# Delineating Thin-Bed Tight Gas Sand Reservoir with Prestack Joint PP/PS Inversion*

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## Abstract

The thickness of single sandstone is about 30-60m and the thickness of single gas sandstone is less than 10m. However, the extent of gas sandstones is greater than 80,000 km$^2$ in the Ordos Basin of Northwestern China. It poses challenges to predict the gas sand reservoir because of drastic lateral lithological variations in the fluvial sediments in Dyas. The P-velocity or impedance of tight gas bearing sand decreases, which may be the same as that of shale surrounding rock. A prestack stochastic inversion of joint PP and PS data conducted recently provided an effective technique for solving the problem and successfully delineating the characteristics of the reservoir.

Converted wave (Sv-wave) velocity analysis approach is always a difficult problem in 3C seismic data processing. Conventional 3C velocity and image are generally computed in different time scales; PP wave is processed with PP time scale and PS wave with PS time scale. PP and PS wave data are basically processed separately causing errors in horizon calibration between PP and PS waves. Joint inversion of PP and PS reflection data has been hindered by the difficult task of registration or correlation of PP and PS events. It can perhaps be achieved by registering the events during inversion but the resulting algorithm is generally computationally intensive.

In this paper, we report on a converted wave velocity analysis approach from 3C data that can image P and Sv-waves in the same PP or PS wave time scale. In fact, we carry out the velocity analysis in depth domain such that common conversion points are updated at each iteration of velocity analysis. Thus, mapping to PP and PS time scales is trivial. This method circumvents the horizon calibration problem in the data interpretation between PP and PS waves and image them accurately. At the same time, this method provides PP and PS wave velocities suitable for pre-stack migration. The prestack PP and PS wave joint stochastic inversion is achieved by using the PP and PS wave angle gathers using a very fast-simulated annealing (VFSA) algorithm. The objective function attempts to match both PP and PS data; the starting models are drawn from fractional Gaussian distribution constructed from interpolated well logs. The proposed method has been applied to real data to estimate the P- and shear-wave impedance, density and velocity ratio. The application of prestack stochastic inversion of joint PP and PS data resulted in lower Vp/Vs in gas bearing sands compared with dry sands. The correlation between the inversion and the existing well data shows the lower Vp/Vs can provide more accurate reservoir characterization.

## Introduction

Multi-component seismic technology offers several advantages, including reservoir characterization using PP and PS waves. It is highly effective in lithology determination and, for fluid and fracture identification. However, we are faced with the difficulties of estimating converted shear wave velocities and joint PP and PS inversion. Conventional methods for processing the PS wave data assume a simple propagation path, namely, a down going P-wave and a reflected up going shear wave. The converted wave is considered a virtual or effective wave whose velocity neither the P wave velocity nor the shear wave velocity. The PP wave is processed with the PP time scale and the PS wave with the PS time scale. PP and PS wave data are processed separately. The final PP and PS wave velocity gather and stack data or migration data have different travel times at the same depth, which makes horizon calibration and registration very difficult during joint inversion.

Agullo (2004) describes a 3-step inversion methodology: getting shear wave impedance from PP wave and PS wave inversion respectively because they have different time scales; correlating the low frequency content of the two kinds of impedance to get velocity ratio $\gamma$; calculating the joint PP and PS inversion. Linear or nonlinear inversion is completed according to the method. However, the crucial PP and PS time correlation problem remains to be solved. Different techniques exist for correlating PP and PS data, but they implicitly assume that PP and PS contacts are similar or have at least the same sign, an assumption that is often violated, especially at the reservoir level. The key to the proposed technique is that it accurately reconciles PP and PS reflection times.

Dariu, et al., (2003) described a globally optimized multi-component AVO inversion technique using simulated annealing algorithm. Test of this global optimization method on synthetic and real case studies were very successful. Scaling factors are calculated by matching the total energy of the real data to that synthetic data, and then using it to calibrate the real data before inversion.

In this paper, first we address the problem of processing the PP wave and the PS wave in the same timescale domain. Deng et al. (2010) describe the converted shear wave velocity analysis – a method that we employ here. So the final PS wave section or gather are displayed in the PP wave time. Then we develop a VFSA algorithm of prestack PP & PS wave joint inversion.

## Method

The goal of prestack inversion is to make use of reflection amplitude, travel time and waveform data at non-normal incidence to estimate acoustic impedance and Poisson's ratio so that a robust interpretation of lithology and fluid content can be made (Sen, 2006). Because of adding the shear information in the inversion, prestack PP & PS joint inversion can increase the accuracy of the shear impedance, and furthermore improve velocity ratio and Poisson's ratio. In this paper, VFSA algorithm is used for optimization. For forward modeling, the Zoeppritz equation approximations of Aki and Richards (1980) are used to calculate the synthetic angle gathers (Fatti. et. al.1994, Deng et al. 2010).

## Converted Shear Wave Velocity Analysis

For a single isotropic horizontal layer, the following double square root equation can accurately express the converted shear wave time-distance curve.

$$t_{ps} = \sqrt{t_{p0}^2 + \left(\frac{x_p}{V_p}\right)^2} + \sqrt{t_{s0}^2 + \left(\frac{x_s}{V_s}\right)^2} \tag{1}$$

Where $t_{ps}$ is the sum of downgoing P-wave and upgoing shear wave travel times, $t_{p0}$ and $t_{s0}$ are the one-way travel times of P-wave and shear wave respectively, Vp and Vs are the P-wave and shear wave velocities respectively, $x$ is the distance from a source to a receiver, and $x_c$ is the distance from conversion point to a receiver.

If PS velocity analysis is done based on equation (1), shear wave velocity can be obtained. Deng et al. (2010) describe a detailed converted shear wave stack velocity analysis method – a method that we employ here in our analysis. This procedure estimates a prestack migration velocity field. Figure 1 shows the PP and PS wave sections by Kirchhoff prestack time migration, which was obtained after velocity analysis using the method of Deng et al. (2010). The travel times of PP and PS waves for the same event are equal.

**Very Fast Simulated Annealing**. VFSA is a modified form of simulated annealing (SA) - a global optimization method to speed up the annealing process without much sacrifice in the solution. Kirkpatrick et al (1983) first proposed SA. It is analogous to the natural process of crystal annealing, in which a liquid gradually cools to a solid state. The SA technique starts with an initial model, with an associated error. It draws a new model from a flat distribution of models within the pre-defined limits. All the particles are distributed randomly in a liquid phase after been heated to a certain temperature. The crystallization, or the minimum energy state, occurs if annealing process follows a slow cooling schedule. Thermal equilibrium is required at each temperature with the probability:

$$P(E_i) = \frac{\exp(-E_i/(KT))}{\sum_{j\in S}\exp(-E_j/(KT))} \tag{2}$$

Where *E* is the energy function. If it is applied into the inversion problem, the set *S* consists of all possible states and *K* is Boltzmann's constant, which equals one in geophysics problem. By trading state configuration as model parameter and energy function as the error function given by

$$E(\mathbf{m}) = 1/2(\mathrm{d}_{\mathrm{obs}}-g(\mathbf{m}))^{T\text{-}1}C_D(\mathrm{d}_{\mathrm{obs}}-g(\mathbf{m})) \tag{3}$$

Where $g(\mathbf{m})$ is the forward modeling operator and $C_D$ is the data covariance matrix, which consists of observation and theory error. We can rewrite the Gibbs distribution as PPD of model parameters:

$$P(m_i) = \frac{\exp(-E(m_i)/T)}{\sum_{j\in S}\exp(-E(m_j)/T)} \tag{4}$$

VFSA bring biasness to the estimation due to the short tail (Sen and Stoffa 1995). The mean value of samples is not the true expectation value, although they are very close to each other. The new model in VFSA is drawn from a temperature-dependent Cauchy-like distribution centered on the current model. This change has two fundamental effects. First, it allows for larger sampling of the model space at the early stages of inversion when the temperature is high and much narrower sampling in the model space as the inversion converges when the temperature is low. Second, each model parameter can have its own cooling schedule and model space-sampling scheme.

**Prestack data joint inversion.** We follow the idea in Sen and Stoffa (1995) and Srivastava and Sen (2010) to construct the objective function as follows:

$$E = 2\omega_p \frac{\left\| d_p^{obs} - d_p^{pre} \right\|_2^2}{\left\| d_p^{obs} + d_p^{pre} \right\|_2^2 + \left\| d_p^{obs} - d_p^{pre} \right\|_2^2} + 2\omega_{ps} \frac{\left\| d_{ps}^{obs} - d_{ps}^{pre} \right\|_2^2}{\left\| d_{ps}^{obs} + d_{ps}^{pre} \right\|_2^2 + \left\| d_{ps}^{obs} - d_{ps}^{pre} \right\|_2^2} + \mu_1 \left\| m_p^{pri} - m_p^{new} \right\|_l + \mu_2 \left\| m_{ps}^{pri} - m_{ps}^{new} \right\|_l \tag{5}$$

Where $E$ is the objective function, $\| \; \|_1$ is l norm, $d_p{}^{obs}$, $d_p{}^{pre}$ are the observed data and predicted data of PP wave respectively, $d_{ps}{}^{obs}$, $d_{ps}{}^{pre}$ are the observed data and predicted data of PS wave respectively, $m_p{}^{new}$, $m_p{}^{pri}$ are the iterative model and prior model of PP wave respectively, $m_{ps}{}^{new}$, $m_{ps}{}^{pri}$ are the iterative model and prior model of PS wave, respectively; $\omega_p$, $\omega_{ps}$, $\mu_1$, and $\mu_2$ are the coefficients.

We calculate the angle gathers by using of Aki-Richards' approximation (Deng, 2011). Prestack joint seismic inversion simultaneously inverts PP and PS wave amplitudes as a function of offset (angle) to estimate P-impedance, S-impedance and density at each CMP (CCP) location. It is usually termed simultaneous because it inverts for several parameters simultaneously using PP and PS wave angle gather traces. The PP and PS wave data processed by the above method are in the same PP timescale domain.

## Examples

We applied our method to 3C/2D field data. Figure 1 and Figure 2 show PP wave and PS angle gathers. Figure 3 is real gas reservoir section. Drastic lateral lithological variations in the fluvial sediments can be clearly seen. In addition, the great variation of gas sand channel exists in the basin. Figure 4 is the rock physics parameter analysis. According to the figure, velocity ratio (Vp/Vs) and Poisson ratio can be used to predict the gas sand.

Since we process the PP and PS wave data in the same PP timescale domain, we can easily use the gather data to invert for impedance and density directly. The subsurface in our study area contains tight sandstone of fluvial deposits. The reservoir is a channel sandstone. P-impedance and S-impedance sections are displayed in Figure 5. The Vp/Vs ratio shows a relatively low value within a time interval corresponding to gas zone. Thus, we are able to map the extent of gas sandstone. The inverted models match the well data very well at the well location.

## Conclusions

We have developed a new method for joint inversion of prestack PP and PS data. We make use of PP and PS processed in the same PP time scale and employ a Bayesian inversion that produces many acceptable models. The proposed method has been applied to synthetic and real data; the inverted results from synthetic data inversion match very well with model data, and inverted results for real data inversion are consistent with seismic data and log data. These also show that the proposed method has high accuracy for estimating rock physics parameters while it circumvents the horizon registration problem in the data interpretation.

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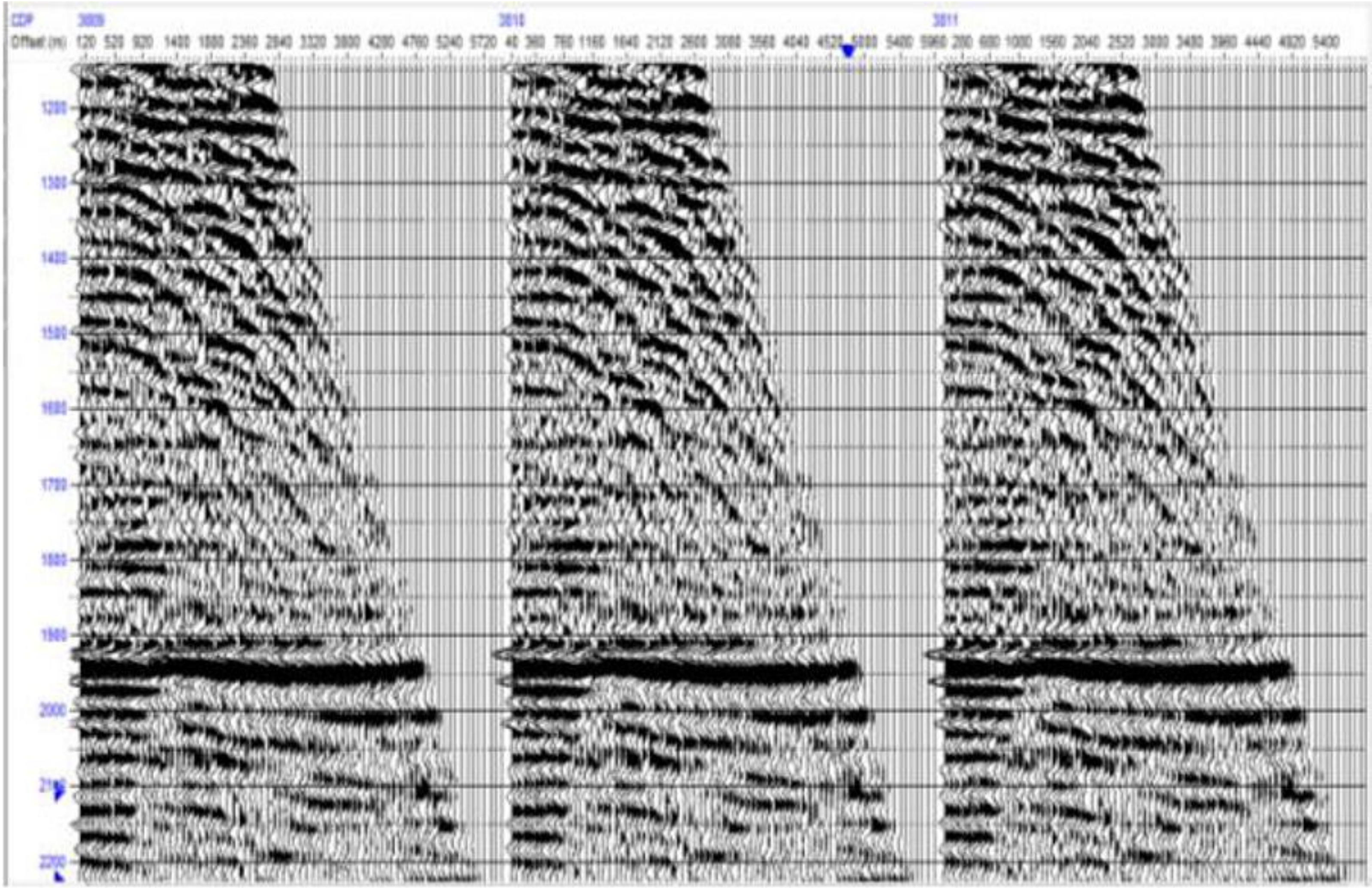

Figure 1. PP wave angle gathers.

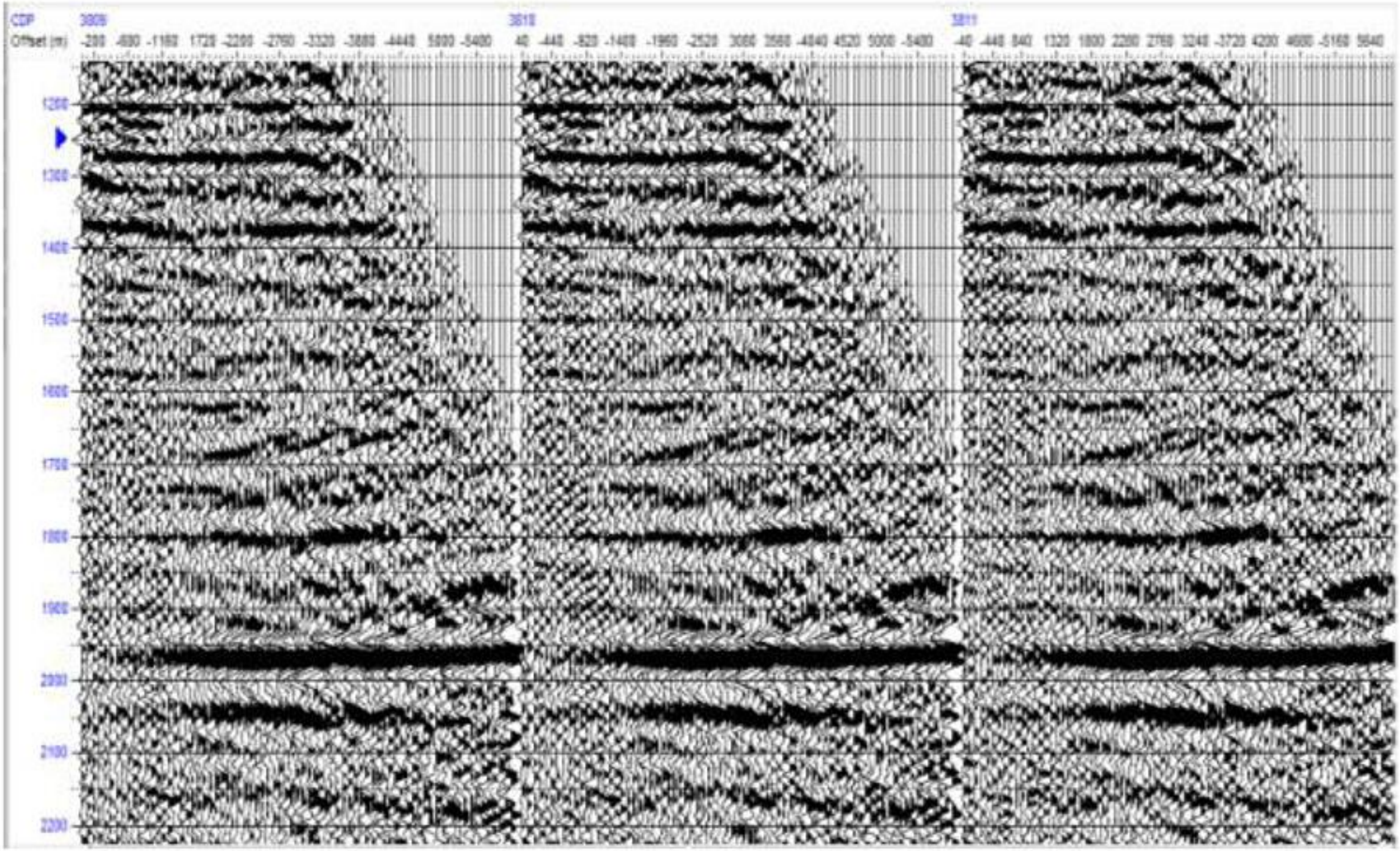

Figure 2. PS wave angle gathers.

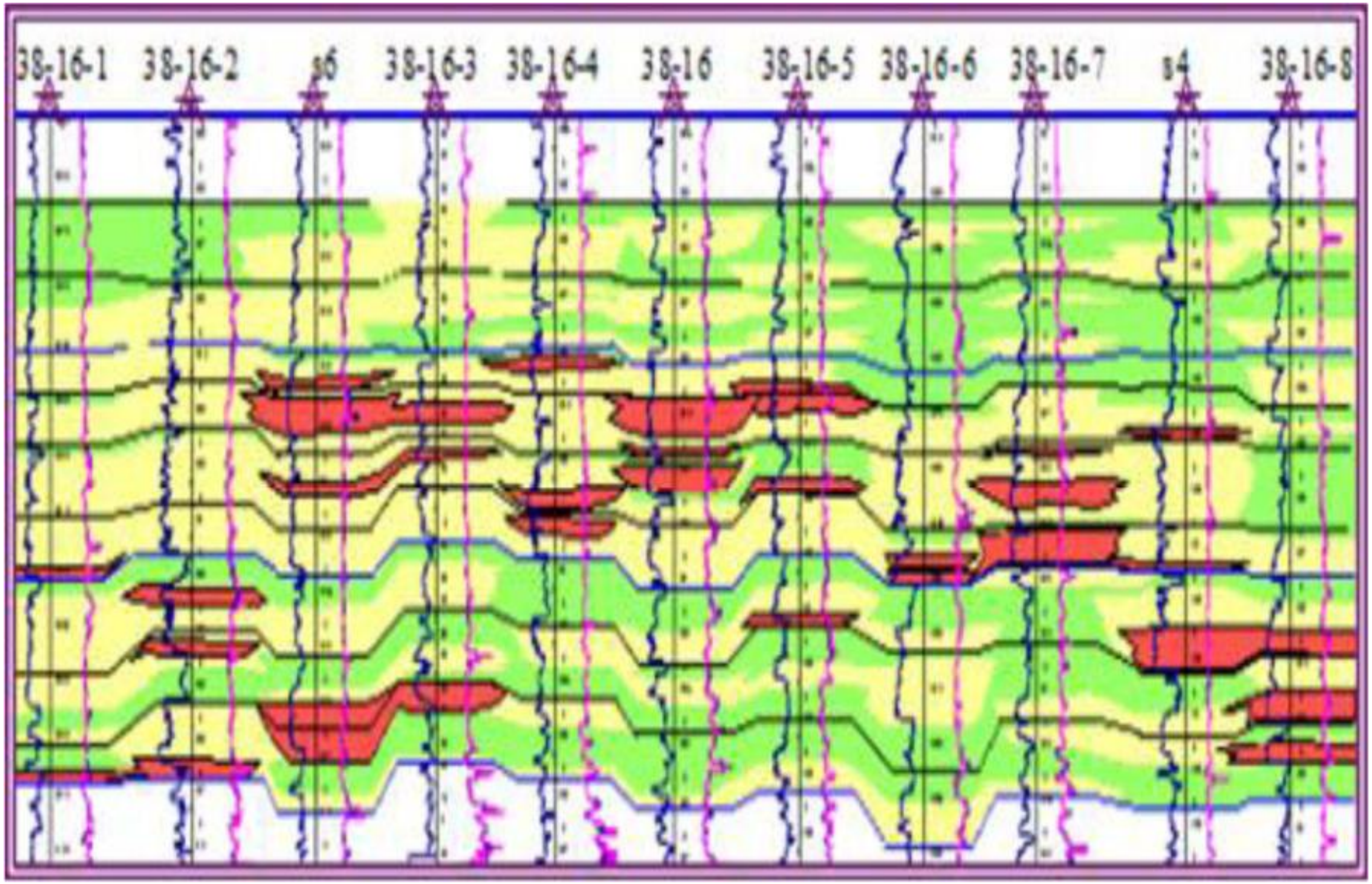

Figure 3. Real gas reservoir section.

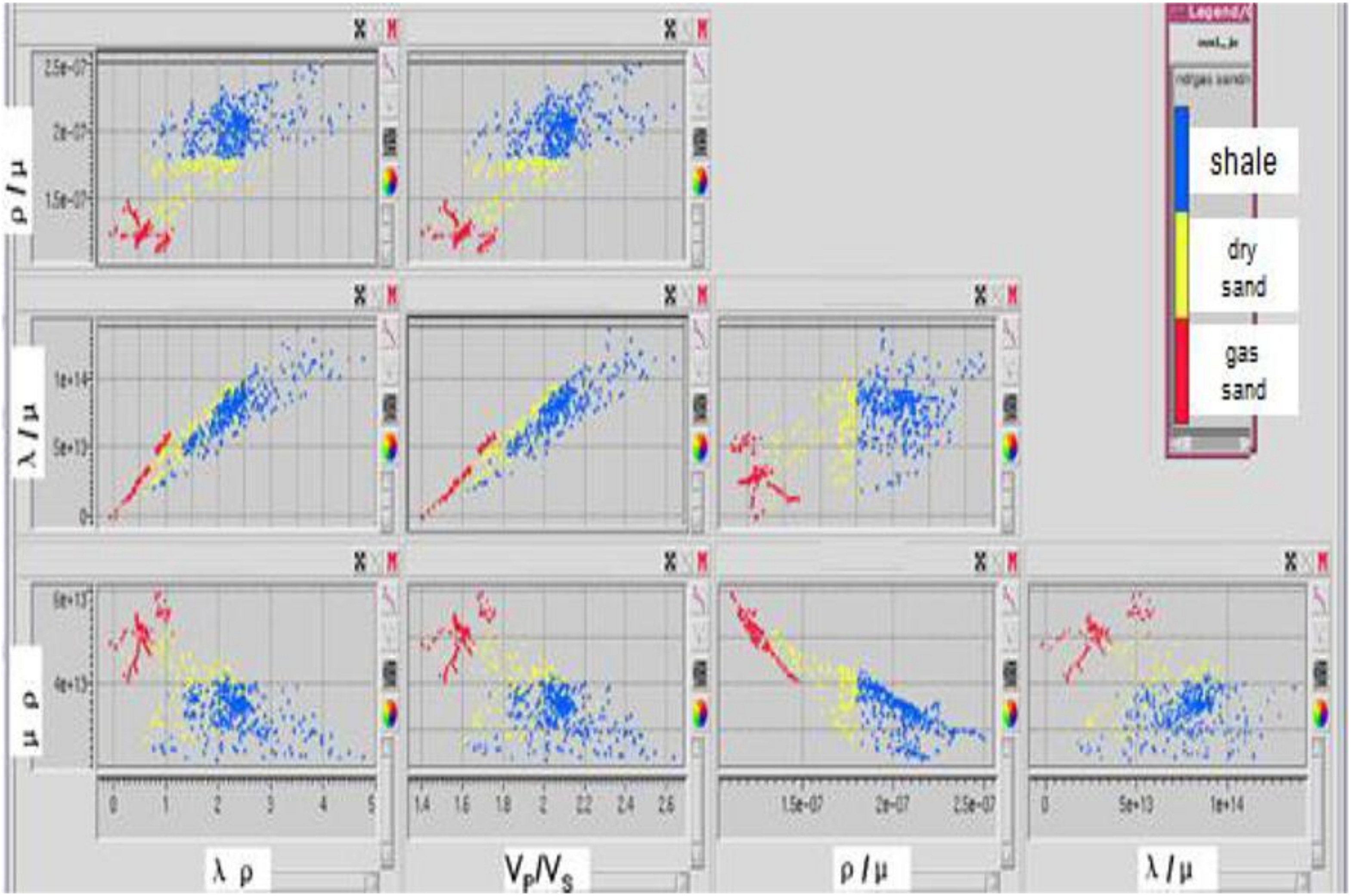

Figure 4. Rock physics parameter analysis.

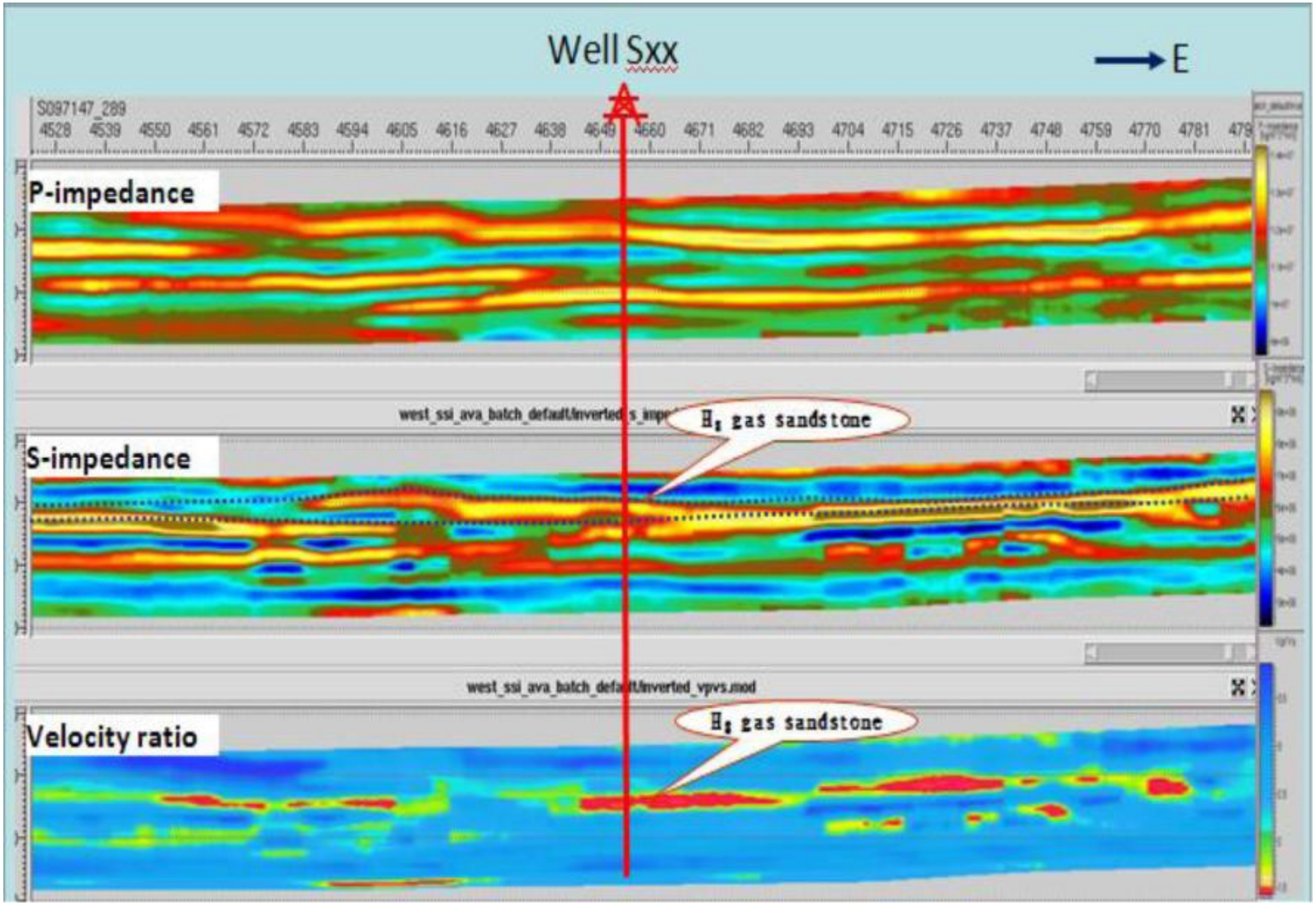

Figure 5. P-impedance, S-impedance and velocity ratio results by joint inversion.