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Original research paper

Potential and favorable areas of petroleum exploration of ultra-deep marine strata more than 8000 m deep in the Tarim Basin, Northwest China☆

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Abstract

At present, deep and ultra-deep oil and gas have become the research and exploration hotspots. With little drilling data available, the geological understanding on deep formations is still in the exploratory stage, but most petroleum geologists have universally acknowledged that the deeply-buried strata of Chinese marine craton basins are equipped with the conditions for abundant oil and gas resources. A series of discoveries have been made in the Ordovician and Cambrian strata. For Precambrian strata, besides breakthroughs in the Sichuan Basin, a lot of research or drilling work has been initiated in other basins. In the Tarim Basin, the current burial depth of the Lower Paleozoic and the Precambrian mainly ranges from 5000 to 12000 m. This is attributed to rapid subsidence and deposition since the Neogene. A large number of exploration discoveries have been made, and commercial productivity projects have been constructed at the depth less than 8000 m. Strata more than 8000 m deep will be a significant major prospecting exploration field in the future. The analyses of hydrocarbon accumulation conditions of the ultra-deep layers of the Tarim Basin provide theoretical guidance for ultra-deep oil and gas exploration. This research is based on source rocks in the Cambrian, Sinian, and Nanhua System, formation and preservation of ultra-deep carbonate reservoirs, phase of petroleum and accumulation assemblages in ultra-deep strata, the exploration fields deeper than 8000 m were also evaluated to sort out the most favorable areas and, future exploration focuses on the Ordovician, Cambrian, and Sinian strata are pointed out.

Keywords: Ultra-deep; Neoproterozoic; Phase of petroleum; Cambrian; Craton basin; Tarim Basin

1. Introduction

In recent years, as oil and gas exploration pushes into the ultra-deep formation, the ancient strata have gradually become the hotspot of research and exploration [1−6]. The Cambrian, Sinian and even the Nanhua System in deep basins gradually became a crucial series of oil and gas geological research [7−11]. Recently, two significant exploration discoveries in China have attracted the attention of the global oil and gas exploration community and academia. One is the Anyue gas field discovered in the Sichuan Basin with more than one trillion cubic meters of natural gas reservoirs [12−15]. It is the largest and oldest gas field discovered in China, where the source rocks are found in the Sinian-Cambrian [15]. The gas is derived mainly from crude oil cracking, and the reservoirs are Sinian-Cambrian dolomite layers at a depth of 5000−6500 m.

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The other is the Central Tarim Uplift in the Tarim Basin, where Well ZS1C obtained industrial oil flow from the Lower Cambrian at 6944 m [16,17]. With oil and gas coming from the source rock of the Lower Cambrian Yu'ertusi Formation, it is a Cambrian primary oil and gas reservoir. These two discoveries pioneering into new deep exploration domain in China, have effectively promoted the exploration and discovery of ancient oil and gas reservoirs. At present, the Cambrian-Sinian System has become one of the critical strata of oil and gas exploration in China. In particular, with the acceleration of deep drilling in the strata more than 8000 m deep in Sichuan Basin and the Tarim Basin where high-quality reservoirs and oil and gas shows have been discovered in the ultra-deep formations. This has boosted the exploration confidence and research enthusiasm on ultra-deep formations.

The Tarim Basin is the largest petroliferous craton basin in China, where the primary target layer is deeply buried, and the deep oil and gas resources are also the bet of many geologists. In the two foreland sub-basins, Kuqa and Kunlun Mountain there, the main part of primary source rocks are more than 8000 m deep, yet no breakthrough has been made in the deep sandstones close to the source rock strata or interbedded with the source rocks. For example, a large number of natural gas fields in the deep formations at a depth of 6500−8000 m in the Cretaceous and Lower Tertiary have been discovered in the Kelasu Structural Belt. However, for the Jurassic and Triassic sandstone horizons interbedded with the source rocks, the ultra-deep formations in the distribution area of major source rocks have not yet been explored, apart from the gas layers found (the oil and gas is mainly sourced from deeper source rock, other than autochthonous source rocks) in the middle and shallow Dixie area. A series of significant exploration discoveries have been made in the Ordovician shallower than 8000 m in the carbonate rock combinations in the platform basin area, especially the deepest (at a burial depth of 7750 m) Paleozoic marine reservoir in the world discovered in the Ordovician [18], has greatly raised the confidence of finding oil in ultra-deep layers. The Cambrian and Precambrian (mainly the Sinian and Nanhua System) have been in the process of expediting exploration. Therefore, through the analysis of ultra-deep source rocks, reservoirs, the phase of oil and gas, and accumulation combinations, combined with comprehensive research on petroleum geology, favorable exploration areas below 8000 m are under evaluation to provide guidance and reference for ultra-deep oil and gas exploration.

2. Ultra-deep source rock

Source rock is the basis of oil and gas exploration, and the potential of deep oil and gas exploration depends on the existence, quality, and scale of source rock. Due to the deep burial of ancient Cambrian and Precambrian source rocks in the basin, few samples have been collected from drilling, so the source rocks of the outcrop areas were the focus of research in this work. The Tarim Craton consists of the Neoarchean-Early Proterozoic metamorphic basement and the overlying Neoproterozoic-Paleozoic marine-continental transitional facies and continental sedimentary formations. In the Early and Middle Neoproterozoic, the southern and northern Tarim Massifs and the Tarim arc terrane between them collided and merged into the unified Tarim craton [19]. During the evolution within the craton basin [10], the first set of sedimentary caprock developed in the Nanhua-Sinian Periods. Therefore, the oldest source rocks in the Tarim Basin may be the Nanhua System and the Sinian. A widespread global transgression happened in the Early Cambrian, leaving a set of widespread black shale. This set of high-quality source rock can be observed in drilling cores and outcrop sections in the Tarim Basin.

2.1. Cambrian source rock

In the Tarim Basin, there is a set of high-quality source rocks at the bottom of the Lower Cambrian Yu'ertusi Formation. The rock is black shale, which is well exposed in the Aksu Area in the northwestern part of the basin [20]. This set of source rock with a thickness of 10−15 m can be found at more than 20 outcrops (Fig. 1), with a quite stable bottom-up lithological combination of siliceous rock → phosphorous rock → black shale → carbonate rock. In the combination, the lower part is composed of gray or black concretionary siliceous rock and phosphorite intercalated with a small amount of thin shale. Above this is black phosphorous shale intercalated with black thin-layered siliceous rock, with more iron nodules of about 2 m thick. In the middle is a black shale layer about 6 m thick interbedded with thin-layer dolomite upwardly. At the top, there is black, yellow-green shale with thin-layered silty marlite, which turns upwardly into gray−white thin layer dolomicrite and nodular dolomite sandwiched with dolomitic shale. Among them, the mudstone has a total organic carbon (*TOC*) of 2%−6% in general, and the black shale layer in the middle has a *TOC* of up to 20%. The source rock samples collected from outcrop sections have a vitrinite reflectance (R_O) between 1.3% and 1.6%. The

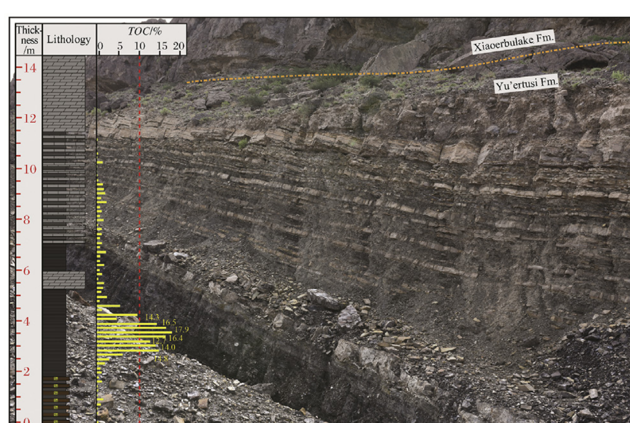


Fig. 1. Lithological and geochemical characteristics of high-quality source rock in the Cambrian Yu'ertusi Formation, Tarim Basin [21].

parental materials for hydrocarbon generation are mainly benthic multicellular algae organisms. This set of high-quality source rock mainly formed in the middle and lower ramp environment, in which ocean upwelling controlled the enrichment of organic matter [21].

Well XH1, the only well in the basin drilled the mudstone in the Yu'ertusi Formation, encountered the source rock of only 30 m thick. The varying thickness of source rock may be related to its development position. Especially in the Tarim Basin, the discovered outcrop locations and Well XH1 are located in the Aksu area in the northern part of the basin, which is close to the paleo-uplift and is in the middle and upper ramps of the continental slope [22], so the source rock is thin. The eastern part of the basin is the subsidence center (the Xishanbulake Formation and Xidashan Formation in the east). Seismic data shows that seismic reflections of the source rock in the central and eastern regions are much clearer, showing an increase of thickness. Therefore, it is speculated that the black mudstone in the deepwater environment of the continental shelf in central and eastern regions may have a greater thickness. Affected by the Keping Movement in the Tarim Basin, and the western part is the uplift area where the Lower Cambrian is absent. Whereas the Aksu area develops black shale of about 15 m; in the eastern part of the basin, there are thick mudstone deposits of the deepwater basin facies (including the Xishanbulake and Xidashan formations) which were already revealed by drilling. Therefore, it is speculated that this set of high-quality source rock in the Lower Cambrian is thicker in the deepwater facies in the middle and eastern parts of the basin [21]. It is demonstrated by seismic tracing that the source rock is widely distributed in the central and eastern parts of the basin, with a thickness of 15–45 m. So its distribution area is estimated at around 260 × 10^3 km^2. The marine oil and gas discovered in the Northern Tarim and Central Tarim areas may be mainly derived from this source rock. Therefore, it is also the most important source rock for the deep formations.

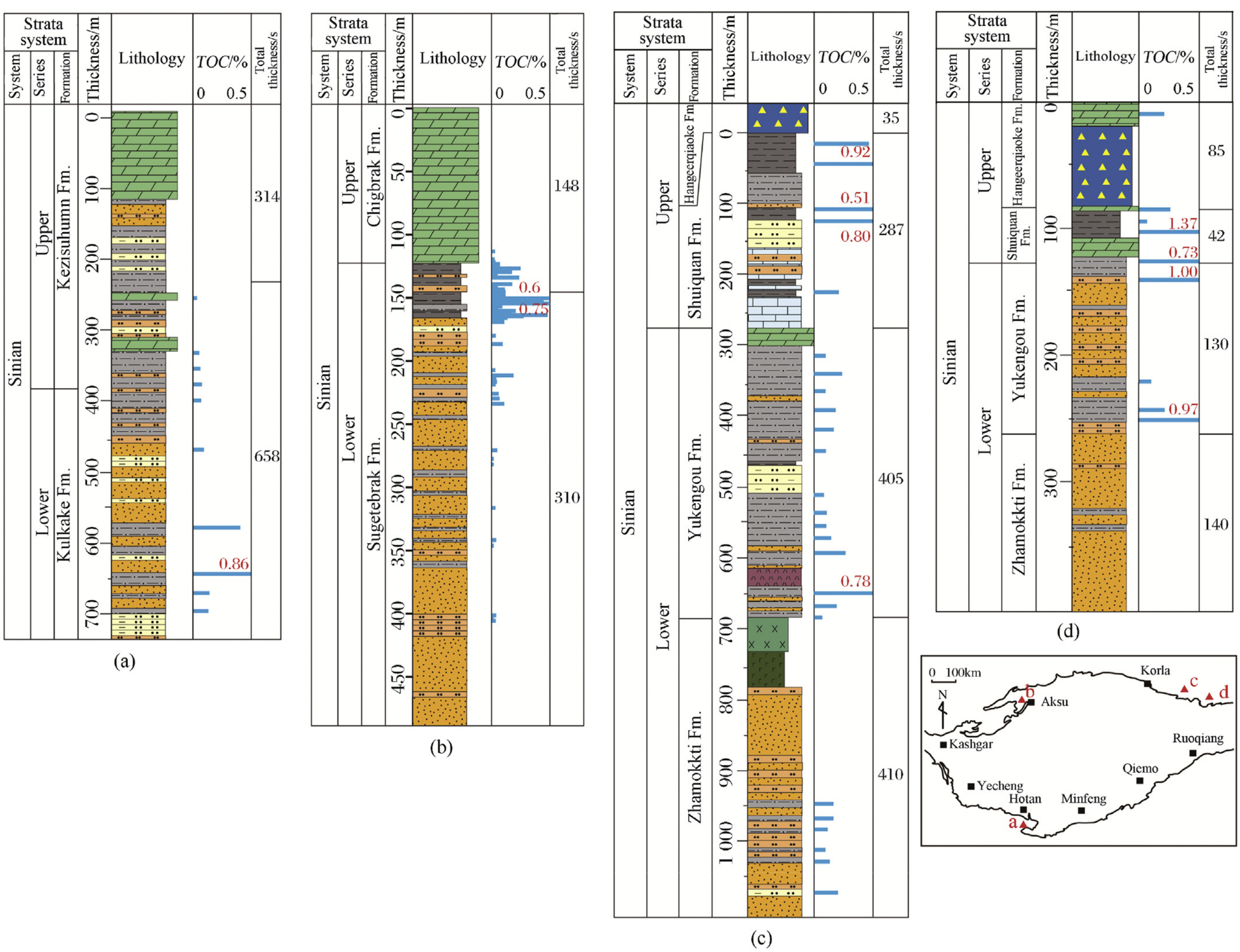


Fig. 2. Comparison of lithology and total organic carbon content of the typical Sinian source rock outcrops in the Tarim Plate. (a)Xinjiang-Tibet Highway Section, southwestern Tarim Basin; (b)Shiairike Section, Aksu area; (c)Qiakemaketieshi profile, southeastern Tarim Basin; (d)Yaerdangshan Section, southern Tarim Basin.

2.2. Sinian source rock

In different areas of the Tarim Basin, the Sinian mudstone occurs in different horizons [7] (Fig. 2). Among them, the upper part of the Sinian Sugetebulak Formation in the Shiairike Section of the northern Akesu area consists of dark gray, gray−green thin-layered silt-bearing mudstone in stable distribution, with a thickness of about 100 m (Fig. 2). Among them, the dark gray mudstone has a *TOC* of 0.2%−0.6% (strongly weathered). The Chigbrak Formation is dominated by medium-to thick-layered dolomite, with thin-layered mudstone in the lower part. It has *TOC* of 0.2%−0.5%, indicating poorer quality.

In the Qiakemaketieshi Section in northeastern margin of the Kuruktag North area, the dark gray and black shale in the Shuiquan Formation, have a *TOC* of 0.2%−0.92%, with a thickness of about 100 m, and relatively good quality [23]. The dark gray and gray-grey black argillaceous rocks in the Yukengou Formation have a *TOC* of 0.2%−0.78% and larger thickness (Fig. 2). In the Yaerdangshan Section of the Kuruktag South area, gray-grey black mudstone at the bottom of the Yukengou Formation has a *TOC* of 0.1%−0.97% and a thickness of 30 m. The thick gray and black muddy shale of the Shuiquan Formation has a *TOC* of 0.2%−1.37% and a thickness of 40 m (Fig. 3). In general, the Sinian source rocks show better developments in the Kuruktag area at the northeastern margin.

The Xinjiang-Tibet Highway Section in the southwestern Tarim Basin consists of the Lower Sinian Yutang Formation, the Kulkake Formation and the Upper Sinian Kezisuhumu Formation

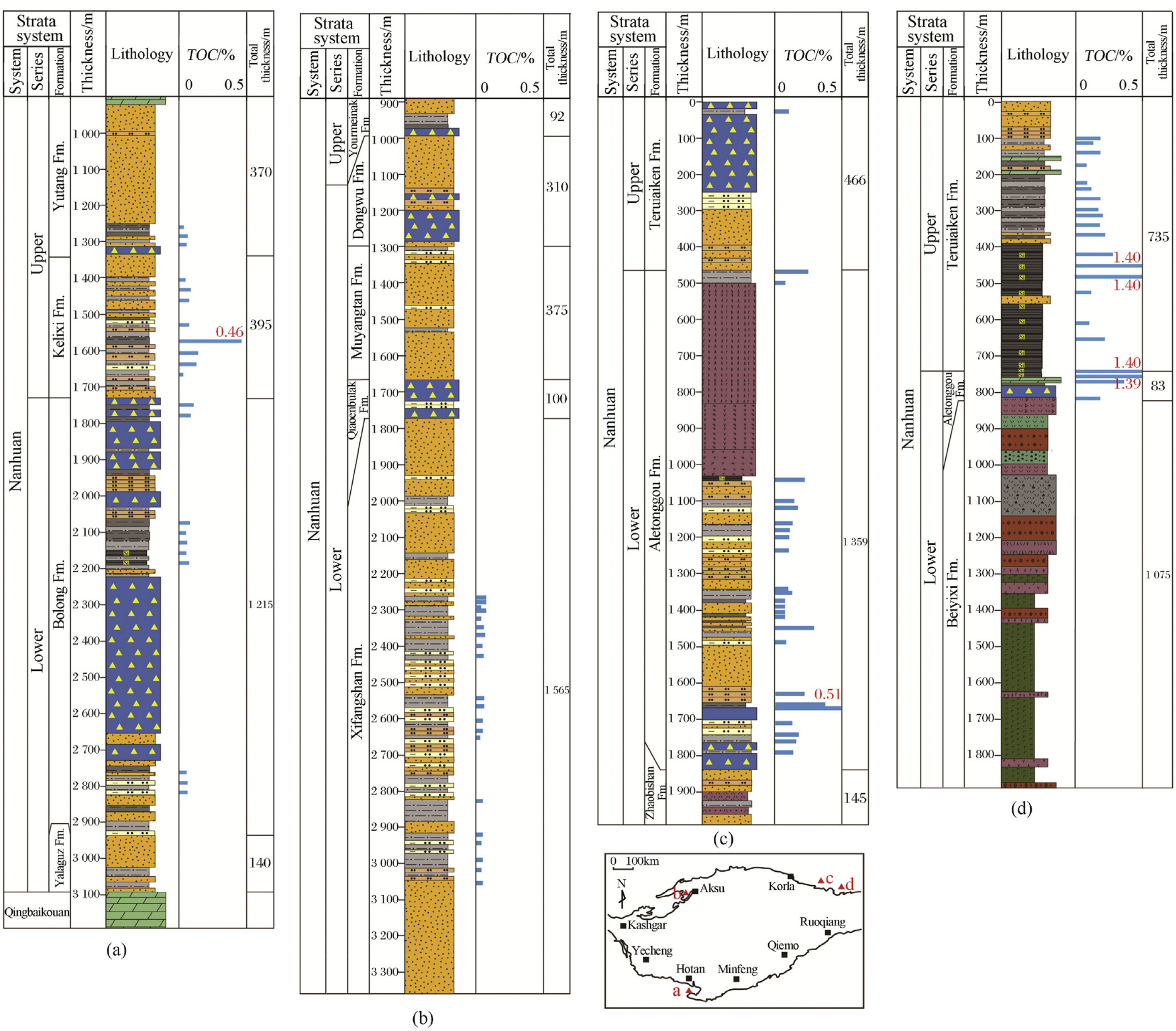


Fig. 3. Comparison of lithology and total organic carbon content of the typical Nanhua source rock outcrops in the Tarim Plate. (a)Xinjiang-Tibet highway section, Southwestern Tarim Basin; (b)Youermeinake Section, Aksu; (c)Qiakemaketieshi profile, Southeastern Tarim Basin; (d)Yaerdangshan Section, Southern Tarim Basin.

(Fig. 2). In the Kulkake Formation, there is a set of gray-black thin-layered argillaceous siltstone and mudstone, with a thickness of about 200 m and *TOC* as high as 0.86%, which are the major source rocks of the Sinian. The Kezisuhumu Formation consists of uneven intercalations of silty mudstone and siltstone in the lower part and dolomite intercalated with stromatolite in the upper part, but there is no source rock.

In general, the Sinian source rocks in the Tarim Basin are mainly mudstone, which occurs in the Shuiquan Formation, Kulkake Formation, Yukengou Formation, and Sugetebrak Formation. Due to the exposed position and strong weathering of the outcrops, fresh samples have not been collected, which is likely the primary reason for the low *TOC*.

2.3. Nanhua system source rock

All the completed wells in the Tarim Basin have not encountered the source rock of Nanhua System (for the source rock is more than 8000 m in depth). Through observation and analysis of samples taken from outcrop sections around the basin, it is believed that thick deepwater mudstone might develop in the Nanhua System of the Tarim Basin [7].

On the Xinjiang-Tibetan Highway Section in the southwestern margin of the Tarim Basin, the Kelixi Formation has thick mudstone and silty mudstone of more than 300 m thick. The mudstone generally has low *TOC* between 0.1% and 0.46% (Fig. 3). The outcrop is severely weathered, making it difficult to obtain fresh samples. It may be primarily responsible for the lower *TOC*.

The Nanhua System in the Yourmeinak Section in the Aksu area in the northwestern margin is completely exposed, including the Xifangshan Formation, Dongqiaoenbulak Formation, Muyangtan Formation, Dongwu Formation, and Yourmeinak Formation. The Xifangshan Formation has abundant mudstone and silty mudstone (Fig. 3), in which, the dark gray mudstone is about 50 m thick, but has low *TOC* of less than 0.1%. The poor quality of the source rock may be related to the weathering of outcrop either.

Bounded by the Xingdi Fault, the Kuruktag area in the northeastern margin is divided into the south and north parts, the Nanhua System in both of them have argillaceous source rocks [23]. The northern area has the Qiakemaketieshi Section (Fig. 3), where the Nanhua System Teruiaiken Formation has gray−green and black mudstone of basin facies, with *TOC* of less than 0.3%. The argillaceous rock in Aletonggou Formation has a TOC of 0.1%−0.51%, falling in the rank of poor-medium source rock, generally. In the southern part represented by the Yaerdangshan Section (Fig. 3), the Teruiaiken Formation has dark gray-black pyrite-bearing shale of more than 300 m thick of open continental shelf facies depositing in the euxinic environment. From the analytical data of Professor Zhong [23], the shale has a *TOC* between 0.2% and 1.4%. The black shale in the lower part mostly has a higher *TOC* of greater than 0.5% (Fig. 3). Therefore, there is source rock in the lower part of the Teruiaiken Formation.

Periphery outcrops, drilling and seismic data in the Tarim Basin show that the rift sequence of the Nanhua-Sinian has a typical binary structure, namely the syn-rifting sequence in the Nanhua System and post-rifting depression sequence in the Sinian (Fig. 4), with distinctly different structural-deposition features. The rifting basin in the Nanhua Period was characterized by a series of grabens or semi-grabens trending NE, showing a rapid "wedge-shaped" filling structure. In the Sinian Period, the rifting basin transformed into a depression, with less faulting and magmatism activities and universal overlapping deposition [7]. The rifting trough in the Nanhua Period controlled the distribution of dark-colored mudstone in the Nanhua-Sinian system. The Nanhua System source rock is mainly distributed in the central rift trough. Due to the limited exposure of outcrops in the Tarim Basin, outcropping locations revealing deep sedimentary system like those in Rift Trough in South China could not be found. Therefore, high-quality source rocks have not been discovered as well. Only thick mudstone was found, mostly intercalated with siltstone, with *TOC* of less than 1.0% generally, reflecting the sedimentary system at the edge of rift trough. Due to the control of rift

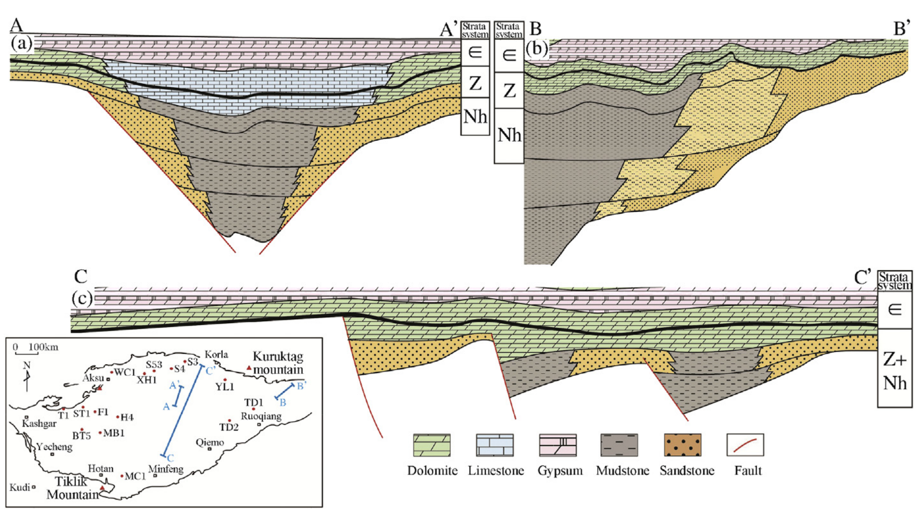


Fig. 4. Tectonic and sedimentary patterns of the Neoproterozoic rift in Tarim Basin.

trough on the distribution of source rock and hydrocarbon-generating center and according to the analysis of seismic data and sedimentary system, it is speculated that there is high-quality source rock in the Nanhua−Sinian System in the rift trough. This rift trough is a set of deepwater deposit of about 50−200 m thick, and is a set of important source rock in the deep formations.

3. Ultra-deep reservoirs

Exploration practice has confirmed that the deep ancient carbonate reservoirs are not affected so profoundly by the buried depth like those in middle and shallow depth. The formation of high-quality reservoirs is mainly controlled by sedimentary facies with strong hydrodynamic conditions, exposure, and leaching in the penecontemporaneous stage, and superimposed transformation of faults [24]. The sedimentary facies with strong hydrodynamic conditions are the material basis for reservoir formation that controls the distribution of karst reservoirs. The unconformity karstification is the key to reservoir formation, controlling the longitudinal zonation of the reservoir. The faulting activities further transformed the reservoir, controlling the lateral distribution of karst reservoirs.

3.1. Ordovician fracture-vug carbonate reservoirs

From the drilling results of the Ordovician, the deep fracture-vug carbonate reservoirs of more than 7000 m in the Tarim Basin are not abundant in matrix pores but dominated by large fractures and large vugs which combine into large-scale aggregates of fractures and vugs spatially. The seismic responses of the reservoir are mainly aggregates composed of large-scale and strong reflections, and bead cluster seismic facies. They are the most direct targets for searching wells with high-yield and stable production [25], and also the critical secret of high drilling success rate and fast productivity establishment of deep carbonate reservoirs in the Tarim Basin in recent years.

The reservoirs have visible stratification in the longitudinal direction and are distributed within 100 m below the sequence interfaces, especially near the fault zones. Spatially, they stack vertically and appear in quasi-layers along the unconformity

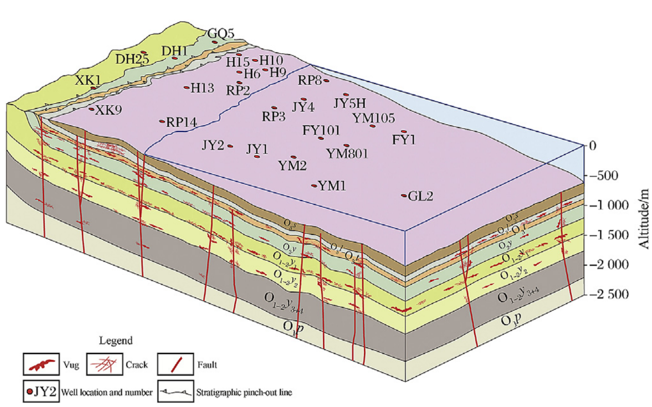


Fig. 5. Development patterns of the Ordovician karst reservoirs in ultra-deep strata of Tarim Basin.

surfaces (Fig. 5). The reservoirs have the apparent characteristic of superimposed karst alteration. Two factors mainly control superimposed karst alteration, interlayer karstification, and faulting. The fractures of faulting which act as karst channels control the lateral distribution scale of a reservoir. The inter-layer karstification controls the quasi-layered characteristic of the longitudinal development of the reservoirs. After the charging of oil and gas in the Late Hercynian Period, quick settlement and deep burial enabled preservation of the reservoir spatial structure and storage capacity of the reservoirs formed earlier.

Reservoir space in the ultra-deep carbonate reservoirs includes three types: pores, vugs, and fractures. Correspondingly, the reservoirs can be divided into cave type, vug type, and fracture type. The cave type, dominated by cave space, is the most important reservoir type of fracture-cavity carbonate rock. The storage space of this type of reservoir is composed of mainly dissolved vugs more than 20 mm in diameter, which appear as beaded reflections on the seismic section (Fig. 6). In the drilling process of this type of reservoir, drilling tool unloading and drilling fluid loss frequently occurred.

Through comprehensive analysis and research of various reservoir prediction techniques with seismic data, and combined with the analysis of logging, drilling, geological and other data, it is found the ultra-deep fracture-cavity carbonate reservoirs are concentrated in the range 100 m below the unconformity surface longitudinally. On the plane, their distribution is controlled by the strike-slip faults and in stripe distribution along faults. The distribution, shape and scale of karst reservoirs control the distribution, shape, and scale of oil pools. Long burial time and multiple alteration periods characterize the formation process of carbonate reservoirs. The high-quality reservoirs formed by multi-stage superposed alteration have the characteristics of complex genesis, diverse reservoir types and significant differences in different blocks. The dissolved pores, vugs, and fissures become effective storage space for oil and gas in deep layers.

By building a geological model and numerical calculation model, the development ability of associated fractures of the fault and the collapse depth of carbonate cavern were calculated. The results show the upper and bottom parts of the existing wall of faults can develop more fractures, while the middle of the fault walls has fewer fractures than the upper and bottom parts, and the development capacity of fracture increases with the decrease of distance to the fault plane. The high-quality carbonate reservoirs are distributed above 8500 m, and the closer to the faults, the more developed the ultra-deep reservoirs. At depths more than 11000 m, large pores gradually disappear, so do effective reservoirs (discussed in detail in another paper). In other words, there are effective reservoirs at a depth of less than 11000 m only.

3.2. Cambrian microbial dolomite reservoir

Through the field outcrop survey, drilling core, thin section analysis, and seismic data interpretation, it is believed that the Cambrian in the Tarim Basin experienced an evolution process from gentle slope to rimmed ramp [26,27]. There are two

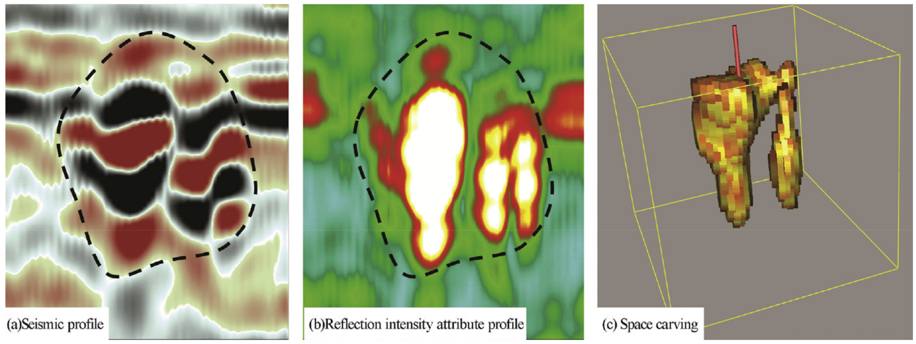


Fig. 6. Bead-like reflection seismic facies and its spatial engraving map of ultra-deep reservoir in Tarim Basin.

types of large-scale reservoirs in the Middle and Upper Cambrian in the Tarim Basin, large-scale gentle slope shoal in the Lower Cambrian Xiaoerbulake Formation and platform margin reef and shoal in Mid-Upper Cambrian (Fig. 7).

Large-scale gentle sloping beaches and microbial reservoirs developed in the Lower Cambrian, which has intergranular and intragranular dissolved pores and microbial cavities as main storage space (Fig. 8) and has a porosity of 2%−5%. They are 3−4 m thick in a single layer, over 50 m thick combined, and about 20×10^3 km^2 in the planar area (Fig. 9).

There are marginal microbial reef reservoirs of 300−900 m thick in the Middle and Upper Cambrian, of which the reef-building organisms were mainly cyanobacteria. The reef morphologies include dendritic skeletons, agglutinated clots, oncolites, and stromatolites. The storage space is mainly composed of microbial grid pores and dissolution pores formed by dissolution and transformation of cavities. The reservoirs have a porosity of 2%−9% (Fig. 10), generally and an area of about 23×10^3 km^2.

3.3. Sinian dolomite

The Sinian dolomite is a set of potential reservoir rock in the Tarim Basin. The rocks are mainly residual granular dolomite, microbial dolomite, and crystalline dolomite. They have formed paleo-karst weathering crust, microbial dolomite and burial hydrothermal alteration reservoirs. From the outcrop in the western part of the basin and limited drilling well data, the paleo-karst dolomite reservoir is the most important reservoir type in the Sinian. The paleo-karst weathering crust dolomite reservoir contains mostly dissolved pores and fractures as storage space, with a porosity of up to 20%. The reservoir is mainly distributed along the unconformity surface at the top of the Sinian 20−50 m below the unconformity surface generally.

The storage space of microbial dolomite reservoir is made up of mostly fenestral pores, foamy layered cavities, lace-shaped dissolved vugs, and intergranular dissolved pores. Although the fenestral vugs, foamy layered cavities, and lace-shaped dissolved vugs are mostly filled by dolomite, residual pores are still visible. Statistics show that the porosity is between 2% and 5%. This kind of reservoir is mainly distributed in the middle of the Upper Sinian and controlled by the high-energy sedimentary facies.

The storage space of dolomite reservoir formed by buried hydrothermal alteration is mainly composed of intercrystalline pores, intercrystalline dissolved pores, karst caves and fractures [28], with a porosity of 1%−4%. This kind of reservoir is mainly distributed along a fault and paleo-karst weathering crust (Fig. 11).

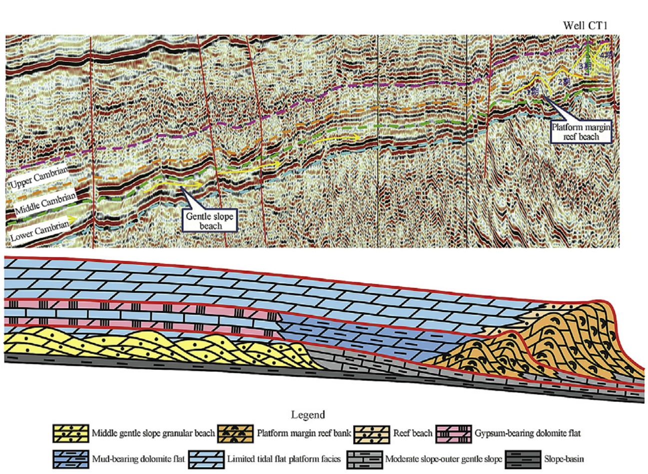


Fig. 7. Seismic profile and sedimentary pattern (two types of reservoirs: gentle slope and platform margin shoal) of the Cambrian in Tarim Basin.

4. The phase of ultra-deep oil and gas

In recent years, with the further deepening of oil and gas exploration, deep gas exploration has continuously made discoveries, for example, the Yuanba gas field discovered in the Sichuan Basin and the Keshen gas field discovered in the Kuqa Depression in the Tarim Basin, their burial depth is 7000−7800 m [29]. In the exploration of crude oil, there are fewer ultra-deep large oil fields discovered, most of which are mainly in the Tarim Basin. According to the traditional theory of petroleum geology, a temperature rise is one of the leading causes of the formation of oil and natural gas. When the temperature is higher than 160 °C or the depth is more than 6000 m, gas begins to crack from crude oil, and then the liquid oil gradually disappears [30]. Therefore, there are “oil and gas windows” and “death lines” in oil and gas exploration [31]. Due to the high temperature in deep layers, gas may crack

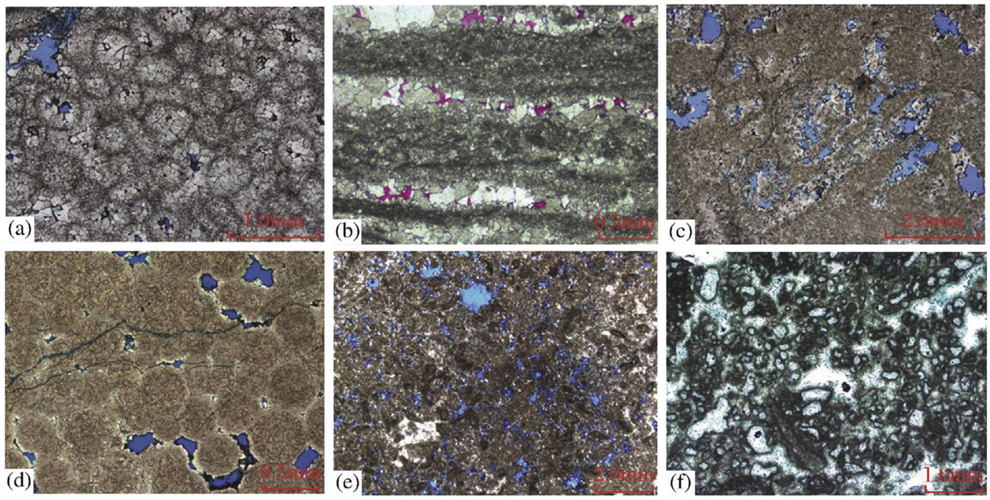


Fig. 8. Microscopic reservoir characteristics of the Lower Cambrian Xiaoerbulake Formation in Tarim Basin. (a) Shiaizikegou, foamy layered dolomite, dissolved cavity hole, $\in_{1}x$; (b) Shutan 1, stromatolite, fenestral vug, $\in_{1}x$; (c) Heishan Section, pelitic agglutinated dolomite, $\in_{1}x$; (d) Chutan 1, oolitic dolomite, intergranular dissolved pores, $\in_{1}x$; (e) Kang 2, psammitic dolomite, intergranular dissolved pores, $\in_{1}x$; (f) Fang 1, foamy layered dolomite, dissolved cavity pore, $\in_{1}x$.

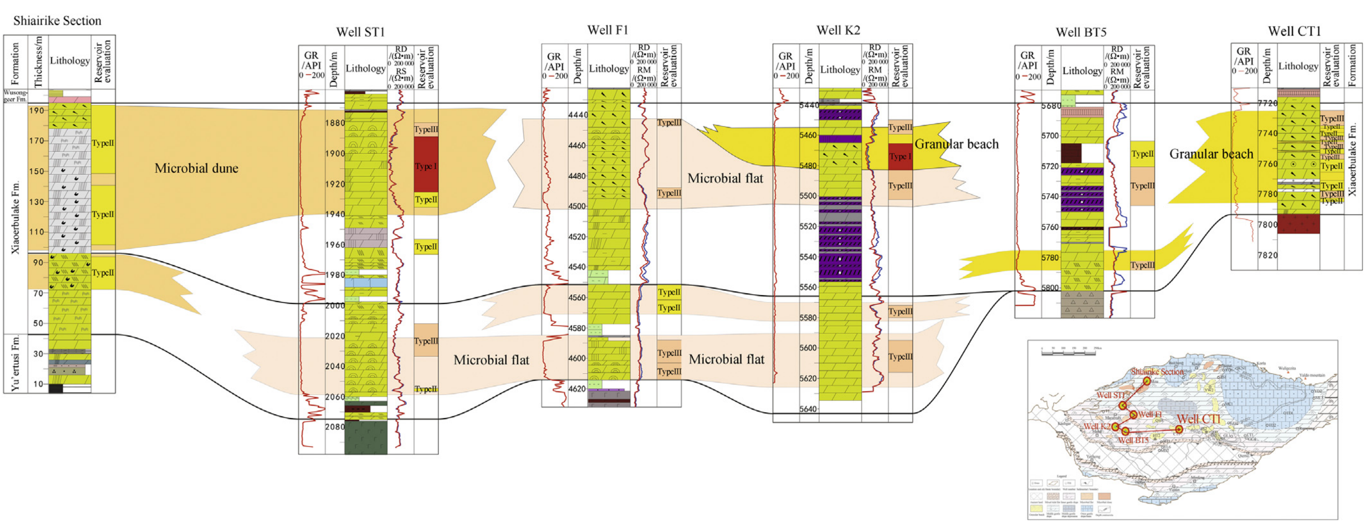


Fig. 9. Cross-well correlation of sedimentary reservoirs in the Cambrian Xiaoerbrak Formation of Tarim Basin.

from the crude oil. Therefore, it is traditionally believed that deep oil and gas exploration is searching gas principally. Recently, Well FY1 drilled on the southern slope of the north of Tarim Basin obtained high-yield oil flow in the deep Ordovician reservoir at 7711 m. The reservoir is a pure oil reservoir without oil cracking [18]. An oil reservoir was also discovered at a depth of 7750 m in Well GL1. Crude oils from these two wells do not have various types, and high abundant adamantane compounds like those in Well ZS1C [32] (Fig. 12a). The content of adamantane compounds in oil from Well FY1 is basically at the baseline of the standard high maturity crude oil, and relatively low in content [18] (Fig. 12b). The discovery of these ultra-deep reservoirs broke the understanding of traditional petroleum geology, indicating that the thermal stability of crude oil may be much higher than being expected. Then at what depth would the crude oil start cracking, and at what depth would the liquid petroleum disappear and the oil reservoir converts into a gas reservoir?

Thermal dynamics is the basis for the cracking of crude oil and plays a pivotal role in the cracking of crude oil [33]. In some deep reservoirs in the Tarim Basin, the reservoir temperature is higher than the conventionally believed cracking temperature of crude oil (160 °C), but the oil has not cracked, and the reservoirs remain conventional oil reservoirs. This information indicates that temperature is not the only factor determining the cracking of crude oil. The combination of lithology, mineral composition, water medium conditions, and pressure, may inhibit or delay the cracking of crude oil. In some marine layers with sulfate, the rapid cracking of crude

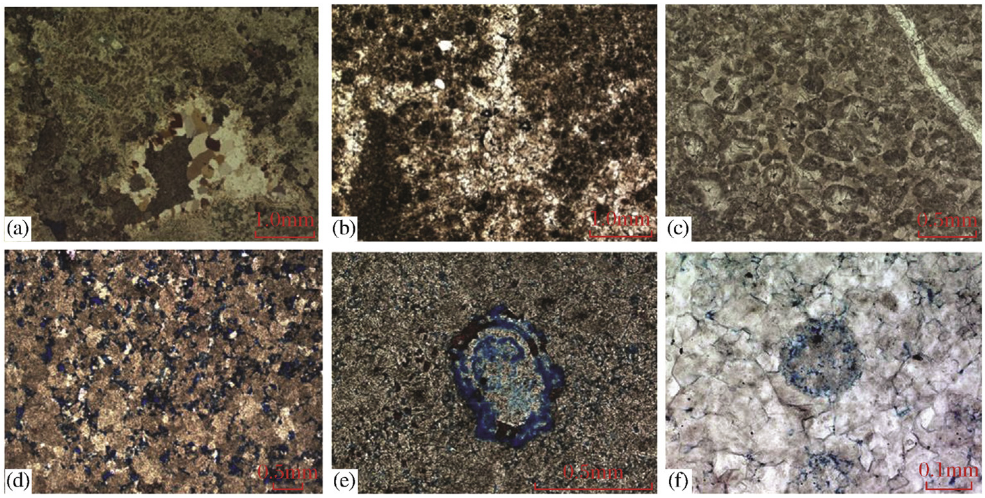


Fig. 10. Microscopic characteristics of the upper Cambrian platform margin reef and shoal complex reservoir in Tarim Basin. (a) Chengtan 1, epiphytic bacteria dolomite, skeletal dolomite and dissolved pores, $\in_3 q$; (b) Chengtan 1, pelitic agglutinated dolomite, fenestral cavity, $\in_3 q$; (c) Chengtan 2, kidney-shaped bacteria dolomite, intragranular dissolved pores, $\in_3 q$; (d) Chengtan 1, dolomicrite, microbial casted pore, $\in_3 q$; (f) Chengtan 1, residual oolitic dolomite, intragranular dissolved pores, $\in_3 q$.

oil could occur due to the thermochemical reaction of sulfate (TSR) [34−36]. Consequently, for the temperature threshold of crude oil cracking into gas, it is considered that the TSR effect in the reservoir can lower the temperature threshold of crude oil cracking and accelerate the degree of cracking, and the geochemical properties and composition of crude oil. Therefore, the compensation of time and temperature all have some effects on oil cracking, apart from the factor of temperature. There are no conditions (no sulfate) for TSR reaction in the oilfields of Fuyuan, Guole, and Yueman Oilfields in northern Tarim Basin [37], and no thioxo-adamantane compounds indicating TSR action being detected; therefore, the first factor can be excluded.

The current geothermal gradient in the Tarim Basin is 2.0−2.2 °C/100 m (mainly in the northern and central Tarim areas, and the geothermal gradients in the central Tarim and Gucheng area are higher), and the maximum depth has been reached since the last 5 Ma. Since 5 Ma, the basin has entered the stage of rapid subsidence, and the thickness of the overlying strata has increased by more than 2000 m, making the paleo-reservoir reach the maximum depth [38,39]. According to the measurement of wells in northern Tarim Basin, the temperatures at a 7500 m depth of the well bottom are about 150−170 °C. Therefore, the low geothermal gradient and insufficient compensation effect of late rapid burial process make crude oil cracking need more considerable burial depth. Through cracking experiments, Pan et al. [40] found that the temperature required for 50% crude oil to convert into methane was above 220 °C. Also, from the thermal simulation experiments of conventional marine crude oil in the Tarim

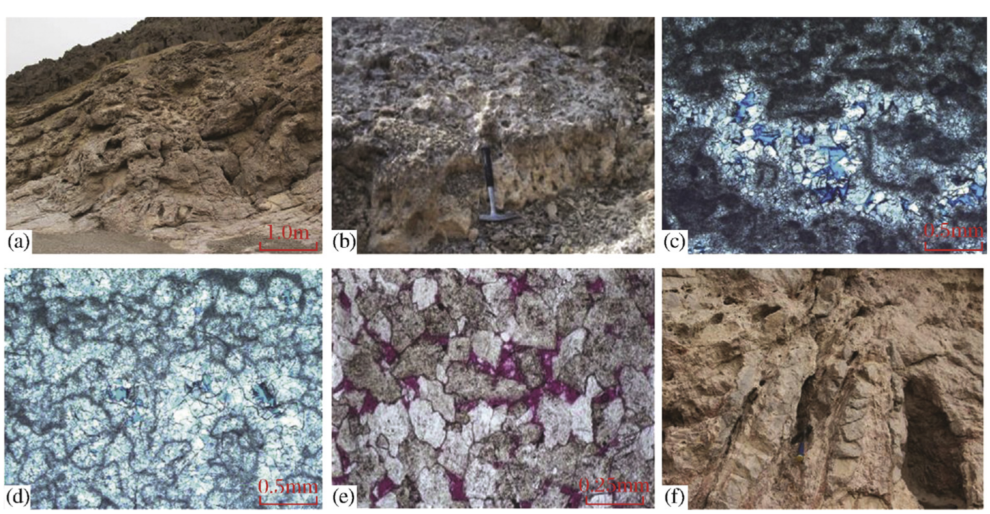


Fig. 11. Macroscopic and microscopic characteristics of the Sinian dolomite reservoirs in Tarim Basin. (a) Western ditch of Xiaoerbulake, karst weathering crust reservoir, Z_2q; (b) Sugaitebulake karst weathering crust Z_2q; (c) Shiairike, lace-shaped vug, Z_2q; (d) Shiairike, foam layered cavity, Z_2q; (e) Tadong 2, fine-grained dolomite, intercrystalline dissolved pores, Z_2s; (f) Western ditch of Xiaoerbulake, hydrothermally-altered reservoir Z_2q.

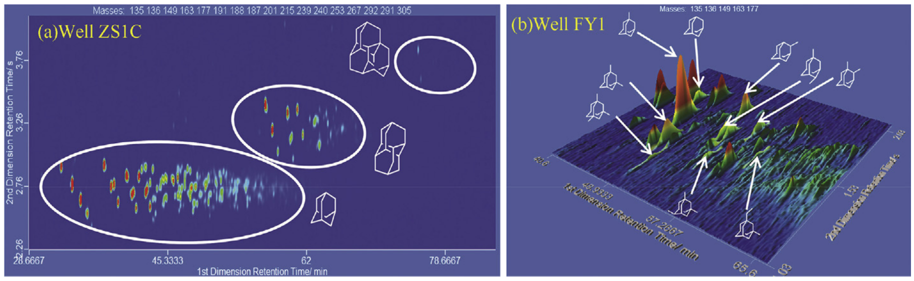


Fig. 12. Comprehensive two-dimensional gas chromatography distribution characteristics of adamantine compounds in crude oil samples from Well ZS1C and FY1 in Tarim Basin.

Basin and the calculation of kinetic parameters of crude oil cracking gas, Zhu et al. [38] estimated that at a constant temperature of 180 °C, it would take 52.8 Ma for the oil to reach the conversion rate of 51%; while in the case of a general continuous increase of burial depth (2 °C/Ma), it would take more than 100 Ma to reach the same degree of cracking. Therefore, stable burial under high-temperature conditions is more conducive to cracking of crude oil. Therefore, according to the thermal history and burial history of the Tarim Basin, the depth at which crude oil starts cracking in Northern Tarim area is about 7500−8000 m, while the large-scale cracking should take place at 8800−9500 m (Fig. 13) and the corresponding reservoir temperature is 210−220 °C. At 9000 m, the liquid oil disappears, that is, 9000 m in the Tarim area is the death line of oil. In other words, formations more than 9000 m deep only contain gas, while formations less than 9000 m deep could have oil. Therefore, the exploration potential of deep crude oil is vast.

5. Analysis of favorable exploration areas

The Sinian-Ordovician in the Tarim Basin has multiple sets of reservoir-cap combinations (Table 1). Among them, the dolomite deposited on the upper semi-restricted platform of the Sinian is transformed into good reservoir due to karstification and constitutes into the right reservoir-cap combination with the Lower Cambrian deepwater mudstone. There are two sets of reservoirs and caprocks in the Cambrian System. One is made up of the granular shoal reservoir of the Lower Cambrian Xiaoerbulake Formation and the gypsum rock in the Middle Cambrian as the caprock. The other is made up of the platform margin reef and shoal reservoir in the Middle-Upper Cambrian, and the marl caprock in the upper platform-slope facies. There are multiple sets of reservoir-caprock combinations in the Ordovician. In the large-scale high-energy granular shoal deposits in the Penglaiba, Yingshan, and Yijianfang formations, karst reservoirs develop due to the exposure and leaching in multiple cycles of sea level fluctuation, which combine with the overlying tight limestone or mudstone caprocks into good reservoir-caprock combinations. These combinations obtain good exploration results. Due to the restriction of exploration cost, the wells drilled so far in the basin are mostly less than 8000 m deep, and the strata more than 8000 m deep in the Tarim Basin will be the focus of exploration in the future. The main favorable exploration areas and zones include the northern slope of Northern Tarim, northern slope of Central Tarim, and the periphery of the Manxi low uplift area.

5.1. Sinian System

In the Sinian System, the transgression-high system tract sedimentary system deposited during the rifting period is composed of the coastal neritic clastic rock and platform

Table 1
Reservoir-caprock combination in the Sinian and Ordovician of Tarim Basin.

No.	Series	Reservoir-caprock combination	Representative well
1	O	Caprock: mudstone in the Sangtamu Formation	H62
	O	Reservoir: Platform margin reef and shoal in the Lianglitage Formation	
2	O	Caprock: Mudstone in the Tumuxiuke Formation	H15
	O	Reservoir: Granular shoal in the Yijianfang Formation	
3	O	Caprock: Overlying tight limestone	GC6
	O	Reservoir: Granular shoal in the Yingshan Formation	
4	O	Caprock: Tight limestone at the bottom of Yingshan Formation	TZ162
	O	Caprock: Granular shoal in the Penglaiba Formation	
5	Є	Caprock: Tight limestone at the bottom of Penglaiba Formation	CT1
	O	Caprock: Reef and shoal bodies in the Middle and Upper Cambrian	
6	Є	Caprock: Gypsum rock in the Middle Cambrian	ZS1
	Є	Reservoir: Granular shoal in the Xiao'erbulake Formation	
7	Є	Caprock: Mudstone in the Yu'ertusi Formation	QG1
	Z	Caprock: Dolomite in the Qigebulake Formation	

facies carbonate rock [41]. They are dolomite reservoir in the upper Sinian, source rock in the Lower Sinian, and mudstone in the Lower Cambrian Yu'ertusi Formation which may act as caprock, constituting a reservoir-caprock combination. Additionally, the source rocks in the Lower Cambrian Yu'ertusi Formation are mainly distributed in the slope-continent shelf facies, and the oil and gas generated by this set of source rock could migrate laterally to accumulate in the Sinian reservoir. Since the burial depth of Sinian generally exceeds 10000 m, paleo-uplifts, and slope areas are favorable places for searching Sinian oil and gas reservoirs (Fig. 13).

5.2. Cambrian subsalt dolomite

In the Early Cambrian, the Tarim Basin experienced large-scale transgression and was controlled by the overall terrain high in the west and low in the east, showing evident differentiation from the west to east. The platform in the west was gentle and wide, belonging to the deposits in the ramped platform [42]. Wells drilled reveal that there is dolomite reservoir developed in the Lower Cambrian Shao'erbulake Formation. Longitudinally, it is adjacent to the source rock of Yu'ertusi Formation, and above the dolomite reservoir is the Middle Cambrian thick-layered salt rock, forming a very favorable source-reservoir-caprock combination [43]. According to the analysis of petroleum geological conditions, it is believed that the favorable exploration zones of the Cambrian subsalt dolomite more than 8000 m deep (at the altitude of approximately −7000 m) are the northern slope of low uplift in Central Tarim Area, southern slope of Northern Tarim Uplift and Gucheng-Xiaotang area (Fig. 14a).

(1) The Central Tarim Uplift started to form at the end of Early Ordovician and ended in the Early Hercynian Period [44]. Well ZS1C has obtained industrial oil flow from the subsalt dolomite, indicating that the Central Tarim Uplift has favorable conditions for forming large primary oil and gas fields. According to seismic prediction, the subsalt dolomite shoal more than 8000 m deep, mainly concentrates on the northern slope of Central Tarim Uplift, with extensive distribution area and large-scale reservoir (Fig. 14b). Also, the upper caprock is mainly gypsum salt rock. From predictions, the northern slope of Central Tarim Uplift has a good chance of discovering large oil and gas fields and is also the most realistic area to make a breakthrough in oil and gas exploration in ultra-deep Cambrian layers more than 8000 m deep.

(2) The Northern Tarim Uplift started to form in the Caledonian Period and has developed successively at a large scale. In the Upper Ordovician, vast oil and gas fields have been found, where oil and gas are enriched and distributed along the strike-slip faults (deep fault linking to oil source), indicating that the oil and gas have migrated vertically. Therefore, the deep oil and gas source conditions are right. To date, the wells drilled haven't encountered the Cambrian subsalt dolomite reservoirs in the Northern Tarim Uplift, but the seismic data shows that the imbricated frontal reflection structure is widely developed on the southern slope of the Northern Tarim Uplift, indicating grain beach deposits (mound and shoals) on gentle slope, which can form large-scale effective reservoirs by dissolution (Fig. 14c). There is high-quality source rock with a large thickness in the Lower Cambrian Yu'ertusi Formation on the southern slope of the Northern Tarim, showing the right source rock conditions. There are gypsum salt and gluten caprocks above the reservoir, indicating that the southern slope of the Northern Tarim Uplift has favorable conditions for forming large lithologic reservoirs and is the most likely area for concentrated ultra-deep reservoirs in the Tarim Basin.

(3) The Gucheng-Xiaotang South area is located in the western part of the Mangal Sag, adjacent to the source rocks of the Mangal Sag. The area was a ramp platform in the Early Cambrian when granular shoal facies deposited. The upper part is the Middle Cambrian gypsum rock and dolomicrite, showing favorable conditions for forming lithologic-stratigraphic reservoirs.

5.3. Cambrian platform margin belt

The Tarim Basin experienced a process of regression-transgression from the end of Early Cambrian to Late Cambrian. Controlled by the overall terrain high in the west and low in the east, steep platform margin developed based on ramp platform margin, which is distributed along the Lun'nan-

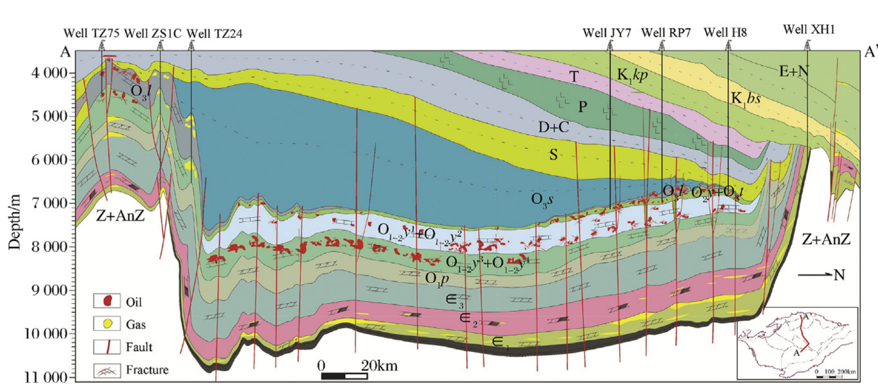
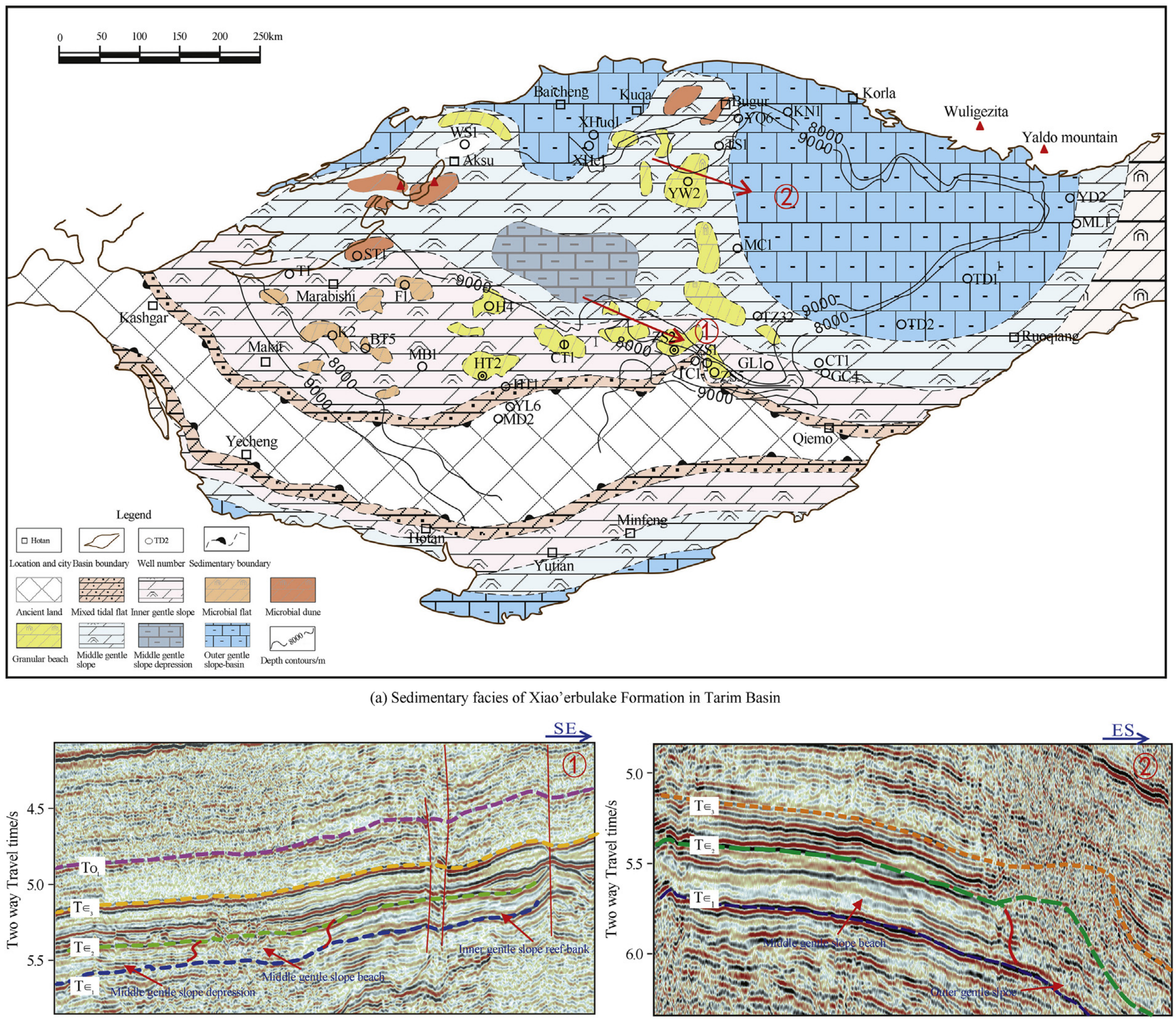


Fig. 13. Prediction of ultra-deep oil and gas properties in Tarim Basin.



(a) Sedimentary facies of Xiao'erbulake Formation in Tarim Basin

(b) Seismic profile in the northern Tazhong Uplift

(c) Seismic profile in the southern Tabei Uplift

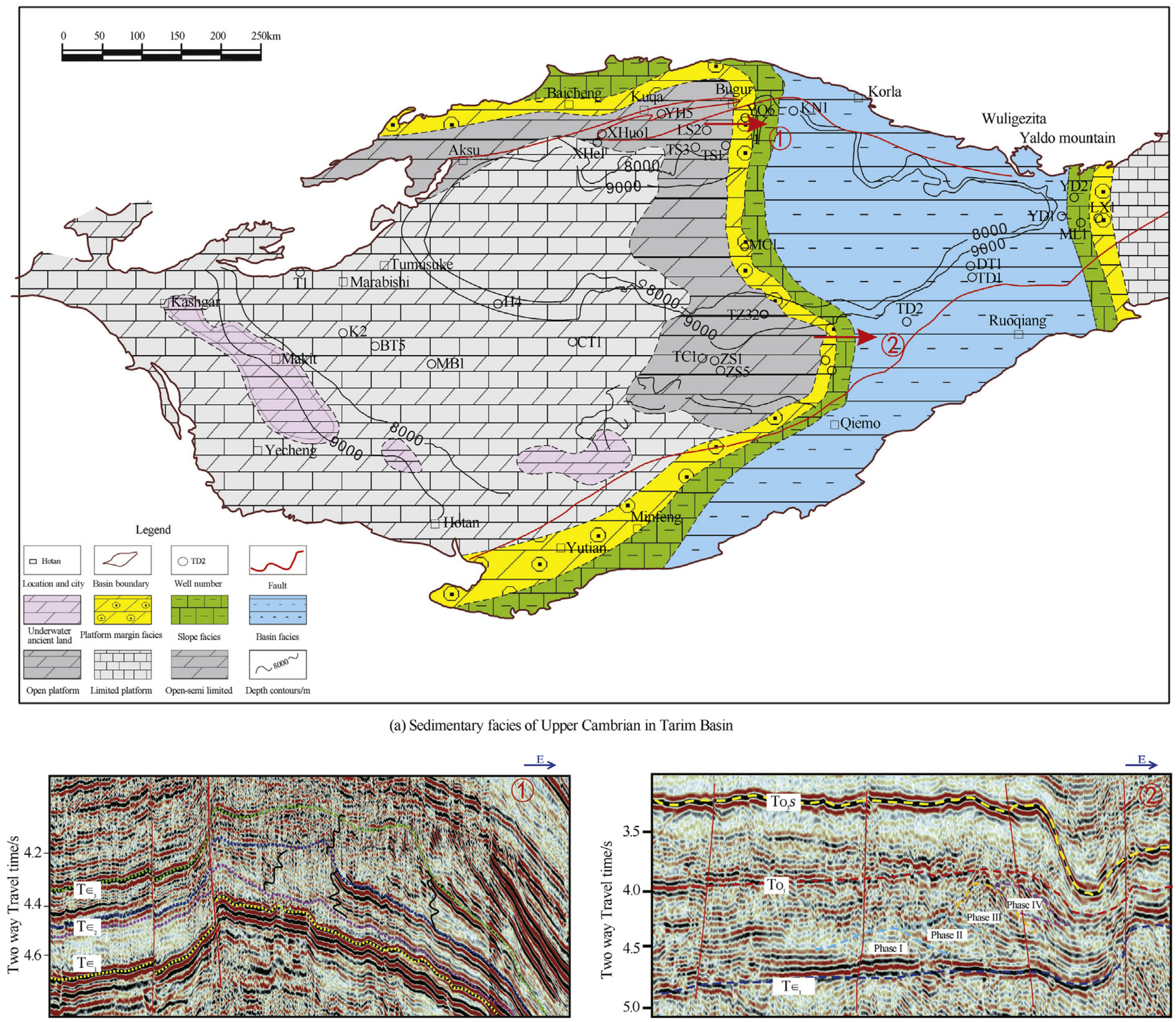
Fig. 14. Sedimentary facies and projected favorable area of the Early Cambrian in Tarim Basin.

Gucheng Line in the west of the Mangal Sag. The northern platform margin belt was denudated due to the formative influences. Starting from the North of Tarim Uplift, and reaching the Gucheng area in Eastern Tarim Uplift, the platform margin belt in western Mangal Sag appears as an arc trending near NS, slightly convex to the west in the middle interval. It is about 433 km long from north to south and about 22–106 km wide from east to west. At present, the exploration of the Cambrian platform margin is mainly concentrated in the Lun'nan area in the north and Gucheng area in the south. The five wells drilled all encountered good reservoirs and detected good oil and gas shows, heralding great prospects of exploration in the platform margin zone [45,46].

Affected by paleo-geomorphology and fluctuation of sea levels, multi-period of reefs developed at the Cambrian platform margin. According to the 3D seismic data, there are four stages of margin reef shoal bodies in the Middle-Upper Cambrian (Fig. 15b and c). According to the analysis of petroleum geological conditions, it is believed that the favorable exploration zones of the Cambrian rim margin (below 8000 m) are in the Lun'nan-Gucheng area (Fig. 15). The Lun'nan-Gucheng area is adjacent to the Lower Cambrian source rock hydrocarbon-generating center, and the platform margin reef shoal reservoir is well developed. Among them, the reservoir-caprock combinations made up of the Upper Cambrian platform margin reef and shoal and tight limestone in the Penglaiba Formation, and the Middle Cambrian platform margin reef and shoal and Upper Cambrian caprocks are key zones for exploration in platform margin facies.

5.4. Ordovician Penglaiba Formation

From the end of Late Cambrian to the Early Ordovician, the Tarim Basin developed a differential pattern from east to west, with platform facies deposit in the west and deepwater basin facies in the east. The platform was tectonically stable, with the development of large-scale granular shoal deposits in Taxi platform, which is the first set of interlayer karst reservoir in this area. Several wells have obtained good gas shows, revealing promising oil and gas exploration potential of



(a) Sedimentary facies of Upper Cambrian in Tarim Basin

(b) 3-D seismic profile in Lunnan area

(c) Seismic profile in northern Gucheng area

Fig. 15. Sedimentary facies and projected favorable area of the upper Cambrian in Tarim Basin.

Penglaiba Formation [47]. According to the analysis of petroleum geological conditions, the potential favorable exploration areas of the Penglaiba Formation (below 8000 m) are the southern part of the Lun'nan Slope and the Keping area (Fig. 16). On the eastern part of the southern slope of the Northern Tarim Uplift is the Lunan Slope, where dolomitized shoal bodies are well-developed in the Penglaiba Formation, the overlying Yingshan Formation has few reservoirs in the third and fourth members with the right sealing conditions. The key to exploration is to find the karst faults linking with the source rocks.

5.5. Ordovician Yingshan Formation

During the deposition period of the Yingshan Formation, the basin inherited the structural pattern of the west platform and east basin in the early stage. The platform was structurally stable, and widespread granular shoals developed in the West Tarim Platform (Fig. 17a). So far, the Tahe Oilfield, Halahatang Oilfield, and the Central Tarim condensate gas field have been discovered. Although these oil and gas fields are very complicated in oil and gas properties [48−55], huge in reserves, they are the main forces of the Tarim Basin. With the rolling of exploration and the deepening of understanding, discoveries have been made in Yingshan Formation of the Guole and Shunbei blocks in the Manxi low uplift area, showing the good prospects of oil and gas exploration in the deep carbonate rocks of the Yingshan Formation. It has been proved by exploration that the NE trending strike-slip faults in the Caledonian Period can effectively communicate with the Cambrian oil source. The karst reservoirs in the Ying 2 Member and the compact limestone in the Ying 1 Member constitute of the right reservoir-caprock combination, which form favorable conditions for the formation of large oil and gas fields. The favorable exploration area for the Ordovician Yingshan Formation (below 8000 m) is in the eastern part of the Manxi low uplift area. The seismic profile of this area shows bead-like and flaky reflections (Fig. 17b and c). Searching for a fault-dissolving body in high coincidence with the NE-trending fault is the key to exploration.

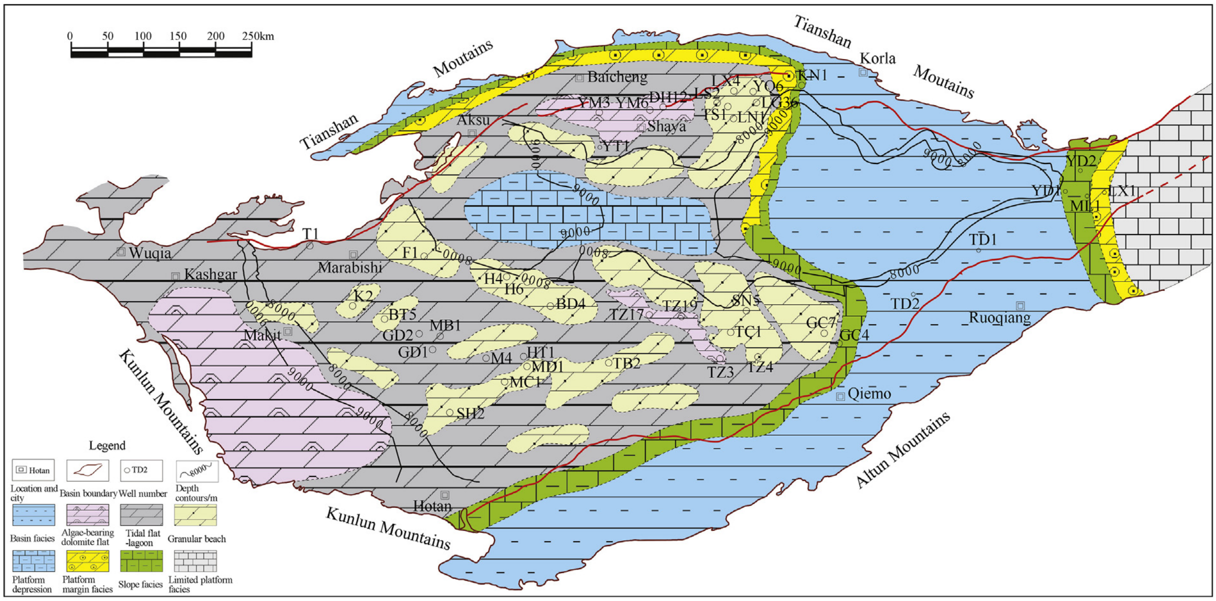
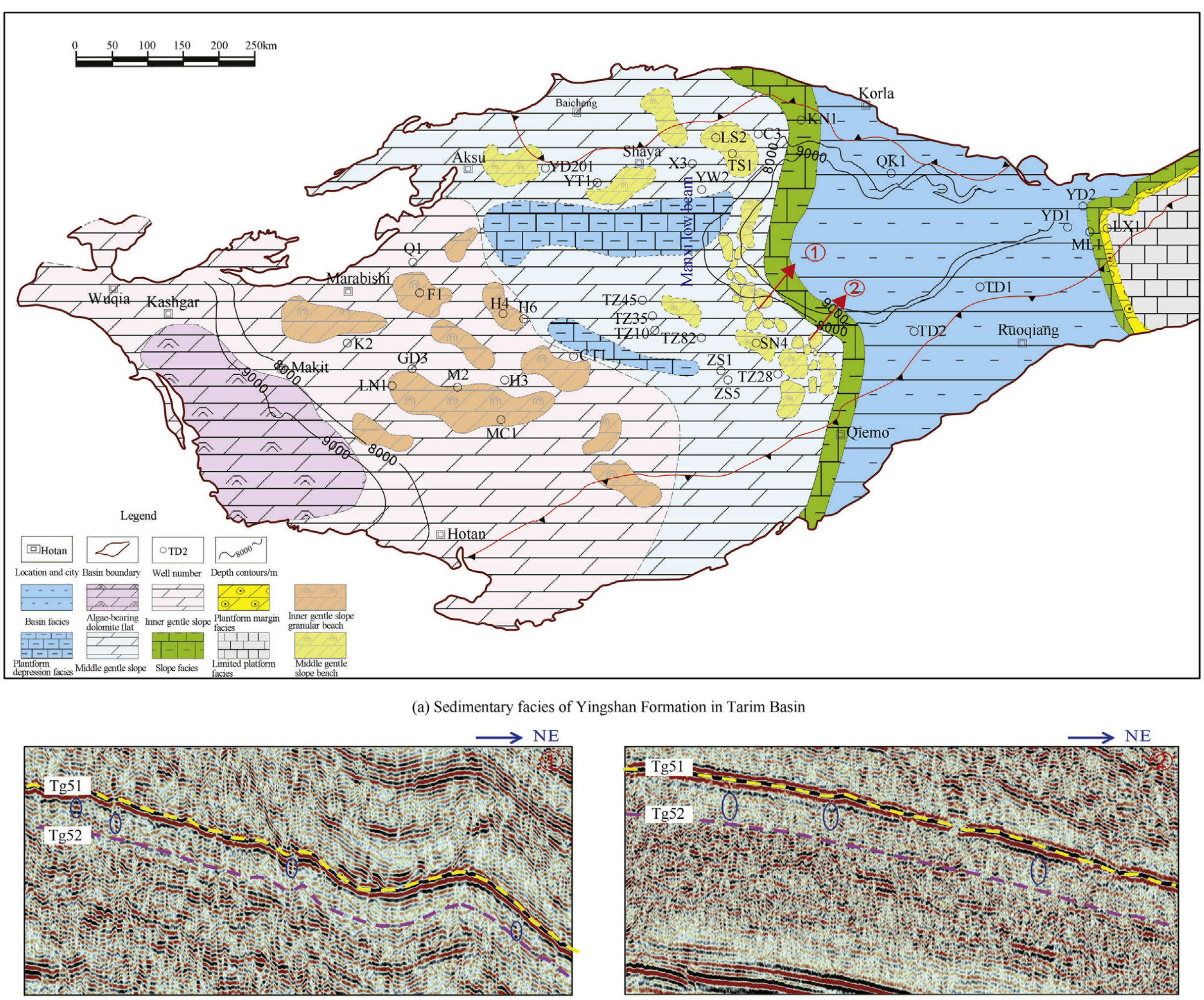


Fig. 16. Sedimentary facies and predicted favorable areas of the Ordovician Penglaiba Formation in Tarim Basin.



(a) Sedimentary facies of Yingshan Formation in Tarim Basin

(b) Seismic profile in Xiaotang area

(c) Seismic profile in Gucheng area

Fig. 17. Sedimentary facies and predicted the favorable area of the Ordovician Yingshan Formation in Tarim Basin.

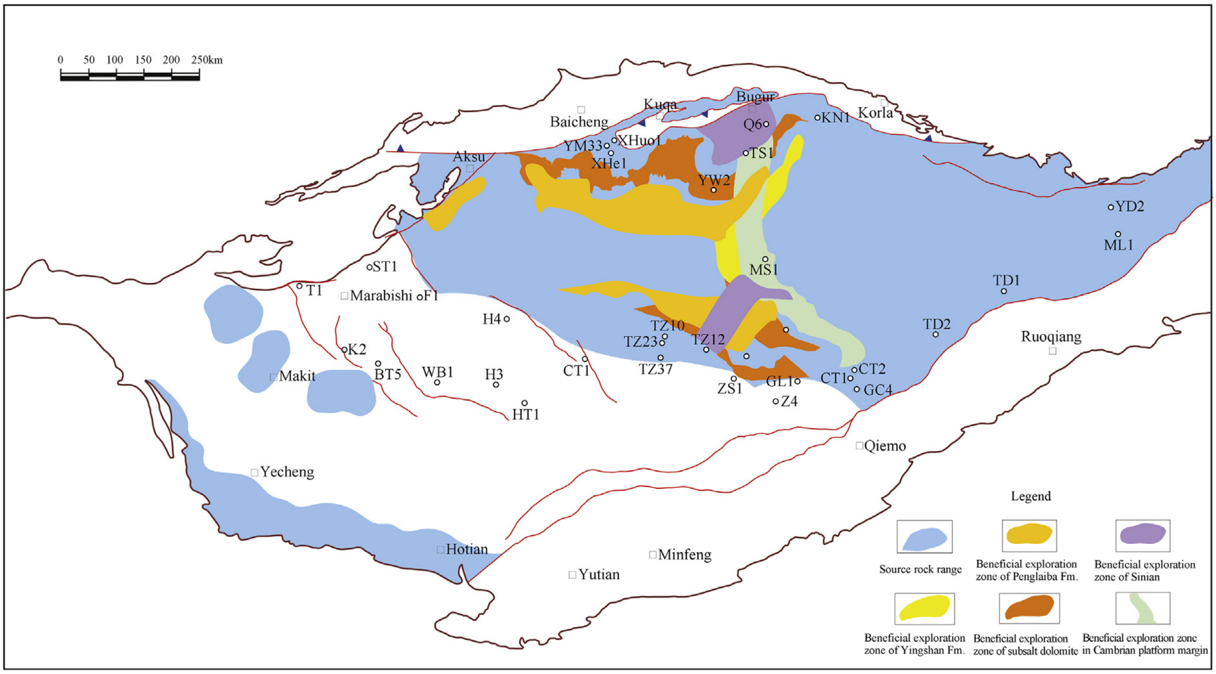


Fig. 18. Prediction of favorable exploration areas for formations more than 8000 m deep in Tarim Basin.

Major favorable zones for exploration in different horizons more than 8000 m deep have been sorted out to superimpose possible high-quality source rocks in the Cambrian and Sinian (Fig. 18). Restricted by source rocks, the agreeable exploration areas for the Sinian are mainly distributed in the East Tarim Uplift, and the Keping faulted arc. The agreeable areas of the Cambrian subsalt dolomite are mainly distributed in the periphery of the paleo-uplift and near the sedimentary line of the Xiao'erbulake Formation. The burial depth of subsalt dolomite in the Gucheng-Xiaotang area is more profound than that in the southern slope of Northern Tarim and the northern slope of Central Tarim. Therefore, the southern slope of Northern Tarim and the northern slope of Central Tarim are the future exploration focuses. The favorable areas of the Cambrian platform margin are mainly distributed in the line of Lun'nan-Gucheng, which has always been taken as the turning point of differentiation between the east and west in the basin. The commendable exploration areas of the Ordovician Penglaiba Formation are distributed in the Keping faulted arc and the northern slope of Northern Tarim. The favorable exploration area for the Ordovician Yingshan Formation is located in the eastern part of the Manxi low uplift area. The exploration of favorable areas below 8000 m in the basin should concentrate on the paleo-uplifts and lithologic facies varying belts around high-quality source rocks, and find large-scale, high-quality reservoirs as exploration leads.

6. Conclusions

In the ultra-deep strata of the Tarim Basin, there are Lower Cambrian, Sinian and Nanhua System source rocks, Ordovician karst reservoirs, Cambrian gentle slope, platform margin reef, shoal reservoirs, and Sinian microbial dolomite reservoirs. Multiple sets of reservoir-caprock combinations are also found. All these suggest ultra-deep layers more than 8000 m deep have adequate accumulation conditions for oil and gas and show great exploration potentials.

In the Tarim Basin, especially in the northern part of the Tarim Basin, the preservation threshold of liquid oil under the background of a low geothermal gradient (2.0 °C/100 m) and rapid burial process can reach up to 9000 m; therefore the exploration potential of ultra-deep liquid petroleum in Northern Tarim is enormous. According to numerical calculation and controlling mechanism of fracture to reserves, large cavities gradually die out, and effective reservoirs disappear below 11000 m. Therefore, there are effective large-scale reservoirs in the buried depth between 8000 and 11000 m. Through the analysis of ultra-deep reservoir-caprock combinations and the superimposed evaluations of source rock, reservoir and caprock, major favorable zones for each horizon below 8000 m have been picked out. Among them, the favorable zone of the Cambrian subsalt dolomite is mainly distributed in the vicinity of the paleo-uplift and the sedimentary facies variation line of the Xiao'erbulake Formation. The southern slope of Northern Tarim and the northern slope of Central Tarim are the keynotes. The favorable areas of the Cambrian platform margin are mainly distributed in the line of Lun'nan-Gucheng. The favorable exploration areas of the Ordovician are in the eastern part of the Manxi low uplift area and eastern part of the southern slope of Northern Tarim. The favorable exploration zone of the Sinian is mainly in the eastern Tarim Slope, and Keping faulted arc. It is recommended to speed up the detailed evaluation and drilling deployment in these areas, to realize significant discovery of ultra-deep oil and gas exploration as soon as possible, and to form the fourth front for oil and gas exploration in the Tarim Basin.

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Conflict of interest

The authors declare no conflict of interest.

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