

# Fracture development in the lower Longmaxi Formation, Zigong area of the southern Sichuan Basin, China

E Fei

Yangtze University

Jiayu Liu

Yangtze University

Tao Li

ltm817@yangtzeu.edu.cn

Yangtze University

Fancheng Zeng

Geophysical Exploration Research Institute, Jilin Oilfield Company

Xiong Pi

Geophysical Exploration Research Institute, Jilin Oilfield Company

Zhiyuan Sun

Geophysical Exploration Research Institute, Jilin Oilfield Company

---

## Research Article

**Keywords:** shale fracture, development characteristics, Fracture Development Model, Longmaxi Formation, Sichuan basin

**Posted Date:** July 29th, 2026

**DOI:** <https://doi.org/10.21203/rs.3.rs-10497599/v1>

**License:**   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

**Additional Declarations:** No competing interests reported.

---

# Fracture development in the lower Longmaxi Formation, Zigong area of the southern Sichuan Basin, China

E Fei<sup>a, b, d</sup>, Jiayu Liu<sup>a, b, d</sup>, Tao Li<sup>a, b, d\*</sup>, Fancheng Zeng<sup>c</sup>, Xiong Pi<sup>c</sup>, Zhiyuan Sun<sup>a, b, d</sup>

<sup>a</sup> School of Geosciences, Yangtze University, Wuhan, Hubei, 430100, China

<sup>b</sup> Hubei Engineering Research Center of Unconventional Petroleum Geology and Engineering, Wuhan, Hubei, 430100, China

<sup>c</sup> Geophysical Exploration Research Institute, Jilin Oilfield Company, PetroChina, Songyuan, Jilin, 138000, China

<sup>d</sup> Hubei Key Laboratory of Complex Shale Oil and Gas Geology and Development in Southern China, Wuhan, Hubei, 430100, China

Corresponding author: Tao Li. E-mail addresses: ltm817@yangtzeu.edu.cn

## ABSTRACT

The shale of the Lower Longmaxi Formation in the Zigong area is stable and serves as the core layer for shale gas exploration and development in this region. Studying the development characteristics of shale fractures is crucial for understanding the enrichment and accumulation of shale gas, as well as for subsequent development and design. This research, based on outcrop, core, well logging and seismic data, identifies the types of fracture development in the Lower Longmaxi Fm shale in Zigong and relates these fractures to the region's structural system. Fractures developed in the Zigong block strike mainly northeast, S-N, northwest and E-W, and their development is mostly related to compressive stress. The NE-trending and near S-N-trending fractures are a group of conjugate shear fractures formed by early NW-trending compressive stress. The NW-trending and EW-trending fractures are a group of conjugate fractures formed under the constraint of early NE-trending structures under the influence of the continuous NE-trending compressive stress since the Oligocene. Fracture density is greatest near faults, around fold crests, and around the upper parts of fold limbs. Based on fracture identification and simulation of in-situ stress, development models for fractures around single thrusts, back-thrusts, oppositely dipping thrusts, vertical strike-slip faults, and imbricate, "Y"-shaped, anti-"Y"-shaped, semi-flower-shaped and flower-shaped structures are established. Favourable areas for fracture development in the study area are then predicted. Fractures in the Zigong area are mainly developed near NE-trending faults, and structural highs are densely developed. The fracture development models established in this study can provide valuable insights for the identification of fracture development characteristics in similar geological settings.

**Key words:** shale fracture; development characteristics; Fracture Development Model; Longmaxi Formation; Sichuan basin

## 1. Introduction

The shallow layers of the Sichuan Basin have been developed into four commercial shale gas production zones: Fuling, Changning, Weiyuan, and Zhaotong, with an annual gas output approaching  $200 \times 10^8 \text{ m}^3$ , demonstrating the enormous potential of shale gas resources (Dong et al. 2018, Fan et al. 2020). Currently, deep shale gas exploration and development in the Sichuan Basin focuses on the Wufeng Fm and Longmaxi Fm at depths of 3,500 to 4,500 meters. Proven geological resources amount to  $9.6 \times 10^{12} \text{ m}^3$ , with a favorable area of approximately  $1.6 \times 10^4 \text{ km}^2$ . The Zigong area, located within the Zigong structural belt of the southwestern Sichuan Basin, features a stable plane distribution of the Longmaxi Formation, with thicknesses ranging from 530 to 590 meters. The distribution of shale gas is relatively stable, achieving high yields and showcasing the potential for large-scale production.

The study of shale fractures is crucial for the exploration and development of shale oil and gas, as their development characteristics significantly influence reservoir space, preservation conditions, shale gas well productivity, and the effectiveness of hydraulic fracturing (Du et al. 2025,

Konstantinovskaya et al. 2025, Li et al. 2025). In the Zigong area, the natural fractures are primarily composed of tectonic fractures, diagenetic fractures, and hydrocarbon generation fractures, resulting from the influence of multiple, multi-directional tectonic stresses. The main factors affecting shale fracture development include tectonic activity, stress characteristics, the brittle mineral content of rocks, organic matter content, burial history, and strata thickness(Shang et al. 2021). Previous studies have found that natural fractures in the southern Sichuan Basin are predominantly shear fractures with angles exceeding 75°, followed by tensile fractures, interlayer joints and mesh fractures(Liu et al. 2020, Wang et al. 2024). The formation of these fractures is largely influenced by the extrusion stresses from two to three-stage structures since the Yanshan period. These fractures form a multi-directional, multi-stage shear and tensile fracture system, with dominant orientations in the northeast, northwest, near S-N, and near E-W directions(Xie, Qin and Fan 2019, Xu et al. 2019, Yang et al. 2024). Current research on shale fracture development primarily focuses on individual fracture characteristics, such as shape, scale, and size(Sun et al. 2025, Ademilola and Pashin 2025, Guo et al. 2025). However, the research into shale fracture development mechanisms is still largely theoretical, with insufficient in-depth analysis of specific tectonic backgrounds. To date, a comprehensive fracture development model under a specific tectonic setting has yet to be established(Zhao et al. 2023, Shi et al. 2022, Stoeckhert et al. 2015).

Based on core observations, outcrop investigations, seismic interpretation, conventional logging, and imaging logging data from the Zigong area, this study systematically analyzes the characteristics of shale fractures in lower Longmaxi Fm. Through a comprehensive examination of regional tectonic evolution, stress transformation processes, tectonic styles, and structural features, a structural framework is established to guide the investigation of fracture development characteristics and patterns. By analyzing the formation mechanisms of tectonic styles within the study area, the fracture development patterns are clarified in conjunction with fracture occurrence, superposition stages, assemblage styles, and controlling factors. On this basis, a shale fracture development model constrained by the regional structural framework is proposed. The fracture development patterns established in this study provide a basis for predicting regional fracture distribution, identifying favorable zones for shale oil and gas exploration and development, and offering a comparative reference for recognizing shale fracture development characteristics under similar geological settings.

## **2. Geological overview**

The Zigong area is situated within the low-steep structural belt of the southern Sichuan Basin (Fig.1). The Sichuan Basin is located in the northwestern part of the Upper Yangtze Plate, the Qinghai-Tibet Plateau activity area to the west, and the South China Block to the east. Its basement developed on the pre-Sinian crystalline foundation and subsequently experienced three major tectonic episodes during the Indosinian, Yanshan and Himalayan periods. As a superimposed basin containing both marine and continental strata, the Sichuan Basin has been significantly influenced by multi-stage tectonic movements, resulting in a structural framework characterized by open folds and faults at the surface and large-scale fault systems in the basement(Fan et al. 2020).

The low-steep structural belt in southern Sichuan has undergone multiple phases of subsidence, uplift, and erosion. Between approximately 60 and 45 Ma, tectonic stresses generated in western Sichuan were transmitted toward central Sichuan, leading to rapid uplift and contributing to the development of thrust faults at the base of the Zigong area. Concurrently, the overlying strata were uplifted, resulting in the formation of the Zigong anticline. During 45-30 Ma, uplift of the southwestern limb of the Weiyuan anticline and the relative tectonic stability of the southern

Longquan Mountain area promoted further uplift of the Zigong anticline. From approximately 30 to 15 Ma, tectonic stresses associated with the rapid uplift of the Longmen Mountain belt were transmitted to the Zigong anticline, producing a superimposed structural configuration characterized by vertically stacked thrust faults and anticlines. Since 15 Ma, the continued rapid uplift of the Longmen Mountain has exerted a strong influence on the Sichuan Basin, causing accelerated uplift of the Zigong anticline and ultimately forming a “in the shape of a watch’s broom” structural pattern. This structure trends from northeast to southwest and consists of multiple broom-like, dispersed gentle synclines and low-to-steep anticlines that progressively weaken toward the southwest(Li et al. 2023, Yang et al. 2024).

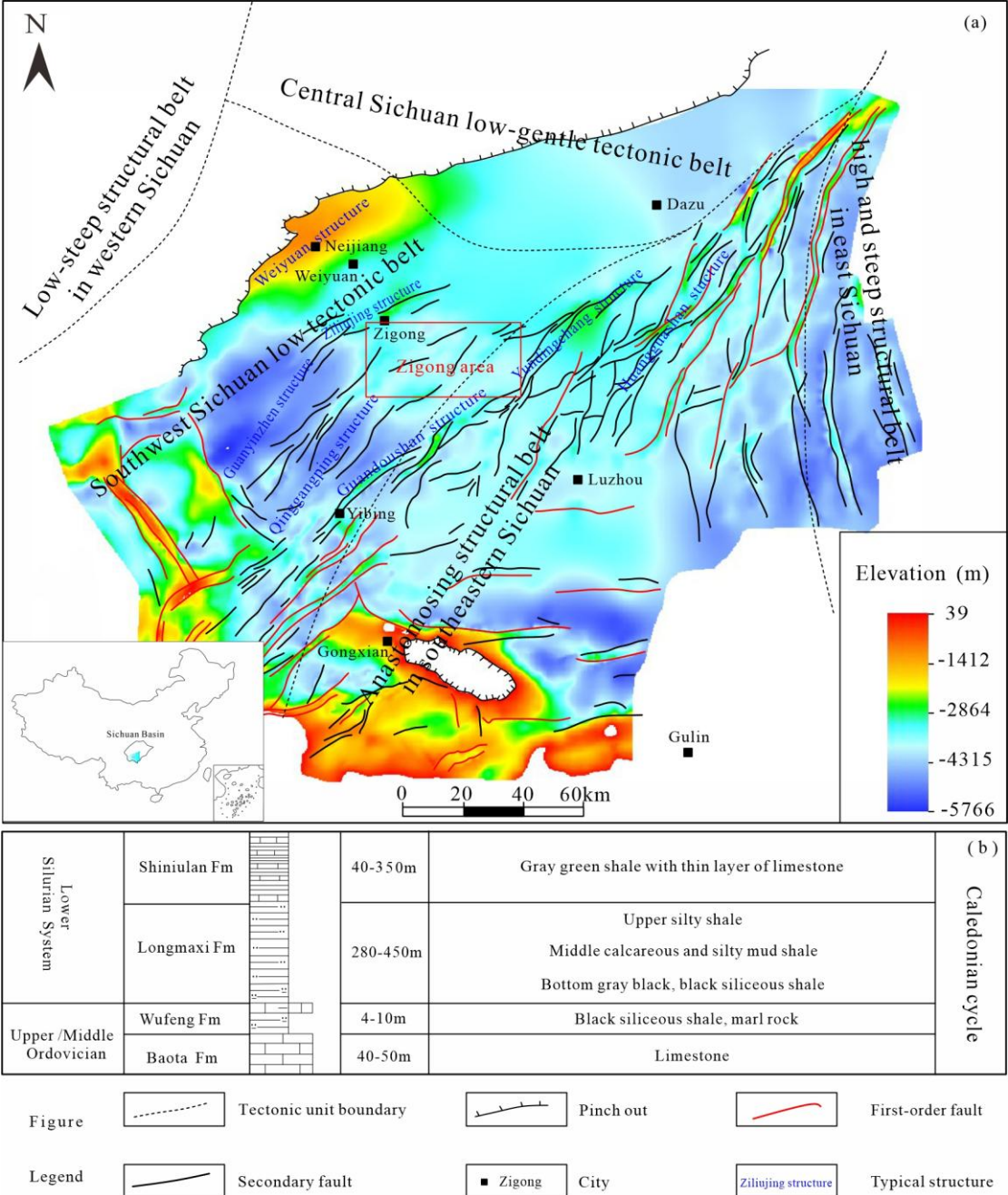


Fig.1 Brief geological map of Zigong area in Sichuan Basin.(a) Structural location map of the study area; (b) comprehensive stratigraphic column.

The Zigong area represents a sedimentary depocenter within a surrounding gentle slope-platform setting. During deposition, relatively deep-water conditions prevailed, accompanied by a

strongly reducing environment. As a result, thick sequences of black siliceous shale, calcareous shale, and carbonaceous shale were developed(Zhao et al. 2017, Fan et al. 2020). The high-quality shale intervals at the base of the Wufeng Fm and within the lower Longmaxi Fm are characterized by thin bedding, high total organic carbon content, elevated siliceous content, deep-water depositional environments, and low sedimentation rates. The Longmaxi Fm conformably overlies the Wufeng Fm and is overlain by the Shiniulan Fm(Wang et al. 2025). Deposition was relatively stable, with formation thickness ranging from approximately 280 to 450 m and a laterally consistent distribution. Owing to its favorable geological characteristics and substantial thickness, the Longmaxi Formation constitutes the principal target interval for shale gas exploration and development in the study area(Wang et al. 2026).

### **3. Samples and methods**

#### **3.1 Sample source**

This study integrates outcrop observations, core descriptions, conventional well logging, imaging logging, three-dimensional seismic data, and seismic inversion data from the Zigong area. By systematically summarizing the characteristics of fracture development and identifying nine typical structural assemblage styles, the study combines analyses of stress evolution and tectonic deformation mechanisms to elucidate the fracture development patterns in the region. On this basis, a fracture development model controlled by a compressional–torsional strike-slip tectonic system is established. The proposed model is subsequently applied to predict favorable targets for shale oil and gas exploration and development in the Zigong area.

#### **3.2 Multi- Method Fracture Identification**

Through integrated fracture characterization from outcrop, core, conventional logging, imaging logging, and seismic data, this study systematically investigated the development characteristics of fractures in the first member of the Longmaxi Formation in the Zigong area. The workflow progressed from identification of fracture “point-scale” features (meter–decimeter–centimeter–millimeter) using outcrop, core, and well logging data to recognition of fracture “surface-scale” features through frequency-divided seismic attribute optimization and well–seismic joint inversion and ultimately to the analysis of fracture development patterns and model construction. In this manner, the research advances from “point” to “surface” and finally to “model” characterization.

Outcrops provide direct and intuitive geological observations. Detailed identification and analysis of fractures in representative outcrops enable clarification of dominant fracture types and occurrence characteristics within the study area. Core data constitute essential physical evidence for understanding subsurface geology; core-based fracture identification allows precise determination of fracture types and development features within the target strata.

Conventional logging curves, including natural gamma ray, acoustic transit time, and dual laterolog resistivity, can effectively identify shale fractures. Owing to the abundance and continuity of logging data, fracture recognition based on these curves achieves relatively high accuracy(Wang et al. 2024). Imaging logging is currently one of the most effective methods for fracture identification, providing high-resolution borehole wall images that clearly capture subtle fracture features and significantly enhance the precision and efficiency of fracture interpretation.

Three-dimensional seismic attributes are effective for identifying regional fracture characteristics, particularly in delineating the development and distribution of faults and large-scale fractures. Attribute extraction procedures are relatively straightforward and practical; however, their predictive capability for micro-fractures remains limited(Sun et al. 2025). The well–seismic joint

inversion method integrates seismic and logging data to predict fracture development through seismic inversion, combining the high lateral resolution of seismic data with the high vertical resolution of logging data. This integrated approach substantially improves the accuracy of fracture prediction(Zhao et al. 2025).

### 3.3 Establishment of a Fracture Development Model under the Control of a Tectonic System

Based on a comprehensive analysis of regional tectonic evolution, stress transformation processes, tectonic styles, and structural characteristics in the Zigong area, the regional structural framework is defined as a compressional-torsional strike-slip tectonic system. Guided by this structural framework and integrating the identified fracture development characteristics described above, the fracture development patterns are systematically analyzed in conjunction with structural styles, fracture occurrence features, stress distribution conditions, and fracture formation mechanisms.

On this basis, a fracture development model controlled by the compressional-torsional strike-slip tectonic system is established. The proposed model is subsequently applied and validated through comparison with previous fracture identification results, enabling the evaluation of favorable exploration targets. This application verifies both the reliability and the practical significance of the established fracture development model(Shi et al. 2022, Zhang et al. 2021b).

## 4 Results

### 4.1 Fracture Development Characteristics Identified from Outcrops

Outcrop observations indicate that shear fractures are predominantly developed in the study area, whereas tensile fractures are relatively minor (Fig.2).

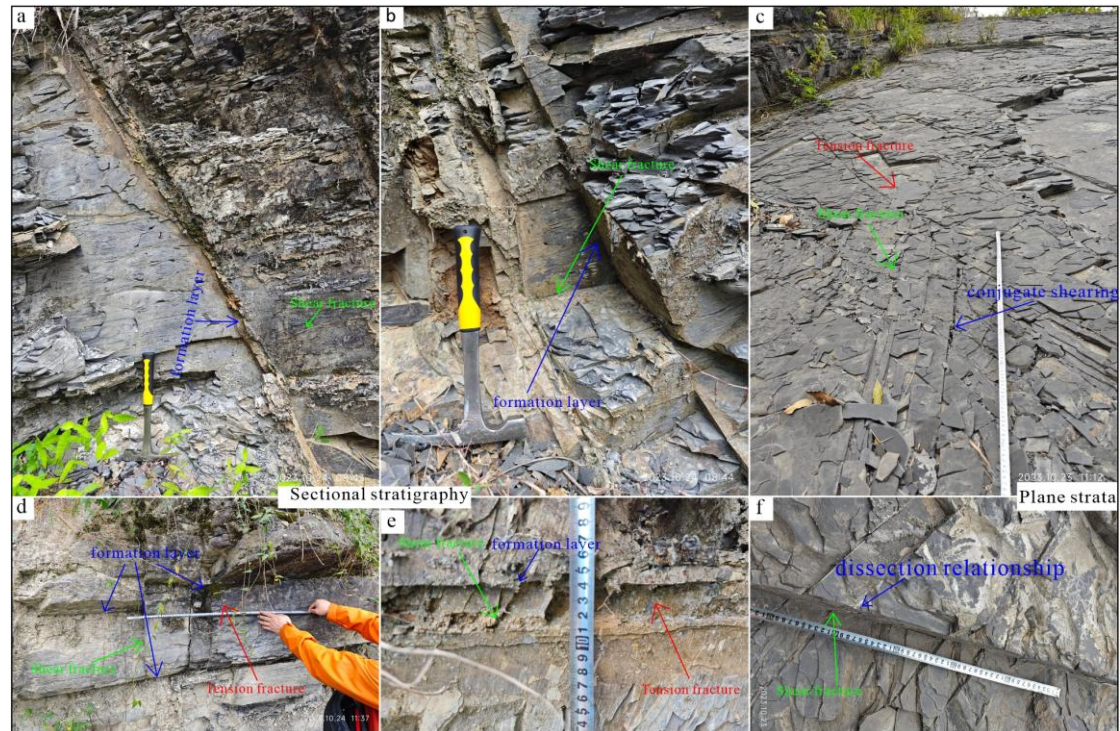


Fig.2 Development characteristics of outcrop fractures in Zigong area (see reference in figure for scale). (a) inclined strata exhibiting well-developed shear fractures along oblique bedding planes; (b) shear fractures with planar bedding planes, showing well-defined development; (c) conjugate shear fractures clearly observed in plan view, with occasional tensile fractures; (d) Horizontal strata characterized by well-developed shear fractures accompanied by tensile fractures; (e) shear fractures developed obliquely relative to bedding planes; (f) prominent shear fractures, with larger fractures forming conjugate patterns that truncate smaller fractures.

The shear fractures can be classified into four principal orientation sets: near northeast ( $30^{\circ}$ - $65^{\circ}$ ), near S-N ( $340^{\circ}$ - $350^{\circ}$ ), northwest ( $310^{\circ} \pm 5^{\circ}$ ), and near E-W (approximately  $90^{\circ}$ ). The shear fracture surfaces are generally planar and laterally continuous. In cross-section, they typically exhibit high-angle oblique relationships with bedding planes or fault surfaces. These fractures are particularly well developed in zones of intense structural deformation, such as faults and fold hinges.

On planar exposures, shear fractures commonly intersect obliquely, forming conjugate fracture systems, although mutual cross-cutting relationships are also observed. They are typically arranged in fracture sets. Among these, the NE- and SN-trending fractures constitute a conjugate pair, while the NW-trending fractures form a conjugate relationship with the near-EW-trending fractures.

In contrast, tensile fractures are mostly bedding-parallel or confined within individual mechanical layers, with limited lateral extension. Their fracture surfaces are relatively irregular and rough, with comparatively larger apertures. Tensile fractures are far less abundant than shear fractures in outcrops. In cross-section, they are primarily developed in the cores of anticlines and are commonly restricted to single mechanical layers. On planar surfaces, they frequently occur near the terminations or intersection zones of shear fractures.

#### 4.2 Fracture Development Characteristics Identified from Core Observations

Observations of representative well cores from the Zigong area indicate that structural fractures are predominantly developed as cross-layer shear fractures, bedding-parallel shear fractures, and tensile fractures (Fig.3).

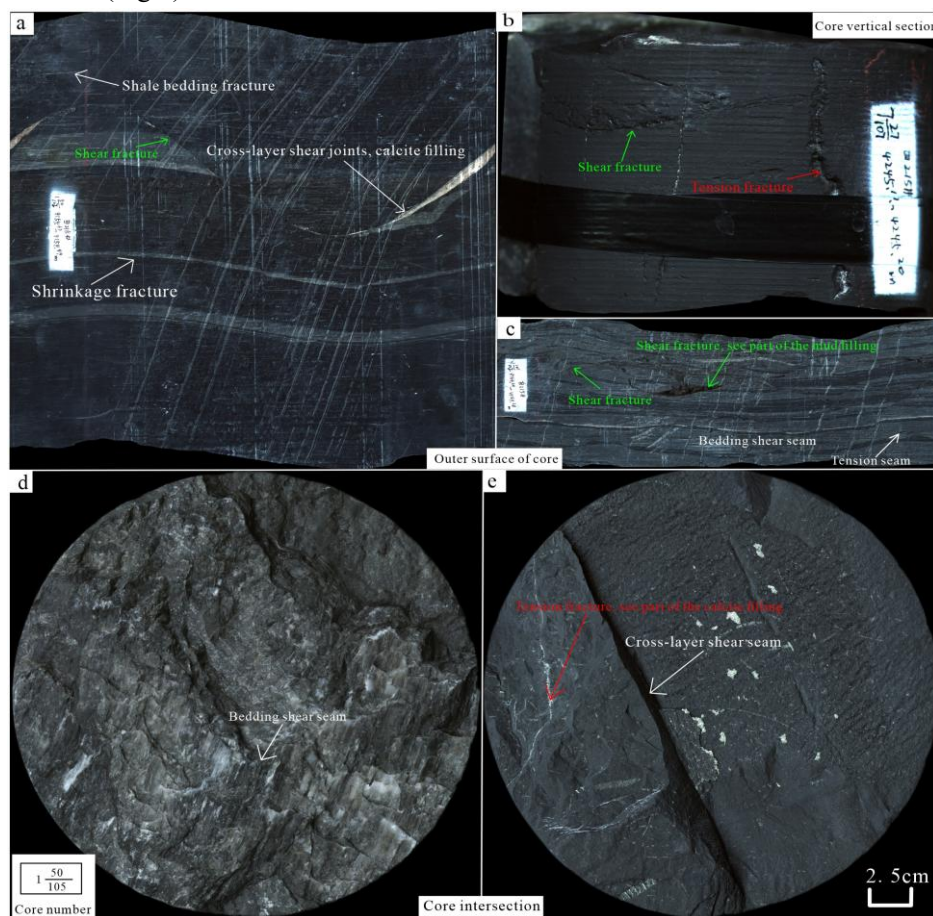


Fig.3 Development characteristics of natural fractures in the core of Longmaxi Formation in Zigong area. (a) bedding-parallel fractures, contraction fractures, and cross-bedding shear fractures, partially filled with calcite; (b) tensile fractures; (c) shear fractures with partial clay filling, exhibiting well-developed bedding-parallel orientation; (d) traces of bedding-parallel shear fracture development; (e) tensile fractures partially filled with calcite and well-

developed cross-bedding shear fractures.

Cross-layer shear fractures, formed by shale failure under tectonic stress, are characterized by relatively straight and planar fracture surfaces with considerable lateral continuity. These fractures commonly occur in zones with high brittle mineral content and typically intersect bedding at high angles or in steep oblique relationships. They often develop in well-defined fracture sets.

Bedding-parallel shear fractures (bedding detachment fractures) are generated by differential deformation of rocks under horizontal compressional or extensional stress. Their fracture surfaces commonly display striations and mineral growth lineations, exhibiting smooth, mirror-like characteristics. These fractures are frequently partially or completely filled with calcite and generally occur parallel or at low angles to bedding planes.

Diagenetic fractures mainly include bedding fractures and contraction fractures. Bedding fractures are typically parallel to shale laminae, with limited lateral extension and relatively small apertures. Contraction fractures, in contrast, tend to have larger apertures and greater extension distances and are commonly filled with calcite and/or organic matter.

Hydrocarbon generation-related fractures are primarily associated with abnormal overpressure within the shale and generally develop perpendicular to bedding surfaces, exhibiting irregular geometries. However, such fractures are rarely observed in the core data of the Longmaxi Formation in the Zigong area.

#### 4.3 Fracture Development Characteristics Identified from Well Logging

Fracture identification in the study area was conducted using conventional logging curves, including acoustic transit time (AC), density (DEN), natural gamma ray (Healy, Yielding and Kusznir), and deep and shallow laterolog resistivity—integrated with imaging logging data. Based on these datasets, statistical analyses of fracture occurrence and distribution were performed.

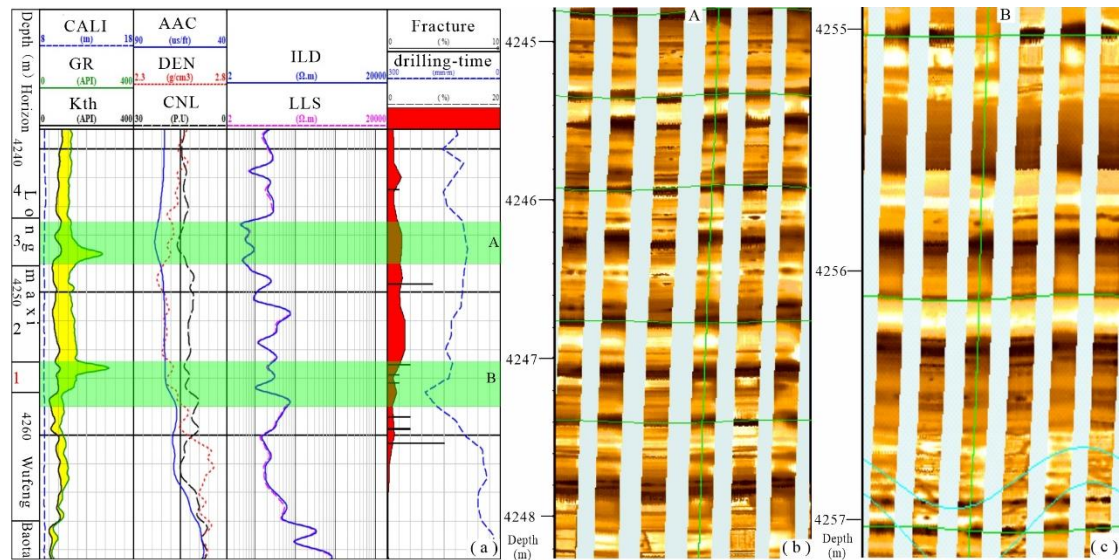


Fig.4 Fracture identification characteristics of imaging logging interpretation

In Well W1, fracture orientations are mainly distributed in the northwest, southeast, and northeast directions, with dominant trends in the northeast and northwest directions. These results are consistent with outcrop and core observations in the Zigong area and reflect the regional tectonic stress transformation characteristics. Fracture dip angles range from 20° to 60°, with medium- to high-angle fractures being predominant. Low-angle fractures are generally interpreted as tensile or bedding fractures, whereas medium- to high-angle fractures are mainly associated with compressional stress and are commonly related to thrust fault activity in the study area. Overall,

these fracture development characteristics represent the superposition of multi-stage tectonic events in the Zigong area (Fig.5).

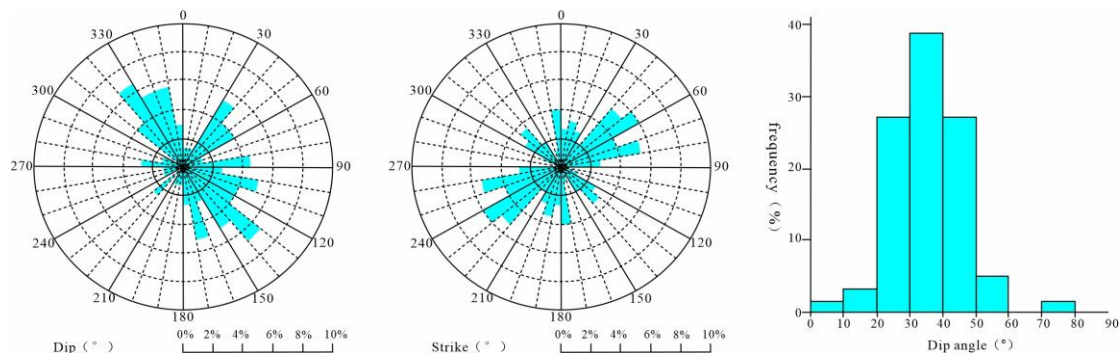


Fig.5 Statistical diagram of fracture elements of conventional logging interpretation

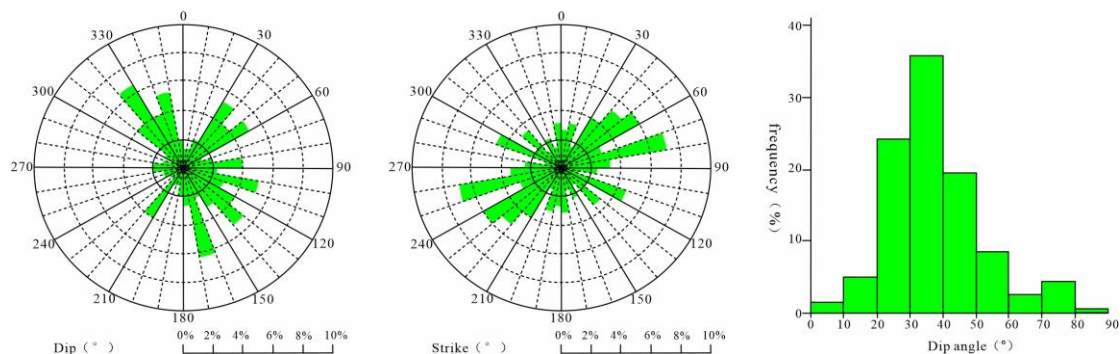


Fig.6 Statistical diagram of fracture elements interpreted by imaging logging

Conventional logging responses in fractured intervals typically exhibit anomalously high GR values, positive anomalies in deep and shallow laterolog resistivity curves, and relatively low-density values. For low-angle and horizontal fractures, the dual laterolog curves commonly display low-resistivity peaks. Imaging logging data (Fig.4b) indicate that five low-angle fractures are developed within the corresponding interval. In contrast, high-angle fractures are generally associated with relatively higher resistivity responses. Imaging logging data for another interval (Fig.4c) shows five fractures in Section B, including three low-angle fractures and two moderately high-angle fractures.

Statistical analysis of fracture parameters derived from imaging logging data in the Zigong area, including Wells W1 and W2 (Fig.4 and Fig.6), indicates that fracture dip angles range from 0° to 80°, with most concentrated between 20° and 50°, suggesting the predominance of low- to moderate-angle fractures. Fracture azimuths are mainly distributed between 320°–350° and 30°–170°, with dominant trends in the near east–west and southwest–northeast directions.

These fracture development characteristics are consistent with the regional compressional tectonic background of the Zigong area. Northeast-trending fractures may represent the secondary orientation of conjugate shear fractures or inherited reactivation of basement faults. Northwest-trending fractures are primarily controlled by persistent northeast-directed tectonic compressional stress. The concentration of dip angles between 20° and 50° indicates the dominance of conjugate shear fractures formed under strong compressional tectonic conditions. In contrast, low-dip-angle fractures (0°–30°) account for a relatively small proportion and are interpreted mainly as bedding fractures related to interlayer slip or primary sedimentary layering.

#### 4.4 Fracture Development Characteristics Identified by Seismic Data

Seismic inversion results further demonstrate that fracture development in the Zigong area is

jointly controlled by faults, folds, and the regional stress field (Fig.7). Fractures preferentially develop along early fault zones, with the highest fracture densities occurring near NE-trending structures and structural highs. These areas therefore represent zones with a high probability of fracture development. Based on the structural control mechanism, the planar distribution of fractures in the Zigong area is inferred to exhibit en-echelon and juxtaposed arrangements.

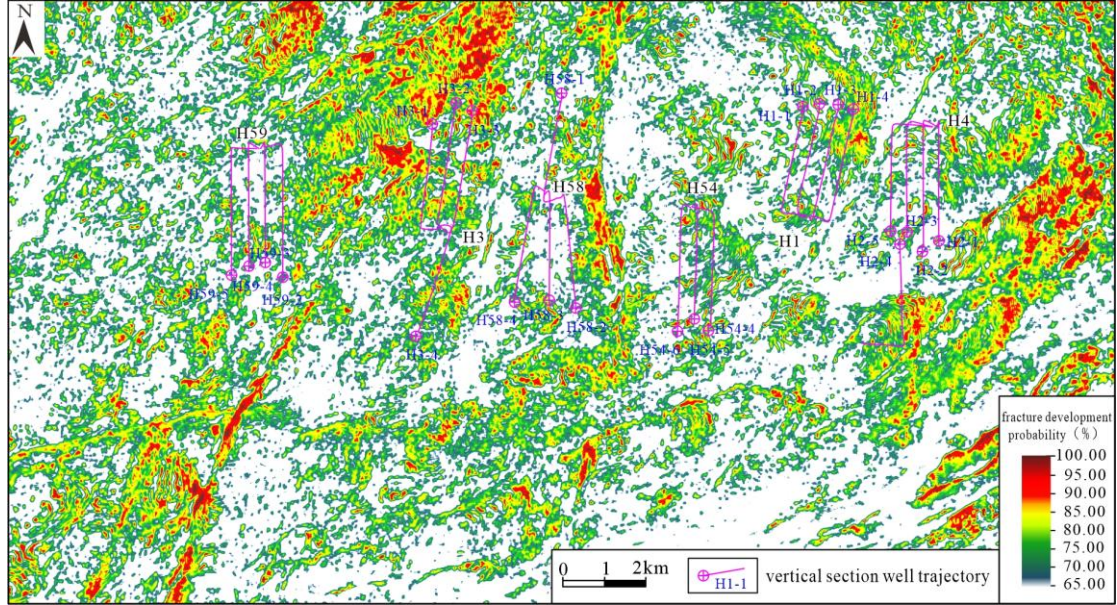


Fig.7 Seismic inversion fracture prediction results in Zigong area

Combined analysis of fracture probability and structural morphology indicates that fractures are significantly more developed near fault zones and anticline highs than within gentle synclinal belts. Although tensile fractures are relatively common at anticline crests and anticlines are widely distributed in the Zigong area, most anticlines in the Zigong block are genetically related to strike-slip tectonics. Because strike-slip deformation is dominated by shear stress, shear fractures are more extensively developed and are the principal fracture type observed. Tensile fractures are mainly formed locally at fold hinge zones or turning ends of anticlines and are less closely related to the primary structural framework of the study area. Consequently, shear fractures generated by strike-slip faulting are markedly more developed than tensile fractures associated with anticline uplift.

Based on fault strike analysis, fracture orientations are inferred to be predominantly NE, near-NS, and NW, reflecting the combined influence of NW-directed and NE-directed compressional stresses.

#### 4.5 Established Fracture Development Model

Based on the structural styles, fracture development characteristics, stress distribution patterns, and fracture formation mechanisms in the Zigong area (Du et al. 2023), the fracture development laws were systematically analyzed, and a fracture development model under a compressional–shear–strike-slip tectonic system was established.

##### (1) Single-Thrust Structure–Fracture Model

The single-thrust fault–anticline assemblage is widely distributed in the Zigong area. Taking the large-scale NW-trending fault developed in the southern part of the study area as a representative example, the fracture development pattern under this structural configuration was analyzed (Fig.8).

This structural style is characterized by a dominant single reverse fault combined with an anticline. The fault dip angle is generally small, the anticline is relatively symmetrical, and the overall structural amplitude is moderate to low. In this model, stress is primarily concentrated in the

vicinity of the fault zone and within the anticline core. Shear stress is dominant in the hanging wall of the reverse fault, whereas tensile stress is mainly concentrated in the core of the anticline.

Fracture development under this configuration is characterized by the coexistence of shear and tensile fractures, with a moderate overall development intensity. Fractures are predominantly medium- to high-angle and of moderate scale. Tensile fractures are mainly developed in the anticline core and typically exhibit relatively large lateral extents, whereas shear fractures are preferentially distributed along both sides of the fault, particularly within the hanging wall of the reverse fault.

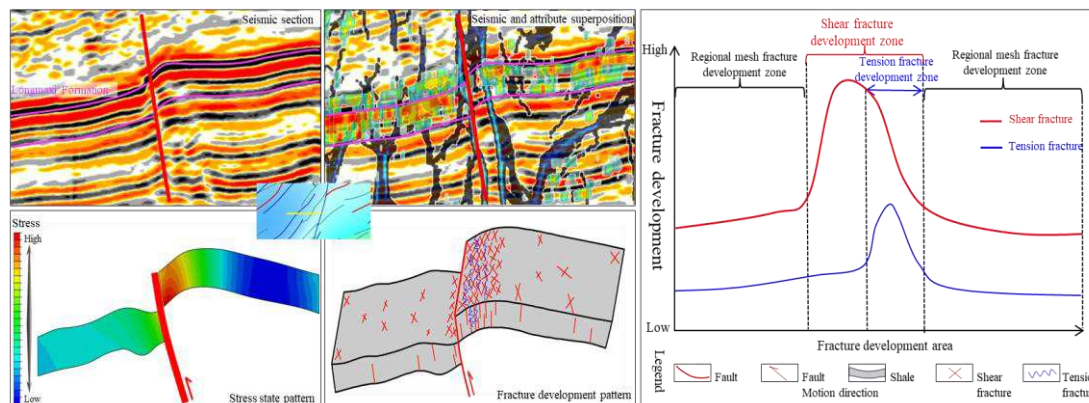


Fig.8 Analysis chart of fracture development characteristics controlled by single-thrust structure

## (2) Flower-Structure–Fracture Model

The flower-structure fault–anticline assemblage is primarily developed in the southwestern anticline zone of the study area, where strata exhibit relatively strong deformation (Fig.9). This structural style is characterized by a flower-shaped reverse fault system combined with a symmetrical, steep anticline. Tectonic activity is controlled by multiple faults with relatively large dip angles, and the anticline is generally well developed and steep.

The stress evolution in this model can be divided into two stages: (i) the fault-activity stage and (Alam et al.) the anticline-activity stage. During the fault-activity stage, stress distribution is strongly controlled by active faults and is mainly concentrated near the fault zones, particularly in the hanging wall. Shear stress is dominant during this stage. In the anticline-activity stage, fault movement weakens and regional stress distribution becomes primarily influenced by the anticline geometry. Stress concentration occurs in the anticline core and is dominated by tensile stress.

As a result, fracture development in this model is relatively intense, with shear fractures being predominant. These fractures are typically high-angle and large-scale. Additionally, tensile fractures commonly develop at structural highs, particularly in the anticline core.

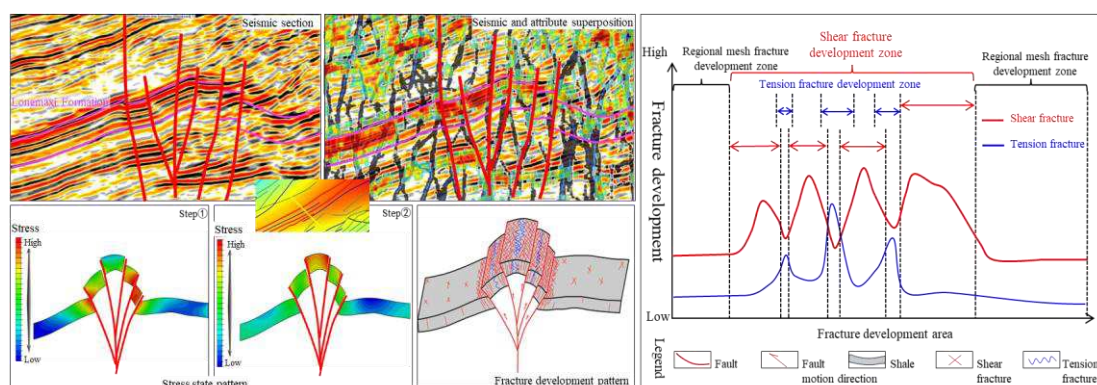


Fig.9 Analysis chart of fracture development characteristics controlled by flower structure

Table 1 Analysis table of structure-fracture development mode of Zigong area

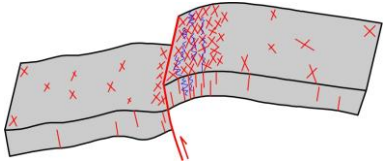
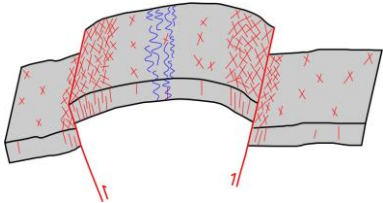
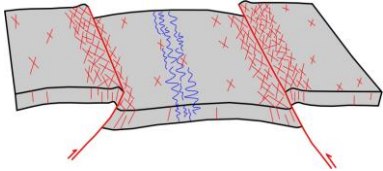
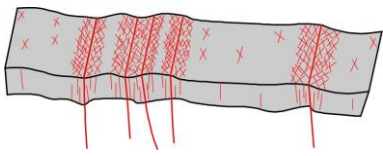
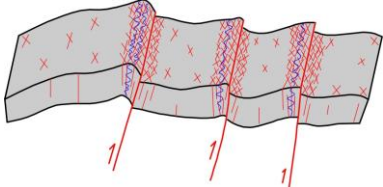
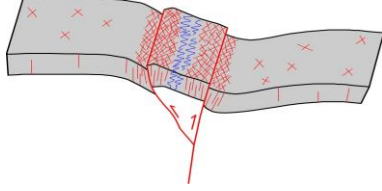
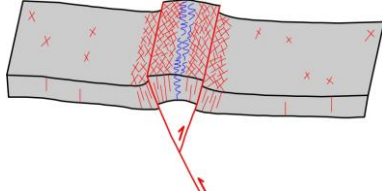
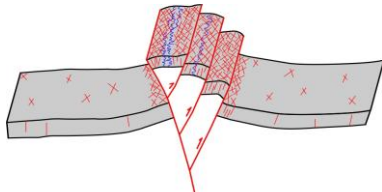
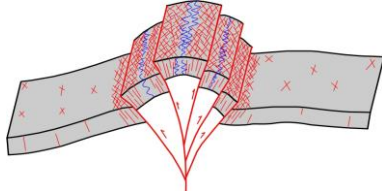
| Mode type                                     | Tectonic feature                                                                                                                                                                                                           | Schematic diagram of fracture development model                                      | Development characteristics of fracture                                                                                                                                                                                                                                                                                                 |
|-----------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Single-thrust Structure-fracture model        | This structural style is primarily controlled by a single reverse fault. The fault dip angle is relatively small, the anticline is asymmetric in geometry, and the overall structural amplitude is low.                    |    | Fracture development is moderate, with predominantly medium- to high-angle fractures and moderate scale. Both shear and tensile fractures are present. Tensile fractures are mainly developed in the middle and upper parts of the structure, whereas shear fractures are primarily developed in the lower part.                        |
| Back-thrust structure-fracture model          | This configuration is mainly controlled by two opposing faults. The faults exhibit relatively large dip angles, and the associated anticline is symmetrical, large in scale, and steeply developed.                        |    | Fracture development is relatively high, characterized by high dip angles, large fracture scales, and a relatively high degree of filling. Both shear and tensile fractures are well developed. Tensile fractures are mainly distributed in the middle and upper parts of the structure, while shear fractures dominate the lower part. |
| Opposed-thrust structure-fracture model       | This structure is also controlled by two faults. The anticline is symmetrical but relatively small in scale and exhibits a gentle, broad geometry.                                                                         |    | Fracture development is relatively weak, with medium- to high-angle fractures, small fracture scales, and a low degree of mineral filling. Shear fractures constitute the dominant fracture type, and fractures in the lower part generally exhibit relatively good effectiveness.                                                      |
| Vertical strike-slip structure-fracture model | This structural style is characterized by near-vertical strike-slip faults cutting through nearly horizontal strata. Fracture development is relatively intense on both sides of the fault, with no significant asymmetry. |  | Fracture development is weak and mainly concentrated along the fault zone, with little difference in fracture intensity on either side of the fault. Two principal fracture sets are observed: one parallel to the fault and another oblique to the fault.                                                                              |
| Imbricate structure-fracture model            | Imbricate reverse fault + asymmetric anticline;<br>It is controlled by multiple faults, the anticline is asymmetric, the scale is small, and the width is slow.                                                            |  | Fracture development is relatively weak, characterized by medium- to high-angle fractures, small fracture scales, and low filling degrees. Shear fractures dominate, and fractures in the lower structural positions tend to have better effectiveness.                                                                                 |

Table 1 (cont.) Analysis table of structure-fracture development mode of Zigong area

| Mode type                                | Tectonic feature                                                                                                                                                                                                         | Schematic diagram of fracture development model                                      | Development characteristics of fracture                                                                                                                                                                                                                                                                       |
|------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| “Y”-shaped structure-fracture model      | This configuration is controlled by multiple reverse faults arranged in an imbricate pattern. The anticline is asymmetric, relatively small in scale, and gently developed.                                              |    | Fracture development is strong, with high-angle, large-scale fractures and relatively high filling degrees. Both shear and tensile fractures are well developed. Tensile fractures are mainly distributed in the middle and upper parts of the structure, whereas shear fractures dominate in the lower part. |
| Anti-“Y”-shaped structure-fracture model | This structural style is mainly controlled by two faults forming a “Y”-shaped geometry. The faults have relatively large dip angles, and the associated anticline is symmetrical, large in scale, and steep.             |    | Fracture development is strong, with high dip angles, large fracture scales, and relatively high filling degrees. Shear and tensile fractures coexist, with tensile fractures concentrated in the middle and upper parts and shear fractures mainly developed in the lower part.                              |
| Semi-flower structure-fracture model     | Similar to the “Y”-shaped structure but with an inverse geometry, this configuration is also controlled by two faults with large dip angles. The anticline is symmetrical, large in scale, and steeply developed.        |    | Fracture development is strong, with high dip angles, large fracture scales, and relatively high filling degrees. Shear and tensile fractures coexist, with tensile fractures concentrated in the middle and upper parts and shear fractures mainly developed in the lower part.                              |
| Flower structure-fracture model          | This configuration is controlled by multiple faults forming a flower-like structure. The faults generally exhibit moderate to large dip angles, and the anticline is symmetrical, large in scale, and steeply developed. |  | Fracture development is strong, with high dip angles, large fracture scales, and relatively high filling degrees. Shear and tensile fractures coexist, with tensile fractures concentrated in the middle and upper parts and shear fractures mainly developed in the lower part.                              |

### (3) Analysis of Structural–Fracture Development Models

Using the above analytical framework, fracture development patterns associated with other structural styles in the study area were systematically examined (Table 1). In total, nine structural–fracture development models were established: Single-thrust structure–fracture model, Back-thrust structure–fracture model, Opposed-thrust structure–fracture model, Vertical strike-slip structure–fracture model, Imbricate structure–fracture model, “Y”-shaped structure–fracture model, Anti-“Y”-shaped structure–fracture model, Semi-flower structure–fracture model, and Flower structure–fracture model.

Each model reflects distinct combinations of structural geometry, stress distribution, and fracture formation mechanisms, collectively revealing the strong structural control on fracture development under a compressional–shear–strike-slip tectonic regime in the Zigong area.

### (4) Application of the Fracture Development Model

By integrating the established fracture development models with the structural characteristics of the study area, the spatial distribution and development patterns of fractures across the entire Zigong area can be systematically clarified (Fig.10).

Understanding shale fracture development is of great significance for shale oil and gas exploration and development. Considering the distinctive characteristics of shale reservoirs—namely self-generation and self-storage of hydrocarbons—several types of favorable exploration targets can be identified (Qi et al. 2026, Zhang et al. 2021a).

First, the **shear fracture–fault intersection zones** represent important exploration targets. Faults provide vertical migration pathways for hydrocarbons, whereas shear fractures enhance lateral connectivity, enabling the intersection zones to possess dual transport capacity. In addition, thrust-related fault activity may create lateral sealing conditions that are conducive to hydrocarbon preservation.

Second, areas characterized by well-developed shear fracture networks are also favorable for shale oil and gas accumulation. Because shale itself functions as both source rock and reservoir, extensive shear fracture networks can significantly enhance reservoir space and permeability. Moreover, the presence of abundant natural fractures can reduce breakdown pressure during hydraulic fracturing operations, thereby improving the effectiveness of reservoir stimulation.

Third, fault-block trap accumulation zones located on structural wings are also potential targets. These traps commonly develop in the footwall of reverse faults, where fault blocks may form structural–lithologic composite traps capable of accumulating hydrocarbons that migrate from structural highs (Tsang, Doughty and Uchida 2008, Zhou et al. 2023).

Considering the fracture development characteristics of the Zigong area, large-scale NE- and near-SN-trending faults are widely developed in the study area and are commonly associated with dense shear fracture systems. These structural settings are favorable for the formation of shear fracture–fault intersection zones and thus represent promising reservoir development areas. Such favorable exploration and development zones are primarily distributed in the northern part of the study area.

Although shear fractures are also relatively developed in the cores of synclines, these locations typically correspond to structurally low positions. Therefore, additional factors—such as the shale brittleness index and the in-situ stress difference coefficient—must be integrated into the evaluation to comprehensively assess their reservoir potential.

Another favorable target is the anticline wing zones within the study area. Anticlines in the Zigong area are commonly associated with fault activity, and the combination of anticline structures

and adjacent faults can create effective sealing conditions along structural flanks. Consequently, hydrocarbons migrating from structural highs may accumulate at relatively elevated positions along the anticline wings, making these zones promising targets for shale oil and gas exploration and development.

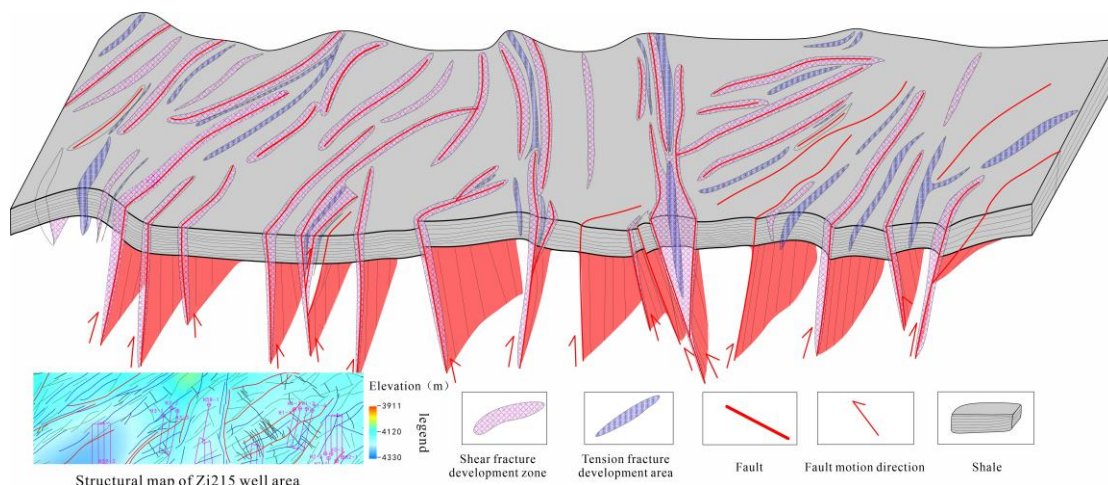


Fig.10 Application effect diagram of shale fracture development model

## 5 Discussion

### 5.1 Current Problems and Development Trends in the Study of Shale Fracture Development Characteristics

At present, research on shale fracture development characteristics mainly focuses on the parameters of individual fractures, such as fracture occurrence, scale, size, aperture, and the analysis of their main controlling factors. However, analyses of controlling factors are largely limited to qualitative interpretations, while quantitative studies examining the relationships between controlling factors and fracture development remain insufficient. In addition, studies on the collective characteristics of multiple fracture systems are relatively limited. Existing research mainly emphasizes fracture density, whereas investigations of fracture assemblage patterns, cross-cutting relationships, and fracture formation sequences remain inadequate (Li et al. 2023, Xiong et al. 2021, Sun et al. 2025).

With increasing global attention to the processes of hydrocarbon enrichment and accumulation, the influence of fracture formation stages on the enrichment and preservation of shale oil and gas has gradually attracted greater interest. Current research trends in the study of shale fracture development characteristics can be summarized as follows. First, studies are shifting from macroscopic fracture analysis toward the investigation of micro-fractures. Second, research on controlling factors is evolving from qualitative descriptions to quantitative analyses. Third, greater emphasis is being placed on understanding fracture assemblage characteristics, intersection relationships, and development stages. Finally, the establishment of quantitative models linking fracture development with its main controlling factors is becoming an important research direction.

### 5.2 Current Problems and Development Trends in the Study of Shale Fracture Development Patterns

Existing research on shale fracture development patterns is largely limited to general theoretical analyses. Detailed investigations that consider specific tectonic settings remain insufficient, and effective analytical methods and evaluation criteria have not yet been fully established. Moreover, studies on fracture development models under particular tectonic backgrounds remain limited. With the continued advancement of exploration and development of organic-rich shale gas both domestically and internationally, it has become increasingly important

to establish fracture development models under different structural backgrounds and to develop reliable methods for predicting fracture distribution. Although numerous fracture prediction techniques have been proposed, these methods are often applied independently. As a result, prediction results derived from different methods are difficult to integrate effectively, which may lead to inconsistencies among results and challenges in reliability evaluation (Shi et al. 2022, Stoeckhert et al. 2015, Sarkar et al. 2025).

Current research trends in shale fracture development can be summarized in several aspects. First, increasing attention is being given to the establishment of fracture development models under different geological and tectonic settings. Second, greater emphasis is being placed on the acquisition and analysis of regional and local in-situ stress data during major tectonic activity periods, with the aim of enabling quantitative prediction of fracture development patterns. Third, fracture prediction methods are being continuously improved, with efforts to strengthen the integration of multiple analytical techniques. Finally, in the field of seismic inversion-based fracture prediction, increasing attention is being paid to the coupling relationships between petrophysical parameters and fracture development, as well as to the development of robust and reliable seismic inversion strategies.

## **6 Conclusion**

(1) Based on integrated analyses of fractures identified from outcrops, cores, conventional logging, and imaging logging in the Zigong area, the fracture development characteristics of the lower Longmaxi Formation were systematically characterized. NE-trending fractures are closely associated with early NE-oriented structural features and are characterized by relatively straight traces. These fractures are interpreted to have formed primarily through drag deformation induced by early NW-directed compressional stress. Fractures trending approximately north–south are predominantly conjugate with NE-trending fractures. NW-trending fractures generally exhibit planar surfaces and commonly intersect early large-scale faults at near-vertical angles. Their formation is considered to be controlled by persistent NE-directed compressional stress since the Oligocene, with distribution constrained by pre-existing NE-trending structures. Nearly east–west-trending fractures commonly form conjugate sets with NW-trending fractures. Fractures with other orientations are likely related to localized stress release during structural deformation; they are less developed and show no clear spatial regularity.

(2) Based on comprehensive analyses of regional tectonic evolution, stress transformation processes, structural styles, and structural characteristics in the Zigong area, the regional tectonic framework is defined as a compressional–torsional strike-slip system. Under the guidance of this structural framework, fracture characteristics and development patterns were systematically investigated. The principal structural styles and their assemblage patterns were clarified, and the formation mechanisms of different structural configurations were analyzed. By integrating fracture occurrence, superposition stages, assemblage relationships, and major controlling factors, fracture development patterns were established, leading to the identification of nine structural–fracture models: the single-thrust structure–fracture model, back-thrust structure–fracture model, opposed-thrust structure–fracture model, vertical strike-slip structure–fracture model, imbricate structure–fracture model, “Y”-shaped structure–fracture model, anti-“Y”-shaped structure–fracture model, semi-flower structure–fracture model, and flower structure–fracture model.

## **Declaration of interest statement**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

This study is supported by Natural Science Foundation of Hubei Province (Grant No. 2023AFD212). Thanks to the Geophysical Exploration Research Institute of China National Petroleum Jilin Oilfield for providing data and support, and thanks to the Hubei Provincial Natural Science Foundation for sponsoring this research.

## References

- Ademilola, J. A. & J. C. Pashin (2025) Integrated multi-attribute transform and seismic driven machine learning technique for geomechanical assessment of Cenozoic reservoirs and seal integrity for carbon storage in the Central Gulf of Mexico. *International Journal of Greenhouse Gas Control*, 147.
- Alam, A. K. M. B., Y. Fujii, N. Hasan & T. Chakma (2025) Hydration-induced fractures in shale with silt layers: A perspective on slope stability. *Geohazard Mechanics*, 3, 136–146.
- Dong, D., Z. Shi, Q. Guan, S. Jiang, M. Zhang, C. Zhang, S. Wang, S. Sun, R. Yu, D. Liu, P. Peng & S. Wang (2018) Progress, challenges and prospects of shale gas exploration in the Wufeng–Longmaxi reservoirs in the Sichuan Basin. *Natural Gas Industry B*, 5, 415–424.
- Du, X.-Y., Z.-J. Jin, L.-B. Zeng, G.-P. Liu, S.-X. Li, M. Ostadhassan, X.-P. Liang, G.-P. Wang & G.-Q. Lu (2025) Characteristics, controlling factors and mechanisms of natural fractures formation in lacustrine shale oil reservoirs: The Chang 7 member in Ordos Basin, China. *Petroleum Science*, 22, 1391–1406.
- Du, X., Z. Jin, L. Zeng, G. Liu, W. He, M. Ostadhassan, X. Liang, S. Yang & G. Lu (2023) Characteristics and controlling factors of natural fractures in deep lacustrine shale oil reservoirs of the Permian Fengcheng Formation in the Mahu Sag, Junggar Basin, China. *Journal of Structural Geology*, 175.
- Fan, C., H. Li, Q. Qin, S. He & C. Zhong (2020) Geological conditions and exploration potential of shale gas reservoir in Wufeng and Longmaxi Formation of southeastern Sichuan Basin, China. *Journal of Petroleum Science and Engineering*, 191.
- Guo, Z., K. Liu, L. Yu, J. Chen, Y. Wu, L. Chen & C. Liang (2025) Characterizing multi-scale heterogeneities in shales: An innovative workflow and application to Paleogene lacustrine shales in the Subei Basin, eastern China. *Marine and Petroleum Geology*, 178.
- Healy, D., G. Yielding & N. Kusznir (2004) Fracture prediction for the 1980 El Asnam, Algeria earthquake via elastic dislocation modeling. *Tectonics*, 23.
- Konstantinovskaya, E., Q. He, D. Hall, W. Phiukhao, M. Steele-MacInnis, N. B. Harris & G. G. Rodriguez (2025) Fracture systems and fluid inclusions in Upper Devonian organic-rich shales in the Western Canada Sedimentary Basin and Rocky Mountains Foreland Belt, West-Central Alberta, Canada. *Earth-Science Reviews*, 271.
- Li, J., Q. Qin, H. Li, J. Zhou, S. Wang, S. Zhao & Z. Qin (2023) Numerical simulation of the palaeotectonic stress field and prediction of the natural fracture distribution in shale gas reservoirs: A case study in the Longmaxi Formation of the Luzhou area, southern Sichuan Basin, China. *Geological Journal*, 58, 4165–4180.
- Li, Z., K. Xi, Y. Cao, Y. Zhang, X. Niu, X. Wang, W. Ma, Y. You, Y. Wang & G. Yuan (2025) Origin and controls on shale oil enrichment of bedding-parallel fractures in the Chang 73 lacustrine shales, Yanchang Formation, Ordos Basin. *Marine and Petroleum Geology*, 182.
- Liu, K., J. Xiong, X. Zhang, X. Fan, L. Li & Z. Chen (2020) Prediction of Fracture Toughness in the Shale Formation Based on Well Logging and Seismic Data: A Case Study of the Lower Silurian Longmaxi Formation in the Sichuan Basin, China. *Geofluids*, 2020, 1–13.
- Qi, N., J. Liu, X. Li, P. Jiang & A. Li (2026) Research on shale acid fracturing reservoir simulation

technology: A critical review. *Geoenergy Science and Engineering*, 257.

Sarkar, P., S. Yoon, J. Kim, S. Baek, A. Sun & H. Yoon (2025) Surrogate models for development of unconventional shale reservoirs by an integrated numerical approach of hydraulic fracturing, flow and geomechanics, and machine learning. *Geomechanics for Energy and the Environment*, 43.

Shang, X., H. Zhao, S. Long, T. Duan & F. Yang (2021) A Workflow for Integrated Geological Modeling for Shale Gas Reservoirs: A Case Study of the Fuling Shale Gas Reservoir in the Sichuan Basin, China. *Geofluids*, 2021, 1–22.

Shi, Z., J. Chen, D. Gong, S. He, X. Jiang, C. Sun & L. Fan (2022) Experimental study on the shear-slip characteristics of natural fractures in shale reservoirs. *Energy Science & Engineering*, 10, 1240–1250.

Stoeckhert, F., M. Molenda, S. Brenne & M. Alber (2015) Fracture propagation in sandstone and slate – Laboratory experiments, acoustic emissions and fracture mechanics. *Journal of Rock Mechanics and Geotechnical Engineering*, 7, 237–249.

Sun, Z., S. Xu, C. Ma, T. Li, J. Zhang & F. Zeng (2025) Shale fracture prediction using integrated seismic methods. *Marine and Petroleum Geology*, 179.

Tsang, C. F., C. Doughty & M. Uchida (2008) Simple model representations of transport in a complex fracture and their effects on long-term predictions. *Water Resources Research*, 44.

Wang, P., L. Tang, K. Ma, Y. Yang, C. Jin, L. Wu & X. Li (2026) The control effect of burial evolution time limit on the organic matter pore structure of shale: A case study of the lower Silurian Longmaxi Formation shale from the periphery of the Sichuan Basin in southern China. *Unconventional Resources*, 9.

Wang, Y., H. Liu, X. Hu, C. Dai & S. Fang (2024) Fracture network types revealed by well test curves for shale reservoirs in the Sichuan Basin, China. *Energy Geoscience*, 5.

Wang, Z., R. Zhao, L. Yang, H. Yin, W. Tang, D. Liu, Y. Gu & Y. Jiang (2025) Paleo-environmental and geological characteristics of Wufeng-Longmaxi marine shale in different paleo-geomorphological units, Eastern Sichuan Basin, China. *Natural Gas Industry B*, 12, 572–584.

Xie, J., Q. Qin & C. Fan (2019) Quantitative Prediction of Fracture Distribution of the Longmaxi Formation in the Dingshan Area, China using FEM Numerical Simulation. *Acta Geologica Sinica - English Edition*, 93, 1662–1672.

Xiong, J., K. Liu, C. Shi, X. Liu & L. Huang (2021) Logging prediction and evaluation of fracture toughness for the shales in the Longmaxi Formation, Southern Sichuan Basin. *Petroleum*, 7, 254–262.

Xu, S., R. Liu, F. Hao, T. Engelder, J. Yi, B. Zhang & Z. Shu (2019) Complex rotation of maximum horizontal stress in the Wufeng-Longmaxi Shale on the eastern margin of the Sichuan Basin, China: Implications for predicting natural fractures. *Marine and Petroleum Geology*, 109, 519–529.

Yang, R., F. Yang, P. Hu, W. Wang, M. Liu & R. Dong (2024) Prediction of fractures by using the stress field in medium to deep shale gas reservoirs: A case study of Late Ordovician–early Silurian shale gas reservoirs in the Nanchuan region, South China. *Journal of Asian Earth Sciences*, 265.

Zhang, J., Y. Zeng, D. Becerra & R. Slatt (2021a) Statistical analysis of geological factors controlling bed-bounded fracture density in heterolithic shale reservoirs: The example of the Woodford Shale Formation (Oklahoma, USA). *Journal of Petroleum Science and Engineering*, 200.

Zhang, Z., X. Kong, Q. Chen, Y. Zhang, Z. Deng, C. Yu, Z. Lei, H. Zhang, X. Wang, G. Yao, L. Yang, X. Tan & K. Zhang (2021b) Quantitative Characterization and Determination of the Main Factors That Control Fracture Development in the Lower Paleozoic Shale in Southeastern Chongqing, China. *Geofluids*, 2021, 1–11.

Zhao, C., J. Liu, C. Lyu, H. Xu & H. Lin (2023) Study on the shear-slip process and characteristics of fracture in shale. *Engineering Geology*, 319.

Zhao, J., Z. Jin, Z. Jin, X. Wen, Y. Geng, C. Yan & H. Nie (2017) Depositional environment of shale in Wufeng and Longmaxi Formations, Sichuan Basin. *Petroleum Research*, 2, 209–221.

Zhao, Y., X.-T. Wen, C.-L. Xie, B. Li, C.-L. Li, X. Pan & X.-Y. Zhou (2025) Simultaneous seismic inversion of effective stress parameter, fluid bulk modulus, and fracture density in TTI media. *Petroleum Science*, 22, 2384–2402.

Zhou, J. Q., L. G. Guo, J. J. Jiao & X. Luo (2023) Geometry-Based Prediction of Solute Transport Process in Single 3D Rock Fractures Under Laminar Flow Regime. *Journal of Geophysical Research: Solid Earth*, 128.