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Posted Date: September 21st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10869431/v1>

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Additional Declarations: No competing interests reported.

Pre-drilling Lost Circulation Prediction in Special Lithology-developed Intervals of the Southern Dagang Exploration Area

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Abstract

Lost circulation is one of the most pervasive downhole complications in drilling operations, often causing prolonged drilling cycles, elevated costs, and in severe cases well abandonment. In the southern Dagang exploration area, formations with special lithologies—including volcanic rocks and bioclastic limestones—are prone to frequent, severe lost circulation events. Conventional prediction methods fail to deliver accurate pre-drilling assessment in this geologically complex setting, due to strong heterogeneity and coupled controlling factors. Here, we analyze lost circulation patterns and geological characteristics from 204 drilled wells to identify the dominant mechanism of catastrophic lost circulation: the coupled development of special lithologies and tectonic fractures. We then present an integrated prediction framework that combines well log reconstruction, multi-parameter seismic inversion, and ant-tracking fracture characterization to delineate the spatial distribution of lost circulation-prone intervals. A decision tree-based risk classification system is established, incorporating lithology type, formation thickness, and fracture intensity as core predictors, to quantify pre-drilling lost circulation risk. Validation across 16 newly drilled wells confirms that the method accurately stratifies risk levels by interval prior to drilling. This approach provides a robust technical basis for optimizing drilling design, mitigating operational hazards, and controlling costs in complex fault-block regions with special lithology development, with transferable insights for analogous petroleum provinces globally.

Keywords: Lost circulation prediction, Multi-parameter seismic inversion, Ant tracking, Decision tree, Special lithologies, Dagang Oilfield

1 Introduction

Lost circulation is a pervasive, costly downhole complication in global hydrocarbon drilling, ranging from minor seepage to total loss of returns that extends drilling cycles, inflates costs, and can cause well abandonment. Bruton et al. (2018) quantified its significant economic impact on deepwater operations, driving extensive research into lost circulation mechanisms and predictive methods.

Wang et al. (2019) characterized fracture-dominated lost circulation mechanisms in carbonate reservoirs, and Lavrov (2016) provided a comprehensive review of mechanisms and mitigation strategies across diverse geological settings. From a causal perspective, Salehi and Nygaard (2012) identified well-connected pore-vug-fracture systems as the primary geological control on fluid loss. Zhao et al. (2021) noted additional complexities from high formation pressures in deep drilling, and Chen et al. (2023) emphasized that the coupling of geological heterogeneity and engineering parameters ultimately governs lost circulation severity.

Seismic-based prediction is the mainstream pre-drilling approach, leveraging seismic lateral continuity to map subsurface heterogeneity. Chopra and Marfurt (2005) established foundational seismic attribute frameworks for reservoir characterization. Building on this, Lu et al. (2024) developed multi-attribute fusion methods for lost circulation risk interval identification, and Chen et al. (2025) proposed a “four-element risk” model for seismic-guided drilling. The ant tracking algorithm, first introduced for fault detection by Pedersen et al. (2006), has been adapted for fracture characterization in volcanic reservoirs (Zhang et al., 2018) and fractured-vuggy carbonate systems (Liu et al., 2020).

Despite these advances, seismic approaches have inherent limitations in geologically complex areas. Barnes (2017) noted that single or limited attribute sets often fail to capture subsurface complexity, and Li et al. (2019) proposed multi-attribute fusion to address this gap. Wang et al. (2020) reviewed multi-source data fusion as a promising direction for enhanced robustness, but Chen et al. (2022) pointed out that the coupling between seismic responses and actual lost circulation mechanisms remains poorly constrained in heterogeneous, multi-lithology settings. Wang et al. (2022) further noted that many data-driven machine learning models lack explicit geological mechanistic underpinnings, limiting their transferability across petroleum basins.

Volcanic rocks and bioclastic limestones represent particularly challenging special

lithologies. Sruoga and Rubinstein (2007) reviewed their unique pore systems and strong heterogeneity distinct from clastic formations. Wang et al. (2015) identified distinct lost circulation patterns in volcanic formations of the Bohai Bay Basin, and Li et al. (2017) documented unique petrophysical properties of bioclastic limestones and their drilling risk implications. Zhang et al. (2023) showed how multi-stage tectonic modification complicates special lithology distribution in fault blocks, and Wu et al. (2024) reported highly variable lost circulation patterns in the southern Dagang area that conventional methods cannot reliably predict.

Seismic inversion techniques have advanced special lithology identification. Russell and Hampson (1991) systematically compared inversion methods for reservoir characterization, and Pendrel (2001) demonstrated geostatistical inversion for integrating well log resolution with seismic lateral continuity. Ma et al. (2014) showed well log reconstruction enhances lithological boundary resolution, and Zhu et al. (2021) developed multi-parameter inversion for improved special lithology discrimination in complex fault blocks.

For risk modeling, Zhang et al. (2020) first proposed a decision tree algorithm for lost circulation assessment using multi-source data, and Zhao et al. (2023) tailored the approach to fractured volcanic reservoirs. Li et al. (2024) explored ensemble learning for improved prediction performance, and Liu et al. (2023) provided a systematic comparison of machine learning methods for lost circulation risk prediction.

Integrating fracture prediction with lithology mapping is critical for mechanism-driven prediction. Zhang et al. (2019) applied seismic fracture prediction in complex fault blocks, and Li et al. (2024) proposed an integrated framework combining lithology mapping and fracture characterization for special lithology settings. Chen et al. (2024) documented the engineering benefits of such pre-drilling prediction technologies in faulted blocks. However, a complete, mechanism-constrained workflow integrating log reconstruction, multi-parameter inversion, fracture detection, and risk modeling—tailored specifically to special lithology-bearing fault blocks—remains lacking.

This study addresses this gap through an integrated, mechanism-driven approach fusing geological, well log, and seismic data. Based on analysis of 204 drilled wells in the southern Dagang area, we first characterize lost circulation patterns and identify the dominant coupled lithology-fracture controlling mechanism. We then develop a special lithology identification workflow combining pseudo-acoustic impedance log reconstruction and multi-parameter geostatistical inversion, integrate ant-tracking

fracture prediction to define three distinct lost circulation seismic response models, and construct a decision tree-based risk model incorporating lithology type, special lithology thickness, and fracture intensity for quantitative pre-drilling risk stratification. Validation against historical and newly drilled wells demonstrates strong predictive performance and practical value for drilling optimization in complex fault-block regions.

2 Characteristics and Controlling Mechanisms of Lost Circulation

2.1 Overview of Lost Circulation Development

The study area is situated in the northern Huanghua Depression, Bohai Bay Basin, and is structurally controlled by the central major fault system, forming a complex fault-block architecture with multi-stage faulting and well-developed fractures. Multi-phase magmatic activity has resulted in multiple sets of volcanic rocks with abundant pores and fractures, contributing to the overall geological complexity.

From 2014 to the present, 204 wells have been drilled in the study area, of which 34 have experienced lost circulation, representing an incidence rate of 16.7%. The majority of lost circulation events are classified as moderate, severe, or total loss of returns. Due to the lack of reliable pre-drilling prediction capabilities, operators have historically adopted passive prevention strategies, as noted above, leading to significant cost increases per well.

2.2 Distribution Patterns of Lost Circulation

Areally, lost circulation wells are predominantly clustered near major faults, but with no sharp boundary between lost circulation and non-lost circulation wells. The closest distance between a lost circulation well and a non-lost circulation well is only tens of meters, reflecting the high complexity and strong heterogeneity of lost circulation distribution (Fig. 1). This patchy, fault-associated distribution suggests a strong structural control on lost circulation, but also highlights the role of local lithological variations.

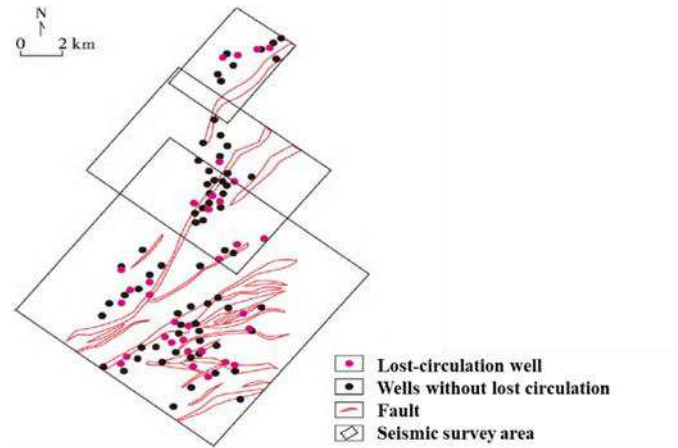


Fig.1 Areal distribution of lost circulation wells in the study area.

Vertically, lost circulation occurs mainly in the Shahejie Formation and the first member of the Kongdian Formation, with lithologies dominated by volcanic rocks, bioclastic limestones, and sandstones. Distinct lost circulation characteristics are observed across different lithologies:

(1) Volcanic and bioclastic limestone intervals exhibit high lost circulation rates and large total losses, with over 85% of events classified as moderate to severe or total loss of returns, posing the greatest threat to drilling operations.

(2) Sandstone intervals have a lower incidence of lost circulation, dominated by minor losses with rates less than 15 m³/h, which are relatively easy to control and cause less damage.

Statistical analysis of drilling parameters shows that standpipe pressure and pump pressure are nearly identical between wells with and without lost circulation. The average drilling fluid density in non-lost circulation wells is 1.16 g/cm³, slightly higher than the 1.15 g/cm³ in lost circulation wells. The formations are characterized by normal pressure systems with no abnormal pressure anomalies. These findings collectively confirm that engineering factors are not the primary trigger for lost circulation in the study area; geological factors exert the dominant control.

2.3 Dominant Mechanism of Lost Circulation

The volcanic rocks in the study area consist mainly of intrusive diabase and extrusive basalt, occurring as interbeds with sedimentary rocks with individual thicknesses ranging from 3 m to 120 m, recording multiple phases of magmatic activity. Areally, they occur as scattered, small-scale bodies along faults, distinct from the large, continuous distributions typical of central volcano edifices. Core observations reveal that basalt forms abundant low-filled primary pores during cooling, with porosities

154 ranging from 18.9% to 26.2% (average 22.1%). Diabase develops extensive contraction
155 fractures. Both pore types provide significant storage volume for drilling fluid loss.
156 Bioclastic limestones, mainly developed in the Shahejie Formation with thicknesses of
157 1–30 m, contain abundant dissolution vugs and pores.

158 Individually, these pore-dominated reservoirs have relatively low permeability and
159 limited lateral connectivity, and are unlikely to cause severe lost circulation without
160 effective permeable pathways. Statistics show that over 85% of lost circulation points
161 lie within 100 m of faults. Tectonic fractures generated by fault activity act as high-
162 permeability conduits that connect isolated volcanic pores and bioclastic limestone
163 vugs, forming continuous, large-scale flow networks for drilling fluid.

164 In summary, the coupled development of special lithologies (providing storage
165 space) and tectonic fractures (providing flow pathways) is the core mechanism
166 controlling lost circulation in the study area, and thus the primary target for pre-drilling
167 prediction.

168 **3 Seismic-based Fine Prediction of Special Lithologies**

169 Accurate delineation of the spatial distribution of special lithologies is the
170 foundation of reliable lost circulation prediction. The special lithologies in the study
171 area are characterized by scattered distribution, small acoustic impedance contrast with
172 surrounding rocks, and consequently low identification accuracy using conventional
173 methods. To overcome these challenges, we adopt a technical workflow combining well
174 log reconstruction and multi-parameter seismic inversion to achieve three-dimensional
175 fine characterization of volcanic rocks and bioclastic limestones.

176 **3.1 Geophysical Response Characteristics of Special** 177 **Lithologies**

178 **3.1.1 Well Log Responses**

179 Core-log calibration reveals distinct well log responses across different lithologies.
180 Volcanic rocks and bioclastic limestones generally exhibit high acoustic impedance (AI)
181 and low natural gamma ray (GR) values; volcanic rocks have higher spontaneous
182 potential (SP) values than bioclastic limestones. Gypsum rocks have similar acoustic
183 impedance to volcanic rocks, making them difficult to distinguish using impedance
184 alone (Table 1).

Table 1 Threshold values of sensitive attributes for different lithologies

Lithology	Acoustic Impedance ($\text{g}\cdot\text{cm}^{-3}\cdot\text{m}\cdot\text{s}^{-1}$)	Natural Gamma Ray (API)	Spontaneous Potential (mV)	Porosity (%)
Sandstone	5000-11000	60-100	<95	>2
Mudstone	4000-10000	70-140	>90	<2
Gypsum rock	7000-12000	25-60	>97	>2
Bioclastic limestone	6000-9000	40-60	<85	>8
Volcanic rock	5000-15000	20-60	>80	>2

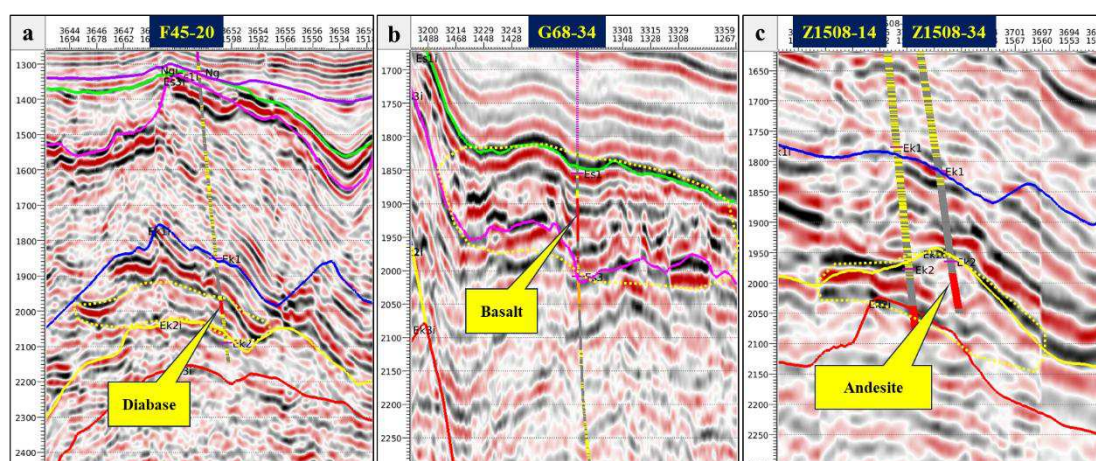
3.1.2 Seismic Response Characteristics

Well-tie calibration demonstrates clear seismic wavefield differences among different special lithologies:

(1) Extrusive basalt produces short-axis, discontinuous, high-frequency, high-amplitude reflections.

(2) Intrusive diabase produces long-axis, continuous, mid-low frequency, high-amplitude reflections.

(3) Bioclastic limestone produces long-axis, continuous, mid-low frequency, medium-high amplitude reflections (Fig. 2).



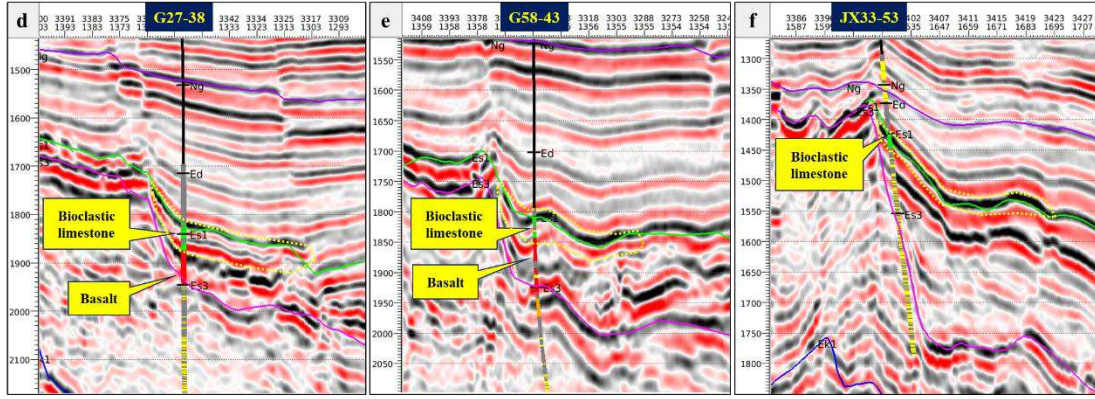


Fig.2 Seismic wavefield characteristics of different lithologies.

(a) Diabase in well F45-20; (b) Basalt in well G68-34; (c) Andesite in well Z1508-14; (d) Bioclastic limestone / basalt in well G27-38; (e) Bioclastic limestone / basalt in well F58-43; (f) Bioclastic limestone in well JX33-53

The root mean square (RMS) amplitude attribute can be used to preliminarily delineate the areal distribution of special lithologies. High-amplitude zones are distributed mainly along the major faults in a nearly north-south direction, consistent with the structural trend.

3.2 Well Log Reconstruction and Multi-parameter Inversion

3.2.1 Pseudo-acoustic Impedance Log Reconstruction

Single acoustic impedance inversion cannot reliably distinguish volcanic rocks, bioclastic limestones, and gypsum rocks, due to significant impedance overlap between special lithologies and surrounding formations. To address this, we develop a log reconstruction method that fuses three parameters: acoustic impedance, natural gamma ray, and spontaneous potential.

The workflow involves three steps: (1) frequency band decomposition and filtering of the three original curves; (2) weighted fusion to generate a pseudo-acoustic impedance trend curve; (3) dimensional normalization to match the numerical range of original acoustic impedance.

After reconstruction, the acoustic impedance values of special lithology intervals are significantly enhanced, while those of sandstone and mudstone intervals remain largely unchanged, effectively amplifying the geophysical differences between lithologies. Combined with GR and SP thresholds, this enables robust differentiation between volcanic rocks, bioclastic limestones, and gypsum rocks (Fig. 3).

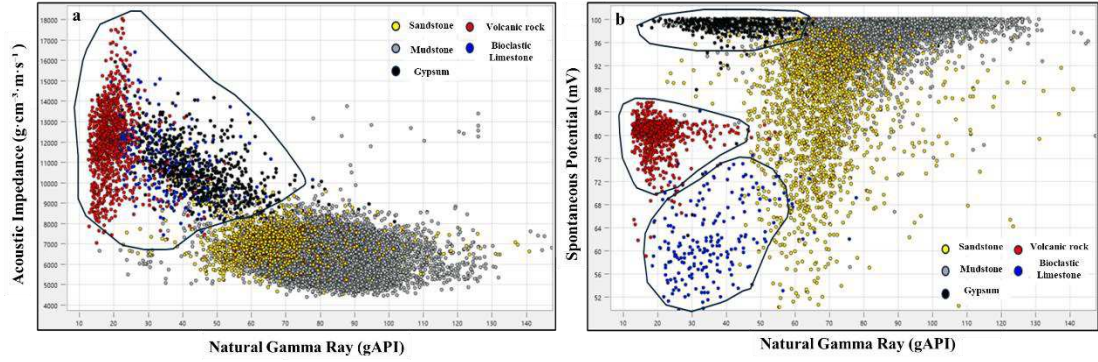


Fig.3 Cross plot of reconstructed acoustic impedance and well log parameters.

(a) Cross plot of reconstructed acoustic impedance vs. natural gamma ray; (b) Cross plot of natural gamma ray vs. spontaneous potential

3.2.2 Geostatistical Multi-parameter Inversion

We employ geostatistical inversion with co-simulation to integrate the high vertical resolution of well logs and the lateral continuity of seismic data, simultaneously inverting for acoustic impedance, GR, and SP volumes. The technical workflow is illustrated in Fig. 4.

The method takes seismic interpreted horizons and faults as the geological framework, builds an initial model using sample wells selected based on waveform similarity, and iteratively optimizes the model within a Bayesian framework to produce high-resolution inversion results. This approach preserves both the fine vertical details from well logs and the lateral geological trends captured by seismic data.

Multi-dimensional validation using single-well profiles, cross-well profiles, and areal attributes confirms high consistency between inversion results and well log data:

- (1) Volcanic rocks are characterized by high impedance, low GR, and moderate SP.
- (2) Bioclastic limestones show high impedance, moderate GR, and low SP.
- (3) Gypsum rocks exhibit high impedance, moderate GR, and high SP.

Taking the Ek₁ member as an example, the RMS attribute of inverted acoustic impedance shows consistent overall patterns with the original seismic RMS amplitude, but with sharper lithology boundaries and greater detail.

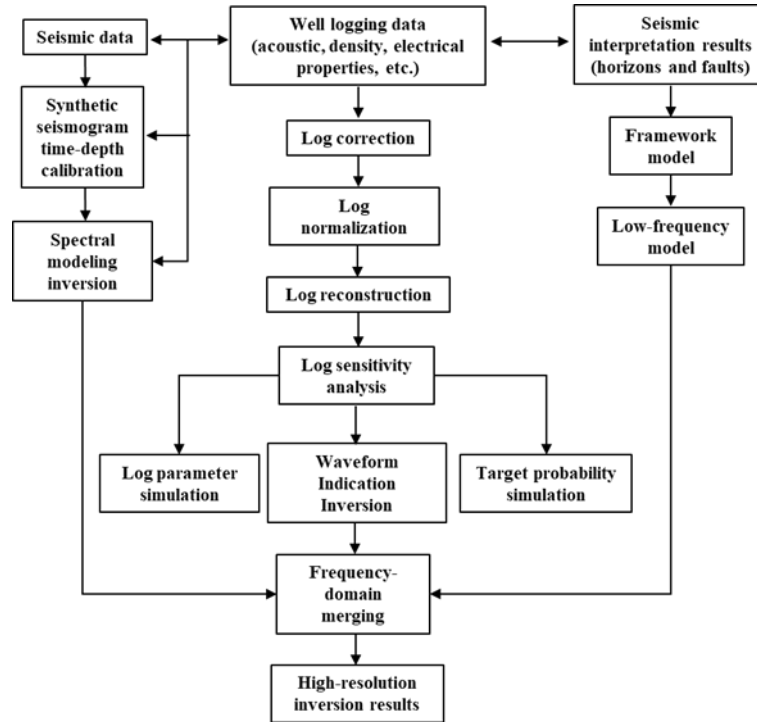


Fig.4 Technical workflow of geostatistical inversion and lithology prediction.

3.3 Validation of Inversion Results

We evaluate the inversion performance through three tiers of comparison: single-well profiles, cross-well transects, and areal attribute maps.

3.3.1 Single-well Profile Validation

Three representative wells are selected from the northern (Zilaitun), central (Zaoyuan-Fenghuadian), and southern (Wanguantun) parts of the study area.

For well Z27-36 (Fig. 5), the inversion results match well with log data: the bioclastic limestone at the bottom of Es1 shows high impedance (red), moderate GR (purple), and low SP (red); the volcanic rocks at the bottom of Es3 and in Ek₁ show high impedance (red), low GR (red), and moderate SP (yellow).

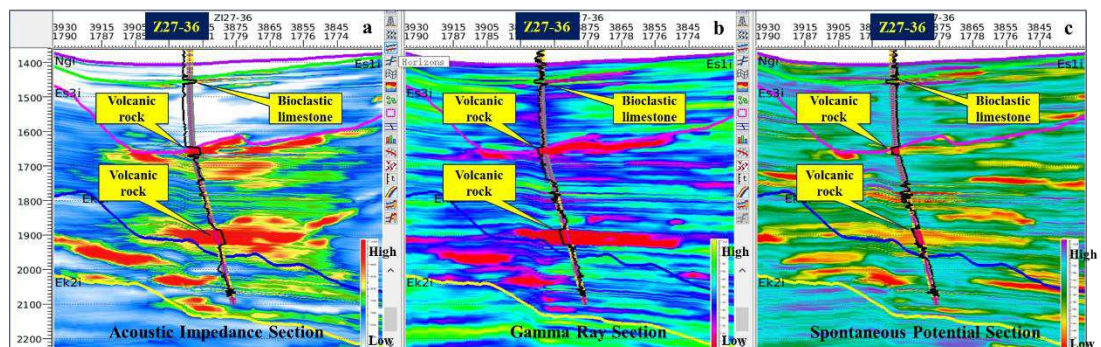


Fig.5 Multi-parameter inversion profile across well Z27-36.

(a) Acoustic impedance; (b) Natural gamma ray; (c) Spontaneous potential

For well F47-16 (Fig. 6), gypsum rock at the bottom of Es₁ exhibits high impedance (red), moderate GR (purple), and high SP (green); volcanic rocks at Es₃ bottom and Ek₁ show the typical volcanic rock response, consistent with well logs.

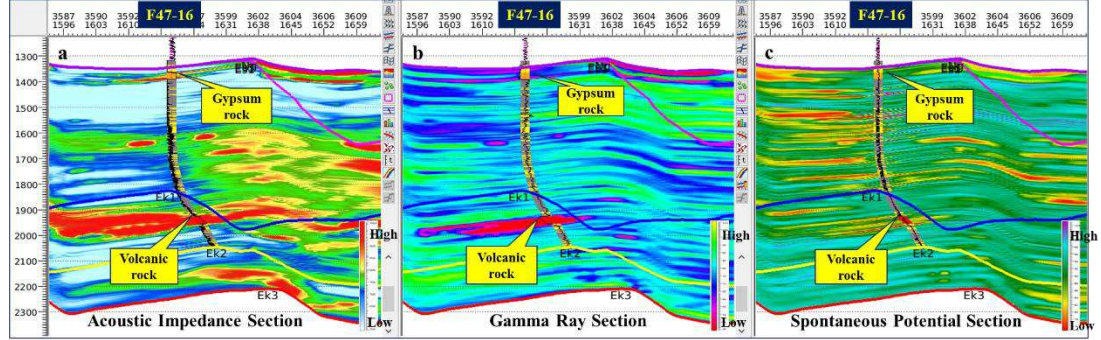


Fig. 6 Multi-parameter inversion profile across well F47-16.

(a) Acoustic impedance; (b) Natural gamma ray; (c) Spontaneous potential

For well W22-32 (Fig. 7), bioclastic limestone in Es₃ shows high impedance, moderate GR, and low SP; two thick volcanic beds in Ek₁ show high impedance, low GR, and moderate SP; underlying gypsum rock shows high impedance, moderate GR, and high SP. All inversion results align closely with well log observations.

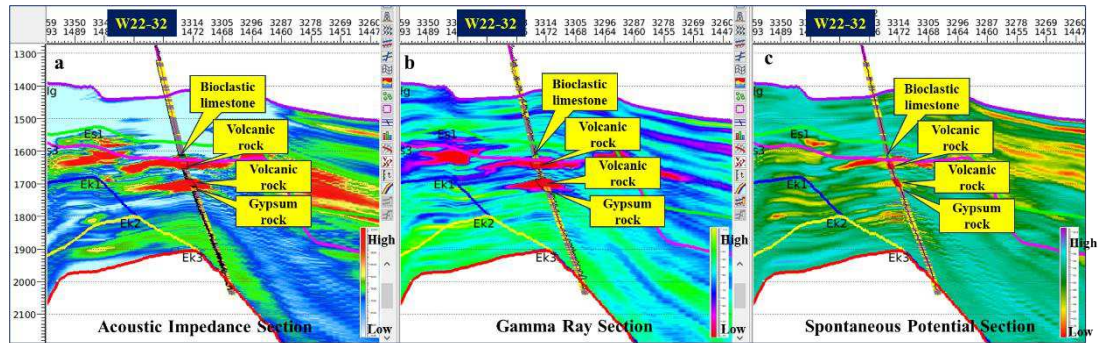


Fig. 7 Multi-parameter inversion profile across well W22-32.

(a) Acoustic impedance; (b) Natural gamma ray; (c) Spontaneous potential

3.3.2 Cross-well Profile Validation

Two cross-well transects are analyzed. The Zao1229-F47-18 transect (Zaoyuan-Fenghuadian area, Fig. 8) shows that inversion results match well log data along the entire profile. Impedance and GR effectively identify volcanic rocks (high impedance, low GR) versus sandstone/mudstone (low impedance, high GR). SP alone cannot distinguish special lithologies due to overlapping value ranges, but serves as an auxiliary parameter to differentiate volcanic rocks from other lithologies when combined with impedance and GR.

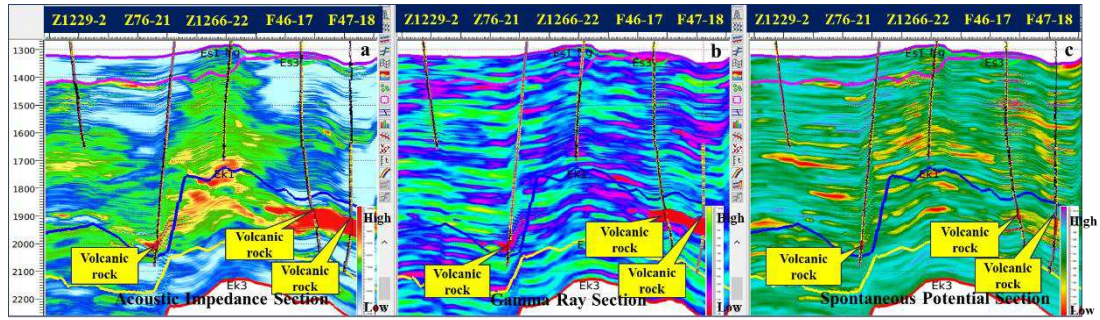


Fig. 8 Multi-parameter inversion profile across the Zao1229-F47-18 well transect.

(a) Acoustic impedance; (b) Natural gamma ray; (c) Spontaneous potential

The Guan36-62-G6-21-3 transect (Wangguantun area, Fig. 9) yields consistent results. Volcanic rocks are mainly developed in the Es₃ member between wells Guan36-55 and Guan37-43. Multiple thin volcanic and gypsum beds are predicted in the Ek₂ member, characterized by high impedance, low GR, and high SP.

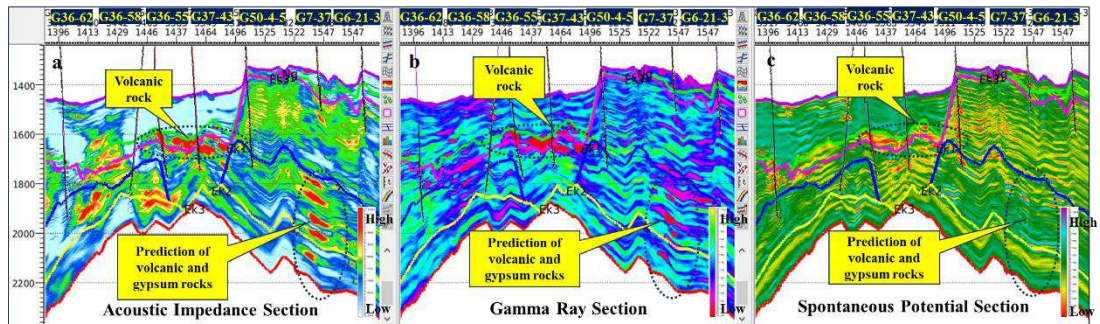


Fig. 9 Multi-parameter inversion profile across the Guan36-62-G6-21-3 well transect.

(a) Acoustic impedance; (b) Natural gamma ray; (c) Spontaneous potential

3.3.3 Areal Attribute Validation

Analysis of RMS attributes for different stratigraphic members reveals consistent areal patterns across the three inverted parameters:

(1) In the Es₁ member (Fig. 10), special lithologies (high impedance, low GR, low SP; shown in red-yellow) are mainly distributed in the western and southern parts of the study area, with poor lateral continuity.

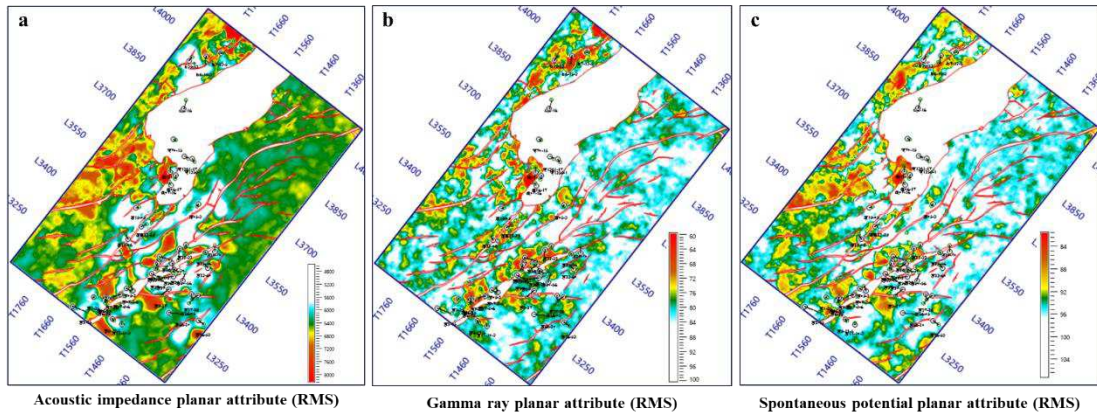


Fig. 10 Multi-parameter areal attributes (RMS) of the first member of Shahejie Formation.

(a) Acoustic impedance; (b) Natural gamma ray; (c) Spontaneous potential

(2) In the Es₂₊₃ (Fig. 11) and Ek₁ members (Fig. 12), special lithologies are concentrated along the central major fault zone in a north-south belt, with local patch-like features.

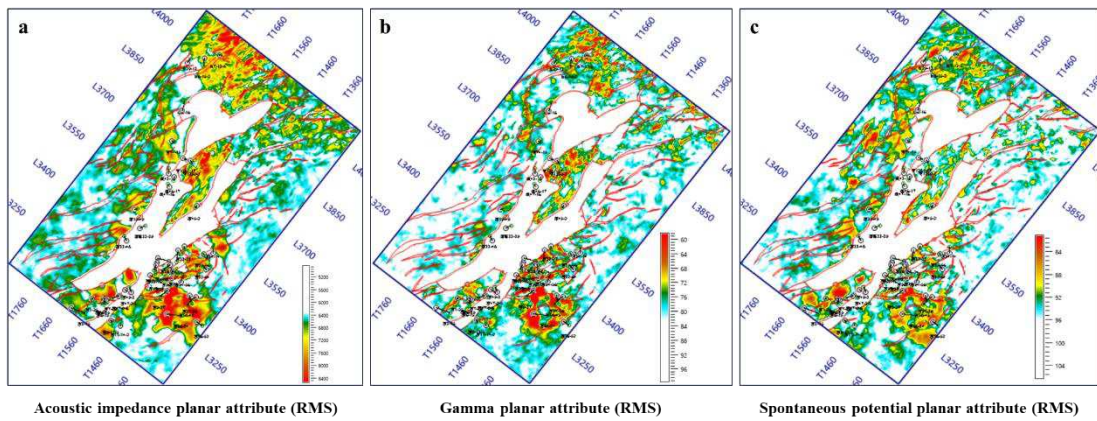


Fig. 11 Multi-parameter areal attributes (RMS) of the second and third members of Shahejie Formation.

(a) Acoustic impedance; (b) Natural gamma ray; (c) Spontaneous potential

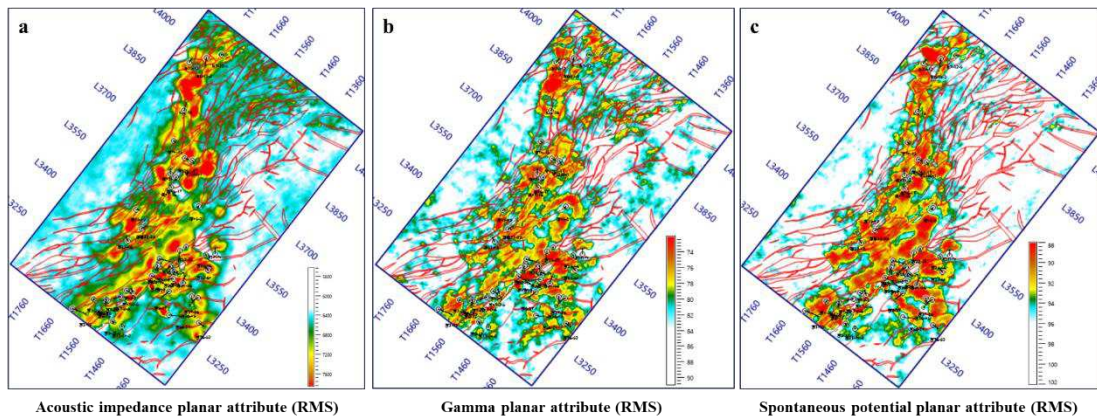


Fig. 12 Multi-parameter areal attributes (RMS) of the first member of Kongdian Formation.

(a) Acoustic impedance; (b) Natural gamma ray; (c) Spontaneous potential

(3) In the Ek₂ member (Fig. 13), the distribution pattern is similar to Ek₁, with north-south belted distribution along the fault zone.

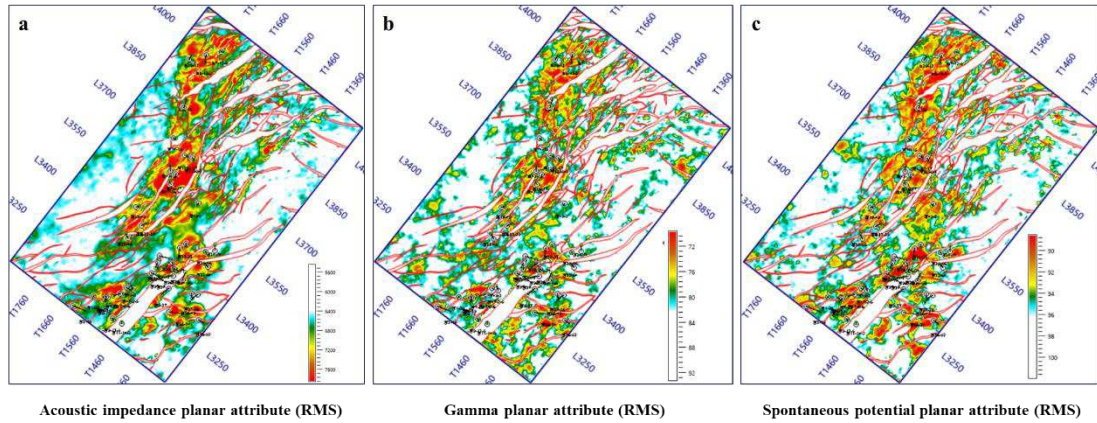


Fig. 13 Multi-parameter areal attributes (RMS) of the second member of Kongdian Formation.

(a) Acoustic impedance; (b) Natural gamma ray; (c) Spontaneous potential

Comparison between inverted acoustic impedance RMS and original seismic RMS amplitude for the Ek₁ member (Fig. 14) shows highly consistent overall spatial patterns, confirming that the inversion results reliably reproduce the original seismic characteristics while enhancing lithology discrimination.

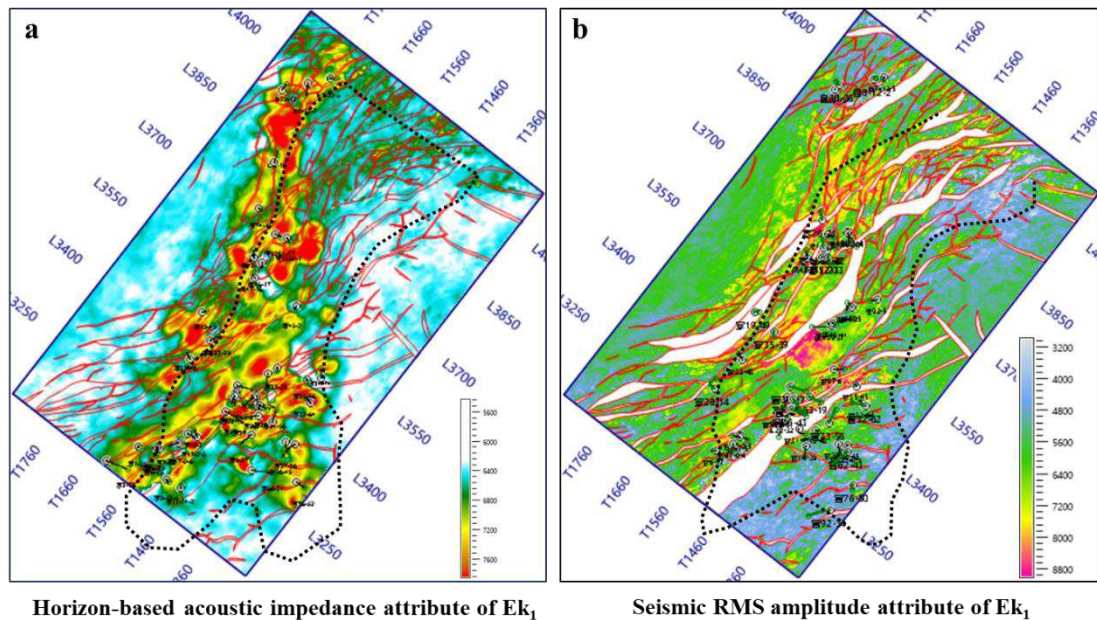


Fig. 14 Multi-parameter areal attributes (RMS) of the Ek₁ member.

(a) Acoustic impedance; (b) Seismic RMS amplitude

3.4 Fine Characterization of Special Lithologies

We adopt a stepwise hierarchical approach to delineate volcanic rocks and

bioclastic limestones using optimized thresholds (Fig. 15): first, sandstone and mudstone are filtered out using member-specific acoustic impedance thresholds; then gypsum is removed using criteria of $GR < 25$ API and $SP < 90$ mV; finally, bioclastic limestones and volcanic rocks are mapped separately.

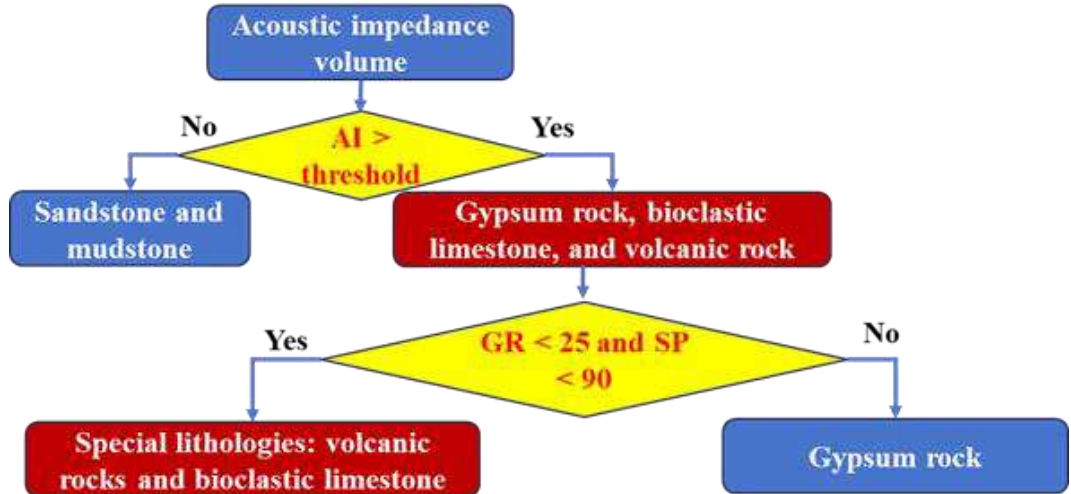


Fig. 15 Flowchart of special lithology prediction.

The impedance thresholds for special lithologies increase slightly with depth, while GR and SP thresholds remain relatively constant across members (Fig. 16). Using the geostatistical inversion results, we apply these thresholds sequentially to extract volcanic rocks, bioclastic limestones, and gypsum rocks, and calculate their respective thicknesses for each stratigraphic member.

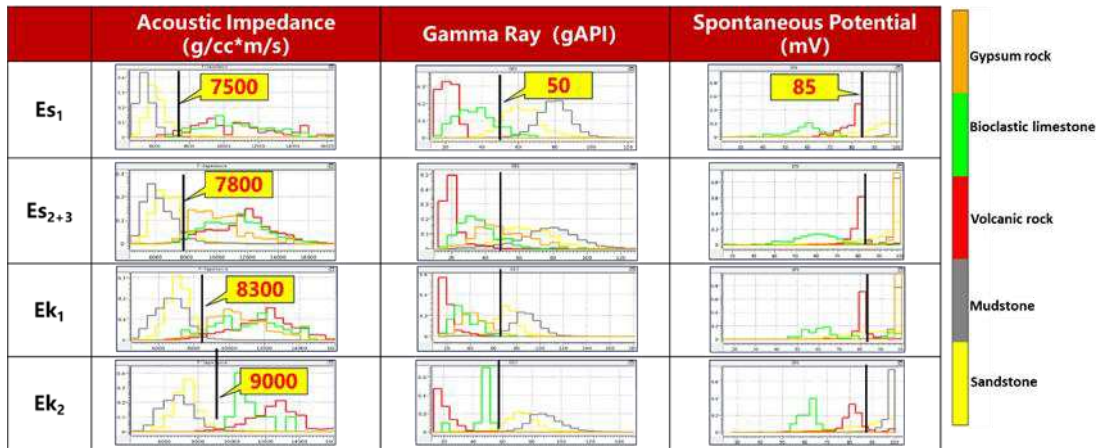


Fig. 16 Distribution of acoustic impedance, gamma ray and spontaneous potential at different stratigraphic levels.

(a) Es_1 member; (b) Es_{2+3} members; (c) Ek_1 member; (d) Ek_2 member

Accuracy evaluation is performed using 144 wells for inversion training and 10 wells for independent validation. The prediction coincidence rate reaches 91.2% for bioclastic limestone and 91.5% for volcanic rock, demonstrating sufficient accuracy for

engineering applications.

4 Fracture Prediction and Lost Circulation Pattern Classification

4.1 Fracture Prediction Using Ant Tracking

We apply the ant tracking algorithm for fracture detection, which simulates the information transfer mechanism of ant colonies foraging for food to automatically identify discontinuous boundaries in seismic data. This method is particularly sensitive to small-scale faults and fractures that are below conventional seismic resolution.

Results show that fractures in the study area are dominated by high-angle tectonic fractures, trending overall NE-SW, consistent with the regional fault strike. Fracture density decreases with increasing distance from major faults, with fault-proximal zones representing the highest fracture density areas. This spatial pattern correlates strongly with the distribution of lost circulation wells, confirming the critical role of fractures in controlling lost circulation.

4.2 Fusion of Lithology and Fracture Data Volumes

To visually characterize the coupling relationship between lithology and fractures, we spatially fuse the lithology identification volume and the ant tracking fracture volume. The ant tracking attribute values are first normalized to a 0–1 range, and the special lithology regions are then mapped onto the fracture volume to create a coupled lithology-fracture data volume. This integrated volume enables simultaneous visualization of well trajectory, lithology type, fracture intensity, and corresponding lost circulation risk along the wellbore (Fig. 17). Validation against 10 wells shows good agreement between the fused data and actual drilling observations.

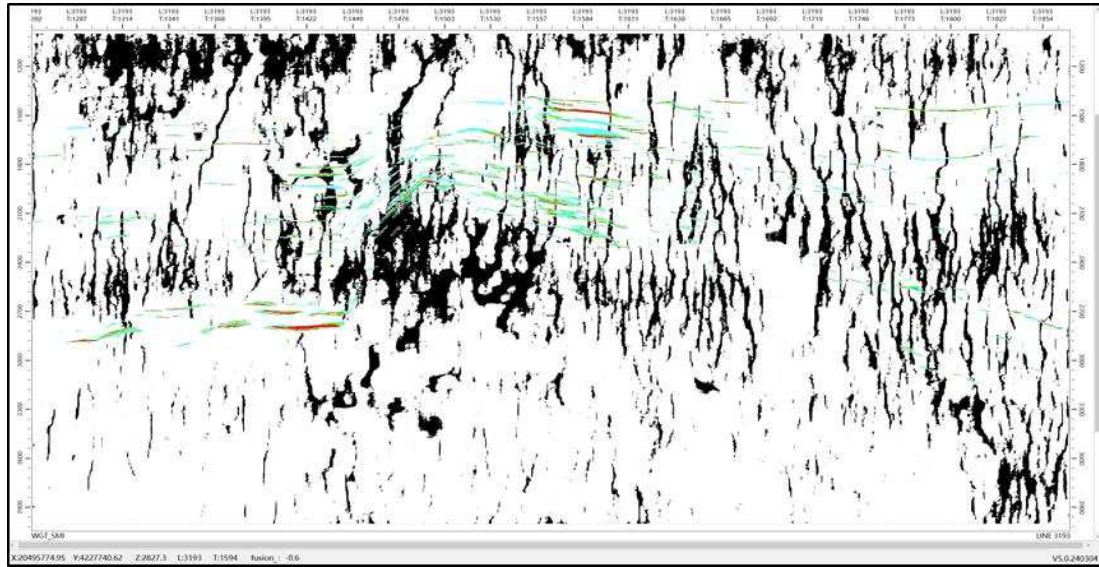


Fig. 17 Profile display of the fracture-lithology fused volume.

4.3 Lost Circulation Types and Seismic Response Patterns

Based on seismic responses and lost circulation characteristics from 204 drilled wells, we classify lost circulation into three distinct types, each with different risk levels and geological controls (Table 2).

Table 2 Statistical characteristics of different lost circulation types

Lost circulation type	Number of sample wells	Number of lost circulation wells	Incidence rate	Lost circulation characteristics
Special lithologies + developed fractures	22	18	82%	Large loss volume, mostly severe lost circulation
Special lithologies + poorly developed fractures	70	10	14%	Moderate to small loss volume, pore-dominated
No special lithologies + developed fractures	22	3	14%	Small loss volume, fracture-dominated

4.3.1 Special lithologies with developed fractures

This type occurs where wells penetrate special lithology intervals with moderate to large fractures. It has a lost circulation incidence rate of 82.7%, dominated by

moderate to severe and total loss of returns. This is the primary type of catastrophic lost circulation in the study area (Fig. 18). The high storage capacity of special lithologies, combined with the high permeability of well-developed fractures, creates efficient fluid loss pathways that result in large-volume, rapid lost circulation.

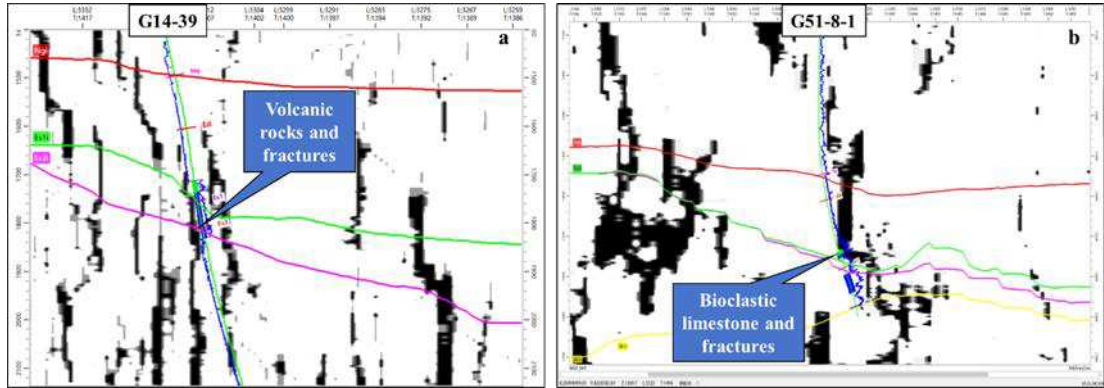


Fig. 18 Seismic reflection characteristics of wells with special lithologies + developed fractures type lost circulation.

4.3.2 Special lithologies with poorly developed fractures

This type occurs in special lithology intervals thicker than 15 m but with limited fracture development. It has a lost circulation incidence rate of 11.2%, dominated by minor to moderate pore-type losses (Fig. 19). Such losses are driven primarily by primary pores and dissolution vugs within the special lithologies, with poor fracture connectivity. Accordingly, compared with the type detailed in Section 4.3.1, it exhibits lower loss rates and milder severity.

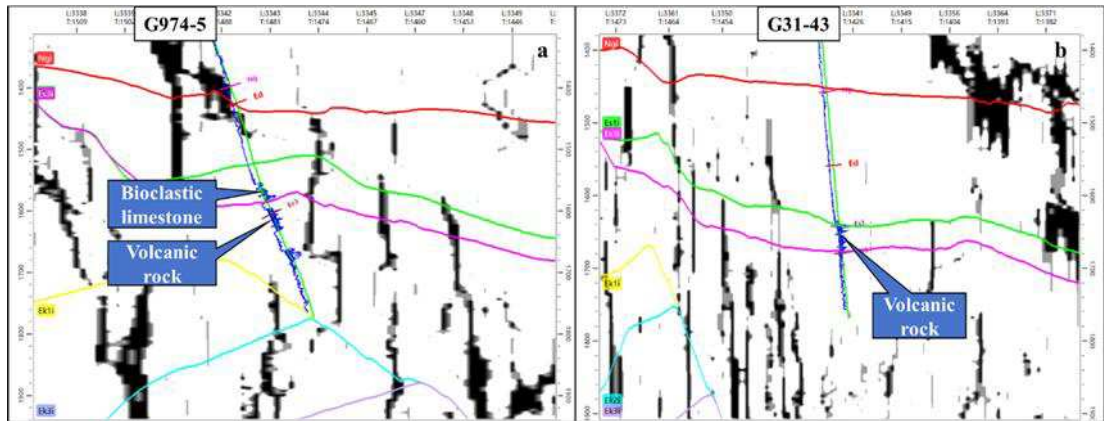


Fig. 19 Seismic reflection characteristics of wells with special lithologies + poorly developed fractures type lost circulation.

4.3.3 Sandstone with developed fractures

This type occurs in sandstone-mudstone intervals with large fractures. The lost circulation incidence rate is 10.4%, with severity dependent on fracture scale. Most

events are minor to moderate losses (Fig. 20). Sandstones generally have lower primary porosity and storage capacity than special lithologies, so even with fractures, the total loss volume is typically limited.

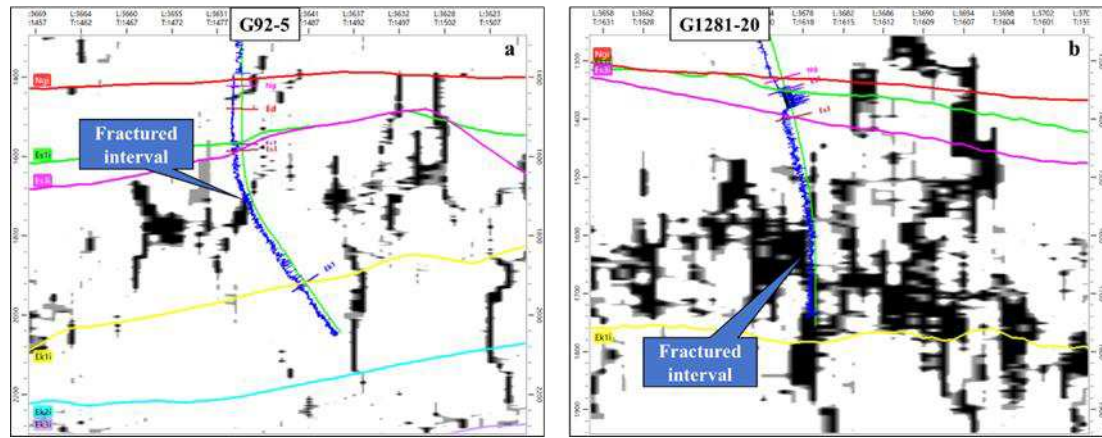


Fig. 20 Seismic reflection characteristics of wells with no special lithologies + developed fractures type lost circulation.

5 Decision Tree-based Lost Circulation Risk Prediction Method

5.1 Construction of the Decision Tree Prediction Model

We construct a decision tree model for lost circulation risk assessment, with lithology, special lithology thickness, and fracture intensity as the core state branches. The probability branches include subcategories of volcanic rock/bioclastic limestone, sandstone, mudstone/gypsum, thickness thresholds, and large/moderate/small fractures (Fig. 21).

Key model parameters are determined based on statistical analysis of historical data:

(1) Thickness threshold: Statistics show that lost circulation risk increases significantly when the single-layer thickness of special lithologies exceeds 15 m. This value is set as the boundary between thick and thin special lithology intervals.

(2) Fracture classification: After normalizing the ant tracking data, fracture intensity is classified as: no fracture (0), small fractures (0–0.3), moderate fractures (0.3–0.6), and large fractures (0.6–1.0).

(3) Risk grading: Three risk levels are defined: high risk (lost circulation probability > 80%), medium risk (10–80%), and low risk ($\leq 10\%$).

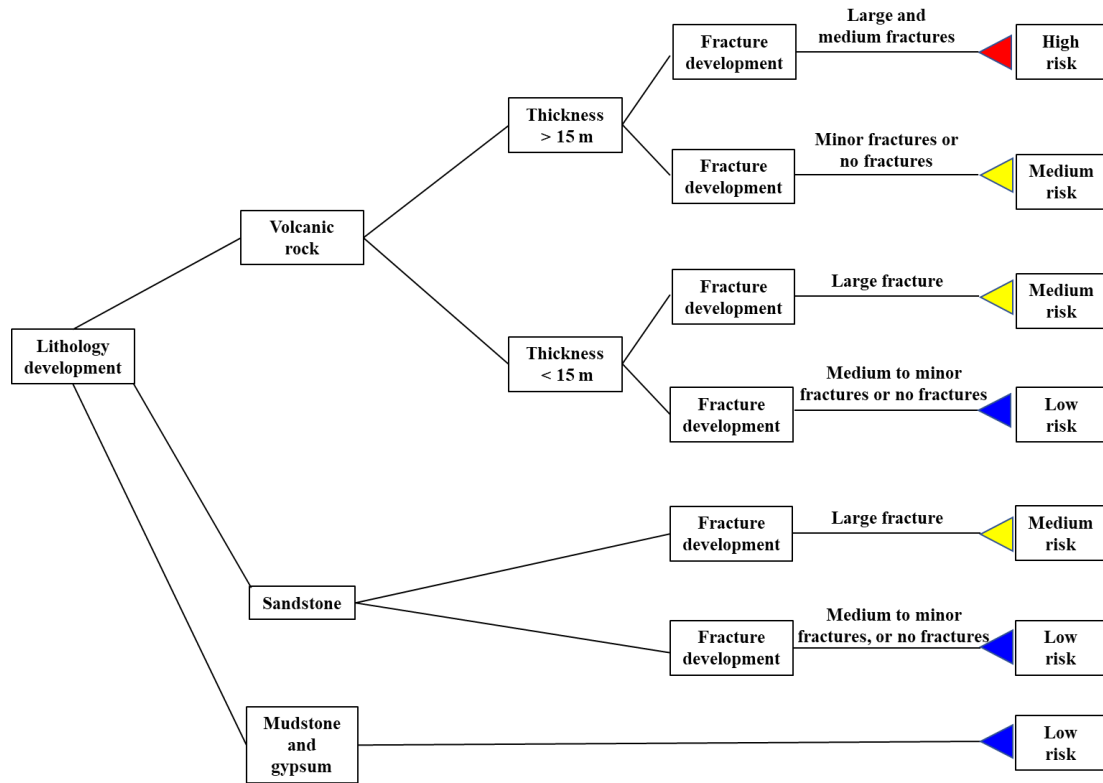


Fig.21 Decision tree model for lost circulation risk assessment.

5.2 Intelligent Prediction Implementation

We develop a computational program based on the decision tree algorithm to automate lost circulation risk calculation. The workflow is shown in Fig. 22: first, well trajectory, lithology volume, and ant tracking volume are input; lithology thickness curves and ant attribute curves are extracted along the well trajectory; then, through sliding window analysis and machine learning training, point-by-point lost circulation risk coefficients are calculated; finally, a lost circulation risk profile and a risk point statistics table are output.

The lost circulation samples are divided into seven categories for model training. The risk coefficient mapping function is optimized using gradient descent to achieve quantitative coupling between lithology, thickness, fracture parameters, and lost circulation risk. The final risk classification criteria are set as: high risk (0.6–1.0), medium risk (0.3–0.6), and low risk (0–0.3).

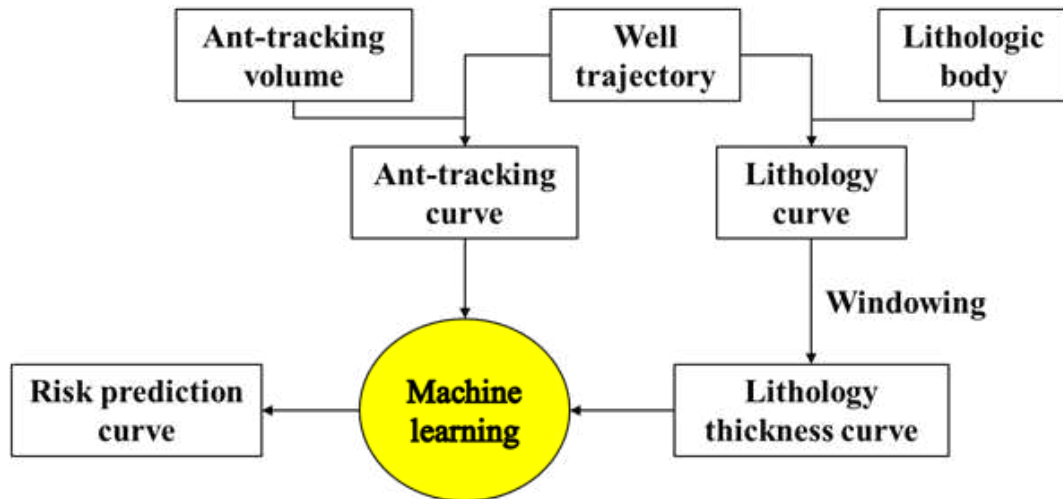


Fig.22 Workflow of lost circulation risk calculation.

5.3 Lost Circulation Risk Evaluation Criteria

We calculate lost circulation risk coefficients for all drilled wells in the study area (Table 3). The results show that most lost circulation events in special lithology intervals have risk coefficients above 0.6. Below 0.6, the probability of lost circulation decreases markedly, and events are dominated by sandstone-related losses.

Based on the risk coefficient distribution, three risk levels are formally defined:

(1) High risk (0.6–1.0): Extremely high probability of lost circulation, dominated by the special lithologies + fractures type.

(2) Medium risk (0.3–0.6): Relatively high probability, dominated by special lithologies with few fractures and sandstone + fracture types.

(3) Low risk (0–0.3): Negligible probability of lost circulation.

Table 3 Calculated lost circulation risk for selected wells with lost circulation

Well name	Risk value	Risk level	Lost circulation lithology	Well name	Risk value	Risk level	Lost circulation lithology
G14-39	0.90	High	Special lithology	Z1508-3	0.66	High	Special lithology
G51-8-1	0.90	High	Special lithology	W22-32	0.66	High	Special lithology
JK39-37	0.90	High	Special lithology	G47-5	0.60	High	Special lithology

Z7-12-5	0.90	High	Special lithology	G52-14	0.60	High	Special lithology
G58-45	0.89	High	Special lithology	J47-5	0.60	High	Special lithology
F43-15	0.78	High	Special lithology	G47-0-4	0.54	Medium	Sandstone and mudstone
G28-47-1	0.76	High	Special lithology	G47-2-5	0.54	Medium	Sandstone and mudstone
G35-65	0.71	High	Special lithology	G6-17	0.54	Medium	Special lithology
G87-6	0.68	High	Special lithology	J33-48	0.54	Medium	Sandstone and mudstone
G27-38	0.66	High	Special lithology	J45-2	0.54	Medium	Sandstone and mudstone
G31-43	0.66	High	Special lithology	Z128-17	0.54	Medium	Special lithology
G32-64	0.66	High	Special lithology	Z1288-9	0.54	Medium	Sandstone and mudstone
G33-48	0.66	High	Special lithology	Z92-5	0.54	Medium	Special lithology
G974-5	0.66	High	Special lithology	Z29-13	0.54	Medium	Sandstone and mudstone
Z1281-20	0.66	High	Special lithology	JX49-11	0.50	Medium	Sandstone and mudstone
Z1508-14	0.66	High	Special lithology				

5.4 Validation with Drilled Wells

We validate the model using representative wells with varying risk profiles:

(1) Well F43-15 (Fig. 23): The prediction curve indicates high lost circulation risk near the special lithology interval. Actual drilling encountered lost circulation at the predicted position, consistent with the prediction.

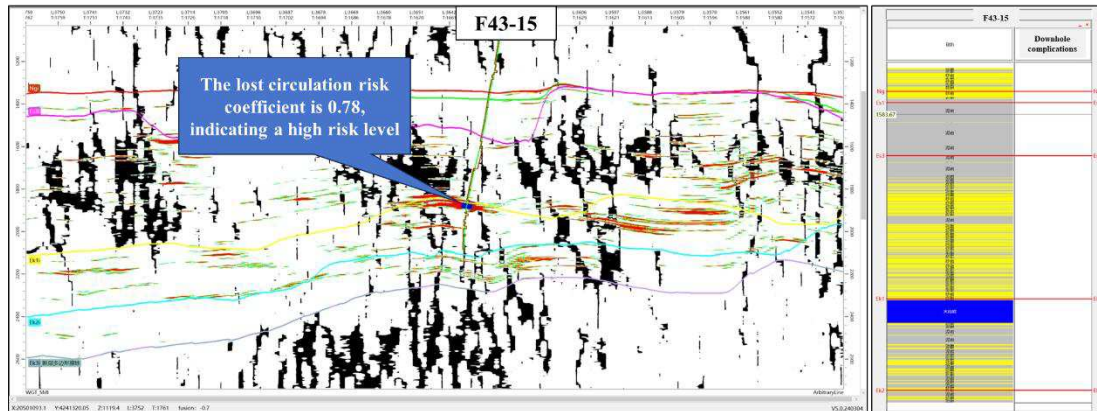


Fig.23 Time profile of lost circulation prediction results for Well F43-15.

(2) Well J33-48 (Fig. 24): Multiple medium risk intervals and one high risk interval are predicted. Lost circulation occurred during drilling, matching the prediction.

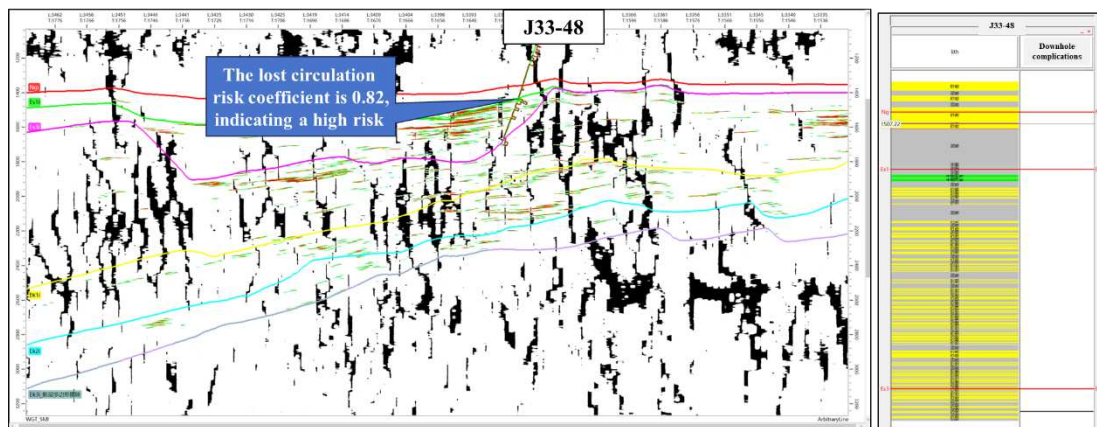


Fig.24 Time profile of lost circulation prediction results for Well J33-48.

(3) Well G14-39 (Fig. 25): High risk is predicted in the bioclastic limestone interval, which corresponds to the actual lost circulation interval.

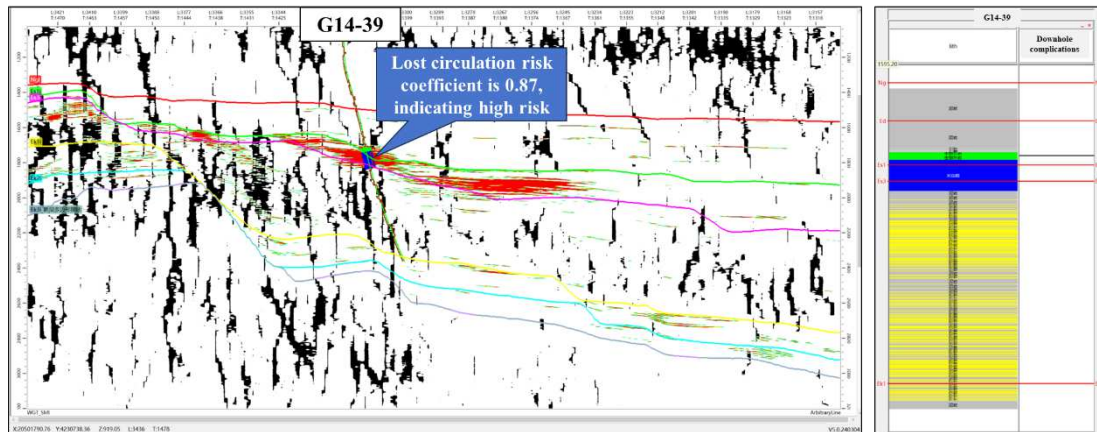


Fig.25 Time profile of lost circulation prediction results for Well G14-39.

(4) Well Z1281-17 (Fig. 26): Multiple medium risk intervals are predicted, with slightly lower risk coefficients. Actual lost circulation occurred within the predicted intervals.

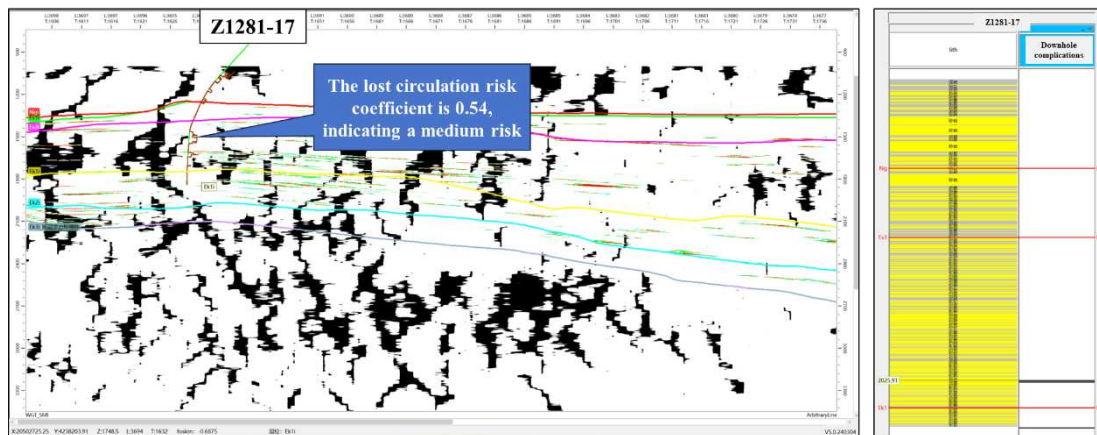


Fig.26 Time profile of lost circulation prediction results for Well Z1281-17.

(5) Well G31-43 (Fig. 27): High risk is predicted, and lost circulation occurred during drilling, consistent with the result.

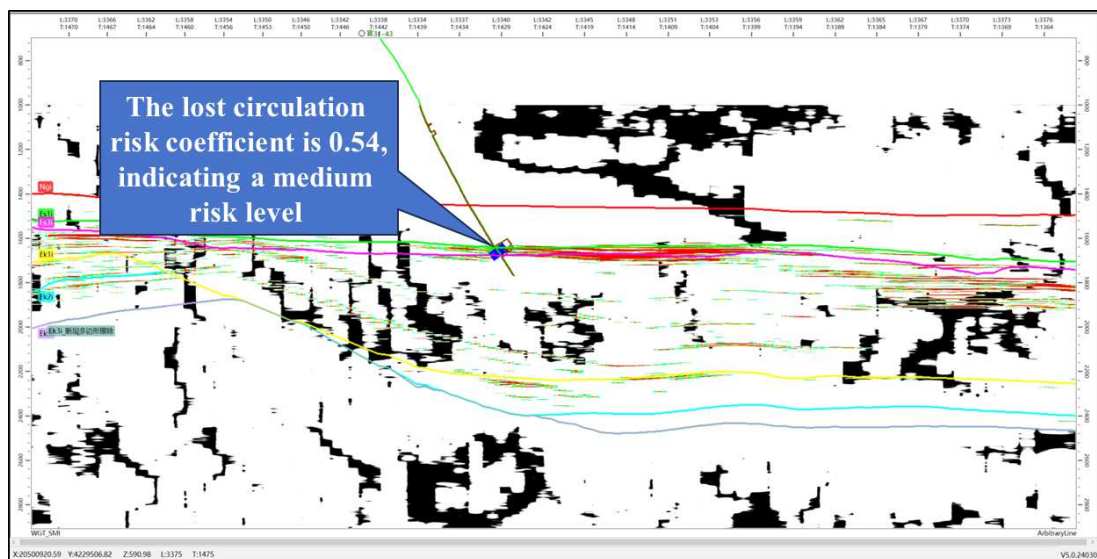


Fig.27 Time profile of lost circulation prediction results for Well G31-43.

(6) Well G33-62 (Fig. 28): High risk is predicted, and lost circulation events were recorded during drilling.

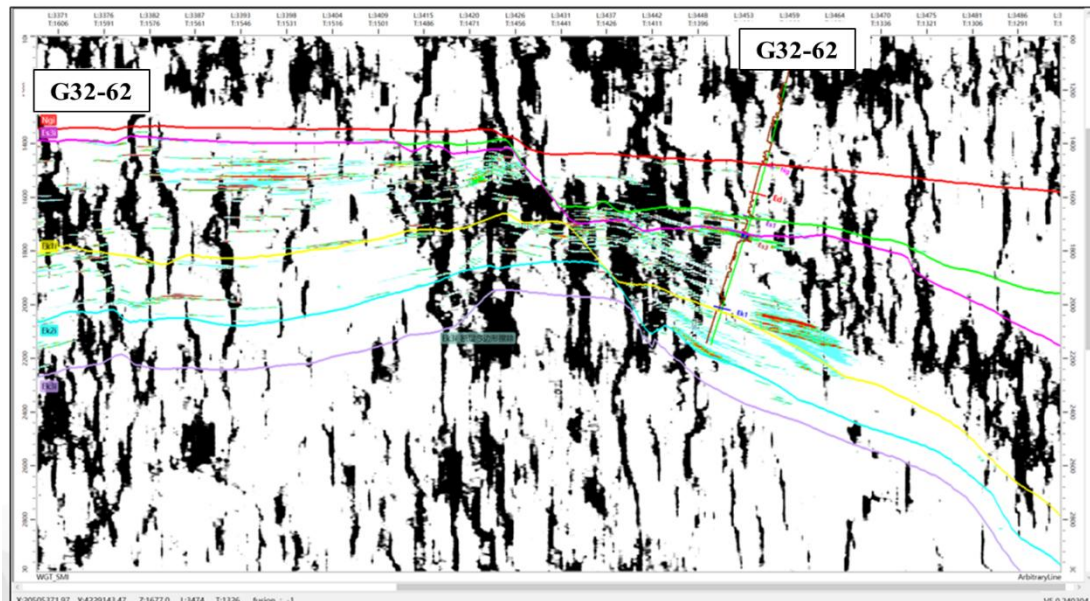


Fig.28 Time profile of lost circulation prediction results for Well G33-62.

(7) Well G45-4-3 (Fig. 29): Low risk is predicted, and no lost circulation occurred during drilling.

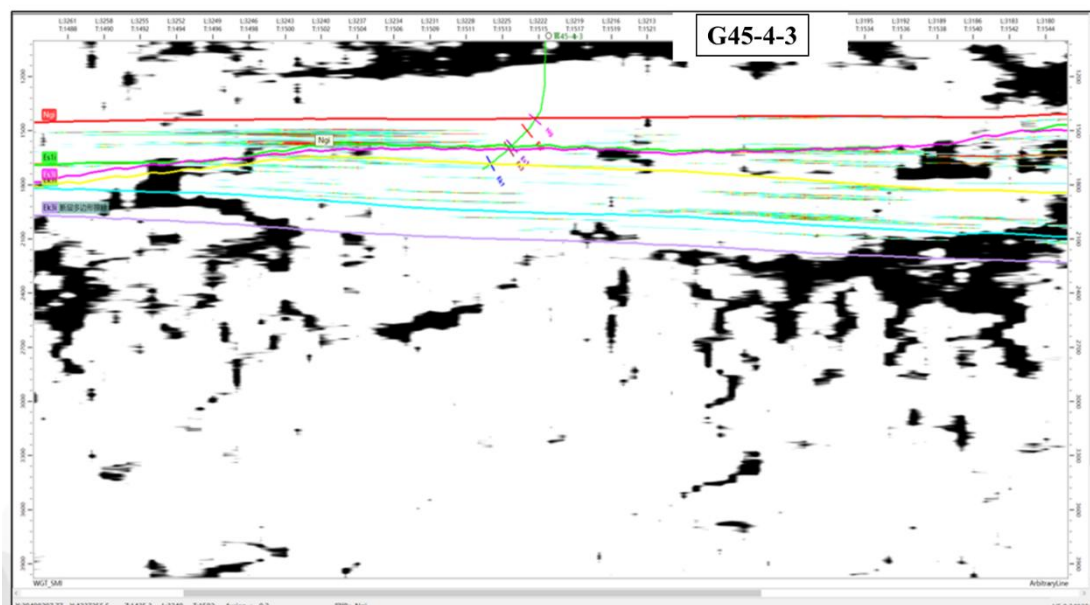


Fig.29 Time profile of lost circulation prediction results for Well G45-4-3.

(8) Well Z18-20 (Fig. 30, Table 4): Two medium risk points are identified. The first, in the Ek₁ member (1688–1924 m, 236 m thick sandstone with fractures, risk coefficient 0.54), and the second, in the Ek₂ member (2070–2104 m, 34 m thick volcanic rock without fractures, risk coefficient 0.50).

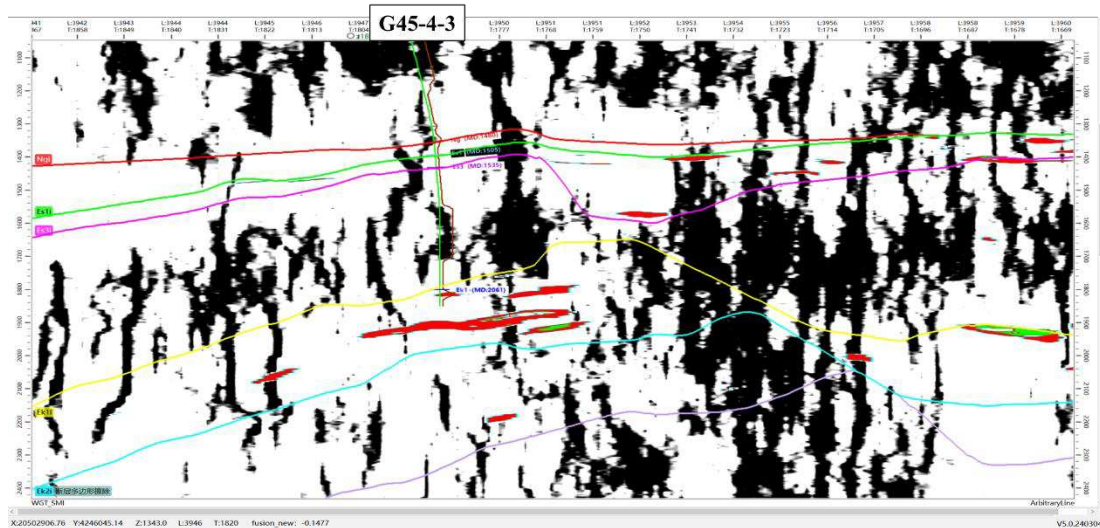


Fig.30 Time profile of lost circulation prediction results for Well Z18-20.

Table 4 Well Z18-20 statistics of lost circulation risk points

Risk point	Stratigraphic member	Predicted depth (m)	Predicted thickness (m)	Predicted lithology	Predicted fracture	Lost circulation risk coefficient	Predicted lost circulation risk
1	Ek ₁	1688-1924	236	Sandstone and mudstone	Present	0.54	Medium
2	Ek ₂	2070-2104	34	Volcanic rock	Absent	0.5	Medium

(9) Well F16-14 (Fig. 31, Table 5): Five medium to high risk points are identified along the wellbore, with lithologies including sandstone and volcanic rock, and varying fracture development.

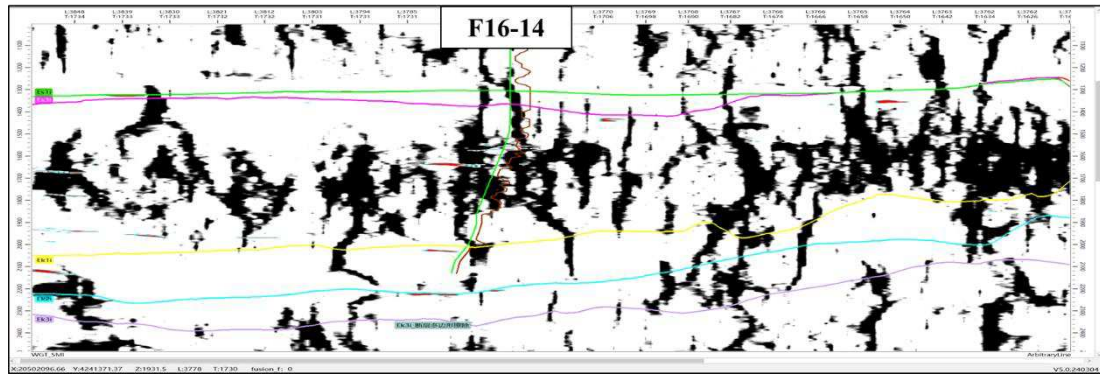


Fig.31 Time profile of lost circulation prediction results for Well F16-14.

Table 5 Well F16-14 statistics of lost circulation risk points

Risk point	Stratigraphic member	Predicted depth (m)	Predicted thickness (m)	Predicted lithology	Predicted fracture	Lost circulation risk coefficient	Predicted lost circulation risk
1	Es ₁ -Ek ₁	1408-1764	356	Sandstone and mudstone	Present	0.51	Medium
2	Ek ₁	1828-1834	6	Volcanic rock	Absent	0.44	Medium
3	Ek ₁	1834-1944	110	Sandstone and mudstone	Present	0.60	High
4	Ek ₁	2066-2194	128	Sandstone and mudstone	Present	0.51	Medium
5	Ek ₁	2220-2330	110	Sandstone and mudstone	Present	0.51	Medium

(10) Well F28-10 (Fig. 32, Table 6): Three medium risk points are identified, including volcanic rock with and without fractures, and fractured sandstone.

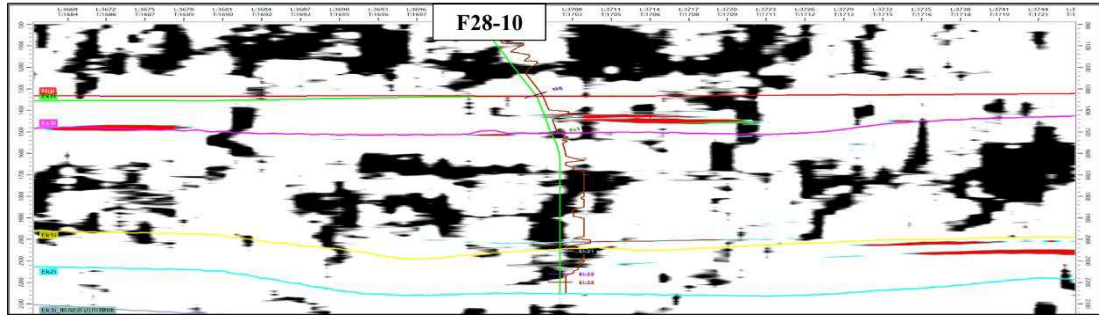


Fig.32 Time profile of lost circulation prediction results for Well F28-10.

Table 6 Well F28-10 statistics of lost circulation risk points

Risk point	Stratigraphic member	Predicted depth (m)	Predicted thickness (m)	Predicted lithology	Predicted fracture	Lost circulation risk coefficient	Predicted lost circulation risk
1	Es ₃	1530-1548	18	Volcanic rock	Present	0.50	Medium
2	Ek ₁	1928-2548	262	Sandstone and mudstone	Present	0.49	Medium
3	Ek ₁	2552-2610	58	Volcanic rock	Present	0.58	Medium

5.5 Analysis of Prediction Results

We apply the method to 154 drilled wells (Table 7). Of these, 25 wells show inconsistent predictions with actual drilling results, giving an overall coincidence rate of 83.8%. For 6 new wells drilled in 2025, pre-drilling predictions were accurate for 5 wells, representing a prediction accuracy of 83.4% (Table 8).

Table 7 Prediction consistency for selected drilled wells

Well name	Lost circulation (Y/N)	Lost severity	Lost circulation depth	Lost circulation lithology	Fracture status	Agreement
G31-43	Yes	Low	1990	Mudstone	Unfractured	Consistent
G47-5	Yes	High	1616	Bioclastic limestone	Fractured	Consistent
G52-14	Yes	High	1852	Bioclastic limestone	Fractured	Consistent
G58-45	No				Unfractured	Consistent
Z92-5	Yes	Low	1733	Sandstone and mudstone	Unfractured	Consistent
J47-5	No			Special lithology interval	Unfractured	Consistent
JX49-11	Yes	Low	1700	Sandstone and mudstone	Fractured	Consistent
G33-48	Yes	High	1856	Bioclastic limestone	Unfractured	Inconsistent
G35-65	Yes	Low	1965	Bioclastic limestone	Fractured	Consistent
G47-0-4	Yes	Low	1740	Sandstone and mudstone	Fractured/faulted	Consistent
W22-32	Yes	Low	1820	Bioclastic limestone	Fractured	Consistent
F43-15	Yes	Low		Volcanic rock	Near fracture	Consistent
G6-17	Yes	Medium		Bioclastic limestone	Unfractured	Inconsistent

G14-39	Yes	High	1987	Bioclastic limestone	Fractured	Consistent
G32-64	Yes	Low		Bioclastic limestone	Minor fracture	Consistent
G51-8-1	Yes	High		Bioclastic limestone	Fractured	Consistent
G974-5	Yes	Low		Volcanic and bioclastic rocks	Unfractured	Inconsistent
J45-2	No			Special lithology	Fractured	Inconsistent
JK39-37	Yes			Bioclastic limestone	Fractured	Consistent
Z29-13	No			Special lithology interval	Unfractured	Consistent
G27-38	Yes	Low		Sandstone and mudstone	Fractured	Consistent
G28-47-1	Yes			Bioclastic limestone	Fractured	Consistent
G47-2-5	Yes	Low		Sandstone and mudstone	Fractured	Consistent
J33-48	Yes	Medium		Volcanic and bioclastic rocks	Unfractured	Inconsistent
Z7-12-5	Yes	High		Volcanic rock	Fractured	Consistent
G87-6	Yes	Medium		Bioclastic limestone	Fractured	Consistent
Z1281-	Yes	High		Volcanic	Unfractured	Inconsistent

17				rock		
Z1281-20	Yes	High	2187	Sandstone and mudstone	Fractured	Consistent
Z1288-9	Yes	Low	2140	Sandstone and mudstone	Fractured	Consistent
Z1508-14	Yes	Low		Sandstone and mudstone	Fractured	Consistent
Z1508-34	Yes	Medium		Volcanic rock	Unfractured	Inconsistent
Z27-36	No			Special lithology interval	Unfractured	Consistent

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Table 8 Prediction consistency for newly drilled wells

Well name	High risk points	Medium risk points	Predicted lost circulation	Actual lost circulation	Prediction result
Z17-6	0	4	None	None	Accurate
Z17-8	0	2	None	None	Accurate
F26-11	0	7	None	None	Accurate
F28-10	0	3	None	None	Accurate
F17-13	0	3	None	None	Accurate
F16-14	0	4	None	Lost circulation	Inaccurate

The discrepancies are mainly attributed to three factors: (1) sub-seismic scale fractures that are below the resolution of ant tracking; (2) lateral lithology variations that are not fully captured by the inversion model; and (3) local engineering factors that can trigger minor lost circulation even in low-risk geological settings. Despite these limitations, the method provides reliable pre-drilling risk assessment for engineering design purposes.

6 Limitations and Future Work

Although the integrated mechanism-driven pre-drilling lost circulation prediction method delivers robust risk stratification and satisfactory accuracy in the southern Dagang complex fault-block area, it has notable limitations that merit further refinement.

First, seismic resolution inherently restricts fracture detection capability. The ant-tracking approach only captures fractures at or above seismic tuning scale; sub-seismic fractures, which can induce unexpected lost circulation, remain unresolved, representing the primary source of prediction mismatch. Second, the current decision-tree risk model is dominated by geological predictors and does not systematically integrate engineering variables such as drilling fluid properties, equivalent circulating density, and hydraulic parameters, which can modulate the threshold and severity of lost circulation under the same geological settings. Third, multi-parameter inversion accuracy depends on well control density and seismic data quality, and may deteriorate in sparsely drilled intervals.

Future research will prioritize: (1) incorporating pre-stack seismic inversion and advanced fracture attributes to improve sub-seismic fracture characterization; (2) coupling geological risk quantification with engineering operational parameters to build an integrated geo-engineering prediction framework; (3) extending the workflow to analogous faulted basins to verify its transferability and generalizability.

7 Conclusions

This study presents an integrated pre-drilling lost circulation prediction method for intervals with special lithologies in the southern Dagang exploration area, based on systematic analysis of controlling mechanisms and multi-source geophysical data fusion. The key findings and contributions are summarized as follows:

(1) Mechanistic insight: Lost circulation in the study area is geologically controlled. Volcanic rocks and bioclastic limestones provide abundant storage space for

drilling fluid via primary pores and dissolution vugs, while tectonic fractures associated with regional faulting act as high-permeability flow conduits. The coupled development of special lithologies and fractures is the core mechanism driving catastrophic lost circulation.

(2) Technical advancement: The combination of well log reconstruction and multi-parameter geostatistical seismic inversion effectively improves special lithology identification accuracy, with prediction coincidence rates exceeding 91% for both bioclastic limestone and volcanic rock. The results reveal that special lithologies are distributed along fault zones in a belt-like pattern and develop at multiple stratigraphic levels vertically.

(3) Predictive framework: Three distinct lost circulation seismic response patterns are established based on coupled lithology-fracture analysis. A decision tree model integrating lithology, thickness, and fracture intensity enables quantitative, stratified pre-drilling risk assessment, achieving a prediction accuracy of 83.4% for newly drilled wells.

(4) Practical implications: This method fully integrates geological, well log, and seismic data, and is particularly suited for pre-drilling lost circulation prediction in complex fault-block regions with special lithology development. It provides a scientific basis for drilling fluid density optimization, lost circulation contingency planning, and wellbore design, with potential for broader application in analogous petroleum basins worldwide.

This study has some limitations that warrant further research. First, seismic resolution limits the detection of sub-seismic fractures, which can contribute to unexpected lost circulation. Second, the current model does not explicitly incorporate engineering parameters such as drilling fluid properties and hydraulics, which can modulate lost circulation severity. Future work will focus on integrating higher-resolution fracture characterization and engineering factors to further improve prediction accuracy and expand the method's applicability.

Data availability

The experimental data supporting the findings of this study are available from the corresponding author upon reasonable request. The data have been uploaded as supplementary files and can be accessed through the submission system.

Funding

The authors declare that the manuscript was not funded.

Competing interests

The authors declare no competing interests.

Acknowledgements

We sincerely thank Mr. Xingsong Liao, Senior Expert at Dagang Oilfield Company, CNPC; Mr. Haijun Zhang, Vice President of the Petroleum Engineering Research Institute; Mr. Jingtao Sun, Director of the Drilling Engineering Technology Research Institute; Ms. Hua Wu, Deputy Director; Ms. Guona Wang, Second-Class Engineer; and Mr. Xiaofeng Tan, Third-Class Engineer, for their valuable guidance and strong support throughout this research.

Author contributions

Software, writing-original drafts, data curation, investigation, writing-review & editing, X.D.; resources, L.X.; methodology, Z.H.; conceptualizing, S.J.; supervision, W.H.; visualization, W.G.; formal analysis, T.X. All authors have read and agreed to the published version of the manuscript.

Additional information

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