Fluid evolution in strike-slip fault zones of lower Paleozoic tight carbonate reservoir in NW Tarim Basin, China
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Summary

Ultra-deep carbonate reservoirs buried more than 7000 m, and the matrix has no effective reservoir space in the northwestern margin of Tarim Basin. Strike-slip fault-related fractures and cavities are the primary reservoir space and control fluid migration. In this study, using outcrops, thin section, δ13C, δ18O, and 87Sr/86Sr isotopes were applied to determine the characteristics of the strike-slip fault and origin of the fluid, combined with the homogenization temperature of fluid inclusions, burial history and thermal history in calcite veins, the formation time and evolution of multi-phase fluid were determined. The strike of the strike-slip fault comprises calcite bands, fault breccias, and fractures filled with minerals such as bitumen, dolomite, and quartz. The study area mainly developed three stages of diagenetic fluids. The first stage was meteoric water in the middle Caledonian, which showed a negative δ18O value, low homogenization temperature, and salinity. The second stage is the Late Hercynian (Early Permian) brine, characterized by more negative δ18O value, high 87Sr/86Sr ratios, and high homogenization temperature and salinity. The third stage is the late Permian meteoric water, characterized by a negative δ18O value, lower homogenization temperature, and salinity than seawater. This study focuses on the fluid activity in the fault zone and the reservoir transformation, making great significance in revealing the formation and development mechanism of strike-slip fault-related fracture and cavity reservoirs.

Introduction

The Tarim Basin in northwestern China (Figure 1) hosts significant hydrocarbon resources within its Paleozoic marine stratigraphic assemblage (Li et al., 2022). The Lower Paleozoic carbonates have yielded significant hydrocarbon resources in the Tarim Basin. Previous studies suggest that reef-shoal and weathering crust karst-controlled hydrocarbon resources and reservoirs are in a large area of quasi-stratified distribution (Wang et al., 2021). However, recent development has discovered that oil and gas enrichment is closely related to strike-slip fault zones (Jiao, 2017). A series of wells deployed along several strike-slip fault zones has revealed good oil and gas production in Tazhong and Tabei uplifts, revealing the control of strike-slip faults on oil and gas (Deng et al., 2022). Previous studies have analyzed the strike-slip fault system in different basin areas, investigating features including its structural style, activity history, and displacement characteristics (Qiu et al., 2022; Yang et al., 2022). Diagenetic fluids in the Tarim Basin are diverse, including meteoric water, hydrothermal brine, and magmatic-hydrothermal fluid, and there are obvious differences in fluids in different regions (Lu et al., 2017). The evolution of multi-stage strike-slip fault-related fluids has not been systematically studied, and it is not easy to evaluate the influence of strike-slip fault-related fluids on reservoir quality.

Method

The DJI Mavic Air2 Pro UAV collected oblique photography outcrop data in Penglaiba. The geometric and
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Kinematic characteristics of strike-slip faults were analyzed based on the oblique photography data collected. The calcite powder was reacted with anhydrous H3PO4 acid at 25 °C for 24 h to release CO2 gas. Thermofisher 253 plus stable isotope mass spectrometer + Flash EA FT determined the carbon and oxygen isotopes. The standard deviations of δ13CPDB and δ18OPDB were less than 0.020 and 0.050, respectively. The 87Sr/86Sr ratio was calibrated by the mass fractionation standard of 87Sr/86Sr = 0.1194. The 87Sr/86Sr ratios were determined on a Fennig MAT-261 mass spectrometer. Taking NBS987 as the standard reference, the measurement accuracy of 87Sr/86Sr is ± 0.00003-0.00007. The microscope used in the fluid inclusion temperature measurement experiment is a multi-functional microscope Lycra 4500P. The temperature measurement equipment is a Likam THMSG600 micro-hot and cold table, and the controllable temperature range is −196–600 °C. The homogenization temperature and freezing point temperature accuracy of this test are ± 1 °C and ± 0.1 °C, respectively. Salinity is calculated by using the freezing point temperature of inclusions.

Results

Fault zone characteristics

The original rock primarily consists of fine-grained calcite and dolomite minerals (Figure 2a-b). The fault breccia has a small amount of dispersed authigenic quartz present (Figure 2c). Fractures within the fault core are filled with bitumen and calcite, with some fractures characterized by bedding filling (Figure 2d). Bitumen-filled vugs and fractures are also present in the fault core, with some remaining unfilled (Figures 2e, 2g). Near the fault core, it is evident that the original rock is encircled by both calcite and bitumen (Figure 2f). The fractures within the damage zone situated between the three faults are predominantly filled with calcite (Figure 2h), while some fractures are filled with dolomite (Figure 2i). According to the cross-cutting relationship between fractures and vugs in the microscopic and outcrop areas and the types of fillings from the surrounding rock to the core, it is considered that there are mainly three stages of diagenesis. From early to late, it is vugs filled with calcite (VC), the first phase of calcite filling fractures (FC1) and the second phase of calcite filling fractures (FC2).

Isotope geochemistry and fluid inclusion

The δ13C, δ18O, and 87Sr/86Sr ratios of two VC, nine FC1, and nine FC2 were analyzed. The δ13C values of VC range from −3.02‰ to −2.86‰, δ18O values range from −5.32‰ to −4.14‰ (Figure 3), and the 87Sr/86Sr ratios range from 0.7092 to 0.7093 (Figure 4). The δ13C values of FC1 ranges from -6.37‰ to -3.46‰, the δ18O values ranges from -13.57‰ to -10.43‰ (Figure 3), and the 87Sr/86Sr ratios ranges from 0.7095 to 0.7103 (Figure 4). The measured homogenization temperature and calculated salinity of fluid inclusions show that the homogenization temperature of VC inclusions ranges from 61 °C to 97 °C, and the salinity ranges from 0.18 to 1.05 wt% NaCl eq. The
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The homogenization temperature of FC1 inclusions ranges from 106 °C to 117 °C, and the salinity ranges from 8.53 to 9.89 wt% NaCl eq. The homogenization temperature of FC2 inclusions ranges from 76 °C to 224 °C, and the salinity ranges from 0.53 to 2.41 wt% NaCl eq (Figure 5).

**Origin and evolution of diagenetic fluid**

The δ¹³C values of Cambrian carbonate rocks range from −2.35‰ to 2.58‰, the δ¹⁸O values range from −3.8‰ to −7.9‰, and the ⁸⁷Sr/⁸⁶Sr ratios are 0.70915 ~ 0.70956, respectively. Salinity ranges from 3.5 to 8.0 wt% NaCl eq (Denison et al., 1998).

The δ¹⁸O value of VC is slightly more negative than that of seawater, and the δ¹⁸O value decreases slightly, which may be caused by meteoric diagenesis (Choquette and James, 1987). The calculated salinity of fluid inclusions is generally lower than 3.5 wt % NaCl eq (Figure 5). This further indicates that VC is most likely formed in the environment of meteoric water, and there may be a small amount of seawater mixing. The result of VC in the study area measured by in-situ calcite U-Pb dating is 485.4 ± 1.9 Ma (Zheng et al., 2020), corresponding to the mid-Caledonian movement. During this period, the overall structure of the northwestern margin of the Tarim Basin was uplifted, and the exposed surface led to the extensive development of dissolved caves in meteoric water (Chen et al., 2022).

White et al. (1975) defined fluids with higher temperatures (5 °C or more) than the surrounding environment as hydrothermal fluids. When the δ¹⁸O value is lower than −10‰, it indicates that the oxygen isotope may have changed significantly compared with the original composition (Zheng et al., 2020). The δ¹⁸O value of FC1 is mainly less than −10‰ (Figure 3), the homogenization temperature of fluid inclusions is greater than 105 °C, and the salinity is generally higher than 8.5 wt% NaCl eq (Figure 5). The origin of the fluid may be the brine of the basin or the magma. The in-situ calcite U-Pb dating shows that the strongest thermal event occurred at 290.5 ± 2.9 Ma and occurred widely in the Early Permian (Dong et al., 2013). The high ⁸⁷Sr/⁸⁶Sr ratio indicates that the fluid is more likely to be derived from the brine of the basin because the Early Permian magma is mostly ophiolite with a low ⁸⁷Sr/⁸⁶Sr ratio (Kawahata et al., 2001). The hydrothermal dissolution caused by the early Permian hydrothermal event formed another fractured-vuggy reservoir along the strike-slip faults. The δ¹⁸O values of FC2 are higher than those of FC1 (Figure 3), the ⁸⁷Sr/⁸⁶Sr ratio is lower than that of FC1 (Figure 4), the homogenization temperature and salinity of fluid inclusions are lower than those of FC1, and the salinity does not exceed 3.5 wt% NaCl eq (Figure 5), indicating the diagenetic fluid of meteoric water. In addition, some fluid inclusions have been found with homogenization temperatures between 150° C and 230° C, which mixing meteoric water and hydrothermal water may cause. However, the salinity is generally low, which negates the possibility. This phenomenon may be due to the deep circulation of meteoric water that may flow along the fault to the deep strata, thus becoming very hot. Subsequently, the heated meteoric water migrated upward, resulting in calcite precipitation. This flow pattern was proposed by Qing and Mountjoy (1992). It is most likely to occur during the subsequent uplift and cooling period of the Late Permian (Liu et al., 2017).

Conclusions

The strike of the strike-slip fault core comprises calcite bands, fault breccias, and fractures filled with minerals such as bitumen, dolomite, and quartz. The damage zone mainly includes calcite, unfilled, and dolomite-filled fractures. The study area primarily developed three stages of diagenetic fluids. The first stage was meteoric water in the middle...
Caledonian, which showed a negative δ¹⁸O value (−5.32‰ to −4.14‰), low homogenization temperature (61 °C to 97 °C), and salinity (0.18 to 1.05 wt% NaCl eq). The second stage is the Late Hercynian (Early Permian) brine, characterized by more negative δ¹⁸O value (-13.57‰ to -10.43‰), high ⁸⁷Sr/⁸⁶Sr ratios (0.7095 to 0.7103), high homogenization temperature (106 °C to 117 °C) and salinity (8.53 to 9.89 wt% NaCl eq). The third stage is the late Permian meteoric water, characterized by negative δ¹⁸O value (−10.20‰ to −7.58‰), lower homogenization temperature (76 °C to 114 °C), and salinity (0.53 to 2.41 wt% NaCl eq) than seawater.