The Potential of Natural Gas Exploration in East Tarim Basin

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Tarim Basin, located in Xinjiang Uighur Autonomous Region in northwestern China, is enriched in abundant oil and gas resources[1-2]. However, East Tarim region is up to now still less explored, as up to now 16 wells in total were drilled, but only two wells show industrial scale oil flow, demonstrating that the success rate of exploration is pretty low and the discovery of oil and gas is extremely rare in this region. Previous research results demonstrate that in East Tarim region, the marine facies hydrocarbon source rocks of Cambrian-lower Ordovician system developed are currently at the stage of over maturation. In regard to the burial history and maturation evolution history, these source rocks were rapidly transformed to the stage of gas generation at the late stage of Caledonian movement due to rapid settlement and high geothermal temperature in mid-late Ordovician Epoch[3-5]. Meanwhile, the reservoir rocks in East Tarim region are mainly reservoir rocks of low porosity and low permeation type, or low porosity and super low permeation type, while the cap rocks are compact sandstones. So it seems that it is very hard to form effective reservoir-cap combination. However, discovery of the two wells showing industrial scale gas flow foretells East Tarim region possibly being a very important area for gas exploration. As a result, this study would take full advantage of geological information as acquired from the exploration drills and discovered wells, and give a scientific analysis of the potential for gas exploration in East Tarim region, based on gas geochemical characteristics, gas source rocks characteristics, compact sandstone reservoir-cap combination, structural development characteristics and their combination relationships, and the results may provide reliable geological data for decision-making concerning gas exploration.

1. Regional geological background

East Tarim region mainly covers five secondary structural units including Kuerle uplift, Kongquehe slope, Manjiaer depression, Yingsuji depression and Dongta low uplift(Fig. 1). Similar to Tarim Basin, Eastern Tarim region behaves as a superimposed complex basin, its structural evolution can be divided into four stages: basement formation stage in pre-Sinian Epoch, relic uplift formation stage in pre-Jurassic Epoch, inland depression basin formation stage in Jurassic-Cretaceous Epoch, and cratonic basin formation stage in Cenozoic[6]. After undergoing multiple stages of structural movements of different types and multiple stages of erosion, only some relict strata of Sinian, Cambrian, Ordovician, Silurian, Devonian, Carboniferous, Permian systems and Mesozoic to Cenozoic erathems were left in East Tarim region(Fig. 2), among them, Cambrian, Ordovician, Jurassic, Cretaceous and Cenozoic rocks are extensively distributed, while other rocks are distributed only in limited areas. Currently two gas reservoirs were discovered in East Tarim region, i.e., YingnanB Jurassic condensate gas reservoir, and MandongA Silurian gas reservoir. In addition, small amount of oil and gas was shown in three other wells drilled. These two gas reservoirs show common

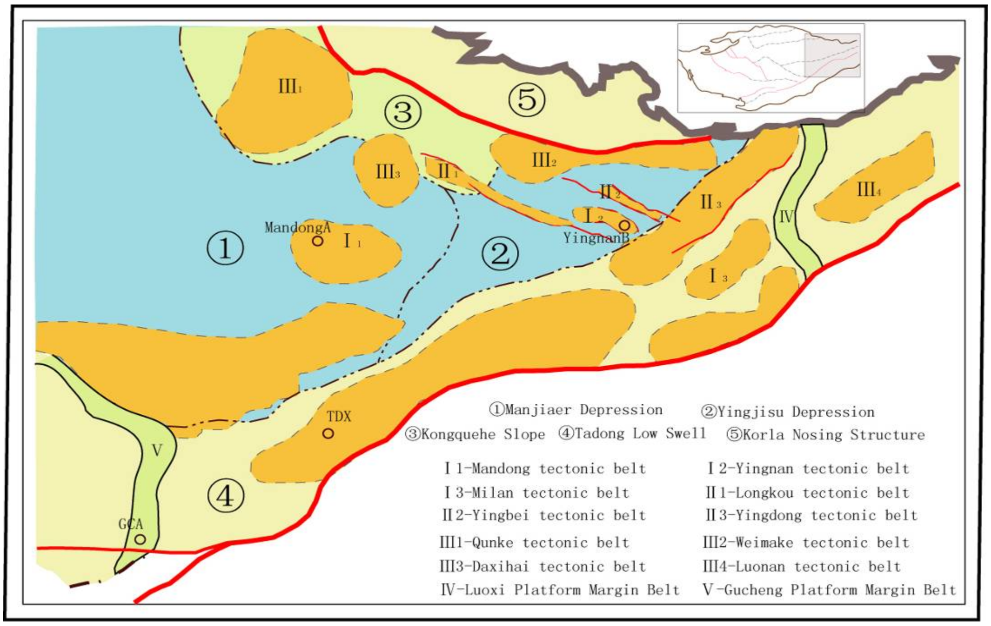


Fig.1 Structure outline map of Tadong Area

characteristics such as inverted order of gas and water occurrence, low gas abundance, high gas column height, and compact sandstone cover. Yingnan B gas reservoir was formed in the latest 10 Ma, but show inconsistentency among hydrocarbon generation history, reservoir formation stage and gas type, which means that the reservoir formation process may be special in East Tarim region (Zhang et al., 2004)[7].

2. Gas geochemical characteristics

Gas from East Tarim region is dominated by high nitrogen wet gas, containing methane content 64.97-76.6%, and nitrogen content 16.33-20.39% and showing desiccation coefficient 0.82-0.88, and very close carbon isotope characteristics as its methane $\delta^{13}C$ is -36.2 - -38.18‰, ethane $\delta^{13}C$ is -30.9 - -37.74‰, indicating that gas was mainly originated from source rock - Cambrian marlite. By adopting Jinxing Dai's sapropel-type gas maturity formula ($\delta^{13}C_1$=15.8LogRo-42.2) [8], gas maturity in East Tarim region is calculated at around 1.8%, demonstrating that the natural gas here has reached high maturation stage.

Gas components, light hydrocarbon components and 3-, 4-Dimethyladamantane content all indicate that the crude here has been cracked to a degree of 80%-90%, so gas generated in Mandong area show characteristics of crude-cracked gas type[9-12].

3. Gas reservoir formation characteristics

3.1 Gas source rocks characteristics

Marine facies argillaceous carbonate rocks of Cambrian–Ordovician systems in lower Paleozoic erathem were developed in East Tarim region, and the rocks serve as hydrocarbon source rocks, as the organic facies is of the compensative hungry basin type. The source rocks as revealed by different drilling programs show average organic carbon content of 1.24%-2.28%, with the maximum being 5.52%; Here the horizon showing organic carbon content being >1% is 120-415m thick, and the organic type being type I. This set of source rocks undergoes earlier stage rapid burial, later stage rapid generation of hydrocarbon, and present stage high maturation to over-maturation. After Caledonian movement, gas generation would continue in these source rocks, while earlier stage formed crude would show secondary cracking for gas formation due to deeper burial depth and higher geothermal temperature. However, some scholars deemed that the Paleozoic organics showing

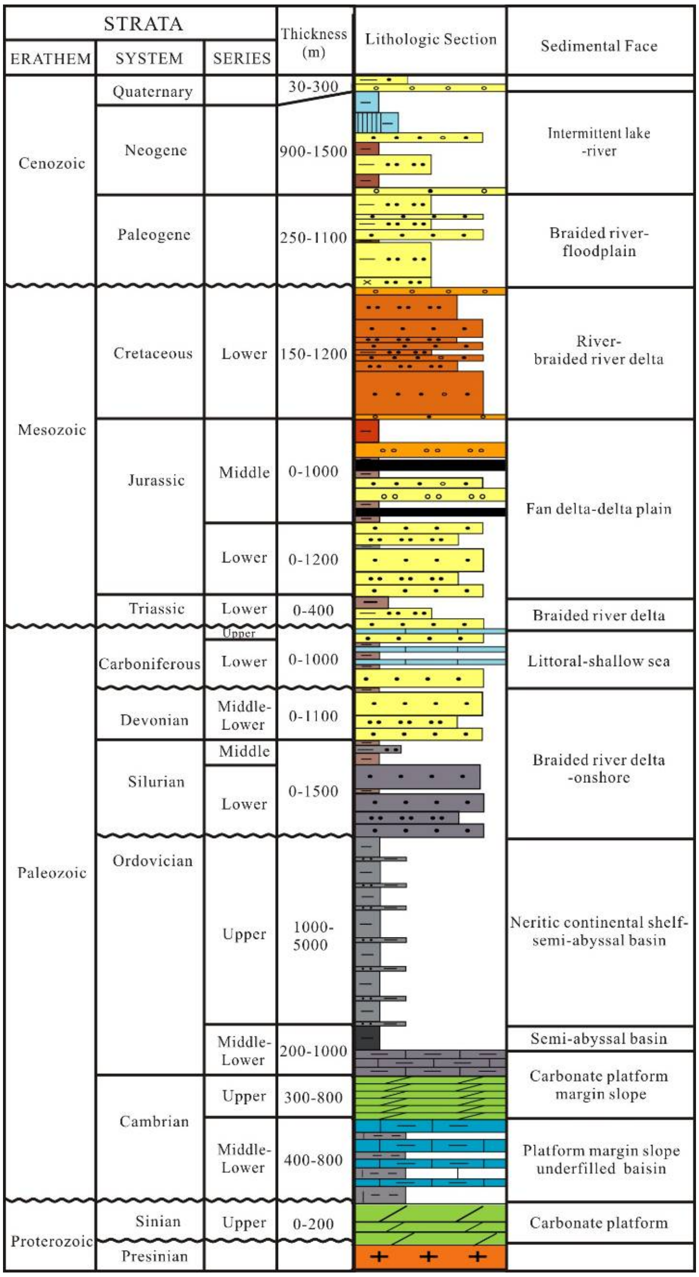


Fig. 2　Geologic column of Tadong Area

extremely high maturity in East Tarim region may be resulted from abnormal thermal events occurring in the deep part of the crust, which may be the dominating thermal power leading to Paleozoic crude cracking in Mesozoic to Cenozoic time[13].

Therefore, the lower Paleozoic strata are capable of generating huge amount of natural gas in East Tarim region, which lasts for a very long time until today. Many scholars estimated that that the natural gas resource in East Tarim region is around $1\text{-}3\times10^{12}m^3$, suggesting that it is one of the most abundant regions in terms of gas production in Tarim Basin[1,2].

3.2 Unconventional reservoir-cap combination

In East Tarim region, four sets of efficient reservoir-cap combinations were developed, and they are: thick-bedded sandstone and compact sandstone cover in lower Jurassic system constitute unconventional reservoir-cap combination, Silurian compact strata and underlying sandstone constitute unconventional reservoir-cap combination. These two combinations are located at the upper part of the strata. In the lower part of the strata, Ordovician mudstone and Cambrian dolomite and the lower Cambrian mudstone and Sinian dolomite constitute two reservoir-cap combinations, which are the favorable sites for crude-cracked gas exploration.

3.2.1 The upper combinations

Jurassic reservoir rock mainly consists of intermediate to fine-grained lithic sandstone and shows a thickness of 330-1,130m, with pore type being mainly authigenic intergranular pores and relic intergranular pores, and to lesser extent, intergranular vugular pores. Also, it shows a porosity of 5-17.5%, a penetration ratio of $2\text{-}10\times10^{-3}\mu m^2$, indicating that it is mainly reservoir rock of low porosity and low penetration type.

Silurian reservoir rocks mainly consist of brownish gray fine-grained lithic sandstone, pebble-bearing fine-grained sandstone, interbedded partially with brownish argillaceous silt and thin layers of mudstone. The reservoir rocks show poor performance, with the pore type being mainly relict authigenic intergranular pores. The rocks show an average porosity of 7.39%, an average penetration rate of $0.42\times10^{-3}\mu m^2$, indicating that the reservoir rocks are of low porosity and super-low penetration type.

Both Jurassic and Silurian covers are compact sandstones. As to whether compact sandstone can be effective cover, numerous researches have been carried out before. Formation of compact sandstone cover is due to the following two factors. First of all, at the same time when gas accumulation leads to reservoir formation, a great amount of gas scatters around, so methane gas would be able to take part in formation of calcium carbonate cement in sandstone, which would decrease the penetration performance of the sandstone at the top of gas reservoir, thus forming effective unconventional cover. Huang et al.[14] and Li et al.[15] deemed that nearly 20% of carbonate cement is of organic origin in East Tarim region, suggesting that carbonate deposition resulted from natural gas consumption is the important reason for formation of compact sandstone, as formation of compact sandstone cover proceeds simultaneously with loss of natural gas. Secondly, compact sandstone at the top of gas reservoir contains abundant and highly scattered honeycomb-like mixed-layer clay minerals, which consist of illite/smectite or chlorite/smectite, and form net-like microporous structures and show high capillary pressure. When these clay minerals are bound by stratigraphic water, water lock effect would occur, which would increase the capillary pressure of microscopic pores, and lead to formation of extremely low penetrating cover(Fig. 3). The outburst pressure for compact sandstone cover mainly ranges between 2-7 MPa, with some samples showing a pressure being as high as 14 MPa. General analysis indicates that the cover rocks show high outburst pressure and so can be good quality cover rocks [16], as very good pressurized enclosure effect can be achieved for gas reservoir formation.

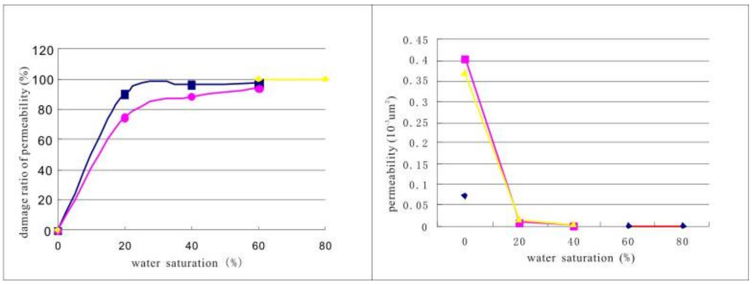
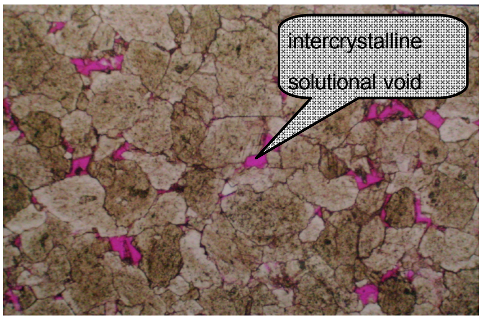


Fig. 3 Water saturation vs. permeability of unconventional caprock of Tadong Area

However, compact sandstone cover generally shows high scattering coefficient, basically ranging between (1.5-3.7)×10^5cm2/s. For gas reservoir, concentrated hydrocarbon shows weak enclosure capability and may scatter around and cause great amount of loss, which may possibly be the main reason for gas loss from the gas reservoir of the upper combination type in East Tarim region. Huang (2007) acquired data of micro-leaking amount of gas from the cover rocks for YingnanB gas reservoir through quantitative simulation of micro-leaking test, and discovered that the accumulated micro-leaking amount ever since late Jurassic is up to 5371.3×$10^8$$m^3$[17], which is really significant for covers like these in East Tarim region.

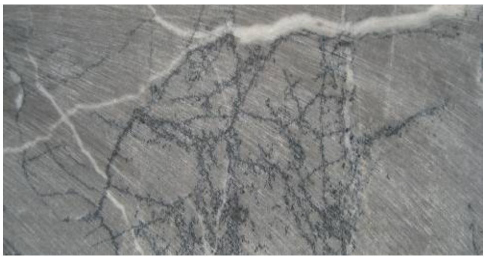
3.2.2 The lower combinations

For the lower part reservoir-cap combinations in East Tarim region, the reservoir rocks are mainly Cambrian hydrothermal dolomite and platform facies dolomite, with single layers being up to 14m thick, and up to 1m thin. Eroded pores and holes are developed in the rocks, with single holes being up to the size of 30.0×50.0mm. However, intergranular pores are not well developed, as intergranular pores of 0.125mm size can only be seen in some part of intermediate-grained dolomite crystals. Multiple stages of fissures were developed in the rocks, with fissures being generally filled up with calcite and quartz(Fig. 4). In the Cambrian dolomite as revealed by drilling, the matrix shows low porosity with an average of 1.13%, and penetration rate with an average of 1.23×$10^{-3}$$\mu m^2$. Cambrian dolomite is inhomogeneous, carbonate hydrothermal solutions and accompanying erosion as well as faulting activities along fissures of reservoir rocks would remarkably improve the performance of the reservoir rocks. Ordovician mudstone and lower Cambrian mudstone covers are distributed extensively in the whole region, and show huge thickness and compact lithology. In East Tarim region, the outburst pressure for crude cracked gas reservoir cover is evenly distributed and is generally greater than 14 MPa; the outburst pressure for the lower combination covers is obviously higher than that for the upper combination covers, suggesting that gas enclosure capability is higher in the lower part than in the higher part. For the lower combinations, Cambrian and Ordovician mudstone and limestone cover shows lower diffusion coefficient, ranging between 7.6-18.3×$10^7$$cm^2$/s, which is far smaller than that for the higher combination covers, further testifying that the lower combination covers shows relatively higher enclosure capability than the upper part combination covers.

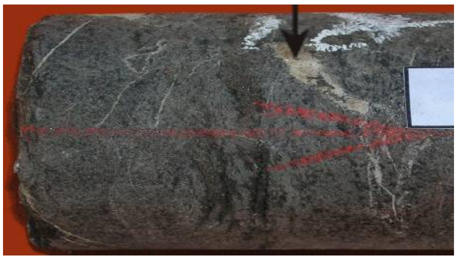


$\in_3$, intercrystalline solutional void of fine-grained dolomite, x50

$\in_1$, bedded distributing of solutional void of dolomite



O_{2y}, early structural fracture and solutional fracture filled with



$\in_1$, solutional void of dark gray dolomite filled with calcite

Fig. 4 Characteristic of lithology of Tadong Area

3.3 Structural characteristics

In East Tarim region, 10 structural belts were developed, the enclosures are mainly anticline or cross-faulted anticline, and the gas enclosures show very high resource reserve. Here there are 3 belts in type I zone (i.e., Mandong structural belt, Yingnan structural belt and Milan structural belt), 3 belts in type II zone (i.e., Longkou structural belt, Yingbei structural belt, Yingdong structural belt), 4 belts in type III zone (i.e., Qunke structural belt, Weimake structural belt, Daxihai structural belt and Luonan structural belt) (Fig. 1). Currently, industrial oil and gas has been acquired in Mandong structural belt and Yingnan structural belt, and good quality oil and gas show was discovered in Longkou structural belt and Yingdong structural belt.

At Caledonian stage, the Cambrian source rocks have entered the stage of maturation, and would generate hydrocarbons, which leads to formation of old oil reservoirs in Cambrian, Ordovician and Silurian systems, and provides material basis for migration and concentration of later stage high temperature over-matured oil and gas. In the process of migration and concentration of oil and gas from old oil reservoir, oil and gas migrates mainly along vertical directions. Therefore, faults with long activation periods cutting through old Cambrian oil reservoir and the overlying enclosure structures are the keys for overlying structures developed in Cambrian system to capture industrial scale oil and gas[18-20]. East Tarim region undergoes multiple stages of structural movement, as multiple levels of faults weredeveloped in the region. These large and deep faults would be very good channels for upward migration of oil and gas formed in Cambrian-Ordovician rocks. Moreover, the intense structural activities at Caledonian-Hercynian stages provide thermal power for abnormal thermal evolution of Cambrian source rocks in East Tarim region. The thermal events accompanying faulting activity can also be destructive to old oil reservoirs, for example, TD X well drilling shows that relic condense oil and dry bitumen were left after hydrothermal alteration of Cambrian-Ordovician rocks, GC A well drilling shows occurrence of gas formed from cracking of oil characterized by high desiccation coefficient. Yingjisu depression is mainly active at the Yanshanian and Indosinian stages, and the enclosures formed are mainly anticline type, cross-faulted anticline type and fault nose type. After the Cretaceous period, the structures in this region tend to be stable, which is favorable for preservation of oil and gas reservoirs.

3.4 Shale gas

Shale gas was generated in shale as characterized by extremely high porosity, penetration and abundant organics, and is a kind of unconventional gas. With success being acquired in shale gas exploration in North America, shale gas exploration receives increasingly the attention of academics all across the world. By comparing with the geological characteristics for shale gas reservoirs like Barnett and Haynesville, it can be postulated that the Ordovician Heitu'ao Formation in East Tarim region can be the target zone favorable for shale gas exploration.

The Ordovician Heitu'ao Formation in East Tarim region consists of mid- to lower Ordovician system, and is comprised of a set of deep water basin facies shale, which was deposited at the margin between Luoxi and Gucheng. Drilling reveals that the formation is 48-187m thick, and shows relict total organic carbon content (TOC) being on average 1.0% -2.84%, indicating practically that the original total organic carbon content would be much higher. Ro ranges between 1.21%-2.65%, and is estimated to be up to 4.5% at the maximum burial depth, suggesting that the source rocks have generally entered the high to over-maturation stage. As Heitu'ao Formation rocks have entered the high to over-maturation stage, the kerogen type cannot be determined by use of H/C and O/C atomic ratios. However, our organic maceral analysis indicates that the organics in Heitu'ao Formation black mudstone/shale is mainly algae and amorphous organics, and the kerogen shows light carbon isotope composition, which ranges between -28.8‰ - -30.9‰. Therefore, it can be postulated that Heitu'ao Formation consists of type I organics.

Heitu'ao Formation rocks mainly consist lithologically of black carboniferous mudstone and shale, siliceous shale and radiolarian siliceous rock. They are hard, brittle, and show poor water absorption and poor plasticity, and contain plate-like rock fragments. The rocks have internal structures characterized by development of fissures and veins, which were either half or fully filled with quartz. Bulk rock X-ray diffraction analysis indicates that at Tadong area the Heitu'ao Formation rocks mainly consist of siliceous components (54%-88%) and clay (<22%), suggesting that the rocks are brittle and tend to produce internal fissures, so are favorable for concentration of natural gas.

As a result, it can be concluded that Heitu'ao Formation in East Tarim region has the geological conditions for formation of shale gas, so shale gas is possibly developed extensively in the entire East Tarim region.

4. Conclusions

The geochemical characteristics of hydrocarbon source rocks, reservoir-cap combinations, and natural gas resources in East Tarim region were analyzed in this study, together with the characteristics for reservoir formation, and the results indicate that East Tarim region is favorable for natural gas formation in terms of geological conditions, so being enriched in natural gas resources and holding great potential for gas exploration. In this study, the conclusions can be summarized as follows :

(1) In East Tarim region, natural gas mainly originates from Cambrian marlitic source rocks, which contain high content of type I organic carbon, and have currently entered the high- to over-maturation stage. At this stage secondary cracking of earlier stage-formed liquid hydrocarbon occurs, which leads to gas formation.

(2) In East Tarim region, four sets of effective reservoir-cap combinations were developed, including Silurian and Jurassic unconventional reservoir-cap combination, Ordovician mudstone and Cambrian dolomite reservoir-cap combination, lower Cambrian mudstone and Sinian dolomite reservoir-cap combination, which are best sites for gas exploration.

(3) In East Tarim region, multiple structural belts were developed, with enclosure being mainly of the anticline type and the cross-faulted anticline type, which can enclose great amount of gas reserve. Meanwhile, the region undergoes multiple stages of structural movement, leading to development of faults of multiple levels, which provide very good channels for upward migration of oil and gas generated in Cambrian-Ordovician rocks.

(4) In East Tarim region, the Ordovician Heitu'ao Formation shale is deposited in large area and shows huge thickness, its abundant organics shows good type and high maturity. Moreover, internal fissures are well developed inside the rock. So shale distribution area can be the target zone favorable for shale gas exploration.

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