

# Application of pre-stack geostatistical inversion in prediction of thin high-quality conglomerate reservoir in Shawan Depression, Junggar Basin

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**Abstract** In the Baikouquan Formation of the Shawan Depression, there exist thin, high-quality conglomerate reservoirs with low porosity and low permeability. Only the underwater gray-green conglomerate with medium porosity is considered a high-quality reservoir. Due to the overlapping wave impedance between these thin high-quality reservoirs and tight layers, traditional post-stack inversion and pre-stack simultaneous inversion methods are ineffective in predicting such thin reservoirs. Pre-stack geostatistical inversion, which combines the advantages of simultaneous inversion and geostatistical inversion, has proven to be effective in this context. This study integrates core, logging, and test data to construct petrophysical charts using P-impedance and  $V_p/V_s$  ratios, identify key reservoir parameters, and apply pre-stack geostatistical inversion to predict thin high-quality conglomerate reservoirs. The results show that pre-stack geostatistical inversion can accurately identify thin high-quality reservoirs, providing a reliable basis for further exploration and development.

**Keywords** Junggar Basin, Shawan Depression, tight conglomerate, high-quality reservoir, pre-stack geostatistical inversion

## 1 Introduction

Reservoir prediction through conventional deterministic seismic inversion (post-stack inversion) is influenced by multiple factors (Connolly, 1999). First, the inversion results often fail to accurately represent the actual high-

quality reservoirs (Gogoi and Chatterjee, 2019). For example, since mudstone contains salt minerals to varying degrees and its velocity is close to that of sandstone, the impedance values of these salt-bearing rocks are not significantly different from those of permeable sandstone. As a result, the wave impedance inversion results are multi-solvable, making lithology discrimination difficult (Su et al., 2009; Cui et al., 2010). Secondly, due to the limitations of seismic resolution, thin interbedded deposits cannot be identified by conventional deterministic seismic inversion. Conventional geostatistical inversion, a post-stack inversion method, can only perform P-wave impedance inversion. When the P-wave impedance of high-quality thin-layer reservoirs overlaps with that of tight layers, the commonly used post-stack wave impedance inversion method cannot meet the requirements for predicting thin-layer reservoirs in this area (Hass and Dubrule, 1994; Dubrule et al., 1998; Rothman, 1998; Grana et al., 2017).

Pre-stack inversion methods include pre-stack elastic impedance inversion, pre-stack simultaneous inversion, and pre-stack geostatistical inversion. The first two methods can obtain rock elastic parameters within the seismic resolution range (Wu et al., 2023), which are consistent with seismic data responses. However, their vertical resolution is restricted by seismic resolution. In the best-case scenario, they can only distinguish sand bodies with a resolution of  $\lambda/8$  (Wan et al., 2012), which is far from sufficient for identifying single sand bodies in the development geology of dense well-pattern areas. Pre-stack geostatistical inversion combines the advantages of simultaneous inversion and geostatistical inversion techniques (Zong et al., 2012), enhancing the prediction of reservoir vertical resolution. The main influencing factor is the frequency of the original seismic data. When

the main frequency of the seismic data is too low, the results will be affected, and conventional pre-stack inversion cannot reflect thin sand bodies (Wang et al., 2011).

The basic principle of the pre-stack geostatistical inversion method is based on the rigorous Markov Chain Monte Carlo (MCMC) algorithm (Grana and Della Rossa, 2010; Zhao, 2010; Liu et al., 2011). It combines pre-stack simultaneous inversion and stochastic inversion techniques to form a new inversion algorithm. Pre-stack geostatistical inversion is based on geostatistics and involves stochastic simulation and the inversion process. By analyzing seismic and well-log data, the variogram can be obtained, and then appropriate stochastic simulation and inversion algorithms are selected to acquire high-resolution data volumes (He et al., 2011; Luo and Zong, 2022). The input data for pre-stack geostatistical inversion include some stacked data volumes, seismic wavelets, stratigraphic framework models, well logs, the probability density functions of various lithologies, and the variogram. This method takes into account the lateral resolution of seismic data and the vertical resolution of logging data, thus enabling high-resolution inversion results.

The advantages of this technique are as follows: it improves the resolution of conventional inversion results, enhances vertical resolution while maintaining lateral resolution (Wang et al., 2012), and can obtain multiple pre-stack elastic parameters. It is an effective solution for predicting thin high-quality reservoirs when the impedance of high-quality reservoirs overlaps with that of tight layers (Li et al., 2007; Zhong et al., 2017).

In this paper, the Well SW1 area of the Triassic Baikouquan Formation in the Shawan Depression is taken as the study area. Given the complex lithologic structure and rapid lateral variation of the reservoir, the pre-stack geostatistical method is used to predict the vertical distribution of gray high-quality thin sand bodies, providing support for exploration and development.

## 2 Petrophysical characteristics of Shawan conglomerate reservoirs

The slope of the Shawan Depression is a gently monoclinic structure, dipping south-eastward, with regional development of platform, anticlinal, or nose-like structures. The Shawan Depression is one of the main oil-generating depressions in the Junggar Basin, with abundant oil and gas sources. The Triassic Baikouquan Formation in the Shawan slope has a fan-delta sedimentary environment, where sedimentary facies change rapidly. The fan-delta plain is developed in the north-west and gradually transitions southward to the fan-delta front. The lithologic structure is complex, and lateral changes are significant. The main lithology is low-

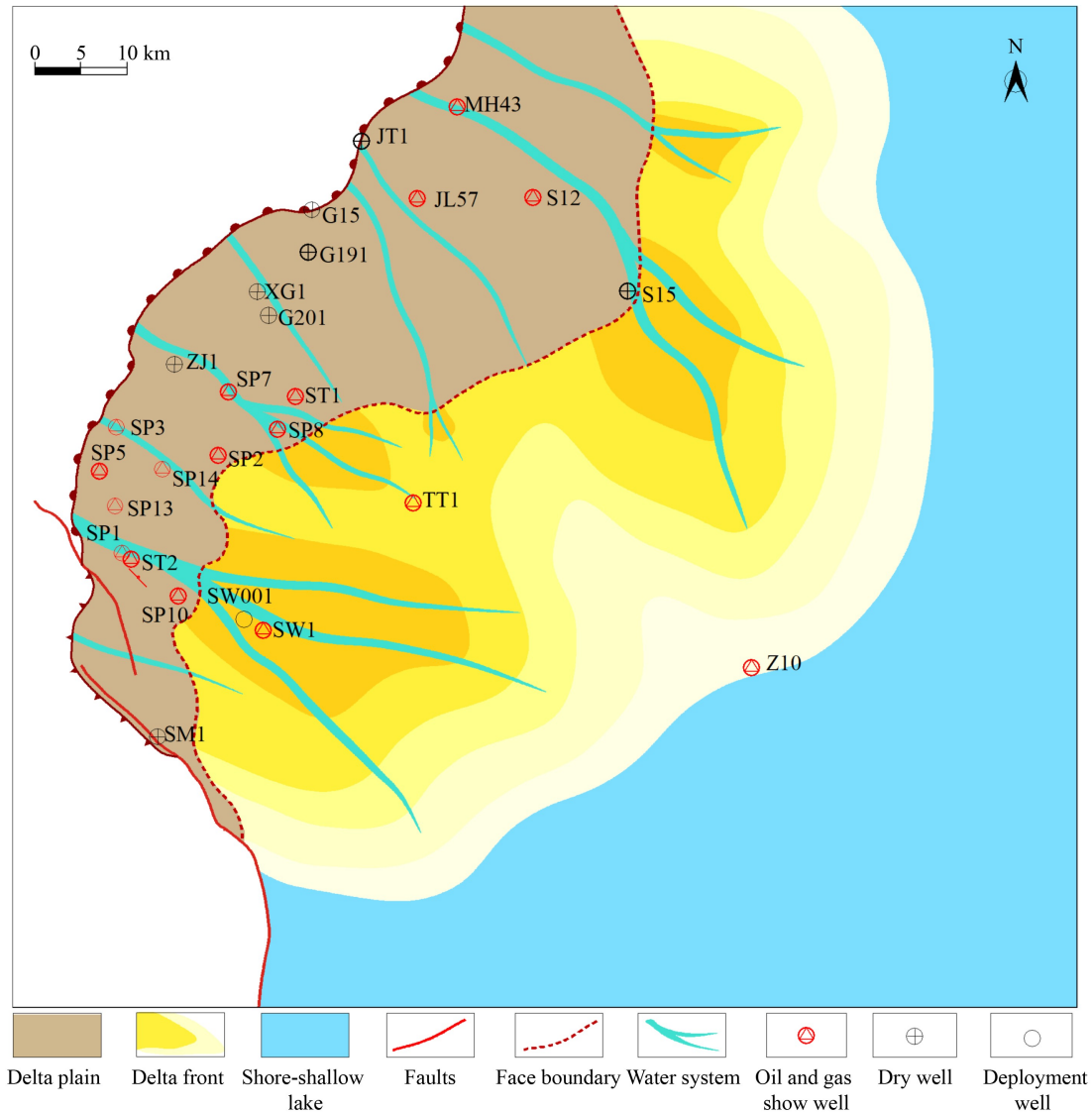
porosity and low-permeability conglomerate. However, in the underwater distributary channels of the delta front, well-sorted gray-green conglomerate with medium-high porosity develops, which is the dominant reservoir in the Well SW1 area (Fig. 1). Well ST2, located in the delta plain facies, is filled with dense conglomerate, while Well SW1, located in the fan-delta front facies, has two sets of high-porosity oil-water co-existent layers with thicknesses of only 7 m and 12 m. Therefore, in the updip direction of SW1, Well SW001 is planned to explore for pure oil layers.

Through the above analysis, the high-quality reservoir in the Baikouquan Formation is underwater gray or gray-green conglomerate. First, logging and coring information is used to classify lithologies into three types: mudstone, mottled tight conglomerate, and gray-green high-quality reservoir. Then, a statistical analysis of the elastic parameters of the Baikouquan reservoir is conducted. From the cross-plots of P-wave impedance and  $V_p/V_s$  (Fig. 2), the impedance of shale ranges from 8000–11500 m/s·g/cm<sup>3</sup>, and that of conglomerate ranges from 9500–12500 m/s·g/cm<sup>3</sup>. Overall, the impedance of conglomerate is higher than that of mudstone, but the high-quality conglomerate reservoir has a significant overlap with the tight layer. Regarding the  $V_p/V_s$  attribute, the effective conglomerate reservoir ranges from 1.6–1.76, the dense conglomerate from 1.76–1.83, and shale is greater than 1.83. Thus, the  $V_p/V_s$  attribute can effectively distinguish between effective reservoirs and dense layers.

Due to the characteristics of the conglomerate reservoir, it is difficult to distinguish effective reservoirs from dense layers using only impedance. This indicates that post-stack inversion technology is not effective in predicting reservoirs in this area. Therefore, pre-stack geostatistical inversion is carried out to effectively identify thin high-quality reservoirs.

## 3 Application of pre-stack geostatistical inversion in thin and high-quality reservoir prediction

Pre-stack geostatistical inversion can improve vertical resolution, while lateral resolution mainly comes from seismic data. Thus, before performing pre-stack geostatistical inversion, a high-quality deterministic pre-stack inversion must be completed first. The main purpose of this step is to provide constraints for pre-stack geostatistical inversion, allowing us to obtain an overall lithology distribution and the proportion of the target zone. These serve as the initial inputs for geostatistics, and the deterministic inversion results also serve as a reference for the lateral prediction accuracy of geostatistical inversion, which can be used for quality control of geostatistical inversion.



**Fig. 1** The Baikouquan formation sedimentary facies.

### 3.1 Pre-stack simultaneous inversion (deterministic inversion)

Through AVO pre-stack inversion, precise body elastic parameters can be simultaneously obtained within seismic resolution. Under the constraint of logging data, simultaneous inversion is performed on partially stacked seismic data at different angles or offsets to obtain P-wave impedance, S-wave impedance, and  $V_p/V_s$ . By analyzing the elastic parameters of the reservoir, it is found that  $V_p/V_s$  can distinguish effective reservoirs from dense conglomerates (dense conglomerates have  $V_p/V_s$  values between 1.76–1.83; effective reservoirs have values less than 1.76). From the profile (Fig. 3),  $V_p/V_s$  obtained from pre-stack simultaneous inversion can distinguish between high-quality reservoirs and dense conglomerates, achieving high-quality reservoir prediction. However, due to the limitation of seismic

resolution, it fails to accurately predict the gray high-quality reservoir of Well SW1. Therefore, pre-stack geostatistical inversion is necessary to predict thin reservoirs.

### 3.2 Pre-stack geostatistical inversion

#### 3.2.1 Main parameters of pre-stack geostatistical inversion

The main parameters of pre-stack geostatistical inversion are the probability density function (PDF) and the variation function (variogram) (Shen et al., 2004). The probability density function describes the probability distribution of an attribute in space, while the variation function, as a function of distance, describes how the similarity between points in space changes with the distance between them. By analyzing the logs of nine wells in this survey, it is found that the probability density functions of P-wave impedance, density, and

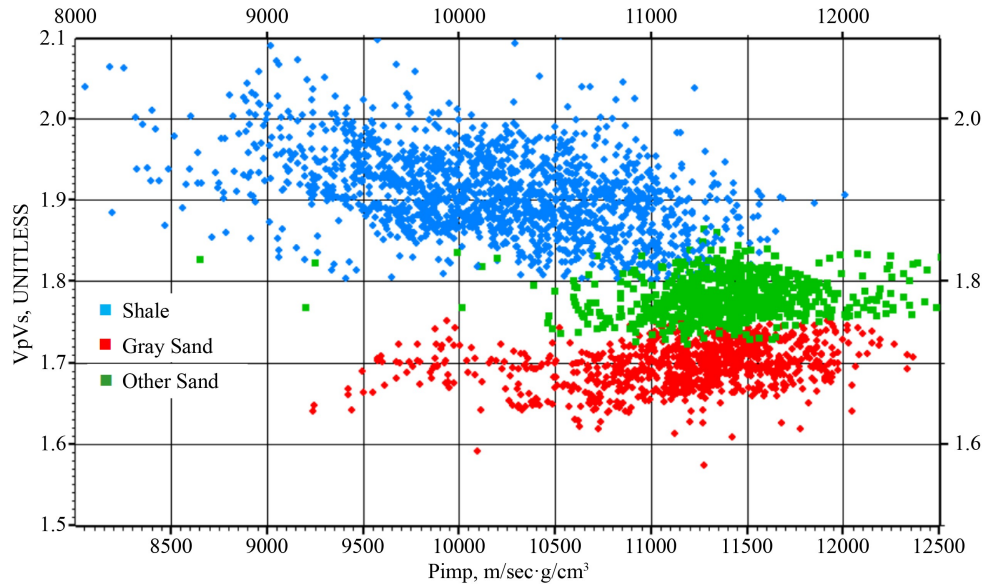


Fig. 2 Pimp and  $V_p/V_s$  crossplot.

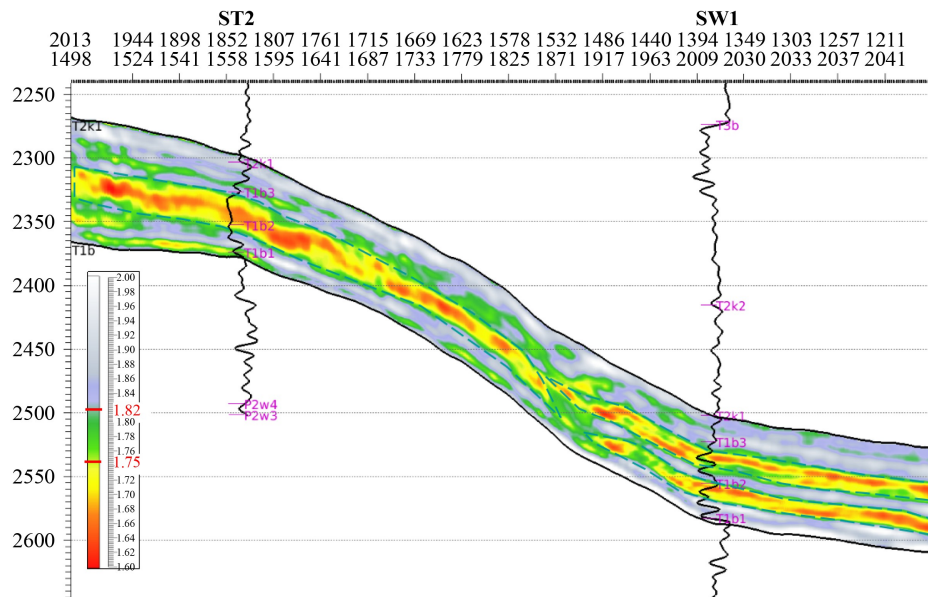
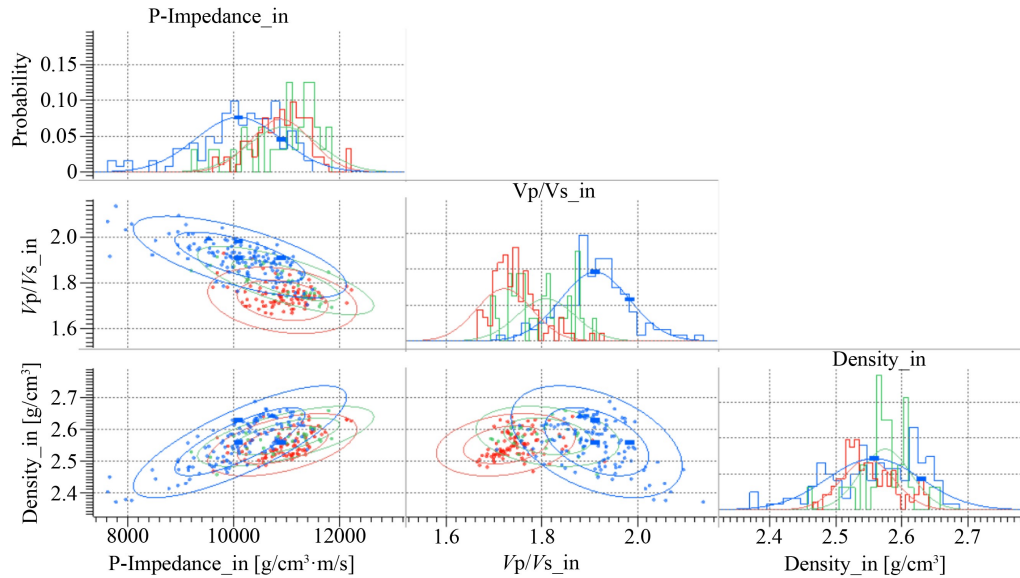


Fig. 3 ST2-SW1  $V_p/V_s$  wells profile.

$V_p/V_s$  follow a Gaussian distribution (Fig. 4). The most crucial parameter of the variation function is the lag distance, which can reflect the average scale of regional variables (such as the thickness and length of sand bodies) in a certain direction. Thus, the lag distance is used to predict the scale of sand bodies. Geologically, the vertical lag distance reflects the vertical thickness of the reservoir and affects the vertical resolution of pre-stack geostatistical inversion, while the transverse lag distance reflects the lateral distribution of the reservoir (Qin et al., 2009; Dong et al., 2013; Fan et al., 2017). The sample points of well curves are used to fit the variation function in the vertical direction, and the trend of the sample points follows an exponential variation function. The

vertical lag distance is determined through function fitting. When the value is 6 m, the variogram of the sample points tends to be stable. Three sets of parameter experiments are conducted with vertical lag distances of 4 m, 6 m, and 10 m. The inversion result is most consistent with the actual situation (the thickness of thin sand bodies in the study area is about 7 m) when the value is 6 m. When the lag distance of the transverse variation function is 1800 m, the variogram tends to be stable. Similarly, three sets of parameter tests are conducted with lateral lag distances of 1200 m, 1800 m, and 2400 m. The inversion result is most consistent with the actual situation (the actual distribution range of sand bodies between wells in this area is about 2000 m) when



**Fig. 4** Histograms and probability density function crossplot.

the value is 1800 m. Therefore, when the vertical and horizontal lag distances are set to 6 m and 1800 m, respectively, the inversion results are in good agreement with the actual well data.

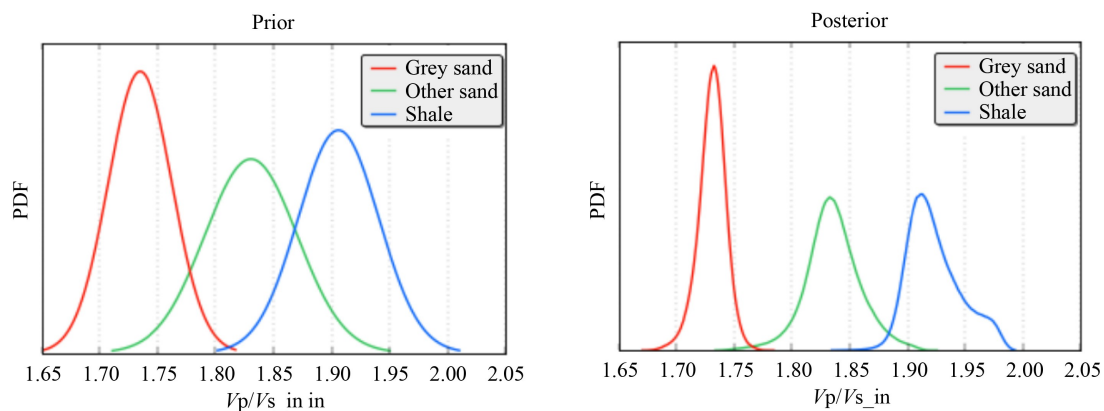
### 3.2.2 Quality control of pre-stack geostatistical inversion

To verify the accuracy of pre-stack geostatistical inversion, quality control of the inversion results is carried out through various means. On the left side of Fig. 5 is the  $V_p/V_s$  input histogram of gray-green conglomerate, tight conglomerate, and mudstone; on the right side is the  $V_p/V_s$  output histogram of the three-lithology inversion. It can be seen that the mean values before and after inversion are basically the same. Due to the different resolutions between the logging curve and the inversion result and the different iteration processes, the variances are slightly different. However, the inversion results can effectively distinguish lithologies. On the left side of Fig. 6 is the input lithology proportion pie-chart of gray-green conglomerate, tight conglomerate,

and mudstone, and on the right side is the output pie-chart of the three-lithology inversion. It can be observed that the proportion of gray conglomerate before and after inversion differs by 1%, the proportion of dense conglomerate by 3%, and the proportion of mudstone by 3%. These errors are within a reasonable range.

### 3.2.3 Effect analysis of pre-stack geostatistical inversion

Pre-stack geostatistical inversion can generate multiple lithology realizations that match wells and are consistent with deterministic inversion results in space. Eventually, multiple geostatistical lithology likelihood realizations are integrated to obtain the final Maximum Likelihood lithology probability bodies. Comparing the results of pre-stack simultaneous inversion and pre-stack geostatistical inversion, the pre-stack simultaneous inversion results (Fig. 7 left) can basically identify the two sets of sand bodies in Well SW1. However, the lower set of sand bodies (green to yellow part) is less obvious than the upper set (yellow to red part). The lower sand



**Fig. 5** Pre-stack geostatistical inversion input (left) and output (right)  $V_p/V_s$  distribution.

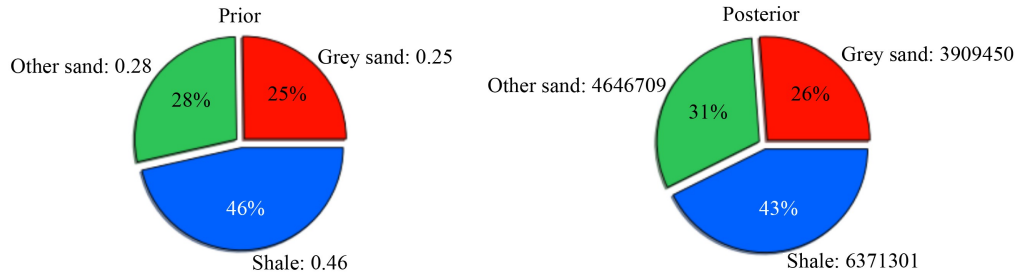


Fig. 6 pre-stack geostatistical inversion input (left) and output (right) lithology scale drawing.

body is laterally intermittently distributed and is misidentified as a set of tight reservoirs to some extent, indicating that the inversion results do not fully match the actual lithology of Well SW1. This is because the thickness of the upper sand body (12 m) is greater than that of the lower sand body (7 m). In other words, pre-stack simultaneous inversion is affected by vertical resolution and cannot accurately identify thin high-quality reservoirs. Well SW001 is predicted to have a set of high-quality reservoirs (yellow part) and a set of tight reservoirs (green part). The pre-stack geostatistical inversion results not only retain the advantages of pre-stack inversion (multiple elastic parameters) but also distinguish thin high-quality reservoirs from tight reservoirs. From the pre-stack geostatistical inversion results (Fig. 7 right), the 7-meter thin sand body in the lower part of Well SW1 can be clearly identified. The lateral distribution of the sand body is more stable, and the inversion results of the two sets of sand bodies in Well SW1 are more consistent with the actual lithology of the single well. Well SW001 is predicted to have two sets of high-quality reservoirs, and it is inferred that the thickness of the upper reservoir is smaller than that of the lower reservoir. According to the analysis of the lithology

results of pre-stack geostatistical inversion (Fig. 8 left), two sets of sand bodies are developed in Well SW1 and Well SW001. The upper sand body of Well SW1 and the lower part of Well SW001 are connected as one set of sand body, while the lower sand body of SW1 and the upper sand body of SW001 are thin sand bodies. The boundaries and distribution ranges of the sand bodies are relatively clear, showing horizontal stacking characteristics. From the pre-stack geostatistical probability section (Fig. 8 right), it can be seen that the probability of thin high-quality sand body development in these two wells is relatively high (red part), indicating that the inversion results are reliable. Through the pre-stack geostatistical inversion method, the resolution of the Baikouquan reservoir has been significantly improved.

Therefore, the results can be used not only for reservoir description and reserve calculation but also as a basis for exploration and development wells.

## 4 Conclusions

1) In the Shawan slope area, the thin high-quality conglomerate reservoirs in the Baikouquan Formation,

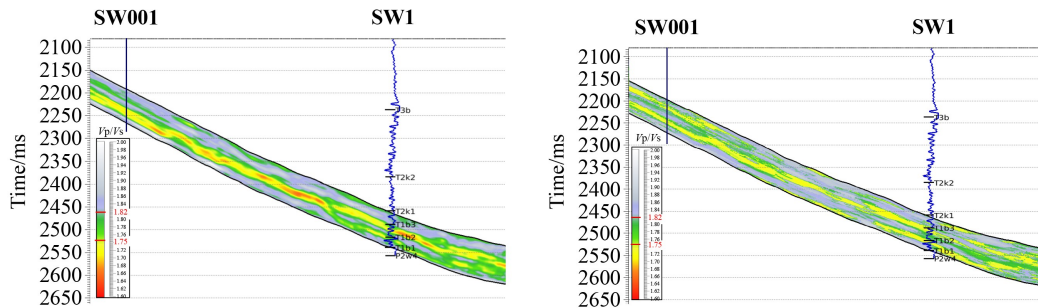


Fig. 7 SW1 pre-stack simultaneous (left) and geostatistical inversion (right)  $V_p/V_s$  section.

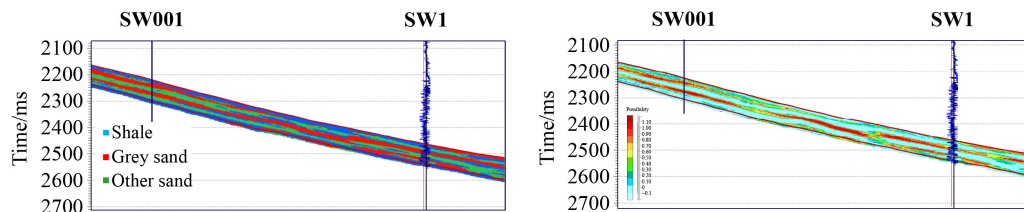


Fig. 8 SW1 pre-stack geostatistical lithology (left) and high-quality reservoir possibility (right) section.

with impedance overlapping that of dense layers, pose challenges for conventional inversion methods. Pre-stack geostatistical inversion effectively integrates geological, logging, and seismic data, combining the vertical resolution of logging with the lateral resolution of seismic data. This method not only solves the problem of thin reservoir prediction but also accurately identifies high-quality reservoirs despite impedance overlap.

2) Pre-stack geostatistical inversion clearly depicts the 7-meter thin high-quality reservoir in Well SW1, with a more stable lateral sand body distribution. It also accurately predicts the two sand-body sets in Well SW001, revealing clear connectivity and superposition between wells. This method provides a reliable basis for further exploration and development.

**Competing interests** The authors declare that they have no competing interests.

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