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Research paper

New insights into the carbonate karstic fault system and reservoir formation in the Southern Tahe area of the Tarim Basin

Xinbian Lu [a], Yan Wang [b], Fei Tian [c,*], Xinhua Li [b], Debin Yang [b], Tao Li [a], Yanping Lv [b], Xinming He [b]

[a] Northwest Oilfield Company, SINOPEC, Urumuqi, Xinjiang, 830011, China
[b] Petroleum Exploration & Production Research Institute of Northwest Oilfield Company, SINOPEC, Urumuqi, Xinjiang, 830011, China
[c] Key Laboratory of Petroleum Resources Research, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, 100029, China

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A B S T R A C T

As worldwide hydrocarbon exploration has extended from shallowly to deeply buried strata, reservoir quality has attracted substantial and persistent interest in petroleum geology. In particular, deeply buried strata (>5500 m) in the Tarim Basin have attracted considerable attention because carbonate reservoirs that have experienced fracture or dissolution have also been shown to demonstrate considerable hydrocarbon potential. Therefore, it is necessary to determine how these reservoirs are developed and distributed in detail from both scientific and practical standpoints.

In this paper, we address this issue using a case study in the southern Tahe area, which is contained within the largest Palaeozoic marine oilfield in China. In the northern Tahe area, mega-paleokarst systems developed in the Ordovician strata; however, the reservoir quality in the southern part of the Tahe area is relatively poor because it is covered by insoluble formations during karstification. Observations of cores and analyses of images of well logging demonstrate that these reservoirs are dominated by caves, vugs and fractures that have developed near faults. We speculate that the faults penetrating insoluble formations represent the main dissolution passages that originally developed these karstic fault systems. Additionally, we analyse a series of outcrops, seismic data, and structures to characterize the spatial geometry of these major faults and their surrounding fractures in detail. Most of these are strike-slip faults, and their subsequent reservoirs can be divided into three categories based on their development, including dendritic, sandwich and slab reservoirs. Recent studies demonstrate that karstic fault reservoirs are most common traps in the study area. Although various types of carbonate karstic fault reservoirs are represented in this region, the dendritic karstic fault reservoir is the most hydrocarbon-rich.

Guided by these initial results, 108 wells were drilled from 2013 to 2014, producing 485 thousand tons of oil and yielding success ratios greater than 89%. The average production of dendritic reservoirs is 37.4 tons per day (t/d), while those of sandwich and slab types are 20.2 t/d and 14.0 t/d, respectively. These results represent significant references for future hydrocarbon exploration and the development of similar deeply buried karstic fault reservoirs in the Tarim Basin and elsewhere.

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1. Introduction

In recent years, hydrocarbon exploration practices around the world have demonstrated that the deep layers of basins (those at depths greater than 4500 m) likely contain abundant oil and gas resources (Dyman et al., 2002; Sun et al., 2013; Zhu et al., 2015; Jia and Pang, 2015). More than 860 deep-layered oil and gas fields have been discovered globally and contain a total of 115.5 × 10^8 tons of proven oil reserves and 76 × 10^8 tons of gas (HIS, 2014). For instance, Well Jack 2 successfully extracted more than 950 m^3 of oil per day (t/d) from a depth of more than 8500 m (28,125 feet) from the Gulf of Mexico (https://en.wikipedia.org/wiki/Jack_2). Additionally, in the Anadarko Basin, the depth of petroleum development ranges from 7663 m to 8083 m, and single wells produce up to 6 × 10^4 cubic metres of oil per day (m^3/d) (Berman and

* Corresponding author.
E-mail address: upc_tianfei@126.com (F. Tian).

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Rosenfeld, 2010). China has also initiated many oil and gas explorations at depths greater than 4500 m; for example, Well NiuDong 1 was drilled in the buried hill of the Bohai Bay Basin at a well depth of 6072 m, producing 643 m^3/d of oil and 5.6×10^4 m^3/d of gas (Zhao et al., 2015). The buried depth of the Yuanba gas field in the Sichuan Basin ranges from 6240 m to 6950 m and contains 159.2 billion cubic metres of proven reserves (Zhang et al., 2016a). Deep-layered formations, especially carbonate strata, represent the major targets of exploration in the Tarim Basin where several huge oilfields (containing reserves of more than 1×10^8 tons of oil) have been found, including Tahe, Halahatang, YingMaiLi, and Tazhong Oilfields (Li et al., 2016; Zhu et al., 2016; Xiao et al., 2016; Zhang et al., 2010). Besides, Tahe Oilfield is the largest known marine carbonate oil and gas field in China. The main formation of this oilfield is Ordovician in age, buried at a depth of more than 5500 m (Tian et al., 2016, 2017).

In the northern region (or "main area") of the Tahe Oilfield (Fig. 1), the main reservoirs are paleokarst reservoirs in the Lower- to Middle-Ordovician Yijianfang and Yingshan Formations. These strata contain soluble limestone that was exposed to the atmosphere while undergoing multiple stages of karstification in the Early Hercynian period (e.g., buried-hill paleokarst, Ruan et al., 2013). These lithologies suggest that paleo-geomorphology is the key factor controlling the development of paleokarst reservoirs. In contrast, the southern region of Tahe Oilfield falls within the peripheral slope area (Figs. 1d and 2), and its Lower- to Middle-Ordovician strata are covered by nearly insoluble Upper Ordovician strata, including carbonate mudstones (Li et al., 2016). Exploration has indicated that the paleokarst reservoirs in the Lower- to Middle-Ordovician strata are relatively weak and that their distribution is primarily controlled by large-scale strike-slip faults. In the southern region of the Tahe Oilfield, this type of reservoir is called a karst-fault paleokarst reservoir (Lu et al., 2015).

Fault zones and systems are considered to play a key role in the architecture of basin sedimentary deposits by controlling their mechanics and fluid flow properties (Shipton and Cowie, 2003; Walsh et al., 2003; Faulkner et al., 2010). Many studies have used strike-slip fault zone architecture to evaluate faults and their influence on fluid flow. Brittle faults contain two structural domains: a central core and its enveloping damage zones, which can be distinguished from the surrounding wall rock (Tondi et al., 2012; Walker et al., 2013; Choi et al., 2016; Peacock et al., 2016). Using outcrop observations and experimental simulations, Kim et al. (2003, 2004), Mitchell and Faulkner (2009), and Choi et al. (2016) analysed the structural characteristics of strike-slip fault damage zones and divided them into three types: tip damage, linking damage and distributed damage. The area affected by a single strike-slip fault can thus be divided into the fault end, the fault wall and the fault connections area. Yielding et al. (1997, 2010), Hasegawa et al. (2005), Kachi et al. (2005), Freeman et al. (2008) further evaluated the probability of fault connectivity within the fault seal of clastic reservoirs by analysing ground stress and the forms, displacement, and rock properties of faults. Multiple studies have also been performed in the Tarim Basin to study the development and characteristics of its fault system and to analyse its fault traps. For example, Lin et al. (2015) identified 20 main basement faults and 18 secondary basement faults in the Tarim Basin and analysed their influence on sedimentary processes. Li et al. (2013), Lan et al. (2015) and Wu et al. (2016) used three-dimensional (3D) seismic data to analyse the effects of thrust faults and strike-slip faults on carbonate platform construction, degrees of development of karstification, and distributions of paleokarst reservoirs in the Central Uplift belt of the Tarim basin at tens of kilometres scale. However, to date, little work has been undertaken to better constrain the distributions, classifications, effectiveness and production characteristics of deep-buried carbonate strata at reservoir scale, and even less work has focused on studying the multistage karsted fractured-cavity reservoirs that are controlled by large-scale strike-slip faults and their derived structures.

The goal of this study is to analyse the structural characteristics of paleokarst fractured-cavity reservoirs in deep buried carbonate strata within the south region of Tahe Oilfield by using outcrop-scale investigations, abundant core samples, and imaging logging data. By analysing well logging data and a high-quality 3D seismic dataset, three different types of fault-controlled paleokarst reservoirs within this region can be identified. And then the classification is then applied over a 750 km^2 region of the Tuofutai area. The concepts of carbonate karstic fault system reservoirs and traps are also discussed in detail to guide future hydrocarbon exploration in deeply buried carbonate paleokarst reservoirs within the south Tahe Oilfield. These results are significant for future the exploration of similar reservoirs in the Tarim Basin.

2. Geological setting

The Tahe Oilfield is 2400 km^2 in size and is located on the southwestern slope of the south-central Akekule Arch (Fig. 1a and b; Yu et al., 2011). The Akekule Arch is located within the North Uplift (Shaya Uplift) of the Tarim Basin, which is east of the Hanikatam Sag, south of the Yakela Faulted Arch, west of the Caohu Sag, and north of the Shuntuoguole Lower Uplift and the Manjiaer Depression (Fig. 1b). The Akekule Arch has undergone multiple stages of tectonic movements, including the Caledonian, Hercynian, Indo-Yanshanian, and Himalayan movements, before becoming a large, nose-like arch in which Palaeozoic strata were tilted to the south during the Himalayan period (Fig. 1c) (Zhang and Yan, 2004; Yang et al., 2010; Chen et al., 2012; Li et al., 2010a; Zhu et al., 2012).

Within this oilfield, hydrocarbon reservoirs have been identified in Triassic, Carboniferous, Devonian, and Ordovician strata, and oil production from Ordovician paleokarst reservoirs accounts for approximately 73% of total oil production (Dou, 2014). From bottom to top, these Ordovician strata are divided into the Penglaiba Formation (O_1p, which is predominantly dolomite), Yingshan Formation ($O_{1-2}ys$, limestone), Yijianfang Formation (O_2yj, predominantly nodular limestone), Querbake Formation (O_3q, knotty limestone containing mud), Lianglitage Formation (O_3l, argillaceous limestone and grainstone) and Sangtamu Formation (O_3s, mudstone and marlite interbedded with siltstone and limestone) (Chen et al., 2012). The Akekule Arch also underwent a series of erosional episodes during the Caledonian and Hercynian movements. The remaining Ordovician formations are uneven, and their contact relationships are complex (Fig. 1d; Fig. 2). The strata in the northern Tahe Oilfield have been denuded; in this region, the Carboniferous Bachu Formation unconformably overlies the Yingshan Formation. A well-preserved, southward-dipping sequence of Ordovician and Silurian strata outcrops in the south (Fig. 2).

Large-scale, deep-seated faults and associated folds in the North Tarim Uplift form a large karst slope, which underwent a series of long-term, superimposed karstification events from the Caledonian to the Hercynian (Li et al., 2013). These events established the morphological diversity of the karst cave systems, producing large-scale karst geomorphology and underground ancient caves, all of which represent the types of karst landforms observed in present-day Guilin (Zeng et al., 2011a; Tian et al., 2016).

Here, it is believed that hydrocarbons were first generated from the Manjiaer depression before migrating through a series of deep-seated faults and accumulating within large karstic fault systems, which form the current deeply fractured-vuggy reservoirs in the north region of the Tarim Basin. Recent exploration and exploitation practices demonstrate that the highest-yield wells are located

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