

Article

Quantitative Characterization of Connectivity in Fracture–Cave Carbonate Reservoirs Under Main Fault Constraints Based on the MFC-FVCP Model and Its Application to Remaining Oil Enrichment Prediction

Xiao Zhang ¹, Qi Chang ¹, Zhen Wang ¹, Xiaobo Peng ² and Shijie Zhu ^{3,*}

¹ Sinopec Corporation, Northwest Oilfield Branch, Urumqi 830011, China; zhangxiao.xbsj@sinopec.com (X.Z.); changqi.xbsj@sinopec.com (Q.C.); wangzh8767.osjw@sinopec.com (Z.W.)

² School of Geophysics and Petroleum Resources, Yangtze University, Wuhan 430100, China; pxbcn@126.com

³ School of Geosciences, Yangtze University, Wuhan 430100, China

* Correspondence: 2024730058@yangtzeu.edu.cn

Abstract

The fracture–cave carbonate reservoir in Unit S91 of the Tahe Oilfield is jointly controlled by strike-slip fault activity, karstification, and later-stage fracture development, resulting in reservoir spaces characterized by strong heterogeneity, strong discreteness, and multi-scale superimposition. The inter-well connectivity of this type of reservoir is not governed by the size of a single fracture–cave body or local fracture density, but rather by the spatial configuration among the main controlling fault, the associated fracture network, and the fracture–cave reservoir bodies. As the reservoir enters the middle–high-water-cut development stage, the production differential between dominant connecting channels and weakly connected fracture–cave bodies further enlarges, leading to marked heterogeneity in the remaining oil distribution. Integrating post-stack seismic data, fracture prediction, RGB attribute fusion, production performance, and numerical simulation data, this paper constructs a main fault-controlled fracture–vug coupling probability (MFC-FVCP) model under the constraint of the main controlling fault. Unlike conventional multi-attribute fusion methods that mainly enhance seismic anomaly visualization, the MFC-FVCP model transforms the main fault constraint, fracture connectivity, and fracture–cave reservoir-body effectiveness into a unified coupling probability. The model uses three core components—the main fault response field, the fracture attribute response field, and the fracture–cave reservoir body response field—to characterize the fault-control effect, fracture-network continuity, and effective reservoir-body response, respectively. By evaluating the coupling probability, the inter-well connectivity potential is assessed, the dominant connectivity areas where fractures and fracture–cave bodies synergistically develop under the constraint of the main controlling fault are identified, and potential remaining oil targets are clarified. The predicted connectivity pattern was further constrained by production performance, nitrogen injection response, and staged oil saturation simulation, which improves the reliability of remaining oil enrichment prediction. The results show that the T74 layer is the dominant development interval of fracture–cave reservoir bodies in Unit S91. These fracture–cave bodies are mainly distributed along the main controlling fault and associated fracture zones in beaded, chain-like, and banded patterns, exhibiting distinct fault-and-fracture control characteristics. Potential point A near well TK858XCH features both good reservoir physical properties and insufficient sweep efficiency, making it a key target for subsequent injection–production adjustment and remaining oil tapping.

Academic Editor: Qingbang Meng

Received: 29 May 2026

Revised: 24 June 2026

Accepted: 29 June 2026

Published: 8 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\) license](https://creativecommons.org/licenses/by/4.0/).

The MFC-FVCP model can incorporate static seismic responses, fracture–cave spatial structures, and dynamic development responses into a unified evaluation framework, providing a quantitative basis for characterizing inter-well connectivity and identifying remaining oil enrichment areas in fracture–cave carbonate reservoirs.

Keywords: Unit S91; MFC-FVCP model; connectivity; structure gradient tensor attribute; fracture density; remaining oil distribution

1. Introduction

The fracture–cave carbonate reservoir in the Tahe Oilfield is jointly controlled by multiphase tectonic–karst processes, paleogeomorphology, and hydrodynamic conditions, resulting in strong heterogeneity in the shape, scale, and spatial distribution of caves and fractures [1–5]. This reservoir complexity leads to diverse inter-well connectivity relationships and significant differences in injection–production responses during development. As the reservoir enters the middle–high-water-cut stage, preferential flow pathways are strengthened, gas and water channeling intensify, and remaining oil becomes more widely dispersed and concealed, severely restricting the improvement of the recovery factor. Although traditional methods can identify large-scale caves and major faults, their ability to characterize small-scale fracture–cave complexes is limited, making it difficult to meet the requirements of remaining oil prediction and well pattern optimization in the late development stage [6–11].

Considerable research has been conducted on fracture–cave reservoirs. Seismic inversion and karst facies-controlled modeling can reveal the macroscopic distribution pattern, but owing to resolution limitations and structural complexity, they mostly remain qualitative and are unable to resolve the spatial assemblage of small-scale fracture systems [12,13]. Tracer monitoring and numerical simulation have played a role in inter-well connectivity evaluation and remaining oil studies, but they often focus on a single scale or method, resulting in insufficient coupling between static models and dynamic data, and a lack of unified quantitative criteria for connectivity classification. In terms of development strategies, attempts have been made to implement techniques such as cyclic water flooding and fluid potential regulation [14,15], but these rely heavily on empirical judgment and lack detailed geological support regarding reservoir connectivity structure and remaining oil distribution. In recent years, methods such as multi-scale multiple continuum models [15–20], topological networks, and deep learning have been gradually introduced, showing potential for quantitative characterization. However, their application remains mostly confined to a single technical route, and a systematic evaluation framework integrating multi-attribute characterization and dynamic data verification has not yet been established [20–22].

To address the significant inter-well connectivity differences in static structure characterization and unclear remaining oil distribution in the connectivity evaluation of fracture–cave carbonate reservoirs, this study constructs the MFC-FVCP model [23–27]. Fault enhancement filtering and direction-constrained ant tracking are used to finely identify main controlling faults and associated fractures. By integrating fault distance decay, fracture orientation matching, and fault size differences, the main fault influence field is established to characterize the constraint intensity of the fault system on fracture development and the spatial configuration of fracture–cave reservoir bodies [28–32]. Furthermore, fracture-sensitive attributes such as ant tracking, variance, curvature, gradient magnitude, and structure gradient tensor are combined to construct the fracture attribute response field. Combined with fracture density results from different time windows of the T74 layer,

the model constrains the planar heterogeneous distribution and vertical continuity of fractures. For fracture–cave reservoir body characterization, RGB attribute fusion is embedded into the MFC-FVCP model, allowing the boundary features, internal anomalies, and spatial continuity of fracture–cave reservoir bodies to be incorporated into the fracture–cave coupling evaluation, thereby transforming from single-attribute identification to quantitative characterization of fracture–cave connectivity relationships. The static connectivity paths characterized by the model are comprehensively compared with production dynamic responses, nitrogen injection performance, and oil saturation simulation results, clarifying the differences in inter-well connectivity intensity under different fault–fracture–cave assemblage patterns and their geological controlling factors [32–35]. The occurrence characteristics and enrichment patterns of the remaining oil are analyzed, and favorable remaining oil enrichment zones are delineated, providing a basis for subsequent scheme optimization and remaining oil tapping.

2. Geological Setting

The study area, Unit S91 of the Tahe Oilfield, is located in the southwestern part of the Akekule Uplift in the Northern Tarim Uplift (Figure 1). It is a typical deep fracture–cave carbonate reservoir in a shallow overburden area. The overburden in the area is relatively thin, and the tectonic setting is generally stable. Multiphase tectonic evolution indicates that strike-slip fault activity and karstification during the Caledonian and Hercynian periods jointly controlled reservoir formation and modification. The reservoir space in the study area is diverse, including karst caves, tectonic fractures, dissolution fractures, and fractured pores, exhibiting an obvious fracture–cave superimposition characteristic. The reservoir mainly occurs in the Middle-Lower Ordovician Yingshan Formation and the Lower Cambrian strata. The lithology is predominantly carbonate, locally interbedded with lenticular micritic limestone, providing favorable conditions for karst development. The fracture–cave reservoir bodies show strong heterogeneity and spatial discreteness in the region, with significant differences in fracture–cave development degree between different depth intervals, forming multiple independent or weakly connected composite reservoir systems. Controlled by the coupling of main faults and paleo-karst channels, the lateral connectivity of the reservoir varies greatly, and the hydrocarbon occurrence state is complex.

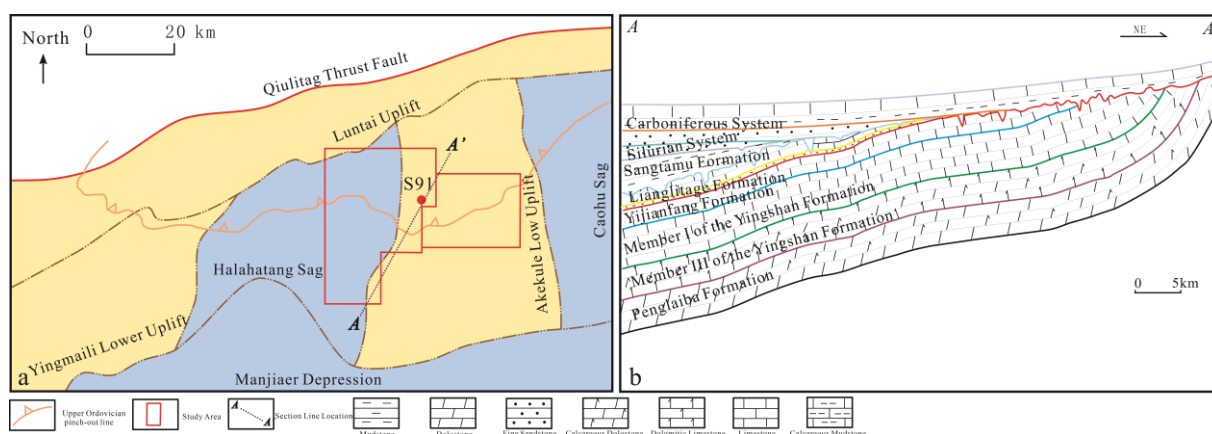


Figure 1. Geological setting and location of Unit S91 in the Tahe Oilfield.

3. Data and Methods

3.1. Fault Enhancement and Ant-Tracking Method

The main controlling faults and their associated fractures in fracture–cave carbonate reservoirs are usually characterized by seismic reflection event offsets, locally reduced coherence, abrupt changes in reflection texture, and enhanced linear discontinuities. Coherence, variance, and structural seismic attributes have been widely used for fault and fracture identification, among which coherence attributes can highlight lateral discontinuities in seismic reflections and serve as one of the fundamental attributes for fault interpretation. However, the fracture–cave carbonate reservoir in Unit S91 of the Tahe Oilfield is jointly affected by karstification, strike-slip fault activity, and multiphase fracture development. The seismic responses often contain fault discontinuities, abrupt fracture–cave boundaries, local strong amplitude anomalies, and random noise simultaneously. Directly using the original seismic volume or a single discontinuity attribute for fault interpretation tends to cause problems such as unclear fault boundaries, poor continuity of associated fractures, and spurious local fracture responses. Therefore, this paper introduces fault enhancement filtering before ant tracking to improve the continuity and identifiability of linear responses of faults and fractures. The main purpose of fault enhancement filtering is to preserve fault boundaries and structural abrupt information while suppressing the interference of random noise and non-structural anomalies on fault identification. Previous studies have shown that fault-oriented structural enhancement processing can improve the continuity of fault attribute volumes and the stability of fault surface construction by enhancing discontinuous responses in seismic volumes and estimating fault strike and dip. Based on this concept, this paper first applies structure-oriented preprocessing to post-stack seismic data to highlight the seismic responses of fault surfaces, fault damage zones, and small-scale linear discontinuities. Ant tracking is then performed on the fault-enhanced volume to avoid noise amplification and fault fragmentation caused by tracking directly on the original seismic volume.

The ant-tracking method is an automatic fault extraction technique based on swarm intelligence. Its basic principle is to simulate the behavior of ant colonies searching for optimal paths, automatically tracking discontinuous anomalies with continuous linear features in a 3D seismic attribute volume. The automatic fault extraction method using artificial ant colonies proposed by Pedersen provides an important technical foundation for automatic 3D seismic fault identification. This method typically uses coherence, variance, chaos, or fault-enhancement attributes as input. By setting parameters such as search step, similarity threshold, pheromone decay coefficient, and iteration number, virtual ants migrate along directions with strong discontinuity and good spatial continuity, ultimately forming linear anomaly volumes of faults and fractures. In recent years, multi-attribute preprocessing and enhanced ant-tracking methods have further demonstrated that appropriate attribute preprocessing can improve fault identification continuity and reduce noise interference.

Considering the obvious directionality of the strike-slip fault system in Unit S91, a directional consistency constraint is introduced on the basis of conventional ant tracking. The core of this constraint is to match the local linear anomaly direction with the strike of the main controlling fault or the regional tectonic stress direction. When the local anomaly direction is highly consistent with the strike of the main controlling fault, it is more likely to represent effective associated fractures induced by fault activity. When the local anomaly direction differs significantly from the main fault strike, its interpretation weight as an effective fracture is reduced. This treatment can, to some extent, mitigate spurious fracture responses caused by cave boundaries, local strong reflection anomalies, and random noise,

making the tracking results more consistent with the geological patterns of fracture development under strike-slip fault control. In this study, ant tracking was performed on the fault-enhanced seismic attribute volume rather than directly on the original post-stack seismic volume. This treatment reduces the possibility that isolated cave boundaries, local strong-amplitude anomalies, and random noise are mistakenly tracked as structural fractures. The ant-tracking parameters were set as follows: 80 iterations, a tracking step of 100 samples, a similarity threshold of 0.70, a pheromone decay coefficient of 0.90, and an initial ant number of 2000. This parameter combination was selected to preserve the continuity of the main faults and associated fractures while avoiding excessive enhancement of weakly continuous non-structural anomalies.

The azimuthal constraint was defined using the interpreted strike of the main controlling fault as the reference direction. Considering the 180° symmetry of fracture strike, the minimum included angle between the local linear anomaly and the main fault strike was calculated. Linear anomalies within $\pm 25^\circ$ were classified as strongly direction-consistent responses and were preferentially retained. Anomalies with angular differences of $25\text{--}45^\circ$ were regarded as weakly direction-consistent responses and were assigned lower weights. Linear anomalies with angular differences greater than 45° were weakened in the connectivity evaluation because they were less likely to represent effective associated fractures controlled by the main strike-slip fault system.

3.2. Main Controlling Fault Constraint Factor

A fault zone is not a single geometric interface but a composite structural unit composed of a fault core, a fault damage zone, and an associated fracture system. The structure of the fault zone and its permeability heterogeneity are important factors controlling fluid migration. A fault can act as a fluid conduit, a barrier, or a conduit–barrier composite system under specific conditions. The fault damage zone usually contains fracture networks of different scales, orientations, and connectivity degrees, and their geometric structures show certain similarities among different fault types such as strike-slip faults, normal faults, and reverse faults. Previous studies have also pointed out that there is a close relationship between fault zone structure, mechanical properties, and fluid flow characteristics, and fault geometry cannot be discussed separately from reservoir flow capacity. In a strike-slip fault system, the fracture density around the fault core generally decreases with increasing distance from the fault core, and macroscopic fractures exhibit a clear spatial pattern in the fault damage zone. Therefore, in the connectivity evaluation of fracture–cave carbonate reservoirs, the main controlling fault should not be treated merely as a structural boundary in seismic interpretation maps, but should be further transformed into a geological constraint factor that can participate in quantitative calculations.

The formation and connectivity of fracture–cave reservoir bodies in Unit S91 are jointly controlled by strike-slip fault activity, fracture development in the fault damage zone, and karst fluid migration. On one hand, the main controlling fault provides a preferential migration pathway for fluids; on the other hand, it induces the development of associated fractures through the fault damage zone, enabling discrete fracture–cave bodies to connect along the fault and fracture zones. If a fracture–cave anomaly is far from the main controlling fault, or if the orientation of surrounding fractures lacks consistency with the main fault strike, then even if the anomaly has a strong amplitude response, it may not have effective inter-well connectivity significance. Therefore, this paper introduces a main controlling fault constraint factor into the MFC-FVCP model to quantitatively characterize the degree to which any spatial location is controlled by the main controlling fault. The main controlling fault not only determines the spatial background of fracture devel-

opment but also influences fluid migration pathways and the assembly pattern of fracture–cave reservoir bodies. Hence, in the static connectivity evaluation, this paper transforms the main controlling fault from a conventional interpretation object into a quantitative constraint factor to characterize the degree of control exerted by the main controlling fault at any spatial location.

Let any spatial location in the study area be x , let the i -th main controlling fault be F_i , and let the number of main controlling faults involved in the calculation be N . Then the main controlling fault constraint factor $M(x)$ is defined as:

$$M(x) = 1 - \prod_{i=1}^N [1 - \omega_i D_i(x) O_i(x) S_i] \quad (1)$$

where $M(x)$ is the main controlling fault constraint intensity at location x , ranging from 0 to 1; ω_i is the comprehensive weight of the i -th fault; $D_i(x)$ is the fault distance decay term; $O_i(x)$ is the orientation matching term; and S_i is the fault size term.

The fault distance decay term is used to describe the gradual weakening of the fault's modification effect on the surrounding reservoir with increasing distance. Considering that the damage zone of a strike-slip fault exhibits significant anisotropy, this paper employs an anisotropic Gaussian function to represent the distance decay effect:

$$D_i(x) = \exp \left[- \left(\frac{d_{i\perp}^2}{2\sigma_{i\perp}^2} + \frac{d_{i\parallel}^2}{2\sigma_{i\parallel}^2} \right) \right] \quad (2)$$

where $d_{i\perp}$ is the perpendicular distance from location x to the i -th fault; $d_{i\parallel}$ is the relative distance from location x along the strike direction of the i -th fault; and $\sigma_{i\perp}$ and $\sigma_{i\parallel}$ are the fault's perpendicular influence radius and strike influence radius, respectively. This formulation captures the spatial characteristic that a strike-slip fault has a larger influence range along the strike direction and a relatively narrower range perpendicular to the fault.

The orientation-matching term describes the directional consistency between local fractures or linear anomalies and the main controlling fault, and is expressed as follows:

$$O_i(x) = |\cos(\theta_f(x) - \theta_i)| \quad (3)$$

where $\theta_f(x)$ is the dominant direction of local fractures or linear anomalies at location x and θ_i is the strike of the i -th main controlling fault. Since fracture strike has 180° symmetry, the absolute cosine form is used to eliminate the effect of direction reversal.

The fault size term is used to characterize the contribution differences of faults at different levels to fracture development and fluid conduits, and is expressed as follows:

$$S_i = \lambda_1 L_i^* + \lambda_2 R_i^* + \lambda_3 C_i^* \quad (4)$$

where L_i^* is the normalized fault length; R_i^* is the normalized fault attribute response intensity; C_i^* is the normalized fault continuity; and λ_1 , λ_2 , λ_3 are weight coefficients, satisfying:

$$\lambda_1 + \lambda_2 + \lambda_3 = 1 \quad (5)$$

The main controlling fault constraint factor $M(x)$ integrates fault distance, size, and orientation matching into a unified quantitative framework and can be used for subsequent fracture–cave connectivity probability calculation. In the calculation of the fault-size term λ_1 , λ_2 , and λ_3 were assigned values of 0.40, 0.40, and 0.20, respectively. The fault-distance decay term and the orientation-matching term were assigned higher weights because the effective connectivity of fracture–cave bodies in Unit S91 is primarily controlled by their proximity to the main strike-slip fault damage zone and by the directional consistency between associated fractures and the main fault strike. The fault-size term was assigned a lower weight because it mainly acts as a scale correction factor. If

fault scale is overemphasized, the model may overestimate all areas around large faults and weaken the contribution of local fracture–cave assemblages controlled by secondary faults.

Sensitivity tests showed that increasing λ_3 led to excessive concentration of high-probability zones around large faults, whereas decreasing λ_1 or λ_2 weakened the constraints of the fault damage zone and fracture orientation consistency, increasing the risk of misidentifying isolated amplitude anomalies as connected units. Therefore, the combination of 0.40, 0.40, and 0.20 provides a reasonable balance between main fault proximity, fracture orientation consistency, and fault-scale correction (Table 1).

Table 1. Model parameters and calibration basis for the MFC-FVCP workflow.

Parameter	Meaning	Value/Setting	Basis
λ_1	Fault-distance decay weight	0.40	Main fault damage-zone control and fracture density decay
λ_2	Orientation-matching weight	0.40	Consistency between local fracture orientation and main fault strike
λ_3	Fault-size correction weight	0.20	Correction for fault length, attribute response, and continuity
Ant iterations	Iteration number for ant tracking	80	Preserves main fault continuity while avoiding over-tracking
Tracking step	Ant-tracking step size	100 samples	Consistent with planar extension scale of main faults and associated fractures
Similarity threshold	Structural similarity filter	0.70	Balances weak associated fracture preservation and noise suppression
Pheromone decay	Pheromone decay coefficient	0.90	Preserves dominant paths and weakens isolated anomalies
Azimuthal tolerance	Strong direction consistency	$\pm 25^\circ$	Defined relative to interpreted strike of main controlling fault

3.3. Multi-Time-Window Fracture Density Characterization

Fractures serve as key flow channels connecting discrete fracture–cave reservoir bodies, and their spatial continuity directly affects inter-well connectivity. Since a single horizon or a single time-window fracture density attribute cannot fully reflect the vertical development characteristics of the fracture system, this study extracts fracture density attributes from multiple time windows around the target interval to characterize the planar heterogeneity, orientation stability, and vertical inheritance of the fracture system. The basic logic of multi-time-window fracture density characterization is as follows: different time windows correspond to fracture responses in different vertical ranges near the target interval. If a fracture anomaly appears in only one time window, it may represent local noise, isolated fractures, or limited-scale anomalies. If high fracture-density values maintain good spatial correspondence and orientation consistency across multiple time windows, it indicates that the fracture system has strong vertical extension capability and potential connectivity significance.

The T74 layer is the main target interval for fracture–cave connectivity evaluation in Unit S91. However, the fracture system and fracture–cave reservoir bodies are not strictly confined to a single seismic horizon. Therefore, three time windows, namely T74+20 ms,

T74+40 ms, and T74+60 ms, were selected to evaluate the vertical inheritance and spatial stability of fracture anomalies around the target interval. The T74+20 ms window mainly reflects near-target fracture responses directly related to the T74 reservoir interval. The T74+40 ms window characterizes fracture continuity within a broader vertical range around the target layer. The T74+60 ms window further examines whether the fault–fracture system maintains vertical inheritance at a larger scale.

To incorporate the multi-time-window fracture information into the coupling model, a fracture connectivity factor $F(x)$ is constructed, expressed as:

$$F(x) = \mu_1 F_d(x) + \mu_2 F_s(x) + \mu_3 F_o(x) \quad (6)$$

where $F(x)$ is the fracture connectivity factor at location x ; $F_d(x)$ is the normalized fracture density; $F_s(x)$ is the normalized fracture development intensity; $F_o(x)$ is the normalized fracture orientation stability; and μ_1 , μ_2 , μ_3 are the weight coefficients.

This factor is not simply equivalent to fracture density, but rather integrates fracture development intensity, spatial continuity, and orientation stability. In areas where fracture density is high but orientations are disordered and continuity is poor, the contribution to connectivity is relatively limited. Conversely, in areas characterized by high fracture density, stable orientation, and good alignment with the main controlling fault, effective fluid conduits are more likely to develop.

3.4. MFC-FVCP-RGB Multi-Attribute Identification Method for Fracture–Cave Reservoir Bodies

Seismic attribute analysis is of fundamental importance for identifying carbonate fracture–cave reservoir bodies. Attributes such as amplitude, coherence, curvature, variance, gradient-based attributes, and spectral decomposition attributes can, from different perspectives, reflect structural discontinuities, variations in reflection energy, lithological changes, and reservoir space anomalies. Chopra and Marfurt systematically reviewed the application of modern volume attributes in structural deformation, carbonate diagenesis, reservoir characterization, and geological body identification, noting that different attributes exhibit different geological sensitivities and that a single attribute is generally insufficient to fully capture the internal structure of complex reservoirs.

RGB multi-attribute fusion is a commonly used visualization technique in recent seismic interpretation. Its basic principle is to assign different attributes to the red, green, and blue channels respectively, and to enhance the synergistic response among multiple attributes through color mixing. Relevant studies have shown that RGB fusion can integrate subtle information from multiple seismic attributes into a single display space, helping interpreters identify sedimentary bodies, structural features, and reservoir anomalies that are not easily discernible from any single attribute. However, it should be noted that the input attributes should have comparable numerical ranges and reasonable physical meanings; otherwise, the color interpretation may become biased.

For fracture–cave carbonate reservoirs, the reservoir bodies typically consist of caves, fractures, dissolution vugs, and multi-scale fracture–cave complexes, and their seismic responses exhibit strong heterogeneity and multiple interpretational possibilities. Previous studies have indicated that fracture–cave carbonate reservoirs are significantly influenced by post-depositional tectonic and karst modifications, resulting in complex reservoir types. It is difficult to reliably delineate the spatial structure of reservoir bodies using only seismic attribute carving or deterministic interpretation methods; therefore, fusion of multi-source geological information is required to enhance the robustness of reservoir characterization. Fracture–cave reservoir bodies generally manifest as composite seismic responses, including strong amplitude anomalies, event disturbances, enhanced structural discontinuities, and abrupt local boundary changes. A single seismic attribute typi-

cally highlights only one aspect of fracture–cave reservoir bodies and cannot simultaneously characterize their boundaries, internal anomalies, and spatial continuity. Consequently, this study adopts the MFC-FVCP-RGB multi-attribute fusion method to identify fracture–cave reservoir bodies.

In this method, three attributes—structure gradient tensor, variance, and gradient magnitude—are selected as the inputs for the three RGB channels. The structure gradient tensor attribute is primarily used to enhance directional changes in seismic reflection structure and discontinuous boundaries. The variance attribute characterizes the disruption of lateral event continuity. The gradient magnitude attribute highlights local amplitude jumps and anomalous boundaries. After normalization, these three attributes are combined to form an RGB fusion vector.

$$C_{RGB}(x) = [w_R P_{sgt}(x), w_G P_{var}(x), w_B P_{grad}(x)] \quad (7)$$

where $C_{RGB}(x)$ is the RGB fusion vector at location x ; $P_{sgt}(x)$, $P_{var}(x)$, and $P_{grad}(x)$ are the normalized structure gradient tensor, variance, and gradient magnitude attributes, respectively; and w_R , w_G , w_B are the weights of the RGB channels.

The weights of the RGB channels were set to 0.40, 0.30, and 0.30 for the structure gradient tensor, variance, and gradient magnitude attributes, respectively. The structure gradient tensor was assigned a slightly higher weight because it is more sensitive to directional changes and discontinuous boundaries of fracture–cave reservoir bodies. The variance and gradient magnitude attributes were used as auxiliary constraints to characterize reflection continuity disruption and local boundary changes. Therefore, the RGB fusion result was not used only as a visualization product; instead, it was transformed into a quantitative reservoir-body effectiveness indicator for subsequent coupling probability calculation.

To enable the RGB fusion result to be used not only for image display but also incorporated into the connectivity evaluation model, this paper further introduces the amplitude anomaly attribute and constructs the fracture–cave reservoir body effectiveness indicator $V(x)$:

$$V(x) = \eta_1 \|C_{RGB}(x)\|_2 + \eta_2 P_{amp}(x) + \eta_3 \|C_{RGB}(x)\|_2 P_{amp}(x) \quad (8)$$

where $V(x)$ is the effectiveness indicator of the fracture–cave reservoir body; $\|C_{RGB}(x)\|_2$ is the Euclidean norm (2-norm) of the RGB fusion vector, used to characterize the composite intensity of structural boundaries and discontinuous responses; $P_{amp}(x)$ is the normalized amplitude anomaly attribute; and η_1 , η_2 , η_3 are weight coefficients.

Among these, $\|C_{RGB}(x)\|_2 P_{amp}(x)$ is the boundary–internal anomaly synergy term. This term is designed to highlight fracture–cave reservoir bodies that exhibit both clear boundary responses and significant amplitude anomalies while reducing misidentification caused by isolated strong-amplitude anomalies or isolated structural boundaries. Through this method, the multi-attribute response of fracture–cave reservoir bodies is transformed into an effectiveness indicator that can participate in probability calculations.

The amplitude anomaly attribute was further introduced to constrain the internal reservoir-space response. This design reduces two types of misinterpretation: isolated strong-amplitude anomalies without structural boundary support and isolated structural discontinuities without effective reservoir-space response. Thus, the effectiveness indicator emphasizes the co-occurrence of boundary response, internal anomaly, and spatial continuity.

3.5. Fracture–Cave Coupling Probability Model

The inter-well connectivity of fracture–cave carbonate reservoirs exhibits significant multi-media coupling characteristics. It is not determined simply by the development degree of a single vug, a single fracture, or a single fault, but is jointly controlled by the fault damage zone, the fracture network, the cave reservoir bodies, and their spatial configuration. Previous studies have shown that deep to ultra-deep fault-controlled fracture–cave carbonate reservoirs generally feature large burial depth, weak seismic response, discrete reservoir space, and strong heterogeneity. Reservoir prediction requires the integrated consideration of fault control, fracture–cave response, and multi-attribute constraint information. Especially in the carbonate reservoirs of the Tarim Basin, fractures not only affect the formation of reservoir space but also control the connectivity between discrete vugs and caves, making them a key factor influencing inter-well connectivity and development performance. For the connectivity evaluation of fracture–cave reservoirs, previous studies have mainly been conducted from two perspectives: static geological characterization and dynamic production response. Static methods mostly rely on seismic attributes, fault interpretation, reservoir body delineation, and geological modeling to describe the spatial configuration of faults, fractures, and fracture–cave bodies. Dynamic methods mainly use production performance, pressure response, tracer monitoring, or injection–production response relationships to invert inter-well connectivity intensity and preferential fluid pathways. In recent years, multi-source information fusion has gradually become an important direction for connectivity research in this type of reservoir. For example, relevant studies have combined seismic, well logging, dynamic production data, and quantitative evaluation methods to characterize the dynamic–static connectivity of fracture–cave marine carbonate reservoirs. Other studies have used multi-geological information fusion methods to improve the reliability of fracture–cave reservoir body identification and modeling.

A fracture–cave coupling probability model is constructed to quantitatively evaluate the likelihood that the fracture network and fracture–cave reservoir bodies will form an effective connected unit under the constraint of the main controlling fault. This model does not simply superimpose high values of fault, fracture, and cave attributes, but emphasizes the synergistic relationship among the three geological elements: the main controlling fault provides the structural and fluid migration background, the fracture network provides connecting pathways between discrete fracture–cave bodies, and the fracture–cave reservoir bodies provide effective storage space. Only when these three elements have a good spatial match in a given area is that area more likely to form an effective inter-well connected unit.

The model expression is:

$$P_c(x) = \frac{1}{1 + \exp[-k(\alpha M(x) + \beta F(x) + \gamma V(x) + \delta M(x)F(x)V(x) - T)]} \quad (9)$$

where $P_c(x)$ is the fracture–cave coupling probability at location x ; $M(x)$ is the main controlling fault constraint factor; $F(x)$ is the fracture connectivity factor; $V(x)$ is the effectiveness indicator of the fracture–cave reservoir body; α , β , γ , and δ are weight coefficients; $M(x)F(x)V(x)$ is the fault–fracture–cave synergy term; T is the threshold parameter; and k is the probability mapping adjustment coefficient.

An effective connected unit is not determined by a high value of a single attribute, but rather by the joint action of the main controlling fault, the fracture network, and the fracture–cave reservoir body. If an area has only a strong-amplitude anomaly but lacks fracture connectivity or is far from the main controlling fault, its coupling probability will not be significantly increased. If an area simultaneously exhibits a fault constraint, fracture

connectivity, and fracture–cave reservoir body response, it is more likely to form a dominant connected unit.

The coupling probability does not represent a simple linear superposition of high-value seismic attributes. Instead, it evaluates the spatial compatibility among the main fault damage zone, directionally stable fracture networks, and effective fracture–cave reservoir bodies. A high-amplitude anomaly contributes significantly to the coupling probability only when it is supported by fault constraint and fracture connectivity. Similarly, high fracture density alone does not necessarily indicate strong connectivity unless the fractures exhibit stable orientation, vertical inheritance, and spatial consistency with the main controlling fault. Therefore, the MFC-FVCP model is designed to distinguish isolated strong anomalies from effective connected units formed by fault–fracture–cave spatial matching.

4. Results and Discussion

4.1. Fault Enhancement and Direction-Constrained Ant-Tracking Results

After fault enhancement filtering has been applied to the post-stack seismic data, the responses of faults and linear discontinuities near the T74 layer in Unit S91 are significantly enhanced. Compared with the original seismic volume, the boundaries of the main controlling faults in the fault enhancement result are clearer, the offset features of local reflection events are more prominent, and the interference of random noise and weakly continuous reflections on fault interpretation is reduced. After fault enhancement processing, linear anomalies that originally appeared as weak discontinuities or locally fragmented responses in the study area are expressed continuously, providing a relatively stable attribute basis for subsequent ant tracking to extract the main controlling faults and associated fractures.

Figure 2 shows the processing steps and identification results of fault enhancement and direction-constrained ant tracking for the T74 layer in Unit S91. Figure 2a presents the original post-stack seismic response, where the reflection events are generally continuous to weakly continuous, but local offsets, abrupt changes in reflection energy, and weak linear discontinuities can be observed at the locations of main fault development. Due to the superposition of random noise, fracture–cave boundary anomalies, and local weak reflections in the original seismic volume, the boundaries of the main controlling faults are not very clear, and some linear structures appear only as faint discontinuous features, making direct fine interpretation of faults and associated fractures difficult.

After fault enhancement filtering, the linear responses of the main controlling faults and their associated fractures near the T74 layer in Unit S91 are significantly improved. Compared with the original seismic volume (Figure 2a), the boundaries of the main faults, which originally appeared as weak discontinuous responses, are transformed into linear anomalies with good continuity in Figure 2b. The fault extension directions become more clearly defined, and the offset characteristics of local reflection events are more prominent. Meanwhile, the branched and pinnate associated fractures on both sides of the faults are further enhanced, and the fracture continuity is markedly better than that in the original seismic data. Random noise and weakly continuous reflections in the original data are suppressed in the enhanced results, making the distinction between faults and non-structural noise more evident. Fault enhancement filtering effectively improves the identifiability of main faults and associated fractures and provides a stable attribute basis for subsequent ant tracking.

On the basis of the fault-enhanced volume, the direction-constrained ant-tracking method is applied to extract the main controlling faults and associated fractures of the T74 layer. The tracking parameters are set as follows: 80 iterations, a step size of 100 samples, a similarity threshold of 0.70, a pheromone decay coefficient of 0.90, and an initial ant

count of 2000. This parameter combination ensures continuity in fault tracking while minimizing noise amplification due to over-tracking. The directional constraint screens the tracking paths by comparing the orientation of local linear anomalies with the strike of the main controlling faults. Linear anomalies within $\pm 25^\circ$ of the interpreted main fault strike are preferentially retained, anomalies with angular differences of $25\text{--}45^\circ$ are assigned lower weights, and anomalies exceeding 45° are weakened in the connectivity evaluation. This treatment improves the geological reliability of the extracted associated fractures and reduces the influence of isolated non-structural responses.

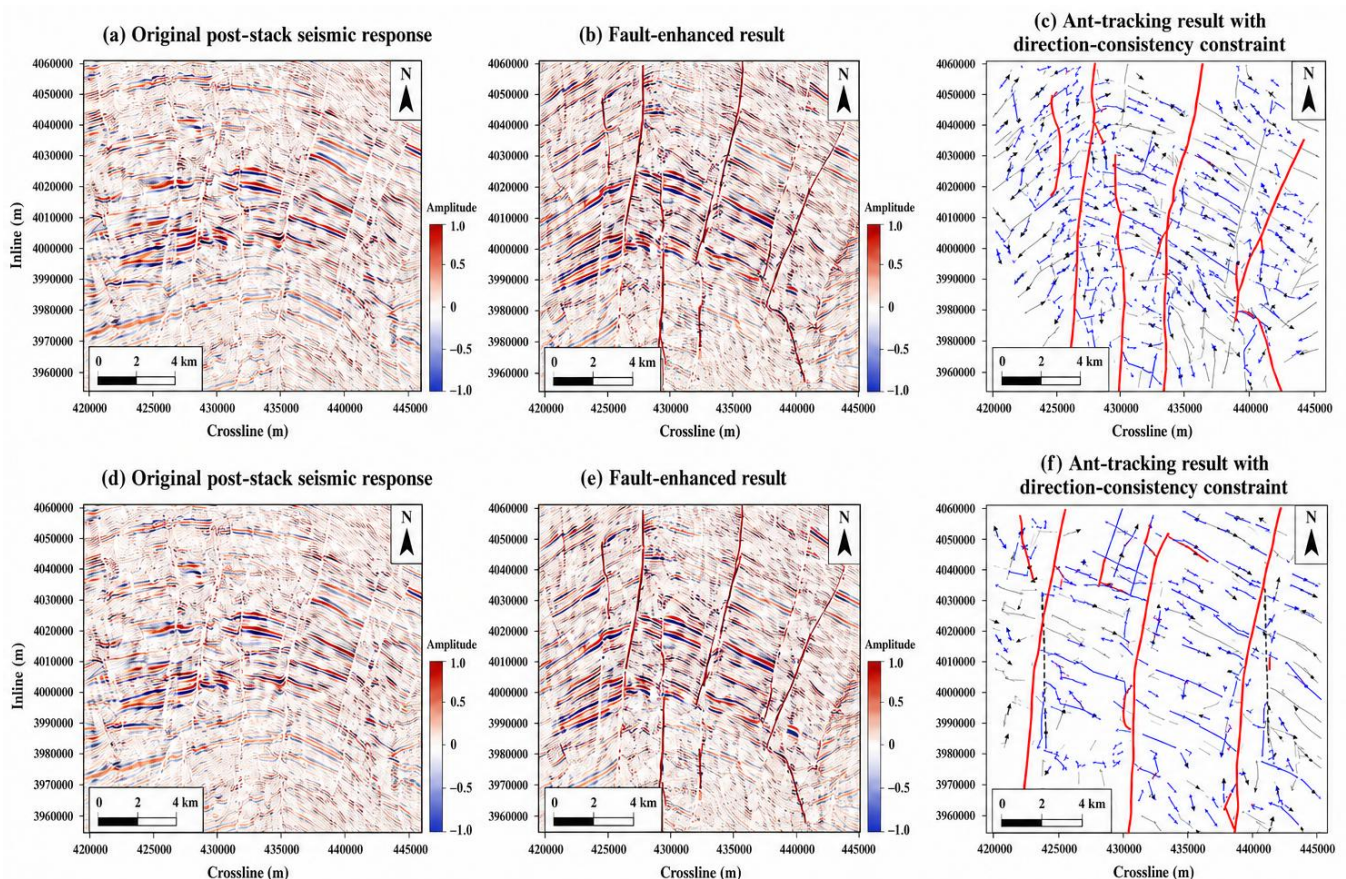


Figure 2. Fault-enhanced and direction-constrained ant-tracking results of the T74 layer. The ant-tracking parameters include 80 iterations, a step size of 100 samples, a similarity threshold of 0.70, a pheromone decay coefficient of 0.90, and an initial ant number of 2,000. The azimuthal tolerance for strong direction consistency was set to $\pm 25^\circ$ relative to the interpreted main fault strike.

As shown in Figure 2c, the ant-tracking result with a directional constraint adequately delineates the main controlling faults and the associated fracture network of the T74 layer. The main controlling faults exhibit a continuous banded pattern in plan view, with ant-tracking paths extending continuously along the main fault zones, indicating that the faults have good spatial continuity and stability. Associated fractures are mainly distributed on both sides of the main faults and preferentially propagate along branching fractures that have good directional consistency with the main fault, locally displaying pinnate, en échelon, and branching patterns. In contrast, fracture branches that are located far from the main fault or have strikes that are significantly different from the main fault show poor tracking continuity, suggesting that their contribution to the connectivity system associated with the main controlling fault is limited.

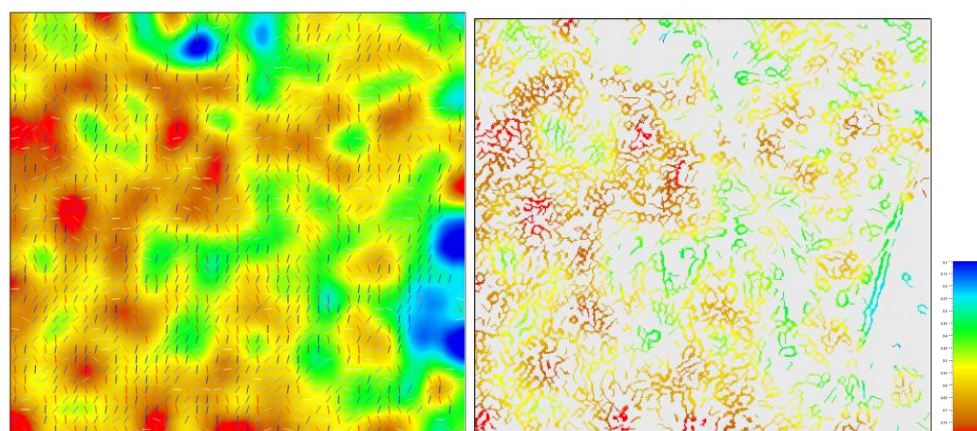
Based on the ant-tracking results, the T74 layer exhibits pronounced directionality and zonation. The main controlling faults extend continuously as banded features in plan

view, with long fault lengths, forming the fundamental structural framework for the development of fracture–cave reservoir bodies and the distribution of the fracture network in the study area. Associated fractures are mainly distributed on both sides of the main faults, at fault intersections, and in local structural transfer zones, locally displaying pinnate and branching patterns. The densest fracture-tracking responses occur in fault intersection areas, indicating that these areas have undergone intense structural fragmentation and exhibit high fracture intensity, making them favorable zones for the subsequent formation of composite fracture–cave connected units. From a spatial distribution perspective, the T74 layer can be divided into three types: main fault-controlled zones, associated fracture development zones, and weak fracture response areas. The main fault-controlled zones are characterized by linear anomalies with strong continuity, clear fault boundaries, and well-defined extension directions. The associated fracture development zones are mainly located on both sides of the main faults, appearing as small-scale but high-density linear anomalies, locally distributed in branching and en échelon patterns. The weak fracture response areas are far from the main controlling faults, where fracture-tracking paths are short, orientations are scattered, and continuity and stability are significantly reduced.

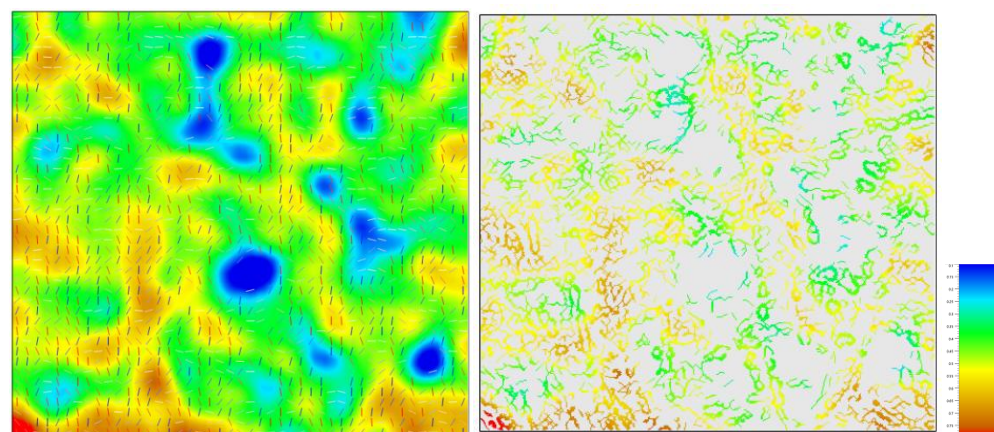
4.2. Multi-Time-Window Fracture Density and Fracture Continuity Characteristics

To identify the vertical inheritance and spatial continuity of the fracture system in the T74 layer, this study compares and analyzes the fracture density, fracture orientation, and fracture development intensity within the T74+20 ms, T74+40 ms, and T74+60 ms time windows (Figure 3). The multi-time-window fracture density results reveal the varying characteristics of fracture anomalies in different vertical ranges near the target interval, thereby avoiding the limitations of judging fracture connectivity based solely on a single horizon slice.

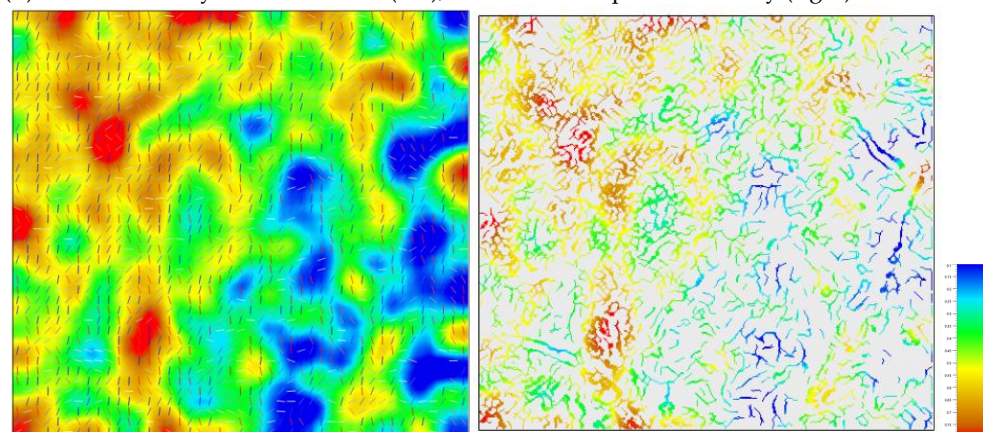
The fracture density analysis shows that within the T74+20 ms time window (Figure 3a), the overall extent of high-fracture-density areas is relatively small and spatially dispersed. Some high-value anomalies are mainly concentrated near the main faults and at local fault intersections, indicating that a certain foundation for fracture development already exists near the target interval. However, the continuity of some fracture anomalies in this time window is poor, and the connections between high-value areas are not significant, suggesting that the near-horizon fracture responses are somewhat localized and that some anomalies may represent only local damage zones or limited-scale fracture development.



(a) Fracture density and orientation (left); fracture development intensity (right) at T74+20 ms



(b) Fracture density and orientation (left); fracture development intensity (right) at T74+40 ms.



(c) Fracture density and orientation (left); fracture development intensity (right) at T74+60 ms.

Figure 3. Multi-time-window fracture density characterization around the T74 target layer. The T74+20 ms, T74+40 ms, and T74+60 ms windows represent near-target fracture response, medium vertical continuity, and larger-scale vertical inheritance of the fault–fracture system, respectively.

Within the T74+40 ms time window (Figure 3b), the extent of high-fracture-density areas expands significantly, and some previously isolated fracture anomalies begin to show spatial connections. The dense fracture zones on both sides of the main faults become more distinct, and stronger fracture development responses appear at local fault intersections. Compared with the T74+20 ms time window, the continuity of fracture anomalies within the T74+40 ms time window is enhanced, indicating that the fracture system tends to extend upward or downward over a certain vertical range. This observation suggests that the fractures near the T74 layer are not strictly confined to a single horizon but possess a certain vertical development thickness.

Within the T74+60 ms time window (Figure 3c), the high-fracture-density areas expand further, and the continuity of local high-value areas becomes even more pronounced. Anomalous responses near the main faults, at fault intersection zones, and within dense fracture zones are more prominent, indicating that the fracture systems in these areas exhibit strong vertical inheritance and spatial stability. In contrast, although local fracture-density anomalies can be observed in areas far from the main faults, their continuity is poor and their correspondence across different time windows is unstable, suggesting that they have a relatively low likelihood of serving as effective connected pathways.

Integrating the fracture density results from the three time windows, the fracture system of the T74 layer exhibits distinct fault-controlled differences and connectivity characteristics. Areas near the main faults show strong fracture responses, high density, and significant directionality, making them the primary locations for the development of potentially dominant connected channels. Fault intersection zones and structural transfer

zones display high-fracture-density values with good spatial inheritance, representing important areas of multi-scale fracture superimposition. In areas controlled by secondary faults, local fracture responses are relatively strong but with limited continuity and stability. In areas far from fault control, fracture responses are weak and fracture–cave bodies lack effective communication pathways, resulting in generally poor connectivity. The multi-time-window comparison also reveals that high fracture density does not necessarily indicate strong connectivity. Only those high-fracture-density areas that maintain a stable response across multiple time windows and show good consistency with the strike of the main controlling faults and the dominant fracture orientation are more likely to represent fracture paths with practical connectivity significance.

Fracture anomalies that remain spatially stable and directionally consistent across the three time windows are interpreted as more reliable connected pathways, whereas anomalies that appear only in a single time window are regarded as uncertain or weakly connected responses. This criterion reduces the uncertainty of single-slice interpretation and provides a more stable input for the fracture connectivity factor in the MFC-FVCP model.

4.3. MFC-FVCP-RGB Identification Results of Fracture–Cave Reservoir Bodies

Based on the seismic attribute volumes of the T74 layer, four types of attributes — structure gradient tensor, variance, gradient magnitude, and amplitude anomaly — are selected as the fundamental inputs for multi-attribute identification of fracture–cave reservoir bodies. These attributes characterize the seismic response differences of fracture–cave carbonate reservoirs based on the aspects of reflection structure variation, event continuity disruption, abrupt local amplitude changes, and strong reservoir space responses, respectively. In the MFC-FVCP-RGB identification process, each attribute is uniformly normalized to reduce the impact of differences in dimension, dynamic range, and amplitude distribution among different attributes on the integrated identification result. Subsequently, the structural attributes, continuity disruption attributes, and local gradient attributes serve as constraints on reservoir body morphology and boundaries, while the amplitude anomaly attribute serves as a constraint on the effective response of reservoir space, enabling comprehensive discrimination of the development location, morphological assemblage, and connectivity potential of fracture–cave anomalies. The core aim of this workflow is to avoid the ambiguity inherent in single-attribute interpretation and to improve the reliability of fracture–cave reservoir body identification through the consistency and complementarity of multi-attribute responses.

Figure 4 shows the planar response characteristics of the structure gradient tensor, variance, gradient magnitude, and amplitude anomaly attributes, respectively. Overall, all four attributes reveal strong heterogeneous anomalies within the T74 layer, but there are obvious differences in anomaly morphology, continuity, and spatial implications. In Figure 4a, the medium-to-high-value responses of the structure gradient tensor attribute are mainly distributed in reticular, chain-like, and locally banded patterns. The anomaly distribution has strong directionality, and some high-value zones exhibit good spatial connections. This attribute is sensitive to directional changes in reflection structure and interface abrupt changes, so its high-value areas mainly reflect the spatial contours of fracture–cave boundaries, fault boundaries, and fault-controlled zones. The banded anomalies with good continuity indicate that some fracture–cave bodies in the study area are not isolated but are controlled by fracture or fault systems along certain structural directions.

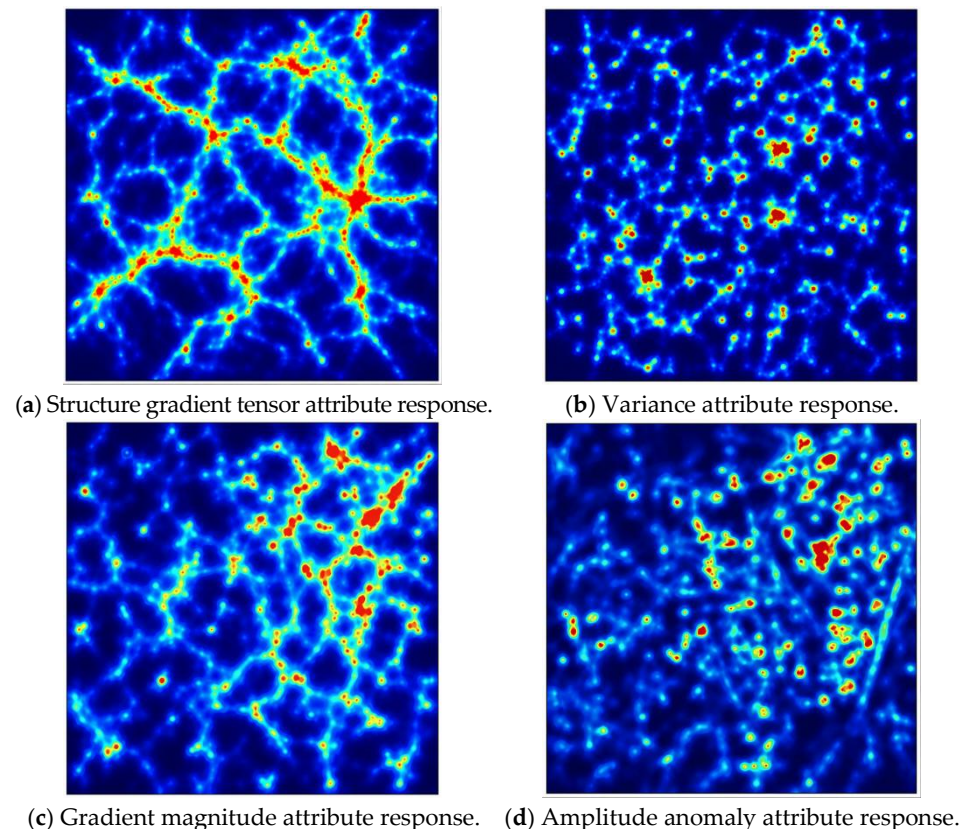


Figure 4. Multi-attribute response characteristics of fracture–cave reservoir bodies in the T74 layer. The structure gradient tensor, variance, and gradient magnitude attributes were assigned to the RGB channels with weights of 0.40, 0.30, and 0.30, respectively, and the amplitude anomaly attribute was used to constrain the internal reservoir-space response.

Compared with the structure gradient tensor attribute, the variance attribute in Figure 4b shows a more dispersed anomaly distribution which is mainly characterized by point-like, patchy, and locally beaded high-value responses. This attribute is more sensitive to the disruption of lateral continuity of reflection events and can highlight heterogeneous disturbances around fracture–cave bodies, local damage zones, and small-scale dissolution anomalies. The numerous isolated or semi-isolated high-value points in the figure indicate that there are many small-scale heterogeneous bodies within the T74 layer, but the spatial continuity of these anomalies is relatively weak. Some high-value anomalies are discontinuously aligned along concealed linear zones, suggesting that they may be related to small vugs or fracture–cave assemblages connected by fractures. Scattered anomalies lacking spatial extension direction and assemblage relationships require further constraint using other attributes to determine their reservoir significance.

The gradient magnitude attribute in Figure 4c primarily highlights areas with large local amplitude change rates, and its anomaly morphology lies between that of the structure gradient tensor attribute and the variance attribute. Compared with the more dispersed point-like responses in the variance attribute, the medium-to-high-value anomalies in the gradient magnitude attribute show more pronounced clustering and edge enhancement features. Compared with the structure gradient tensor attribute, it is more sensitive to local abrupt changes and small-scale anomaly boundaries. In the figure, distinct cluster-like to beaded anomaly assemblages appear in the upper-right, middle-right, and near local linear zones, indicating that these areas may contain composite anomaly bodies composed of multiple small-scale fracture–cave units. Continuous medium-value transition zones are observed around some anomalies, suggesting that the gradient magnitude

attribute can not only identify the core of strong anomalies but can also reflect the gradual change from strong to weak at fracture–cave body boundaries.

Compared with the previous three attributes, the amplitude anomaly attribute in Figure 4d more directly reflects the strong reflection response within the reservoir space. High-value anomalies in the figure are mainly distributed in point-like, cluster-like, and locally beaded patterns, with obvious high-value clusters in some areas, indicating that caves, vug groups, or fracture–cave complexes may be well developed. Especially in the central and right parts of the study area, high-amplitude anomalies are relatively concentrated, showing a strong reservoir space response. However, the amplitude anomaly attribute has limited ability to constrain fracture–cave body boundaries, structural continuity, and fracture connection relationships. Although some isolated strong-amplitude points have high response intensity, they lack stable correspondence in the structure gradient tensor, variance, and gradient magnitude attributes, suggesting that they may represent isolated vugs, local strong reflection interfaces, or non-connected anomalies, and cannot be directly equated with effective fracture–cave reservoir bodies.

Comparison of the four attribute types shows that the fracture–cave reservoir bodies in the T74 layer exhibit obvious composite seismic response characteristics. The structure gradient tensor attribute emphasizes anomaly boundaries and linear structural control, the variance attribute highlights reflection continuity disruption and heterogeneous disturbance, the gradient magnitude attribute enhances local abrupt changes and edge responses, and the amplitude anomaly attribute indicates the strong reflection core within the reservoir space. A single attribute can only reflect one aspect of fracture–cave reservoir bodies, easily leading to bias in anomaly interpretation. For example, relying solely on amplitude anomalies may lead to isolated strong reflections being misidentified as effective reservoir bodies; relying solely on variance attributes may lead to noise disturbances or non-reservoir fragmented responses being interpreted as fracture–cave anomalies. Therefore, an effective fracture–cave reservoir body should exhibit spatial superimposition of multi-attribute responses, i.e., simultaneously possessing clear boundaries, continuity disruption, enhanced local abrupt changes, and strong internal amplitude responses.

From the perspective of spatial assemblage, the areas with common multi-attribute responses are mainly concentrated in the central, upper-right, and middle-right anomaly development zones. These areas show relatively clear banded or chain-like boundaries in the structure gradient tensor attribute, high-value continuity disruption areas in the variance attribute, local boundary enhancement in the gradient magnitude attribute, and corresponding strong internal responses in the amplitude anomaly attribute. The consistency of multi-attribute responses suggests that these areas are more likely to represent fracture–cave composite reservoir bodies with good fracture communication conditions and well-developed reservoir space. In contrast, scattered high-value points far from the main anomaly zones mostly show single-attribute responses, lacking stable boundaries and spatial extension relationships, and their reservoir effectiveness and connectivity significance are relatively weak. Integrating the results of the four attribute types, the fracture–cave reservoir bodies in the T74 layer mainly exhibit three assemblage patterns: beaded, chain-like, and cluster-like. Beaded anomalies consist of multiple point-like or small cluster-like high-value bodies discontinuously aligned along a dominant direction, reflecting that discrete vugs or small caves form local connections under fracture communication. Chain-like anomalies show semi-continuous distribution of multiple medium-to-high-value anomaly bodies along the same direction, indicating strong control by fractures or faults. Cluster-like anomalies usually correspond to larger-scale fracture–cave complexes with strong internal amplitude responses.

4.4. Fracture–Cave Coupling Probability Distribution Results

The fracture–cave coupling probability distribution of the T74 layer is constructed to evaluate the spatial matching degree and potential connectivity between fracture–cave reservoir bodies and the fracture network. Figure 5 shows the fracture–cave coupling profile results along the direction of wells TK877X—T817(K)—TK878—TK892XCH—TK858XCH. In the profile, red anomalies represent fracture–cave reservoir bodies, black anomalies represent caves and damage zones, blue anomalies represent fracture development responses, and the green curves and labels indicate well trajectories and well locations. This profile can intuitively reflect the spatial configuration among fracture–cave bodies, fracture zones, and well locations near the T74 layer, providing an important basis for determining the static inter-well connectivity pattern (Figure 5).

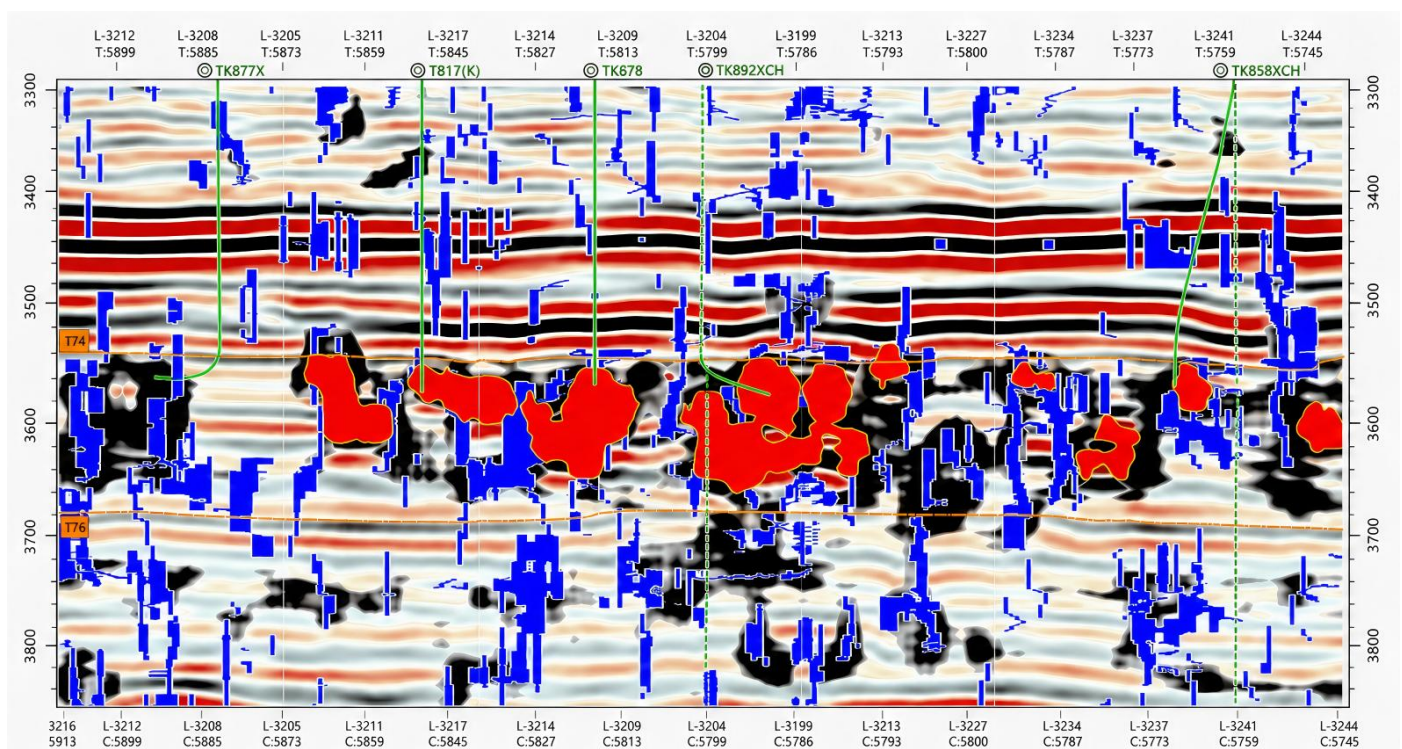


Figure 5. Superimposed distribution map of wells and fracture–cave reservoir bodies in the T74 layer. High coupling probability is controlled by the spatial matching among main fault constraint, fracture connectivity, and fracture–cave reservoir-body effectiveness.

From the profile response, the fracture–cave reservoir bodies are mainly developed near the T74 layer, generally concentrated between approximately 3550 and 3650 ms, and exhibit discontinuous beaded, cluster-like, and locally banded patterns along the lateral direction. The red fracture–cave reservoir bodies are not uniformly distributed; rather, they show strong responses near wells T817(K), TK878, and TK892XCH, as well as in the inter-well areas between them. Among these, the red reservoir bodies between TK878 and TK892XCH are larger in scale, with multiple anomalies exhibiting continuous or semi-continuous distribution near the T74 layer, and showing good spatial superimposition with the blue fracture responses and the black cave and damage zones. This indicates that this area not only has well-developed reservoir space in the fracture–cave bodies but also possesses certain fracture communication conditions.

In the profile, fractures exhibit obvious vertical trans-layer characteristics and locally concentrated distribution. Some fracture zones extend upward and downward from near the T74 layer and overlap with red fracture–cave reservoir bodies or black damage zones,

indicating that the fracture network plays a certain role in connecting fracture–cave anomalies of different scales. Particularly near wells T817(K), TK878, and TK892XCH, the fracture responses are relatively dense and show good correspondence with the distribution of fracture–cave reservoir bodies, suggesting a high degree of fracture–cave coupling in this area, which facilitates the formation of local connected units. In contrast, although fracture responses and local fracture–cave anomalies are also present near well TK877X on the left side of the profile and near well TK858XCH on the right side, the scale of the reservoir bodies, the continuity of anomalies, and the degree of fracture superimposition are relatively weaker, making their connectivity stability lower than that of the central inter-well area.

From the perspective of coupling relationships, the high-coupling-probability areas mainly correspond to three types of spatial superimposition characteristics: first, direct contact or interpenetration between red fracture–cave reservoir bodies and blue fracture zones; second, adjacency or overlap between red reservoir bodies and black cave and damage zones; and third, multiple fracture–cave anomalies arranged in beaded or chain-like patterns near the T74 layer and connected by fracture zones. In the profile, areas satisfying these conditions are mainly concentrated in the inter-well section from T817(K) to TK878 to TK892XCH. This area has large-scale reservoir bodies, strong fracture responses, and well-developed black damage zones, indicating that it possesses the coupled geological conditions of “reservoir space—fracture pathways—damage zone modification,” making it the location with the strongest potential static connectivity in the T74 layer.

Compared with the high coupling areas, some red fracture–cave anomalies, despite being clearly visible in the profile, have relatively lower coupling probability if they lack surrounding blue fracture zone support or have a loose spatial relationship with black damage zones. Isolated red anomaly bodies can be seen at some locations in the profile, but their vertical and lateral fracture responses are weak, and they lack stable communication pathways with adjacent fracture–cave bodies. Such anomalies are more likely to represent locally isolated fracture–cave bodies or weakly connected reservoir bodies and cannot be judged as effective connected units based solely on amplitude or reservoir body scale. This characteristic indicates that the fracture–cave coupling probability evaluation can screen individual fracture–cave anomalies and highlight composite reservoir bodies that truly have connectivity significance.

From the perspective of inter-well connectivity patterns, the TK877X–T817(K)–TK878–TK892XCH–TK858XCH profile can be divided into three connected segments. In the TK877X–T817(K) inter-well segment, the reservoir bodies are relatively scattered. Although local red fracture–cave anomalies and blue fracture responses exist, the continuity between anomalies is limited and the overall performance shows moderate-to-weak coupling. In the T817(K)–TK878–TK892XCH inter-well segment, the reservoir bodies are most concentrated, with clear superimposition of red fracture–cave bodies, blue fractures, and black damage zones, forming a relatively continuous fracture–cave complex, which belongs to the strong-coupling-probability segment. In the TK892XCH–TK858XCH inter-well segment, local reservoir bodies and fracture responses coexist, but the continuity is weaker than that of the central inter-well segment; secondary connected channels can form locally, and the overall performance is indicative of moderate coupling.

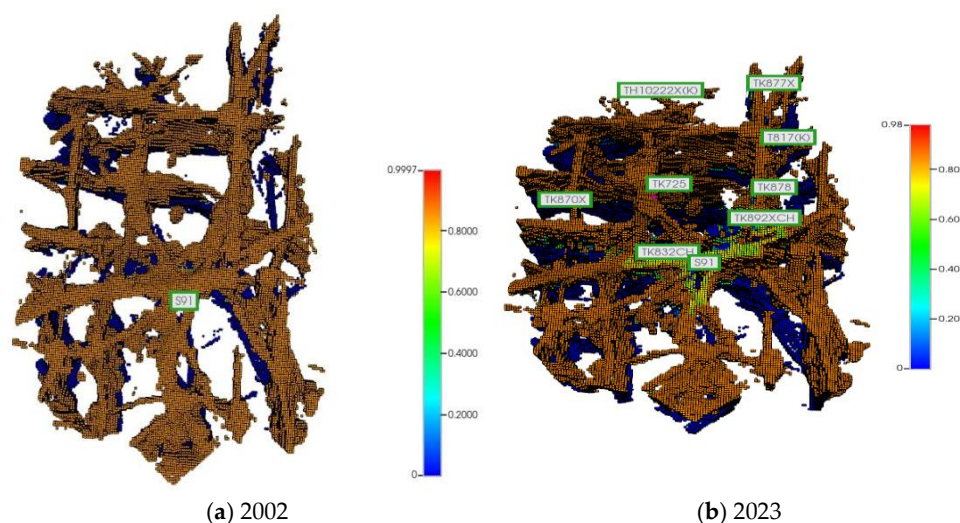
The static inter-well connectivity of the T74 layer is not simply controlled by well spacing but mainly depends on the spatial coupling relationship among fracture–cave reservoir bodies, fracture zones, and cave and damage zones. Inter-well segments with short well spacing paired with a lack of fracture communication may not form effective connections. Conversely, where fracture–cave bodies between wells are continuously or semi-continuously linked, accompanied by the interpenetration of fracture zones and the development of damage zones, dominant static connectivity pathways are more likely to

form. The T817(K)–TK878–TK892XCH inter-well segment is a typical area with such favorable coupling conditions.

Compared with single-amplitude interpretation, the MFC-FVCP result suppresses isolated high-amplitude anomalies far from the main controlling fault. Compared with fracture-density-only interpretation, it avoids overestimating fracture-intensive zones without effective reservoir-body support. Compared with conventional ant-tracking results, the direction-constrained result better preserves fracture responses consistent with the main strike-slip fault system. Therefore, the high-probability zones identified by the MFC-FVCP model better correspond to dominant fault–fracture–cave assemblages and dynamic production responses.

4.5. Remaining Oil Distribution Analysis

Based on the oil saturation simulation results, the spatial distribution and evolution pattern of the remaining oil in the reservoir are revealed. Overall, the reservoir exhibits strong spatial heterogeneity. High-oil-saturation areas are mainly concentrated along the main controlling faults and dense fracture zones, with fracture–cave reservoir bodies showing cluster-like, beaded, and locally banded patterns. Low-oil-saturation areas are mainly distributed in the main flow channels of the main controlling faults and areas affected by frequent injection–production activities. In the early stage, the overall oil saturation of the reservoir was relatively high (Figure 6a). High-saturation areas extended continuously along the main fault strike directions, and local fracture–cave reservoir bodies achieved initial connectivity through associated fractures or fault damage zones, forming potentially dominant static inter-well connected channels. The main controlling faults played a dominant role in reservoir connectivity and the channel areas exhibited high fluid flow capacity, whereas peripheral secondary reservoir bodies had limited connectivity and relatively slow flow velocities. As production continued (Figure 6b), oil saturation in the areas controlled by main faults and dominant fractures decreased significantly, and high-oil-saturation areas began to concentrate in fault intersection zones and edge reservoir bodies controlled by secondary fractures, showing a trend of local remaining oil enrichment. This reflects the pattern that fluids are preferentially produced from the main channels. By 2025 (Figure 6d), oil saturation in the main channel areas further decreased, while secondary fractures and semi-isolated fracture–cave reservoir bodies still maintained relatively high oil saturation, forming a remaining oil pattern characterized by “low saturation in main channels and high saturation in edge reservoir bodies.”



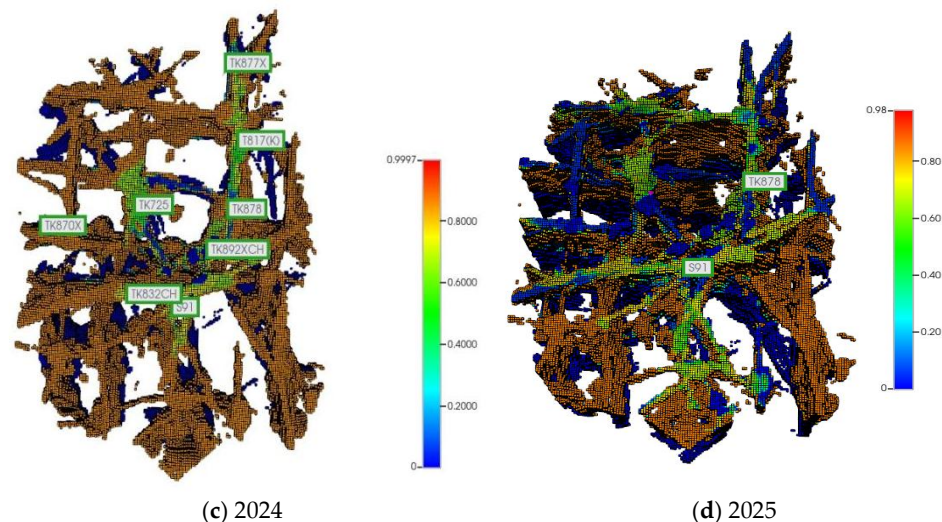


Figure 6. Staged oil saturation evolution constrained by production history matching. The 2002 map represents the early-stage reference saturation field, whereas the 2023, 2024, and 2025 maps represent staged oil saturation fields constrained by production history matching.

The staged oil saturation maps were derived from a numerical simulation model constrained by seismic interpretation, fracture–cave reservoir-body characterization, production history, and injection–production relationships. The model framework incorporated the interpreted main faults, associated fracture zones, fracture–cave reservoir-body distribution, porosity and permeability properties, initial oil–water distribution, fluid properties, relative permeability curves, and well control constraints. The reliability of the simulated oil saturation field was evaluated through history matching of cumulative oil production, cumulative water production, water cut, pressure response, and nitrogen injection performance. The 2002 oil saturation map was used as the early-stage reference, whereas the 2023, 2024, and 2025 maps represent staged oil saturation fields constrained by production history matching (Figure 7).

4.6. Practical Application

Based on the MFC-FVCP model, the static and dynamic connectivity of the fracture–cave carbonate reservoir in Unit S91 is comprehensively characterized, enabling systematic identification of remaining oil potential zones and guidance for development optimization. Model analysis shows that the distribution of the remaining oil in the reservoir is not determined solely by porosity–permeability conditions, but is jointly controlled by the spatial configuration of the main controlling fault, the fracture system, and the fracture–cave reservoir bodies. In areas dominated by the main fault zone and its associated fractures, well-connected fracture–cave reservoir bodies form preferential fluid pathways, the reservoir can be continuously displaced, and the remaining oil saturation decreases significantly with ongoing production. In contrast, in areas controlled by secondary faults or local fractures, the fracture–cave reservoir bodies are mostly semi-isolated or locally beaded in distribution, with insufficient connectivity, resulting in significant remaining oil retention and the formation of potential enrichment zones.

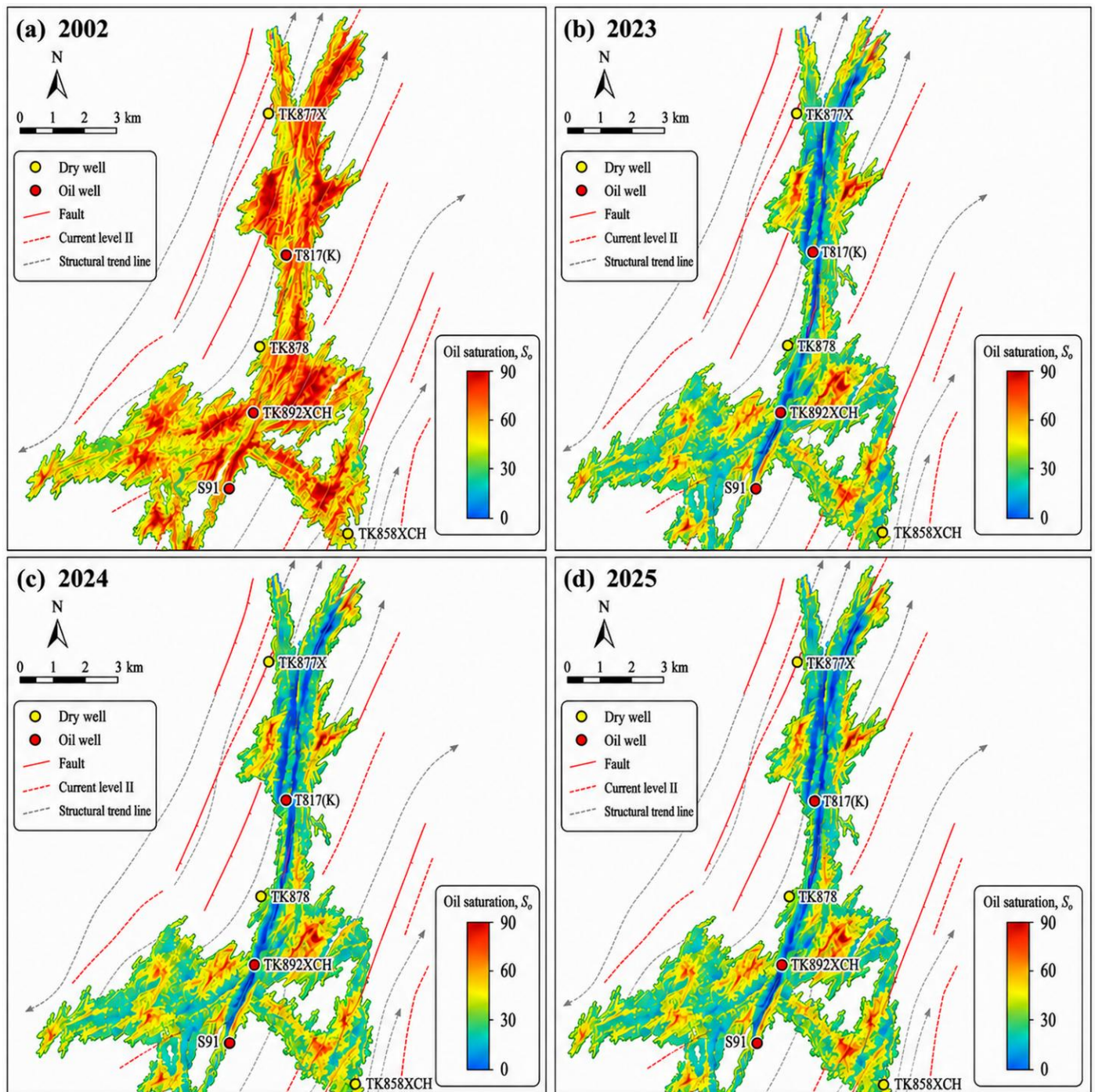


Figure 7. Evolution of oil saturation and remaining oil distribution in the S91 unit (colors represent oil saturation, S_o , ranging from 0 to 90%. Solid red lines indicate major faults, dashed red lines indicate secondary faults, red circles represent oil wells, and yellow circles represent dry wells. With continued production, the remaining oil gradually changes from continuous distribution to localized enrichment, mainly retained in weakly connected or fault-controlled areas).

The analysis of potential point A further illustrates the spatial distribution characteristics of the remaining oil (Figure 8). In this area, the fracture–cave reservoir bodies are moderately sized and densely distributed, and the local fractures have limited connectivity, resulting in an insufficient sweep of the injected medium into this region, thereby forming a producible remaining oil enrichment zone. It can be clearly stated that the enrichment of remaining oil in the potential area depends not only on the physical properties of the reservoir but also on the spatial coupling relationship between faults and fracture–

cave reservoir bodies. Such areas not only retain reservoir space but also possess the basis for fluid re-mobilization, making them key targets for priority deployment of injection–production wells or local stimulation in subsequent development.

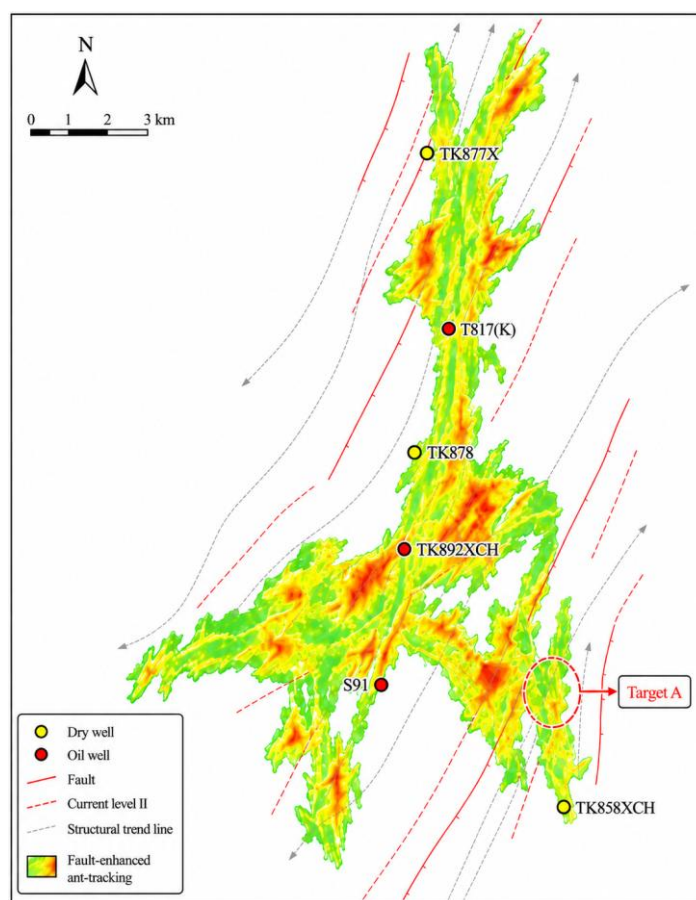


Figure 8. Plan view of remaining oil enrichment zones and target A in Unit S91.

Target A located near well TK858XCH is not situated in the strongest main fault-controlled flow channel. Instead, it occurs along the margin of the dominant channel or within a secondary fracture-controlled fracture–cave reservoir body. The MFC-FVCP result indicates that this area has a clear fracture–cave reservoir-body response but a lower coupling probability than the central high-connectivity belt. The staged oil saturation simulation shows that the area still maintains relatively high oil saturation in the late development stage, indicating insufficient sweep by injected fluids. Therefore, Target A was not selected solely according to a high-oil-saturation anomaly, but was jointly constrained by effective reservoir space, moderate-to-weak connectivity, relatively high late-stage oil saturation, and dynamic evidence of insufficient sweep.

Compared with the strongly connected main channels, Target A has better remaining-oil preservation conditions. Compared with completely isolated fracture–cave bodies, it still has a certain basis for fracture stimulation and fluid re-mobilization. Therefore, it can be regarded as a priority target for injection–production adjustment, local gas injection, sidetracking, or acid-fracturing stimulation.

The model also reveals the dynamic evolution pattern of the remaining oil. As the production time advances, the oil saturation in the dominant channels of the main fault zone gradually decreases, while the potential areas and marginal reservoir bodies still maintain relatively high oil saturation, exhibiting a distribution pattern of “low saturation in main channels and high saturation in marginal reservoirs.” This evolution characteristic reflects that fluid displacement preferentially proceeds along the dominant connected

channels, whereas semi-isolated reservoir bodies and weakly connected fracture–cave bodies become long-term remaining oil retention zones due to limited fluid transfer. This not only verifies the predictive rationality of the MFC-FVCP model but also provides a quantitative basis for remaining oil development strategies. In practical development, the MFC-FVCP model can guide the optimization of injection–production layouts. For remaining oil near the edges of dominant channels, the injection–production correspondence can be adjusted and the injection cycle or gas injection can be optimized to enable the fluid to effectively sweep the marginal fracture–cave reservoir bodies, ensuring that the remaining oil in the marginal potential areas can be effectively mobilized.

5. Conclusions

- (1) The fracture–cave carbonate reservoir in the T74 layer of Unit S91 in the Tahe Oilfield exhibits obvious multi-stage coupling control characteristics of faults, fractures, and fracture–cave bodies. The main controlling faults and their intersection zones are the primary structural boundaries controlling reservoir differentiation and fluid migration, governing the preferential migration direction of karst fluids and the banded, chain-like, and beaded distribution of fracture–cave reservoir bodies. The associated fracture network serves as the connecting pathway between discrete fracture–cave bodies, and its development density, orientation stability, and vertical inheritance determine whether the fracture–cave bodies can be transformed from isolated reservoir units into effective connected units. The results indicate that fracture–cave reservoir bodies located within the main fault zones, fault intersection areas, and dense fracture zones are more likely to form continuous or semi-continuous dominant inter-well-connected channels. In contrast, fracture–cave bodies far from the main controlling faults or lacking stable fracture connectivity, even with locally strong seismic responses, are mostly isolated or semi-isolated reservoir bodies with relatively limited static connectivity and development potential.
- (2) The multi-attribute identification results show that the fracture–cave reservoir bodies in the T74 layer are not single-amplitude anomalies but composite seismic response units composed of abrupt structural boundary changes, reflection continuity disruption, local gradient enhancement, and internal strong-amplitude anomalies. The structure gradient tensor attribute, variance attribute, gradient magnitude attribute, and amplitude anomaly attribute have different sensitivities to reservoir body boundaries, heterogeneous disturbances, local abrupt changes, and reservoir space responses, respectively. Areas with common multi-attribute responses can more effectively indicate fracture–cave composite reservoir bodies with reservoir significance and potential connectivity, whereas single strong-amplitude anomalies or isolated fragmented responses, if lacking fault and fracture support, should not be directly interpreted as effective connected reservoir bodies.
- (3) The constructed fracture–cave coupling probability model under the constraint of the main controlling fault achieves quantitative characterization of the spatial coupling relationship among faults, fractures, and fracture–cave reservoir bodies. The high-coupling-probability areas are mainly distributed along the main fault zones, fault intersection areas, and dense fracture zones, representing the primary locations for dominant static connected channels. Medium-coupling areas are mostly located at the edges of the main channels and in secondary fault-controlled areas, possessing certain reservoir space and limited communication conditions, making them important locations for remaining oil enrichment. The staged oil saturation simulation and dynamic response analysis further indicate that high-connectivity channels are preferentially swept during long-term production, whereas marginal or semi-isolated fracture–cave bodies retain relatively high oil saturation. Potential point A near

well TK858XCH simultaneously exhibits well-developed fracture–cave reservoir bodies, limited fracture connectivity, insufficient sweep, and relatively favorable remaining-oil preservation conditions, making it a high-priority target for subsequent injection–production adjustment and remaining oil tapping. This model provides a quantifiable geological constraint framework for inter-well connectivity evaluation and favorable remaining-oil area prediction in fracture–cave carbonate reservoirs.

Author Contributions: X.Z.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing—original draft. Q.C.: Data curation, Investigation, Validation, Visualization. Z.W.: Resources, Project administration, Supervision, Writing—review and editing. X.P.: Formal analysis, Methodology, Validation, Writing—review and editing. S.Z.: Conceptualization, Supervision, Project administration, Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financially supported by Sinopec Corporation Northwest Oilfield Branch under Contract No. 34400000-24-ZC0613-0107.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: We would like to thank Sinopec Corporation, Northwest Oilfield Branch, and Yangtze University for their support during this study.

Conflicts of Interest: Authors Xiao Zhang, Qi Chang and Zhen Wang were employed by the Sinopec Corporation, Northwest Oilfield Branch. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The Sinopec Corporation, Northwest Oilfield Branch had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

x	Any spatial location in the study area; unit: m. It is recommended to use the metric system for plane coordinates or grid coordinates
i	Index of the i -th main controlling fault; dimensionless
N	Number of main controlling faults involved in the calculation; unit: count
$I_F(x)$	Influence intensity of the main controlling fault on the reservoir location; dimensionless, range [0,1]
ω_i	Comprehensive weight of the i -th main controlling fault; dimensionless; normalization is recommended
$D_i(x)$	Intensity of fault influence decaying with distance; dimensionless
$A_i(x)$	Matching degree between the dominant fracture orientation and the fault strike; dimensionless, range [0,1]
S_i	Comprehensive characterization of fault size, attribute response, and continuity; dimensionless
$d_{\perp i}$	Perpendicular distance from location x to the i -th fault; unit: m
$d_{\parallel i}$	Relative distance from location x along the strike direction of the i -th fault; unit: m
$\sigma_{\perp i}$	Influence radius perpendicular to the fault; unit: m
$\sigma_{\parallel i}$	Influence radius along the fault strike; unit: m, generally larger than the perpendicular influence radius
$\theta_f(x)$	Dominant direction of local fractures or linear anomalies; the unit in figures can be degrees ($^\circ$), but radians (rad) are recommended when used in cosine functions
θ_i	Strike of the i -th fault; unit consistent with $\theta_f(x)$
L_i^*	Normalized fault length; dimensionless, obtained by normalizing the original fault length
R_i^*	Normalized fault attribute response intensity; dimensionless, can be derived from ant tracking, coherence, or fault probability volumes

C_{i^*}	Normalized fault continuity; dimensionless, used to characterize the stability of fault extension
$\lambda_1, \lambda_2, \lambda_3$	Weights of the fault size factor; dimensionless. In the main text, the values are 0.40, 0.40, and 0.20, respectively
$C_{RGB}(x)$	RGB multi-attribute fusion vector; dimensionless
$P_{sgt}(x)$	Normalized structure gradient tensor response; dimensionless, normalized to [0,1] before being input into the model
$P_{var}(x)$	Normalized variance response; dimensionless, normalized to [0,1] before being input into the model
$P_{grad}(x)$	Normalized gradient magnitude response; dimensionless, normalized to [0,1] before being input into the model
$P_{amp}(x)$	Normalized amplitude anomaly response; dimensionless, used to reflect caves, fracture–cave complexes, and beaded reflection anomalies
w_R, w_G, w_B	Weights of the R, G, and B channels; dimensionless. In the main text, the values are 0.40, 0.30, and 0.30, respectively
$\gamma_R, \gamma_G, \gamma_B$	Nonlinear enhancement parameters for the RGB channels; dimensionless, used to suppress low-value background and enhance high-value anomalies
$B_v(x)$	Initial fracture–cave anomaly response; dimensionless
η_1, η_2, η_3	Weights of the initial fracture–cave anomaly response; dimensionless, satisfying $\eta_1 + \eta_2 + \eta_3 = 1$
$R_f(x)$	Comprehensive response intensity of fracture attributes; dimensionless; normalization to [0,1] is recommended
$R_v(x)$	Final response intensity of the fracture–cave reservoir body; dimensionless, range [0,1]
a, b, c, d	Weights of the control terms in the final response field; dimensionless; can be determined by validation or sensitivity analysis
τ	Threshold adjustment parameter of the Sigmoid response; dimensionless, used to control the degree of differentiation between high and low values in the response field

References

1. Yang, H.; Wang, L.; Bi, Z.; Guo, Y.; Gui, J.; Zhao, G.; He, Y.; Guo, W.; Qiu, G. Experimental Investigation into the Process of Hydraulic Fracture Propagation and the Response of Acoustic Emissions in Fracture–Cavity Carbonate Reservoirs. *Processes* **2024**, *12*, 660. <https://doi.org/10.3390/pr12040660>.
2. Su, Z.; Gao, S.; Li, Z.; Li, T.; Kang, N. Integrated Waterflooding Effect Evaluation Methodology for Carbonate Fractured–Vuggy Reservoirs Based on the Unascertained Measure–Mahalanobis Distance Theory. *Processes* **2024**, *12*, 274. <https://doi.org/10.3390/pr12020274>.
3. Tang, B.; Ren, K.; Lu, H.; Li, C.; Geng, C.; Wei, L.; Chai, Z.; Wu, S. Study on Residual Oil Distribution Law during the Depletion Production and Water Flooding Stages in the Fault–Karst Carbonate Reservoirs. *Processes* **2023**, *11*, 2147. <https://doi.org/10.3390/pr11072147>.
4. Cheng, H.; Yuan, F.; Zhang, S.; Li, L.; Luo, X.; Chen, B. Investigation on Water Invasion Mode and Remaining Oil Utilization Rules of Fractured–Vuggy Reservoirs: A Case Study of the Intersection Region of S99 Unit in Tahe Oilfield. *Processes* **2023**, *11*, 1833. <https://doi.org/10.3390/pr11061833>.
5. Jing, C.; Duan, Q.; Han, G.; Nie, J.; Li, L.; Ge, M. Quantitative Interpretation Model of Interwell Tracer for Fracture–Cavity Reservoir Based on Fracture–Cavity Configuration. *Processes* **2023**, *11*, 964. <https://doi.org/10.3390/pr11030964>.
6. Zhao, M.; Xin, X.; Yu, G.; Hu, R.; Gong, Y. Mechanistic Study and Optimization of High Water Cut Phase Management Strategies in Fracture–Vuggy Carbonate Reservoirs with Bottom Water. *Processes* **2023**, *11*, 3135. <https://doi.org/10.3390/pr11113135>.
7. Cheng, H. The Enhanced Oil Recovery Effect of Nitrogen-Assisted Gravity Drainage in Fractured–Vuggy Carbonate Reservoirs. *Processes* **2023**, *11*, 2316. <https://doi.org/10.3390/pr11082316>.
8. Li, J.; Zhang, W.; Qu, B.; Zhen, E.; Qian, Z.; Ma, S.; Qin, F.; You, Q. Physical Modeling of High-Pressure Flooding and Development of Oil Displacement Agent for Carbonate Fracture–Vuggy Reservoir. *Processes* **2025**, *13*, 71. <https://doi.org/10.3390/pr13010071>.
9. Wang, J.; Feng, Y.; Cao, A.; Zhang, J.; Chen, D. Co-Injection of Foam and Particles: An Approach for Enhanced Oil Recovery in Fractured–Vuggy Carbonate Reservoirs. *Processes* **2024**, *12*, 447. <https://doi.org/10.3390/pr12030447>.

10. He, S.; Chen, B.; Yuan, F.; Wang, X.; Wang, T. Dynamic Reserve Calculation Method of Fractured-Vuggy Reservoirs Based on Production Performance. *Processes* **2024**, *12*, 640. <https://doi.org/10.3390/pr12040640>.
11. Wang, Y.; Guo, W.; Sun, G.; Zhou, X.; Lin, J.; Ding, M.; Huang, Z.; Cao, Y. Remaining Oil Distribution and Enhanced Oil Recovery Mechanisms Through Multi-Well Water and Gas Injection in Weathered Crust Reservoirs. *Processes* **2025**, *13*, 241. <https://doi.org/10.3390/pr13010241>.
12. Yue, S.; Guo, W.; Ding, M.; Li, A. Improving Recovery Mechanism Through Multi-Well Water and Gas Injection in Underground River Reservoirs. *Processes* **2025**, *13*, 2743. <https://doi.org/10.3390/pr13092743>.
13. Li, J.; Qu, B.; Zhen, E.; Ma, S.; Liu, Y. Production Law of Shielding Oil in Fractured Carbonate Reservoirs. *Processes* **2024**, *12*, 2432. <https://doi.org/10.3390/pr12112432>.
14. Pei, J.; Zhang, Y. Prediction of Reservoir Fracture Parameters Based on Machine Learning. *Processes* **2022**, *10*, 2445. <https://doi.org/10.3390/pr10112445>.
15. Zhang, Z.; Gao, C.; Gao, Y.; Niu, C.; Ma, S. Theoretical Simulation of the Resistivity and Fractured–Cavernous Structures of Carbonate Reservoirs. *Processes* **2024**, *12*, 43. <https://doi.org/10.3390/pr12010043>.
16. Cao, X.; Ren, J.; Xin, S.; Guan, C.; Zhao, B.; Xu, P. Study of Acid Fracturing Strategy with Integrated Modeling in Naturally Fractured Carbonate Reservoirs. *Processes* **2024**, *12*, 808. <https://doi.org/10.3390/pr12040808>.
17. Cheng, Y.; Luo, X.; Zhuo, Q.; Gong, Y.; Liang, L. Description of Pore Structure of Carbonate Reservoirs Based on Fractal Dimension. *Processes* **2024**, *12*, 825. <https://doi.org/10.3390/pr12040825>.
18. Hu, J.; Yang, S.; Jiang, Y.; Deng, H.; Wang, M.; You, L.; Li, Q.; Bai, H.; Shen, B. Experimental Study on Edge Water Invasion of Strongly Heterogeneous Carbonate Gas Reservoirs Based on NMR Technology. *Processes* **2024**, *12*, 1361. <https://doi.org/10.3390/pr12071361>.
19. Xu, X.; Zhai, X.; Ke, A.; Lin, Y.; Zhang, X.; Xie, Z.; Lou, Y. Prediction of Leakage Pressure in Fractured Carbonate Reservoirs Based on PSO-LSTM Neural Network. *Processes* **2023**, *11*, 2222. <https://doi.org/10.3390/pr11072222>.
20. Cao, Y.; He, Q.; Liu, C. Numerical Investigation of Fracture Morphology Characteristics in Heterogeneous Reservoirs. *Processes* **2022**, *10*, 2604. <https://doi.org/10.3390/pr10122604>.
21. Zheng, S.; Yang, M.; Kang, Z.; Liu, Z.; Long, X.; Liu, K.; Li, X.; Zhang, S. Controlling Factors of Remaining Oil Distribution after Water Flooding and Enhanced Oil Recovery Methods for Fracture-Cavity Carbonate Reservoirs in Tahe Oilfield. *Pet. Explor. Dev.* **2019**, *46*, 786–795. [https://doi.org/10.1016/S1876-3804\(19\)60236-3](https://doi.org/10.1016/S1876-3804(19)60236-3).
22. Wang, J.; Qi, X.; Liu, H.; Yang, M.; Li, X.; Liu, H.; Zhang, T. Mechanisms of Remaining Oil Formation by Water Flooding in Fracture-Cavity Carbonate Reservoirs. *Pet. Explor. Dev.* **2022**, *49*, 1110–1125. [https://doi.org/10.1016/S1876-3804\(22\)60336-7](https://doi.org/10.1016/S1876-3804(22)60336-7).
23. Li, Y.; Hou, J.; Li, Y. Features and Hierarchical Modeling of Carbonate Fracture-Cavity Reservoirs in Tahe Oilfield. *Pet. Explor. Dev.* **2016**, *43*, 655–662. [https://doi.org/10.1016/S1876-3804\(16\)30076-3](https://doi.org/10.1016/S1876-3804(16)30076-3).
24. Yuan, D.; Hou, J.; Song, Z.; Wang, Y.; Luo, M.; Zheng, Z. Residual Oil Distribution Characteristic of Fractured-Cavity Carbonate Reservoir after Water Flooding and Enhanced Oil Recovery by N₂ Flooding of Fractured-Cavity Carbonate Reservoir. *J. Pet. Sci. Eng.* **2015**, *129*, 15–22. <https://doi.org/10.1016/j.petrol.2015.03.016>.
25. Lu, G.; Zhang, L.; Liu, Q.; Xu, Q.; Zhao, Y.; Li, X.; Deng, G.; Wang, Y. Experiment Analysis of Remaining Oil Distribution and Potential Tapping for Fractured-Vuggy Reservoir. *J. Pet. Sci. Eng.* **2022**, *208*, 109544. <https://doi.org/10.1016/j.petrol.2021.109544>.
26. Sun, Z.; Yang, R.; Yang, P.; Zhang, S.; Li, Y.; Zhao, S.; Geng, F. Characteristics of Chaotic Weak Reflection in Carbonate Fracture-Cavity Reservoirs: A Case Study of Ordovician Reservoirs in Block 10 of the Tahe Oilfield, Tarim Basin, China. *ACS Omega* **2023**, *8*, 31071–31084. <https://doi.org/10.1021/acsomega.3c03010>.
27. Chang, S.; Wang, M. The Identification of the Development Stages of the Karstic Fracture–Cavity Carbonate Reservoirs: A Case Study on the Lungu Oilfield, Tarim Basin. *Front. Earth Sci.* **2023**, *11*, 1238759. <https://doi.org/10.3389/feart.2023.1238759>.
28. Zhang, C.; Zhou, W.; Liu, C.; Wang, X.; Xu, H. Characteristics, Main Controlling Factors and Prediction of Complex Fracture–Cavity Reservoirs of Buried Carbonate Hills in the Weixinan Depression, Western South China Sea. *Front. Earth Sci.* **2022**, *10*, 865355. <https://doi.org/10.3389/feart.2022.865355>.
29. Li, J.; Lu, W.; Sun, J. Hydraulic Expansion Techniques for Fracture-Cavity Carbonate Rock with Field Applications. *Appl. Sci.* **2024**, *14*, 5851. <https://doi.org/10.3390/app14135851>.
30. Bahorich, M.; Farmer, S. 3-D Seismic Discontinuity for Faults and Stratigraphic Features: The Coherence Cube. *Lead. Edge* **1995**, *14*, 1053–1058. <https://doi.org/10.1190/1.1437077>.
31. Marfurt, K.J.; Kirlin, R.L.; Farmer, S.L.; Bahorich, M.S. 3-D Seismic Attributes Using a Semblance-Based Coherency Algorithm. *Geophysics* **1998**, *63*, 1150–1165. <https://doi.org/10.1190/1.1444415>.

32. Chopra, S.; Marfurt, K.J. Seismic Attributes—A Historical Perspective. *Geophysics* **2005**, *70*, 3S0–28S0. <https://doi.org/10.1190/1.2098670>.
33. Pedersen, S.I.; Skov, T.; Randen, T.; Sønneland, L. *Automatic 3D Fault Interpretation by Artificial Ants*. EAGE Expanded Abstracts 2002; European Association of Geoscientists & Engineers: Houten, The Netherlands, 2002. <https://doi.org/10.3997/2214-4609-pdb.5.G037>.
34. Zhao, J.; Sun, S.Z. Automatic Fault Extraction Using a Modified Ant-Colony Algorithm. *J. Geophys. Eng.* **2013**, *10*, 025009. <https://doi.org/10.1088/1742-2132/10/2/025009>.
35. Caine, J.S.; Evans, J.P.; Forster, C.B. Fault Zone Architecture and Permeability Structure. *Geology* **1996**, *24*, 1025–1028. [https://doi.org/10.1130/0091-7613\(1996\)024<1025:FZAAPS>2.3.CO;2](https://doi.org/10.1130/0091-7613(1996)024<1025:FZAAPS>2.3.CO;2).

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.