## Introduction

Thin sandstone interlayers are common features in the continental rift basin, which is one of the major types of oil/gas reservoirs. The difficulties in the prediction of thin interlayers include not only the improvement of the vertical resolution, but also keeping the lateral resolution and stability. In addition, the cementation effect in the late stage of digenesis not only complicates the lithology, but also results in the difficulty of identifying the effective formations through the seismic methods.

To effectively identify the sandstone interlayers, we carry out a case study for the sandstone interlayer identification in a reservoir of China in this paper. The thickness for every single sand body of these sandstone interlayers in this reservoir is normally smaller than 10 m, which is much smaller than the 1/4 of seismic wavelength (around 35 m). Furthermore, some sand bodies are composed of tuffaceous sandstone, which contain limestone cements. These limestone cements can significantly decrease the porosity and the permeability, hence, such tuffaceous sandstone interlayers are not effective oil/gas formations. This means that the identification of the effective sandstone interlayers is the identification of the clean sandstone, which needs to exclude the tuffaceous sandstone. In the following sections, we propose a workflow to identify these effective sandstone interlayers, which includes the rock physics modelling considering the cementation effects, the pre-stack space-variant inversion, and the Bayes identification of the interlayers.

## Pre-stack space-variant inversion

For the prediction of the lithologic trap containing complex interlayers, the lateral control (or space stability) of the seismic inversion results is very important. For this purpose, we propose the pre-stack space-variant inversion method in this paper. This method is developed based on the pre-stack three-parameters inversion method. First, to improve the correction efficiency of the initial model in the iteration of the inversion, we construct the objective function using the Bayes regularization method as follows:

$$\mathrm{F}(r)=\frac{\alpha}{2}(\mathrm{d}-Gr)^T(d-Gr)+\frac{\beta}{2}\log\left[\frac{1}{1+r^Tr}\right]+\frac{\mu}{2}\left(\mathrm{K}r-\xi\right)^T\left(Kr-\xi\right), \quad (1)$$

where the first term is the error term of the model.

Then, we can add the space-variant factor $C$ into equation (1) and carry out the weight normalization, which yields:

$$\mathrm{F}(\theta)=\frac{\alpha\cdot\mathrm{C}(x,y,\theta)}{2\max(C)}(d-Gr)^T(d-Gr)+\frac{\beta}{2}\log\left[\frac{1}{1+r^Tr}\right]+\frac{\mu}{2}\left(\mathrm{K}r-\xi\right)^T\left(Kr-\xi\right). \quad (2)$$

The advantages of the new method are as follows: 1) Make the best use of the information from the dominant frequency band of the seismic data; 2) Enhance the lateral correction ability of the low frequency model; 3) Reduce the reliance of the inversion results on the initial model. The inversion results are shown in Figure 1. It can be seen that the pre-stack space-variant inversion can greatly improve the space stability of the inversion results and at the same time avoid the occurrence of local extremum.

The application of the space-variant factor not only changes the initial values of the inversion, but also increase the searching space during the iteration optimizing procedure. However, for most multi-parameter optimization methods, the occurrence of local extremum can be avoided as long as the conjugate condition along the searching direction is satisfied. The method used in this paper is the modified Powell conjugate direction optimization algorithm. The results of the iteration are shown in Figure 1 and 2.

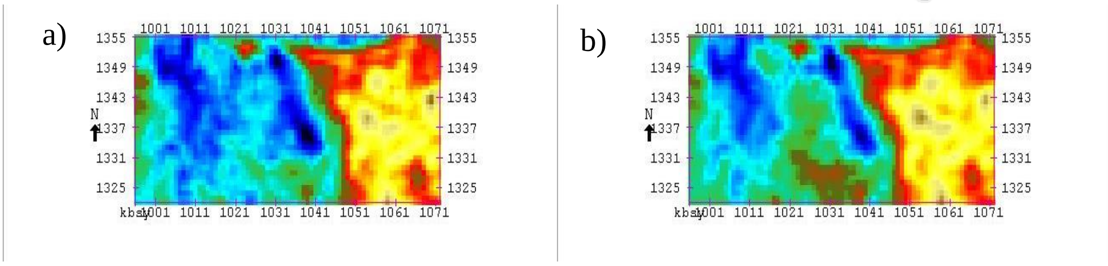


***Figure 1.*** *The change of the horizontal profile for the thin interlayers before (a) and after (b) the space-variant inversion.*

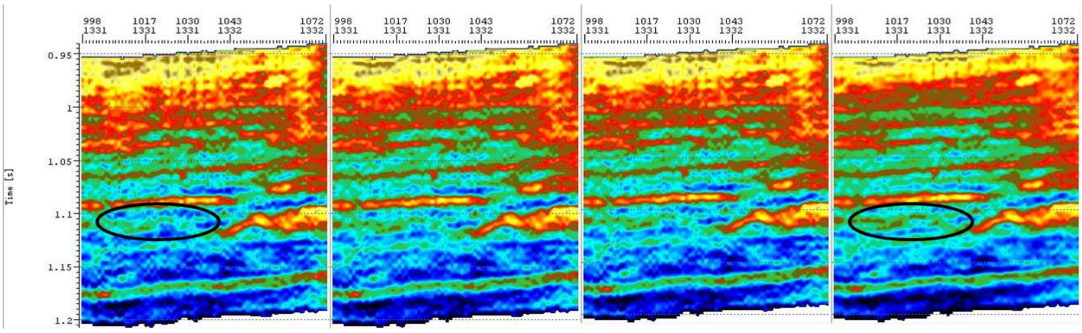


***Figure 2**. The change of the vertical profile for the thin interlayers during the iteration procedure in the space-variant inversion.*

## Case study

### *Rock physics modelling*

To predict the lithology from the rock elastic parameters, we need to build the rock physics template. Based on the available P- and S-wave velocities and the density logging data in this reservoir, the ratio of *Vp* to *Vs* and Poisson ratio can be calculated. Hence, we can build the crossplot of *Vp*/*Vs* with Poisson ratio, as shown in Figure 3a. It can be clearly seen that this crossplot can effectively identify the clean sandstone, shale, and tuffaceous sandstone. To further validate the effectiveness of the crossplot in identifying the lithology, we carry out the rock physics modelling using the Xu-white model (Xu and White, 1996) and the CCT model (Guo and Han, 2016). For the clean sandstone and the shale, the pores with different aspect ratio distribute in the sand or shale matrix, which fulfils the assumption of Xu-white model. Hence, we can apply Xu-white model to calculate their elastic properties. For the tuffaceous sandstone, the cementation effect of the limestone cements has important influence on its elastic properties. To take into account the cementation effect, the CCT model can be applied to compute its elastic properties. Using the logging data, the input parameters for both Xu-white and CCT model can be obtained. Then the elastic properties for the clean sandstone, shale, and tuffaceous sandstone are calculated and the crossplots of *Vp/Vs* with Poisson ratio are given, as shown in Figure 3b. Comparing Figure 3a and 3b, it can be found that they are in good agreement with each other. Hence, Figure 3a can be used as the rock physics template for lithology identification.

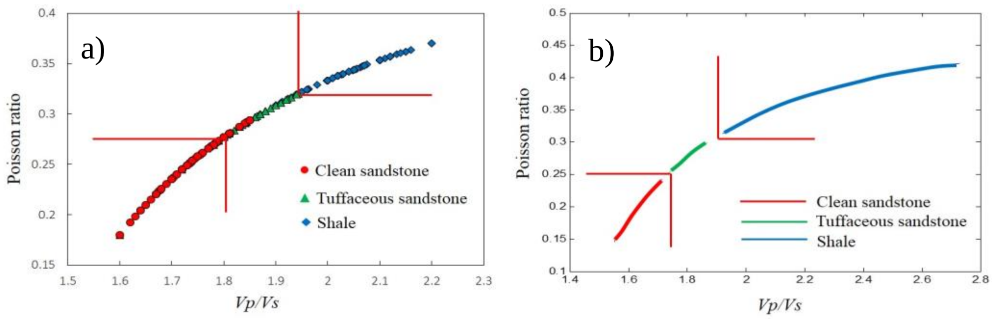


***Figure 3**. Crossplot of Vp/Vs with Poisson ratio. a) logging data. b) modelling results.*

*Pre-stack space-variant inversion*

In this reservoir, there are only a few wells and they are not distributed evenly. After performing the pre-stack elastic parameters estimation, the wells that can be used for the initial model construction further reduced. Hence, it is difficult to construct the initial model for the inversion. Furthermore, the difference between the completeness of the three parameters results in the different restriction degree in space for the different models. Hence, the local divergence can easily occur in the inversion. To solve these problems, the following improvements are made: 1) adjust the space restriction mechanism (staggered form); 2) Select the wells that are calibrated well after stack and reserve their P-wave velocity and density data; 3) Reserve the important control points of the S-wave velocity; 4) Avoid the linear correlation in the space caused by the simultaneous restriction of the three parameters. Figure 4 shows the inversion results based on different initial model restrictions. It can be seen that the improved three-parameter staggered modelling method can effectively overcome the space abnormity caused by the poor lateral resolution of the thin interlayers.

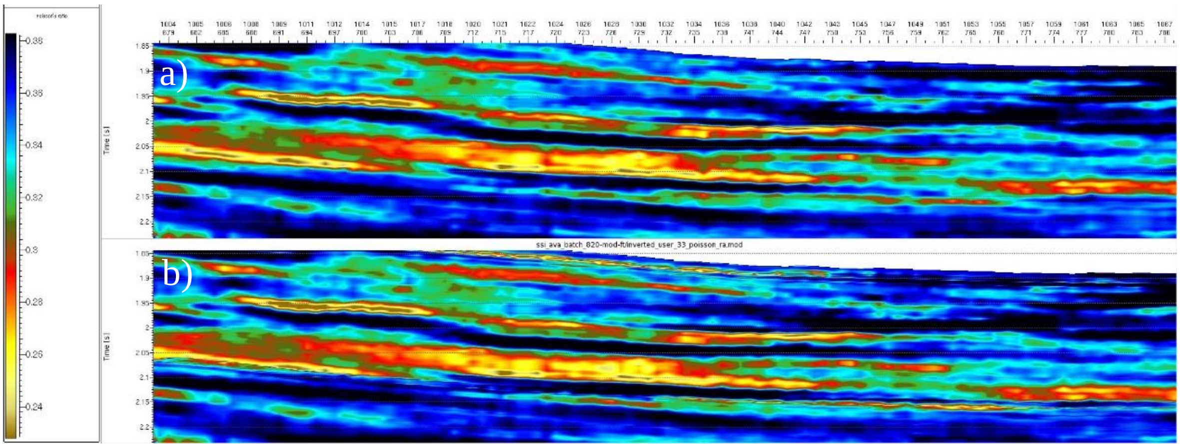


***Figure 4.*** *Comparison of P-wave impedance profile given by pre-stack inversion. a) Improved three-parameter staggered modelling. b) Conventional modelling.*

*Bayes identification of the interlayers*

Bayes identification of interlayers is a combination of the established rock physics template and the pre-stack inversion results, which can give the sensitive parameters to the lithology. Single or multiple sensitive parameters can be obtained. The probability density function can then be generated by using the statistical techniques. By applying the probability density function on the inversion data, we can obtain a straightforward and macroscopic probability results for the lithology. The pre-stack inversion provides the attributes of P- and S-wave velocities, density, and Poisson's ratio, based on which the Bayes identification of formation lithology is performed and the probability body for the clean sandstone, tuffaceous sandstone, and shale are given. The high probability represents the high likelihood of the specific lithology. Conversely, the low probability means the low likelihood of this lithology. The effective sandstone interlayers are those with high probability for clean sandstone. This technique gives the quantitative description of the rock physics template by using the mathematical statistic method, which enables the quantitative interpretation of the multiple data provided by the pre-stack inversion. The formation lithology and the effective oil/gas formation are thus identified.

*Results*

The prediction results for the sandstone interlayers are given in Figure 5. Both the vertical profile and horizontal slice for the clean sandstone probability are provided. The probability results for the tuffaceous sandstone and shale are not shown as they are not effective oil/gas formations. The clear distribution for the clean sandstone interlayers can be observed. It can found from the vertical profile that there are primarily three sand bodies. Based on this prediction result, the exploration wells are deployed. The sandstone interlayers are successfully drilled, which contains high content of oil and gas. This demonstrates the effectiveness of the workflow proposed in this paper for identifying the sandstone interlayers.

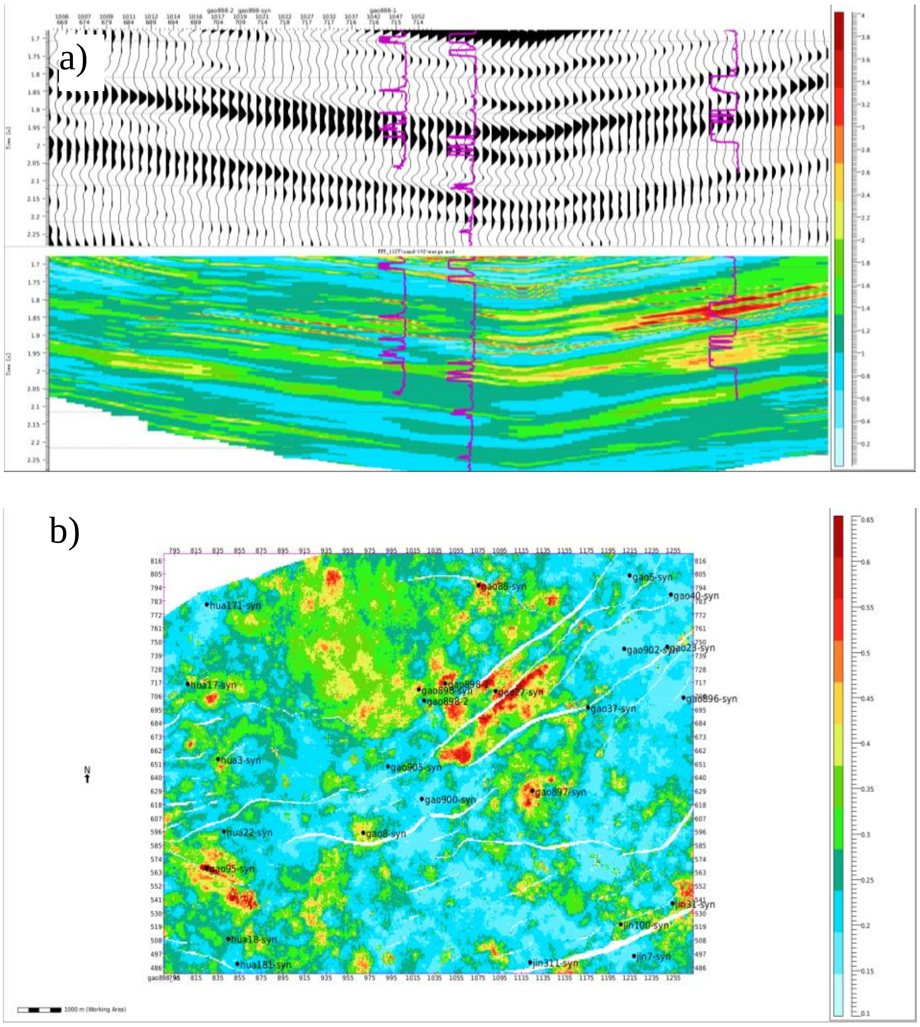


***Figure 5.*** *Prediction results for sandstone interlayers. a) vertical clean sandstone probability profile. b) horizontal clean sandstone probability slice.*

## Conclusions

The objective of this paper is to propose the workflow for the effective identification of the sandstone interlayers through the integration of the logging and seismic data. Following the steps of rock physics modelling, pre-stack space-variant high resolution seismic inversion, and Bayes identification, the thin sandstone interlayers in the reservoir are identified. due to its low porosity and permeability of the tuffaceous sandstone interlayers, they are excluded in the proposed workflow, only the clean sandstone interlayers are identified. The results show the clear distribution of the clean sandstone interlayers. The exploration wells are deployed based on the prediction results. The interlayers are successfully drilled, which contains high content of oil and gas.

## References

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