Characteristics of strike-slip faults and hydrocarbon potential of carbonate fault-karst reservoirs: A case study in the eastern Tarim Basin, China

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Summary

The concept of "fault-karst" reservoirs has been proposed based on the studies of fault deformation, karstification, and dissolution processes within fault zones in the Tarim Basin. Particularly, the strike-slip faults play a significant role in modifying the Ordovician carbonate reservoirs and accumulating hydrocarbon in the basin, making them a hot spot in hydrocarbon geological analysis. Utilizing new 3D seismic data and seismic attribute analysis, our study investigates the structure and evolution characteristics of strike-slip faults from three perspectives, including sectional, planar views, and active tectonic stages, as well as their effects on carbonate reservoirs in the area. We delineate two primary sets of fault systems, i.e., deep strike-slip faults exhibiting steep or flower patterns formed during the Early to Middle Caledonian, and shallow negative flower structure normal faults developed from the Late Caledonian to Hercynian periods. Throughout the region, NE-oriented strike-slip fault zones are predominantly developed and evolve from single linear strike-slip faults within the platform to horsetail or feather like faults towards the platform margin. Extensive fracturing significantly enhances karst processes, leading to the more developed fault-karst reservoirs. Exploration achievements have proven the significant hydrocarbon potential associated with NE-oriented strike-slip fault zones, highlighting the exploration and development prospects of the study area.

Introduction

Recent studies have shown that fault-karst reservoirs in Ordovician of the Tarim Basin are crucial for hydrocarbon resources and have promising potential for future oil and gas exploration and development (Jiao, 2017; Ma et al., 2018; Lai et al., 2021; Deng et al., 2022). These reservoirs are formed through fracturing of formations caused by tectonic movements along strike-slip fault zones. Subsequent dissolution and modification by various types of fluids moving along the faults result in reservoirs filled with oil and gas, primarily distributed along deep and large strike-slip fault zones. Therefore, a detailed analysis of the strike-slip fault system is crucial for exploring fault-karst reservoirs.

In the Yuman area of the Tarim Basin, only 2D seismic data were previously available, making it challenging to identify NE- and SN-oriented strike-slip faults, limiting detailed research on Ordovician fault-karst reservoir exploration. However, in 2022, a new 3D seismic survey covering 672 km² was deployed in the area. Utilizing this data, we conduct a detailed analysis of the strike-slip fault characteristics, assess differences in reservoir space modification by these fault systems, and identify favorable exploration zones.

Geological background

The Tarim Basin, located in the southern area of the Xinjiang Uyghur Autonomous Region, was formed with the evolution of the Tarim Craton. It stands as the largest inland basin within China, covering an area of about 600,000 km^2. The northern and western borders of the basin are adjacent to the Tianshan orogenic belt, while its southern part is flanked by the West Kunlun and Aerjin orogenic belts (Figure 1).

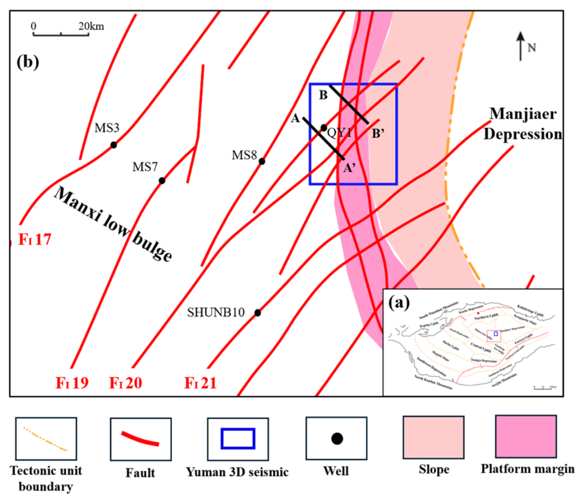

Figure 1. (a) Tectonic division map of the Tarim Basin (modified after Gao and Fan, 2015; Lai et al., 2021). (b) Distribution of NE- and SN-oriented faults in the Fuman-Yuman area and the location of wells.

The system of strike-slip faults mainly occurs in the Ordovician carbonate rocks, which developed during the Middle Caledonian tectonic movements, and has undergone multi-stage activities in subsequent periods (He et al., 2006; Yang et al., 2020). The Fuman-Yuman area predominately develops two sets of NE- and SN-oriented strike-slip faults (Figure 1). Numerous wells drilled in the western Tarim platform area have verified the presence of large-scale

Ordovician carbonate fault-karst reservoirs associated with these strike-slip faults and multi-stage fluid reformation.

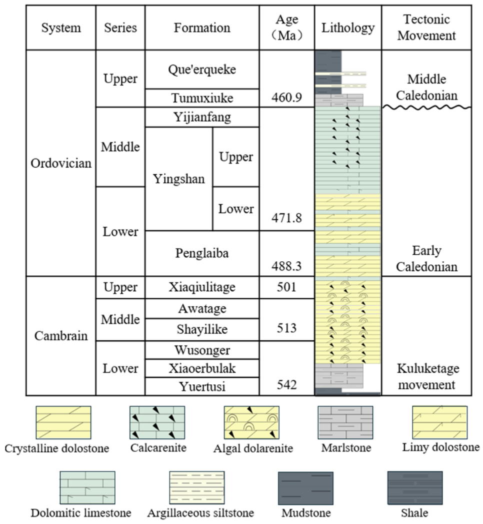

Figure 2. Stratigraphic chart of carbonate reservoir in the study area.

Our study area is in the Yuman area located on the Manxi platform margin, adjacent to the Manjiaer Depression within the eastern Tarim basin. The Ordovician strata in the area represent various paleogeographic environments and sedimentary types (Figure 2).

Data and Method

The Yuman 3D seismic survey covers an area of approximately 672 km^2, composing 1200 inlines and 1500 crosslines with a 2 ms sampling interval. Our study utilized the pre-stack depth migration dataset from the Yuman 3D seismic survey, and the processed seismic data were imported into the Geoeast software developed by CNPC Exploration Software Co., Ltd. for interpretation.

Identification characteristics of strike-slip faults were primarily divided into three aspects, i.e., sectional, planar, and active tectonic stage. We investigated the geometric and structural features of NE-trending strike-slip faults across the Cambrian to Carboniferous sequences, analyzing variations in fault displacement and structure to discern changes in stress fields. Utilizing curvature attributes on map views, we delineated the horizontal structure and distribution patterns of these faults, quantifying the discontinuities in reflector curvature caused by faulting. Integrating regional tectonic history, we constrained the timing of fault activities based on initiation and termination stratigraphic sequences, determining the timing of faults from the geologic periods of the hosting strata. Additionally, we utilized structural tensor attributes, which define and quantify geological structures by exploiting spatial variations in acoustic impedance, to characterize the spatial distribution and scale of beaded reflections formed by karstification along strike-slip faults. These karst features were composited with fault predictions at key horizons to analyze associated karstification patterns. This integrated geological and geophysical method effectively identified the characteristics of the strike-slip faults but also set the stage for prioritizing exploration targets of carbonate fault-karst reservoirs in the study area.

Characteristics of strike-slip faults in the study area

Cross-section characteristics

From seismic sections, the primary NE-oriented strike-slip faults in the study area are characterized by small displacements at great depth, with the fault planes predominantly steep. These faults extend downward to the Cambrian base and upward through the top of the Ordovician formations of the Que'erqueke Group. Some of these faults continue to be active, extending into the Silurian-Carboniferous formations, but the faults above the Carboniferous are not obvious.

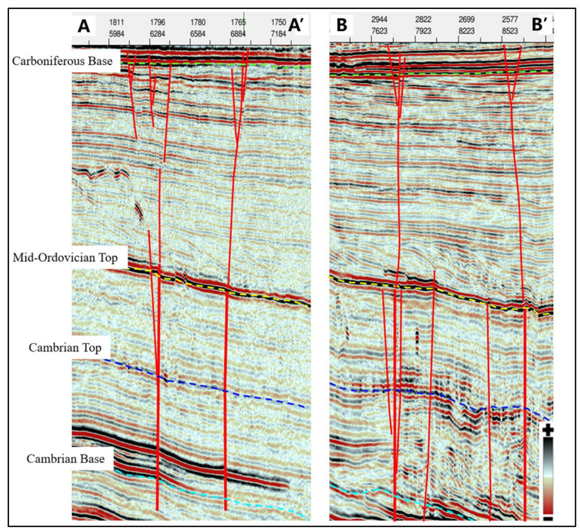

Figure 3. Interpreted seismic cross-sections of strike-slip faults (locations shown in Figure 1), displaying steep faults within the Cambrian, diverging upward into multiple faults, and negative flower structure faults near the base of the Carboniferous.

In certain areas, the main fault and branch faults form a flower-structure pattern. In the Cambrian, it appears as an upright fault, diverging upward into multiple faults. The upper part is mostly fractured to or near the top of the Mid-Ordovician, while the lower part converges at a certain angle on the main fault. Deep faults at the base of the Upper Ordovician exhibit compression-related deformation features, reflecting compressive stress. In contrast, shallow faults display a different structural style, characterized by a series of normal faults forming a negative flower structure, indicative of the extensional stress (Figure 3).

Planar distribution characteristics

In the study area, NE-oriented faults predominate, and SN-oriented strike-slip faults are developed along the platform margin, with both sets of strike-slip faults densely developed in a net pattern, displaying typical characteristics. From the curvature attribute results, two sets of strike-slip faults in the area have been developed successively in multiple stages (Figure 4). The deep and large faults cut through the Cambrian source rocks and exhibit high connectivity. One primary NE-oriented strike-slip faults covering 36 km and two secondary faults covering 54 km have been identified.

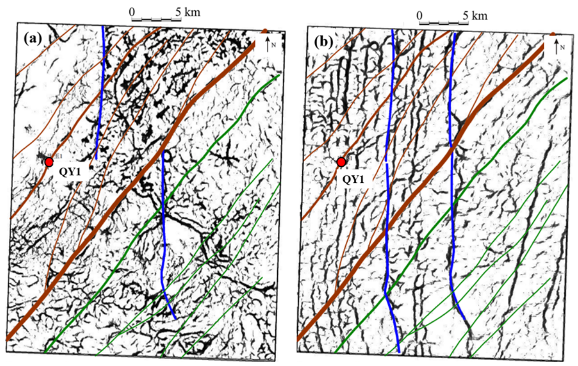

Figure 4. Results of the curvature attribute. (a) Mid-Ordovician top; (b) Cambrian base. Two sets of strike-slip faults (blue for SN-oriented faults, brown and green for the main and branches of two NE-oriented strike-slip faults) have been developed successively from the Cambrian to the Mid-Ordovician.

Regionally, the NE-oriented faults evolve from single linear strike-slip faults within the platform to horsetail or feather-like faults towards the platform margin. These NE-oriented faults have been active over multiple phases, expanding from the southwest to the northeast direction (Figure 5).

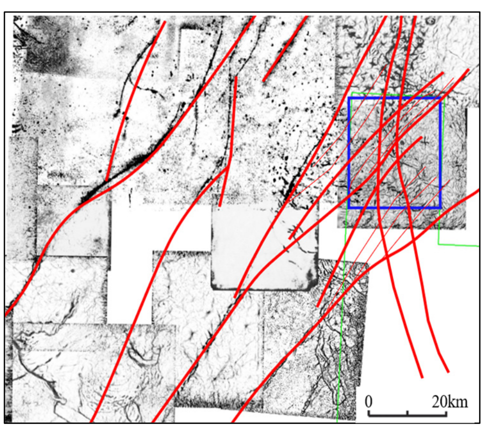

Figure 5. Curvature attribute of the Mid-Ordovician top in the western Tarim platform area, demonstrating the regional distribution patterns of strike-slip faults.

Multi-stage activities

The faults in the study area have experienced multiple stages of tectonic movements. By integrating regional seismic attributes, tectonic evolution history, and fault activity characteristics (He et al., 2006; Qiu et al., 2019; Kong et al., 2020), it has been confirmed that the fault system in the area primarily experienced two phases, i.e., the Early to Middle Caledonian and the Late Caledonian to Hercynian periods (Figure 6).

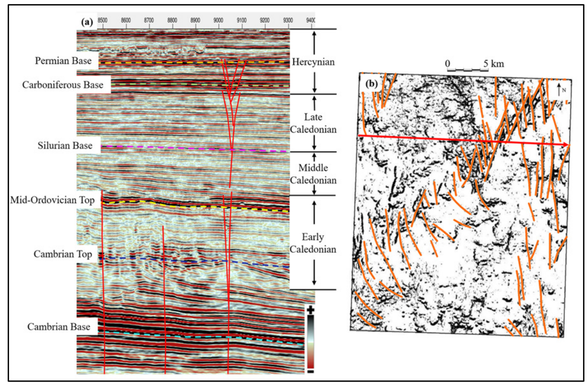

Figure 6. (a) Seismic section revealing different tectonic activity periods in the study area. (b) Curvature attribute of Carboniferous base, showing a series of NW-oriented en echelon normal faults.

During the early Caledonian period, the tectonic setting in the central Tarim area was characterized by weak extension within the craton (Kong et al., 2020). In the study area, small-scale extensional normal faults are developed with limited displacement. During the mid-Caledonian period, influenced by the orogenic movements of the West Kunlun and Aerjin mountains, the carbonate rock platforms began to uplift regionally under the action of compressive stress. The development of right-lateral NW-oriented thrust faults in the central Tarim uplift led to the formation of NE-oriented strike-slip faults in the study area. In the late Caledonian period, the regional stress in the northern slope area of central Tarim shifted from compressive to extensional, resulting in the development of a series of extensional strike-slip faults. This period also marked the presence of a series of NW-oriented en echelon normal faults (Figure 6), displayed on cross-sections as negative flower structures.

The control factors of strike-slip faults on oil and gas

Influenced by structural fracturing and hydrothermal dissolution alterations under deep burial conditions in the study area, a variety of reservoir spaces have formed in the Ordovician carbonate rocks. These include caves associated with steep faults, high-angle fractures, and dissolution pores developed along fractures (Figure 7). NE-oriented strike-slip faults cut down to the base of the Cambrian, enabling communication with the Cambrian source layers and forming geological conditions for the vertical migration of oil and gas.

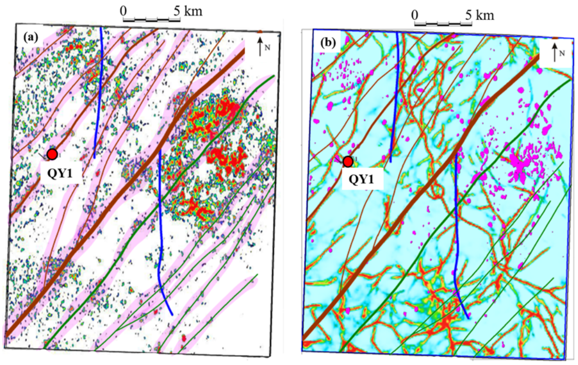

Figure 7. (a) Structural tensor attribute of the Upper Yingshan Formation, showing the distribution of beaded reflections. (b) Composite map illustrating the distribution of beaded reflections in the upper Yingshan Formation and the faults prediction at the Mid-Ordovician top.

The study area is under the control of platform margin reefs, faults, and karst formations, facilitating both vertical and horizontal connectivity among reservoir bodies. From the seismic cross-sections, beaded reflection features are widely developed in the upper Yingshan Formation, displaying a leopard-spot pattern of dense distribution (Figure 8). This pattern indicates large-scale karst development during this period (Figure 8), with fault-karst bodies being the primary type of reservoir. Consequently, this has resulted in the concentrated area of high-quality reservoirs.

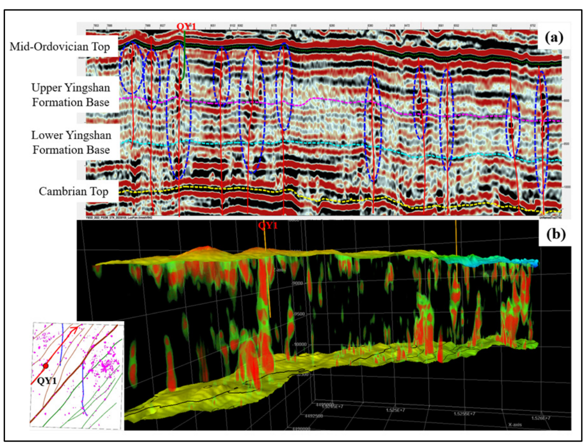

Figure 8. (a) Seismic section along NE-oriented strike-slip faults (the branch of $F_{I}20$). (b) 3D visualization of structural tensor attribute volume, reflecting the scale of fault-karst reservoirs along the fault.

Exploration applications of fault-karst reservoirs

Exploration achievements in the western platform of the Tarim Basin have confirmed that carbonate fault-karst reservoirs have outstanding exploration results and possess significant reserves.

Within the NE-oriented strike-slip fault zones, several wells have achieved remarkable breakthroughs, with daily oil and gas equivalent production exceeding 1000 tons. In the $F_{I}17$ fault zone, Well MS3 achieved a daily production of 1610.9 m^3 oil and 52.5×10^4 m^3 gas. In the $F_{I}19$ fault zone, Well MS72 yielded a daily production of 1040 m^3 oil and 20×10^4 m^3 of gas. Closest to the study area, Well MS8 within the $F_{I}20$ fault zone produces 423 m^3 of oil and 93.8×10^4 m^3 of gas daily. In 2023, the first well deployed in the area, QY1, located on the main branch of the $F_{I}20$ fault zone, showed promising results in the upper Ying Formation, with total hydrocarbons reaching over 90%. These high-yield wells have led to significant discoveries in the Middle Ordovician, demonstrating the excellent exploration prospects of carbonate reservoirs in the study area.

Conclusions

In the study area of the eastern Tarim Basin, NE-oriented faults predominate, with SN-oriented strike-slip faults developing along the platform margin. These NE-oriented faults evolve from single linear strike-slip faults within the platform to horsetail or feather like faults towards the platform margin, indicative of their complex evolution. Active over multiple phases, these faults create complex pathways that facilitate both the migration and trapping of oil and gas reserves.

Fault activities in the study area occurred in two distinct phases, i.e., the Early to Middle Caledonian and the Late Caledonian to Hercynian periods. Deep faults exhibit steep or flower patterns, while shallow faults show extensional negative flower structures. The multi-phase activities of strike-slip faults play a significant role in controlling the migration and accumulation of oil and gas in the region.

The exploration of carbonate fault-karst reserves in the Tarim Basin has yielded significant breakthroughs, confirming the overall abundance of oil and gas in the western platform area. The advancement demonstrates the high-yield potential of the NE-oriented strike-slip faults and the excellent exploration prospect of carbonate fault-karst reservoirs in the study area, holding promising implications for future exploration and development efforts in the region.