

# Logging Evaluation Methods for Irreducible Water Saturation in Tight High-Water-Cut Gas Reservoirs: A Case Study of the Dongsheng Gas Field in the Ordos Basin

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## Abstract

As a crucial parameter for the evaluation and development decision-making of high-water-cut tight sandstone gas reservoirs, irreducible water saturation ( $S_{wi}$ ) plays a decisive role in reservoir productivity assessment and development plan design. However, traditional determination methods such as the existing core mercury injection experiment and nuclear magnetic resonance (NMR) logging inversion suffer from high costs, long cycles, and low coverage, which severely restrict gas reservoir development decisions. Taking the high-water-cut tight sandstone gas reservoir in the Dongsheng Gas Field of the Ordos Basin as an example, this paper proposes a new low-cost and continuous prediction method based on conventional logging data and the Random Forest (RF) machine learning algorithm. Through logging sensitivity analysis, the pore structure index (PSI) and density-neutron difference were introduced, and combined with the Random Forest algorithm, 5 sensitive parameters (GR, PERM, PSI, AC, DEN) were selected. Using the  $S_{wi}$  calculated from the NMR logging  $T_2$  spectrum of 1,135 sets in 18 wells as the true value, a prediction model was constructed. For the test set of the model, the coefficient of determination ( $R^2$ ) is greater than 0.9, and the mean absolute error (MAE) is less than 0.05, indicating reliable generalization ability. The prediction results of this method in Well A of the Dongsheng Gas Field are highly consistent with the NMR results. This method can realize continuous evaluation of the entire well section, significantly reduce the reliance on special logging and associated costs, and provide technical support for low-cost and high-precision reservoir evaluation of tight gas reservoirs in the gas field.

## Keywords

Irreducible Water Saturation; Conventional Logging; Machine Learning Model.

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## 1. Introduction

Irreducible water saturation ( $S_{wi}$ ) is a key parameter for evaluating the microscopic pore structure and fluid distribution of low-porosity, low-permeability, and high-water-cut gas reservoir formations. It refers to the percentage of water trapped in the pores of rocks by capillary forces and other effects under natural conditions that cannot flow, relative to the pore volume<sup>[1]</sup>. The irreducible water saturation of tight sandstone reservoirs can directly reflect the fluid occurrence state of the reservoir and serves as a critical basis for avoiding misjudging effective gas zones as water zones or vice versa<sup>[2]</sup>. Meanwhile, an increase in irreducible water saturation leads to a significant decrease in gas phase permeability<sup>[3]</sup>. By accurately calculating the irreducible water saturation, a quantitative relationship between it and gas phase permeability as well as gas production capacity can be established, enabling accurate prediction of single-well productivity and gas reservoir recovery.

Currently, the evaluation methods for irreducible water saturation mainly fall into two categories: experimental determination and logging interpretation. Experimental methods include the centrifugal capillary pressure method, gas-displaced water dynamic method, and nuclear magnetic resonance method, which achieve direct determination of irreducible water saturation through core experimental analysis. Logging interpretation methods involve constructing irreducible water interpretation models based on logging data and experimental results. For instance, Gao Chuqiao et al. established an empirical formula based on the statistical relationship between porosity and irreducible water saturation, emphasizing the controlling effect of pore structure on irreducible water<sup>[4]</sup>. Yang Kebing et al. used petrophysical experimental data to determine the irreducible water saturation through the slope characteristic (-1.55) of the resistivity-water saturation relationship curve<sup>[5]</sup>. Li Gang integrated high-pressure mercury injection, relative permeability, and nuclear magnetic resonance experiments to establish an NMR logging irreducible water saturation calculation model classified by porosity<sup>[6]</sup>.

## 2. Regional Geological Overview

The Dongsheng Gas Field is located in the northern margin of the Ordos Basin, spanning three major tectonic units: the Yimeng Uplift, the Yishan Slope, and the Tianhuan Depression<sup>[7,8]</sup>. The gas field has been controlled by the paleotectonic framework since the Caledonian movement. The provenance is derived from the weathered rock formations in the northern denudation area, which were deposited after weathering, denudation, and transportation<sup>[8,9]</sup>. The sedimentary facies transition from neritic shelf facies to marine-continental transitional facies. The study area is located in the western part of the gas field (Fig. 1), tectonically situated south of the Sanyanjing Fault. A braided river sedimentary system is developed here, with river channels distributed in a sheet-like pattern horizontally and stacked vertically, forming a reservoir space with strong heterogeneity and a low net-to-gross ratio<sup>[10,11]</sup>.

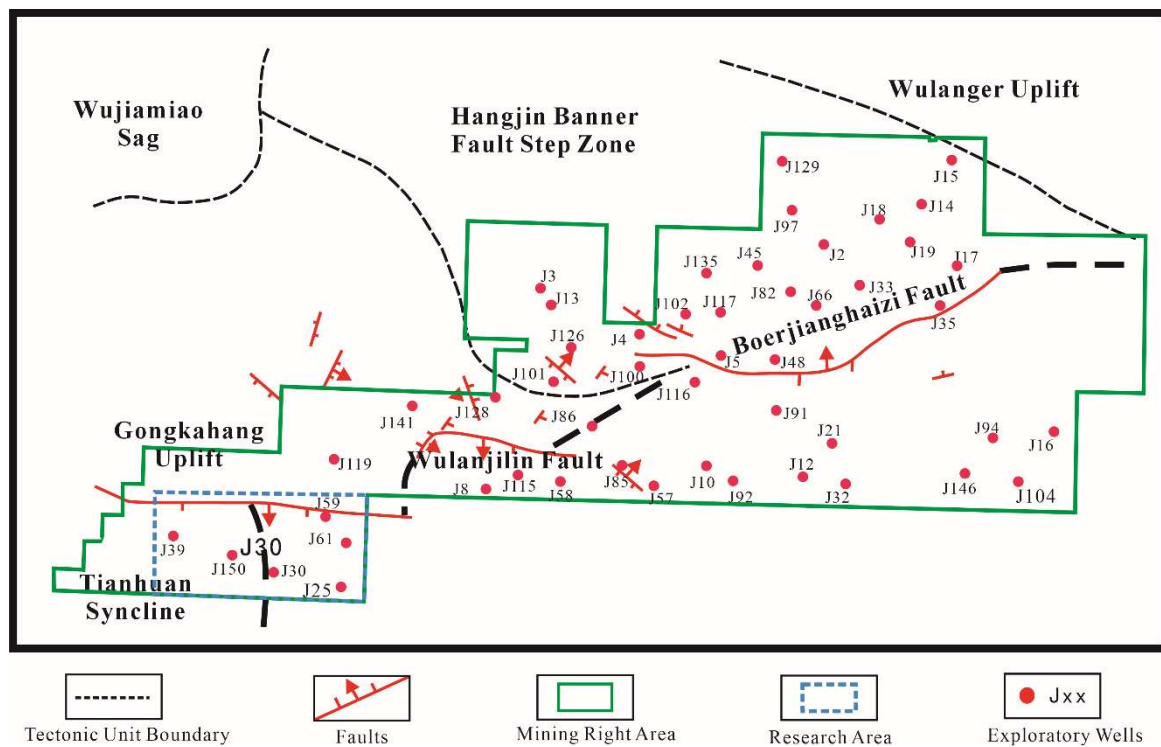


Fig. 1 Tectonic Map of the Study Area in the Dongsheng Gas Field

The main producing layer in the study area is the He 1 Member of the Lower Shihezi Formation, with a burial depth of 3,500–3,800 meters. The lithology is dominated by lithic quartz sandstone and quartz sandstone, with a porosity of 7.5%–9.0% and a permeability of 0.5–0.8 mD, belonging to an ultra-

low porosity and low-permeability tight reservoir. Affected by the thinning of source rocks at the basin margin and the absence of coal-bearing strata, the hydrocarbon generation intensity is low, with a gas saturation of only 40%–50% and a reserve abundance of  $(0.5\text{--}0.7)\times 10^8 \text{ m}^3/\text{km}^2$ . It is one of the tight gas reservoirs with the lowest gas saturation in the Ordos Basin. The gas reservoir has an average casing pressure of 4.6 MPa, an average daily gas production per well of approximately  $0.8\times 10^4 \text{ m}^3$ , an average water-gas ratio of  $9.4 \text{ m}^3/10^4 \text{ m}^3$ , and a natural decline rate of 29.1%. It exhibits the "three highs and two lows" characteristics of low pressure, low production, high decline rate, high water cut, and high water-gas ratio, with a low recovery degree and high development difficulty, making it a typical difficult area for the efficient development of tight gas reservoirs.

### 3. Analysis of Influencing Factors on Irreducible Water Saturation

#### 3.1 Clay Minerals

The average content of clay minerals in the tight sandstone reservoirs of the study area is 18.36%, mainly consisting of kaolinite, illite, and chlorite. The irreducible water saturation of this reservoir is jointly controlled by the total content and type of clay minerals, showing a positive correlation with the total clay content. The blocking effect of filamentous illite on pore throats is the dominant factor leading to the increase in irreducible water. Secondly, the aggregates formed by authigenic kaolinite generate a large number of micropores, thereby intensifying the accumulation of irreducible water<sup>[8]</sup>.

#### 3.2 Pore Structure

Pore structure affects the distribution of irreducible water through the capillary force effect. Pore type, throat radius distribution, and pore-throat connectivity are important factors influencing irreducible water saturation<sup>[12]</sup>. The complex pore structure of tight sandstone reservoirs significantly enhances the sensitivity of irreducible water saturation to the pore structure, which in turn affects the irreducible water saturation by changing the morphology of fluid occurrence spaces and the characteristics of seepage channels. There is a good correlation between the pore structure index and irreducible water saturation.

### 4. Analysis of Influencing Factors on Irreducible Water Saturation

#### 4.1 Principle of the Random Forest Algorithm

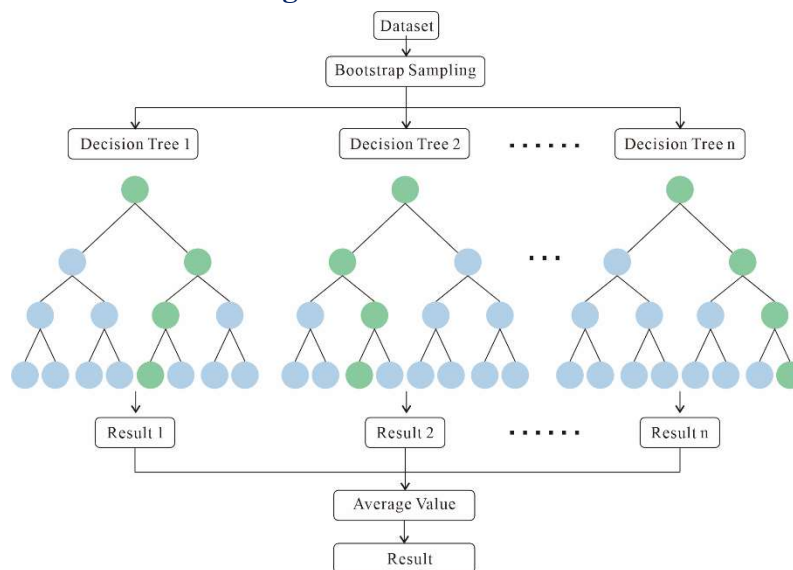


Fig. 2 Schematic Diagram of the Random Forest Algorithm

Proposed by Breiman in 2001, the Random Forest (RF) is an ensemble learning algorithm based on decision trees, suitable for modeling and analyzing high-dimensional and non-linear data<sup>[13]</sup>. Its core idea is to construct multiple independent decision trees and integrate the prediction results of each

tree using the "voting method" or "averaging method". This effectively reduces the overfitting that may occur in a single decision tree and improves the generalization ability and prediction accuracy of the model (Fig. 2). This algorithm has strong applicability for integrating multiple logging variables and revealing the complex logging response mechanisms in tight reservoirs.

## 4.2 Model Establishment and Evaluation

### 4.2.1 Data Preprocessing

There are differences in dimensions among the original logging curve data. To eliminate the impact of different dimensions of logging curves and improve the stability of model training, the min-max normalization method was first used to standardize all input feature data, with the calculation formula shown in Equation 2:

$$x_{nor} = \frac{x - x_{min}}{x_{max} - x_{min}} \quad (1)$$

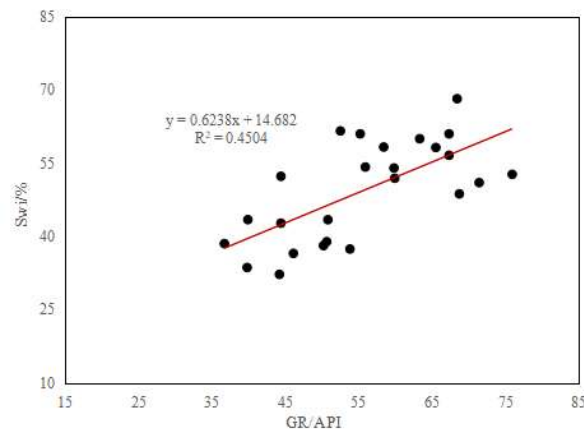
In the equation,  $x$  is the original logging data;  $x_{min}$  and  $x_{max}$  are the minimum and maximum values of the corresponding logging curve, respectively; and  $x_{nor}$  is the normalized value.

In addition, the mean value  $\pm 3$  times the standard deviation was used as the discrimination criterion to identify and eliminate outliers beyond this range, reducing the interference of abnormal samples on model training.

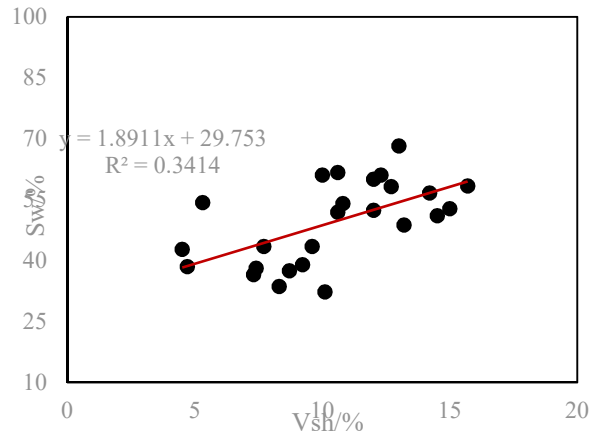
### 4.2.2 Determination of Input Features

Clay minerals and pore structure are important factors affecting irreducible water saturation. Conventional logging data can only be used as sensitive parameters for irreducible water saturation if they have a strong response to the reservoir's microscopic physical properties (pore structure) and clay content.

The natural gamma (GR) value increases in intervals with enriched clay minerals (Fig. 3), and the shale content (Vsh) shows a positive correlation with irreducible water saturation (Fig. 4). The acoustic travel time logging reflects the total porosity ( $\phi$ ) of the formation but has relatively weak ability to distinguish the micropores where irreducible water is mainly stored. Micropores are well-developed in argillaceous sandstones, often resulting in an abnormally high AC value. The resistivity (RT) decreases abnormally in intervals with enriched micropores due to the enhanced conductivity of irreducible water, which is likely to cause misjudgment of water-bearing layers.



**Fig. 3** Correlation between Natural Gamma and Irreducible Water Saturation



**Fig. 4** Correlation between Shale Content and Irreducible Water Saturation

Based on the response of conventional logging curves, the pore structure index (PSI) and density-neutron difference ( $D_{dc}$ ) were additionally introduced in this paper to amplify the response characteristics of logging curves to irreducible water saturation (Equation 2,3):

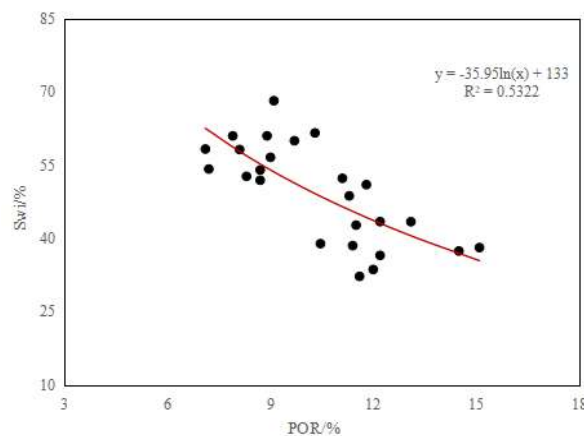
$$PSI = \sqrt{\frac{K}{\phi}} \quad (2)$$

In the equation, K is the permeability (unit: mD), and  $\phi$  is the porosity (unit: %).

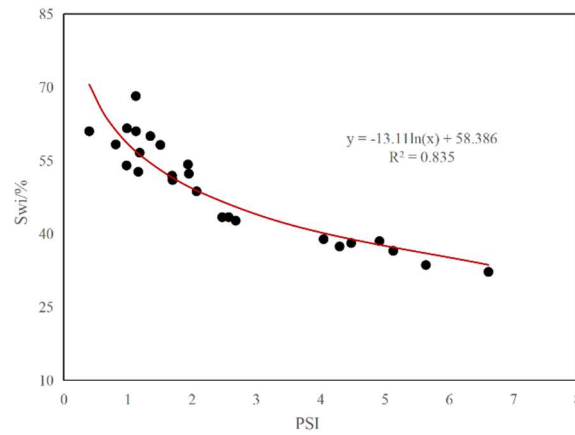
$$D_{dc} = \Delta|CNL - DEN| \quad (3)$$

In the equation, DEN is the density logging value and CNL is the neutron logging value.

In the same reservoir, the porosity may sometimes be the same while the permeability varies significantly, which is caused by differences in pore structure and thus affects the irreducible water saturation of the rock, Irreducible water saturation shows a good correlation with porosity and pore structure index (Fig. 5, Fig. 6). A decrease in the compensated density (DEN) value indicates an increase in porosity but cannot distinguish differences in pore-throat size. The compensated neutron log (CNL) is sensitive to hydrogen nuclei, and both clay-bound water and micropore water lead to an increase in the CNL value.  $D_{dc}$  was used to quantify the development intensity of micropores.



**Fig. 5** Correlation between Porosity and Irreducible Water Saturation



**Fig. 6** Correlation between Pore Structure Index and Irreducible Water Saturation

#### 4.2.3 Model Establishment

Taking the Jin 30 Well Block of the Dongsheng Gas Field as the research object, irreducible water saturation data calculated from the NMR logging  $T_2$  spectrum of 18 wells were selected as the sample source, and a total of 1,135 depth-point data sets were collected. These data cover major reservoir types such as sandstone, argillaceous sandstone, and low-permeability reservoirs, ensuring the representativeness of the data. The input features  $X$  include 10 logging parameters and sensitive indicators such as GR, Vsh, RD, AC, DEN, CNL, POR, PERM, PSI, and  $D_{dc}$ ;  $S_{wi}$  serves as the target label  $Y$  for model prediction; the dataset was randomly divided into a training set and a test set at a ratio of 8:2.

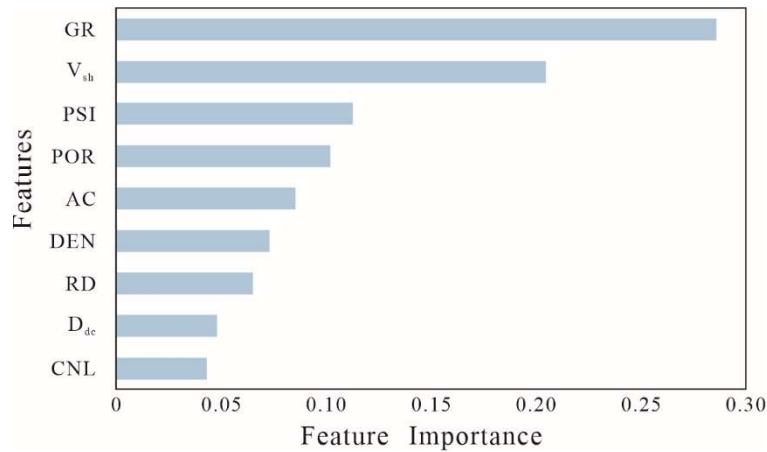
#### 4.2.4 Hyperparameter Optimization and Performance Evaluation

Core optimization parameters such as the number of trees ( $n_{estimators}$ ), maximum depth, and minimum number of samples required for splitting were targeted. The grid search method was used to exhaustively traverse the parameter combination space, and five-fold cross-validation was employed to optimize the model hyperparameters. The optimal parameters of the model were determined as follows: the number of trees is 340, the maximum depth is 9 layers, and the minimum number of samples for splitting is 2. When the number of input features reaches this configuration, the algorithm accuracy peaks at 0.92, and the accuracy decreases after exceeding this peak (Table 1).

**Table 1.** Hyperparameter Optimization Results of the Random Forest Model

Hyperparameter	Optimization Range	Best Value
max_depth	[5-30]	9
n_estimators	[1-500]	340
min_samples_split	[2-4]	2

The importance of input parameters was ranked using the feature importance of the Random Forest, and the importance scores of each logging curve and sensitive parameter to the irreducible water saturation label  $S_{wi}$  were calculated. After ranking, the feature priority was determined. The feature importance output by the Random Forest reveals the parameter sensitivity ranking (Fig. 7). By traversing the number of features, it was determined that the optimal input parameters are the top 5 features in terms of Random Forest importance (GR\_nor, PERM\_nor, PSI\_nor, AC\_nor, DEN\_nor). At this point, the model performance is optimal, with the correlation coefficient ( $R$ ) of the Random Forest reaching 0.92 and the cross-validation (CV) standard deviation being only 0.05. The remaining 4 parameters contribute minimally to the model and are potentially redundant.

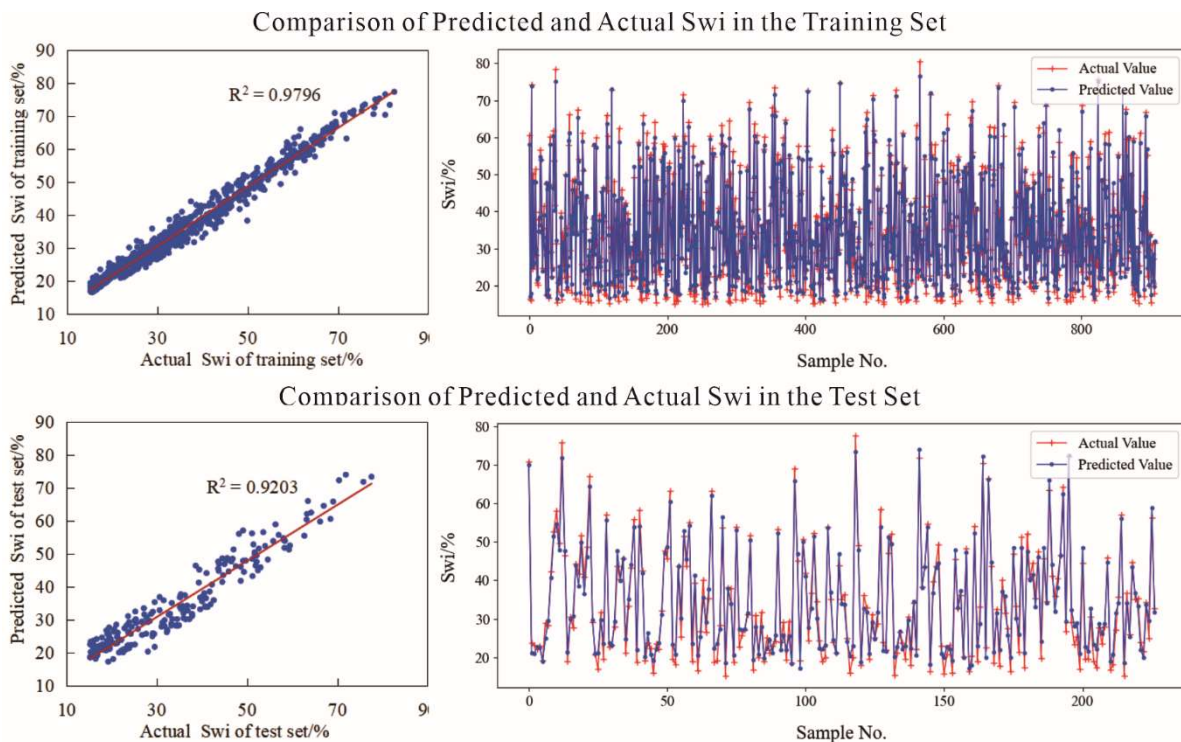


**Fig. 7** Feature importance analysis of the irreducible water saturation prediction model

Since  $S_{wi}$  is continuous data, parameters such as the coefficient of determination ( $R^2$ ), mean absolute error (MAE), mean absolute percentage error (MAPE), mean squared error (MSE), and root mean squared error (RMSE) were selected to evaluate the model performance. The results show that the Random Forest model has good performance, small errors, and high accuracy (Table 2). The  $R^2$  values of the training set and test set are 0.98 and 0.92, respectively; the MAE values are 0.021 and 0.031, respectively; and the MAPE values are 5.31% and 8.14%, respectively (Fig. 8).

**Table 2.** Three Scheme comparing

Model	Dataset	$R^2$	MAE	MAPE	MSE	RMSE
Random Forest	Training Set	0.98	0.02	5.31%	0.0007	0.026
	Test Set	0.92	0.03	8.14%	0.0013	0.037



**Fig. 8** Prediction Effect of the Random Forest Model for the H<sub>1</sub> Member in the J30 Well Block

### 4.3 Model Establishment and Evaluation

To verify the accuracy and generalization ability of the constructed random forest model for the practical calculation of irreducible water saturation in tight high-water-cut gas reservoirs, Well J1 in the study area, which was not involved in model training, was selected for validation in this study. The model was applied to predict the irreducible water saturation of the He 1 Member in this well, and the prediction results are presented in Fig. 9. The correlation coefficient between the model-predicted values and the NMR logging interpreted results reaches 0.94, which indicates that the established model not only has high prediction accuracy but also exhibits good generalization ability, and can be reliably applied to the evaluation of irreducible water saturation in tight high-water-cut gas reservoirs.

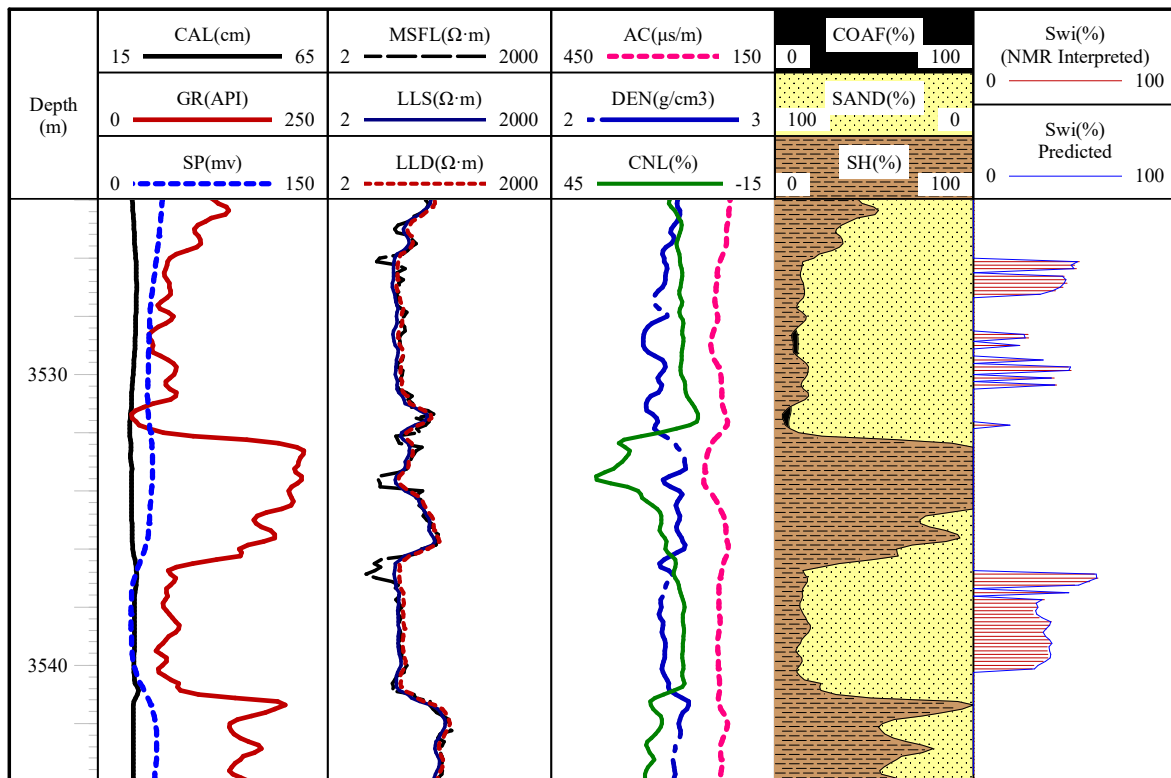


Fig. 9 Prediction of  $S_{wi}$  in Wells J1

## 5. Conclusion

This study establishes a Random Forest prediction model based on conventional logging data, realizing the continuous calculation of irreducible water saturation both vertically and horizontally in the study area, and addressing the problems of high reliance on special logging and high costs. The key conclusions are as follows:

- (1) In tight high-water-cut gas reservoirs, pore structure and clay minerals are the main factors affecting irreducible water saturation;
- (2) The model reveals the contribution characteristics of key parameters, with the feature importance ranking being  $GR > V_{sh} > PSI > POR > AC$ , which confirms the synergistic control mechanism of clay minerals and pore structure;
- (3) By integrating the non-linear relationships of multiple parameters, the Random Forest model significantly improves the calculation accuracy of irreducible water saturation ( $MAE < 0.05$ ). In Well A of the Dongsheng Gas Field, the  $S_{wi}$  predicted by the model is highly consistent with the NMR results (correlation coefficient = 0.92).

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