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ORIGINAL PAPER

Accumulation model based on factors controlling Ordovician hydrocarbons generation, migration, and enrichment in the Tazhong area, Tarim Basin, NW China

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Abstract The hydrocarbon accumulation model of Ordovician reservoirs in the Tazhong area, Tarim Basin, was investigated based on the analysis of the key factors controlling hydrocarbon generation, migration, and enrichment process and history. The results show that the hydrocarbon generation processes are controlled by Cambrian–Lower Ordovician and Upper Ordovician source rocks distributed in the Tazhong area and the Manjiaer Sag. Vertical hydrocarbon migration distance is controlled by the vertical source-reservoir distribution, faults, and caprocks. Structure played a major role in the lateral hydrocarbon migration along NW-SE direction. Lateral migration pathways were governed by unconformities, transport faults, and reef-beach body reservoirs. A part from the sedimentary control, hydrocarbon enrichment is controlled by recent tectonic events. The hydrocarbon charging points refer to the intersection of northeast- and northwest-trending faults. Two types of hydrocarbon accumulation models could be retained, (a) mixed-sourced area model, in which the hydrocarbons are sourced from both the Tazhong area and the Majiaer Sag, and (b) single-sourced area model, in which the hydrocarbons are only sourced from the Tazhong area itself.

Keywords Hydrocarbon generation · Migration · Enrichment · Accumulation model · Ordovician carbonate reservoirs · Tarim Basin · China

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Introduction

Marine carbonate hydrocarbon reservoir exploration has been an increasingly important subject in China since the 1990s (Jin et al. 1998; Luo et al. 2008). The marine carbonate rocks of the Tarim Basin, western China, cover over an area of approximately 30×10^4 km^2 and contain abundant oil and gas resources that have been poorly explored (Jin et al. 1998; Qiu and Wang 2005). The deep Ordovician carbonate hydrocarbon reservoirs in the Tazhong area, located in the middle of the basin, have been the subject of many investigations because of the complex hydrocarbon accumulation characteristics (Lv et al. 1999; Wu et al. 2009; Yang et al. 2011; Wu et al. 2012). In the last 20 years of exploration and development, the Upper Ordovician Lianglitage Formation reef-type reservoirs (represented by the Tazhong I condensate field) and the Lower Ordovician Yingshan Formation weathering crust reservoirs (represented by the Zhonggu 43 well area) have been identified as significant reservoir discoveries (Yang et al. 2011). At present, the discovered proved and probable initial oil in place is over 5×10^8 tons and proved and probable initial gas in place is over $10,000 \times 10^8$ m^3 in the Ordovician of the Tazhong area, which has proved to be one of the richest oil and gas areas of the Tarim Basin. However, because of the strong heterogeneity of Ordovician carbonate reservoirs, theories for the mechanisms of hydrocarbon accumulation and distribution of these reservoirs have caused some controversies (Zhai et al. 1999; Lv et al. 2004; Yang et al. 2007; Yang et al. 2007b). The current lack of systematic research on factors controlling hydrocarbon accumulation and of a detailed hydrocarbon accumulation model are the main restrictions on fast and effective oil and gas exploration (Liang et al. 2000; Zhao et al. 2001; Zhao et al. 2002; Cai et al. 2007; Li et al. 2008a). In this paper, we present a comprehensive analysis of the factors controlling hydrocarbon generation, migration, and enrichment, try to establish hydrocarbon accumulation models, and attempt to predict favorable hydrocarbon accumulation zones in the Ordovician carbonate rocks of the Tazhong area.

Geological setting history of the Tazhong

The Tazhong area lies in the center of the Tarim Basin, south of the Manjiaer Sag, and covered an area of approximately 22, 000 km^2. It is an inherited paleo-uplift with extensive fault systems. The NW trending overthrust fault system mainly consists of Tazhong No. 1 fault, Tazhong No. 10 fault, and Tazhong No. 40 fault. The NE trending strike-slip fault system mainly consists of Tazhong 49 fault and ZG 43 fault. The complex fault systems divided the area into five structural units: the No. 1 Fault Zone, the North Slope, the Central Faulted Horst Belt, the South Slope, and the East Burial Hill (Fig. 1).

The Ordovician strata in the Tazhong area correspond to a large carbonate platform, including the Lower Ordovician Penglaiba Formation, the Lower Ordovician Yingshan Formation, the Upper Ordovician Lianglitage Formation, and the Upper Ordovician Sangtamu Formation (Fig. 2). In the Tazhong area, three reservoir–caprock assemblages can be distinguished, (Fig. 2): (1) the Upper Ordovician Lianglitage Formation reef reservoir, the Upper Ordovician Sangtamu Formation mudstone caprock (e.g., the Tazhong 24–26 condensate field), (2) the Lower Ordovician Yingshan Formation weathered crust reservoir with the Upper Ordovician muddy limestone as the caprock (e.g., the Zhonggu 43 condensate gas reservoir), and (3) the Lower Ordovician Penglaiba Formation dolomite acting as both reservoir and caprock (e.g., the Tazhong-162 condensate gas reservoir). The carbonate reservoir of the Lianglitage Formation is mainly composed of reefal bioclastic limestone displaying dissolution and leaching processes, forming extensive secondary porosity which greatly improved the reservoir properties (Chen et al. 2007). The weathering crust reservoir of the Yingshan Formation has an erosional unconformity contact with the Upper Ordovician and is mainly composed of sand-gravel limestone with low primary porosity and permeability. The reservoir pore space was developed with response to secondary dissolution processes, greatly enhanced by the presence of faults and fractures (Sun et al. 2012). The Penglaiba Formation is mainly a dolomite reservoir, which is considered as a potential target for future oil and gas exploration activities in the Tazhong area (Zheng et al. 2013).

The tectonic evolution of the Tazhong area includes five discernible stages: stable platform development in early Caledonian time, isolated table-land development during the middle–late Caledonian (Middle Ordovician–Silurian), uplift in the early Hercynian, development of underwater uplift in late Hercynian time (Carboniferous–Permian; Jia 1999), and the Indosinian–Himalayan orogeny, when there were overall fluctuations in the uplift (Lv et al. 2004). Multiple source rocks, several stages of tectonic movement, adjustment, and alteration have led to multiple stages of hydrocarbon generation, expulsion, charging, and accumulation. The hydrocarbon generation/expulsion history showed that the major periods of hydrocarbon accumulation occurred at the late Caledonian–early Hercynian, Hercynian, and Himalayan. The largest amounts of oil and gas were accumulated within the investigated area during the Hercynian event (Zhao et al. 2001; Zhou et al. 2006; Zhang et al. 2011a).

The overall distribution of oil and gas fields in the Tazhong area is the result of complex geological evolution, which featured by laterally "E–W blocking, N–S zoning, oil in the west, and gas in the east" (Han et al. 2008), and characterized by the superimposition of the multi-layer and multi-type reservoirs in vertical, with Upper Ordovician Lianglitage reef reservoirs and Lower Ordovician Yingshan weathering crust reservoirs (Wang et al. 2011). The principle Ordovician reservoirs in the Tazhong area mainly contain gas condensate. The oil is mainly light condensate with a density of 0.76–0.84 g/cm^3, a viscosity of 0.75–8.21 mPas, a sulfur content of 0–0.67 %, and a wax content of 0.76–14.32 %. The gas/oil ratio of the reservoirs range from 0 to 62,393 m^3/m^3 and the dry coefficient is generally greater than 0.92. Gases such as H_2S are also present with variable proportions varying from 10 up to 23,000 ppm. The ranges presented here show that the geochemical characteristics of the oil and gas in the Ordovician are complex and varied.

Samples and workflow

For purposes of this study, all the testing and production data, well logging data, seismic cross-sections were kindly furnished by collected from the Tarim Oilfield Company, PetroChina. The Silurian and Ordovician oil samples were separated into hydrocarbon, water contents, and solid impurities and then stored at low temperatures for further laboratory analyses. Gas chromatography-mass spectrometry (GC-MS), the main method in the analysis of compounds of oil samples, used a silica chromatographic column to separate the crude oil into fractions in the laboratory. Hexane and benzene were used to extract the saturated and aromatic hydrocarbons,

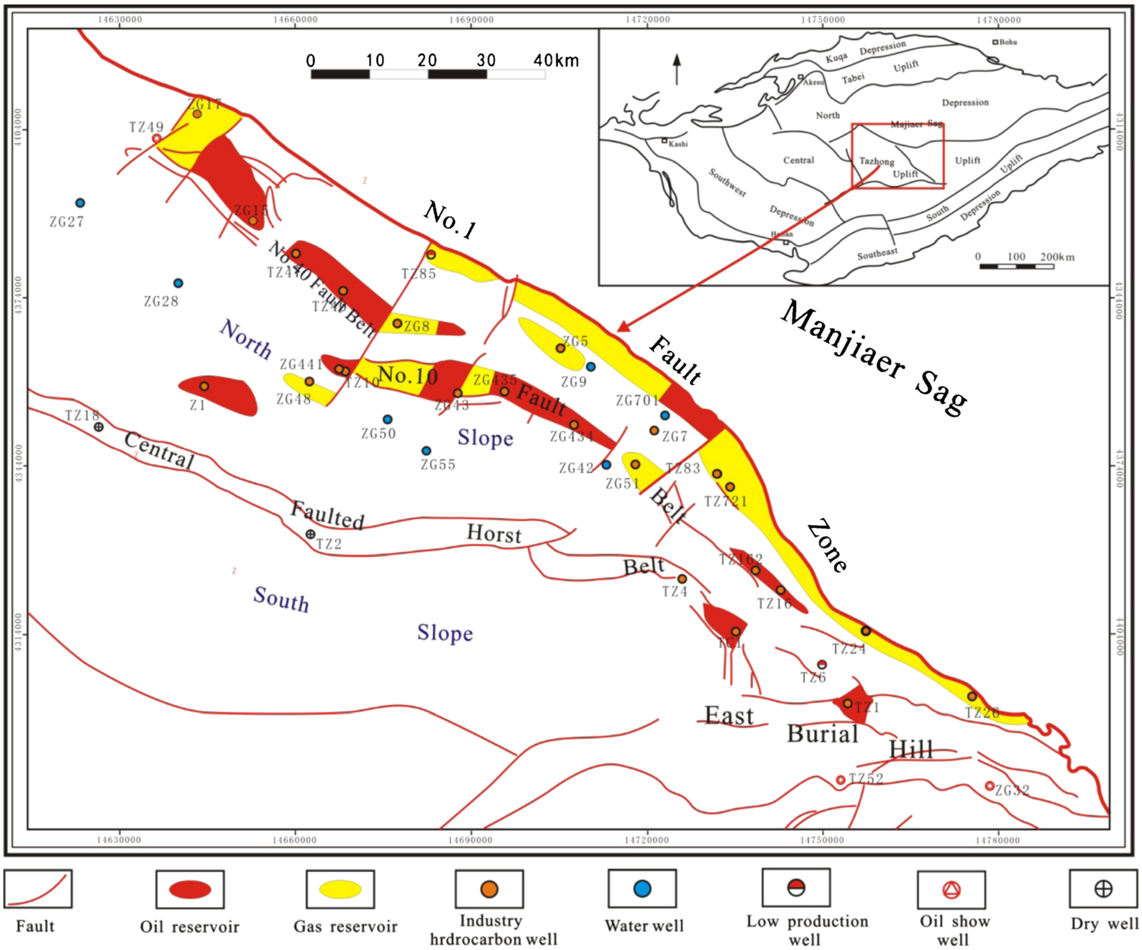


Fig. 1 Geological structures and hydrocarbon reservoirs in Ordovician rocks of the Tazhong area

respectively (Pang et al. 2013). Ether was used to extract the non-hydrocarbon compounds. To reduce the loss of testing compounds, we used a vacuum rotary evaporation solvent to individually concentrate different hydrocarbons and preserved them in low temperature (Li et al. 2008). Then, we analyzed the content of saturated, aromatic hydrocarbons and non-hydrocarbon compounds with an SSQ710 Model GC-MS. Hydrocarbons were analyzed using a DB-5 quartz capillary column (30 m × 0.53 mm). For routine GC analysis, a constant temperature of 100 °C was set for 1 min and then heated to 200 °C at a rate of 4 °C/min, followed by programmed heating from 200 to 300 °C at 4 °C/min with initial and final hold times of 1 and 30 min, respectively. Helium was used as the carrier gas at a linear velocity of 32 cm/s, with the injector operating at a constant flow of 0.9 mL/min. The MS was operated at a source temperature of 230 °C with anionisation energy of 70 eV.

The workflow of hydrocarbon accumulation model investigation used in this article includes analyzing the hydrocarbon generation history based on the previous research; reconstructing the migration direction and paths using the geological and mathematical statistics methods; determining key factor controlling hydrocarbon enrichment sites by analysis of high-quality reservoirs distribution, summarizing the process and mechanisms of hydrocarbon accumulation by integrating the hydrocarbon properties and geochemical characteristics with well production, and, finally, predicting hydrocarbon distribution in undrilled intervals.

Factors controlling hydrocarbon generation

Characteristics of source rocks

The oil and gas sources in the Tarim Basin have been the subject of numerous studies (Grahama et al. 1990; Zhang et al. 2000; Sun et al. 2003; Wang and Xiao, 2004; Li et al. 2010a; Li et al. 2010b). It has been widely accepted that the hydrocarbons in the carbonate rocks, Tarim Basin, were mainly sourced from two sets of source rocks developed in the Middle-Upper Ordovician and Cambrian-Lower Ordovician successions. However, the principal source rock has been a matter of contention. The Cambrian–Lower Ordovician source rock and the related

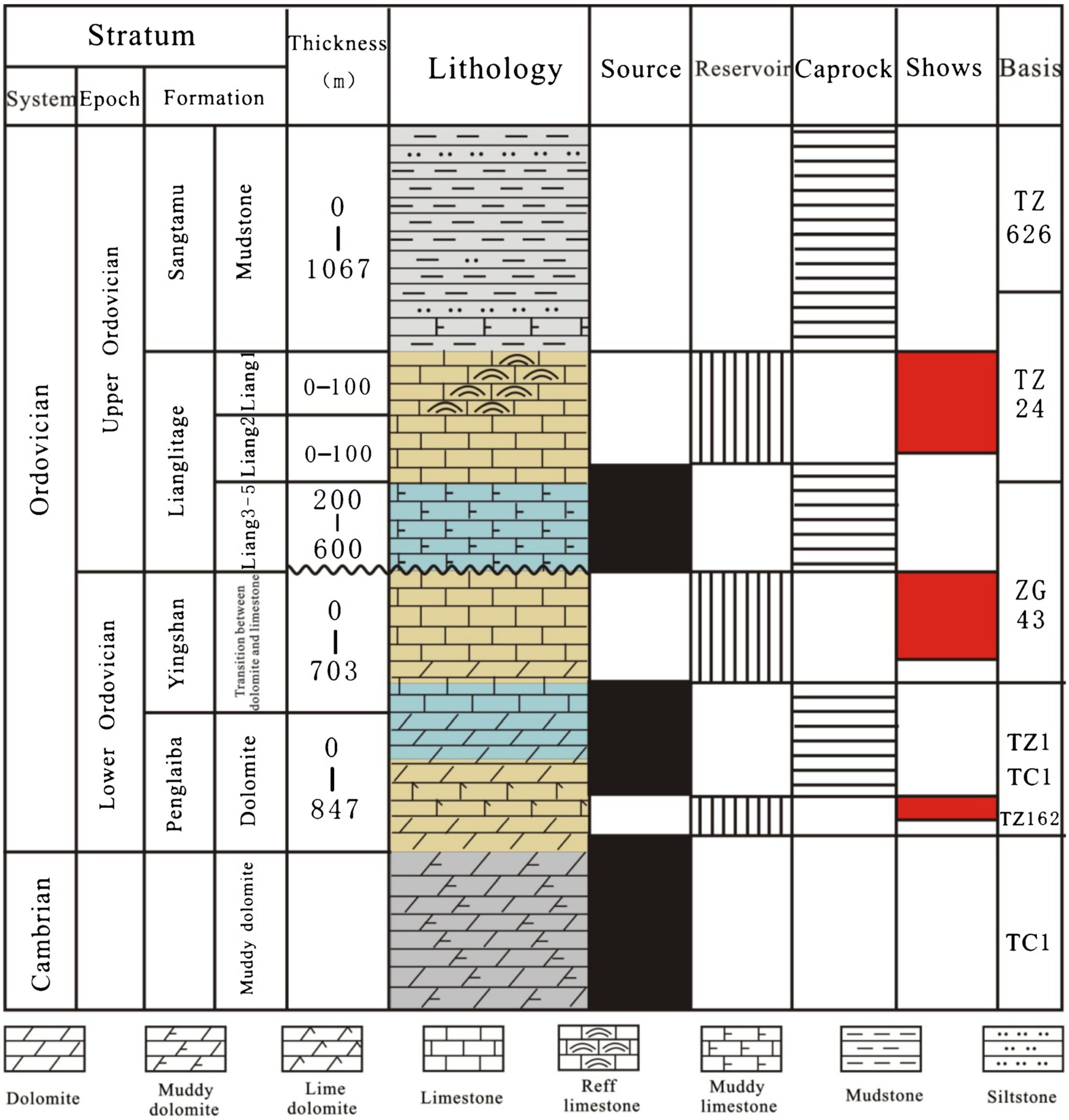


Fig. 2 Synthetic stratigraphic chart, showing Ordovician source rocks, reservoirs, and cap rocks in the Tazhong area

crude oil have higher levels of dinosteranes, triaromaticdi nosteranes, 4-methyl-24-ethyl cholestane, 24-norcho lestane, and gammacerane, together with low levels of diasteranes and regular steranes with a slanted-line or reverse-L distribution (C27 < C28 < C29). In contrast, the Middle-Upper Ordovician source rock and its related crude oil generally show the presence of regular steranes have a V-shaped distribution (C27 > C28 < C29). A higher abundance of phenylisoprenoids is considered to be related to Cambrian source rocks (Sun et al. 2003).

There are two source areas in the Tazhong petroleum system. One is the Tazhong area itself, the other is the Majiaer Sag, and both of which have the two sets of source rocks (Huang 1994; Xiao 1994; Hao et al. 1996; Xiao and Liu 1998; Li 1998; Zhang et al. 2000; Han et al. 2011). The Middle-Upper Ordovician source rocks in the Tazhong area are featured with a content of total organic carbon (TOC) ranging from 0.47 to 1.18 % and a hydrogen index (HI) ranging from 41 to 162 mg/g (Xiao et al. 2000). According to measured reflectance values of bitumen and marine vitrinite, the source rocks are still in the peak to late stages of oil generation, with an equivalent VRo (vitrinite reflectance) of 0.95–1.20 % (Xiao and Liu 1998). This set of source rocks is widely distributed over the whole North Slope with a cumulative thickness of 80–120 m (Huang 1994; Liang 1999; Liang et al. 1998; Xiao and Liu 1998). While the Cambrian-Lower Ordovician source rocks in the Tazhong area contain a suite of black shale with TOC of 0.74–2.31 %. In the Manjiaer Sag, the two sets of source rocks had also been proved (Chen et al. 2000; Hanson et al. 2000; Zhang et al. 2000; Li et al. 2008; Cai et al. 2009; Pan et al. 2009). The Cambrian-Lower Ordovician source rocks show typical characteristics of depositing in an oxygen deficit sedimentary environment, with the lithology composed mainly of black phosphatic silica, phosphorite, and black shale. The thickness of the source rocks ranges from 300 to 450 m, the TOC, from 0.52–5.03 % (Xiao et al. 2000), and the hydrocarbon index, from 2.10 to 250.37 mg/g. While Middle-Upper Ordovician source rocks consist of dark limestones and argillaceous limestones with thickness of 100–200 m, TOC of 1.20–2.56 %, and the hydrocarbon index of 6.10 to 531.06 mg/g. Because of the great buried depth of Cambrian-Ordovician strata in the sag, these source rocks are all in the overmature stage, with Ro values ranging between 0.5 and 1.2 % (the VRo value was transformed from solid bitumen reflectance) (Hanson et al. 2000; Zhang et al. 2000).

Mechanism of hydrocarbon generation

Investigations of compound specific isotopes, fluid inclusions, and age-indicating biomarkers suggested that hydrocarbons reservoired in the Ordovician of the Tazhong area were generated from mixed source units over multiple phases (Li et al. 2010a; Li et al. 2010b; Yang et al. 2011). Laterally, hydrocarbons from the northern Manjiaer Sag are mixed with the hydrocarbons from the Tazhong area itself. With hydrocarbon supply intensity decreasing, little or no hydrocarbon generated from the Manjiaer Sag can accumulate in the west area of the North Slope, where the hydrocarbon mainly sourced from the Tazhong area itself (Li 1998; Zhang et al. 2000; Lv et al. 2004; Han et al. 2011). Vertically, hydrocarbons from the Middle-Upper Ordovician source rocks are mixed with the hydrocarbon from Cambrian–Lower Ordovician source rocks. With increasing depth, the relative content of hydrocarbons from the Cambrian–Lower Ordovician sources increases proportionally (an average of 56 % for Yingshan Formation reservoirs and an average of 51 % for Lianglitage Formation reservoirs) (Li et al. 2010a; Li et al. 2010b).

Factors controlling hydrocarbon migration

In the Tazhong area, hydrocarbons underwent vertical and lateral migration.

Factor controlling vertical hydrocarbon migration

The Cambrian–Ordovician source rock units provide hydrocarbon for the overlying Lower Ordovician Yingshan and Upper Ordovician Lianglitage Formations in the Tazhong area (Li et al. 2008a; Zhang et al. 2000), suggesting the occurrence of vertical migration processes. Vertical hydrocarbon migration is controlled by the vertical source-reservoir distribution, faults, and caprocks.

Factors controlling short-distance migration

The vertical source-reservoir distribution controls the vertical short-distance hydrocarbon migration. Due to the multi-phase superposition of reef-bank deposits, tectonic movements, and combined effects of secondary alteration processes (e.g., dissolution), the Lower Ordovician Yingshan Formation reservoir can be subdivided into an upper weathering crust reservoir section with high porosity and permeability and a lower relatively tight reservoir section (Yu et al. 2011; Ji et al. 2012). The boundary of the two sections was identified at 250–300 m beneath the unconformity surface (Lan et al. 2014). The Upper Ordovician source rocks (the lower part of Lianglitage Formation) directly overlaid the upper section and controlled the oil-bearing characteristic of layers in the upper section. The Cambrian–Lower Ordovician source rocks (the bottom of the Yingshan Formation, the Penglaiba Formation, and the Cambrian) directly underlined the lower section and controlled the oil-bearing characteristic of layers in the lower section. Figure 3 shows that the closer the layer of the relatively tight reservoir section is to the Cambrian–Lower Ordovician source rocks, the lower the probability of a dry layer being present (Fig.3a), and a greater oil saturation occurs when the reservoir is oil-bearing (Fig.3b), so does the layers of the weathering crust reservoir section to the upper Ordovician source rocks. The vertical distribution of the source rocks and their relative reservoirs was the basis of the vertical near-source hydrocarbons charging with short distance.

Factors controlling long-distance migration

Faults control the vertical long-distance hydrocarbon migration. Oil-migration faults could be classified into two types, (a) the NW trending overthrust faults (Tazhong No. 1 fault, Tazhong No. 10 fault, and Tazhong No. 40 fault) and NE trending strike-slip faults (ZG441, ZG43, ZG432 and ZG51 faults) (Fig.1).

The favorable matching relationship between the timing of fault activity and hydrocarbon accumulation shows the importance of hydrocarbon migration through faults. The overthrust faults that were active from the Sinian to the Silurian (Zhang et al. 2009) had formed before the first hydrocarbon accumulation period. The Tazhong No. 1 fault, contacted with source rocks both within the Tazhong area and the Manjiaer Sag, directly controlled mixed hydrocarbons from the two source rocks distribution areas. The No. 10 fault and No. 40 fault, contacted with source rocks within the Tazhong area,

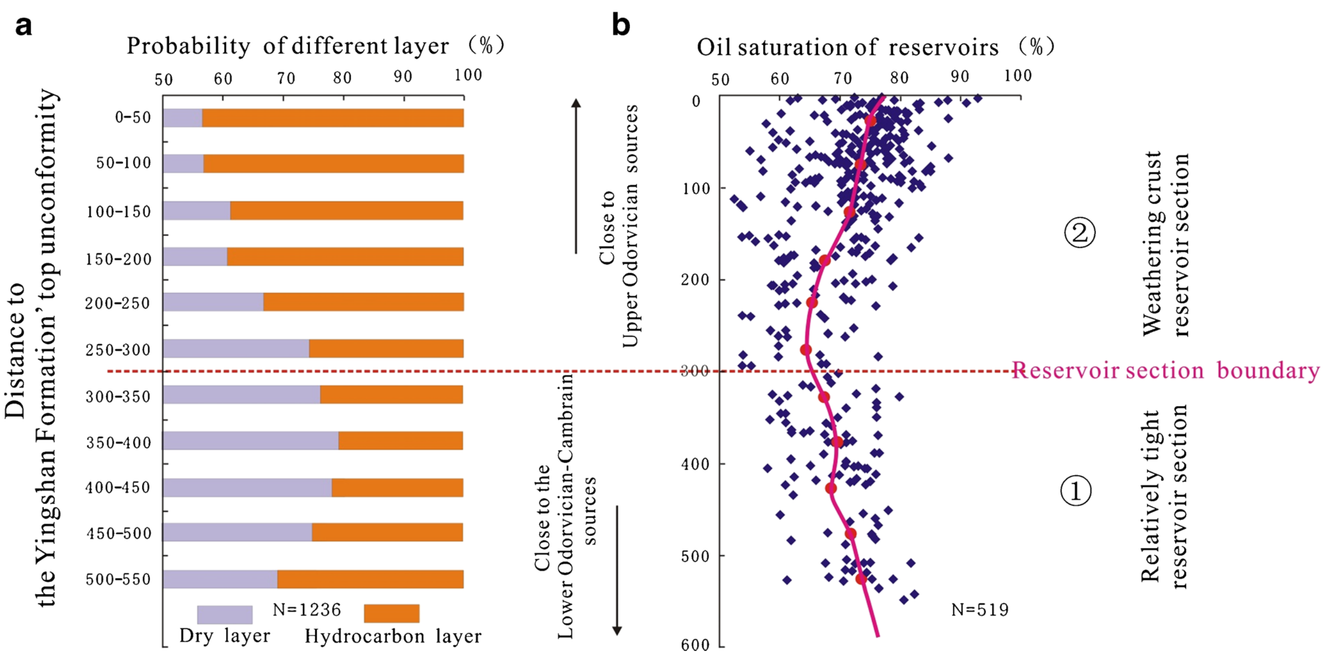


Fig. 3 Controls on hydrocarbon accumulation. **a** The relationship between hydrocarbon occurrence probability and the distance to the source rocks (unconformity). **b** The relationship between oil saturation and the distance to the source rocks (unconformity)

controlled mixed hydrocarbons from the two sets of source rocks in the Tazhong area itself. The NE trending strike-slip faults had smaller fault displacements and experienced three discernable evolution stages: the start of fault activity during the end of the Early Ordovician, a period of predominantly folding during the Late Ordovician, and a post-Ordovician decline in large-scale fault activity (Wu et al. 2012). The strike-slip and thrust faulting are favorable for hydrocarbon migration in the accumulation periods, as demonstrated in the well areas around Tazhong 83 (adjacent to No. 1 fault), Tazhong 16 (adjacent to No. 10 fault), Tazhong 47 (adjacent to No. 40 fault), and Tazhong 11 (adjacent to ZG10 strike-slip fault), which are associated with compound oil–gas fields where the oil layers are significantly greater than within the oil–gas fields away from these oil migration faults, such as the Zhonggu 6 well area (Fig. 4). A comparison of the geochemical parameters between crude oil samples from Ordovician and Silurian in TZ12 well, adjacent to Tazhong No. 10 fault, shows that from Ordovician to Silurian reservoirs, the Ts/Tm ratio, C_{29}Ts/Ts/Tm (C_{29}Ts + C_{29}Tm) ratio, 4-MDBT/1-MDBT ratio, 4,6-DMDBT/1,4-DMDBT ratio, 2,4-DMDBT/1,4-DMDBT ratio, and the amount of nitrogen compounds were all reducing, while 1,8-DMCA/1,7-DMCA ratio and 1,8-DMCA/2,7-DMCA ratio increased gradually, so does the TZ11 well, adjacent to ZG10 strike-slip fault (Fig. 4). Reservoirs with low viscosity, low sulfur, low wax content, high gas/oil ratio, and high V/Ni ratio are found near the ZG441, ZG43, ZG432, and ZG51 strike-slip faults. As the distance from the strike-slip faults increases, the oil viscosity, sulfur, and wax content increase, whereas gas/oil ratio and V/Ni ratio decrease (Fig. 15b). The geochemical parameters and hydrocarbon properties also indicated that the oil-migration faults control the vertical hydrocarbon migration over long distances.

The NW trending overthrust faults and NE trending strike-slip faults together jointly controlled the vertical long-distance hydrocarbon migration. The intersections of NE and NW faults formed hydrocarbon charging points, where charged hydrocarbon was first introduced into the Ordovician reservoirs of the Tazhong area (Gartrell 2004; Xiang et al. 2009; Pang et al. 2013a).

Role of caprocks in migration

In the Tazhong area, hydrocarbons were sealed by four sets of caprocks: Lower-Middle Cambrian gypsum-salt caprocks, Ordovician muddy limestone caprocks, Silurian mudstone caprocks, and Carboniferous gypsum-mudstone caprocks (Jin, 2014). Furthermore, the Ordovician muddy limestone caprocks could be subdivided into two sets of caprocks. One is the Sangtamu Formation mudstone, found in extensive layers above the Upper Ordovician, which sealed both the Lianglitage Formation reservoirs and the Yingshan Formation reservoirs in the Ordovician. The other is the Liang 3–5 section muddy limestone, found within the lower part of the Upper Ordovician Lianglitage Formation, which sealed the Yingshan Formation reservoirs in the Ordovician only. Exploration results in the Tazhong area showed that all of the stratigraphic units extending from Cambrian to Carboniferous contain oil and gas occurrences (Fig. 5). However, proven oil and gas reserves suddenly decrease from the Cambrian–Ordovician carbonate reservoir units to the Silurian–Carboniferous clastic reservoir units. The Permian

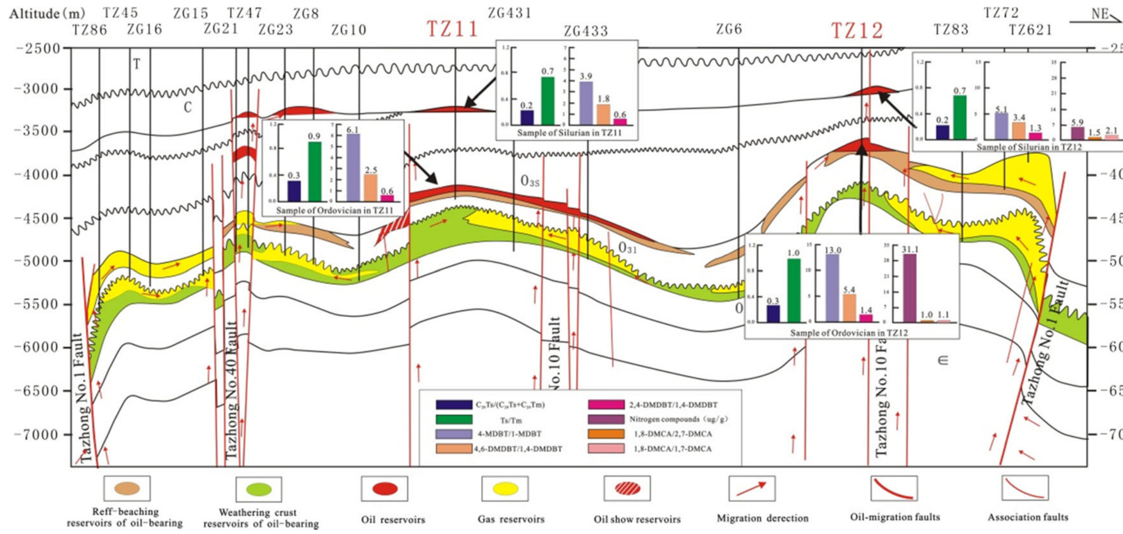


Fig. 4 Northeast-southwest seismic section, showing the hydrocarbon accumulation/migration patterns within the Tazhong area. The TZ11 and TZ12 are wells from which Ordovician and Silurian crude oils were sampled. ∈: Cambrian; O_1p: Penglaiba Formation, O_1y: Yingshan Formation, O_3l: Lianglitage Formation, O_3s: Sangtamu Formation. S: Silurian; D: Devonian; C: Carboniferous; P: Permian; T: Triassic

and overlying stratigraphic series have no oil or gas shows (Fig. 5). For the Ordovician, the hydrocarbon reserves and reservoirs distribution range of the Yingshan Formation are greater than the Lianglitage Formation (Fig. 5). The reservoirs oil-bearing characteristic differences of different stratigraphies indicated vertical hydrocarbon migration in the Tazhong area were mainly sealed by the two sets of caprocks.

Combined effects

From the above analyses of factors controlling vertical hydrocarbon migration, it can be established that the distance over which vertical hydrocarbon migration could occur is controlled by vertical source-reservoir distribution, faults, and effective seals.

When oil-migrating faults transected the two sets of Ordovician caprocks to the Silurian or Carboniferous, vertical hydrocarbon migration distance was much greater. Thus, hydrocarbons migrated from the lower carbonates to the upper clasolites and formed multiple reservoir units with sealing by respective caprocks. (e.g., Tazhong 47 well area) (Figs. 4 and 5).

When oil-migrating faults transected the Liang 3–5 section marl caprock only, the distance of vertical hydrocarbon migration is limited. In this scenario, most of hydrocarbons were sealed by the Sangtamu Formation caprocks and accumulated in the Lianglitage and Yingshan Formations to form multiple target stratum reservoirs of carbonate, such as the Tazhong 83 well area (Figs. 4 and 5).

When the oil-migration faults transected neither the Sangtamu Formation nor the Liang 3–5 section marl caprock, the faults are not the main vertical hydrocarbon migration carrier for Ordovician reservoirs. In this scenario, hydrocarbon featured with short distance migration which controlled by the vertical source-reservoir distribution (Figs. 4 and 5).

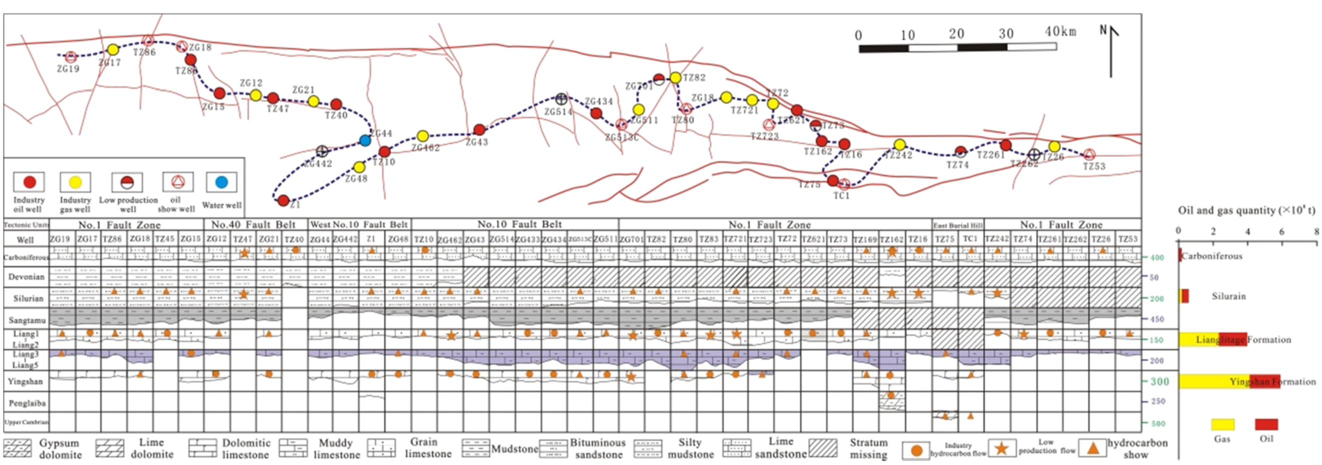


Fig. 5 The relationship between hydrocarbon-bearing display and caprocks of the Tazhong area

Factors controlling lateral hydrocarbon migration

It is thought that after hydrocarbon vertical migrating into Ordovician reservoirs, hydrocarbon continued lateral migrating by buoyancy (Pang et al. 2012). The extensive distribution of the discovered hydrocarbon reservoirs also identified Ordovician hydrocarbon laterally migrated with a large scale (Figs. 1 and 4).

Factors controlling migration direction

Research shows that secondary hydrocarbon migration direction is controlled by regional tectonic evolution (Du et al. 2011; Wang et al. 2009). The Ordovician hydrocarbons would have migrated laterally from the lower parts to the higher parts in the Tazhong area. The structure controlled the direction of lateral Ordovician hydrocarbon migration.

Using the "volume balance" theory and calculation of the denudation rate of strata (Qi et al. 2003), the structural forms of the top of the Yingshan Formation and Lianglitage Formation, during the major accumulation period, were modeled. The structural distribution shows high parts were located in the south and east and low parts were located in the north and west. The analysis of the structural setting shows that hydrocarbon migration was locally from the northwest to southeast (Fig.6). In details, the No. 1 Fault Zone, the No. 10 Fault Belt, and the inherited high zone around the Zhong 1 well form the main pathways for lateral hydrocarbon migration, explaining the high frequency of hydrocarbon wells drilled along these areas (Fig. 6).

Factors governing migration pathways

Three types of lateral migration pathways could be distinguished, and these include unconformities, transport faults, and reef-beach body reservoirs.

The Middle Ordovician tectonic activity is highlighted by the development of an unconformity (the boundary of Lower Ordovician Yingshan Formation and the Upper Ordovician Lianglitage Formation), which covered the entire North Slope (Yu et al. 2011). Because of multi-episodic dissolution and fracturing, the unconformity has an associated reservoir belt with high porosity and permeability, ranging from 0 to 300 m beneath the unconformity surface (Lan et al. 2014). According to well logging data, the drilling breaks and drilling fluid leaks were mainly centralized around 300 m beneath the unconformity. The closer the distance is to the unconformity surface, the larger probability of drilling breaks and the larger the quantity of drilling fluid leaks occurs (Fig. 7). These drilling accidents and the found asphalt/hydrocarbon inclusions in the reservoirs indicated that connected dissolution holes and fractures exited in the associated reservoir belt which provided favorable paths for lateral hydrocarbon migration (Fig. 8). Furthermore, production testing results suggest that the closer the reservoir to the unconformity surface, the larger probability for oil-gas enriching, the larger reservoir hydrocarbon production (if it is oil-bearing) occurs (Fig. 7). In addition, variation in oil viscosity, sulfur content, wax content, gas:oil ratio, V:Ni ratio may account for the lateral hydrocarbon migration along the unconformity (Fig. 15b).

Geochemical parameters investigation showed hydrocarbon laterally migrated over a long distance along the reef-beach body reservoirs in the Ordovician, Tazhong area (Lv et al. 2010; Han et al. 2008). Most of these reef-beach bodies, separated by interbank sea deposits in NE–SW horizontal direction, are NW-SE trending and occur generally as wide lenses (Fig. 9). The distribution of the reef-beach bodies created a challenge for the lateral long-distance migration along the NE–SW direction. In the study area, the NE trending large-scale strike-slip faults provide viable pathways for this hydrocarbon migration (Fig. 9). Therefore, the faults made of hydrocarbon migrate a lateral long distance along the reef-beach body reservoirs.

Combined effects

The Ordovician hydrocarbon migration direction and the migration pathway distribution direction coupled to determine the lateral hydrocarbon migration distance. When the lateral migration direction is in good agreement with the transport fault strike and the reef-beach body reservoirs distribution direction, it is a benefit for the lateral hydrocarbon migration over long distances, about dozens of kilometers. When the lateral migration direction is in good agreement with the transport fault strike or the reef-beach body reservoirs distribution direction, the lateral hydrocarbon migration was suppressed to some extent and had a relatively shorter distance. When the lateral migration direction is neither in good agreement with transport fault strike nor the reef-beach body reservoirs distribution direction, the lateral migration was in a short distance and nearby accumulation had usually occurred.

Synthesizing Figs. 6 and 9, the lateral migration direction is in good agreement with the transport fault strike and reef-beach body reservoirs distribution direction on the No. 1 Fault Zone and the No. 10 Fault Belt. Thus, the two areas were the most favorable hydrocarbon enrichment zones in the Ordovician of the Tazhong area. Due to the space configuration of the lateral migration direction, the transport fault strike, and the reef-beach body reservoirs, the lateral hydrocarbon migrations to the ZG28 and ZG50 well area were limited, explaining the significant number of failed wells. As a whole, with the transportation of the unconformity additionally, the Yingshan Formation reservoirs were relatively more easily been hydrocarbon enriched than the Lianglitage Formation reservoirs in the North Slope (Fig. 5).

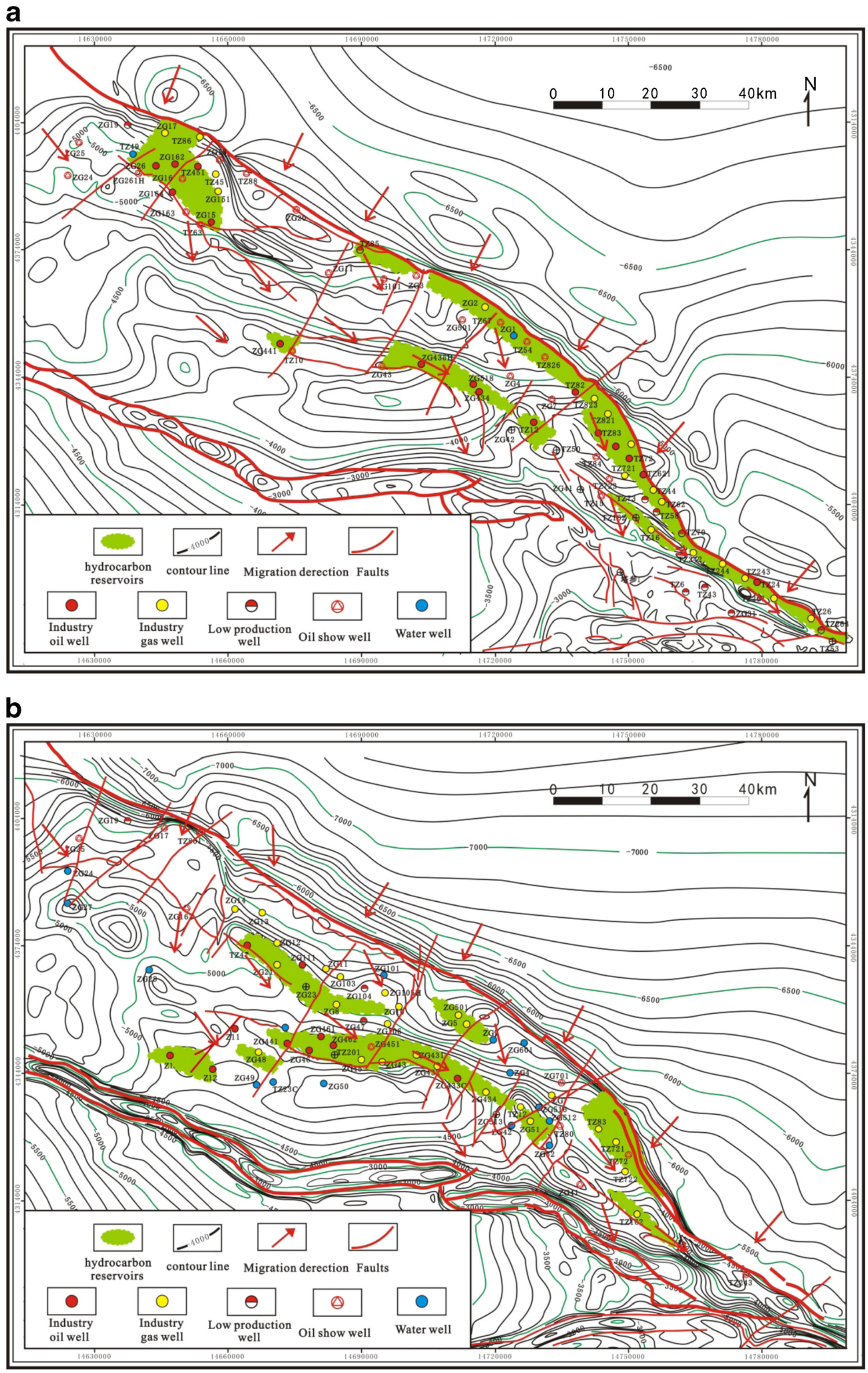


Fig. 6 The relationship between hydrocarbon distribution and structure of oil-bearing layer in the Tazhong area. **a** Relationship between hydrocarbon distribution and structure within the Top of the Lianglitage Formation. **b** Relationship between hydrocarbon distribution and structure of the Top of the Yingshan Formation

Factors controlling hydrocarbon enrichment

It is thought that after hydrocarbons generating from source rocks, Ordovician hydrocarbon migration was followed by hydrocarbon enrichment in high quality reservoirs with high porosity and permeability. Vertically, hydrocarbon enrichment layers are controlled by reservoir deposition environments, which are controlled by

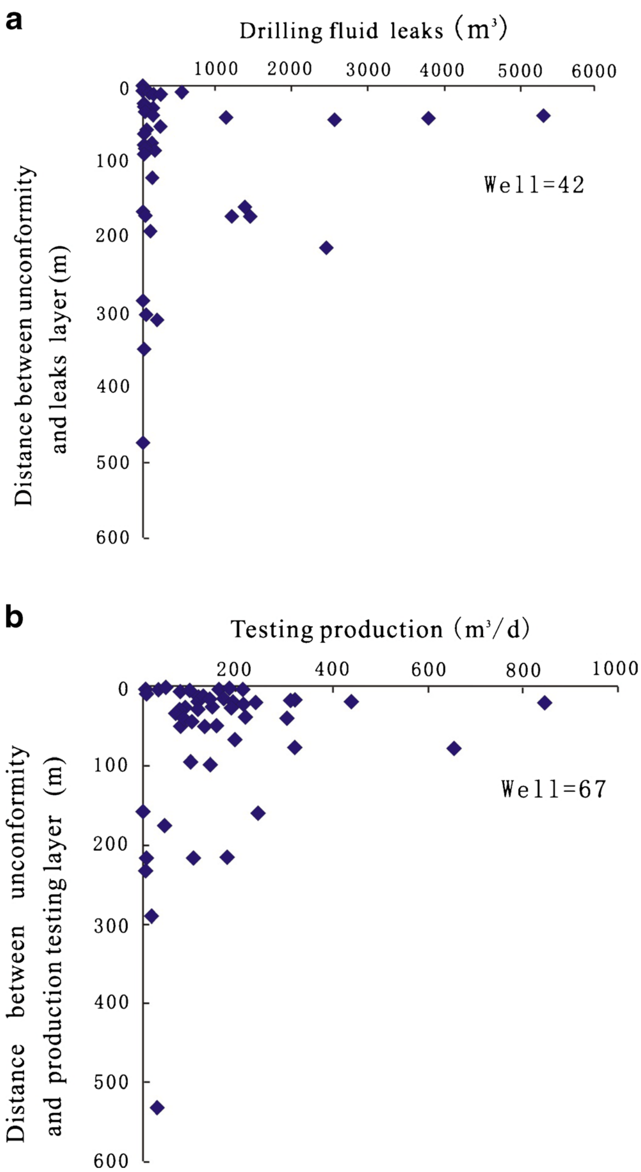


Fig. 7 Controls of the Yingshan Formation top' unconformity on hydrocarbon accumulation. **a** The relationship between drilling fluid leaks and the distance to the unconformity. **b** The relationship between testing production and the distance to the unconformity

base-level cycles and accommodation space variations. Laterally, hydrocarbon enrichment sites are limited to the sedimentary microfacies and crack–hole systems distribution.

Factors controlling hydrocarbon enrichment layer

Under stable tectonic setting, sedimentary structures and facies are highly controlled by base-level cycles, which were associated with accommodation space variations. An attempt to construct base-level cycles allows the identification of sedimentary cycle and vertical layer distribution. Thus, a good understanding of the vertically high quality reservoir layer distribution would be determined.

Following the sequence stratigraphy theory established by Vail PR et al. (1991), date of 54 exploration wells, 2D and 3D seismic interpretation, and previous research (Yang et al. 2010; Lin et al. 2012; Liu et al. 2013), sequence stratigraphy framework of the Ordovician was carried out. Accordingly, the investigated stratigraphic series could be divided into 9 three-order sequences (Fig. 10). The analysis of changes in depositional environments reveals that there is general sea level rising during the deposition of the Ordovician. During the Ordovician, Tazhong area underwent strong tectonic evolvement, and the palaeogeomorphology has changed greatly. In late of early Ordovician (SQ1), Tazhong area had relatively stable tectonic setting. Base-level changed from rising to falling slowly and mainly developed carbonate platform with dolomite sedimentary. From early Ordovician to middle Ordovician (SQ2–SQ4), Tazhong area experienced continuous structure uplift. Base-level fell rapidly, the accommodation space diminished gradually, and the study area mainly developed beach with oolites and intraclastic graistones. With the base-level falling, the Lower-Middle Ordovician had undergone erosion during the middle Ordovician, which resulted in the most important unconformity on the Yingshan Formation' top. After the Tazhong uplift forming, the tectonic setting tended to be relatively stable again in the late Ordovician. During early of late Ordovician (SQ5–SQ6), the base-level changed from falling to rising slowly. The Tazhong area started to undergo transgression, and accommodation space increase gradually. At the turning position from falling to rising of the base level, huge thick shaly limestone section deposited, which is the main hydrocarbon source rock and favorable caprock (Liang 3–5 section). After this period, the base-level rose fast and the transgression reached its climax during the middle of late Ordovician (SQ7 – SQ9). With high-energy hydrodynamic depositional conditions in this time, the Tazhong area mainly developed organic reef and particles beach. Due to the above-mentioned large scale sea-level rise with the large area of transgression, the carbonate platform of Tazhong area was flooded, and deep shelf-basin developed in the Tazhong area in the late of late Ordovician.

In a word, the base-level generally underwent a process of slow rising–slow falling–rapid falling–slow rising–rapid rising. Associated with these base-level cycles and accommodation space variations, there developed nine short-term sea-level cycles and sequence boundaries during Yingshan Formation and Lianglitage Formation deposition period (Fig. 10). Four sequence boundaries (SB2 to SB5) can be distinguished within

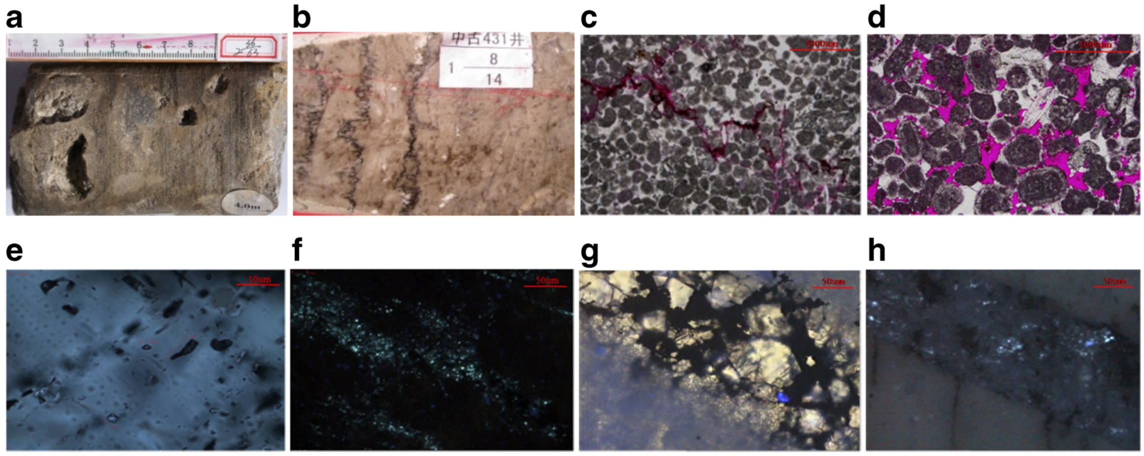


Fig. 8 Core samples and thin sections from the Lianglitage and Yingshan Formation carbonate reservoirs in the Tazhong area. **a** Core sample (ZG9, O_1y, 6301.2 m): limestone with embedded sand and gravel, irregular dissolved pores and fissures, partial filling, good connectivity. **b** Core sample (ZG431, O_1y, 5438.7 m): micrite, horizontal stylolithes, dissolved pore system; partial filling with mud and asphalt, good connectivity. **c** Thin section viewed under plane polarized light (ZG 203, O_1y, 6568.4 m): oolitic limestone (sparite), fissures partially filled with asphalt. **d** Thin section viewed under plane polarized light (ZG 203, O_1y, 6571.8 m): dolomitic limestone (sparite), intergranular dissolved pores, good connectivity. **e** Fluorescence-detected thin section (TZ 83, O_1y, 5682.5 m): dolomite, intragranular dissolved pores, hydrocarbon inclusions. **f** Fluorescence-detected thin section (ZG 7, O_1y, 5839.0 m): dolomitic limestone, intercrystalline dissolved pores, hydrocarbon inclusions. **g** Thin section viewed under plane polarized light (ZG 7,O_1y,5836.5 m): micrite dolomitic limestone (micrite), fissures partially filled with asphalt. **h** Fluorescence-detected thin section (ZG 7,O_1y,5836.5 m): dolomitic limestone (micrite), fissures partially filled with asphalt, hydrocarbon inclusions. O_1y: Yingshan Formation, O_3l: Lianglitage Formation

the Yingshan Formation, which correspond to four turning positions of sea level relatively. In response to these sea level falls and subsequent dissolution by fresh meteoric waters, the Yingshan Formation developed four high quality reservoir units beneath the sequence boundaries. Meanwhile, five sequence boundaries (SB6 to SB10) can be identified within the Lianglitage Formation, which also reflected turning positions of sea level. Five reservoir-caprock assemblages were distinguished within the Lianglitage Formation around the sequence boundaries, where the reefs or beach deposits form reservoir units and the mudstone or marl correspond to caprocks.

As notes, nine porous and permeable reservoir units provided vertical sites for Ordovician hydrocarbon enrichment. Because of the scarcity of deep drilling, only seven of the units (the five in the Lianglitage Formation and the upper two in the Yingshan Formation) had been discovered (Han et al. 2008; Yang et al. 2011). The lower two porous and permeable reservoir units of the Yingshan Formation may be potential targets for future oil and gas exploration activities in the Tazhong area.

Factors controlling hydrocarbon enrichment sites

High quality sedimentary microfacies are the base of high quality reservoir development, and crack-hole system improved the physical property of the reservoir. They couple to account for the hydrocarbon enrichment sites in lateral.

Six types of sedimentary microfacies, such as reef, beach, mound, restricted platform, interbank sea, and slope facies were recognized within the Lianglitage and Yingshan Formations (Yang et al. 2011). Data analysis from 78 exploration wells shows that hydrocarbons are mainly found in the reef-beach reservoirs. Less significant hydrocarbon amounts are found in the reef-mound reservoirs and restricted platform reservoirs. Minor amounts are also accumulated in the interbank sea and slope facies reservoirs (Fig. 11). The crack-hole system features with connective dissolution holes and fractures and is established in response to the processes of sedimentation, diagenesis, and tectonism (Duggan et al. 2001; Wang & Lv 2004; Green & Montjoy 2005). The reservoir characteristic shows hydrocarbon had enriched in the holes and fractures (Fig. 8).

The porosity and permeability maps of the Ordovician reservoirs have been modeled by combining the sedimentary facies (reservoir quality is positively correlated with reef and beach facies), the fracture distribution (there is a positive correlation with fracture density), and the structural framework (weathering crusts, important to reservoir quality, are positively correlated with structural highs). The maps show the commercial oil and gas wells so far discovered are all located in reservoirs with relative high porosity and permeability (porosity >2 %, permeability >0.1 mD) (Fig. 12). Based on the above, we examined the correlation between logged

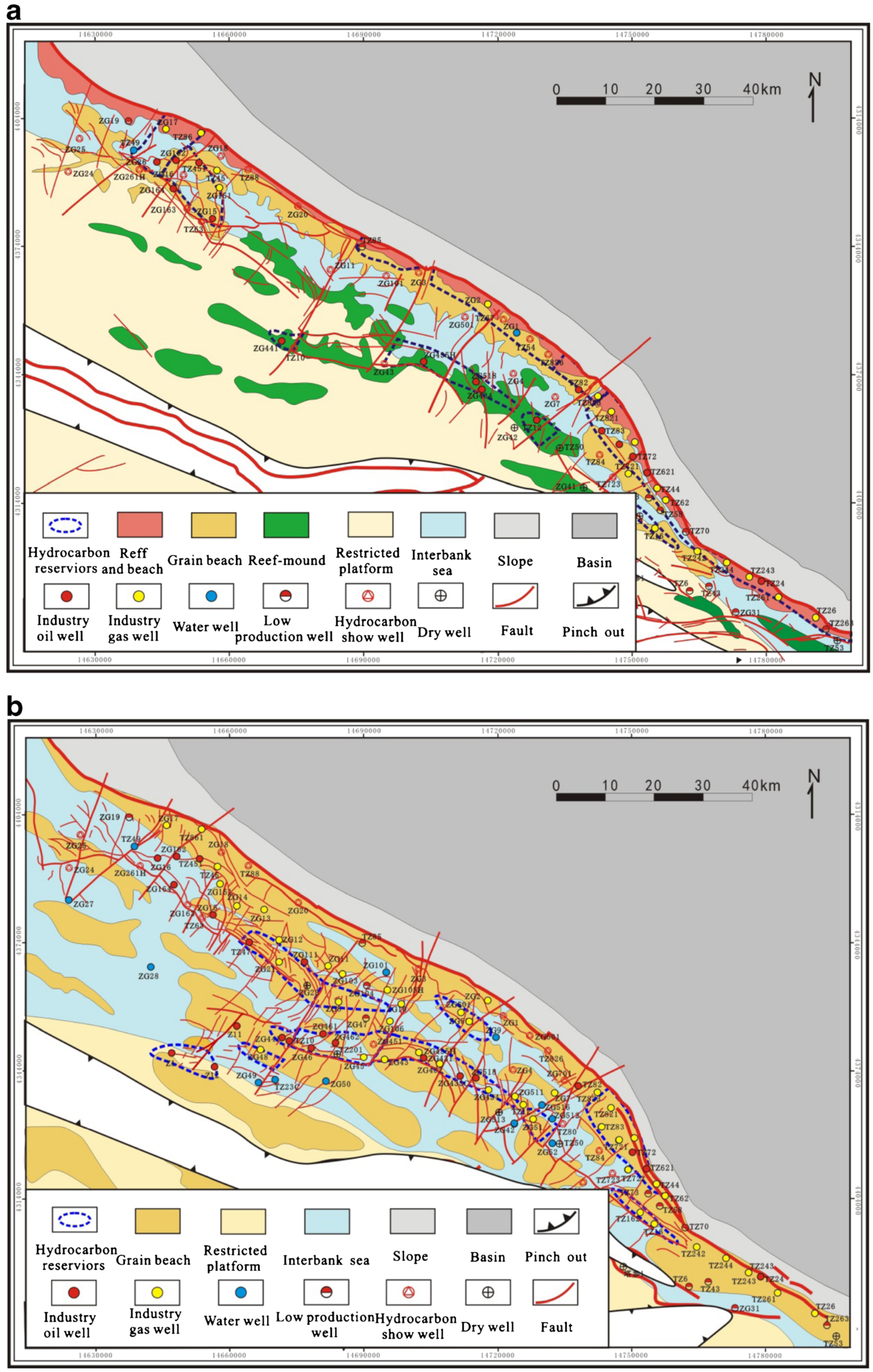


Fig. 9 Sedimentary facies and fault systems in the Tazhong area. **a** Fault systems developed at the Lianglitage Formation level. **b** Fault systems developed at the Yingshan Formation level

reservoir porosity (permeability) and the interpreted hydrocarbon levels for 45 wells in the Ordovician. The results show that the higher the porosity and permeability within a hydrocarbon layer are, the greater the oil saturation is (Fig. 13). The high porosity and permeability reservoirs, controlled by the sedimentary facies and crack-hole system, controlled the hydrocarbon enrichment range in lateral.

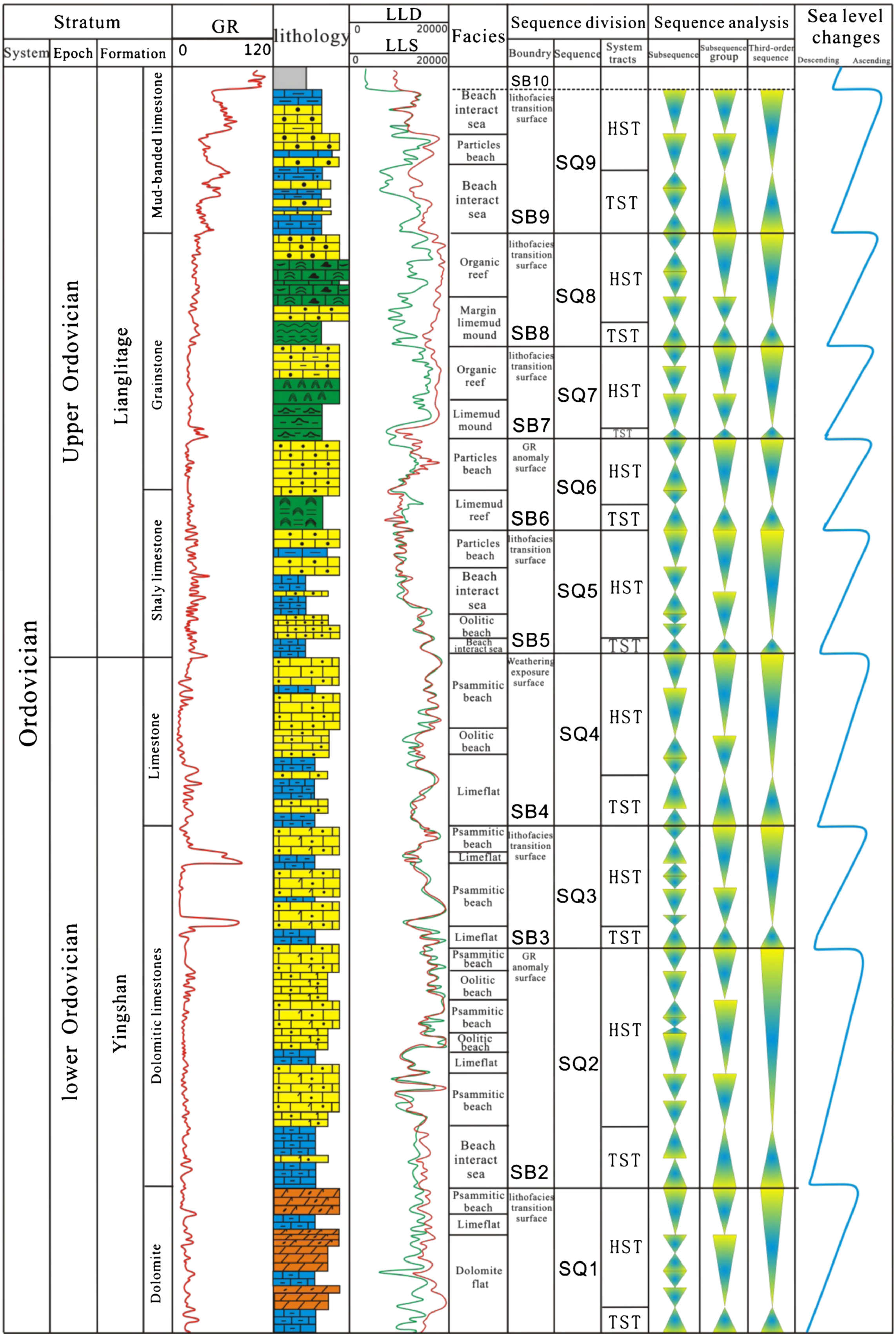


Fig. 10 Sequence stratigraphy framework of the Lianglitage and Yingshan formations in the Tazhong area

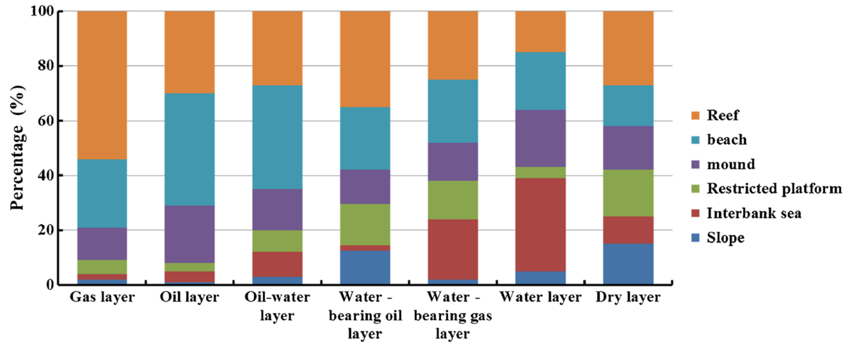


Fig. 11 Relationship between the hydrocarbon-bearing layers and the Ordovician microfacies in the Tazhong area

Hydrocarbon accumulation model

Hydrocarbon accumulation mechanism

After expulsion from the Cambrian-Ordovician source rocks in the Tazhong area and Majiaer Sag, hydrocarbons vertically migrated into the Ordovician reservoirs of the Tazhong area and then underwent lateral migration along a NW–SE direction. Finally, hydrocarbons, generated from different source units in different area, were mixed with each other and accumulated in the high quality reservoirs. This hydrocarbon accumulation process is highlighted by the formation of the hydrocarbon charging points. The charging points refer to the intersection of northeast- and northwest-trending faults, where charged hydrocarbon first was introduced into the Tazhong area and got accumulation nearby. There are anomalies of hydrocarbon properties and well production on the hydrocarbon charging points. With increasing distance from the charging points, the anomalies weakened.

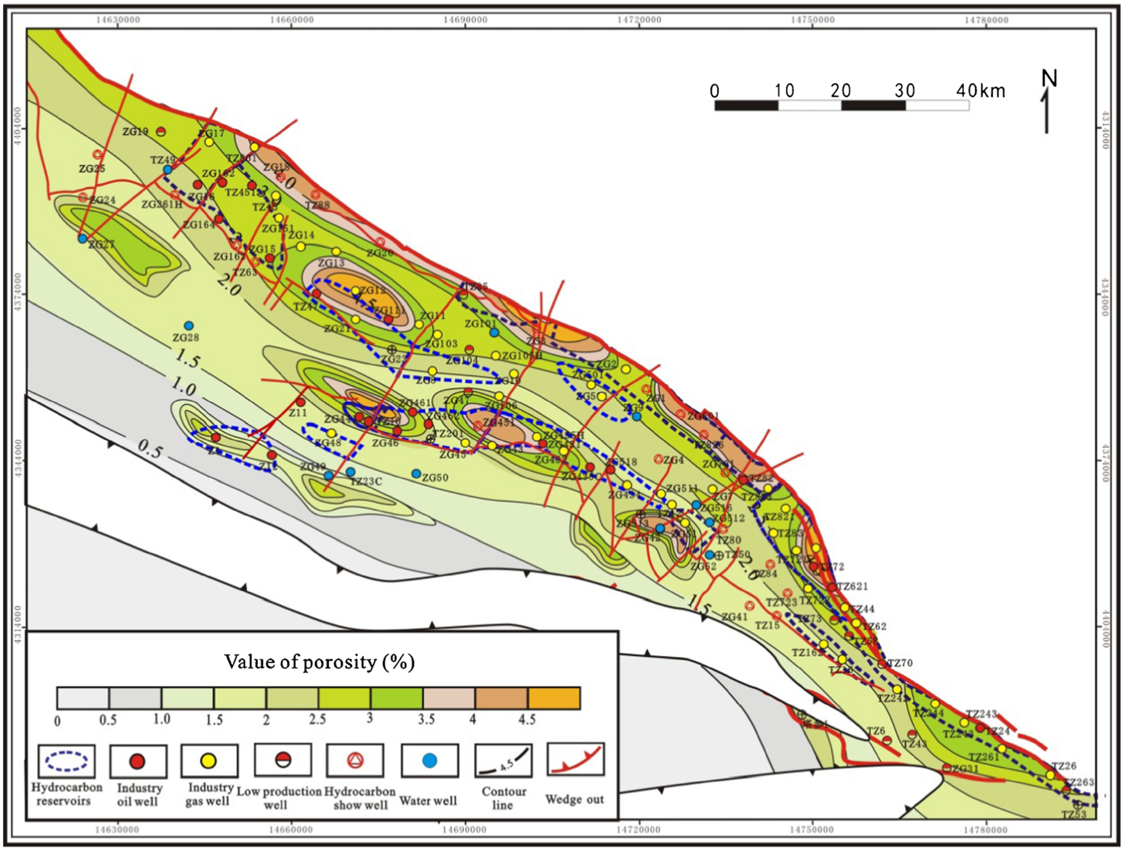
Figure 14 shows that 11 principal hydrocarbon charging points exist in the Ordovician units of the Tazhong area, which could be classified into two point belts: (a) the external charging point belt (ZG17, TZ85, ZG3, TZ82, TZ621, and TZ24) and (b) the internal charging point belt (ZG22, ZG441, ZG43, ZG432, and ZG51). Previous research indicated hydrocarbon from the Majiaer Sag introduced into the Tazhong area only from the external six charging points (Li et al. 2010a; Pang et al. 2013b). The hydrocarbon properties change consistently in the vicinity of the charging points; the values of dry gas coefficient and hydrogen sulfide contents are high and those of oil density are low. However, with increasing distance from the charging points, the dry gas coefficient value and hydrogen sulfide contents decrease, whereas the oil density values increase. Figure 15a is the schematic cross section which showed the main geological features and reservoir units of the external charging point belt. In the vicinity of charging points, most of the crude oils are light colored and the reservoirs are condensate reservoirs. With increasing distance from the charging points, the oil gradually blackens and the reservoirs become oil rich. Figure 15b is the schematic cross section which showed the main geological features and reservoir units of the internal charging point belt. In the vicinity of the charging point, reservoirs have low oil viscosity, low sulfur and low wax content, and high gas:oil and V:Ni ratio. However, as the distance from the charging point increases, the oil viscosity, sulfur, and wax content increase, whereas the gas:oil and V:Ni ratio decrease. These indicated hydrocarbons were introduced to the Ordovician reservoirs from the 11 intersections of NW trending overthrust and NE trending strike slip flower faults. Using the analysis of the relationship between the production of wells and the distance from the charging points in the study area, it can be observed that reservoir production capacity significantly decreases with distance from the charging points. At distances of greater than 20 km, failed wells occur and there are no industrial hydrocarbon wells (Fig. 16). An evident distance threshold for hydrocarbon charging and accumulation in these carbonate reservoirs exists. The traps, stay beyond the threshold (20 km), could not get hydrocarbon accumulation. Thus, the internal five charging points together jointly controlled an internal hydrocarbon charging and accumulation boundary, which is 20 km far away from the internal injection point belt. The external hydrocarbon charging and accumulation boundary, controlled by the external six charging points, also formed (Fig. 14).

The regular variation in hydrocarbon properties and well productions showed that as the distance from the charging points increased, hydrocarbon supply intensity decreased, hydrocarbon enrichment probability diminished, and the hydrocarbon exploration risk increased. Thus, hydrocarbon charging points controlled Ordovician hydrocarbon accumulation and distribution, and the two hydrocarbon charging and accumulation boundaries divided the study area into different hydrocarbon accumulation units.

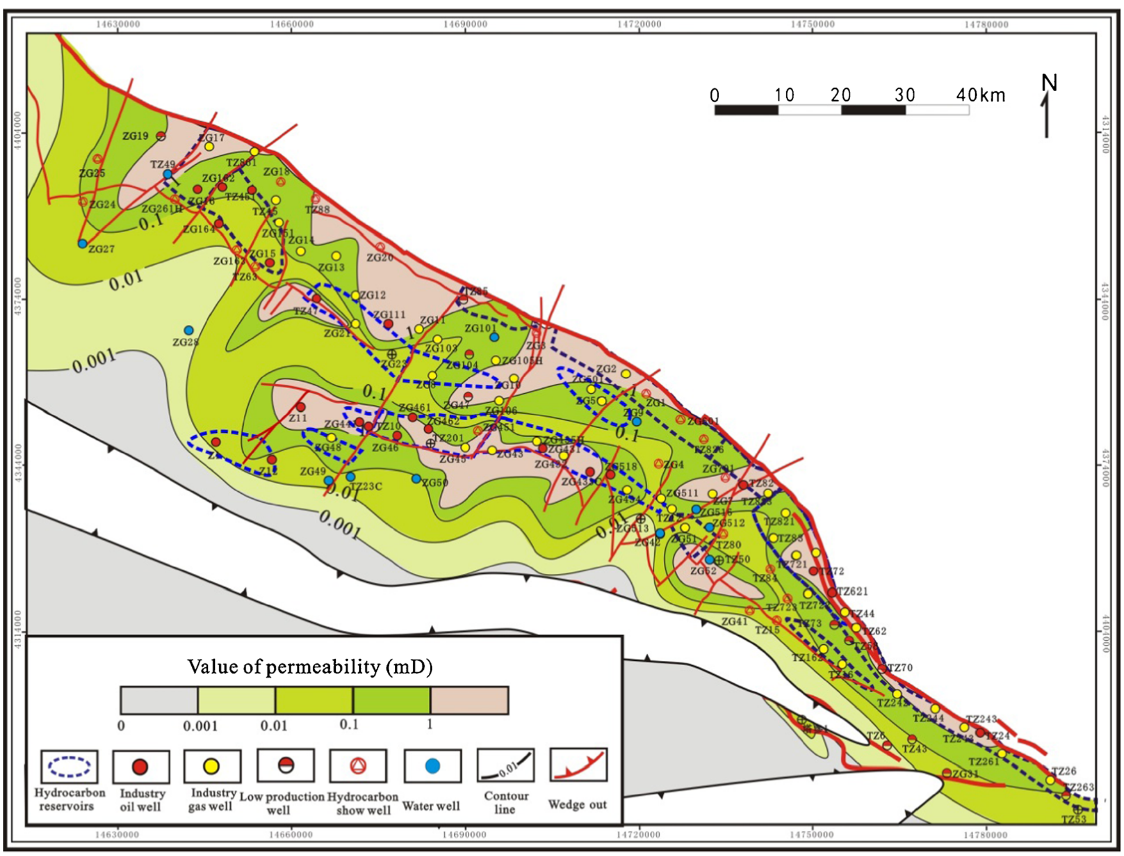
Summary of hydrocarbon accumulation model

Hydrocarbon accumulation model is the high generalization of the hydrocarbon accumulation and distribution,

Fig. 12 Relationship between hydrocarbon occurrence and reservoir physical properties. **a** Hydrocarbon distribution as function of porosity. **b** Hydrocarbon distribution as function of permeability a


0 10 20 30 40km
N
Value of porosity (%)
0 0.5 1.0 1.5 2 2.5 3 3.5 4 4.5
Hydrocarbon reservoirs
Industry oil well
Industry gas well
Low production well
Hydrocarbon show well
Water well
Contour line
Wedge out

b


0 10 20 30 40km
N
Value of permeability (mD)
0 0.001 0.01 0.1 1
Hydrocarbon reservoirs
Industry oil well
Industry gas well
Low production well
Hydrocarbon show well
Water well
Contour line
Wedge out

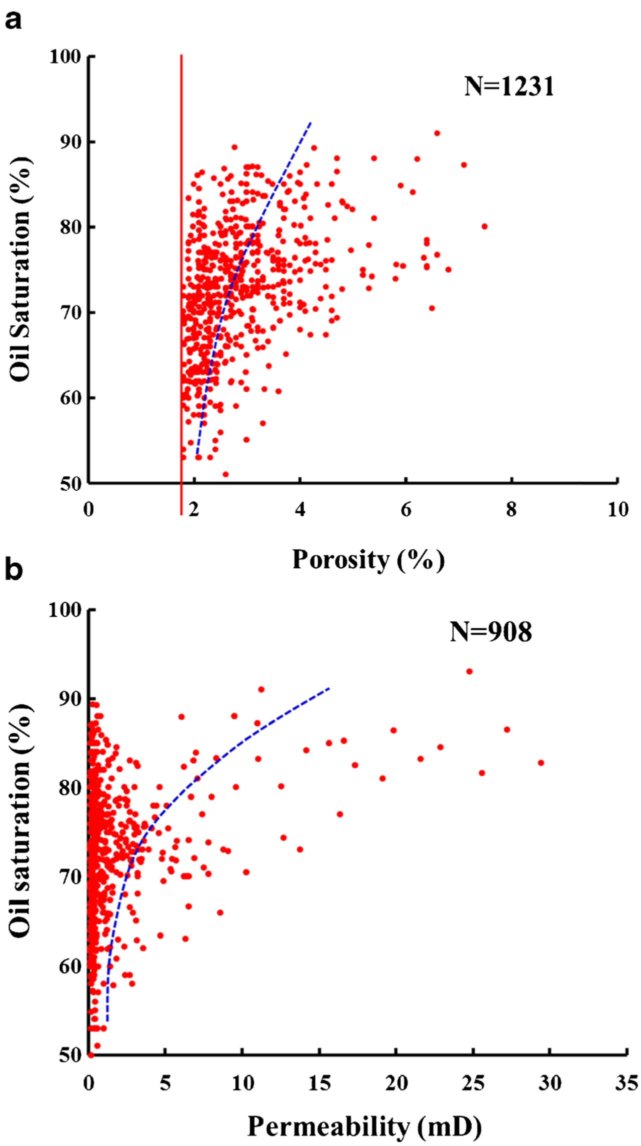


Fig. 13 Relationship between oil saturation and physical properties of reservoirs. **a** Relationship between oil saturation of hydrocarbon layer and porosity. **b** Relationship between oil saturation of hydrocarbon layer and permeability

which systematically summarizes the history and process of hydrocarbon generation, migration, and enrichment (Shen et al. 2009). Based on the above-mentioned hydrocarbon accumulation mechanism and hydrocarbon generation, migration, and enrichment history, the accumulation models of the study area had been classified into two types, (a) mixed-sourced area model, in which the hydrocarbons are sourced from both the Tazhong area and the Majiaer Sag, and (b) single-sourced area model, in which the hydrocarbons are only sourced from the Tazhong area itself. The boundary of the two models is the external hydrocarbon charging and accumulation boundary (Figs. 14 and 17).

Mixed-sourced area model

Based on this model, reservoir units are found mainly distributed in the east area of the external hydrocarbon charging and accumulation boundary (located between the No. 1 Fault Zone and the No. 10 Fault Belt) (Figs. 14 and 17). Hydrocarbons recovered in this area can be originated from the Tazhong area itself as well as the Manjiaer Sag. Hydrocarbons, derived from the Manjiaer Sag, were vertically introduced into the Tazhong area through the external six charging points and laterally migrated into west area of the study area via unconformity and faults. However, because the hydrocarbon supply intensity decreased, little or no hydrocarbons could migrate to the area beyond the external hydrocarbon charging and accumulation boundary (20 km). Thus, they accumulated in the area within the external hydrocarbon charging and accumulation boundary. Meanwhile, hydrocarbon, derived from the Tazhong area itself, was vertical introduced into the Tazhong area through the charging points and also accumulated in the same area after short distance lateral migration. As a result, hydrocarbons from the Manjiaer Sag are mixed with hydrocarbon from the Tazhong area itself. Furthermore, based on the vertical source-rock distribution, the mixed-sourced area model could be further classified into a lower-source upper-reservoir model and a lower-source middle-reservoir upper-source model.

(1) Lower-source middle-reservoir upper-source model

The Yingshan Formation reservoir (e.g., the Zhonggu 8 condensate field and the Zhonggu 5–7 condensate field) of the east area of external hydrocarbon charging and accumulation boundary can be ranged under this model (Fig. 17). As notes, the top of the Yingshan Formation developed a highly porous and permeable reservoir section. The reservoir section was directly overlaid by the Upper Ordovician source rocks (the lower part of the Lianglitage Formation) and directly underlying by the Cambrian–Lower Ordovician source rocks (the bottom of the Yingshan Formation, the Penglaiba Formation, and the Cambrian stratum). The distinctive “sandwich combination” form of source rock and reservoir rock resulted in the occurrence of mixed hydrocarbons: (1) the hydrocarbons from the Upper Ordovician migrated downward (over short distance by near-source charging) into the section and (2) the hydrocarbons from the Cambrian–Lower Ordovician migrated upward (over short distance by near-source charging and over long distance by oil-migration faults transporting) into the section.

(2) Lower-source upper-reservoir model

The Lianglitage Formation reservoir (e.g., the Tazhong 24–26 condensate field) of the east area of external hydrocarbon

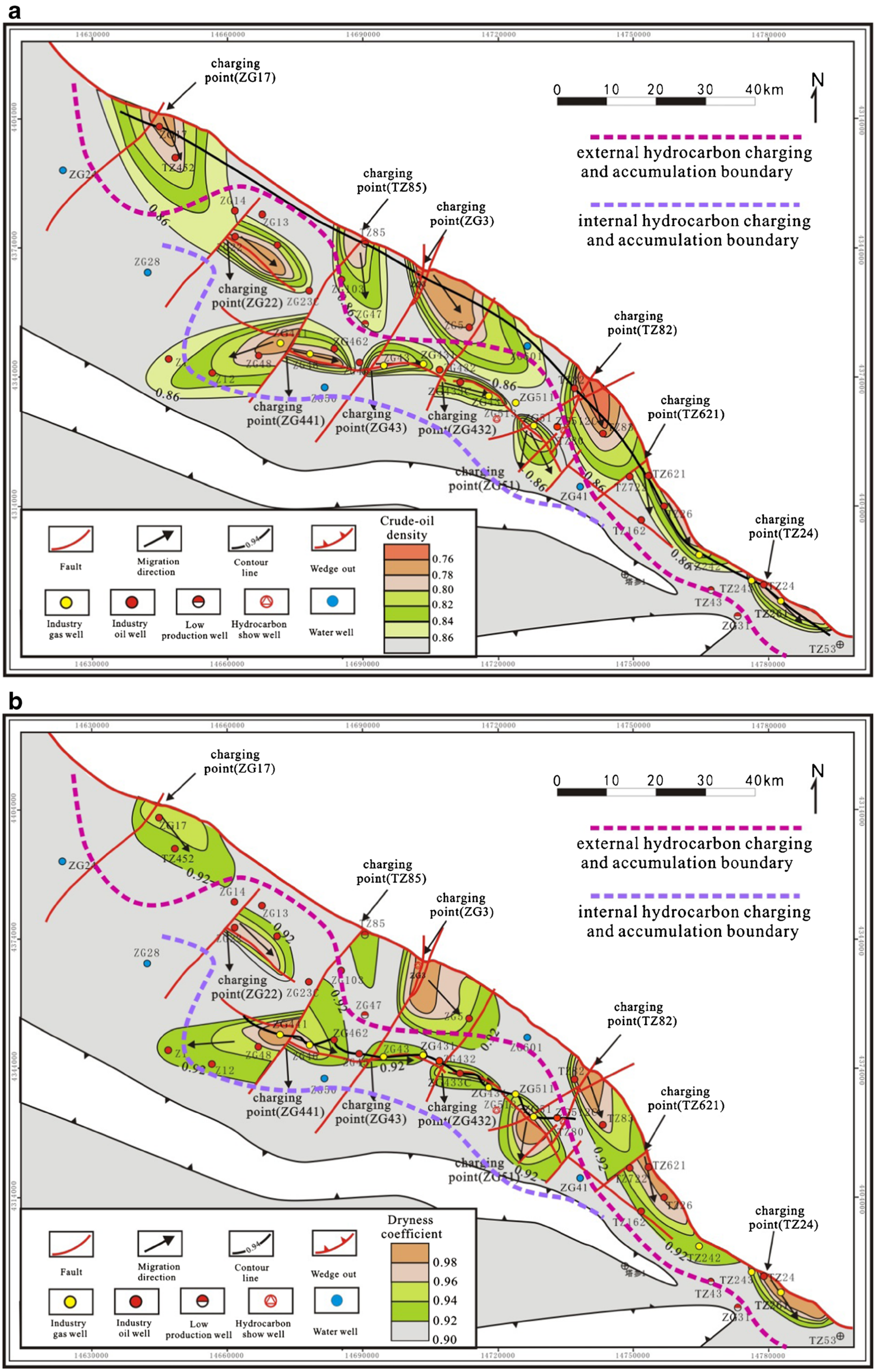


Fig. 14 Contour of hydrocarbon properties in Ordovician rocks of the Tazhong area. **a** Crude-oil density changing regularity near the charging point. **b** Dryness coefficient changing regularity near the charging point. **c** Hydrogen sulfide content changing regularity near the charging point

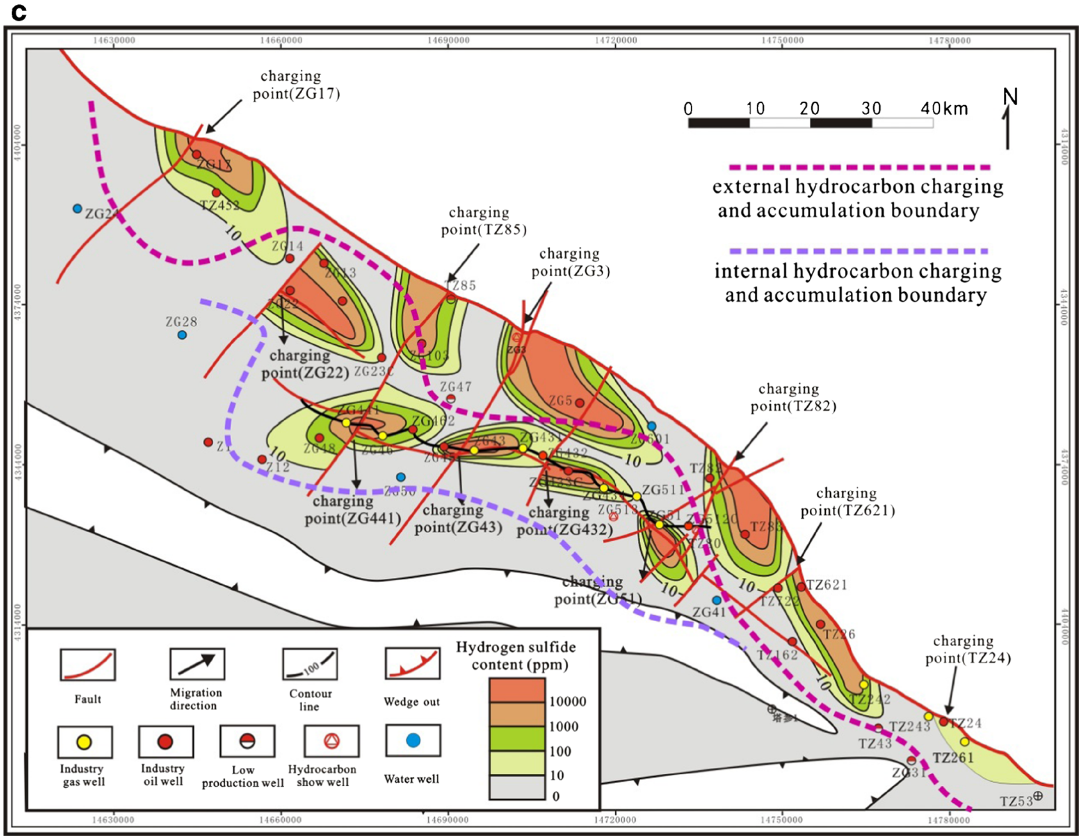


Fig. 14 (continued)

charging and accumulation boundary can be ranged under this model (Fig. 17). The Lianglitage Formation reservoirs are located above the Upper Ordovician source rocks (the lower part of the Lianglitage Formation) and the Cambrian–Lower Ordovician source rocks (the bottom of the Yingshan Formation, the Penglaiba Formation, and the Cambrian stratum). Hydrocarbons, generated from the Upper Ordovician source rock units, migrated upward (over short distance by near-source charging or the faults) into the reef-body reservoirs. Meanwhile, hydrocarbons, generated from the Cambrian–Lower Ordovician source rocks, migrated upward (over long distance by oil-migration faults transporting) into the reef-body reservoirs.

Single-sourced area model

Based on this model, reservoir units are found mainly distributed between the external and internal hydrocarbon charging and accumulation boundary (located in the inner area of the North Slope) (Figs. 14 and 17). According to the above-mentioned distance threshold for hydrocarbon charging and accumulation in Ordovician carbonate reservoirs (20 km), little or no hydrocarbons from the northern Manjiaer Sag could migrate over a sufficiently long distance to get accumulation in the area beyond external hydrocarbon charge boundary. Thus, the hydrocarbons reservoired in carbonate rocks of this model, introduced only through the internal five charging points, were mainly from the Cambrian-Ordovician source rocks within the Tazhong area. Furthermore, this model also could be classified into the lower-source upper-reservoir model and the lower-source middle-reservoir upper-source model. The former and latter are distinctively represented by the Zhonggu 43 condensate field in the Yingshan Formation and the Zhonggu 441 condensate field in the Lianglitage Formation (Fig.14, Fig.17).

Discussion

The comprehensive analysis of the discovered Ordovician reservoirs within the Tazhong area, in terms of geological, geochemical, and geophysical characteristics, reveals the factors controlling hydrocarbon generation, migration, and enrichment history. Findings derived from this study provide theoretical and practical significance for further exploration in this area. The co-existence of internal hydrocarbon charging points, unconformities, excellent reservoir units, and well developed seals in the inner North Slope area indicate that

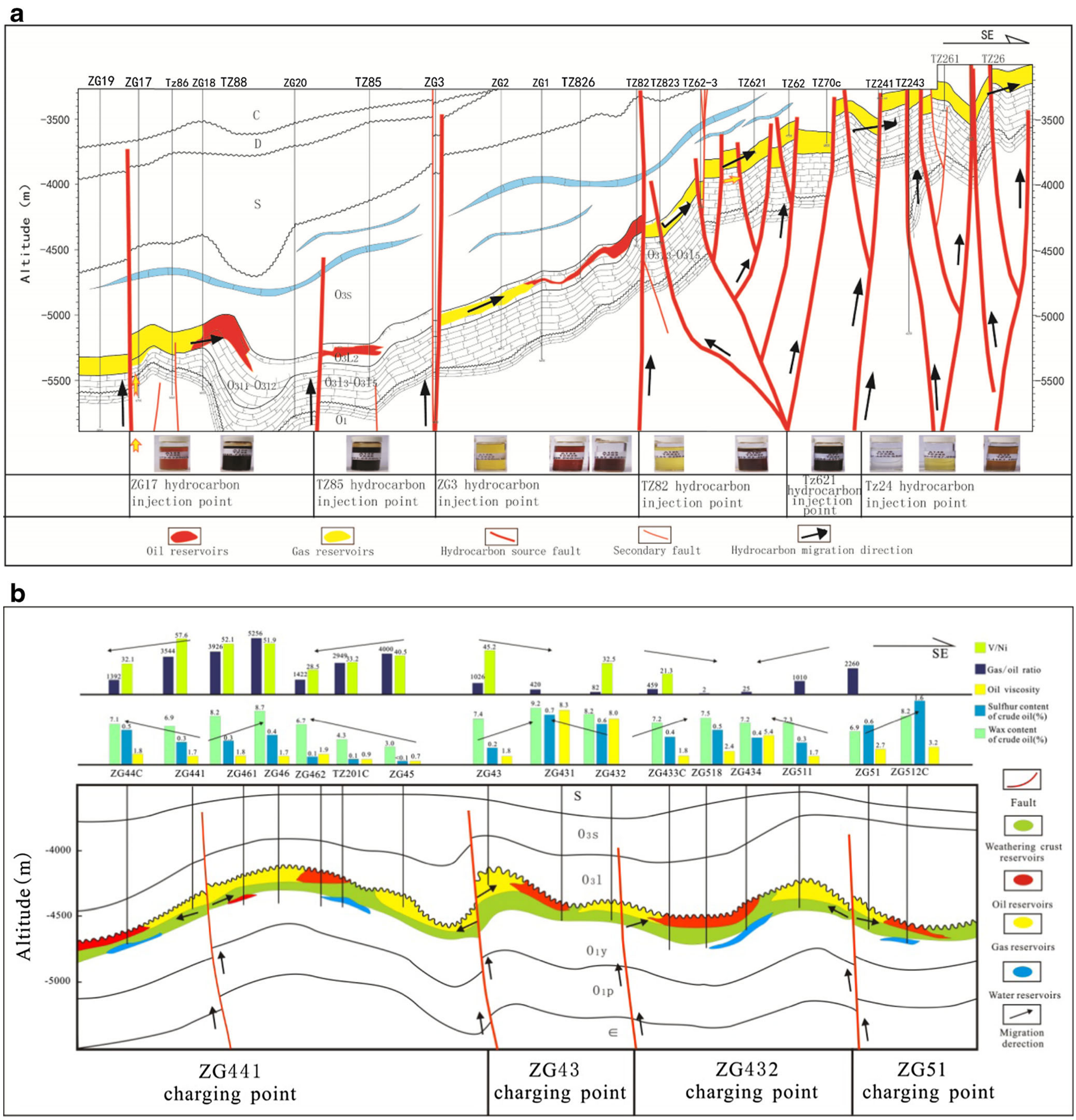


Fig. 15 Schematic cross sections, showing the main geological features and reservoir units in the Tazhong area. **a** Section of the external charging point belt. **b** Section of the internal charging point belt. ∈: Cambrian; O_1p: Penglaiba Formation, O_1y: Yingshan Formation, O_3l: Lianglitage Formation, O_3s: Sangtamu Formation. S: Silurian; D: Devonian; C: Carboniferous; P: Permian; T: Triassic

exploration efforts should be placed towards the west into the inner area of the North Slope in lateral. The stratigraphic units, including the lower part of the Yingshan Formation, Lower Ordovician Penglaiba Formation, and the Cambrian, are found either fault linked or in a direct contact with the Cambrian–Ordovician source rocks. As notes, the closer the oil-bearing reservoir is to the source rocks, the bigger probability to the oil-bearing of the reservoirs will be. The geological condition and variety of characteristic of hydrocarbon in reservoirs with different depth indicate that whether the super deep stratum would be oil-bearing or not depend on the highly porous and permeable reservoir units. Jiao et al. (2003), Yuan et al. (2012), and sequential stratigraphic investigation in this study reveal the existence of the highly porous and

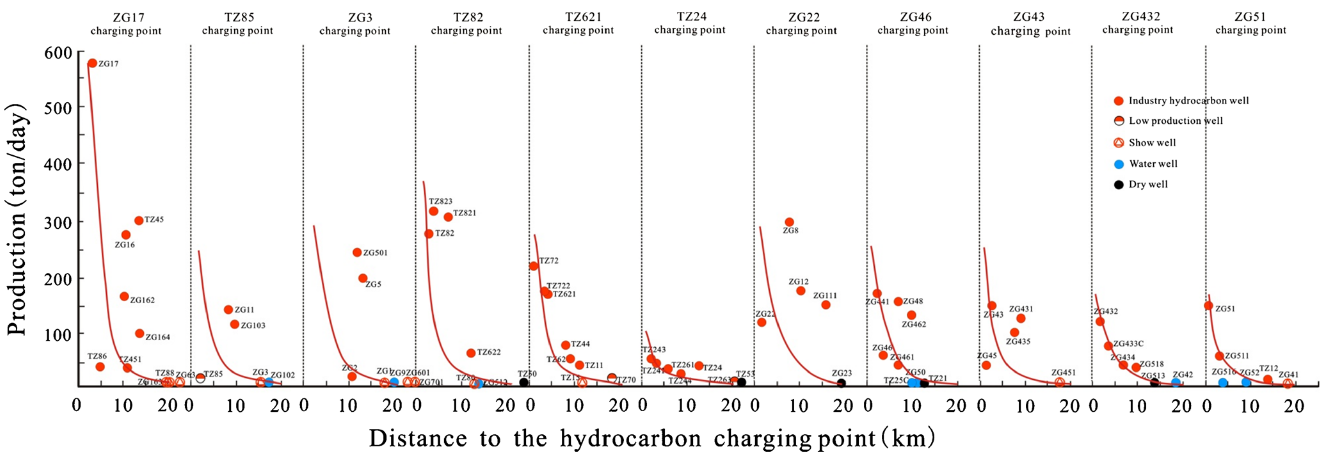


Fig. 16 Relationship between distances to hydrocarbon charging points and daily production from the Ordovician reservoirs in the Tazhong area

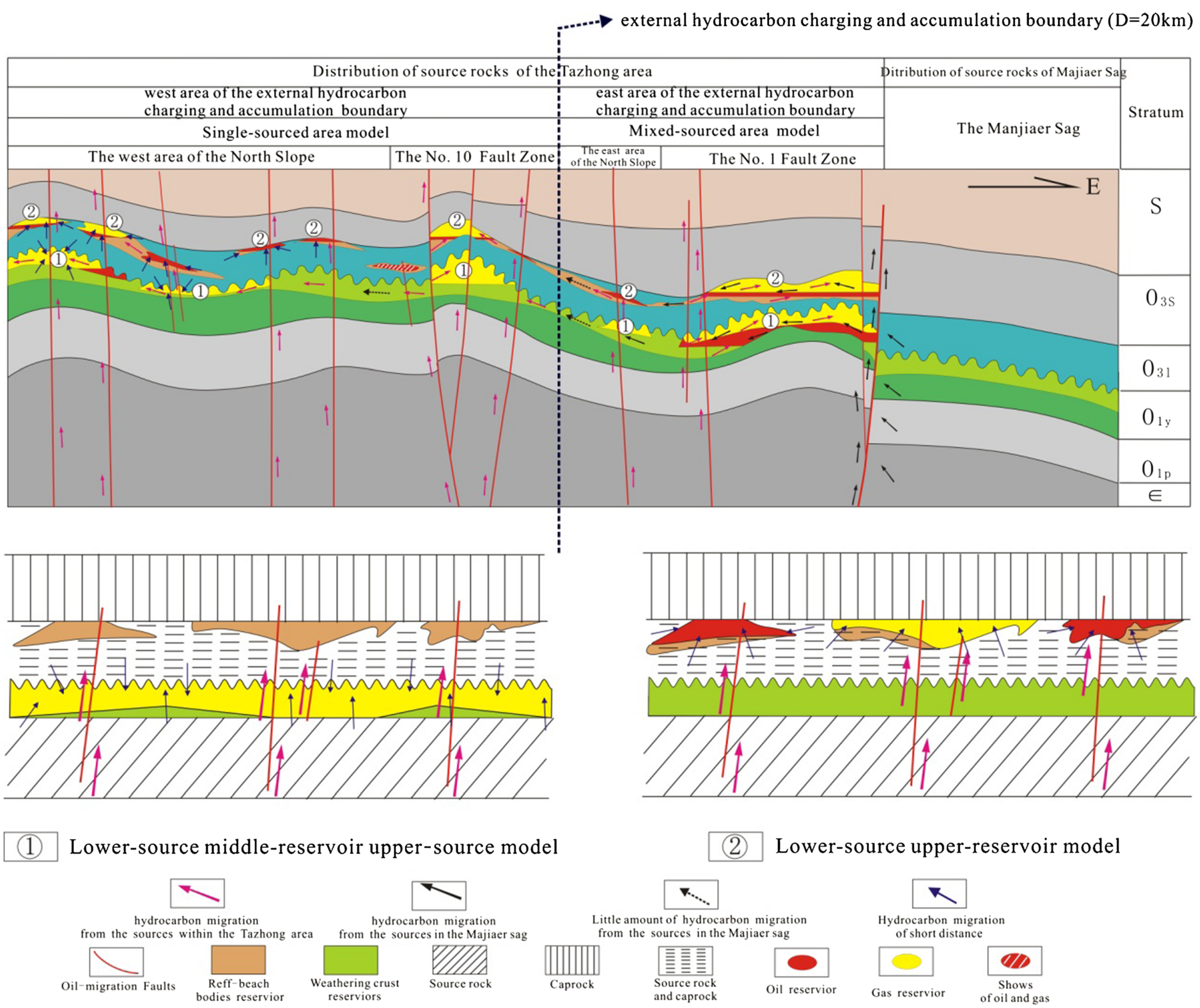


Fig. 17 Accumulation models of oil-gas from source rocks discharge into Lianglitage and Yingshan Formation reservoirs. ∈: Cambrian; O_1p: Penglaiba Formation, O_1y: Yingshan Formation, O_3l: Lianglitage Formation, O_3s: Sangtamu Formation. S: Silurian

permeable dolomite reservoirs in the super deep stratum, which indicated the super deep stratums are the favorable target area in the future hydrocarbon exploration.

Conclusions

(1) Hydrocarbon generation in the Tazhong area was controlled by mixed sources including the Cambrian–Lower Ordovician and the Upper Ordovician source rocks within the Tazhong area and the Manjiaer Sag. Vertical migration distance was controlled by vertical source-reservoir distribution, faults, and caprocks. Structure played a major role in the hydrocarbon migration along NW-SE direction. Lateral migration pathways were governed by unconformities, transport faults, and reef-beach body reservoirs. A part from the sedimentary control, hydrocarbon occurrence and distribution are controlled by recent tectonic events.

(2) Hydrocarbon was introduced into the Tazhong area through 11 hydrocarbon charging points, the intersections of NE, and NW fault sets. Hydrocarbon supply intensity decreased with the distance increasing from the charging points, and hydrocarbon charge distance threshold is 20 km. The existence of the external hydrocarbon charging and accumulation boundary indicated little or no hydrocarbons from the northern Manjiaer Sag could migrate into the inner area of the Tazhong area.

(3) Hydrocarbon accumulation models of the Ordovician, Tazhong area, can be classified into two types, (a) mixed-sourced area model and (b) single-sourced area model. The boundary of the two models is defined based on the external hydrocarbon charging boundary. Taking into consideration the vertical source-reservoir distribution, the aforementioned models could be further divided into a lower-source upper-reservoir model and a lower-source middle-reservoir upper-source model.

(4) Further exploration target in the Tazhong area should be taken further to the west along the inner area of the North Slope laterally. Vertically, the bottom of the Yingshan Formation, Lower Ordovician Penglaiba Formation, and the Cambrian form potential targets in the Tazhong area.

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