

## Feasibility Study of Three-Dimensional Spectral Element Forward Modeling Method Considering Induced Polarization Effects in Gas Content Detection of Tight Sandstone Reservoirs

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### SUMMARY

Similar to shale gas, tight sandstone gas is also one of the two main exploration areas in current unconventional natural gas, and it is an important future source to replace conventional oil and gas resources. However, accurate prediction of favorable reservoir space is currently the main bottleneck in the exploration and development of tight sandstone oil and gas. In order to analyze and study the distribution patterns and characteristics of underground tight sandstone gas, this paper first calculates three-dimensional forward simulation parameters based on a rock physics model established in the study area. Then, three-dimensional forward modeling of tight sandstone reservoirs with different porosities and gas saturations is conducted using the time-domain spectral element method. Finally, through comparative analysis of the forward modeling results, relatively ideal conclusions are obtained, providing a theoretical basis for subsequent relevant inversions in the area.

**Keywords:** Spectral element method, Induced polarization effects, Tight sandstone reservoir, Three-dimensional forward modeling

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### INTRODUCTION

Tight sandstone gas, as an unconventional gas reservoir, can effectively compensate for the decline in conventional natural gas resources and is one of the important areas for increasing gas reserves and production in China. The reservoir characteristics include tight lithology, low porosity, low permeability, low gas reservoir pressure coefficient, low closure amplitude, and low natural productivity. Therefore, accurately delineating the "sweet spot" areas where tight sandstone gas accumulates and effectively exploring and developing such gas reservoirs are issues of widespread concern for petroleum geologists and reservoir engineers (Tang, 2007). Electromagnetic exploration is a low-cost and low-risk non-invasive exploration method that can acquire information without disturbing underground structures and has the advantage of deep detection depth and relatively high spatial resolution, which helps in identifying small gas accumulations in tight sandstones. Therefore, analyzing electromagnetic data can quantitatively infer gas content in sandstones, providing important references for exploration and development.

The transient electromagnetic method with electrical sources is an important branch of artificial-source electromagnetic exploration, mainly using grounded long conductors as excitation sources to

emit a pulse electric field or step wave underground, and then observing the pure secondary field derived after the interruption of the primary field using receivers to explore the electrical distribution characteristics of different subsurface media. It is currently widely used in field exploration operations. This paper simulates the application effect of the transient electromagnetic method with electrical sources in tight sandstone reservoirs through forward modeling and reveals the distribution patterns of high-quality reservoirs. Traditional forward modeling methods only simulate the temporal changes of the electric field when different resistivities exist underground, which is no longer sufficient for simulating tight sandstone reservoirs with complex physical conditions. Therefore, this paper considers the Induced polarization (IP) effects of reservoirs to better describe the distribution patterns and characteristics of tight sandstone gas.

To integrate forward modeling with actual geological conditions, this paper calculates the corresponding forward modeling parameters based on formulas derived from a conductivity model constructed using rock physics methods and conducts three-dimensional forward modeling work using the time-domain spectral element method. By analyzing the temporal variations and characteristics of the electric field components in reservoirs with different

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porosities and gas saturations, this study demonstrates the feasibility of using this method for gas content detection in tight sandstone reservoirs and provides relevant references for subsequent data processing and inversion interpretation.

## METHODS

Compared to other numerical simulation methods, the spectral element method (SEM) has the flexibility of finite element method in simulating complex terrains, while using Gauss-Lobatto-Legendre high-order orthogonal polynomials as basis functions for spectral integration calculations in each discrete grid, ensuring both accuracy and efficiency in computations. Additionally, the time-domain spectral element forward modeling method used in this study discretely implements the time variable directly through time-domain control equations, avoiding the impact of frequency-time transformation method selection on computational accuracy and the problem of unstable solutions in complex electromagnetic models (Yin, 2013; Cai, 2017). The main approach is to transform the electrokinetic model into the time domain through Ohm's law in differential form, calculate the formula for the time-domain conduction current density, and substitute it into the conventional control equations to obtain the time-domain discretization equation considering the IP effects (Equation 1):

$$\begin{aligned} \nabla \times \nabla \times \mathbf{E}_i + \frac{\mu}{(K+1)\Delta t_i} \left[ \frac{(2K+1)(K+1)\Delta t_i + \tau(2K+1)^2}{(K+1)\Delta t_i + (1-\eta)\tau(2K+1)} \sigma_0 \mathbf{E}_i - \right. \\ \left. \frac{(2K+1)\tau(K+1)^2 \sigma_0}{(K+1)\Delta t_i + (1-\eta)\tau(2K+1)} \mathbf{E}_{t_{i-1}} + \frac{(2K+1)\tau K^2 \sigma_0}{(K+1)\Delta t_i + (1-\eta)\tau(2K+1)} \mathbf{E}_{t_{i-2}} - \right. \\ \left. \frac{(K+1)^3 \Delta t_i}{(K+1)\Delta t_i + (1-\eta)\tau(2K+1)} \mathbf{J}_{t_{i-1}} + \frac{K^2(K+1)\Delta t_i}{(K+1)\Delta t_i + (1-\eta)\tau(2K+1)} \mathbf{J}_{t_{i-2}} \right] \\ = -\mu \frac{\partial \mathbf{J}^s}{\partial t} \end{aligned} \quad (1)$$

During the time discretization process, a variable step size second-order backward Euler format, as shown in Equation (2), is used to ensure both computational efficiency and solution stability in the forward modeling process:

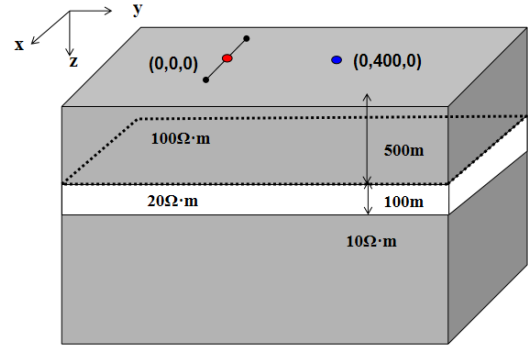
$$\frac{\partial \mathbf{F}_i}{\partial t} = \frac{(2K+1)\mathbf{F}_i - (K+1)^2 \mathbf{F}_{t_{i-1}} + K^2 \mathbf{F}_{t_{i-2}}}{(K_i+1)\Delta t_i} \quad (2)$$

This paper mainly focuses on the Debye model, which is the Cole-Cole model with a frequency-dependent coefficient of 1. It can characterize the frequency dispersion characteristics of polarized medium conductivity and is relatively simple and convenient to implement. The calculation formula is as follows:

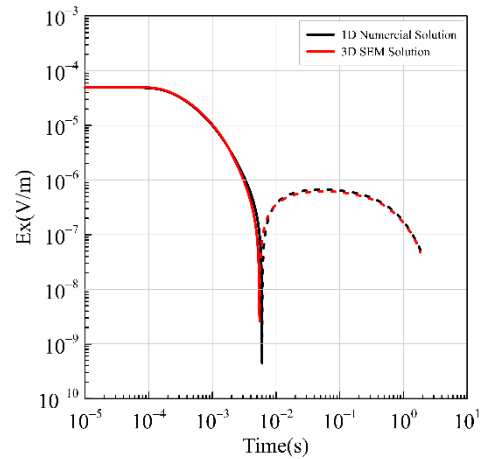
$$\sigma(\omega) = \sigma_0 \left[ (1-m) \left( 1 - \frac{1}{1+i\omega\tau} \right) \right]^{-1} \quad (3)$$

## RESULTS

To validate the correctness and feasibility of the algorithm considering the IP effects, the algorithm proposed in this paper was used to calculate the electric field response of a layered model as shown in Figure 1 and compared with a one-dimensional analytical solution. The geological parameters were set as shown in Table 1. By observing the comparison results of the electric field response curves shown in Figure 2, it can be seen that the two curves fit well, with significant errors only occurring near the negative response due to instability in the solution.



**Figure 1.** Three-Layered Media Model with Low-Resistivity Polarization Layer



**Figure 2.** Validation of SEM Accuracy Considering IP Effects in Layered Media

**Table 1.** Parameters of Three-Layered Media Model with Low-Resistivity Polarization Layer

Resistivity (Ω·m)	Thickness (m)	Polarizability (F/m)	Time constant (s)
100	500	0	0
20	100	0.5	1
100	∞	0	0

### Forward Modeling Parameter Design

To explore the feasibility of using the forward modeling algorithm for gas content detection in tight sandstone reservoirs, this paper conducted forward modeling simulations in the Zhongjiang Gas Field in Sichuan, China, combining rock physics methods. Component analysis was performed on outcrops and well samples in the Zhongjiang area, and scanning electron microscope experiments were conducted on outcrops from different blocks. A formula for calculating the conductivity model was established:

$$\sigma(\omega) = \frac{\sigma_f}{F_f} + \frac{\sigma_H}{F_H} \left[ 1 - \sum_{i=1}^N \left( \frac{g_i}{1 + i\omega\tau_i} \right) \right] \quad (4)$$

Here,  $F_f$  and  $F_H$  correspond to the formation factors of formation fluids and clay minerals, respectively.  $\sigma_H$  represents the conductivity of clay minerals, while  $\tau_i$  and  $g_i$  correspond to the polarization time constant and relative polarization intensity caused by local capacitance, respectively. This model is the discrete form of the spectral Debye model, where the high-frequency limit includes the conductivity of pore fluids and clay, while the low-frequency limit only includes the conductivity of pore fluids. By combining complex resistivity experiments, one can effectively analyze the impact of different factors such as temperature, pressure, and saturation on the dielectric properties of rocks. By using the Archie relationship to characterize the bulk conductivity corresponding to pore fluids and the clay-to-surface conductivity relationship to characterize the surface conductivity under the action of clay fluids, the model parameters for Equation 4 can be obtained:

$$\begin{cases} \sigma_f = 8 \\ F_f = \phi_f^{-1.6172} S_f^{-1.6492} \\ \sigma_H = 0.01862 \\ F_H = F_c = \phi_c^{-0.9126} \end{cases} \quad (5)$$

In the Zhongjiang Gas Field area, reservoir resistivity and polarization vary significantly with different rock properties and gas saturations. When there is no natural gas in the reservoir during water injection, it acts as a water layer. As natural gas is injected, it displaces free water in the pores, causing the reservoir to transition from a water layer to a gas-water alternating layer and a gas layer. Due to the presence of capillary water and bound water, a small amount of water can also be present in the gas layer. Based on the reservoir classification criteria of the Zhongjiang Gas Field shown in Table 2, various parameters were designed for the

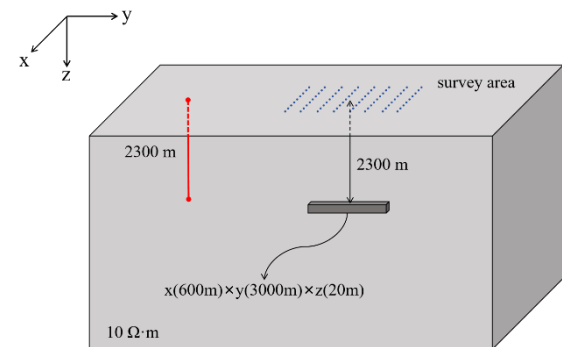
forward modeling simulation, as presented in Table 3.

**Table 2.** Reservoir Division Criteria of Zhongjiang Gas Field

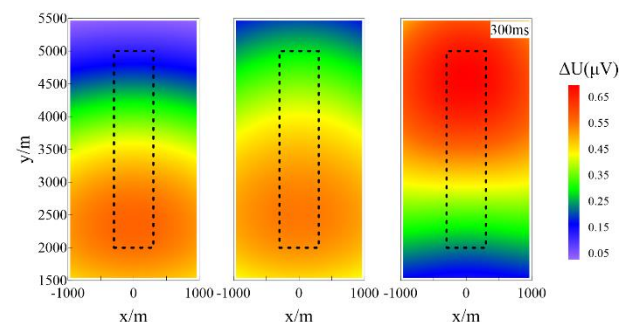
Reservoir	Rho ( $\Omega \cdot m$ )	Porosity	Gas content
Gas	>30	$\geq 0.09$	$\geq 60\%$
Gas-water	20-40	$\geq 0.07$	<60%
Water	<20	$\geq 0.07$	<65%

### Forward Modeling

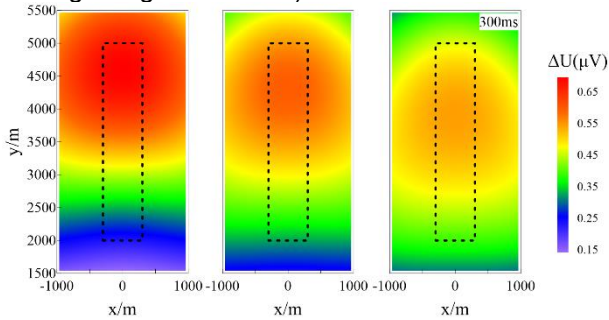
According to actual geological data in the Zhongjiang area, the high gas-enriched zones in the Zhongjiang Gas Field have narrow channels, with channel abrupt changes ranging from 400-600m. The thickness of channel sand bodies is relatively small, with a maximum thickness of 60m. The measured resistivity of the surrounding rocks is 10  $\Omega \cdot m$ . Based on these conditions and field data collection equipment, a forward model as shown in Figure 3 was set up. The resistivity and corresponding polarization were set around Table 2, with all time constants set to 1. Two sets of comparative experiments were conducted based on this model: (1) analyzing the impact of different reservoirs on the response of potential difference with the same porosity (Figure 4). (2) analyzing the impact of different porosities in gas layers on the response of potential difference (Figure 5). The following parameters have been used for page setup in this document.



**Figure 3.** Gas Content Detection Model of Tight Sandstone Reservoir



**Figure 4.** Response Characteristics of Potential Difference for Different Reservoirs with a Porosity of 0.1. (Left is water layer, middle is gas-water zone, and right is gas reservoir)



**Figure 5.** Response Characteristics of Potential Difference for Different Porosities in Gas Reservoirs. (Left is 0.1, middle is 0.12, and right is 0.14)

### CONCLUSIONS

The following conclusions can be drawn from Figures 4 and 5 (black dashed boxes indicate anomaly locations):

1. During field detection, the smallest observable response by the instrument is 0.06  $\mu\text{V}$ . As shown in the figures, towards the later stages, the signal may attenuate to a level that no longer meets the instrument's observation requirements.
2. With the same porosity, as gas content increases in the reservoir, the potential difference response away from the source side gradually increases, while the potential difference response near the source side decreases.
3. Within gas layers, as porosity increases, the potential difference response of the reservoir away from the source side gradually increases, while the potential difference response near the source side decreases.

In electromagnetic exploration, the forward modeling method is a crucial factor that determines whether accurate inversion can be achieved subsequently. With the rapid development of

transient electromagnetic methods in recent years, studying the temporal variations of electromagnetic responses has become an important research focus. This study investigates the feasibility of the time-domain spectral element method considering dielectric effects in practical applications. Initially, different sets of forward modeling parameters for resistivity and polarization were obtained by combining rock physics methods for varying porosities and gas contents. Subsequently, using a controlled variable approach, the characteristics of potential difference responses of anomalous bodies under different scenarios were briefly analyzed. The variations in potential differences near and away from the source side of anomalous bodies can be utilized to infer the approximate physical properties of these anomalies. The results demonstrate the effectiveness and feasibility of the 3D transient electromagnetic SEM considering IP effects in detecting gas-bearing tight sandstones.

### ACKNOWLEDGEMENTS

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**Table 3.** Design of Forward Modeling Model Parameters Table

Porosity	Gas Saturation	Water Saturation	Modeled Resistivity ( $\Omega \cdot \text{m}$ )	Modeled Polarizability (F/m)	Reservoir
0.1	0.2	0.8	7.48	0.05	Water
0.1	0.6	0.4	23.46	0.1417	Gas-water
0.1	0.8	0.2	73.60	0.3412	Gas
0.12	0.8	0.2	54.80	0.3129	Gas
0.14	0.8	0.2	42.71	0.2900	Gas