrimination to sandstone, mudstone and gas-bearing sand. Therefore, it can be used to predict He8 reservoir quantitatively.

According to the well-seismic data analysis in the work area, the Vp/Vs ratio from prestack seismic inversion can be applied to identify 5m above gas sands (**Figure 8b**). Although the Vp/Vs ratio is of higher sensitivity and discrimination to sandstone and mudstone, abnormal values often exist in the seismic inversion results, which usually show lower Vp/Vs ratio, and with impedance value too high or too low. Thus, by using the crossplot interpretation between Vp/Vs ratio and S-impedance, we can predict sandstone and gas sand more accurately.



(a)



(b)

Figure 6—The seismic response characteristics of wedged sandstone forward modeling. (a)Wedged sandstone forward modeling. (b)Wedged sandstone forward models and seismic data recognizable scales.

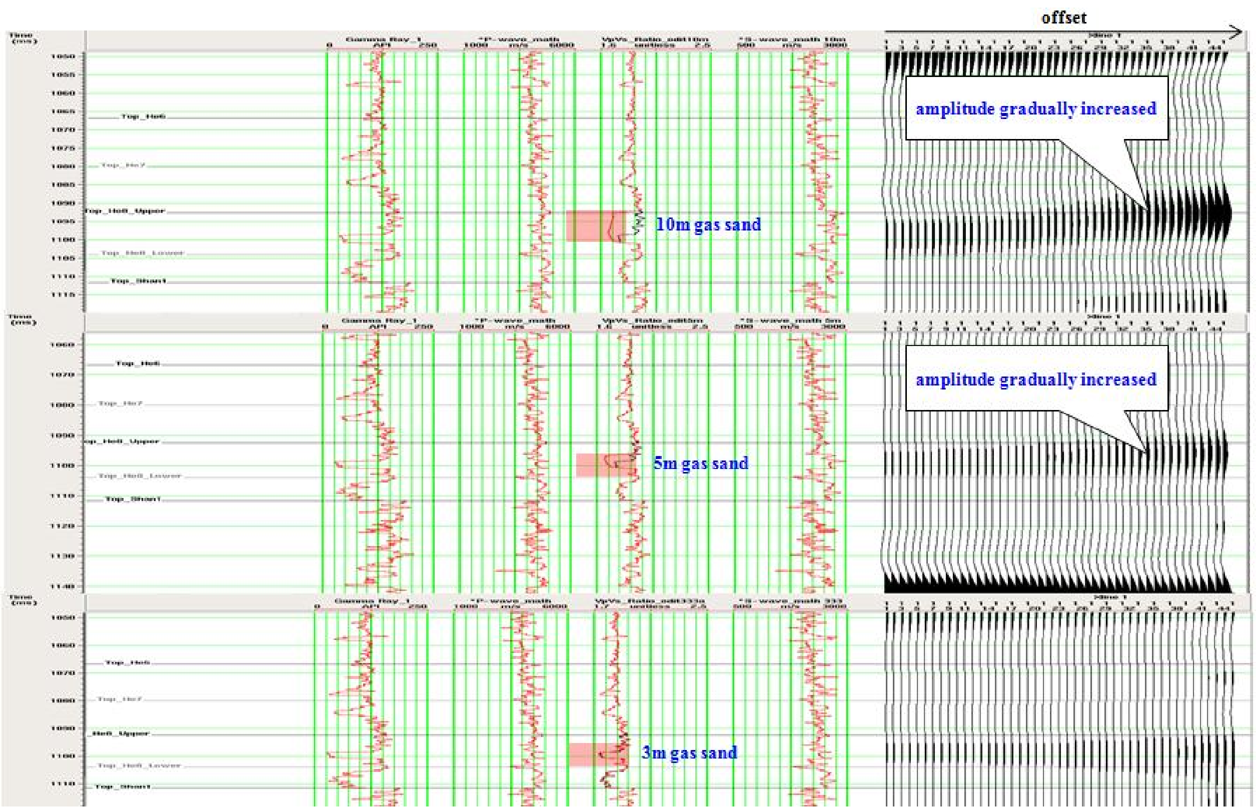


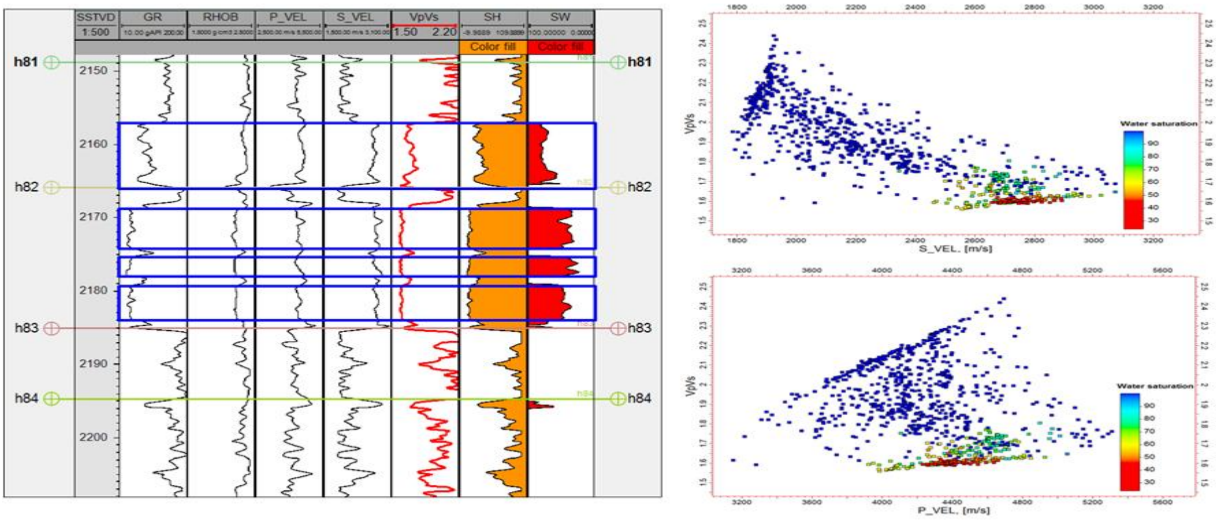
Figure 7—AVO forward modeling of different gas sand thickness in He8 zone.

The Refined Prestack Seismic Inversion

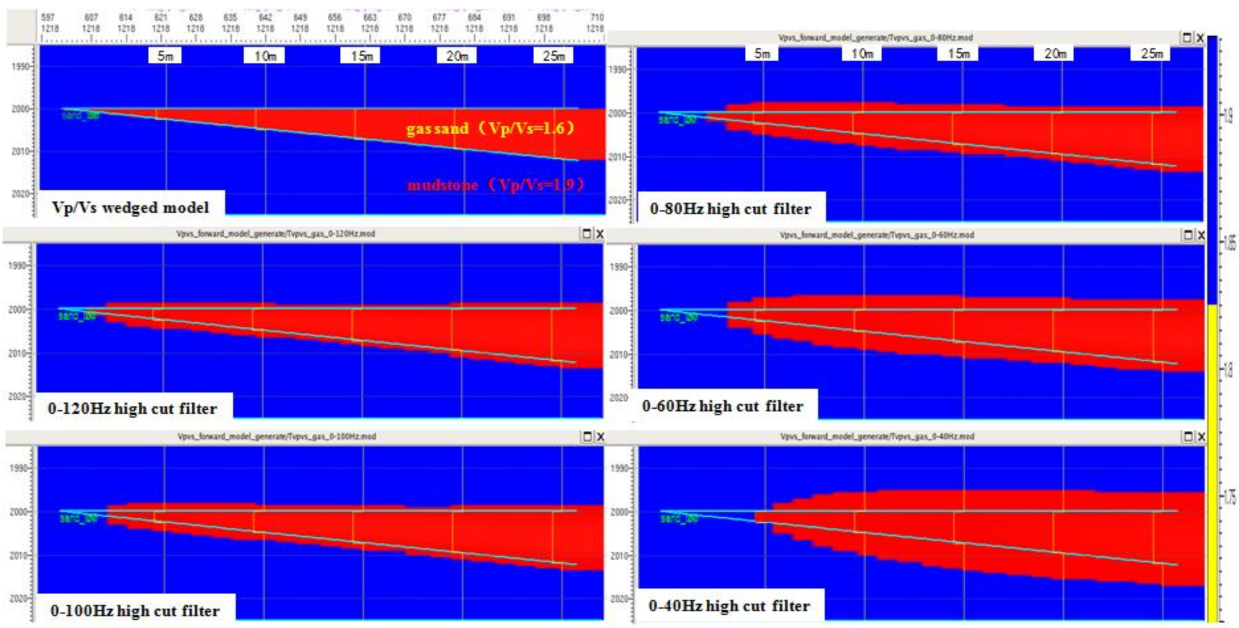
The Fundamental Principles of Prestack Simultaneous Inversion. The prestack simultaneous inversion is a technique that uses prestack migration CRP(common reflection point) gather data, and well logging data, such as Vp,Vs and density, to simultaneously produce various rock physics parameters, such as P-impedance, S-impedance, Vp/Vs ratio, and PR(Poisson Ratio), which can be used to differentiate the lithology, properties, and oil and gas bearing of the reservoir (Shao et al. 2016). The technique is classified as travelling time method and amplitude method. The latter is often applied, and its basic theory is from the matrix expression of Zoeppritz equation.

Data Preparation. For the sonic and density log, it is necessary to conduct environmental correction and normalization processing respectively to eliminate the curve distortion. And for the multi-well logs, it is necessary to conduct crossplot and histogram analyses to remove the data which are not able to meet the need of prestack inversion.

Generally, 3 to 5 substack data volumes are used in the prestack simultaneous inversion. In this study, based on the prestack amplitude reserved processing results, we determined to use three substack data volumes as 3°-14°,13°-22° and 21°-35° (i.e. near, mid and far angle stack, respectively) to conduct the inversion.



(a)



(b)

Figure 8—The rock physics analysis of He8 reservoir in the work area. (a) Well log interpretation and rock physics chart on the well SNX-08. (b) Wedged gas sand forward models and seismic data recognizable scales.

Key Steps and QC(Quality Control)

The key steps of prestack simultaneous inversion include angle wavelet extractions and refined horizon calibrations. The QC in the inversion mainly consists of model creation, selection of λ value， design of the low frequency filter, and control of the trend restriction lines.

Prestack Simultaneous Inversion Effect Analysis. Three data volumes such as P-impedance, S-impedance and Vp/Vs ratio were obtained from prestack simultaneous inversion. The inversion sections through a drilled well (**Figure 9**) show higher S-impedance at the well location, which indicates the developed sandstone; and P-impedance and Vp/Vs ratio at the well location are lower, which indicates the better reservoir properties and gas-bearing sand. For the drilled well with 25.9 m of He8 sandstone and 13.3 m of gas sand, the inverted results are well matched with the real drilling ones.

In this study, five wells were involved in the prestack simultaneous inversion, and other 28 wells were used to verify the inversion effect as blind ones. We can evaluate the quality of inversion results by the comparative analyses between inverted logs at well locations and real logs. The statistical analysis results from 28 validated wells indicate that 21 wells are of good and moderate well-seismic fit. Under the same evaluation criterion, the proportion of well-seismic fit has increased significantly from 44% to 75%, which indicates a better inversion effect. Furthermore, seven wells are of poor well-seismic fit due to poor migration imaging quality, which is caused by non-uniform far offset distribution at boundary of the work area.

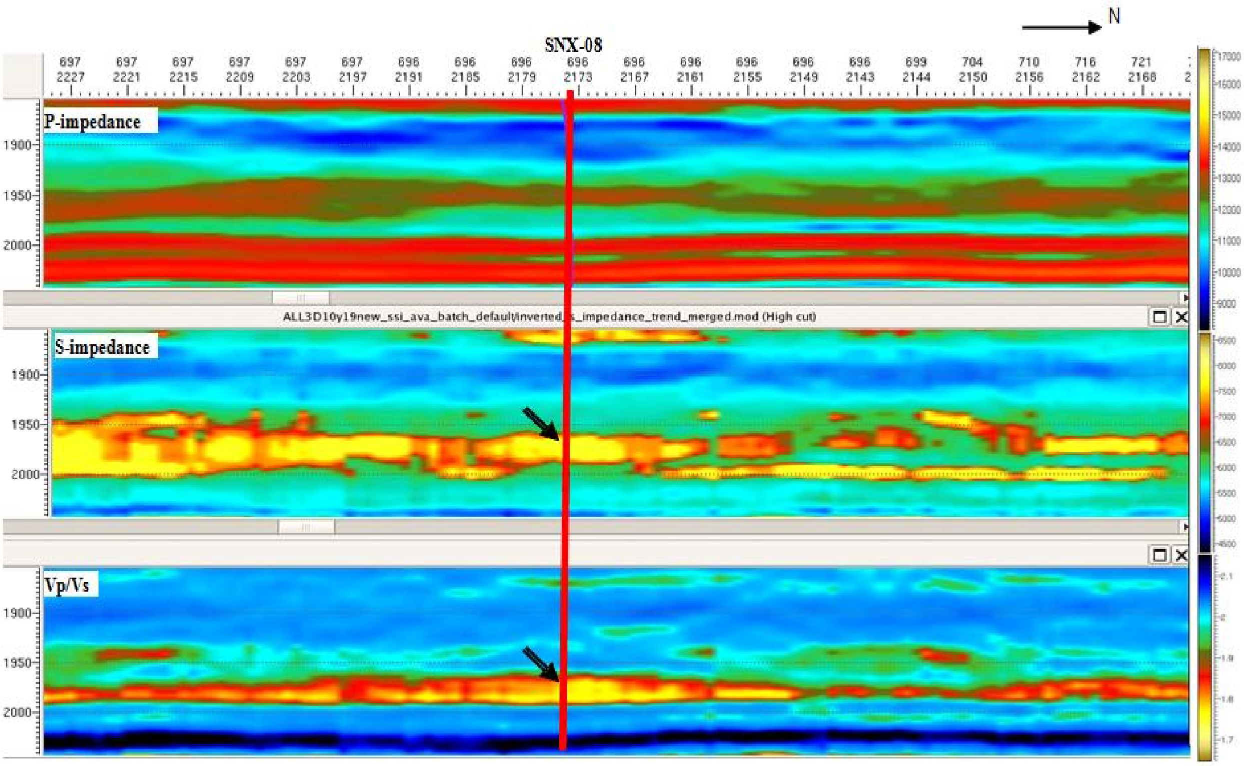


Figure 9—Prestack simultaneous inversion sections through drilled well SNX-08.

Results and Discussions

This study has created a set of high-resolution reprocessing workflow with amplitude and fidelity reserved for the seismic data in cooperation block, and it has formed seismic data processing technology series based on tomostatics, prestack fidelity reserved denoising, well-control wide frequency processing, and OVT domain processing. Meanwhile, in the pilot area, we also obtained prestack gathers and migration stack data with high fidelity, moderate S/N and wider frequency band, which are able to meet the needs of reservoir prediction.

By the crossplot interpretation between Vp/Vs ratio and S-impedance from prestack simultaneous inversion, we got the map of He8 sandstone thickness in the pilot area (**Figure 10a**), and obtained better prediction effect with 82% of coincidence rate.

On the basis of AVO characteristics of He8 reservoir in the pilot area, we qualitatively predicted the gas-bearing property (**Figure10b**) by analyzing seismic amplitude variation in the target zone on near and far offset stack sections, and the coincidence rate is 73%. At the same time, by using crossplot interpretation between Vp/Vs ratio and S-impedance from prestack simultaneous inversion, we got the map of He8 gas-bearing sand thickness in the pilot area (**Figure 10c**), and the coincidence rate is 75%. The effective reservoir prediction obtained satisfied results.

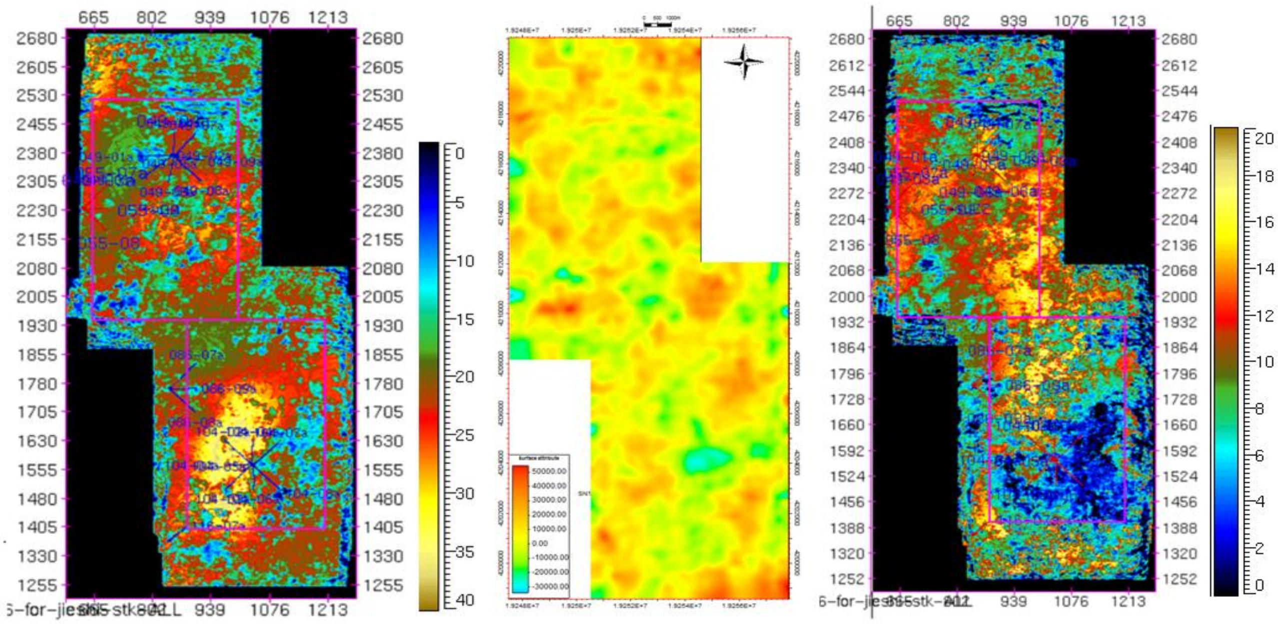


Figure 10—(a) Map of He8 sandstone thickness. (b) Map of AVO attribute analysis of He8 reservoir. (c) Map of gas-bearing sand thickness of He8 zone.

Conclusions

1. For the most of raw single shot data in the pilot area, the high frequency constituent is still preserved but of weaker energy. By applying prestack seismic data processing techniques with wide frequency, fidelity reserved and amplitude reserved at its core, the energy of high frequency constituent in the data was enhanced, and we obtained the reprocessed data with high fidelity, wide frequency band, high resolution and good consistency, compared to the previous processing results.
2. The reprocessed seismic data can be used to identify 10m above single sandbody or sand group, and 5m above gas sand. AVO attribute analysis can be used to qualitatively predict gas-bearing property of He8 reservoir. By using crossplot interpretation between Vp/Vs ratio and S-impedance, we can quantitatively predict thickness of He8 sandstone and gas sand.
3. Both well-seismic match of AVO characteristics of He8 reservoir in the pilot area and well-seismic fit of prestack seismic inversion results are improved significantly, compared to the previous studies.

4. The techniques and results from this study in the pilot area can be applied to the whole cooperation block, and it plays an important guidance role to the development of international cooperation block in Sulige gas field.

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Conflicts of Interest

The author(s) declare that they have no conflicting interests.

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