Research progress and prospect of Ordovician carbonate rocks in Tahe oilfield: karst feature

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Abstract

Inspired by structural geology, karstology, geomorphology, as well as petroleum geology, coupling excellent documented research works and the field investigation, the status and prospect for the studies on karst feature of Tahe oilfield are discussed comprehensively. Results indicate: (a) the majority of research works have appeared since 2000 and can be classified as three categories and 12 subclasses, in which caves, fracture cave systems and fault-karst reservoirs are considered as the main research topics, (b) existed studies can be divided into four stages, and fault-karst reservoir analysis is a hot spot recently, focusing on the scale of the formed reservoir. It is the common sense that faults control both fractures and caves. Originally, there exist close relationships among karst phenomena whether they're on the ground or underground. Revealing these relationships mentioned above is the important direction for the studies of Tahe oilfield in the future. As for the areas where faults are widely distributed in karst, there exist hierarchical properties in karstology: (1) fault controls topography and landform, (2) fault, topography and landform control the water system and (3) fault, topography, landform and water system control karst. These hierarchical properties are the basic connotation of the laws for karst evolution, and the vital goals of the karst study of Tahe oilfield as well. Applications of methods and techniques and field-karst investigation are the solid guarantees to achieve these goals.

Keywords Karst · Research · Progress · Prospect · Tahe oilfield

Introduction

Tahe oilfield is located at Akekule uplift in Shaya uplift belt of northern Tarim Basin. Akekule uplift is a long-term inherited uplift with large scale and thick carbonate strata.

The most important paleo-karst reservoir is developed in Ordovician carbonate rocks. Yingshan formation (O1-2y) is the main development layer of Ordovician paleo-karst reservoir in Tahe oilfield, followed by Yijianfang Formation (O2yj). Additionally, a small number of paleo-karst reservoirs are also developed in qarback formation (O3q) and Lianglitage Formation (O3l). Superior paleo-karst reservoir is one of the basic geological conditions for the formation of Tahe oilfield. In order to assist and secure the efficient exploration and development of Tahe oilfield and the deep oil and gas exploration with carbonate rocks, i.e., the main reservoirs in Tabei and Tazhong of Tarim Basin, this paper conducts compressive investigations on the achievements and understanding of the middle and lower Ordovician carbonate karst research in Tahe oilfield, its progress and prospect are summarized seriously.

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Progress

Massive efforts have been devoted to karst research of Ordovician carbonate rocks in Tahe oilfield for a long time, the achievements are rich, including: (a) the research of Tarim Basin and a wider range, such as stratigraphy (Wang 1999), sedimentology (Sun 2001), structural geology and geotectonic (Lee 1955), oil and gas exploration area (Dai et al.; Jin et al. 2017; Jia et al. 2013), structural system oil-control model (Yuzhu 2018), structure and hydrocarbon distribution (Sun et al. 2002) and reservoir characteristics (Sun et al. 2020); (b) the academic contributions of Akekule uplift, such as structural characteristics (Li 2006), fault characteristics (Ji et al. 2008), paleo-tectonic restoration (He et al. 2011), reservoir tectonic stress field (Ding et al. 2009; Liu et al. 2020), tectonic evolution (Ren et al. 2008; Feng 2012; Wu 2013), the influence of tectonic movement on carbonate rocks (Yu and Fu 2006), etc. In addition, there are related studies on some areas or structural belts in Tarim Basin (Sun et al. 2019a; Luo et al. 2012; Wu et al. 2012); (c) the field investigation of karst phenomena in outcrop area of northern Tarim basin, involving of characteristics of paleo-karst (Liu et al. 2013a; Gao et al. 2014), karst cave system (Shi et al. 2014), controlling factors of paleo-karst cave (Li et al. 2013), characteristics of karst collapse body (Liu and Cai 2010), karst zonation (Feng et al. 2010), development model of paleo-karst (Zhang et al. 2013), outcrop characterization of paleo-karst reservoir (Liu et al. 2010), vertical fracture-controlled development model (Liu et al. 2011), etc. This is a special field investigation in the outcrop area of northern Tahe oilfield during the 13th five-year plan period in order to extend the study of karst in Tahe oilfield; (d) research on Tahe oilfield or its different divisions, such as fine structural interpretation (Guo 2015), structural characteristics (Deng 2012), structural evolution of T74 ancient erosion surface (Sun et al. 2018a), structural evolution (Zhang et al. 2011; Cai 2011), structural differential evolution (Zhang et al. 2020), etc.

Ordovician Karst types in Tahe oilfield include epi-karst (atmospheric fresh water karst), hydrothermal karst (Li et al. 2010) and syngenetic quasi-syngenetic karst, etc. Notably, epi-karst is the main type, which has been confirmed by many indicators (Xu et al. 2012; Liu et al. 2007; Ruan et al. 2011; Hu et al. 2015; Cao et al. 2012; Li et al. 2015).

Ordovician epi-karst in Tahe oilfield has evident karst zonation phenomenon (Sun et al. 2017; Qu et al. 2015; Zou et al. 2016). Karstification is mainly developed in middle Caledonian and Hercynian. The middle Caledonian karst is divided into I, II and III episodes, and Hercynian karst is divided into Early Hercynian and late Hercynian (Wan

et al. 2009; Lyu et al. 2009). Close attention has been paid to the study of Karst Characteristics in the middle Caledonian (Yan et al. 2011; Liu et al. 2006; Yu 2005) and Hercynian (Yang et al. 2013a), as well as the comparative study of karst in the Early Hercynian and middle Caledonian (Sun et al. 2018b). Karst cycle is an important aspect of karst research. Karst zonation phenomenon (Sun et al. 2017; Qu et al. 2015; Zou et al. 2016) is closely related to karst cycle (Liu 2004).

Key research focused on the study of karst in Tahe oilfield and its sub-regions should be highlighted (Xiao et al. 2010), encompassing the study of paleo-karst collapse body (Wang et al. 2017a) and collapse filling characteristics (Jin et al. 2015a). The research on karst cave includes the identification of the scale of karst cave reservoir (Hu et al. 2018), the characteristics of karst cave and its filling, and the control of fracture on karst cave reservoir (Qin et al. 2018). Among them, the study of cave filling includes seismic facies identification of cave filling (Yang 2019), cave-filling characteristics and their vertical physical property changes (Sun et al. 2019b; Zhang et al. 2014), cave-filling mechanism (Tian et al. 2018), etc. The research on caves includes cave identification and prediction (Li and Wang 2003), cave development characteristics (Jing et al. 2005), cave filling (Yu et al. 2017; Wang 2017; Kang et al. 2014; Liu et al. 2008a; Su et al. 2015), connectivity of cave system and cave reservoir characteristics (Xu 2008; Xiao et al. 2003a, b) and modeling (Liu et al. 2018).

On the basis of the research, it is recognized that Ordovician deep underground river and shallow underground river in Tahe oilfield are karst products during various periods, with poor spatial inheritance. The shallow underground river is reticulated and has a high probability of filling and the deep underground river system is linear (Sun et al. 2019c). There are three types of cave-filling materials: transport-type sediment, collapse-type deposit and chemical-type cement (Sun et al. 2019b). There are three genetic types of karst collapse body: fault-induced collapse body, overlying strata load collapse body and late supergene karst collapse body (Wang et al. 2017a; Yang et al. 2017). Coarse clastic sediments (Zhang et al. 2014), collapse breccia and coarse clastic sediments have excellent filling properties (Kangxun 2014a; Jin et al. 2015b). Cave-filling degree can be divided into unfilled, partially filled and fully filled (Sun et al. 2019b). Results show that the filling material in the tunnel is coarse, the grain size of the filling material is large, the chemical cement content is small, the cementation degree is low, the filling degree is low, the filling physical property is good, the oil-bearing property is high, and the development related property is mature.

In terms of quantity, the research contributions of fracture cave are the most in the Ordovician carbonate karst research in Tahe oilfield, which can be summarized as terms related

to fracture cave and their use, fracture cave unit definition, classification and division, fracture cave identification and prediction (Chen et al. 2002), fracture cave structure, connectivity, segmentation, fracture cave filling and modeling, etc. Among them, there are many related terms used, including fracture cavity (Wang et al. 2011; Lyu and Ding 2009; Liu et al. 2008b), fracture cavity body (Li et al. 2014a; Lyu et al. 2017a), fracture cavity unit (Jin et al. 2015c; Li 2007), fracture cavity system (Yu 2007; Ahmatjan 2009; Rao et al. 2007; Sheikholeslami et al. 2021a, b), fracture cavity reservoir (Yu et al. 2019), fracture cavity reservoir (Liao et al. 2013; Wang 2014; Zhanghua 2013; Guo 2012), fracture cavity reservoir (Sun et al. 2019d), etc.

Fracture cavity unit division is an important foundation of fracture cavity research, involving the study of fracture cavity unit division method (Song and Liu 2011; Chen et al. 2007) and the specific division of fracture cavity unit (Yang et al. 2015; Cao 2007; Zhang 2010; Li 2008; Zhang et al. 2007a). The study of fracture cavity structure includes the study of fracture cavity structure (Sun et al. 2017; Jin and Tian 2013; Zhang et al. 2018; Tian 2013) and fracture cavity reservoir structure (Wang 2015). Research on the characteristics of fracture cavity filling (Hu et al. 2014), the physical properties of fracture cavity filling materials, the degree of this map and its origin and distribution (Wang 2017; Kangxun 2014b; Jin et al. 2015d) act as indispensable parts of the research on fracture cavity characteristics. Reservoir connectivity (Song et al. 2013; Li et al. 2014b; Hu and Yang 2005; Yang 2004; Sun et al. 2019e; Yi et al. 2011), fracture cavity separation (Rong et al. 2015), and reservoir separation (Li 2016) reflect the distribution characteristics of fracture cavity reservoir space from different perspectives. Reservoir modeling (Yan et al. 2013; Zhang et al. 2007b) and numerical simulation (Hu et al. 2013) give the results of fracture cavity distribution in the sense of mathematical modeling.

Vertically, the structure composition of fracture cave units in different karst zones is different. The surface karst zone is composed of surface rivers, sinkholes and other fracture caves. The fracture cave in seepage karst zone is composed of water retaining cave and seepage well. The fracture cave in runoff karst zone is composed of hall cave, main stream cave, tributary cave and terminal cave (Sun et al. 2017). The underground paleo-river has strong heterogeneity and complex spatial structure. The fracture cavity structure on the plane can be divided into two categories: continuous strip and discontinuous mass (Li 2008). The main reservoir types include dissolution pore type, karst fracture cavity type, karst cave type and fracture type.

The research of fault solution represents a new direction of Ordovician carbonate paleo-karst research in Tahe oilfield. The existing research achievements include fault solution characterization (Wang et al. 2019a), fault solution reservoir seismic reflection characteristics (Yang 2018) and

fault solution reservoir separation (Bao and Zhang 2017), etc.

Based on the research, it is recognized that fault solution reservoir is a new type and new target of deep carbonate oil and gas exploration and development in China (Yang 2018; Bao and Zhang 2017; Lu et al. 2018). Also, it is a heat research topic in Tahe oilfield and its periphery, Tabei uplift and Tazhong north slope. From the perspective of oil and gas field exploration and development, the emphasis of this research is lay on the scale of fault-controlled karst reservoir (fault solution), which shares commercial value to a certain extent. The larger the scale, the larger the reserves and the higher the productivity, the more oil and gas production capacity. On the basis of large-scale fault research, the key addressing this problem is to determine the favorable location of fault solution and the large reservoir space related to fault solution.

Generally speaking, the research on this focus can be summarized as five aspects: the first is the research on the fault system of strike slip fault (zone), the second is the research on the segmentation and activity difference of strike slip fault (zone), the third is the research on the stratification and activity period of strike slip fault (zone) and the activity characteristics of different activity periods. The fourth is about the genesis of strike slip fault (belt) and relevant genetic model (Huang 2014; Yang et al. 2013b; Li et al. 2018). The fifth is about the Karst Characteristics of strike slip fault (belt) and its oil–gas rich characteristics (Li et al. 2017a; Deng et al. 2018; Qiu et al. 2017; Han et al. 2016a; Huang 2014; Zhen et al. 2015). Many achievements and understandings have been obtained over this critical problem, such as the three understandings in reference (Lu et al. 2018): (1) the size of fracture cavity reservoir in fault solution trap is mainly controlled by the deformation scale and dissolution intensity of strike slip fault zone, and high-quality fracture reservoir is usually developed along the main fault zone, which is mostly banded and locally divergent; (2) in the tension and compression torsion sections of strike slip fault zone, the local deformation of strata is evident, and the flower structure style is mostly developed. The fracture zone is wide, and the effect of dissolution and transformation is strong. The reservoir space mainly belongs to large caves, which is the most developed part of fracture cave reservoir. High-angle vertical faults are mostly developed in the translation section, and the reservoir development range is relatively narrow. Along the strike slip fault zone, the development degree of fractured vuggy reservoir is obviously segmented; (3) the cross-section surface of fault solution has typical three-division structural characteristics, which can be divided into core, edge and bedrock section. The core of fault solution is located in the middle of strike slip fault zone, which is characterized by large degree of fragmentation, strong karstification and large scale of reservoir space.

The research on the dominant factors of karstification serves as the basis of the research on the distribution and development law of karst, mainly including lithology (Li et al. 2017b), fault, paleo-topography, paleo-geomorphology and water system (surface river, underground river and sub-surface flow). The research results of fault-controlled karst are mainly reflected in the understanding of strata-bound and fault-controlled reservoir types of Tahe oilfield (Lu et al. 2018), fault-controlled karst reservoir (Han et al. 2016b), control of Ordovician paleo-karst by fault (Wu et al. 2017, 2005; Zhou et al. 2011), fault cave reservoir (Qin et al. 2018), etc. The achievements of paleo-geomorphology research include paleo-geomorphology restoration (Wang et al. 2014; Yuan 2002; Karst Research in China 1979), paleo-geomorphology characteristics and evolution (Li et al. 2016b), paleo-geomorphology formation mechanism (Wang and Li 2001), karst Canyon cave system development model (Li et al. 2017c), karst mesa division and cave layer correlation (Li and Cai 2016), paleo-geomorphology control over caves (Li et al. 2016c), paleo-geomorphology control over reservoirs (Cao et al. 2014; Han et al. 2016c), etc. The research of ancient water system includes identification method of karst ancient water system (Sun et al. 2019f), ancient river channel (Guo 2016; Sheikholeslami and Farshad 2021), Daotang River and its genesis (Liu and Cai 2009), water system change of karst basin (Cai et al. 2009), erosion and karstification of source undercurrent and its genetic mechanism (Xu et al. 2005), docking phenomenon of ancient water system (Sun et al. 2018c), characteristics of ancient water system (Xia et al. 2019), deposition and geochemistry of surface river and underground river (Jin et al. 2015e), structural characteristics of fracture, cave of ancient underground river (Zhang et al. 2018) and underground river reservoir (Sun et al. 2019c).

It is very important to study the inherent relationship among the controlling factors of karstification. In the study of Ordovician carbonate karst in Tarim Basin, reference (Li and Kang 2012) studied the relationship between paleo-geomorphology, paleo-drainage and fault system in Tahe oilfield.

In accordance with existed research, it is recognized that fault is one of the main controlling factors of karst development and distribution. The medium-large faults in Tahe Area are mainly cave-controlling faults, which govern the distribution of deep karst caves (Wu et al. 2017). The karst development and concentration degree of large-scale faults are fairly high (Wang et al. 2011; Wu et al. 2017; Sun et al. 2018d). For example, on the plane of karst reservoir in the slope area, the karst reservoir is distributed as a strip along with the fault, and vertically, the reservoir falls in the range of 0–50 and 100–150 m from the top of Ordovician Yijianfang Formation (Li et al. 2016c). Moreover, the deep and shallow underground rivers are

karst products during different periods, and their spatial inheritance is poor. The shallow underground rivers are reticulated and have a high probability of filling. The deep underground river system is linear (Zhen et al. 2015).

Reservoir development degree is mainly controlled by paleo-karst zonation vertically, and by karst paleo-geomorphic unit type and fault development degree horizontally (Li et al. 2016c). Faulting and paleo-karst are the main factors controlling reservoir formation and distribution (Liu 2006). Faults play an important role in controlling the formation and distribution of karst reservoirs in the slope area, and the class II and class III-1 faults developed in multiple stages have obvious control over karst reservoirs (Li et al. 2016c).

In terms of karst development principle of Ordovician carbonate rocks distributed in Tahe oilfield, achievements and understandings include karst development law (Ekber 2006), karst reservoir development law (Xu et al. 2008; Qu 2006) and karst reservoir distribution law (Liu 2006; Jin 2001). Achievements and understanding of karst development model include karst development model and its controlling factors (Sun et al. 2018d, 2018e; Luo 2006; Zhou et al. 2009), reservoir space development characteristics and geological model (Chen et al. 2013), karst reservoir formation mechanism and development distribution model (Lyu and Zhao 2012), etc.

Through the research, it is recognized that karst development in Tahe oilfield has the characteristics of multiple karst zones (Qu et al. 2015; Chen et al. 2013), multiple cave layers (Jing et al. 2005), uneven development depth (Han et al. 2016b) at the vertical direction, differences from north to South (Yan et al. 2011) and differences from east to West (Ruan et al. 2011) at the plane direction. Different geomorphic units have different characteristics of karst development, and karst-plateau and karst-slope areas have high degree of karst development (Li et al. 2017c). The karst development depth is large and the concentration degree is high in the fracture parts above the scale (Wang et al. 2011; Wu et al. 2017; Sun et al. 2018d). There are mainly two types of reservoirs, i.e., karst reservoir controlled by weathering crust and fault solution reservoir controlled by corrosion strike slip fault zone (Lu et al. 2018).

The technologies and methods involved in the study of karst toward outcrop area of Tabei include 3D Digital Outcrop and geological modeling based on lidar technology (Zheng et al. 2014), geological information recognition and extraction according to field data and Google Earth image (Shi et al. 2016), physical simulation of karst caves detected by GPR (Wang et al. 2008), mathematical simulation of groundwater system (Xia and Guo 1992) and geological information extraction (Shi et al. 2016). 3D laser scanning (Jin 2019) is also an important enrichment and technology for karst research in outcrop area.

There are many theories, methods and techniques involved in the study of carbonate karst in Tahe oilfield, including theories, methods and techniques in the fields of karstification, geology (Yang et al. 2014), logging (Fei et al. 2012; Wang et al. 2017b), seismic (Wang et al. 2019a, 2017b; Fei et al. 2012; Li 2012; Sun et al. 2018f; Li et al. 2012) and reservoir engineering (Wang et al. 2007).

In the study of karst phenomena in Tahe oilfield, seismic and logging methods and techniques are mainly utilized, such as identification and prediction of paleo-karst caves (Yang 2019; Li and Wang 2003), identification of cave-collapse bodies (Kang et al. 2014), prediction of cave-filling degree, identification and analysis methods (Yu et al. 2017; Wang 2017; Yang et al. 2014), characterization of cave-filling materials (Su et al. 2015), identification of fracture cave bodies (Wang et al. 2017b, 2019b; Li et al. 2012; Fan 2005; Li 2005), identification of fracture cave and its filling materials (Fei et al. 2012), identification of fracture cave and its filling materials (Fei et al. 2012), multi-scale fracture cave classification (Lyu et al. 2017a), fracture cave unit division (Song and Liu 2011; Chen et al. 2007; Yang et al. 2015; Cao 2007; Zhang 2010), fracture cave effectiveness analysis (Wu 2004), reservoir prediction (Qin et al. 2018; Sun et al. 2018f; Wang 2011; Zhang 2019) and reservoir modeling methods and techniques (Sun et al. 2019c; Yan et al. 2013; Zhang et al. 2007b; Hu et al. 2013). In terms of main controlling factors and related impacts, fault detection technology (Bao et al. 2016; Liu et al. 2013b), fault solution description technology (Wang et al. 2019a), extensive description of karst residual mound (Zhang et al. 2017), karst paleo-geomorphology restoration technology (Kang and Wu 2003; Cao et al. 2015), paleo-geomorphology genetic combination identification method (Wang et al. 2003) and paleo-drainage identification method (Sun et al. 2019f, 2018e) are mainly used.

To sum up, the relevant researches of karst research in Tahe oilfield are summarized into three categories and twelve categories (Table 1). The three categories include regional and outcrop studies (A) with 35 papers, there are 97 researches on karst research in Tahe oilfield (B), related methods and techniques (B), and the number of researches is 37. On the basis of the statistics, the distribution characteristics of literature quantity are shown in Table 1 and Fig. 1. The characteristics suggest that Tahe oilfield karst research (B) has the largest number and is the main body of research.

As shown in Table 1, regional and outcrop studies (A) can be further divided into three categories: regional geological studies (A1), including the studies of Akekule uplift, Tarim Basin and the wider area, as well as karst studies of related areas and structural belts in Tarim Basin. Investigation toward outcrop area of Tabei oilfield (A2) and geology of Tahe oilfield (A3). Study of karst in Tahe oilfield (B) can be further divided into seven categories. Study of karst type

(B1), study of karst stage and cycle (B2), study of karst cave and cave (B3), study of fracture cave unit (B4), study of fault solution (B5), study of main controlling factors (B6) and study of law and model (B7). Related methods and technologies (C) can be further divided into two categories, including methods and technologies related to karst research in Tahe oilfield (C1), and methods and technologies related to outcrop areas such as Tabei oilfield (C2). Table 1 and Fig. 2 show the characteristics of the corresponding literature.

It should be pointed out that the study of karst caves in Tahe oilfield (B3) includes the study of karst caves and cave fillings, and the study of fracture cave unit (B4) includes the study of fracture cave fillings. According to the number of researches, the top three topics are fracture cave unit research (B4), main controlling factors research (B6) and related methods and technologies of karst research in Tahe oilfield (C1). It can be demonstrated that these three types of research are highly valued and the research workload is heavy. On the time axis, as shown in Fig. 3 and Table 1, the distribution of the number of relevant researches on karst research in Tahe oilfield since 2000 shows a strong periodicity, which can be divided into four stages: 2001–2005, 2006–2010, 2011–2015 and 2016–2020 (year). The start and end timing of each stage is consistent with the time arrangement of China's tenth five-year plan to 13th five-year plan. It should be noted that in 2020, just over half of the literature is still incomplete, and it is not used in data statistics, tabulation and mapping.

The number of researches in the first three stages (2001–2005, 2006–2010, 2011–2015) showed a step-by-step steady enhancement (Fig. 3a), and specific changes of the average number of researches in each stage were 4.6, 8.0 and 12.8 (articles/year). Compared with the first and second stage, the number of related researches at the fourth stage (2016–2020) is significantly increased, with an average of 9.75 (articles/year). However, compared with the third stage (2011–2015), an overall downward trend emerges. The causes behind this phenomenon are still unknown.

Prospects

Tahe oilfield has a large area, abundant oil and gas reserves, thick carbonate karst reservoir and deep burial depth. The prospect of oil and gas exploration and development in Tahe oilfield and its periphery, Tabei uplift, northern slope of Tazhong uplift and other areas is promising. There is an urgent demand for extensive carbonate karst research. The prospect of Ordovician Karst in Tahe oilfield is discussed based on the preliminary analysis of the characteristics of three categories and twelve categories.

As mentioned before, karst cave, fracture cave unit and fault solution body are the most important karst research

Table 1 The number of references statistics in Karstic studying in the Tahe oilfields

Year	A*			B							C		Numbers	
	A1**	A2	A3	B1	B2	B3	B4	B5	B6	B7	C1	C2		
1955	1												1	3
1992												1	1	
1999	1												1	
2001	2			1					1	1			5	23
2002	1			1			1		1				4	
2003						2					4		6	
2004							2				1		3	
2005					1	1	1				2		5	
2006	1		1		1		1			4			8	40
2007				1			4			1	4		10	
2008	2					2	2					1	7	
2009			1		2		2		2	1			8	
2010		3	1		1		1		1				7	
2011	2	1	2	1	1		2		1		3		13	64
2012	4		1	2			1		1		3		12	
2013	1	3	1		1		5			1	3		15	
2014		2			1	2	4		2			1	12	
2015			1	2	1	1	5		1		2		12	
2016					2		1		7		2	1	13	39
2017	1					1	2	1	3		2		10	
2018	1					1	1	2			3		8	
2019	1			1			1		1		3	1	8	
2020***			2											
	18	9	8	9	11	10	36	3	21	7	32	5		
	35			97							37			

Fig. 1 A major categories statistical analysis histogram of the number of references

- A1-Regional geology; A2-Tabei area outcrop;
 A3-Geology in Tahe oilfield;
 B1-Karstic types; B2-Cycle and phases of karst;
 B3-Karst cave; B4-Fracture and cave units;
 B5-Fault controlling dissolution;
 B6-Main control factor for karst reservoirs;
 B7-Developmental laws and patterns;
 C1-Methods and techniques for Karst research;
 C2-Methods and techniques for Tabei area outcrop.

Fig. 2 A classify statistical analysis histogram of the number of references

objects in Tahe oilfield, and fault solution body is the research hotspot, which needs to be further studied. The focus of research is supposed to be put on the scale of fault solution (reservoir controlled by fault). The larger the scale, the larger the oil and gas reserves and the higher the

commercial value. If the scale is too small, it fails the commercial value for oil and gas development.

Because of the different environmental conditions, the main types of karst phenomena in different areas will change. For example, taking the denudation (pinch out) line of the upper Ordovician Sangtamu formation in Tahe oilfield as the boundary, the north side is mainly epi-karst (weathering crust karst), and the south side is mainly fault-controlled karst. The research objects or focuses of karst in the North and South direction are different. However, fault is usually one of the main knowable factors of epi-karst, sometimes even the most important. Under the condition of being covered by non-soluble rock series, significant karstification can also occur in the soluble rock series. A large number of field investigation results of karst phenomena show that there is a close genetic relationship among faults, fractures and karst caves (caves), which is summarized as follows: (a) the control of fractures by faults, the high density, large scale and strong karstification of fractures near the fault zone, which has been well known by people; (b) the fault zone controls the large-scale karst caves, such as Yinshui cave in Xianning, Hubei, wanhuayan cave in Chenzhou, Hunan, Qiliang cave in Fenghuang, Hunan, etc; (c) under the macro-control of faults, fracture-control large karst caves, such as Longwang cave in Cili, Hunan Province. Faults can also control the formation and distribution of large karst caves by controlling fold structures, such as the Haitang Cave in you County, Hunan Province, which is formed on the background of anticline controlled by xincaopo fault. The length, width and height of the tunnel are more than 60 m, 50 m and 50 m, respectively, and the volume of the tunnel is more than 150,000 m³. Accordingly, karst phenomena such as fracture dissolution, fracture dissolution, caves, deposition and precipitation in the process of dissolution are organic

Fig. 3 Map the distribution of the number of references changed over time

matters, and the surface and underground karst phenomena are a unified system. To solve this problem is helpful to understand the key problems in the determination of karst and the development of karst in Tahe oilfield.

There are many types of karstification in Tahe oilfield, and the prospect of exploration and development is broad. As far as the atmospheric freshwater karst of carbonate rocks is concerned, its essence is the dissolution of carbonate rocks by atmospheric freshwater (including the precipitation phenomenon in the process of dissolution). Its main controlling factors include climate, structure (such as fold, fault, fracture, etc.), topography and water system. Due to the different geological conditions, the main controlling factors act different roles. However, the study of karst development law needs to reveal the comprehensive control of multiple controlling factors on karst development and distribution. It is not enough to summarize the control of a certain factor (or a few factors) on karst.

Law is the scientific representation of the inevitable trend of the development and change of things. Karstification is a process of dynamic change. Many factors not only impose a comprehensive control on karstification, but also restrict each other and change constantly with the progress of karstification, and form a dynamic system with close genetic relationship with the development and change of karst phenomena. For Ordovician Karst in Tahe oilfield, whether fault-controlled karst or epi-karst, the control-effect of fault is critical. A large number of field investigations of karst phenomena show that the areas where faults play an important role in controlling karst show that: (1) faults have obvious control over topography and geomorphology; (2) faults, topography and geomorphology have obvious control over water system; (3) faults, topography, geomorphology and water system have obvious control over karst phenomena.

After more than 20 years of research, Tahe oilfield karst research has achieved fruitful results, but also found many problems. Some of these problems need to be solved by

further work, while others need to resort to new theories, new methods, new technologies and field work. In the analysis of the characteristics of the progress in the field of technology and methods related to karst research in Tahe oilfield, it has been mentioned that the research of carbonate karst in the overburden area is mainly based on seismic and logging technology and methods, which is more detailed, more accurate and theoretical to reveal the law. Other techniques and methods related to karst research are no exception, such as bottom penetrating radar and three-dimensional laser scanning technology used in outcrop karst research, which have achieved good results as well. At present, 3D laser scanning technology is widely used in tunnel construction and construction engineering, but rarely used in karst cave research. High-price feature of 3D laser scanner and the high repair-cost after damage limit its application in karst research. However, 3D laser scanning can obtain all-round and continuous measurement in the cave, so as to obtain accurate measurement results of (large) cave morphological characteristics. This result can well reveal the control principle of fractures on the development and distribution of large caves, which is worthy of further application and investigation.

Due to the particularity of geological phenomena, the field is a natural laboratory for geological research. In view of the existing problems or doubts in the research, strengthening the field research of karst phenomenon is definitely one of the important directions of karst research in Tahe oilfield. There are at least two factors to be considered in the selection of field-karst phenomenon research sites, one is the similarity with the research object, the other is the adaptability to the research objective. The higher the similarity with the research object, the stronger the analogy. The stronger adaptability to the research purpose, the more helpful to solve the problems emerged in the karst research of Tahe oilfield. Practice has proved that xikele, Yijianfang, Sanjianfang and Liuhuanguo are fairly suitable outcrops

for karst research in Tahe oilfield. Of course, new outcrop areas can also be selected, such as Wushi County in Aksu area, Xinjiang, where the geological characteristics are very similar to Tahe oilfield (badahantag and karaujirk). The Cambrian Ordovician system in the both places is exposed in a large area, partly covered with Silurian system and surrounded by Carboniferous system and quaternary system. However, these two places are deep into the hinterland of high mountain area, so the traffic and working conditions are extremely difficult. We can further consider the outcrop areas with large area, rich types of karst phenomena and many faults controlling karst phenomena, such as the carbonate karst outcrop area in Lishui basin of Hunan Province. Such outcrop areas have strong adaptability to the purpose of karst research in Tahe oilfield.

Summary and conclusions

1. Tahe oilfield was discovered in 1998, and the literature reflecting the achievements and knowledge of karst research in Tahe oilfield mainly appeared after 2000. Its research contents can be summarized into three categories and twelve categories. Three categories include regional and outcrop research, Tahe oilfield karst research, and related methods and technologies. Among them, regional and outcrop research can be further divided into three categories, namely, regional geological research, Tabei outcrop area research and Tahe oilfield geological research. The karst research in Tahe oilfield can be further divided into seven categories, namely, karst type research, karst stage and cycle research, karst cave and cave research, fracture cave unit research, fault solution research, main control factor research, law and model research.
2. Karst cave (cave), fracture cave unit and fault solution are three important karst research objects in Tahe oilfield. In terms of the number of researches, most of them are related to the study of fracture cave unit, the application of methods and techniques and the main controlling factors of karst development, ranking the first, second and third, respectively. Since 2000, the karst research in Tahe oilfield can be divided into four stages, and the time of each stage is consistent with that of the 10th five-year plan to 13th five-year plan. Fault solution is the focus of karst research in Tahe oilfield. The focus of this research is the scale of fault-controlled karst reservoir.
3. Faults have obvious control over fractures, faults have obvious control over karst caves, and fractures under macro-control of faults have obvious control over karst caves. Karst phenomena such as fault dissolution, fracture dissolution and karst caves are closely related to each other, and surface and underground karst phenomena are closely related to each other. It is an important direction of karst research in Tahe oilfield to extensively study the organic relationship between faults, fractures and karst caves and the genetic relationship between surface and underground karst phenomena.
4. For the karst development area where faults play an important role in controlling, other than the influence of lithological factors, faults have obvious control over topography and geomorphology, faults, topography and geomorphology have obvious control over water system, and faults, topography, geomorphology and water system have obvious control over karst phenomena. This hierarchical control relationship is the fundamental connotation of karst development law, it is also an important target for the study of karst development law in Tahe oilfield.
5. The field is the natural laboratory of geology, and the field investigation of karst phenomena serving for the karst research in Tahe oilfield will be further strengthened. In the field investigation site selection of karst phenomenon, we will consider the similarity with Ordovician carbonate karst in Tahe oilfield and the adaptability with the karst research content in Tahe oilfield.
6. The application of methods and technologies have fundamental role in promoting the karst research in Tahe oilfield. Strengthening the application of methods and technologies is still a crucial task in the karst research in Tahe oilfield. As far as karst research in outcrop area is concerned, GPR technology and three position laser scanning technology can deeply solve the problems related to karst research. Through 3D laser scanning in the cave, long-distance and continuous measurement results can be obtained.

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Declarations

Conflict of interest The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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