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Original article

Characterization of paleo-karst reservoir and faulted karst reservoir in Tahe Oilfield, Tarim Basin, China

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Abstract:
The Ordovician carbonate reservoir is the most productive deep-earth reservoir in Tahe Oilfield and other oilfields in Tarim Basin. Exploration and production successes in recent years reveal a new reservoir type, namely faulted karst reservoirs, which is closely related to regional strike-slip faults and very different from the well-recognized paleo-karst reservoir. The paleo-karst reservoirs distribute mainly in weathering crust regions in the northern Tahe Oilfield. Their primary reservoir spaces are meter-scale caves and the fluid conduits are predominantly the unconformable surfaces. In production, paleo-karst reservoirs always have sufficient energy, therefore high productivity. The faulted karst reservoirs mainly develop in southern Tahe Oilfield, controlled by the different ordered strike slip faults and related dissolutions. Their reservoir space is smaller than which of paleo-karst reservoirs. The predominant fluid conduits in these reservoirs are the faults. In production, reservoirs along major strike-slip faults have sufficient energy, high productivity and slow watercut increase like paleo-karst reservoirs. While in areas with less strong energy, faulted karst reservoir exhibits weak productivityand rapid watercut increase, implying a rule of “big fault big reservoir, small fault small reservoir, no fault no reservoir. A comprehensive understanding of the geophysical features, distribution characteristics, reservoir property, and production behaviors of the two reservoir types will assist further exploration and production in Tahe Oilfield and other basins containing such reservoirs.

1. Introduction

Karst-related carbonate reservoir is common and important in carbonate petroleum accumulations (Loucks and Anderson, 1980; Kerans, 1988; Budd et al., 1995; Loucks, 1999, 2007; Sayago et al., 2012; Burberry et al., 2016). Reported depth ranges of these reservoirs vary from 350 to 5335 m, most of which less than 3000 m; the strata involved include Ordovician, Silurian, Carboniferous, Permian, Jurassic, and Cretaceous, summarized by Loucks (1999).

Previous researches focused on the effect of fracturing when discussing faults and fractures in carbonates (Jenkins et al., 2009; Lu et al., 2012; Bisdom et al., 2014; Burberry and Peppers, 2017). During the development of naturally fractured carbonate reservoirs, understanding the change in fracture permeability is the basis for production evaluation and scientic development (Ameen et al., 2010; Hennings et al., 2012; Ge et al., 2020; Zhang et al., 2020). It is well accepted that fractures and fracture networks play an important role in fluid flow and transport properties of oil and gas reservoirs (Zhang et al., 2013; Cox, 2016; Wei and Xia, 2017; Velayatham et al., 2018), and fluid flow is well established along the damage zone of the shear slip (Kim et al., 2004; Wibberley et al., 2008; Childs et al., 2009; Kim and Sanderson, 2010; Faulkner et al., 2011; Galloway et al., 2018; Brandes and Tanner, 2020), while discussion on fault-related regional dissolution (karstification) is rare.

In Tahe Oilfield, the Ordovician carbonate in the depth range of 5300~5600 m provides nearly 1/3 of the total oil reserves (Tian et al., 2016, 2017). Most of the Lower-Middle Ordovician reservoirs in northern Tahe Oilfield are

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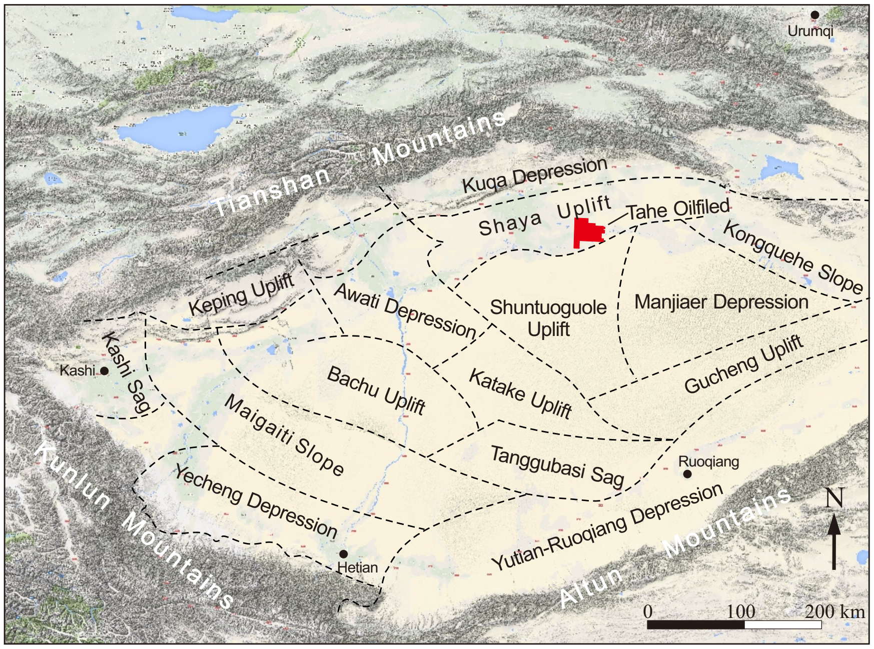

Fig. 1. Structural map of Tarim Basin and the location of Tahe Oilfield.

recognized as paleo-karst reservoirs which were exposed to the atmosphere and experienced multiple stages of karstification in the Early Hercynian period (Ruan et al., 2013; Li et al., 2018). To date, little work has been undertaken to better constrain the distributions, classifications, effectiveness and production characteristics of paleo-karst reservoirs in such deep horizons.

Unlike in northern Tahe Oilfield, in southern Tahe Oilfield the Lower-Middle Ordovician strata are conformable with the barely soluble Upper Ordovician strata, indicating relatively weak epi-karstification in these strata (Li et al., 2016). Though the epi-karstification is insignificant, the oil reserve in the southern area is not much less than in the northern paleo-karst reservoirs. The reservoirs in the southern area are generally on or along the regional faults (Lu et al., 2017; Tian et al., 2019). In-depth investigation of the relationship between fault and karst would be helpful in reservoir characterization and exploration.

In this paper, we characterized the paleo-karst reservoir and fault-related reservoirs in Tahe Oilfield based on the 40-year exploration and production practices of paleo-karst reservoirs, and the breakthrough in recent 5 years of fault-related karst reservoirs. The characterization includes geophysical features, spatial distributions, reservoir properties, and production performances of these two reservoir types. A comprehensive understanding of the reservoir characteristics will assist further exploration and production in Tahe Oilfield and other basins containing such deep-buried reservoirs or faulted carbonates.

2. Geological background

Tahe Oilfield is the first large-scale Paleozoic marine carbonate oilfield in China. It is located in the middle and southern part of Shaya Uplift in the Northern Tarim Basin (Fig. 1). The Shaya uplift is a paleo-uplift that has undergone multi-period tectonic movement, long-term deformation superposition on the pre-Sinian metamorphic basement (Jiao and Zhai, 2008; Zhai, 2013).

In the Middle-Late period of Caledonian movement, the northeast area of Shaya was gradually uplifted, and massive NNE and NNW strike-slip faults were developed under the NS compression. Karstification then took place in the Lower-Middle Ordovician in this area. In the Early Hercynian movement, the northeast area continued to be uplifted, and the southern area was dipped downward. Late-Hercynian movement enhanced the structure. Therefore, the northern Shaya Uplift was continuously uplifted, hence exposed for a long time and subjected to weathering, erosion, atmospheric freshwater leaching, and consequently lost the Upper Ordovician but formed extensive karst fractures and caves in Lower-Middle Ordovician. Whereas the Middle-Upper Ordovician in southern Shaya Uplift was intact as they were in the downward (Jiao and Zhai, 2008).

The middle-lower Ordovician carbonate strata in the Tahe oilfield have undergone multi-stage tectonic movements and formed a series of fault systems with different levels and scales. The predominant directions of the faults were NNE and NNW. These faults formed a “checkerboard” shape on the plane and zigzag shapes in some areas. We summarized the major characteristics of the faults in Table 1.

3. Data and method

This study uses high resolution seismic profiles, drilling logs, wirelines, and production curves to analyze and categorize the carbonate reservoirs in Tahe Oilfield (Table 2). Technics we use in data processing include multi-attribute vol-

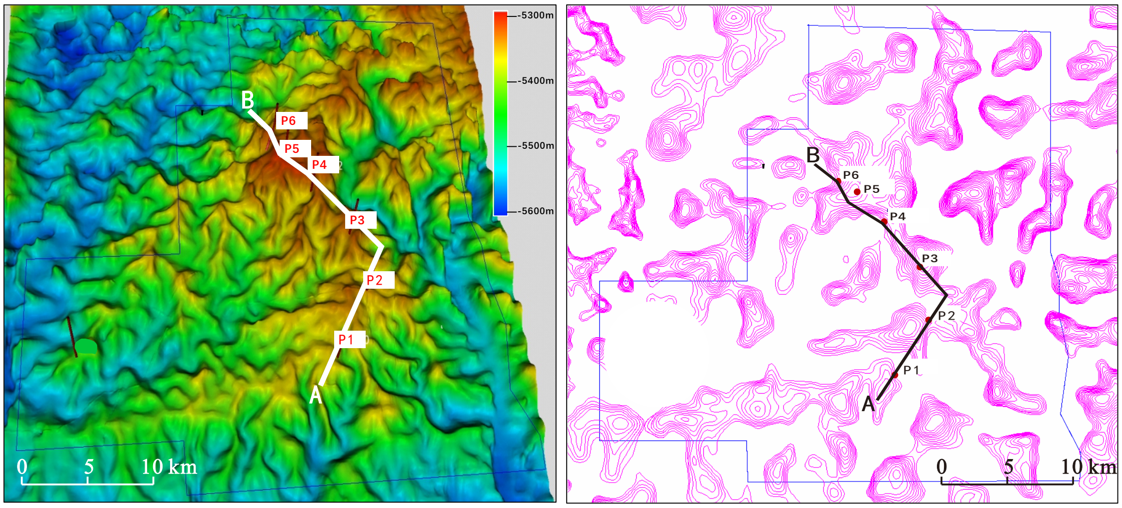

Fig. 2. Typical residual-hill reservoirs recognized by paleo-morphology restoration.

Table 1. Classification of strike slip faults in North Tarim Basin and its control of reservoir and hydrocarbon accumulation.

Level	Type	Scale	
		Length (km)	Displacement (m)
I	strike-slip	50-92.1	25-50
II	strike-slip	12.1-16	20-40
		11-15.2	20-37
III	strike-slip	5-7.8	15-30
	thrust or strike-slip	5-7.4	15-30
	thrust or strike-slip	2.1-5.6	5-8.6

Table 2. Details of the data used in this study.

Type	Quantity	Remark
Seismic profile	3845.3 km^2	3D
Drilling logs	1525 wells	435 horizontal wells
Wirelines	1024 wells	435 horizontal wells
Production curves	541 wells	185 horizontal wells

ume analysis, geo-body interpretation, paleo-geomorphology restoration, and conceptual geological model summarization.

Key seismic parameters we adopted in paleo-morphology restoration, fault identification, and reservoir type classification include bright spots, fault patterns and disturbed strata. Based on seismic data and logging data of all wells, an acoustic impedance inversion data set was established using Jason software and restricted sparse pulse inversion method. The inversion data set shows good vertical and horizontal resolution and provides an effective tool in reservoir identification. The first step of our comprehensive approach is to use fracture-cavity identification equations and conventional logging data to detect paleo-karst features or faults. These equations are obtained from core and image logging information. Next, we use synthetic seismograms to convert the single-well interpretation results from the depth domain to the time domain. Then, the acoustic inversion data set of paleo-karst reservoirs is analyzed. We set the acoustic impedance threshold of the main rock and cave to a value that allows the spatial distribution of the cave to be characterized and results are much clearer than those obtained from conventional seismic amplitude data sets. Finally, by tracking the distribution of caves, the paleo-karst reservoirs were mapped and abstracted from seismic profiles. Subsequently, the structure and genetic type of two reservoir types in this area were interpreted along with the analysis of their production behaviors.

4. Results

Based on the comprehensive analysis of well data, seismic interpretation, and production curves, we have summarized the characteristics differentiating the two reservoir types into four aspects including geophysical features, spatial distribution, reservoir properties, and production behaviors.

4.1 Geophysical features

4.1.1 Paleo-Karst Reservoir

Paleo-karst reservoirs in Tahe Oilfield are buried hills composed of Upper Ordovician carbonates distributing on or beneath the regional unconformable surface. These reservoirs can be further divided into residual-hill reservoir and paleo-channel reservoir.

Residual-hill reservoirs are featured by the high-amplitude mounds and beaded seismic reflection zones, and large-scale cave systems are mostly located in the top of the residual hills. While low-intensity mounds and chaotic seismic reflection features represent small fracture-cave systems or fracture zones (Fig. 2). Using these features, we have done the paleo-geomorphology restoration and recognized 122 residual hills in Tahe Oilfield. The accumulative area of these 122 residual hills reaches 171.5 km^2, with a single residual hill covers

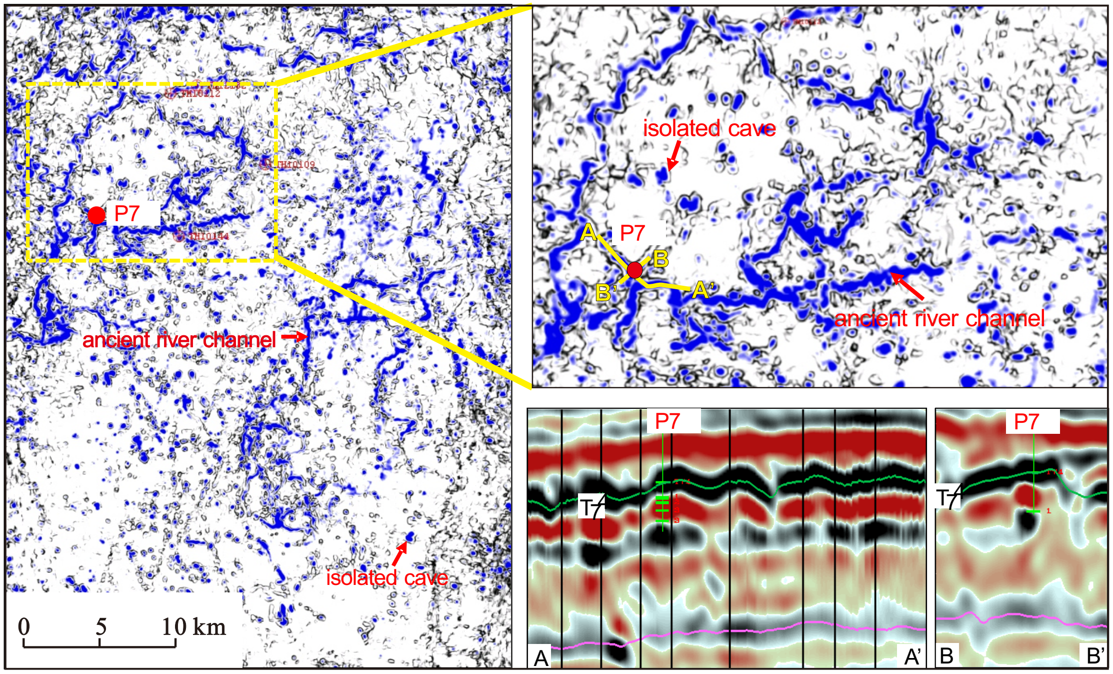

Fig. 3. Typical Paleo-channel reservoir distribution maps and the seismic profile.

0.02~20.5 km^2.

Paleo-channel reservoir are featured by continuous short-axis strong reflection along the ancient river channel and beaded seismic reflection characteristics in varied directions (Fig. 3). Using these features, we have recognized 77 paleo-channel in Tahe Oilfield. The accumulative length of these channels reaches over 300 km, and the width range from 146 to 650 m.

4.1.2 Faulted Karst Reservoir

The large strike-slip faults in the northern Tarim Basin have obvious effects on the Ordovician carbonate reservoirs. Specifically, the fracture-cave zones have a good match with the dissolution fault zone and the tectonic deformation zone. The intensive faulting area along the NNE and NNW strike-slip faults are often the areas with the strongest dissolution.

Faulted karst reservoirs show varied geophysical correspondences in different locations refereeing to the faults. As a dissolution fault zone can have different stress segments on the plane (e.g., translational section, compression and torsion section, tensile section), the reservoir characteristics and seismic features are segmented accordingly. Generally, high-quality reservoirs develop along the major fault zone, which are mostly strip-shaped and partially divergent. Due to the multi-phase activity of the strike-slip faults, the vertical patterns vary as well (e.g., single-branched upright strike-slip, flower-like structure, Y-shaped). When adding the stratigraphy and lithology the vertical patterns get more complicated and heterogenous (e.g., upright strike-slip plus flower-like structure, upright strike-slip plus Y-shaped structure) (Fig. 4). Based on these analyses, we summarized the geophysical features of faulted karst reservoirs in Table 3.

We have recognized 78 faulted-karst reservoirs in Tahe Oilfield. The accumulative area of these reservoirs reaches 347.7 km^2, with a single residual hill covers 0.04~25.3 km^2. The accumulative area of faulted-karst reservoirs is significantly greater than that of paleo-karst reservoirs.

4.2 Reservoir Properties

4.2.1 Paleo-Karst Reservoir

The paleo-karst reservoirs are mainly characterized by the coexistence of caves, fractures, and pores, in which caves are the most important reservoir space, and the volumes of the reservoir space changes significantly (from a few millimeters of dissolution pores to large caves of tens of meters). These reservoirs are composed of multiple fracture-cave units of different sizes and geometric shapes. These units can be superimposed and connected to each other, or they can be completely constant in volume and distributed in an isolated state.

4.2.2 Faulted Karst Reservoir

The faulted-karst reservoirs are characterized by the fractures or the coexistence of fractures and caves. The volumes of the reservoir space change significantly according to the location along the fault zones. As the compression-torsion segments of the strike-slip faults are strong in deformation, they have wide fracture zones and provide spaces for dissolution. Caves are most developed in these segments, usually in meters. The transitional segments of the strike-slip faults are primarily high-angle vertical fractures with poor associated deformations; thus, the reservoirs in the transitional segments

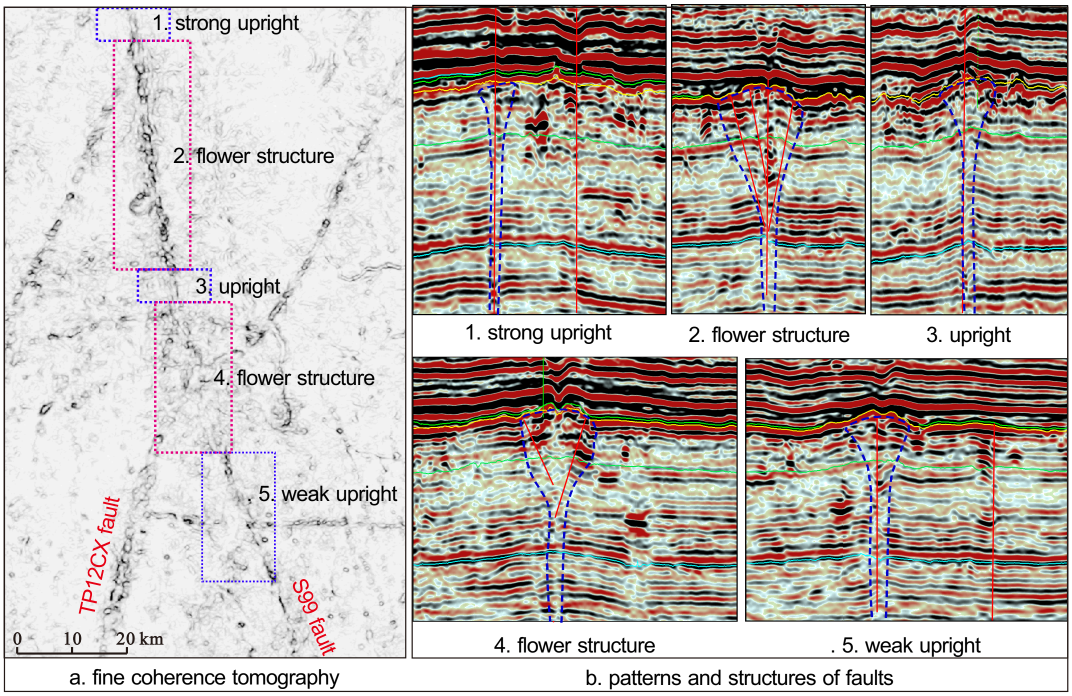

Fig. 4. The composition of major strike slip faults. a: recognition and dissection of major faults by fine coherence tomography, the S99 fault can be divided into five segments. b: interpreted seismic profiles of different segments.

Table 3. Geophysical features of faulted-karst reservoirs.

Reservoir	Seismic reflection	Wirelines			Drilling logss		
		Resistivity (Ω·m)	Density (g/cm^3)	Sonic (μs/ft)	Curve	Bit drop	Drilling time (min/m)
Matrix	continuous	>2000	2.7-2.8	>50	steady	non	25-40
Fracture, fracture-pore	continuous-weak disordered-weak	600-3000	2.5-2.6	40-50	fluctuated	minor	13-25
Cave, fracture-cave-pore	disordered-weak disordered-strong beaded	40-2000	2.5-2.6	35-45	zigzag/fluctuated	major	5-12

are relatively narrow, the caves may be in centimeters.

4.3 Spatial Distribution

The identification through geophysical features and reservoir properties reveals the paleo-karst reservoir and faulted reservoir distribute distinctly in spatial.

4.3.1 Paleo-Karst Reservoir

Horizontally, the paleo-karst reservoirs distribute mainly in weathering crust regions in the northern Tarim Basin (Fig. 5).

Vertically, they are mostly stratified and restrained by regional unconformity, especially the paleo-geomorphology and paleo-water systems of weathering crust. According to the statistics of more than 1200 wells in this area, large-scale fractured cave system, especially caves of different scales, are concentrated within 0~300 m below the unconformity surface (the weathering crust), and mostly developed in the range of 0~60 m.

4.3.2 Faulted Karst Reservoir

Horizontally, the faulted karst reservoirs mainly develop in Upper Ordovician in southern Tarim Basin (Fig. 5).

Vertically, the faulted karst reservoirs are not constrained in specific depth ranges or stratum. They may extend along the faults and form reservoirs at different depths, making a vertical beaded pattern. In summary, the distribution of faulted karst reservoir extends larger and deeper than the paleo-karst reservoirs.

4.4 Production Behaviors

4.4.1 Paleo-Karst Reservoir

The paleo-karst reservoirs, in which the large caves in the

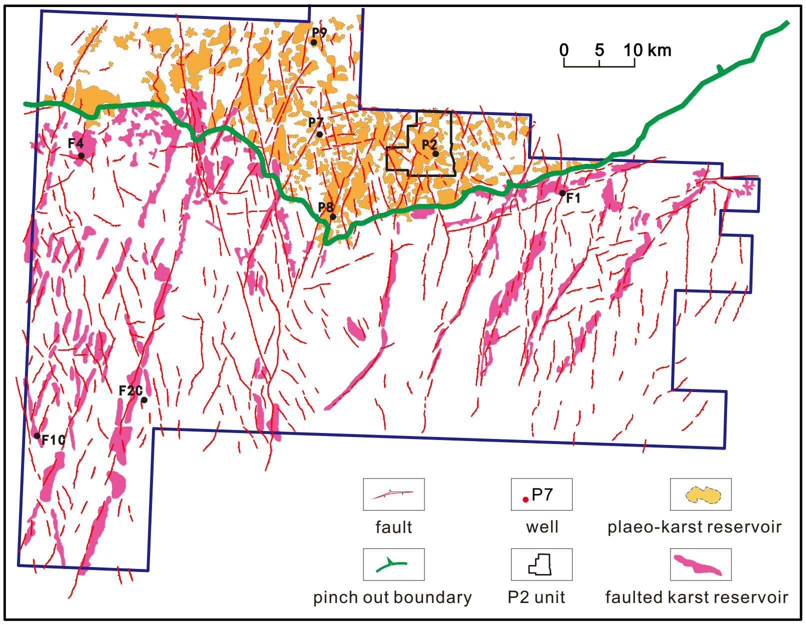

Fig. 5. Distribution map of the two reservoir types.

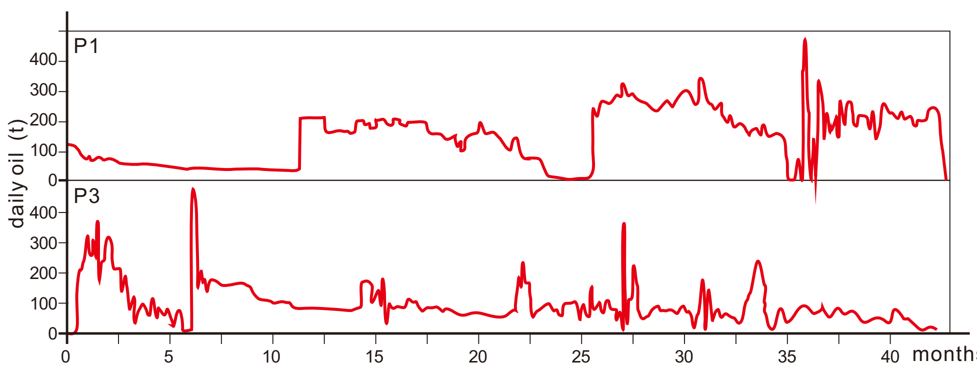

Fig. 6. Production curves of paleo-karst reservoirs.

residual hill or hill groups are the predominant reservoir space, are demonstrated by great amount of oil reservoirs and good connectivity of different cave-fracture unit. These reservoirs have sufficient energy (pressure) and high productivity of single wells. The production curves are often in a "π shape, indicating the existence of an increasing stage and a stabilized stage; and the following decline stage can be divided into rapid decline and slow decline (Fig. 6).

4.4.2 Faulted Karst Reservoir

According to the characteristics of single well productivity, energy and decline characteristics of more than 300 wells along different levels of faults, it is pronounced that the oil and gas enrichment on the major fault zone is high and the oil well productivity is great, implying a simple rule of "big fault big reservoir, small fault small reservoir, no fault no reservoir (Fig. 7).

Level I faults are major strike-slip faults, reservoirs around which are high in primary productivity (30~100 t/d) and reservoir energy (sufficient for a two year flow production), and slow in decline (decline rate generally <15%). For Level II faults, which are branch faults along the Level I faults, reservoirs have moderate primary productivities (10~30 t/d), moderate reservoir energy (flow production last shorter than 1 year), and rapid in decline (decline rate ~15%). For Level

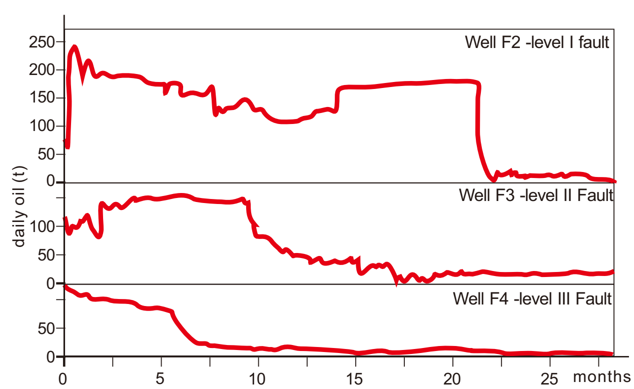

Fig. 7. Production curves of faulted karst reservoirs.

Table 4. Fault categorized production statistics of faulted-karst reservoirs.

Fault level/quantity	Wells	Primary productivity (t/d)	Averaged well production ($\times 10^4$ t)	Primary decline rate (%)	Intensity of energy
I/6	138	44	4.7	13.5	strong
II/28	120	21.9	2.6	21.2	moderate
III/44	59	14.3	1.2	25	weak
Sum/Ave	317	30.3	3.3	19	/

III faults, which are fractures in the matrix, reservoirs are poor in oil accumulation and energy (Table 4).

5. Disccusion

5.1 Reservoiring Mechanisms

5.1.1 Paleo-Karst Reservoir

Both the residual hill reservoir and paleo-channel reservoir are related to regional unconformable surfaces, specifically the distribution of paleogeomorphology and paleo current. These reservoirs are constraint in the 0$\sim$300 depth range below the regional weathering crust, and can form stratified sheet-like oil plays beneath the regional weathering crust (Fig. 8). They are composed of multiple fractured-vuggy units of different scales and geometric forms, and presents the characteristics of “vertical superimposition and quasi-layered distribution”. From the perspective of reservoir formation, the development and formation of paleo-karst reservoirs is mainly controlled by the leaching of precipitation from the atmosphere, forming the reservoir space dominated by large-scale caves with a good horizontal connectivity. From the perspective of the oil and gas accumulation, the oil and gas in paleo-karst reservoirs migrate laterally through the regional multi-stage unconformity surface as the drainage system, which has the characteristics of lateral migration and accumulation, contiguous accumulation, and superimposed accumulation.

5.1.2 Faulted Karst Reservoir

For faulted karst reservoirs, the well productivity, energy, decline characteristics vary significantly among different fault levels or different locations of same fault level. Each reservoir is a relatively independent reservoir with its own energy, and oil-water interface, and are not necessarily related to the unconformable surfaces. These reservoirs are like curtains hanging through the strata (Fig. 9). They distribute like patches on the plane, seeming to be connected to each other. In the nature they are independent, and parameters like reserve, energy, and decline rate may be vastly different in the neighboring reservoirs. Faulted karst reservoirs are mainly controlled by dissolution and strike-slip fault zones, and they are dam-shaped in space. They distributed in irregular and discontinuous strips along the fault zone, and the section has obvious discontinuity along the longitudinal direction of the fault zone. From the perspective of reservoir formation, faulted-karst reservoirs are controlled by both fracture and dissolution. Large-scale caves develop in the core areas of the dissolution fracture zone, but the caves are significantly smaller than which in the paleo-karst reservoirs. Faulted-karst reservoirs are not closely related to the regional unconformities and structural elevations. They generally show good vertical connectivity but poor lateral connectivity. From the perspective of the oil and gas accumulation, oil and gas primarily migrated and accumulated along the vertical direction of the strike-slip fault zone, and then migrated and accumulated in a “T” shape laterally along the fracture network system, exhibiting a rule of vertically migration and sectionally accumulation.

5.2 Exploration and Production Implications

5.2.1 Paleo-Karst Reservoir

Exploration of paleo-karst reservoir is always important in carbonate strata. In Tarim Basin the favorable horizons for paleo-karst reservoirs can be found within the 500 m intervals beneath the regional unconformable surfaces. For the paleo-karst reservoirs with small caves, reservoir units are mostly characterized by insufficient energy and less favorable productivity. We have applied acidifying, fracturing, water flooding, and nitrogen flooding to achieve better recovery, and the results are favorable.

5.2.2 Faulted Karst Reservoir

Faulted karst reservoir is a new type, new target and new horizon for oil and gas exploration and development of deep marine carbonate. We have avoided the major faults for years as they were considered to be fluid flow conduits. The breakthrough in faulted karst reservoirs in Tahe Oilfield allow us to expand the exploration target from the traditional paleo-karst reservoirs to the reservoirs formed by the faults. In light of the faulted karst theory (big fault big reservoir), we have turned the southern area of Tahe Oilfield into a new promising oilfield.

The faulted karst reservoirs are young in production. The decline rules and energy supplies are still in the watch. It is urgent to deepen the research on the characteristics of marine carbonate reservoirs through theoretical breakthroughs and technological innovations to promote the exploration and development practices of such reservoirs.

6. Conclusion

Ordovician carbonate reservoirs in Tahe Oilfield can be categorized into paleo-karst reservoirs and faulted karst reservoirs based on their geophysical features, distribution char-

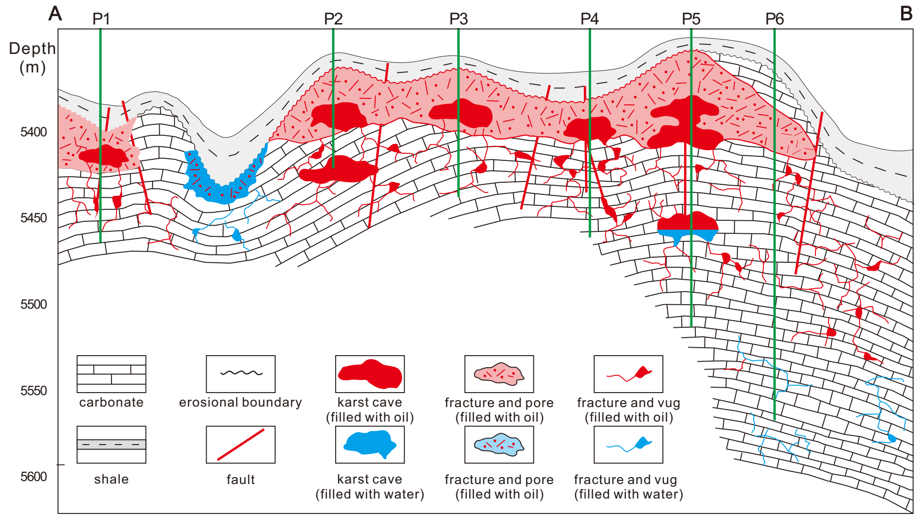

Fig. 8. Typical profile of paleo-karst reservoir in Tahe Oilfield. Profile position see Fig. 2.

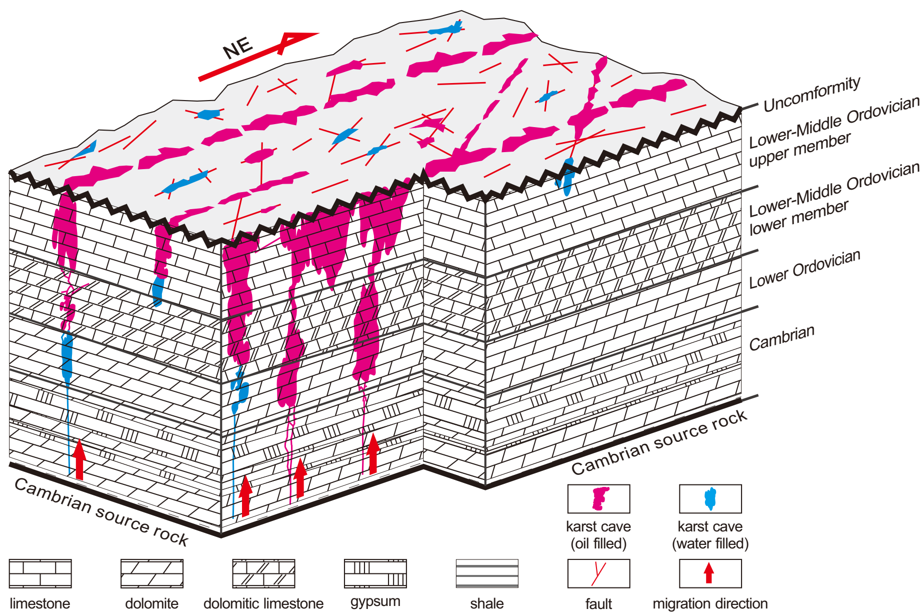

Fig. 9. Conceptual model of hydrocarbon accumulation in faulted karst reservoir.

acteristics, reservoirs properties, and production behaviors. The paleo-karst reservoirs distribute mainly in weathering crust regions in the northern area of Tahe Oilfield. They are characterized by good lateral connectivity, meter-scale caves, sufficient energy, and high productivity. The faulted karst reservoirs are controlled by the different leveled strike slip faults and related dissolutions. They mainly form in southern Tahe area where paleo-karst poorly developed. They have good vertical connectivity but not well connected laterally.

The recognition of faulted karst reservoirs has brought breakthroughs in oil exploration and production in Tahe Oilfield in recent years. This theory deepens our current understanding of deep buried karstification and the significance of faults in forming favorable reservoir spaces. We are looking for dissolution surfaces along deep fault damage zones in basin slopes and depressions to find more faulted karst reservoirs. Till present the theory is simple but effective. However, in-depth researches and technic innovations relating to these reservoirs are needed to make the exploration and production sustainable.

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Conflict of interest

The authors declare no competing interest.

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