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Article

Effect of Multi-Stage Strike Slip Faults and Fluids Effect on the Origin and Evolution of a Deep Carbonate Reservoir in the Southern of Tahe Oilfield, Tarim Basin

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Abstract

In Tarim Basin, China, carbonate strata at great burial depths contain abundant petroleum. There has been no notable weathering of the Middle and Lower Ordovician limestone in the southern area of Tahe Oilfield due to the shielding effect of the Upper Ordovician strata; however, the origin and evolution of these carbonate reservoirs is controversial. Based on cores, well logging, image logging, and new 3D seismic data analysis, these reservoirs in the study area were divided into three types: dissolved pores, fractures, and caves. The characteristics and formation of Paleozoic faults in the southern Tahe oilfield have been studied. The results indicate that four stages of fault systems developed: extensional faults in the Cambrian-Early Ordovician, strike-slip faults in the Middle Ordovician, and reactivation of strike-slip faults in the Silurian-Devonian, and faults related to volcanic activities in the Permian. Cathodoluminescence, geochemical parameters, and fluid inclusions are used to investigate fault-controlled fluid compositions. There are four main types of diagenetic fluids (meteoric water, formation water, hydrothermal fluid, and mixed fluids) and their diagenesis evolution is discussed. The coupling relationship between diagenetic fluids and strike slip faults controls the development of reservoirs. During the karstification process, mixed dissolution of meteoric water and hydrothermal fluids contributed greatly to the development of these carbonate reservoirs, with multi-stage inherited faults controlling the fracturing of cave reservoirs. Two stages of NNW and NNE trending “X” conjugate strike-slip fault systems formed in the Middle Caledonian and Early Hercynian was important for diagenetic fluids migration and dissolution. The faults formed during the Late Hercynian are the main area of hydrothermal fluid migration, resulting in both hydrothermal dissolution pores and cave formation. This work shows that it can provide theoretical guidance for deep oil and gas exploration and development.

Keywords: Tarim Basin; deep carbonates reservoirs; strike slip faults; diagenetic fluids

1. Introduction

Marine carbonate rock reservoirs are rich in hydrocarbon resources, which account for approximately 70% of global hydrocarbon reserves, and have been an important field for petroleum geologists [1–3]. With continuous innovations in global hydrocarbon exploration, development theory, and technology, deep and ultra-deep fields are gradually being targeted [4,5]. Hence, in recent years, investigation into incremental reserves of deep and ultra-deep oil and gas around the world is increasing rapidly. According to Information Handling Service (IHS) (2014) data[6], 187 oil and gas

reservoirs have been discovered in ultra-deep reservoirs (> 6000 m), with proven recoverable reserves of 943×10^8 tons, accounting for 39.99% of the total recoverable reserves in the world. In the past 20 years, a series of breakthroughs have also been made in deep hydrocarbon exploration in China. For example, several deep oil and gas fields have been discovered and developed in both the Tarim and Sichuan Basins. Hydrocarbon reserves were found in Cambrian strata at depths of more than 8000 m in well TS 1, in the northern Tarim Basin[7,8]. With a buried depth of 6500–8000 m, fracture-vuggy carbonate reservoirs also developed in Ordovician rocks in the Halahatang Oilfield[9,10]. These findings indicate that there are high qualities, abundant hydrocarbon reservoirs in deep carbonate oilfields, which have great potential for oil and gas exploration and development.

The Paleozoic marine carbonate reservoirs of the Tarim Basin experienced multi-stage tectonic events and complex diagenetic alteration during their long geologic history, which resulted in complex reservoirs with distinct features[9,11,12]. For carbonate strata at great burial depths, primary porosity and permeability commonly disappear due to various physico-chemical effects, such as intensive cementation and compaction [13,14]. Therefore, the carbonate matrix (CM) generally has both low porosity and permeability[15,16]. Reservoirs formed by secondary dissolution are the main reservoir space for deep hydrocarbon accumulation [17–19]. Three types of carbonate reservoirs exist, according to the main controlling factors of Ordovician strata in the Tarim Basin: Reef – shoal (by micofacies)[20,21], paleo-karst (by weathered crust)[22–24], and "sweet spot" cavity reservoirs (by fault) [25,26].

The Tahe Oilfield is located on the south of the Tabei Uplift; it is a famous integrated marine carbonate oil and gas field, which has proven geological reserves exceeding 13.5×10^8 tons [27]. The most prolific strata are the Lower–Middle Ordovician Yijianfang Formation (O_{2y}) limestone, and the Yingshan Formation (O_{1-2y}) limestone and dolomite. In the northern or "main" area of the Tahe Oilfield, affected by multi-stage tectonic uplift, weathering, and denudation[28], the Upper Ordovician strata are almost completely eroded [22,29]. Therefore, long-term exposure, leaching, and karstification occurred in both the Yijianfang (O_{2y}) and Yingshan Formations (O_{1-2y}). The paleokarst systems mainly developed under the influence of multi-stage karstification for millions of years. In contrast, the southern area of Tahe Oilfield falls within the peripheral slope area (Figure 1(b) and (c)); the Upper Ordovician strata did not undergo strong denudation due to the relatively weak intensity of multi-stage tectonism in this area[30]. Therefore, the upper part of Lower–Middle Ordovician limestone is covered by a thick nearly insoluble layer of Upper Ordovician argillaceous limestone. Local petroleum exploration and development have proved that there are high-quality, rich reservoirs in the southern region of Tahe Oilfield[31]. There is no obvious weathering of Middle and Lower Ordovician limestone due to the shielding effect of the Upper Ordovician strata. Therefore, the genetic mechanism, controlling factors, and distribution rules of deep high-quality carbonate reservoirs in the southern area of Tahe Oilfield are clearly different from those in the northern area of Tahe Oilfield.

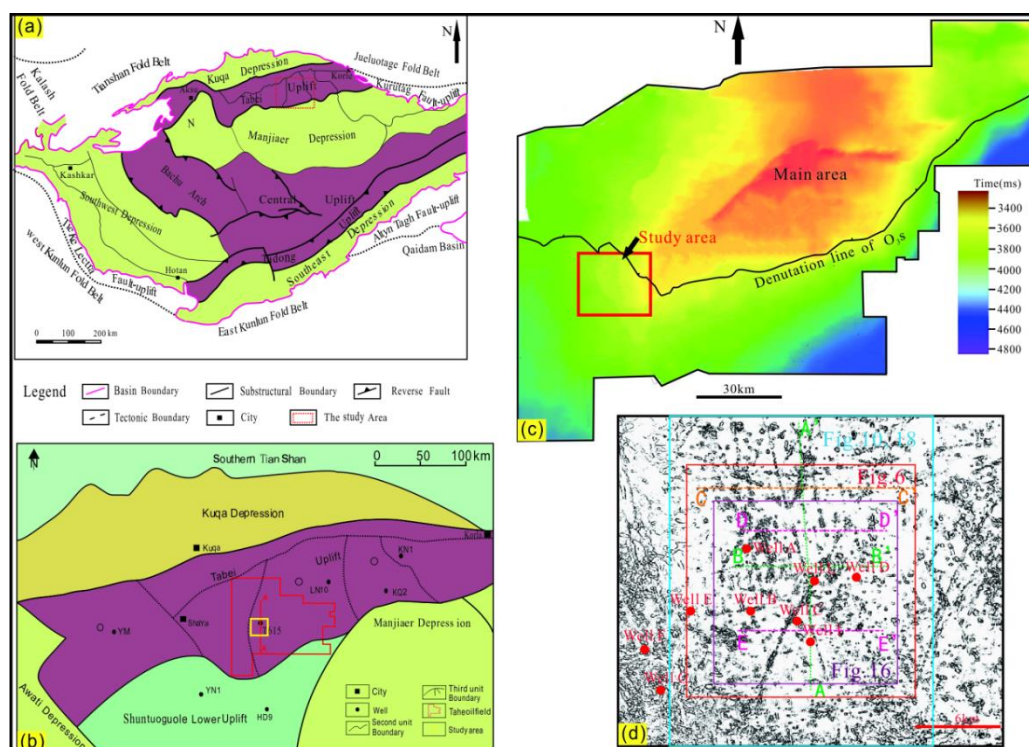


Figure 1. Location, map and coherence attribute of the Tahe Oilfield in the Tarim Basin; (a) Tectonic outline of Tarim Basin with the studying area in the Tabei Uplift of Tarim Basin; (b) Secondary structural units in the Tabei Uplift in the Tarim Basin; (c) Paleogeomorphic map of Upper Ordovician strata in Tahe Oilfield. The study area is in the southern area of Tahe oilfield and the upper Ordovician (insoluble strata) stratum are preserved to a certain thickness; (d) Coherence attribute map of study area along T₄ layer.

The formation and maintenance of high quality deep carbonate reservoirs are controlled by many factors. It is well known that fault systems and their distribution play a key role in hydrocarbon migration and accumulation in petroliferous basins[32,33]. Fault systems may also have important controls on subsurface fluid flow acting as localized conduits[34–36] or barriers[37,38], caused by the difference of permeability and surrounding rock in fault zones of several orders of magnitude[36]. Faults in carbonate strata are more distinctive as they not only demonstrate the interplay of the two above mentioned roles, but also the area impacted by the physical and chemical actions of various diagenetic fluids[39]. During the long-term burial period, considering both tectonic activity and fault growth, different diagenetic processes (e.g., cementation and dissolution) occurred in the fault zones under a series of physical and chemical actions, resulting in the formation of different types of reservoir spaces [40,41]. Rock fracturing and fault system development and distribution are assumed to enhance the permeability of significant physical modifications in deep carbonate strata[41,42]. The types and activity characteristics of diagenetic fluids are the main factors affecting dissolution and reformation within deep carbonate strata[43]. Many scholars believe that the diagenetic fluids in deep carbonates mainly include meteoric water[17,44], hydrothermal fluids[45–47], organic acids, and acidic fluids produced by thermochemical sulfate reaction (TSR)[48–50], which increases the reservoir capacity. The difference of diagenetic fluid properties leads to the difference of dissolution ability and reservoir scale in deep carbonate formation. We have not yet fully understood the origin and evolution of carbonate reservoirs which covered by the thick and insoluble in the southern area of Tahe Oilfield, how Paleozoic strike slip faults and diagenetic fluids affect reservoir development is still unclear. These key problems restrict the further exploration and development of deep hydrocarbon resources in Tahe Oilfield.

Based on cores, well logging, image logging, and seismic data, in this study, we characterize the fault system and carbonate reservoir features in detail in deep strata of the southern area of Tahe Oilfield. The characteristics of diagenetic fluids are studied based on C, O, and Sr isotopes, as well as

fluid inclusions in the southern area of Tahe Oilfield. The objectives of this study are as follows: (1) to determine the relationship between the strike slip fault and carbonate reservoir; (2) to analyze the types and evolution of diagenetic fluids for such carbonate reservoir dissolution; and (3) to discuss the effect of strike slip faults and diagenetic fluids on the origin and evolution of carbonates reservoirs.

2. Geological Setting

The Materials and Methods should be described with sufficient details to allow others to replicate and build on the published results. Please note that the publication of your manuscript implicates that you must make all materials, data, computer code, and protocols associated with the publication available to readers. Please disclose at the submission stage any restrictions on the availability of materials or information. New methods and protocols should be described in detail while well-established methods can be briefly described and appropriately cited.

The Tarim Basin covers an area of up to 56×10^4 km² in northwest China[51]. The Basin is a superimposed petroliferous basin, surrounded by three orogenic belts: the Tianshan tectonic belt in the north, the Altun tectonic belt in the South, and the West Kunlun tectonic belt in the southwest[52]. The Tahe Oilfield, with an area of 2400 km², is located in the south of the Tabei Uplift in the Tarim basin (Figure 1(a)). The Tabei Uplift borders the Kuqia depression in the north and Manjiaer depression in the south. It is an ancient uplift developed on the pre-Sinian metamorphic basement, which experienced multiple tectonic movements. The Tahe Oilfield is rich in hydrocarbon resources, with the main hydrocarbon production area originating from the Lower–Middle Ordovician carbonate reservoir, accounting for more than 70% of the total production. The study area is located in the southern area of Tahe Oilfield (Figure 1 (b), (c), and (d)).

The basement of the Tarim Basin is composed of pre-Sinian craton metamorphic rock, which is overlain by a sedimentary sequence with a 16000 m maximum thickness between the Sinian and the Quaternary[53]. The Paleozoic marine strata are developed in the Ordovician, Cambrian, and Upper Sinian, of which the Ordovician carbonate rocks are currently the main oil producing horizon. The Ordovician stratigraphic sequences in the southern area of Tahe Oilfield from bottom to top can be divided into six stratigraphic units[54].

(1) The Lower Ordovician Penglaiba Formation (O_{1p}): 250–400 m thick, developed from a tidal flat-shallow shelf environment, primarily composed of silty fine crystalline dolomite and calcareous dolomite;

(2) The Lower–Middle Ordovician Yingshan Formation (O_{1-2y}): 600–900 m thick, the result of a restricted platform-open platform environment, primarily composed of yellow gray to light gray micritic limestone and dolomitic limestone, which is conformable with the underlying O_{1p} Formation;

(3) The Middle Ordovician Yijianfang Formation (O_{2yj}): mainly consisting of microcrystalline limestone and sandy limestone, from an open platform environment; and the three Upper Ordovician deposits mainly consisting of marginal slope-shelf and continental platform depositional environments;

(4) The Querbake Formation (O_{3q}) and (5) the Lianglitage Formation (O_{3l}): mainly composed of knotty limestone containing mud and argillaceous limestone;

And (6) The Sangtamu Formation (O_{3s}): mainly consisting of siliciclastic mudstone and sandstone, with a thickness up to 900 m, and showing unconformable contact with the overlying Silurian strata[54]. The O_{3s} Formation is composed of insoluble siliciclastic rocks with a large thickness; hence, it is often regarded as a regional caprock, which blocks the exposure and dissolution of the underlying carbonate strata. The insoluble O_{3s} Formation pinch-out line divides the Tahe Oilfield into its northern and southern parts[54]. Compared with the northern region, the Upper Ordovician strata in the southern region are relatively intact (Figures 2 and 3).

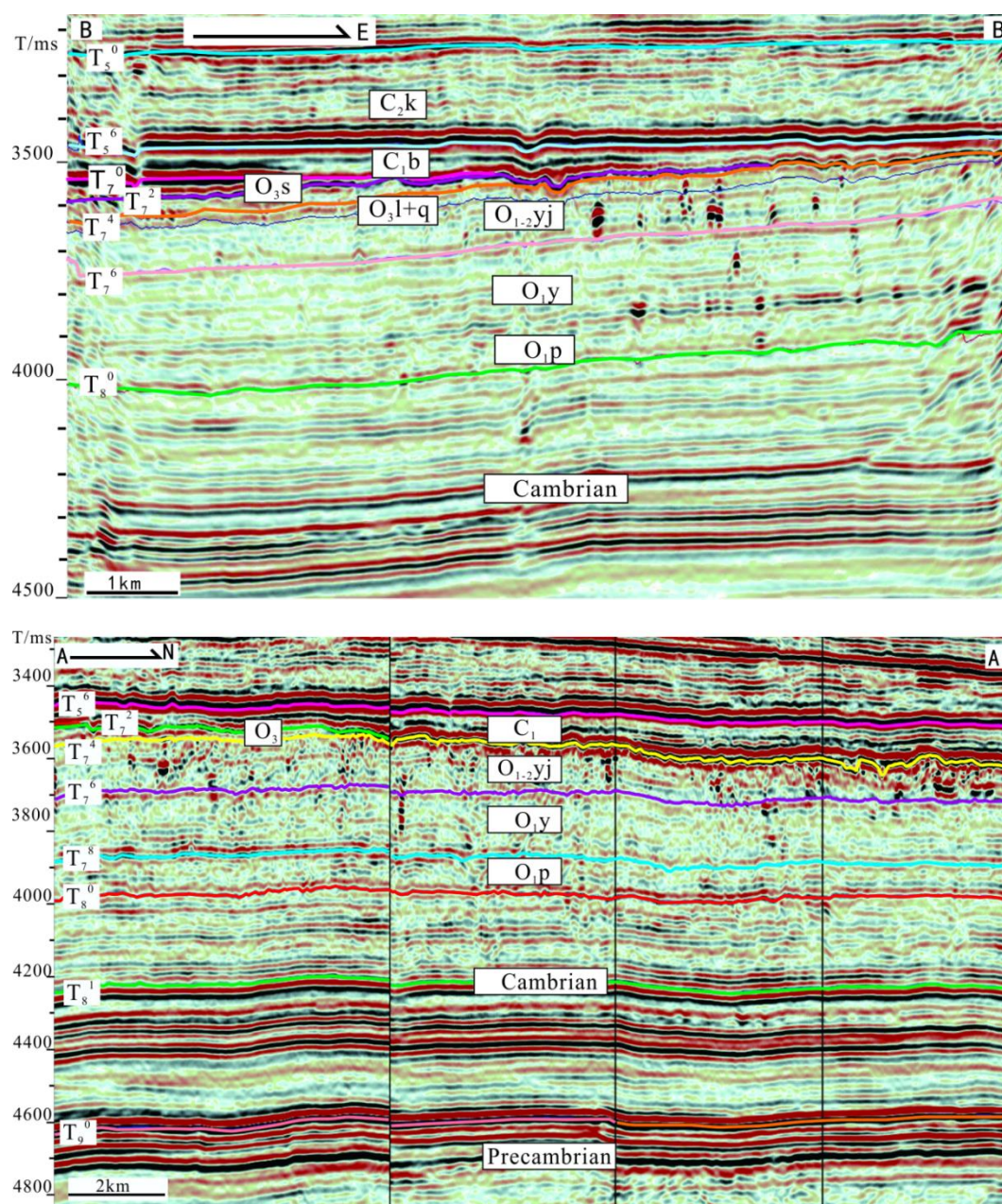


Figure 2. Stratigraphic profiles across the southern of Tahe Oilfield. (a) Cross section A-A', showing a N-S direction; (b). Cross section B-B', showing a W-E direction. T₅⁶: the seismic reflection interface on top of the Carboniferous Bachu Formation; T₇⁰: the seismic reflection interface on top of the Upper Ordovician Sangtamu Formation; T₇²: the seismic reflection interface on top of the Upper Ordovician Lianglitage Formation ; T₇⁴: the seismic reflection interface on top of the Middle Ordovician Yijianfang Formation (mainly reservoirs); T₇⁶: the seismic reflection interface on top of the Middle-Lower Ordovician Yingshan Formation (mainly reservoirs); T₇⁸: the seismic reflection interface on top of the Lower Ordovician Penglaiba Formation; T₈⁰: the seismic reflection interface on top of Cambrian strata (mainly source rocks); T₉⁰: the seismic reflection interface on top of Precambrian strata.

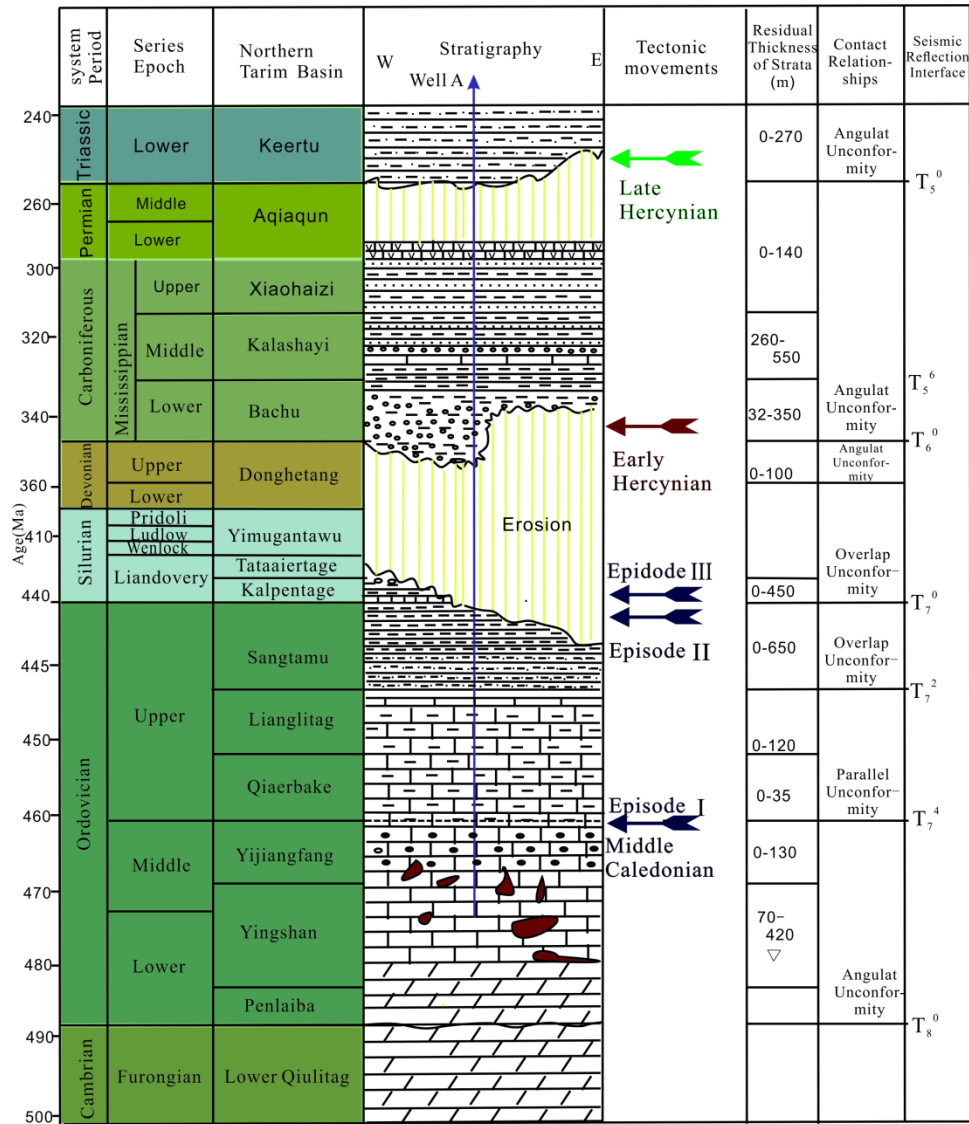


Figure 3. Generalized stratigraphic column of southern area of Tahe oilfield, the formations from the Upper Cambrian to the Lower Triassic (Adapted from Tian et al., 2016). T_5^0 : the seismic reflection interface on top of the Permian; T_5^6 : the seismic reflection interface on top of the Carboniferous Bachu Formation; T_7^0 : the seismic reflection interface on top of the Upper Ordovician Sangtamu Formation; T_7^2 : the seismic reflection interface on top of the Upper Ordovician Lianglitag Formation; T_7^4 : the seismic reflection interface on top of the Middle Ordovician Yijiangfang Formation; T_8^0 : the seismic reflection interface on top of Cambrian strata.

After the formation of the Pre-Sinian metamorphic basement, the Tabei Uplift underwent the multistage major regional tectonic movements: Caledonian, Hercynian, Indosinian-Yanshanian, and Himalayan. Among them, the Middle Caledonian and Early Hercynian tectonic movements played an important role in the structural morphology and fault development of Tahe Oilfield. From the Early Sinian to Early Ordovician, the Tarim block broke away from the Rodinia supercontinent, and the northern Tianshan Ocean expanded in the northern part of the Tarim plate[52,55]. The Middle Caledonian tectonic movements in the Middle Ordovician led to the northward movement of the Tarim plate and subsequent collision with the northern East Tianshan plate, which resulted in changing the background stress from tension to compression, creating the Tabei Uplift.

The Middle Caledonian tectonic movements can be divided into three episodes: the first episode movement had little influence on Tabei uplift. The second episode movement formed by the collision between the southern Tarim Basin and the South Kunlun plate was relatively weak, and the Tabei uplift continued to rise. The third episode movement caused by the collision between the southern

Tianshan Ocean island arc and the northern margin of Tarim Basin further uplifted the northern part of Tabei Uplift and formed the unconformity between Silurian (S) and Ordovician (O)[56].

The early Hercynian movement occurred at the end of the Devonian Period, causing strong erosion of the Devonian, Silurian, and Upper Ordovician strata, and creating an angular unconformity between the Carboniferous (C) and Ordovician (O). The Late Hercynian movement took place during the Middle Permian–Late Permian. There largely developed volcano erupting and effusing of the lava from the deep stratum in Tarim Basin, the thickness of 10 to 100 m of magmatic rocks caused by the Tarim Large Igneous Province are encountered in most wells in the southern Tahe Oilfield[57].

Due to the differential uplift of the Tabei uplift, there are obvious differences in carbonate reservoir development between the northern and southern area of Tahe Oilfield. As a result of multi-stage tectonic movement, the Devonian, Silurian and Upper Ordovician strata were denuded in the northern area of Tahe Oilfield. The Middle and Lower Ordovician (O_{2y} and O_{1-2y}) carbonate rocks are subaerially exposed, and were leached and dissolved by atmospheric fresh water, which developed into a mainly paleokarst drainage system. On the contrary, in the southern area of Tahe oilfield, the Middle-Lower Ordovician carbonate rocks remained covered by regional caprock; hence, these strata did not directly undergo erosion and karstification by atmospheric fresh water. This implies that the southern Tahe oilfield hydrocarbon reservoir development is mainly affected by faults.

3. Data and Methods

3.1. Core Samples, Well Logging, and Seismic Data

Currently, more than 93 wells have been drilled into the Middle-Lower Ordovician carbonate strata of the southern Tahe Oilfield. Most of these are vertical wells with finished depths exceeding 6000 m. The cores from 13 coring wells were observed comprehensively, and 485 core photographs were collected to analyze the rock type and characteristics of the carbonate reservoir. Over 270 thin sections cut from the carbonate rock cores from 13 representative wells were observed through cathodoluminescence (CL) using a Zeiss Axio Imager fluorescence microscope in the Key Laboratory of Reservoir Geology, in Shandong Province. Obvious differences in the geophysical response between the fracture-cavity and the tight CM were found. A total of 93 sets of conventional logging data and 15 Formation Microscanner Images (FMIs) were obtained from the wells in the study area; together, these provided sufficient data for characterizing the fractures and caves within individual strata.

The high-precision 3D seismic dataset covering approximately 398 km² of this study area was processed in 2013, with a data bin size of 15 m × 15 m. The overall vertical sample rate of the seismic volume was 2 ms, and the target formation of dominant frequency was approximately 35 Hz. The large-scale reservoir shows "a string of beads" strong amplitude in seismic sections[58]. This seismic data was processed via a series of steps, and the coherence and curvature attributes of different target horizons were extracted from the seismic data volume to identify and predict the characteristics of faults and fractures. Variance and curvature attributes are the seismic attributes that can calculate the difference between waveforms or traces in 3D seismic volume, which is very sensitive to fault interpretation. The plane distribution of the carbonate reservoir is characterized by extracting the amplitude variation rate attribute, while the spatial variation of the carbonate reservoir is characterized by 3D sculpture volume. We used SVI software (by PetroSolution Tech, Inc.) to identify the extent of faults and carbonate caves by characterizing both the spatial distribution pattern of the faults and the spatial morphology of the resulting karst caves. The detailed workflow of this process includes three steps:

(1) Use a Noise Filter to de-noise the original seismic data to improve its image clarity, extracting the composite attributes of both Tensor and Envelope attributes from the processed seismic volume;

(2) Fault and geological body signal enhancement and recognition; and (3) fuse and display the identified faults and geological bodies.

3.2. Geochemistry

The 15 core samples were crushed into millimeter-sized fragments and pure calcite vein particles were picked out. The pure calcite particles were ground into 200 meshes -- fine powder for testing by a grinding apparatus. The experimental process is detailed in Han et al. (2019). All isotope experiments were carried out at the Institute of Geology and Geophysics, Chinese Academy of Sciences. C and O data are reported as per mil (‰) $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values relative to Pee Dee belemnite (VPDB international standard), respectively. The precision for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ measurement was $\pm 0.2\text{‰}$.

A total of 12 powder samples were analyzed using a Finnigan MAT Triton TI for Sr isotope compositions. Rock powders and 2 mL of 6 M HCl were used for a dissolution reaction in a jar, for 24 h at a temperature of 100–110 °C. Results were controlled by repeated analysis of the NBS-987 standard, averaging ($n=26$) 0.710202 ± 0.00004 (2σ), normalized to $^{87}\text{Sr}/^{86}\text{Sr}$, and equal to 0.1194[15].

Fluid inclusion (FI) micro-thermometric analysis was performed on the calcite samples using the Linkam THMGS600 heating-freezing stage. Homogenization temperature measurements were obtained using a heating rate of 10 °C/min. Comprehensive analysis was performed on 456 fluid inclusions in calcite, which filled dissolution pores, fractures, and caverns within 11 wells.

4. Results

4.1. Reservoir Types and Characteristics

The Ordovician carbonate reservoirs in the southern area of Tahe Oilfield were not generated by weathering crust karstification because the Middle-Lower Ordovician carbonate rocks have not undergone large-scale upliftment nor been exposed to the surface for a long time. Over its long geological history, the Middle-Lower Ordovician carbonate strata experienced complex cementation and long-term strong compaction; hence, the contribution of CM porosity and permeability to reservoir space is very small. The matrix porosity of the Middle-Lower Ordovician carbonate rocks ranges from 0.6 to 3.8%, with an average of 1.62%; the permeability is mainly distributed as $0.02\text{--}21.02 \times 10^{-3} \mu\text{m}^2$, with an average of $1.32 \times 10^{-3} \mu\text{m}^2$. Moreover, the carbonate strata underwent both multi-stage tectonic movements and multi-stage dissolution by diagenetic fluids, thus forming a complex heterogeneous porous system dominated by dissolved pores, fractures, and caves, which developed into the main reservoir space.

The dissolved pores of the Middle-Lower Ordovician hydrocarbon reservoirs mainly include intergranular dissolution pores, some intragranular and intercrystalline dissolution pores, and moldic pores (Figure 4a and f). The fluids flowing along the fractures have better contact with surrounding rock on both sides; these fluids dissolve the calcite to form dissolved pores (Figure 4c). The intergranular residual pores and intragranular pores formed by the dissolution of calcite minerals are filled again in the later stage (Figure 4b). The other types of intergranular pores occur between dolomite crystals; dolomite agglomerates are distributed in the stylolite structure, and the intercrystalline pores are filled with asphaltene (Figure 4d and e).

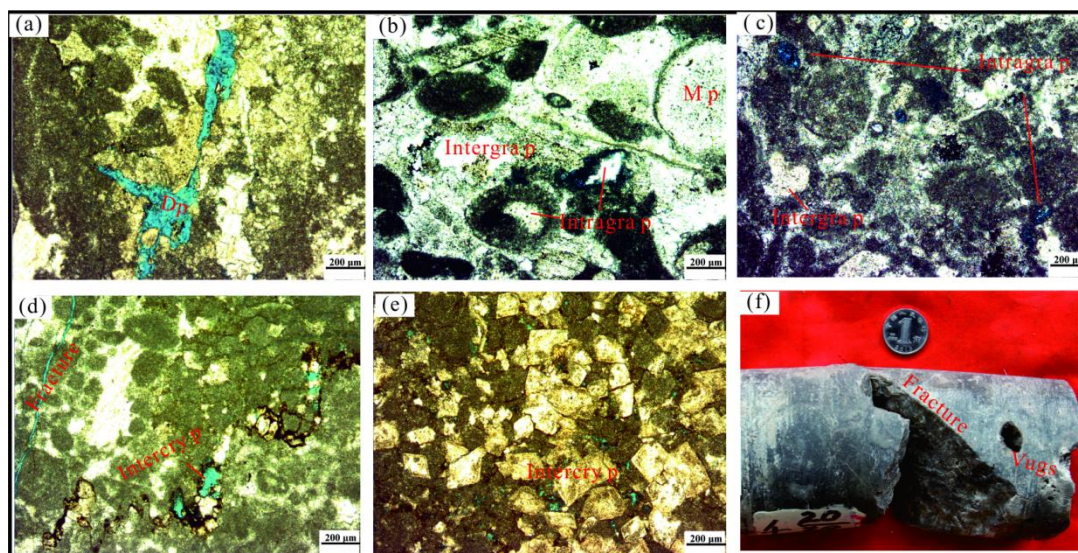


Figure 4. Photographs of pores and fractures from the thin sections and cores. (a) Unfilled dissolved pore(Dp)(Well A, 6110.43m, O₁₋₂); (b) Moldic pores(Mp), intergranular pore(Intergra p) and intragranular pore(Intragra p) filled with calcite(wellA, 6034.51m, O₁₋₂); (c) Unfilled intragranular pore(Well A, 6067.31m, O₁₋₂); (d) Microfractures and intercrystalline pores in dolomite along stylolite(Well F, 5555.61m, O₁₋₂); (e) Intercrystalline pores in dolomite, unfilled(Well G, 5662.23m, O₁₋₂); (f) Dissolution vugs around fracture(Well B, 5895.10m, O₁₋₂).

Fractures are not only an important reservoir space in carbonate rocks, but they also function as a main fluid migration pathway[59]. Structural fractures are one of the main types of reservoirs in the study area, which are mainly distributed on both sides of the fault zone and in the axial region of folds. These are mainly medium-small fractures, wherein small fractures account for 79.7% and medium fractures account for 17.9% of the total fractures (Figure 5a). The low angle fractures that account for 59.7% are short and flat, and most of them are filled with calcites and clays (Figure 5b and c). The medium angle and high angle fractures are tension-shear fractures; their fracture surface is relatively straight, the width of the fracture aperture is more than 0.1–1 cm, and they are unfilled or half-filled with calcites and dark organic matter (Figure 5d). These fractures appear on the FMI as sinusoidal lines, and the amplitude of sinusoidal lines of fractures with different dip angles are varied. The greater the amplitude of the sinusoidal lines, the larger the fracture dip angle, and vice versa. The faults and derived fractures show good response characteristics on the attribute of maximum negative curvature maps[60]. The most developed structural fractures, which are linear or reticular (in the blue yellow area), are distributed on both sides of the fault; and the larger the fault, the wider the development range of the fractures on both sides (Figure 6).

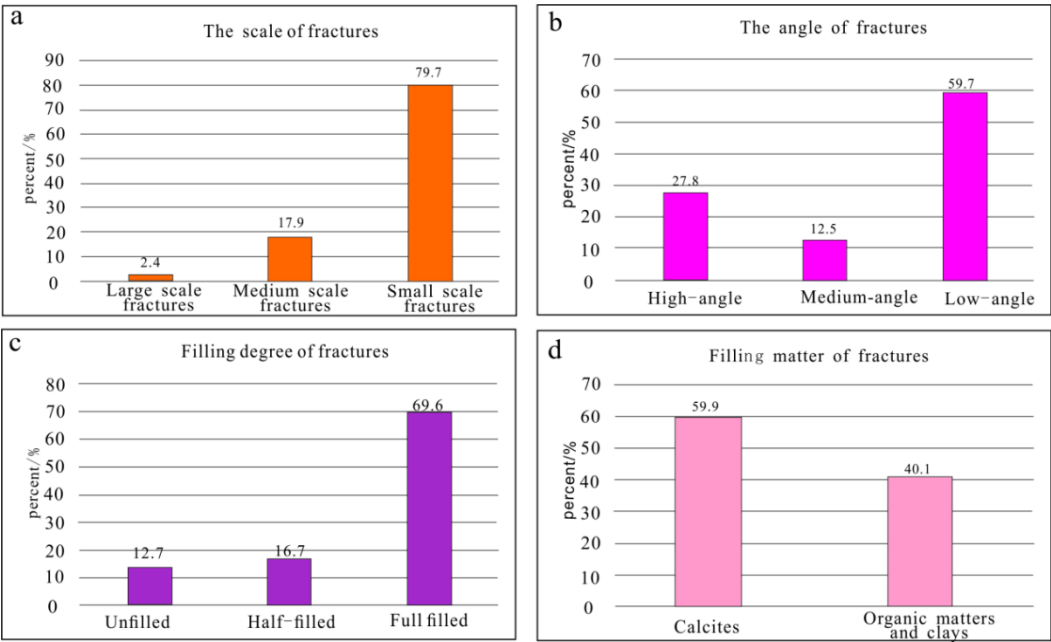


Figure 5. Fracture information statistics from the cores(N=768).

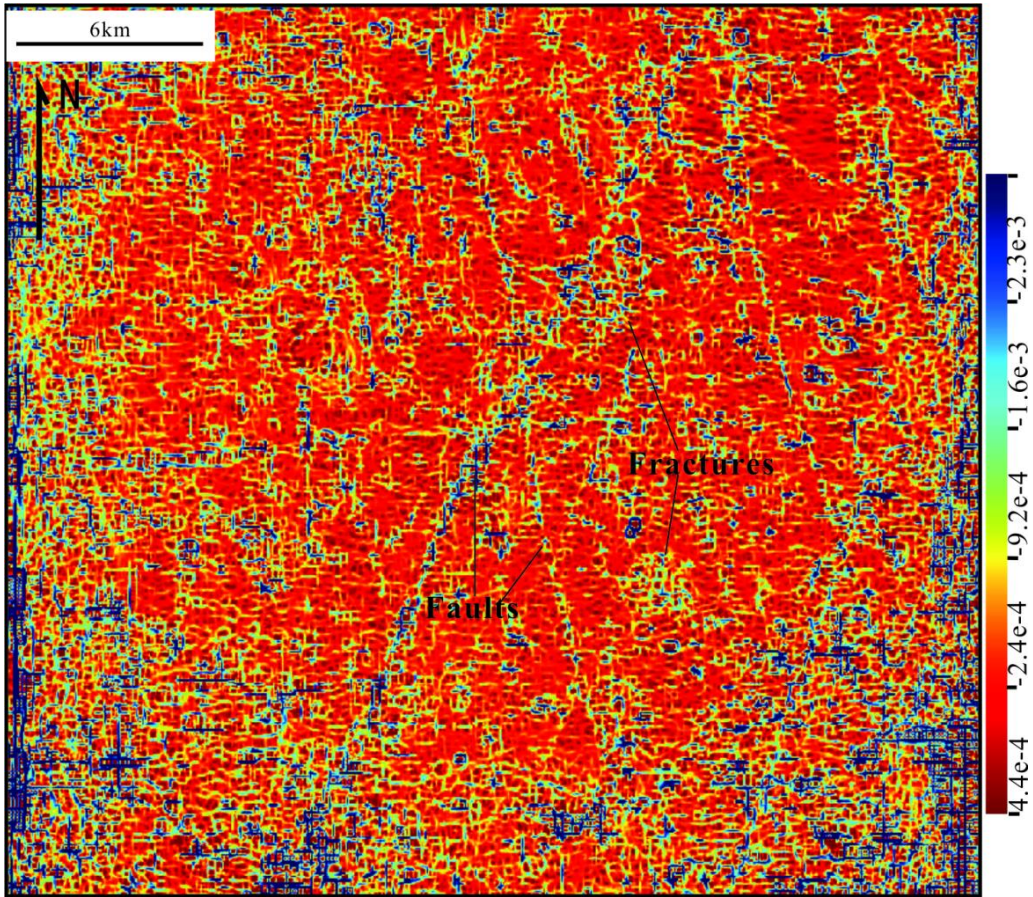


Figure 6. The attribute of maximum negative curvature along the top of Middle-Lower Ordovician Yingshan Formation (T7⁶).

The diameter of large caves is more than 100 mm; hence, owing to its large scale, it cannot be completely observed on the core. Karst breccia formed by cave collapse and calcareous debris sediments brought in with flowing water can be observed on the cores. This can be easily identified by dropout, mud loss, and sudden acceleration during drilling. The well logging response of the caves shows that the natural gamma (GR) value increases, the diameter expands clearly, the deep

investigate induction log (LLD) and shallow investigate induction log (LLS) value decreases significantly and shows a positive difference, the density logging (DEN) value decreases, and the acoustic time difference (AC) value and neutron (CN) also show a clear increases. The FMI logs show dark black and disordered images (Figure 7). On the seismic section, owing to the velocity and impedance differences between the caves and surrounding CM, the deep buried cave complexes are displayed as ‘bright’ spot-shaped reflections (Figure 7), which implies strong reflection amplitudes, long longitudinal extensions, and small horizontal ranges [31]. This is the main reservoir space of oil and gas, indicating high well production. In this study, we used the attribute of amplitude change rate, which is sensitive to extremely high amplitudes, for characterizing caves complexes. When seismic waves propagate in homogeneous carbonate rock, the change in the seismic wavelength is small. However, when encountering caves the seismic wavelength will change, showing a high amplitude and frequency response. Therefore, the amplitude change rate of the CM is a low value and appears as a blue area; in contrast, the fracture cave reservoir development zone shows a high value and displays a bright red color (Figure 8a). The spatial distribution characteristics of cave bodies in carbonate rock can be observed more clearly using 3D models of the caves. The extraction of the enhancement tensor and envelope attributes and carving of the cave body used SVI software, selected appropriate threshold values of the attributes to depict the fracture cavity body, thus allowing us to better understand deeply buried paleokarst reservoirs, and the caves mostly isolated in spatial distribution and have poor region connectivity (Figure 8b). The supergene karstification of meteoric water is not developed in the Middle- Lower Ordovician carbonate rocks in this area, and there is no formation of a paleokarst drainage system. Hence, the reservoir development is mainly controlled by the fault system.

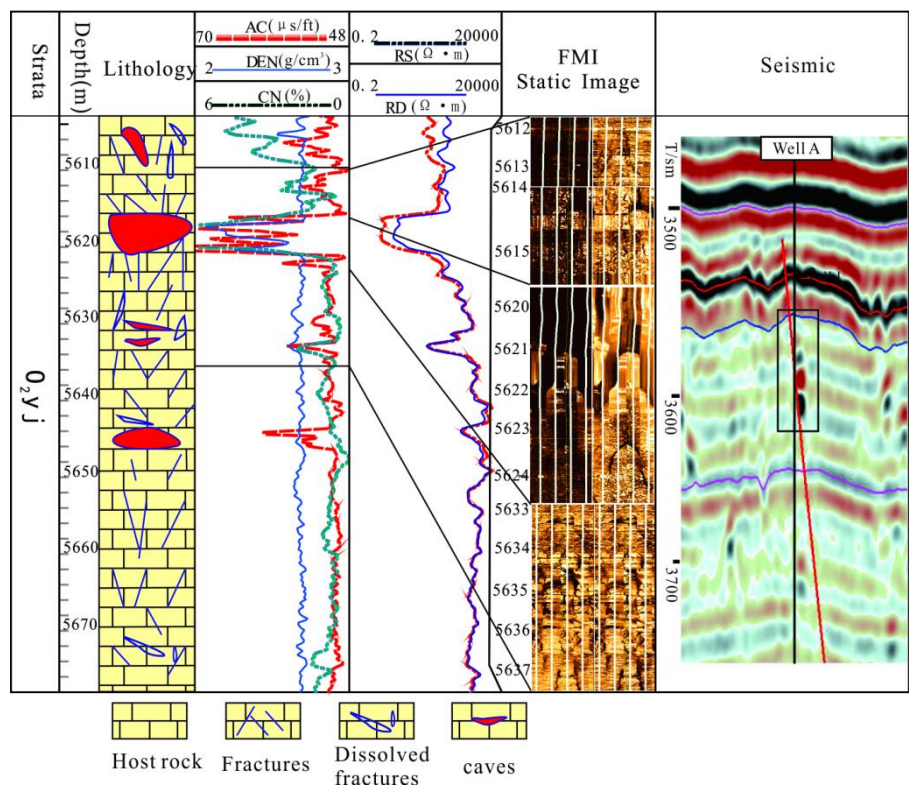


Figure 7. Well log and geological interpretation of Well A, showing a fracture cavity reservoir. See Figure 1d for the well location.

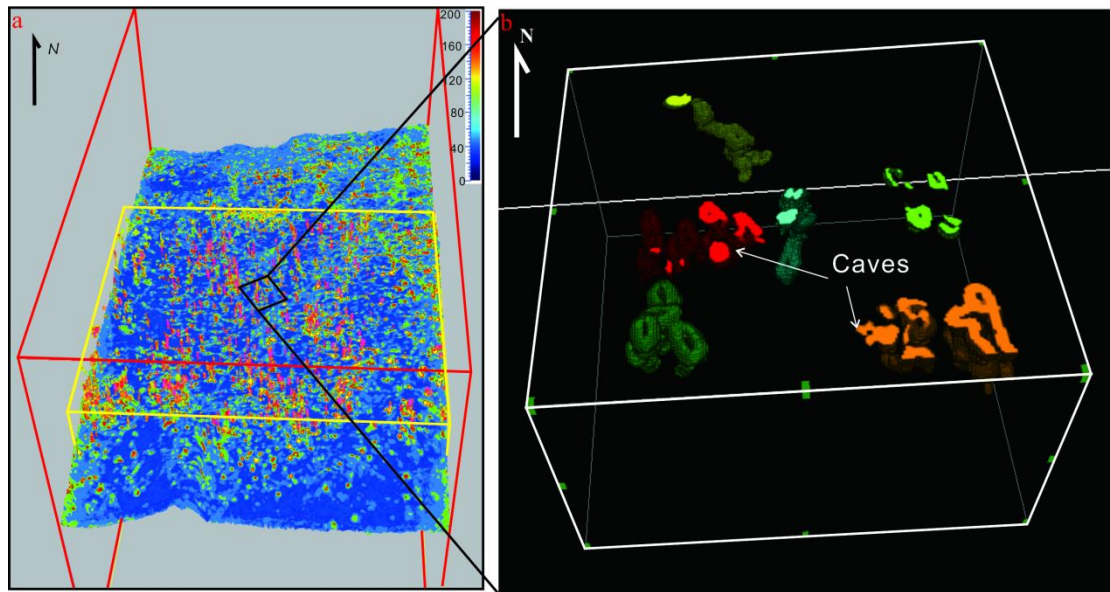


Figure 8. A 3D topographic map of the caves in the study area generated from a 3D seismic dataset. (a) The amplitude change rate showing of fracture cavity; (b) Carving of caves body used SVI software.

4.2. Paleozoic Fault Characteristics and Evolution

As the quantitative estimation of the fault formation period is difficult, we primarily determine the relative formation period of the faults within the seismic section. Based on the analysis of regional tectonic stress field, the formation period is determined by the relationship between faults with neighboring stratigraphy and unconformity in the seismic section. When a fault cuts off a stratum, this indicates that the fault is younger than the stratum; conversely, when another fault terminates the stratum, the fault is determined to be older than the stratum[52].

4.2.1. Multi-Stages of Paleozoic Faults

According to the above criteria estimate of the fault formation period, faults in the study area can be divided into four stages using new 3D seismic data: extensional faults in the Cambrian–Early Ordovician; strike-slip faults in the Middle Ordovician; reactivation of strike-slip faults in the Silurian–Devonian; and faults related to volcanic activities during the Permian.

(1) Extensional normal faults during the Cambrian–Early Ordovician

In the early Caledonian period, the Tarim Basin was located in an extensional environment due to the spreading of the Ancient Tianshan Ocean, the Ancient Kunlun Ocean, and the Altyn Ocean. The slope area of the Tahe Oilfield in the Tabei Uplift, is subjected to relatively weak N-S extension, forming two groups of early normal extensional faults in both the NEE and NWW directions (Figure 10a). The fault plane is steep and straight, with relatively minor throw values, and a part of the fault plane cuts downward through the top of the Precambrian strata (T_9^0). Under the influence of subsequent multiple period tectonic movements, the extensional faulting was reactivated and became complex (Figure 9).

(2) Strike-slip faults in the Middle Ordovician

In the Middle Caledonian, the tectonic stress field of the Tarim Basin changed from extensional to compressional, and the Tahe Oilfield region underwent S-N compression stress action. A group of NNW and NNE trending “X” conjugate shear faults with large extension lengths (Figure 10b) and good continuity can be seen clearly on the stratum coherence attribute map (Figure 11a) and maximum curvature attribute map (Figure 11b). The faults formed during this period are characterized by their large scale, as they cut through several strata on the seismic section. The inherited faults also cut through the top surface of the deep Cambrian strata (T_9^0) (Figure 9).

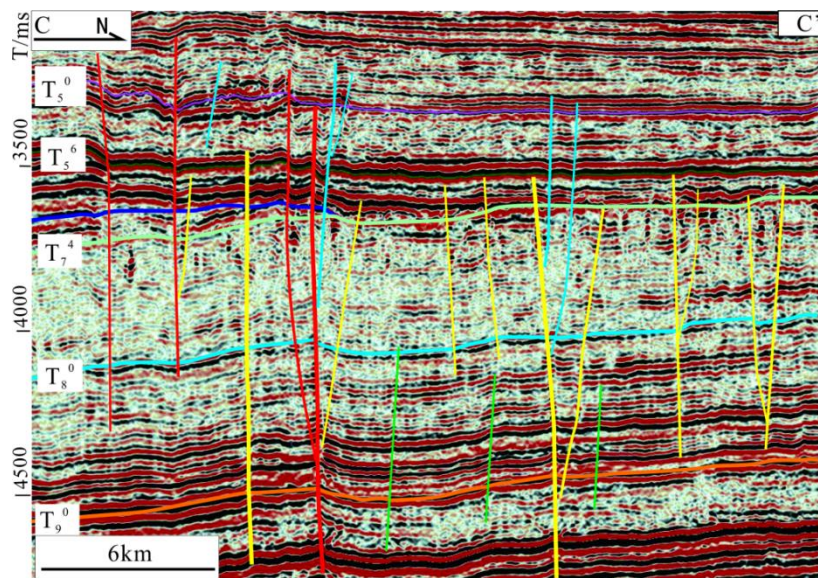


Figure 9. Seismic profiles across the study area showing the Paleozoic faults and stratigraphic interpretations. See Figure 1: C-C' for location. Faults are in their color definitions: Early Caledonian in green, Early/Middle Caledonian–Early Hercynian in yellow, Early/Middle Caledonian–Late Hercynian in red, Early Hercynian and Late Hercynian in navy.

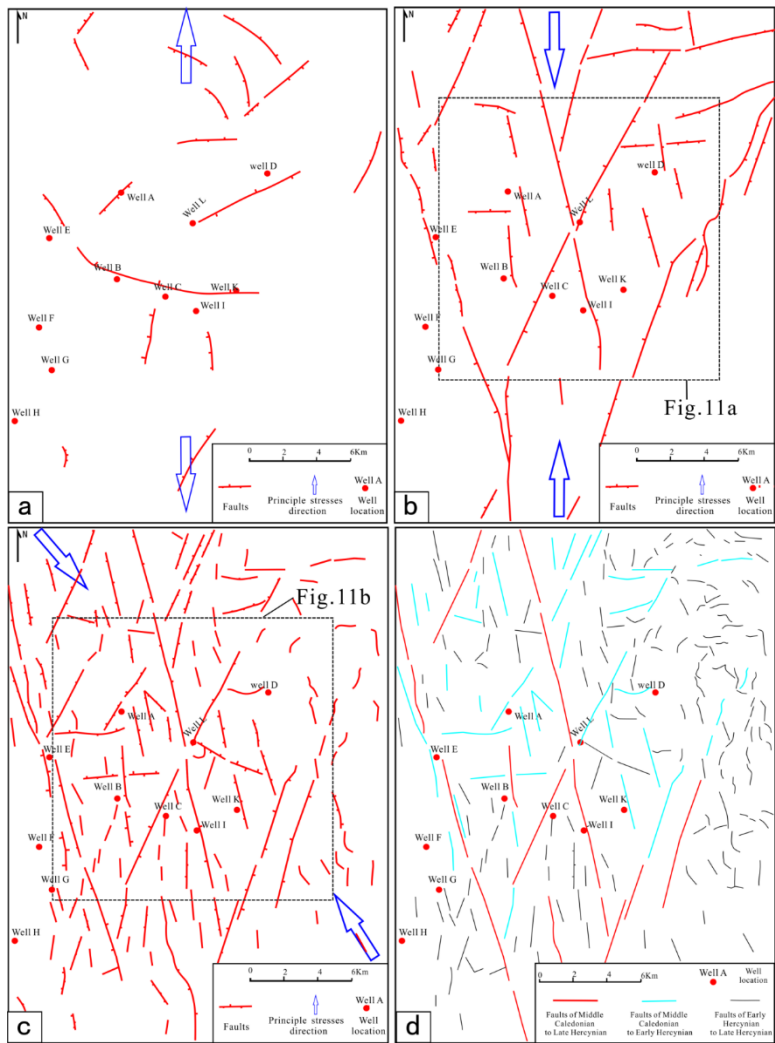


Figure 10. Distribution of fault system in different stages. (a) Faults formed in Early Caledonian period; (b) Faults formed in Middle Caledonian period; (c) Faults formed in Early Hercynian period; (d) Characteristics of inherited faults.

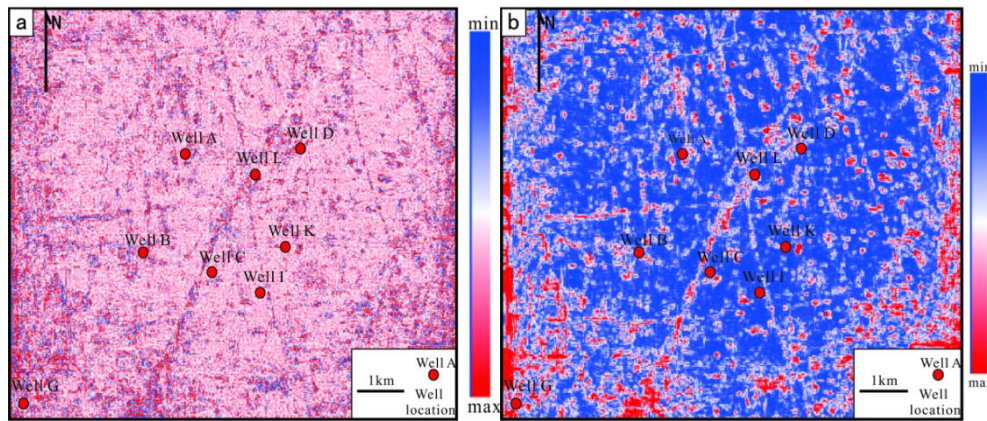


Figure 11. The curvature attributes of different layer showing different stages faults.(a) Faults formed in Middle Caledonian period;(b) Faults formed in Early Hercynian period.

(3) Reactivation of strike-slip faults in the Silurian-Devonian

In the Early Hercynian tectonic movement, the direction of the compression stress field transformed from S-N to the NW and SE direction. This period is the most important in terms of tectonic movements for large-scale fault development in the Tahe oilfield. Under the action of strong tectonic compression-torsion stress, a series of derived faults developed on both sides of the NNW and NNE trending "X" conjugate strike slip faults (Figure 10c). The faults formed in the Middle Caledonian, then moved further and upward, cutting through the Upper Ordovician Sangtamu Formation (T_7^0). There are four types of structures of strike slip faults on the seismic section: positive flower-structure, negative flower-structure, half flower-structure. The flower-structure is characterized by the steep and straight fault plane of the main fault, which plunges directly into the deep Cambrian strata. The derived faults are distributed on both sides of the main fault, converging from the shallow to the deep and intersecting with the main fault. Positive flower-structure is characterized by "compression, reverse fault and anticlinal fold" and negative flower-structure is characterized by "extension, normal fault and syncline structure". The half flower-structure develops derived faults only on one side of the main fault (Figure 9).

(4) Faults related to volcanic activities during the Permian

At the end of Early Permian, the Tarim Basin was in a continental rift extensional environment due to the comprehensive action of the ancient Tianshan Fold Belt and the subduction of the Old Tethys Ocean. Basic volcanic eruptive rocks and neutral-acid eruptive rocks occurred widely in the Tarim Basin. As a result of the volcanic activities, a series of extensional normal faults was formed, which were mainly distributed along the pre-existing faults; their strike directions are varied, and lengths are relatively short.

4.2.2. Inheritance of Paleozoic Faults

The faults in the study area were comprehensively affected by multi-stage tectonic movements, and the tectonic stress field and evolution characteristics are complex. Therefore, the fault activity may continue over a long period, developing simple to complex evolutionary characteristics, from small to large scales. According to the plane distribution characteristics and evolutionary history of faults on the seismic section, the fault formation and final relative faulting period was determined and analyzed; this is summarized as follows:

(1) From Middle Caledonian to Late Hercynian continual activity

These faults are characterized by multi-stage activity and inherited development, which often manifested as the reactivation of early formed faults under the action of late tectonic movement. With structural inversion, the nature and scale of faults often change. These faults formed in the Middle Caledonian and stopped being active in the Late Hercynian: two groups of NW-SE faults with long extensions (Figure 10d), cutting downward through T_9^0 and upward to T_5^0 on the seismic section (Figure 9).

(2) From Middle Caledonian to Early Hercynian continual activity

This area includes faults formed in the Middle Caledonian that stopped activity in the Early Hercynian With the further stress increase, some strike slip faults were reactivated in the middle Caledonian when the derived strike slip faults developed on a large scale. These are distributed in the NNW and NNE direction (Figure 10d), cutting downward through T80 and terminating upward at T5⁶ on the seismic section (Figure 9).

(3) Early Hercynian and Late Hercynian active faults

Most of these faults were formed by single stage tectonic movements, and the later stage tectonic movements had little influence on them. With relatively small scale and short profile extensions, they only cut downward through T7⁴ and terminated upward at T5⁰ (Figure 9).

Owing to the heterogeneity of the tectonic stress field intensity and the transformation of direction of tectonic movements, large-scale strike slip faults indicate clear segmentation on the plane, with complex differences in the nature, scale, and structural style of the faults.

4.3. Geochemical Characteristics

4.3.1. C and O Isotopes

C and O isotopes can reflect the changes in ancient sedimentary environments. The isotopic compositions of C and O in the CM, pore-filling fine-crystallinecalcite (PC), fracture-filling middle-coarse crystalline calcite (FC), and cavity-filling coarse crystalline (CC) samples are summarized in Table 1. All samples in this study were collected from the Yingshan and Yijianfang Formations. The changes in various geological factors in marine sedimentary environments are relatively small; hence, the chemical and thermodynamic properties of carbonate rocks formed in this environment are relatively stable[57].

Table 1. The isotopic compositions and rare earth elements of calcites in fissure-cave in Tahe Oilfield.

Sample number	Formation	Types	Depth (m)	δ ¹³ C	δ ¹⁸ O	⁸⁷ Sr/ ⁸⁶ Sr
				‰ VPDB	‰ VPDB	
2-1	O ₁₋₂ y	FC	5870.7	-1.3	-11.8	0.709449
2-2	O ₂ yj	CC	5856.35	-4.26	-14.17	0.709375
2-3	O ₁ y	CC	5656.35	-3.787	-7.957	0.71012
2-4	O ₂ yj	FC	5586.81	-4.499	-8.261	0.709603
2-5	O ₂ yj	FC	5806.35	-2.6	-10.8	0.709328
2-6	O ₂ yj	FC	6162.64	-4.67	-8.77	0.709325
2-7	O ₂ yj	CM	5723.6	-1.5	-6.4	0.708765
2-8	O ₂ yj	CM	5665.1	-0.9	-6.6	0.708764
2-9	O ₂ yj	CM	6058.3	0.5	-6.7	0.708741
2-10	O ₂ yj	CM	6180	0.3	-6.3	0.708813
2-11	O ₁ y	CC	5816.33	-2.25	-12.66	0.709505
2-12	O ₁ y	CC	5447.5	-1.498	-13.227	0.709
2-13	O ₁ y	CC	5447.8	-1.653	-13.498	0.709035
2-14	O ₁ y	CC	5448.5	-1.703	-13.629	0.709122
2-15	O ₂ yj	CC	5673.5	-3.21	-12.77	0.709362
2-16	O ₂ yj	PC	6323.5	0.72	-5.461	0.709883
2-17	O ₂ yj	FC	5896.6	-1.5	-12.7	0.709908
2-18	O ₂ yj	FC	5898.66	-1.778	-9.519	0.710177
2-19	O ₂ yj	FC	5892.42	-1.6	-13.3	0.709857

2-20	O ₁	FC	5960.1	-1.948	-8.199	0.710042
2-21	O ₁	FC	5960.5	-0.87	-9.154	0.709704
2-22	O _{2yj}	FC	6078.65	-4.137	-7.3	0.709225
2-23	O ₁	FC	5693.72	-3.298	-8.5	0.709379
2-24	O ₁	FC	5958.82	-1.4	-9.3	0.709221
2-25	O _{2yj}	PC	5518.01	-0.6	-6.2	0.708723
2-26	O _{2yj}	PC	6289.04	-0.9	-6.8	0.708176

FC: fracture-filling middle-coarse crystalline calcite; CC: cavity-filling coarse crystalline calcite; PC: pore-filling fine crystalline calcite; CM: carbonate matrix.

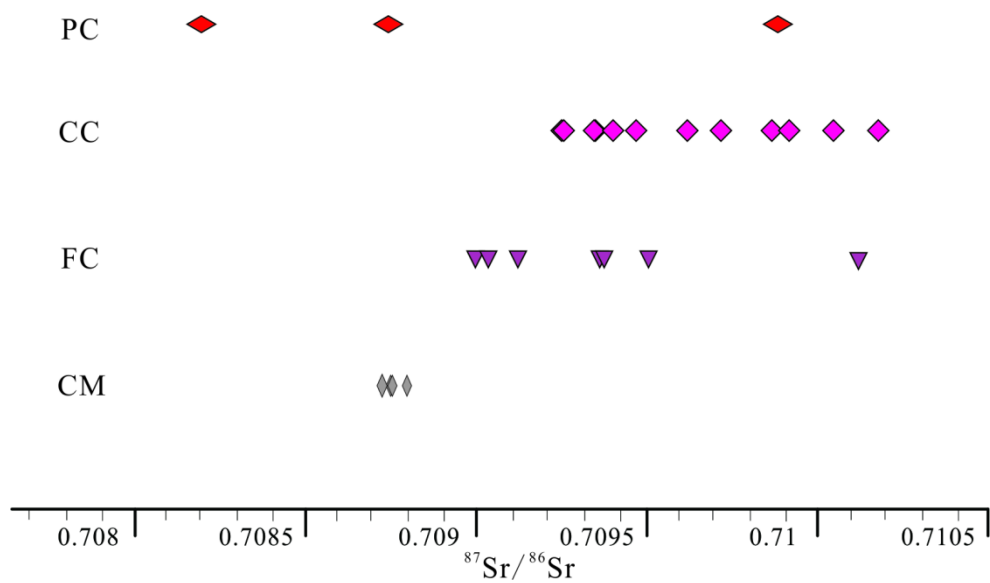
The CM samples have $\delta^{13}\text{C}$ values ranging from -1.5‰ to 0.5‰ VPDB (average -0.4‰ VPDB), and $\delta^{18}\text{O}$ values from -6.7‰ to -6.3‰ VPDB (average -6.5‰ VPDB) (Table 1). The isotopic compositions of C and O are consistent with those of the un-eroded Ordovician carbonate rocks.

The FC samples have $\delta^{13}\text{C}$ values ranging from -4.67 to -0.87‰ VPDB (average -2.47‰ VPDB), and $\delta^{18}\text{O}$ values from -13.3‰ to -7.3‰ VPDB (average -9.8‰ VPDB). The $\delta^{13}\text{C}$ values of the PC samples vary from -0.9 ‰ to 0.72‰ VPDB (average -6.15‰ VPDB), and their $\delta^{18}\text{O}$ values vary from -6.8‰ to -5.46‰ VPDB (average -13.08‰ VPDB).

The CC samples have $\delta^{13}\text{C}$ values ranging from -4.26‰ to -1.50‰ VPDB (average -2.62‰ VPDB), and $\delta^{18}\text{O}$ values from -14.17‰ to -7.96‰ VPDB (average -12.65‰ VPDB). In addition to the CM samples, the O and C isotope values of other samples also exhibit an obvious negative offset. The negative $\delta^{18}\text{O}$ values in calcite are mainly caused by the interference of external fluids during late diagenesis, such as atmospheric fresh water with poor $\delta^{18}\text{O}$ and hydrothermal fluids with higher temperature causing $\delta^{18}\text{O}$ values to decrease [43,57]. The isotopic composition of C in CO₂ is different due to variations in fluid sources and forming environments. CO₂ was released from mantle magma degassing with $\delta^{13}\text{C}$ values in the range of -7‰ to -5‰, produced by the transformation of organic matter with $\delta^{13}\text{C}$ values ranging from -30‰ to -10‰, and released from carbonate minerals in clastic sedimentary or argillaceous rocks with $\delta^{13}\text{C}$ values ranging from -15‰ to -9‰[57].

4.3.2. Sr Isotope

The ⁸⁷Sr/⁸⁶Sr ratios of Middle and Lower Ordovician CM ranged from 0.708741 to 0.708813 (average 0.708770) (Table 1), and the ⁸⁷Sr/⁸⁶Sr ratios in study area are mostly located in the range of Ordovician marine carbonate as determined by Denison (Denison et al., 1998). The PC samples have ⁸⁷Sr/⁸⁶Sr ratios ranging from 0.708176 to 0.709883 (average 0.708927); except for one sample with a very high value (0.709883), the range is the same as that for CM samples. The FC and CC samples have ⁸⁷Sr/⁸⁶Sr ratios ranging from 0.709221 to 0.710177 (average 0.709601), and 0.709 to 0.71012 (average 0.709359), respectively (Figure 12). High ⁸⁷Sr/⁸⁶Sr ratios indicate the contribution of external sources and other rich ⁸⁷Sr fluids, such as crust source Sr provided by meteoric freshwater. Deep intermediate acid volcanic rocks can also contribute to increase in ⁸⁷Sr/⁸⁶Sr ratios (Lu et al., 2017; Han et al., 2019).



FC: fracture-filling middle-coarse crystalline calcite; CC: cavity-filling coarse crystalline calcite; PC: pore-filling fine crystalline calcite; CM: carbonate matrix

Figure 12. Strontium isotope compositions of Ordovician calcite and limestone in Tahe Oilfield.

4.3.3. Fluid Inclusions

The evolution of petroliferous structural basins is accompanied by the formation, development, and evolution of fluids. The Ordovician reservoir in the Tahe Oilfield is a marine carbonate deposit which has experienced a long process of structural evolution, and suffered from multiple tectonic movements and structural deformations. The fluid inclusions in calcite veins in different parts of the Ordovician carbonate strata record the temperature, pressure, and other thermodynamic information of different periods throughout the tectonic history. The characteristics of homogenization temperatures of fluid inclusions in carbonates in southern area of Tahe Oilfield are presented in Figure 13. The homogenization temperature of fluid inclusions varied from 43.2 °C to 261.3 °C; these are divided into three groups based on distribution range of homogenization temperature of fluid inclusions : < 60 to 140 °C, 140 to 170 °C, and 170 °C to more than 200 °C.

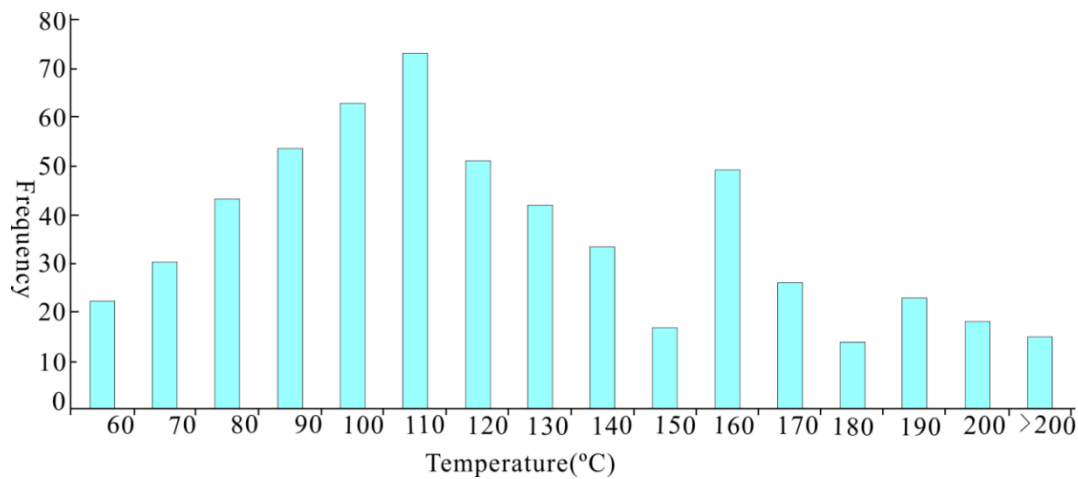


Figure 13. Statistical analysis of homogeneous temperature distribution of calcite saline inclusion.

5. Discussion

5.1. Fluids Types and Evolution Constraints According to Petrological and Geochemical Characteristics

The Ordovician carbonate strata in the Tahe Oilfield are deeply buried and have experienced multi-stage tectonic movement and fault activity. These thick carbonates have been subjected to transformation by multi-stage fluid dissolution; they have also formed various types and generations of carbonate cements. Optical photomicrographs, CL, and core samples indicate that five generations of cement or fractures/cave-filling calcites formed during burial diagenetic evolutionary history.

The first stage calcite (C1) was formed in the syngenetic-contemporaneous period. Under the action of atmospheric fresh water, the internal selective dissolution of carbonate rock particles formed mold pores, or intragranular pores filled with calcites (Figure 14a). The second stage calcite (C2) is generally fine-grained and grows around carbonate particles (Figure 14a and b). The third generation cemented calcite has coarse grains and a rough crystal surface, which is filled in the residual intergranular pores after the formation of the second generation calcite (Figure 14a and b). The C2 and C3 are mainly formed by burial dissolution and cementation. The fourth stage calcite (C4) is a clean calcite filled with dissolution pores, showing a bright orange ring under CL. The fifth stage calcite (C5) is a clean medium coarse crystal calcite with bright orange rings under CL (Figure 14c, d, e and f). Both the C4 and C5 are related to hydrothermal fluids.

In the three intervals of homogenization temperatures of fluid inclusions (Figure 13), there were three phases of fluids with different temperatures participating in diagenesis. The data support a wide distribution range in the low temperature section, indicating the homogenization temperature of fluid inclusions in the medium deep burial diagenetic environment. These diagenetic fluids were mainly atmospheric fresh water and formation fluids. Two abnormal sections of high temperature data indicate the dissolution of hydrothermal fluids at different temperatures during two separate periods.

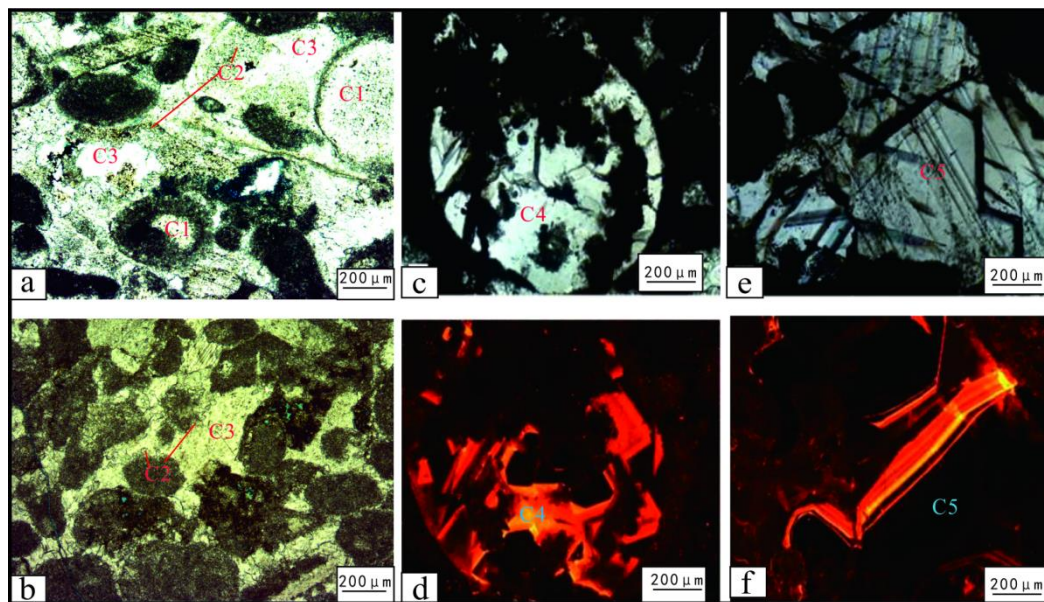
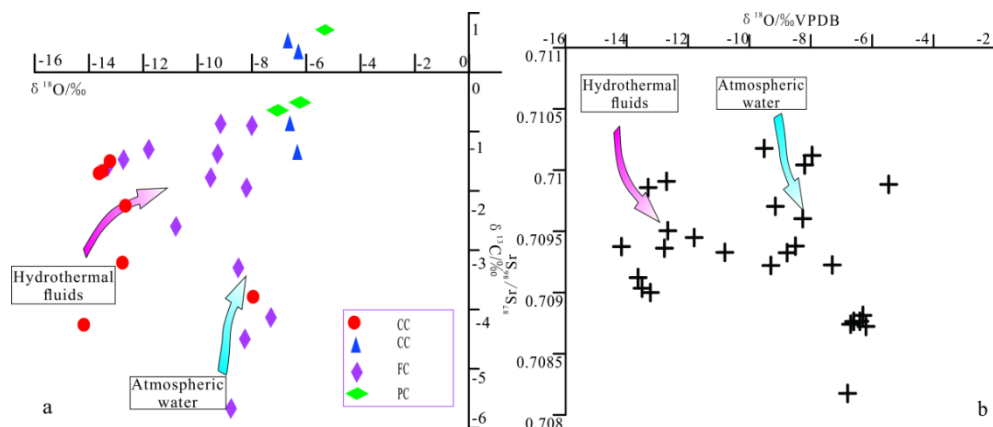


Figure 14. Photographs showing five generations of fractures/cave-filling calcites. (a) and (b) Plane light photomicrograph showing that C1, C2 and C3 calcites in the limestone at 6034.51 m and 6115.53 in Well L; (c) and (d) Dissolution pores filling with clean C4 calcite, bright orange band under cathodoluminescence at 5984.12 m in Well A. (e) and (f) C5 calcite with interference fringe, dark inside and orange band outside on cathodoluminescence at 5972.38 m in Well A.

The $\delta^{18}\text{O}$ values of calcite cement in the Middle-Lower Ordovician carbonate rocks in the study area are clearly negative; the minimum value reached 14.17 ‰ VPDB. The negative $\delta^{18}\text{O}$ values may be attributed to the meteoric water and deep hydrothermal fluids. During the middle Caledonian,

Early Hercynian, and Late Hercynian tectonic movements, the Tahe Oilfield formed multi-stage structural faults, which provided favorable conditions for atmospheric fresh water to enter this thick carbonate formation through otherwise impermeable layers. At the same time, there were four important volcanic events in the Tarim Basin history, including the Permian volcanic activity in the Late Hercynian, which was the most active, and distributed over a large area. Hydrothermal fluids derived from magma moved upward along the fault, which led to a rise in temperature of the formation fluid. From the perspective of isotopic equilibrium fractionation, temperature controls the isotope fractionation coefficient of water rock reactions. The highest temperatures of extrusive volcanic rock can reach thousands of degrees, and these differentiated hydrothermal fluids have a very high temperature, resulting in the negative shift of $\delta^{18}\text{O}$ values of calcite cement, along with a large migration range. However, the negative $\delta^{18}\text{O}$ migration degree of calcite cement formed by atmospheric fresh water is relatively small. The HCO_3^- content in meteoric freshwater is affected by CO_2 in the atmosphere, and $\delta^{13}\text{C}$ shows a partial negative shift. Deep magmatism can also release more CO_2 , which provides $\delta^{13}\text{C}$ with a slight negative migration. When atmospheric fresh water mixes with formation water, the isotopic characteristics of the mixed fluids are between those of atmospheric fresh water and formation water (Figure 15a).

The atmospheric fresh water concentrate large quantities of ^{87}Sr , which seeps into the carbonate rocks along the faults, thus increasing the $^{87}\text{Sr}/^{86}\text{Sr}$ value. At the same time, the hydrothermal fluid formed by magmatism also forms calcite veins with high $^{87}\text{Sr}/^{86}\text{Sr}$ value (Figure 15b).



FC: fracture-filling middle-coarse crystalline calcite; CC: cavity-filling coarse crystalline calcite; PC: pore-filling fine crystalline calcite; CM: carbonate matrix.

Figure 15. The $\delta^{13}\text{C}$ - $\delta^{18}\text{O}$ (a) and $\delta^{18}\text{O}$ - $^{87}\text{Sr}/^{86}\text{Sr}$ (b) relationship of Ordovician calcite in Tahe Oilfield.

5.1.2. Diagenesis and Fluid Evolution

Based on petrological observations, fluid inclusions, and isotopic data, the diagenetic processes can be broadly divided into four stages: penecontemporaneous eogenetic, early mesogenetic diagenetic, hydrothermal diagenetic, and late mesogenetic diagenetic [61].

These carbonate strata experienced multiple tectonic uplifting movements and suffered from meteoric freshwater dissolution in the penecontemporaneous eogenetic stage, which occurred during the first episode of the Middle Caledonian and main diagenetic processes, and included selective dissolution and calcite cementation (Jia et al., 2016). It can be observed that a large number of intergranular pores and moldic pores are filled with abundant cements (C1).

With the decline of tectonic movement during a stable sedimentary placement period, the study area entered the early mesogenetic diagenesis stage[14]. The main diagenetic process includes secondary dissolution, pressure solution, recrystallization, compaction, cementation, and filling[62]. The dissolution of the constructive diagenetic process includes both buried and mixed fluids dissolution. The pores and cavities formed during this period are mostly filled by calcite and other minerals, e.g., C2 and C3. In the middle deep burial stage, the organic matter in the source rock

produced acidic fluids rich in organic acids, CO₂, and H₂S in the mature stage. When the acid fluid is unsaturated to calcium carbonate, it will be extremely corrosive to the carbonate rock[63]. The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of calcite range from -6.8‰ to -5.5‰ VPDB, and -1.5‰ to 0.72‰ VPDB, respectively. The homogenization temperature of fluid inclusions varied from 60 °C to 90 °C. The dissolution process of mixed fluids is relatively complex. During the second and third episodes of the Middle Caledonian and Early Hercynian, a large number of large-scale strike slip faults formed, and a large number of associated fractures formed around these faults[64]. These fault systems directly communicated with the surface and had contact with the meteoric freshwater environment. The atmospheric fluids penetrated downward along the fault zone and dissolved the carbonate rock, forming pores and cavities. As the calcium carbonate in the fluid gradually reaches the saturation state, the dissolution weakened. However, when the saturated fluids mixed with formation water, the dissolution occurred again; therefore, the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of calcite cements are between those of meteoric freshwater and formation water, ranging from -10.8‰ to -8.2‰ VPDB, and -2.6‰ to -0.87‰ VPDB, respectively.

From the Early to Late Permian period, intense magmatic activities occurred in the Tabei Uplift region. High temperature hydrothermal fluids differentiated from the magma, which was rich in CO₂, H₂S, SO₂, and other volatile substances. The dissolving hydrothermal fluid migrated along the faults to the soluble carbonate rock stratum, and flowed laterally along the fractures and within the early dissolution cavities, resulting in different degrees of dissolution on the carbonate rock, leading to the formation of superimposed and transformed pores and caves. Similarly, some minerals such as calcites and hydrothermal products filled in the secondary pores and caves that formed in the early stage (C4 and C5). Hydrothermal associated minerals such as dolomite, quartz, barite, and fluorite precipitated in the fractures and dissolution cavities. The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of calcite range from -14.17‰ to -11.8‰ VPDB, and -4.67‰ to -1.3‰ VPDB, respectively. The homogenization temperature of fluid inclusions varied from 160 °C to 200 °C. The hydrothermal fluid has a high temperature; hence, when hydrocarbons enter into carbonate stratum and oxidation reduction reaction between sulfate and hydrocarbon happened, thermochemical sulfate reactions (TSRs) occur, and a large amount of acidic substances such as CO₂ and SO₂ are produced. These acidic substances dissolved in the hydrothermal solution have very strong corrosivity; if these substances continue to move upward, they will further corrode and transform the early dissolution pores.

As the basin entered the stable sedimentary stage, the diagenetic stage evolved into the late mesogenetic diagenesis. During this period, tectonic and TSR dissolution were the main factors that affected the pores, while cementation, compaction and filling were the main destructive factors.

5.2. Effect of Faults on Carbonate Reservoir Development

Faults are not only the main migration channel of underground fluid, but also the main region of carbonate reservoirs development[37,65]. Different faults develop different complex internal structural characteristics within a fault zone[66]. In turn, fault zones are composed of complex fracture networks, which provide seepage channels for the surface fluids to flow into the deep strata[67]. Different properties of faults have obvious differences in their control of fracture development. The regions of faults intersection formed multiple groups of fracture systems, which were then affected by multi-stage stress fields. The development of fractures improves the physical properties of carbonate rock for fluid accumulation; hence, the fault intersections are favorable for carbonate hydrocarbon reservoir development. All or most intersections are distributed within fault zones or develop on both sides of fault zones, which indicates that these zones are the most developed for fracture cavities to develop into reservoirs (Figures 16 and 17). Similarly, the fracture cave reservoirs predicted from the amplitude change rate attribute map are mostly distributed on both sides of the fault zones, at the tips of the fault lines, and within the overlapping area between the two faults. The fracture cave reservoirs are distributed in short strips along direction of the fault extension (Figure 18).

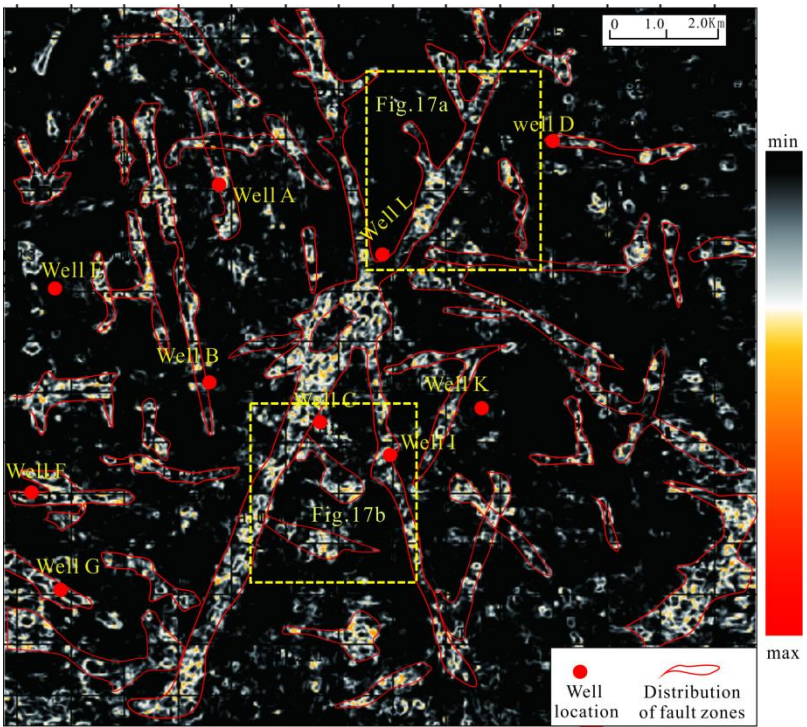


Figure 16. Fracture zones distribution in of instantaneous phase map.

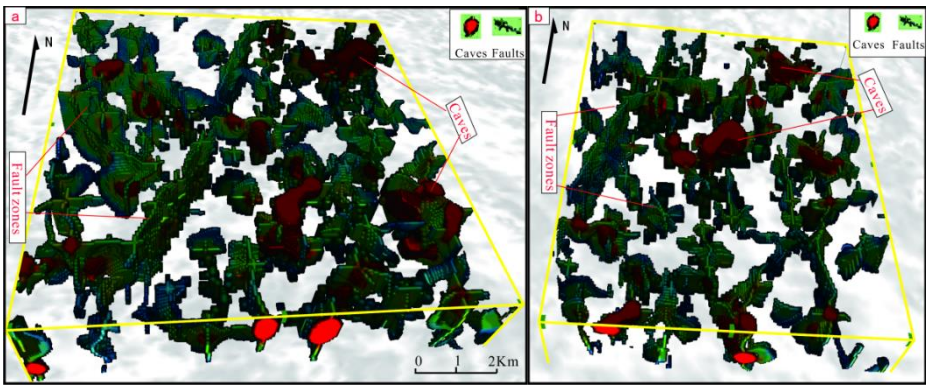


Figure 17. Maps of 3D sculpture of fault and caves body (a and b).

There are obvious differences in the controlling effect of faults formed in different active periods on the distribution of carbonate reservoirs. The fracture cave reservoirs developed near the NE and NW trending strike slip fault, where the drilling leakage phenomenon was obvious. The longer the duration of fault activity, the stronger the karstification, and more corrosion fractures and caves formed. Therefore, the control effect of faults formed during both the Middle Caledonian to Late Hercynian, and the Middle Caledonian to Late Hercynian on reservoir distribution and hydrocarbon enrichment are obviously stronger (Figure 18). These multi-stage inherited faults clearly controlled the fracture cave reservoirs. Most of the faults that formed in the Middle Caledonian continued to be active during the Early Hercynian and Late Hercynian. Therefore, these faults continued downward into the basement or upward towards the surface, providing pathways for the upward and downward migration of deep hydrothermal fluids or atmospheric fresh water. The fault zones are also where dissolution was strongest, which helped control the development of deep reservoirs.

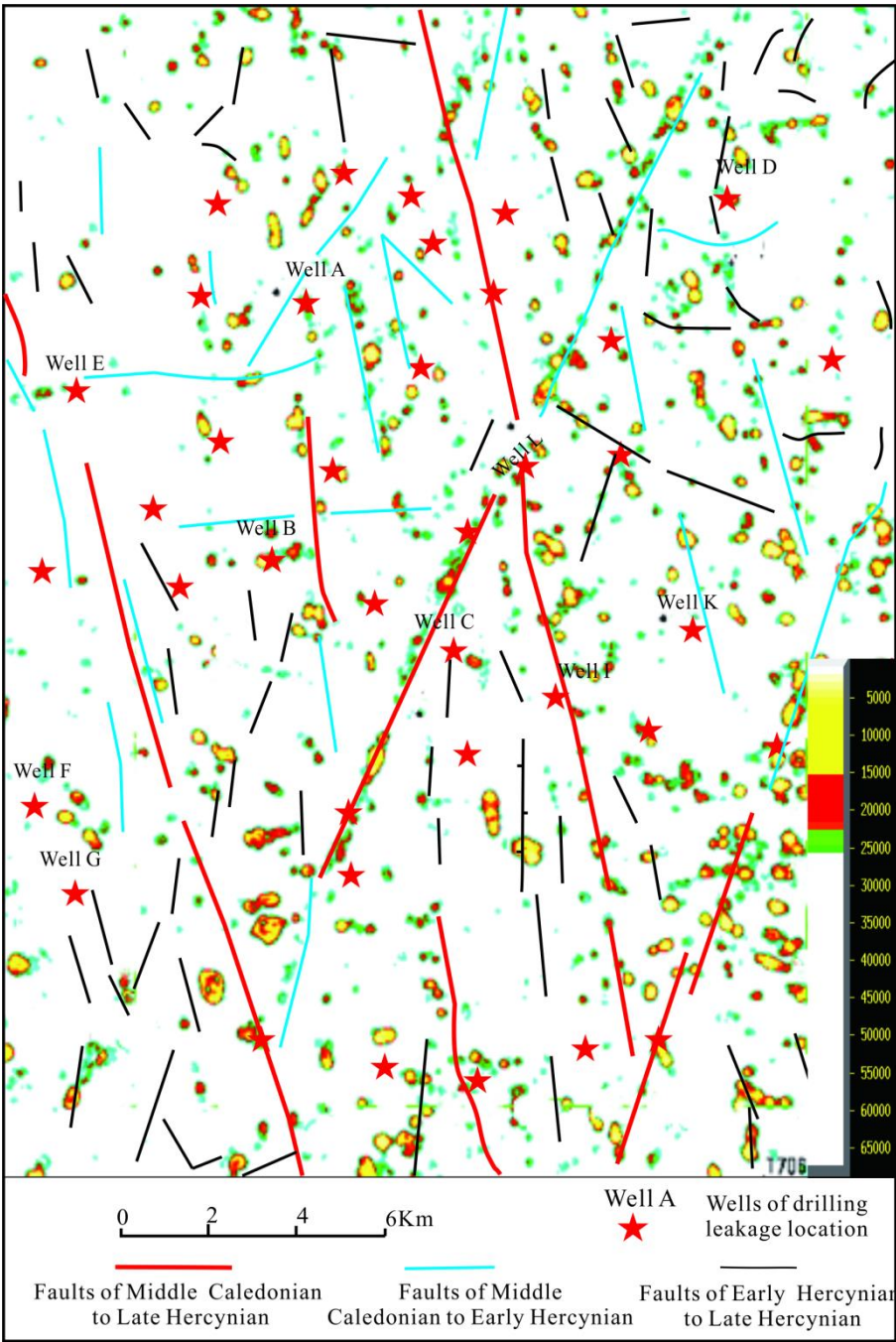


Figure 18. The congruent map of amplitude change rate attributes and fault systems, showing the fracture cave reservoirs controlled by faults.

5.3. *Effect of Strike Slip Faults and Diagenetic Fluids on the Origin and Evolution of Carbonate Reservoirs*

There are several types of dissolution that can occur during a geological period. Dissolution processes during different geological periods transform and overlap with each other, forming complex carbonate reservoirs (Figure 19).

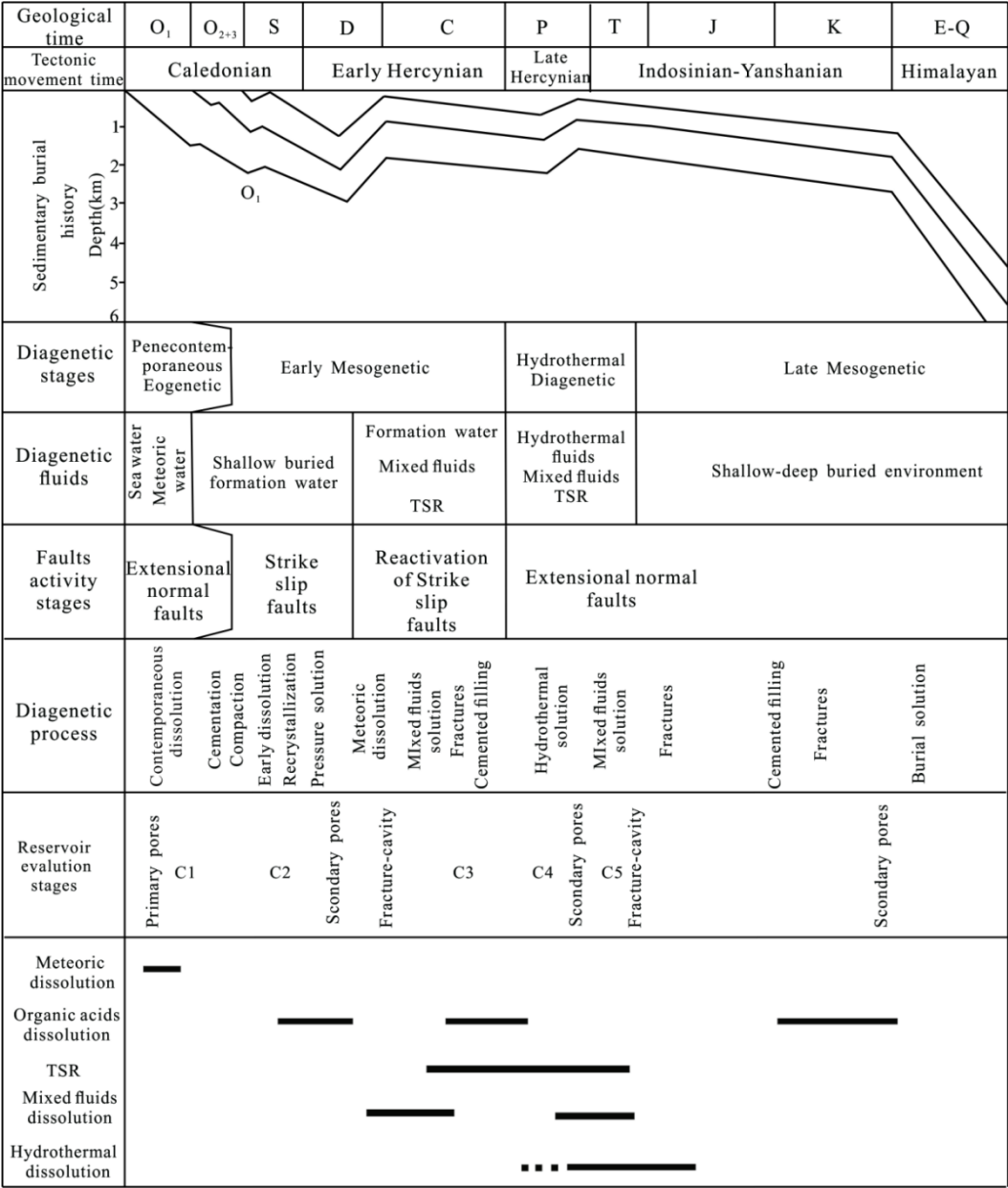


Figure 19. Burial history and paragenetic sequence of the O_{1-2yj} and O_{1y} Formation in the southern area of Tahe oilfield.

After the deposition of the Yijianfang Formation (O_{1-2yj}), a tectonic uplift occurred during the Middle Caledonian, and the Tarim Basin was compressed in the N-S direction. Due to the relatively weak influence of tectonic movements in the Tabei area, some small-scale faults and fracture systems were formed. The carbonate reefs and shoals were exposed to the sea for a short time. The carbonate rocks were leached by atmospheric fresh water, and paracontemporaneous diagenesis occurred, without compaction, pressure solution, and cementation.

The third episode of the Middle Caledonian tectonic movement occurred at the end of the Sangtamu Formation (O_{3s}). The NNW and NNE strike slip faults formed under N-S compression stress; some of these faults were inherited. During this period, the faults broke through the T₇⁰ interface, continuing downward to the T₉⁰ interface. Atmospheric fresh water infiltrated the carbonate formation through the fault zone, and a large amount of organic acids were generated. However, due to the short tectonic uplift and stability during this period, some small isolated dissolution caves and fractures developed.

The Early Hercynian is the most important tectonic movement for the formation and development of fault-controlled carbonate reservoirs in the study area. Under the action of NW-SE

trending regional stress, the inherited strike slip faults in the Middle Caledonian developed strong activity along the scale and the width of the fault zone became larger. At the same time, a series of NNW, NW, and NE trending faults and folds formed. These large-scale strike slip faults extended upward to the T_{57} interface and downward to the T_{90} . The faults connecting the surface provided the long-term conditions for atmospheric fresh water to penetrate and dissolve the Middle and Lower Ordovician limestone strata along the faults and fracture zones. TSR occurred deep within the formation, which generated significant amounts of H_2S and CO_2 during the thermal degradation of the organic matter in the strata. The dissolution fluids converges to the fault zone and migrates upward to where fractures and dissolution vuggy formed in the early stage, occurs dissolution transformation to form new reservoirs. The well-preserved large-scale karst caves, the dissolution vuggy layer, and fracture reservoir were clearly controlled by faults and were found distributed along the fault zones (Figure 20).

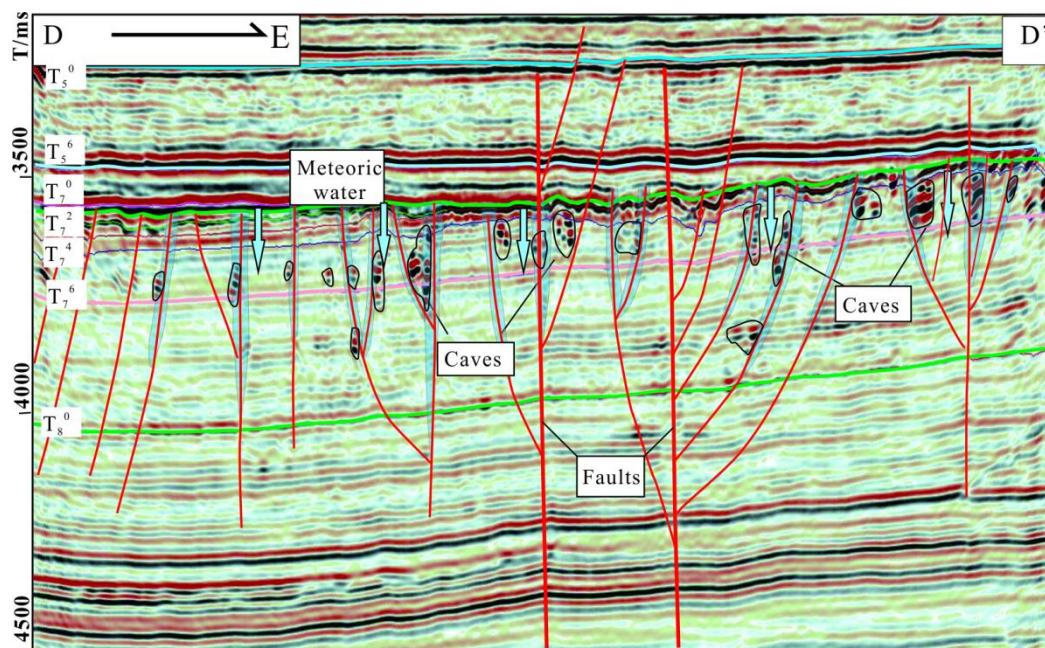


Figure 20. Seismic profiles across the study area showing the Paleozoic faults and carbonate reservoirs development characteristics in the Early Hercynian. See Figure 1: D-D' for location.

During the late Hercynian tectonic uplift at the end of Permian, more faults developed and some of them broke through the surface of the Kalashayi Formation. Hydrothermal fluids associated with volcanic activities during this period converged in the fault zone and migrated upward. At the same time, TSR and volcanic activities released a large amount of CO_2 and H_2S acid gas, which dissolved in the water and contributed to dissolution of the carbonate rock. Meteoric water migrated to these deep strata along the fault zone from the surface, dissolving the carbonate rock, and improving its permeability. The mixing of atmospheric fresh water, hydrothermal fluids, and formation water also enhanced the dissolution ability of the fluids. Karstification had the effect of superimposing the dissolution effects on the reservoir formed in the earlier stage, further enlarging the scale of the reservoir, while simultaneously forming some new reservoirs (Figure 21).

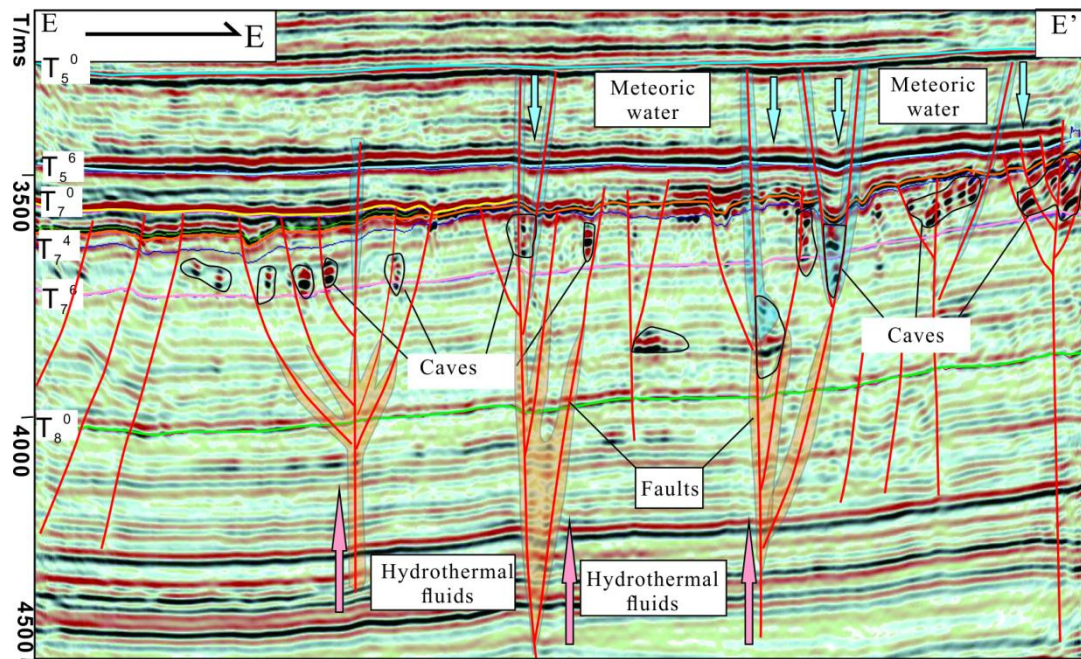


Figure 21. Seismic profiles across the study area showing the Paleozoic faults and carbonate reservoirs development characteristics in the Late Hercynian. See Figure 1: E-E' for location. T_5^0 : the seismic reflection interface on top of the Carboniferous Bachu Formation; T_7^0 : the seismic reflection interface on top of the Upper Ordovician Sangtamu Formation; T_7^2 : the seismic reflection interface on top of the Upper Ordovician Lianglitage Formation; T_7^4 : the seismic reflection interface on top of the Middle Ordovician Yijianfang Formation (mainly reservoirs); T_7^6 : the seismic reflection interface on top of the Middle-Lower Ordovician Yingshan Formation (mainly reservoirs); T_7^8 : the seismic reflection interface on top of the Lower Ordovician Penglaiba Formation; T_8^0 : the seismic reflection interface on top of Cambrian strata (mainly source rocks); T_9^0 : the seismic reflection interface on top of Precambrian strata.

6. Conclusions

(1) The Ordovician carbonate reservoirs in the southern Tahe Oilfield were not generated by weathering crust karstification because of the shielding effect of the Upper Ordovician strata in southarea of Tahe oilfield. The carbonate reservoirs in this area were divided into three types: dissolved pores, fractures, and caves.

(2) These strata experienced three stages of large-scale geologic events, namely, the Middle Caledonian, Early Hercynian and Late Hercynian tectonic movements, which played an important role in the development of fracture-vuggy reservoirs. Further, four stages of fault systems are classified: extensional faults in the Cambrian-Early Ordovician, strike-slip faults in the Middle Ordovician, reactivation of strike-slip faults in the Silurian-Devonian, and faults related to volcanic activities in the Permian.

(3) Four dominate types of diagenetic fluids, such as meteoric water, formation water, hydrothermal fluid, and mixed fluids, played an important role in the development of carbonate reservoirs, with particular contributions of mixed fluids and hydrothermal fluids.

(4) The mixed dissolution of meteoric water is coupled with two stages of tectonic faults: the Early Hercynian and Late Hercynian.; the most important contribution to the reservoir occurred in the Early Hercynian. Hydrothermal dissolution mainly occurred during the large-scale volcanic activities in the Late Hercynian. TSR dissolution mainly occurred from the Early Hercynian to Late Hercynian, with certain dissolution capacity. Organic acid dissolution within formation water occurred during the subsidence burial period, which mainly occurred in the Late Caledonian, Late Hercynian, and Yanshanian-Himalayan.

7. Patents

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