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Research article

Petroleum geological features and exploration prospect of deep marine carbonate rocks in China onshore: A further discussion☆

Zhao Wenzhi*, Hu Suyun, Liu Wei, Wang Tongshan, Li Yongxin

PetroChina Research Institute of Petroleum Exploration & Development, Beijing 100083, China

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Abstract

Deep marine carbonate rocks have become one of the key targets of onshore oil and gas exploration and development for reserves replacement in China. Further geological researches of such rocks may practically facilitate the sustainable, steady and smooth development of the petroleum industry in the country. Therefore, through a deep investigation into the fundamental geological conditions of deep marine carbonate reservoirs, we found higher-than-expected resource potential therein, which may uncover large oil or gas fields. The findings were reflected in four aspects. Firstly, there are two kinds of hydrocarbon kitchens which were respectively formed by conventional source rocks and liquid hydrocarbons cracking that were detained in source rocks, and both of them can provide large-scale hydrocarbons. Secondly, as controlled by the bedding and interstratal karstification, as well as the burial and hydrothermal dolomitization, effective carbonate reservoirs may be extensively developed in the deep and ultra-deep strata. Thirdly, under the coupling action of progressive burial and annealing heating, some marine source rocks could form hydrocarbon accumulations spanning important tectonic phases, and large quantity of liquid hydrocarbons could be kept in late stage, contributing to rich oil and gas in such deep marine strata. Fourthly, large-scale uplifts were formed by the stacking of multi-episodic tectonism and oil and gas could be accumulated in three modes (i.e., stratoid large-area reservoir-forming mode of karst reservoirs in the slope area of uplift, back-flow type large-area reservoir-forming mode of buried hill weathered crust karst reservoirs, and wide-range reservoir-forming mode of reef-shoal reservoirs); groups of stratigraphic and lithologic traps were widely developed in the areas of periclinal structures of paleohighs and continental margins. In conclusion, deep marine carbonate strata in China onshore contain the conditions for widely and intensively preserving hydrocarbons, so large oil or gas fields are expected.

Keywords: China onshore; Marine carbonate rocks; Deep zone; Source kitchen; Intensive reservoirs; Resource potential; Exploration prospect

1. Introduction

The marine carbonate rocks in China, unlike those in other countries, are mostly distributed in lower structures of basins. They are ancient and deeply buried, with a large time span, a multiple hydrocarbon-bearing series of strata and a complex reservoir-forming history [1,2]. In recent years, with the deepening of geologic recognitions and the progress of exploration technologies, a series of significant breakthroughs have been made in the exploration of deep marine carbonate reservoirs in China. For instance, firstly, with more efforts in the two palaeohighs in the Tarim Basin (northern Tarim Palaeohigh, Tazhong Palaeohigh), an Ordovician Yingshan Fm karstic fracture-vug type large oilfield was discovered in the Halahatang area on the slope at the southern fringe of the northern Tarim Palaeohigh, and significant breakthroughs were made in several target zones like Ordovician Lianglitage Fm reef-shoal and Yingshan Fm karst on the northern slope of the Tazhong faulted zone. Secondly, through exploration in the

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* Corresponding author.
E-mail address: zwz@petrochina.com.cn (Zhao WZ).
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reef-shoal in the platform fringe zone of Kaijiang-Liangping trough in the Sichuan Basin, some large gas fields like Tieshanpo, Luojiazhai, Puguang and Longgang were discovered. Besides, by further exploration in the Lower Paleozoic-Sinian carbonate rocks in the Palaeohigh of central Sichuan Basin and its slope area, strategic breakthrough was made — a large Cambrian Longwangmiao Fm integral gas reservoir was discovered. Thirdly, by virtue of enhanced exploration to the carbonate weathered crust karst reservoir in the Ordos Basin, a new breakthrough was made in the karstic zone in the western Jingbian gas field, and a new gas-bearing series of strata were discovered in the Mawu_{4-10} member of Ordovician ($O_1m_5^4$–$O_1m_5^{10}$). Based on the recent exploration results, the buried depth of hydrocarbon-bearing series of strata is universally deeper than 4000 m, or even 7000 m in the Tarim Basin, exhibiting favorable prospects of deep-ultra-deep marine carbonate reservoirs.

2. Trend of marine carbonate exploration

2.1. Definition of deep zone

The definition of a deep zone doesn't follow any strict criteria in the world, but varies depending on countries. Generally, oil and gas reservoirs with a buried depth of more than 15 000 ft (4500 m) are defined as deep reservoirs.

In the *Calculation Specifications for Petroleum Reserves* issued by the National Mineral Reserves Committee (China) in 2005, a buried depth of 3500–4500 m is defined as a deep zone and buried depth >4500 m as an ultra-deep zone. In drilling engineering, 4500–6000 m is adopted as a deep zone, and more than 6000 m as an ultra-deep zone. Due to the difference in geothermal fields and exploration practice of eastern and western China, deep and ultra-deep zones are cognized as 3500–4500 m and more than 4500 m respectively in eastern China, and 4500–5500 m and more than 5500 m in western China. Even as per the traditional definition of a deep zone in western China, the marine carbonate discoveries made over the years in China are also included as deep zones.

2.2. Trend of marine carbonate exploration

2.2.1. Marine carbonate exploration in the world

Marine carbonate reservoirs take a dominant position in the world oil and gas production. According to the statistics of IHS in 2000, marine carbonate hydrocarbon resources account for about 70% of the total in the world, and the proved recoverable oil and gas reserves account for 50% of the total. In 2011, the oil and gas output of marine carbonate reservoirs accounted for about 63% of the total oil and gas output of the world.

Triggered by the international increasing energy supply and demand contradiction, carbonate reservoirs attract the global sights with more and more investment. Deep carbonate reservoirs have become the hotspot of petroleum exploration and development in the world. As is shown in the statistics on the buried depth of main pay zones in the large carbonate fields discovered before 2009, prior to 2000, the number of large fields with a buried depth of main pay zone exceeding 4000 m accounts for 14.8% of the global large carbonate fields; after 2000, this proportion has risen to 58.6% (Fig. 1). Deep carbonate reservoirs have become an important target to discover large fields in the world. For example, in the hotspot areas like the Latin American and the Far East, where some carbonate fields were discovered recently, the buried depth of main pay zones is generally more than 4000 m. Some large fields have main pay zones exceeding 5000 m, e.g., the Yoloten-Osman giant gas field discovered in Turkmenistan in 2004, and the Kish-2 giant gas field discovered in Iran in 2005.

2.2.2. Marine carbonate exploration in China

Compared with the basins in the world, those hydrocarbon-bearing basins in China are dominantly superimposed basins, and the marine carbonate strata are mostly distributed in the lower structures and they are ancient and deeply buried. The exploration of marine carbonate strata in China have experienced a complicated and hard process from the exploration of Lower Triassic Jialing Jiang Fm in the Sichuan Basin at an early stage, to the discovery of buried hills in the Bohai Bay Basin and Jingbian gas field in the Ordos Basin, and to the discovery of Lunnan-Tahe oilfield in the Tarim Basin.

Now, marine carbonate exploration in China is extending gradually from middle-deep zones to deep-ultra-deep zones. Based on the statistics on exploration depth in China, the depth of major reservoirs discovered prior to 2000 is generally less than 4500 m. For example, in the Renqiu oilfield discovered by carbonate buried hill exploration in the Bohai Bay Basin and the Jingbian gas field discovered by carbonate weathered crust reservoir exploration in the Ordos Basin, the buried depth of all major reservoirs is less than 4000 m. In recent years,

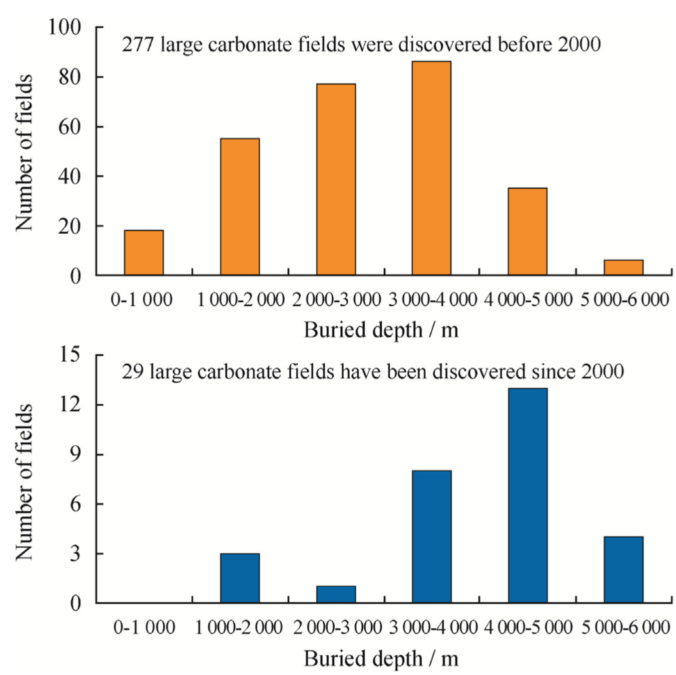

Fig. 1. Buried depth of large carbonate fields discovered in the world before and after 2000.

with the deepening of carbonate reservoir researches and the progress of exploration technologies, the depth of exploration has been increased obviously. In the Sichuan Basin, the depth of marine carbonate exploration has broken through 5000 m, or 7000 m maximally; in the Tarim Basin, the depth of exploration is generally is more than 6000 m, or 8000 m maximally. Deep zones have become a key realm of breakthrough and discovery of onshore marine carbonate exploration in China. Among the 10 large-scale oil and gas discoveries made recently by PetroChina Company Limited (hereinafter referred to as PetroChina), 4 discoveries are marine carbonate reservoirs, and the depth of major pay zones all exceeds 4500 m, indicating that they are deep zone discoveries (Table 1).

3. Geologic features of onshore deep marine carbonate reservoirs in China

Marine carbonate reservoirs in China are located in the lower structures, and they are ancient and deeply buried. These features result in their higher thermal evolution level of source rocks, complicated diagenetic process of reservoirs, high heterogeneity, multiphasic reservoir-forming and multiphasic adjustment. The process of hydrocarbon generation, migration, accumulation and adjustment of marine reservoirs is considerably complicated [3]. Regardless of such unfavorable factors, ancient marine carbonate reservoirs still have the foundations and conditions for forming large fields.

3.1. Two types of hydrocarbon source kitchens like conventional source rocks and cracking of liquid hydrocarbon retained inside source rocks are developed, and both can supply hydrocarbon on a large-scale

3.1.1. Onshore deep-ultra-deep carbonate reservoirs possess favorable conditions for the development of high-quality source rocks

Compared with large cratons abroad, the cratons in China are much smaller, with an area usually of hundreds of thousands of square kilometers. Owing to smaller blocks, the cratons in China are sensitive to the tectonic activities around them; under the control of all levels of faults in the periphery and inside of the basins, the deposition and subsidence of different tectonic units inside the cratons are diversified apparently. Relatively low-lying areas or blocks are usually in reducing environments, and they become the favorable development areas of source rocks. For instance, Paleozoic Lower Cambrian, Middle Cambrian, Middle Ordovician and Middle-Upper Ordovician basinal argillaceous source rocks are developed in the Tarim Basin, with an organic carbon content ranging 1.24%–5.52%, 1.45% averagely, a total thickness ranging 250–750 m, and an area about 26×10^4 km^2. Cambrian, Lower Silurian, Lower Permian and Upper Permian deep water shelf facies, slope facies, trough facies and paludal facies high-quality source rocks are developed in the Sichuan Basin, with an organic carbon content ranging 1.04%–6.52%, a total thickness ranging 750–950 m, and an area of 19×10^4 km^2.

Table 1
Large-scale discoveries in marine carbonate exploration by PetroChina in recent years.

Oil/gas field	Buried depth/m	Horizon	Discovery/year
Tazhong Tarim	4500–6200	O	2003
Halahatang Tarim	5900–7100	O	2008
Longgang Sichuan	5800–7100	P-T	2006
Anyue Sichuan	4500–5390	Z-∈	2011

The Middle-Late Proterozoic in China also possesses the environmental conditions for the development of high-quality source rocks. In the North China, affected by the cracking and extending of Qinqi trough and Xingmeng trough in Proterozoic, 6 aulacogens like Helan, Jinshaan, Jinyu Yanliao, Bayan Obo – Chartai and Xuhuai were developed on the marginal zones of craton land blocks from west to east, which were filled by several thousand meter thick sediments, where there is no lack of effective source rocks. For instance, observed from the outcrops in the Jibei depression, three sets of source rocks of Gaoyuzhuang Fm (3rd, 5th and 6th members) are developed, with a thickness of 38, 69 and 57 m respectively, lithology mainly of mudstones, argillaceous dolomites and dolomitic mudstones, an organic carbon content ranging 0.38%–2.23%, and the mean value of organic carbon content in each member is all more than 0.5%. A number of NE trend intracontinental rifts were developed in the Upper Yangtze plate in Nanhuan period, and they had the environmental conditions for the development of source rocks [4]. For instance, 9 m thick Upper Sinian Doushantuo Fm black algae rich argillaceous source rocks were revealed by well Nǚji drilled in the Sichuan Basin, with an organic carbon content ranging 0.9%–1.75%, 1.73% averagely, and $R_o > 3.0\%$.

3.1.2. Two types of hydrocarbon source kitchens are developed in deep zones, and both can supply hydrocarbon on a large-scale

The following two types of hydrocarbon source kitchens are developed in the marine series of strata in China.

1) Hydrocarbon source kitchens are formed by conventional marine source rocks. Multiple sets of high-quality source rocks in which argillaceous rock predominates are developed in the basins like Tarim, Sichuan and Ordos in China, which not only are distributed widely with large thickness, but also have higher organic carbon content, and together with coal measures, constitute the major part of conventional hydrocarbon source kitchens. This type of hydrocarbon source kitchen has a long hydrocarbon generation history and sufficient evolution, can supply abundant hydrocarbon sources for the large-scale accumulation of deep carbonate hydrocarbon. It is characterized by mainly generating oil at an early stage and gas at late stage and has experienced complete "oil generation" and "gas generation" peaks, and the total resources generated by it are large.

2) Gas source kitchens formed by the cracking of dispersive liquid hydrocarbon retained in source rocks. After the source rocks having discharged hydrocarbon at a liquid window stage, the quantity of dispersive liquid hydrocarbon retained in it is still quite high, which can generate gas on a large-scale at a high-overmature stage and thus form effective gas source kitchens [5,6]. Many groups of hydrocarbon generation kinetics modeling experiments confirm that a great deal of kerogen is degraded into gas at mature − early highly-mature stages with $R_o < 1.6\%$, whereas liquid hydrocarbon is cracked into gas at high-overmature stages with $R_o > 1.6\%$; the gas generation of liquid hydrocarbon occurs later than kerogen, but the quantity of generated gas is 2–4 times that of kerogen. Therefore, the liquid hydrocarbon retained in source rocks having entered high-overmature stages can still generate substantive gas at a late stage; this cognition has largely improved the exploration potential of deep carbonate reservoirs, especially the exploration potential of natural gas. Based on the aforesaid cognition, Well Gucheng 6 was recently drilled in the Gucheng area of the Tarim Basin; without implementing any stimulation, 26.4×10^4 m^3 daily gas flow was obtained from the 6144–6169 m interval of the Ordovician carbonate reservoir [7]. Owing to the catalysis of rock minerals, the light hydrocarbon composition of cracked gas of hydrocarbon retained inside source rocks is somewhat different from that of cracked gas in palaeo-oil reservoirs [5]: the relative content of cyclane is higher in the cracked gas of hydrocarbon retained inside source rocks, whereas the relative content of paraffin is higher in the cracked gas of palaeo-oil reservoirs; high content of cyclane was detected in the gas samples taken from Well Gucheng 6, and the cyclane/(normal hexane + normal heptane) ratio is 10.67, confirming that the dispersive liquid hydrocarbon cracked gas formed at a late stage can make an important contribution to the large-scale accumulation of gas in deep carbonate reservoirs.

3.2. Two types of karstification and two types of dolomitization have been experienced, and large-scale effective reservoirs are developed in deep carbonate strata

Three types of effective reservoirs (sedimentary-diagenetic, interstratal–intrastratal leaching and buried-hydrothermal reworking) are widely developed in China [8]. The physical property of a carbonate reservoir is not restricted by the buried depth, and large-scale effective reservoirs can still be developed in the deep-ultra-deep carbonate strata.

3.2.1. Interstratal karstification and bedding karstification

The reworking of atmospheric fresh water denudation to the exposed carbonate rocks resulted in the formation of complicated fracture-vug reservoir systems (mostly occurred in limestone series of strata) and cavity reservoir systems (mostly occurred in dolomite series of strata) [9,10]. Interstratal karst and bedding karst are the two important types of karst developed in Paleozoic carbonate reservoirs in China.

An interstratal karst is the product of short-term uplifting and exposition of carbonate formation; hypergenic karstification occurs along unconformities or faults, and thus forms pores, vugs and fractures, etc. A karstification surface is an interface with gentle topographical relief, and the lithologic difference of upper and lower formations is little. Taking the Tarim Basin as an example, four episodes of interstratal karsts are developed in Ordovician, and they are located at top Penglaiba Fm, top Yingshan Fm, top Yijianfang Fm and top Lianglitage Fm respectively, with a total effective exploration area of more than 6×10^4 km^2. A bedding karst is mostly developed in the periclinal part of carbonate palaeohighs, adjacent to the buried hill karsts spatially; the surface water results in lateral bedding filtration and corrosion towards the downdip direction of formations along the early interstratal karst surfaces or other hypergenic karst surfaces, and finally discharges towards the overlying formations or ground surfaces along faults. The large differential pressure resulted from the buried hill karst water in the structural highs of contiguous areas causes the formation of lateral bedding pressure bearing deep-underflow, and its cycling depth can reach hundreds of to thousands of meters [10]. The periclinal part of northern Tarim Palaeohigh in the Tarim Basin is located in the vantage point of bedding karst development, and the distribution area of a reservoir is about 1×10^4 km^2.Although the hydrodynamic conditions for forming interstratal karsts and bedding karsts are different to some extent, the manifestation of reservoir spaces formed is relatively consistent, mainly composed of different scale of vug-fracture systems. Loucks [11] presents that when the buried depth of a fossil cave exceeds 1700 m, the cave type porosity comes down below 20% of the total porosity, whereas the inter-breccia porosity formed by a cave collapse reaches the maximum (Fig. 2). In other words, when the buried depth exceeds 1700 m, most caves collapse under the overlying formation pressure, and the inter-breccia pores formed among the chaotic slump breccias are the principal pore source of strata below 1700 m of buried depth. However, the phenomena of substantial loss of drilling fluid and bit unloading still exist below 5000 m of buried depth in the Tarim Basin, indicating the existence of open caves in deep zones, which is obviously inconsistent with the viewpoint of Loucks. For the sake of ascertaining the depth cutoff of carbonate cave preservation, on the basis of substantial example statistic and experimental analysis, Zheng Xingping et al. establish a cave preservation depth quantitative prediction type curve (Fig. 3) [12], and draw the following three conclusions: a. as for the cave of the same rock type, when the ratio of distance from the exposed surface to the cave scale (h/L) is more than five, the collapse resistance depth of the cave can exceed 6000 m; b. as for the cave of the same scale, the collapsed depth of a dolomite cave is 1.7 times that of a limestone cave; and c. the cave in the inside area of carbonate strata has an apparently stronger collapse resistance capacity than that in the buried hill area. The above understanding demonstrates the carbonate cave preservation depth cutoff

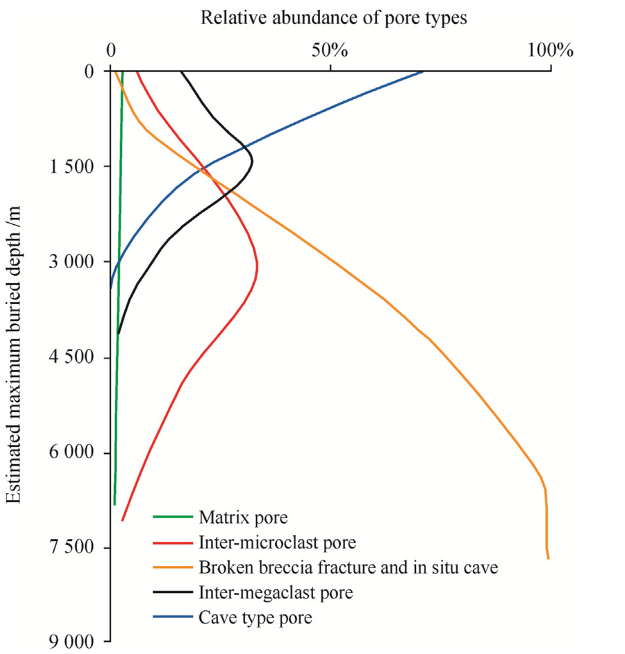

Fig. 2. Relative proportion evolution of various pore types in a fossil cave reservoir system (from Ref. [11]).

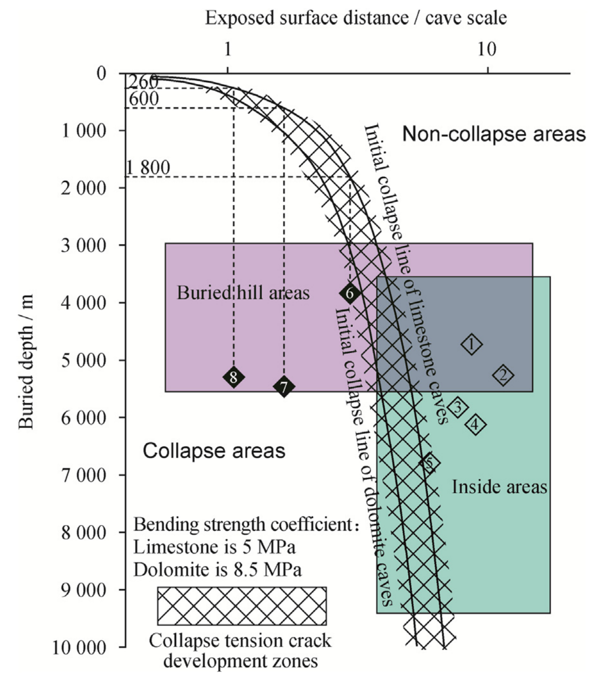

Fig. 3. Cave preservation depth quantitative prediction type curve (from Ref. [12]).

theoretically, proving that a great deal of open porous spaces are still preserved in the deep and ultra-deep carbonate reservoirs. Then, combined with the multilayers and widely distributed characteristics of karst reservoirs, it can be inferred that the deep carbonate karst reservoirs can be distributed on a large-scale.

3.2.2. Buried dolomitization and hydrothermal dolomitization

In a deeply buried environment, affected by the combined action of high temperature, high pressure and wide-span buried time, the diagenetic fluid can sufficiently transform the surrounding rocks into high-quality dolomite reservoirs [8], including buried dolomite reservoirs and hydrothermal dolomite reservoirs.

Buried dolomitization occurred in the buried depth stage and is characterized by macrocrystalline dolomites, pores are usually relatively developed, and buried dolomite reservoirs are widely distributed in layers macroscopically. Taking the Penglaiba Fm dolomites in the Tarim Basin as an example, the distribution area of reservoir exceeds 3×10^4 km^2, the single layer thickness of an effective reservoir ranges 3–5 m, the samples with a porosity of more than 2.5% account for 18%, and the porosity is as high as 12.2%. Hydrothermal dolomitization refers to under-appropriate conditions of temperature and pressure, the magnesium-rich hydrothermal fluid (especially bittern) migrates upward along the tensional faults, strike-slip faults or fault systems, intrudes the surrounding rocks with good permeability at the time of encountering the barrier with poor permeability, and thus results in dolomitization [13]. Among the three large basins like Tarim, Sichuan and Ordos, relatively typical hydrothermal dolomite reservoirs are only distributed in on large-scale in the Tarim Basin, and this is related to the extensive magmation occurred in Permian in the Basin [14]. The Yingshan Fm hydrothermal dolomite reservoirs in the Tazhong Basin are dominantly macrocrystalline dolomites, the pore is primarily of intercrystal type and of intercrystalline dissolved type, and the porosity and permeability are relatively high. In Well Zhonggu 9 of the Tazhong Basin, the single layer net thickness of a dolomite reservoir is 16 m maximally, the maximum porosity is 16.1%, and the maximum permeability is 637 mD. The hydrothermal fluid generally takes faults, unconformities and rocks with good permeability as its channel; therefore, hydrothermal dolomite reservoirs are mostly distributed in the vicinity of the faulted zones (Fig. 4). Compared with other types of dolomite reservoirs, the distribution of this type of reservoir has certain limitation.

3.3. Progressive burial is coupled with annealing heating so that deep carbonate rocks can form reservoirs by spanning tectonic phases

The hydrocarbon generation and accumulation issue of ancient marine series of strata has been widely studied by lots of researchers, with universal viewpoints as follows: the ancient marine series of strata source rocks (Cambrian-Ordovician) in China mostly became mature and started to generate hydrocarbon in late Caledonian – early Hercynian, and are in high-overmature stages nowadays; the oil and gas reservoirs formed at an early stage suffered from substantial destruction and transformation in geologic history, and the scale and exploration potential of reserved primary reservoirs are relatively limited. Therefore, there are a good many doubts about

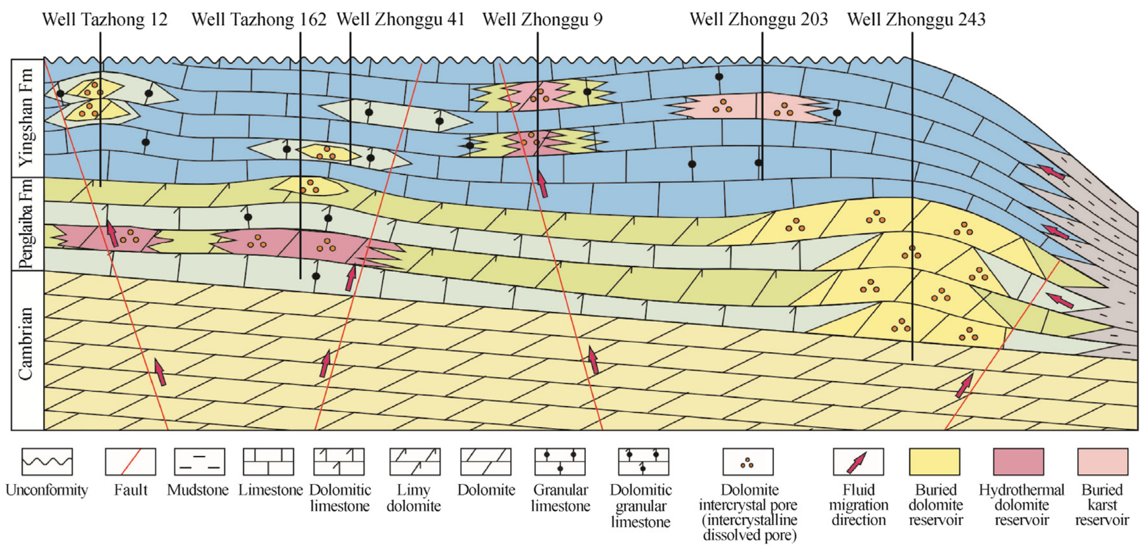

Fig. 4. Buried dolomitization and hydrothermal dolomitization modes of the Tarim Basin (from Ref. [8]).

oil and gas exploration potential, especially the oil exploration potential of deep carbonate reservoirs.

However, observed from the thermal evolution history, the hydrocarbon-bearing basins developed in western-central China generally experienced a process of high geotemperature at an early stage and low geotemperature at a late stage (cooled gradually since Mesozoic), and the heating of marine source rocks are basically in an annealing process [14,15]. Furthermore, a great deal of hydrocarbon generation modeling experiments approaching the subsurface real environment (controlled by both temperature and pressure) are conducted by us. Experimental results show that under the background of the gradual decline of geothermal gradients and the conditions of multiple depositions – repeated denudation and rapid deep burial at a late stage, the R_o is 1.5% and more than 1.8% in the oil-generating peak period and gas-generating peak period respectively. Compared with the kerogen maturation and hydrocarbon generation results presented by Tissot [16], these results are characterized by an apparent delay of hydrocarbon generation. In other words, under the coupling action of "progressive burial" and "annealing heating", the hydrocarbon generation and discharge peak period of some ancient source rocks can be retarded, and a great deal of liquid hydrocarbon can still be generated and accumulated at a late stage.

This paper takes the Cambrian source rocks in the Tarim Basin for example. The Tarim Basin experienced a thermal evolution history of high geotemperature at an early stage and low geotemperature at a late stage (cooled gradually since Mesozoic), and the heating of ancient marine source rocks are basically in an annealing process. Furthermore, owing to the apparent differential settlement of the Basin, the burial evolution history is obviously different in different tectonic provinces. A relevant study shows that there are mainly three types of burial evolution patterns in the Cambrian-Ordovician of the Basin (Fig. 5): a. persistent progressive burial type represented by Well Manxi 1; b. type of deep-buried at an early stage and uplifted at a late stage represented by Well Tadong 2; and c. Type of continually shallow-buried at an early stage and rapidly deep-buried at a late stage represented by Well Lungu 38. In the third pattern, the burial process and the geothermal field "annealing" process acted jointly, caused the ancient source rocks to be retained in the "liquid window" from Late Silurian to Paleogene-Neogene, having a continuance as long as 4×10^8 a (Fig. 6). Because some ancient source rocks (blue (in the web version) part in Fig. 5) stayed in the "liquid window" for a long time, the generated hydrocarbon could evade the destruction of multiphasic tectonic movements, and a great deal of liquid hydrocarbon has still been generated and accumulated since Paleogene.

Directed by the understanding that ancient source rocks could generate hydrocarbon and form reservoirs at a late stage by spanning important tectonic phases, the petroleum resource potential of carbonate reservoirs in the Tarim Basin is reassessed. The area of source rocks stayed in the "liquid window" scope for a long time (i.e., source rocks conforming to the burial evolution pattern represented by Well Lungu 38) is ascertained as about 15×10^4 km^2, accounting for 58% of the marine source rock area, and the petroleum geologic resource potential is increased from 42×10^8 t to 85×10^8 t, i.e., there is an increase of 43×10^8 t, indicating that a considerable scale of petroleum resources are still kept in the ancient carbonate reservoirs in the platform area of the Tarim Basin.

3.4. Deep carbonate rocks can form reservoirs in a large-area, with low reserve abundance but large reserve scale

It is universally accepted by the previous researchers that hydrocarbon accumulation in the marine craton basins of China is characterized by "multiphasic hydrocarbon generation, multiphasic accumulation, multiphasic adjustment", and the accumulation history and hydrocarbon distribution are quite complicated [1–3,17–22]. It is shown by our recent

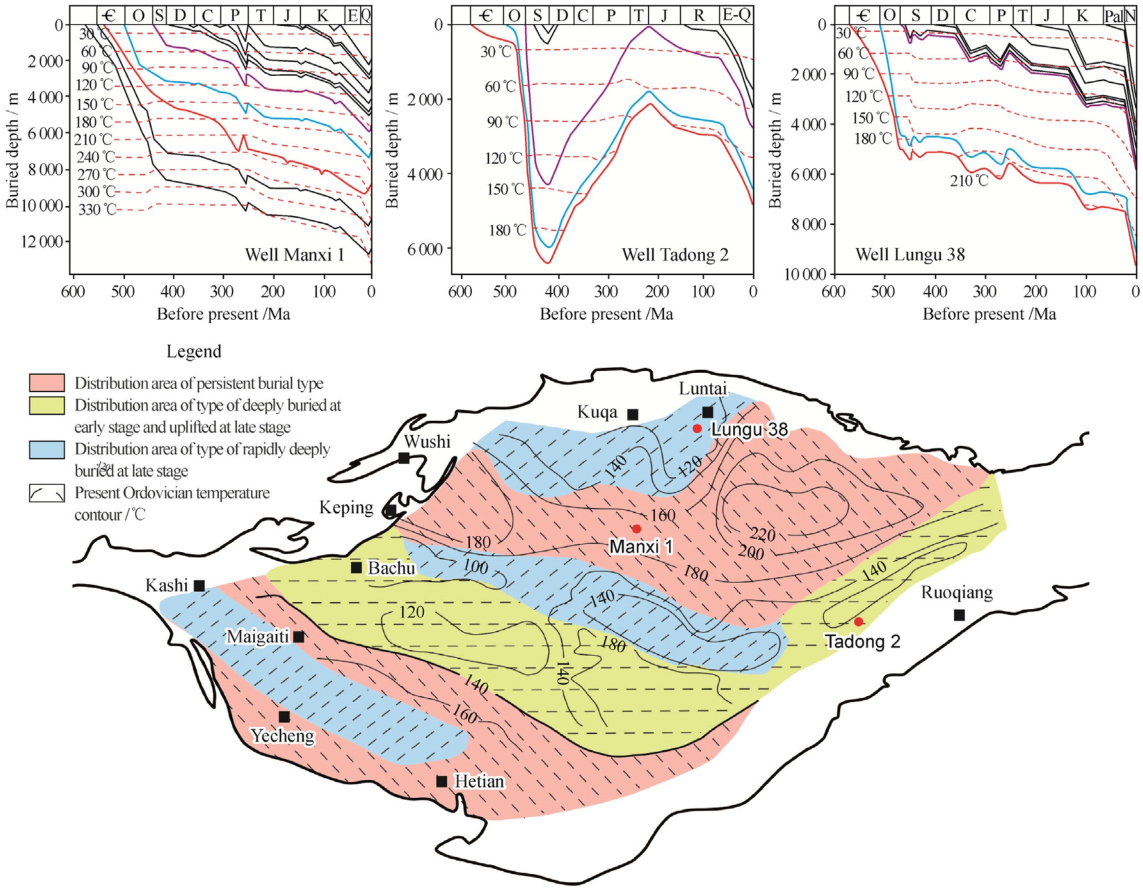

Fig. 5. Three types of burial evolution patterns and the horizontal distribution map of Cambrian-Ordovician in the Tarim Basin.

study that as for the ancient marine carbonate reservoirs developed in China, affected by four factors like large-scale hydrocarbon generation and migration of ancient marine source rocks at a late stage; multiphasic superimposed transformation by bedding, interstratal karsts and hydrothermal fluid corrosion as well as dolomitization; stratigraphic and lithologic traps widely developed in the periclinal area and platform fringe zones of palaeohighs; and hydrocarbon migration network composed by faults and unconformities, three types of large-area reservoir-forming modes are at least developed [9]: a. stratoid large-area reservoir-forming mode of karst reservoirs in the slope area of an uplift; controlled by the stratoid karst reservoirs in the slope zone of an uplift, hydrocarbon accumulation experienced a process of "buoyancy accumulation, fracture channelization, phase control by vug-fracture combination, episodic infusion and stepped migration and accumulation", oil and gas reservoirs formed are dominantly of stratigraphic type and characterized by stratoid large-area distribution; b. back-flow types of large-area reservoir-forming modes of buried hill weathered crust karst reservoirs; controlled by the buried hill weathered crust karst reservoirs, the hydrocarbon formed in the overlying source rocks migrated downward under the action of source-reservoir differential pressure, the oil and gas reservoirs formed are dominantly of stratigraphic type and characterized by flaggy large-area distribution along the base level of erosion; and c. wide-range reservoir-forming modes of reef-shoal reservoirs; the hydrocarbon formed by source rocks migrated both laterally and vertically taking the faults and unconformities as its migration channels, the oil and gas reservoirs formed are dominantly of lithologic type and characterized by zonal wide-range distribution.

Based on the statistics on the 128 oil reservoirs and 123 gas reservoirs discovered in carbonate strata in China, 83.6% of which are lithologic and stratigraphic reservoirs; the reserve abundance of the discovered oil reservoirs is generally 10×10^4–70×10^4 t/km^2, and that of discovered gas reservoirs is mostly 1×10^8–6×10^8 m^3/km^2, with low-to-medium reserve abundance predominant (Fig. 7). Observed from an anatomical research, the oil and gas reservoirs developed in ancient carbonate strata in China are characterized by clustered distribution on the whole, and the scale of a single reservoir is not large (exclusive of the efficiently-formed oil and gas reservoirs like Changxing-Feixian'guan Fm in the Puguang area and Longwangmiao Fm in the Moxi area of the Sichuan Basin); however, the hydrocarbon distribution scope of oil and gas reservoir complexes composed of numerous oil and gas reservoirs is quite extensive, and the reserve scale is quite large. Take the exploration of deep Ordovician karst reservoirs in the northern Tarim Basin for example, the hydrocarbon distribution there is controlled by fracture-cavity units. In the Tahe oilfield discovered by Sinopec, 100

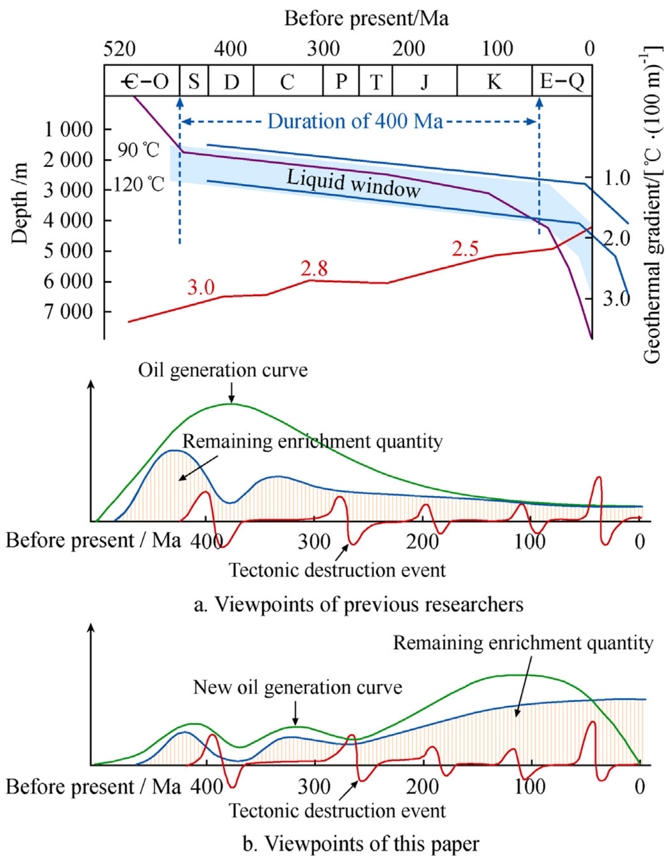

Fig. 6. Hydrocarbon accumulation event analysis of marine carbonate reservoirs in the Tarim Basin by spanning important tectonic phases.

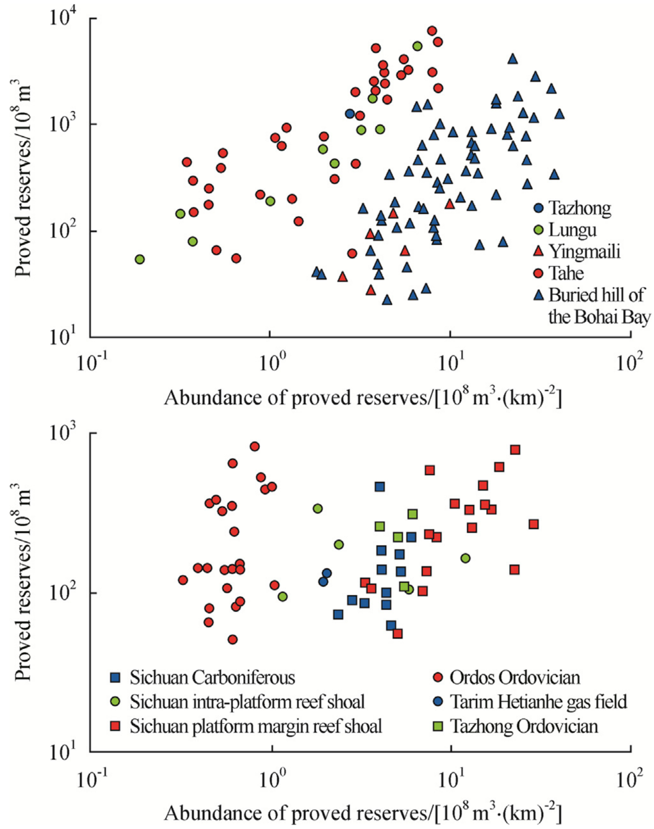

Fig. 7. Reserves vs. reserve abundance of carbonate reservoirs.

fracture-cavity units can be marked off within a 0.28×10^4 km^2 oil domain, the area of each fracture-cavity unit is about 28 km^2 averagely, and the average reserve scale of a single fracture-cavity unit is less than 1000×10^4 t. As for the Lungu oilfield discovered by PetroChina, the oil-bearing area is about 617 km^2, in which 104 fracture-cavity units can be marked off. The mean area of a single fracture-cavity unit there is 5.9 km^2, and the average proved reserve of a single fracture-cavity unit is 145×10^4 t. For the moment, the exploration in the northern Tarim Basin has controlled a hydrocarbon area of about 1.5×10^4 km^2. The proved oil and gas in place of the Tahe oilfield is 11.7×10^8 t oil equivalents, and a 5×10^8 t scale reserve province is formed in the Halahatang area, and the reserve scale is quite large.

4. Prospects of deep carbonate exploration

The distribution area of marine carbonate strata exceeds 450×10^4 km^2 in China. According to the new round of oil and gas resource estimate nationwide, the hydrocarbon resource potential of marine carbonate reservoirs of China is 380×10^8 t oil equivalents. The earlier marine carbonate exploration in China mainly concentrated on the key blocks of the three basins, but the area actually put into exploration was 20×10^4–50×10^4 km^2, accounting for about 34% of the carbonate distribution area. By the end of "the 11th Five-Year Plan", the cumulative proved oil in place of marine carbonate reservoirs in China was 15.2×10^8 t, the gas in place was 1.36×10^8 m^3, the proved rate of petroleum resources was only 15%, and the remaining petroleum resources are still very abundant.

The petroleum resources of ancient deep carbonate reservoirs in China have the potential to be further promoted.

The ancient marine carbonate strata developed in China have two types of hydrocarbon source kitchens like conventional source rocks and gas cracked from liquid hydrocarbon retained inside source rocks at a late stage, both of which can supply hydrocarbon on a large-scale. The earlier oil and gas resource estimate mainly considered the contribution of conventional hydrocarbon source kitchens to the hydrocarbon accumulation, instead of considering the contribution of gas source kitchens formed by the late cracking of dispersive liquid hydrocarbon retained inside source rocks. Actually, the gas source kitchens formed by the cracking of hydrocarbon retained inside source rocks are characterized by late gas generation time, which has largely evaded the destruction of late tectonic movements to the hydrocarbon accumulation, and have a higher hydrocarbon accumulation efficiency and preservation probability, and can largely improve the potential and prospect of discovering natural gas in the deep carbonate reservoirs of China. Recently, based on the understanding of organic matter "successive gas generation" [3], the resource

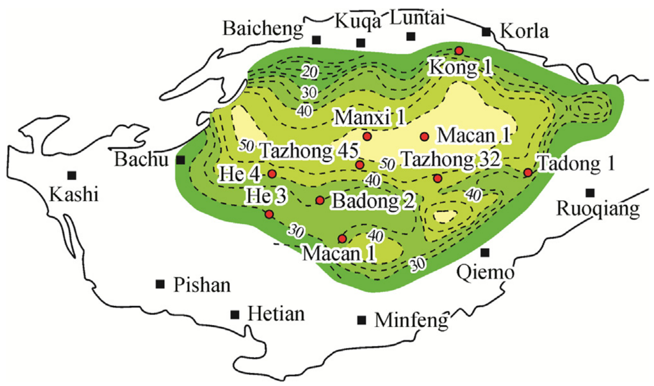

Fig. 8. Contour map of percent proportion of oil cracked gas in the marine strata of the Tarim Basin to its total marine petroleum resources.

potential of high-overmature areas in the Tarim Basin has been studied and evaluated, indicating that the contribution rate of the late cracked gas from the liquid hydrocarbon retained inside source rocks of the Tarim Basin to the petroleum resources of the marine series of strata of the Basin exceeds 50% (Fig. 8), and the total gas resources can reach 2.4×10^{12} m^3. The resource potential of the nationwide marine high-overmature areas is also assessed, indicating that the source rock distribution area is 230×10^4 km^2, and the natural gas geologic resource extent is increased by $5 \times 10^{12}-8 \times 10^{12}$ m^3.

There are still some realms with lower cognitive degrees in deep carbonate reservoirs, e.g., understanding issue of Middle-Late Proterozoic potential in China. There are source rock development conditions in the Mesoproterozoic aulacogen of the North China region and the Sinian rift of the Sichuan Basin; furthermore, in the Sichuan Basin, largely distributed Doushantuo Fm and Dengying Fm Deng III member argillaceous source rocks have been discovered in Sinian, further indicating that there are favorable petroleum resource exploration potentials in the Mesoproterozoic-Neoproterozoic of China.

5. Conclusions

Deep carbonate reservoirs in China onshore possibly have higher-than-expected resource potentials, and are promising for discovering large fields. They are the important target of petroleum exploration for reserves replacement in China. Our findings are specifically manifested in four aspects.

1) There are two kinds of hydrocarbon kitchens which were respectively formed by conventional source rocks and liquid hydrocarbon cracking that were detained in source rocks, and both of them can provide large-scale hydrocarbons.
2) As controlled by the bedding and interstratal karstification as well as the burial and hydrothermal dolomitization, large-scale effective reservoirs are developed in the ultra-deep carbonate strata.
3) Under the coupling action of progressive burial and annealing heating, some ancient marine source rocks can form reservoirs by spanning tectonic phases; marine carbonate reservoirs are rich in oil and richer in gas.
4) Large-scale uplifts were formed by the stacking of multi-episodic tectonism and oil and gas could be accumulated in three modes; groups of stratigraphic and lithologic traps were widely developed in the areas of the periclinal structures of paleohighs and continental margins, with low reserve abundance but a large reserve scale.

Meanwhile, it should be noted that deep carbonate reservoirs are located in the lower structures of superimposed basins, basically characterized by more gas than oil, complicated reservoirs and high temperature and pressure. It is hard to use the conventional petroleum geology theories to effectively guide the petroleum exploration of deep zones. Therefore, strengthening the basic research and exploration of deep petroleum geology and developing the deep petroleum exploration theories are of realistic significance to the sustainable, steady and sound development of oil and gas industry in China.

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