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Research Progress in the Petroleum and Natural Gas Geological Theory of China

MA Yongsheng* and ZHAO Peirong

China Petroleum & Chemical Corporation, Beijing 100728, China

Abstract: The Chinese landmass, as a composite region, consists of multiple small continental blocks, such as Sino-Korea, Yangtze, Tarim, etc., and orogenic belts. Because of its distinctive tectono-sedimentary evolution, China's oil/gas-bearing regions differ remarkably from that elsewhere in the world. For instance, in comparison to the Middle East oil/gas-bearing regions which are characterized by Mesozoic-Cenozoic marine oil/gas-bearing beds, early oil and gas discoveries in China are distributed mainly in Mesozoic-Cenozoic continental sedimentary basins. Generation of oil from terrestrial organic matter, or terrestrial oil generation, and the formation of large oil/gas fields in continental sedimentary basins were previously the major characteristics of petroleum geology of China. However, in the past 20 years, a series of major oil and gas discoveries from marine strata have been made. Marine oil/gas fields in China are mainly distributed in the Tarim, Sichuan, and Ordos basins, which are tectonically stable and covered with Mesozoic-Cenozoic deposits. In these basins, hydrocarbon-bearing strata are of old age and the oil/gas fields are commonly deeply-buried. Cumulatively, 995 oil/gas fields have been found so far, making China the fourth largest oil-producing country and the sixth largest gas-producing country in the world. In terms of petroleum and natural gas geology, theories of hydrocarbon generation from continental strata, such as terrestrial oil generation and coal-generated hydrocarbons, etc., have been established. Significant progress has been made in research on the sequence stratigraphy of continental strata, formation mechanisms of ultra-deep clastic reservoirs, and hydrocarbon accumulation in the continental subtle reservoir. Regarding research on the marine petroleum geology of China, with respect to the major characteristics, such as deeply-buried reservoirs, old strata, and multiple phases of transformation, important advances have been made, in areas such as the multiple-elements of hydrocarbon supply, formation of reservoirs jointly controlled by deposition, tectonic activities, and diagenetic fluid-rock reactions, and oil/gas reservoirs formed through superimposed multi-stage hydrocarbon accumulation. As more and more unconventional hydrocarbon resources are discovered, unconventional oil and gas reservoirs are under study by Chinese petroleum geologists, who endeavor to come up with new discoveries on their formation mechanisms.

Key words: petroleum geology, natural gas geology, research, China

1 Introduction

China is a composite region comprised of numerous small continental blocks, such as Sino-Korea, Yangtze, Tarim, etc., and orogenic belts (Ren et al., 2006). Among these continental blocks, though Sino-Korea is the largest, its surface area is only one twelfth of that of the North America craton. Compared to a large craton, such as that of North America, which has a stable basement covered by sedimentary rocks with almost horizontal bedding, small cratons such as Sino-Korea, Yangtze, and Tarim are characterized by an active basement with less stability, highly-deformed sedimentary cover, and strong tectonic activities.

China's landmass has experienced a complex tectonic plate- evolution (Ren et al., 2006; Yang, 2015, Zhai et al., 2002). In the Proterozoic Eon and the Early Paleozoic Era, the Sino-Korea, Yangtze, and Tarim continental blocks were distributed close to the equator (Wan, 2004, 2006; Li et al., 2014) and deposited a set of undeformed marine carbonate rocks and clastic rocks therein. Both the Tarim and Sino-Korea plates collided with Laurasia in the Late Paleozoic. In the meantime, marine and marine-

* Corresponding author. E-mail: yongshma@126.com

terrigenous clastic rocks were deposited, and terrigenous clastic rocks were deposited throughout the Permian. In the Yangtze plate, marine carbonate rocks were mainly deposited in the Late Paleozoic. In the Late Triassic, affected by the Indosinian movement, the Sino-Korean-Yangtze suture occurred and most regions of China's landmass entered the continental realm, and the basic pattern of Mesosoic-Cenozoic basins emerged on terrestrial China. In the Late Triassic and Early Cretaceous, influenced by the expansion of the Mongol-Okhotsk Ocean, a series of Jurassic-Cretaceous continental rift basins developed in the north of China's landmass, and large oil/gas bearing basins such as Songliao and Erlian formed therein (Jin and Song, 2005). In the Cenozoic, impacted by the subduction of the Indian plate and the associated collision and compression, the Tibetan Plateau uplifted rapidly and large compressional depression basins formed in central and western China. Influenced by the strong subduction of the Pacific plate, multiple extensional rift basins formed in eastern China.

Because of the distinctive history of tectonic-sedimentary evolution, China's oil/gas-bearing regions are substantially different from those elsewhere in the world. In comparison to a representative example, such as Mesozoic-Cenozoic marine oil/gas bearing beds in the Middle East, early oil and gas discoveries in China were distributed mainly in Mesozoic-Cenozoic continental sedimentary basins (Luo et al., 2005) . Understanding and recognition of terrestrial oil generation and major oil/gas discoveries in continental basins are Chinese geologists' special contribution to petroleum geological theory. Marine oil/gas fields are mainly distributed in the Tarim, Sichuan, and Ordos basins. In these multi-cyclic superimposed basins covered by Mesozoic-Cenozoic sedimentary deposits, oil/gas bearing strata are old and the reservoirs are deeply-buried (Ma et al., 2002, Zhao et al., 2002). In comparison to the world main oil/gas bearing regions which are characterized by relatively simpler structural geology and monocyclic tectonic evolution, China's oil/gas bearing regions have complex structural geology, having experienced multiple cycles of tectonic evolution. Multi-cyclic oil/gas bearing systems formed by multiple phases of hydrocarbon generation and multi-cyclic source-reservoir-caprock assemblages, with multiple types of oil/gas reservoirs, is one of the other important characteristics of China's oil/gas bearing regions.

2 Current Status of Oil/Gas Exploration and Development in China

China is one of the first countries worldwide to discover and start using oil and natural gas. According to historical records, China has been using oil and natural gas for about 3000 years. Written record of oil seepage can be found as early as the eleventh century at the time of the Song Dynasty (Lu, 1994). In the year 1878, the first modern oil well was drilled with a well depth of 120 meters, and the daily production reached 0.75 tons. Prior to 1949, four small oil fields in Yanchang in Shanxi province, Laojunmiao in Gansu province, Duzishan in Xinjiang province, and Chukuangkeng in Taiwan province, as well as seven small gas fields in Shengdengshan and Shiyougou in Sichuan province, Jinshui and Zhudong in Taiwan province were discovered in China. At that time, the total proved oil reserves were no more than 0.3 billion tons, and the proved natural gas reserves were no more than 4 billion cubic meters. The oil production in 1949 was 70 thousand tons, and the natural gas production was 0.1 billion cubic meters (Wang, 2008).

During the 65 years since the establishment of the People's Republic of China, China's petroleum and oil gas industry developed rapidly. By the end of 2014, 995 oil/gas fields (697 oilfields, and 258 gas fields) had been discovered in total. According to the BP statistical review of world energy (BP 2015), China's total proved oil reserves are 25 billion tons, or 18.5 thousand million barrels equivalently, ranking fourteenth in the world. In 2014, China's annual crude oil production reached 2.1 billion tons, or 4,246 thousand barrels daily, ranking fourth in the world. China is also the second largest oil consuming country. China's total proved natural gas reserves are 3.5 trillion cubic meters, ranking twelfth in the world. In 2014, China's annual natural gas production reached 1,345 billion cubic meters, ranking sixth in the world. China is also the third largest natural gas consuming country.

China's oil fields are mainly distributed in Cenozoic continental sandstones in the Songliao, Bohai rift basins in eastern China, Jurassic continental sandstones in the Zungar Basin, Triassic continental sandstones in the Ordos Basin, and Ordovician marine carbonate rocks in the Tarim Basin in western China. China's natural gas is mainly distributed in Tarim, Sichuan, Ordos, and Qaidam basins in western China and shallow offshore areas in eastern and southern China. The age of the strata in which natural gas fields are distributed ranges from Precambrian to Quaternary.

In the past twenty years, several gas fields with reserves of a hundred billion cubic meters of gas, such as Puguang, Yuanba, Pengzhou, Anyue, and Jingan, and oil fields with reserves of a hundred million tons of oil, such as Tahe, Halahatang, and Tazhong have been discovered in ultra-deep marine carbonates in the Sichuan, Tarim, and Ordos basins in China. At the same time, stratigraphic-lithological oil fields with reserves of a hundred million tons of oil, such as Jiyuan, Ansai, Fengcheng, Honghe, and Huaqing, etc. have been discovered in the continental basin. Gas fields with reserves of a hundred billion cubic feet of gas, such as the ultra-deep Crassus Gas Field discovered in the Kuqa foreland fold belt in the Tarim Basin, and Sulige, Chengdu gas fields, etc. have also been discovered.

Research achievements of China's petroleum and natural gas geologists provide fresh perspectives and theoretical guidance for China's oil and gas exploration. Additionally, continuous discoveries of new oil and gas fields provide abundant source materials for the theoretical development of China's petroleum and natural gas geology. China's petroleum and natural gas geological theories, featuring the continental oil/gas geological theory and a geological understanding of high-evolution, ultra-deep marine oil and gas, have already become an important part of petroleum and natural gas geological theory in the world.

3 Research Progress in Petroleum and Natural Gas Geological Theory of China

3.1. Continental petroleum geological theory

China is one of a few countries that have large-scale and giant-scale oil and gas fields formed in continental basins. Geological recognition and research achievements in continental petroleum geology are an integral part of the petroleum and gas geological theory of China. Chinese petroleum geologists have made every endeavor to contribute to continental petroleum geology, and major research outcomes are described in detail in the following sections.

3.1.1 Continental source rocks

As early as the 1930s, Chinese geologists had started to explore the possibility of oil being generated from continental basins. It was Zhongxiang Pan who published his contribution, "Non-marine origin of petroleum in north Shansi, and the Cretaceous of Szechuan, China" in the AAPG Bulletin (Pan, 1941) that first brought out and elaborated the point "Non-marine petroleum in China." He argued that petroleum not only comes from marine beds, but also can be generated from freshwater sediments, i.e., non-marine (or continental) strata. Starting from the 1960s, as a series of giant-scale continental oil fields such as Daqing and Shengli, etc. were discovered, Chinese geochemists specializing in organic geochemistry (Hu and Huang, 1991, Huang, 1982; Huang et al., 1984) carried out systematic investigations of the basic geological conditions required for terrestrial oil generation. They determined and identified the organic geochemical indicators and parameters, biomarker compounds, and hydrocarbon expulsion threshold for continental source rocks and the associated oil and gas. These discoveries provided theoretical support for oil/gas source rock correlation, evaluation of petroleum source rocks and resource calculation, and established the geological theory of terrestrial oil generation of China (Li, 2000, 2007).

China's coal reserves and production rank among the highest in the world. Coal reserves in China are distributed throughout the Lower Carboniferous, Permo-Carboniferous, Upper Permian, Upper Triassic, Middle-Lower Jurassic, Upper Jurassic, and Tertiary regions, totalling eight coal-bearing strata. In the 1970s, Chinese geochemists started to focus their attention on researching coal-generated hydrocarbons. Based on large geochemical datasets, Chinese natural gas geologists and geochemists (Dai, 1979, 1980, 2009; Dai et al., 2010; Fu et al., 1990; Qi et al., 1987) have systematically established the identification standard and index system for coal-formed gas genesis, and proved the presence of coal-formed gas reservoirs in China. They drew the conclusion that coal-generated hydrocarbons in China are primarily gas and secondarily oil. According to the static key elements for hydrocarbon accumulation and the dynamic hydrocarbon accumulation process, they summarized the accumulation and distribution pattern of coal-formed gas, established the related theory and method for resource assessment and target prediction. Early natural gas exploration in China aimed to discover the accumulation zone of marine carbonate rocks, marine mud shale and lacustrine shale generated oil-type gas, and transitioned to discover that of oil-type gas and coal-formed gas. Such a transition facilitated the development of China's natural gas industry, and promoted the discovery of large-scale gas fields in Cenozoic strata in the Sichuan and Ordos basins.

To date, the proven degree of oil/gas resources in the continental rift basin in the east is more than 50%. In order to better estimate the quantity of resources in oil/gas bearing continental basins and provide theoretical guidance for hydrocarbon exploration, a new generation of Chinese geochemists carried out experiments and modeling studies on the hydrocarbon expulsion process of continental source rocks and performed the related statistical analyses. Hydrocarbon expulsion from source rocks is one of the least understood parts of current petroleum geochemistry. Hydrocarbon expulsion efficiency is not only the key parameter for forecasting conventional resources, but also for predicting unconventional resources, such as unconventional oil and gas. Starting in the 1960s, geochemists had already achieved quite a solid understanding of the mechanism and the efficiency of hydrocarbon expulsion from source rocks (Pang et al., 1997) . Chinese geochemists sampled lacustrine source rock samples from 14 oil-rich continental basins and statistically analyzed the hydrocarbon generation potential index of pyrolysis at different R_o conditions. The data suggested that the key elements controlling both the amount of hydrocarbon expulsion and efficiency of lacustrine source rocks are organic matter abundance, type, and degree of maturity (Chen et al., 2014). Hydrocarbon expulsion efficiency and generation threshold for different types of organic matter have also been statistically studied.

In combination with natural evolution profiles revealed by drilling wells, Cai et al. (2012) and Zhang (2012), etc. carried out a physical simulation experiment of hydrocarbon generation and expulsion on source rocks formed in freshwater and saltwater lake environments in Bohai Bay Basin. Their studies suggested that hydrocarbon generation from source rocks in a saltwater environment can be divided into early and late phase. In contrast, hydrocarbon generation from source rocks in a freshwater lake environment (Fig. 1) only occurs in the late phase. Source rocks in a saltwater environment cross the hydrocarbon expulsion threshold at a depth of 2500 meters, whereas freshwater source rocks cross this threshold at 3000 meters. These findings breached the traditional notion that source rocks in a freshwater lacustrine environment are the major source rocks. In fact, source rocks in a salinized environment are shown to have high hydrocarbon generation and expulsion efficiency. Utilizing these new findings, the identified remaining oil/gas resources increased by 52.3%. The new findings provided theoretical support for petroleum exploration in deep strata in the Bohai Bay Basin.

In the meantime, Chinese geochemists carried out simulations of hydrocarbon expulsion and statistical analysis on siliceous, calcareous, and clay-type source rocks of different mineral compositions, and source rocks

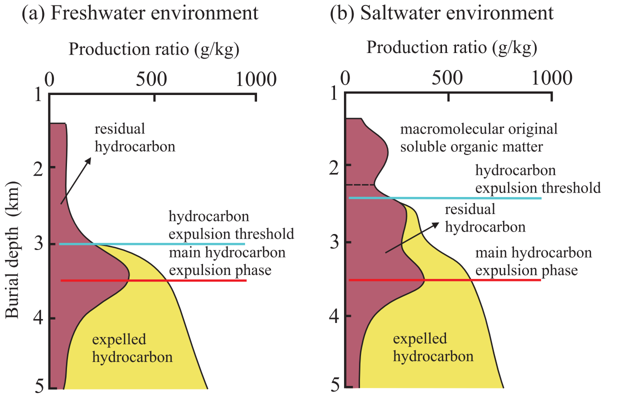

Fig. 1. Hydrocarbon expulsion modes of source rocks in different environments in Dongying sag (Cai, 2012).

with various types of organic matter (Qin et al., 2013, 2014; Hu et al., 2014). These studies determined the hydrocarbon expulsion modes, efficiency, and thresholds for lacustrine source rocks of various depositional environments, of different types of organic matter, and of distinct mineral compositions. Due to these studies, further understanding of the remaining oil and gas resources in oil-rich lacustrine basins has been achieved.

3.1.2 Terrestrial clastic reservoir

(1) Continental sequence stratigraphy, detailed reservoir characterization. Modern sequence stratigraphy related theory and methodology originated from the research on sequence stratigraphy of marine basins. In the 1970s, based on the sequence analysis of passive continental margins, Vail et al. (1977, 1991) established the theory and methodology system of seismic stratigraphy and sequence stratigraphy. At the end of the 1980s, sequence stratigraphy was brought into China. Integrated with the characteristics of China's hydrocarbon exploration, Chinese sedimentologists (Li and Lin, 1995, Gu, 1995; Xu, 1997) applied the research method of sequence stratigraphy into the study of continental sedimentary basins, and achieved significant progress regarding the origin of continental sequences, comparison and sequence classification, and evolutionary patterns of sequences. They suggested that, in contrast to marine sequences which are controlled by global sea level fluctuations, continental stratigraphic sequences are controlled mainly by three factors: tectonics, climate, and origin. Tectonic cyclicity controls the formation of the first- to fourth-order sequences. Lake-level fluctuations caused by climate change control the high-frequency sequence. Tectonic movements, climate change, and source supply function together, controlling the structure of continental sequences, sedimentation type, and distribution.

In recent years, with the aim of precisely forecasting sand bodies of lacustrine origin through detailed analysis of outcrops, comparison with modern sedimentary systems, and experimental verification by flume tests, Chinese sedimentologists have determined the distribution pattern and geostatistical parameters of sand bodies of various dimensions and multiple types, such as shallow water delta, meandering river, braided river, and alluvial fan. Different sedimentation modes have been built to provide theoretical guidance for forecasting subtle sand bodies in continental basins (Zou et al., 2008; Sun et al., 2010, 2015).

(2) Formation mechanism of ultra-deep clastic reservoirs. Along with further exploration of ultra-deep clastic rocks in the rift basin in eastern China in addition to the Tarim basin, China's continental oil/gas exploration shifted from middle-shallow strata to deep, and ultra-deep strata. Chinese geologists discovered high quality sandstone reservoirs at depths of 3000-6000 meters in the Tarim Basin (Zhong et al., 20072008, Wang et al., 2016), Sichuan Basin (Peng et al., 2009), Zunggar Basin (Jin et al., 2011), Ordos Basin (Luo et al., 2002), and rift basins in eastern China (Cao et al., 2013; Meng et al., 2010). These sandstone reservoir rocks have a porosity higher than 10% with a few reaching 20%. The permeabilities are generally higher than 10×10^{-3} μm^2, which are beyond the normal compaction trend of sandstone porosities (Yuan et al., 2015). Quartz sandstone, lithic sandstone, and feldspathic litharenite are the common reservoir rock types of these Paleozoic, Mesozoic, and Cenozoic sandstones. Recently, a series of high-yield large-scale gas fields with stable production have been discovered in the Kuqa area in the Tarim Basin at a depth of 6500-8000 meters. Deep buried sandstone reservoir rocks at a depth of 8000 m from the Kesheng 902 well (Wang et al., 2016) have porosities in the range 4%–8%.

Chinese scholars have conducted substantial research with respect to the formation mechanism of deep clastic reservoirs in various basins. Their research suggests that appropriate early depositional environments are the prerequisite for formation of deep reservoirs. Depositional environment controls the dimension of sand bodies, stacking patterns, grain composition, granularity, sorting, roundness, and matrix content. These factors apparently have control on late diagenetic evolution. Diagenesis controls the present porosity and permeability and the effective value of deep reservoirs. Secondary pores formed by dissolution of underground fluid and tectonic fractures are the primary factors for the formation of high-quality reservoirs. Factors such as an optimal burial pattern, i.e., a long period of shallow burial at the early stage and swift deep burial at the late stage, abnormally high formation pressure, low stress regions formed by gypsum-salt related diapirism, early hydrocarbon injection, and sand-mud interbeds exert indirect influence on high-quality reservoirs.

3.1.3 Geological theory of hydrocarbon accumulation in continental subtle oil/gas reservoirs

In the 1960s and 1970s, Chinese petroleum geologists summarized the distribution pattern of oil/gas reservoirs in Songliao Basin and proposed the 'theory of source control': formation and distribution of oil/gas fields are distributed at the center or periphery of the sag where the hydrocarbons were originally generated (Hu, 1982, Zhang et al., 1982). Therefore, oil/gas exploration in continental basins should begin with an explicit understanding of the location of the center of the source rock distributions, and proceed by selecting favorable traps within or nearby the center for exploration. The theory of source control played an important role in the early exploration of continental basins in eastern China. Subsequent important discoveries have been made in the Bohai Bay Basin.

As oil/gas exploration moved further into continental rift basins, geologists recognized the role played by faults in controlling the faults, traps, and complexity of oil/gas distribution. In rift basins, deposition is controlled by basement faults or syn-sedimentary faults. In the structural reversal period, anticline or fault structural traps and stratigraphic-lithological reservoirs are often developed in fault zones. Based on these models, geologists have summarized six categories and twelve basic modes of multiple oil and gas accumulation zones, and have thus provided important theoretical guidance for exploration in China's continental basins (Hu et al., 1986; Li, 2000).

In the 1990s, as exploration in continental basins expanded further, the scale of discovered structural traps and the discovery ratio started to decrease. Oil/gas exploration transformed into a search for stratigraphic-lithological reservoirs. In order to precisely forecast sand bodies, Chinese geologists specifically carried out high-precision description and comparison of continental stratigraphic sequences. They discovered that depositional paleogeomorphology is the key factor controlling continental lacustrine basins on sandstone bodies. In addition, steep slope and gentle slope step faults, intrabasinal and convex slope breaks formed by faulting in basinal tectonic movements, all control the formation and distribution of sand bodies (Lin et al., 2000; Zhang, 2006).

Multiple episodes of tectonic movement in rift basins formed several nonconformities and widely-distributed fault networks of different orders and combination styles, becoming oil/gas migration conduits. Depending on the specific combination pattern, four different types of basic conduit systems are recognised: 'net-carpet' style, 'T' style, 'staircase' style, and 'fissure' style (Li et al., 2003). Oil/gas reservoirs formed by reservoir bodies controlled by these conduit systems and fault ramps are characterized by a regular distribution pattern in specific temporal and spatial terms. Chinese geologists also realized that hydrocarbon accumulation of stratigraphic-lithological oil and gas also depends on formation pressure and petrophysical parameters. In places where formation pressure is high, reservoir rocks of relatively poor quality can also have an accumulation of hydrocarbons, although the lower limit of the permeability required of reservoir rocks is correspondingly depressed. Alternatively, if the permeability of reservoir rocks is higher, hydrocarbon accumulation can also occur in places where formation pressure is lower. A method of using displacement pressure and porosity to represent fluid dynamics and source rock petrophysical parameters needed for hydrocarbon accumulation to quantitatively or semi-quantitatively forecast the filling degree of oil and gas in stratigraphic-lithological traps has thus been established (Zhang, 2006, 2012).

The research and understanding described above shaped the geological theory underlying the exploration 'roadmap' in continental stratigraphic-lithological oil/gas reservoirs: within a high precision stratigraphic framework, one first investigates the pattern and characteristics of basin-controlled sand bodies-conduits-hydrocarbon accumulation, determining different oil/gas migration-accmulation modes; then, through application of exploration-related technologies, an optimal selection and evaluation of exploration targets is made. Firstly, through research of ramp control on sand bodies to forecast the growth and distribution of reservoir rocks, select the optimal exploration zone. Then, evaluate the effectiveness of conduit systems and the specific pathway of conduits, and determine the characteristics of combination and distribution of oil/gas reservoirs to select the direction of exploration. Finally, according to fluid potential and reservoir rock properties (two inter-related factors), determine the exploration strategy and plan prospective well locations. Under the guidance of the theory and exploration roadmap described above, in the past thirty years, large oil fields in continental rift basins in eastern China have been discovered annually with proved oil reserves of more than one hundred million tons every year.

While carrying out exploration in stratigraphic-lithological traps in continental basins, Chinese geologists determined that the distribution dimension, quantity, and proved reserve ratio of oil/gas fields in sags with different resource abundances varies greatly. An oil-rich sag is where there are high-quality source rocks and high resource abundance is characterized by 'sag-wide oil bearing' (Zhao et al., 2005, 2011). Oil/gas reservoirs are formed and distributed in not only positive structural zones, but also in the structural lows of negative structures in the sag. Therefore, when undertaking exploration in an oil-rich sag, we should consider the sag as an integrated system, look for oil/gas reservoirs of a variety of types, and extend the exploration scope in continental basins.

3.2 Ultra-deep marine oil and gas geological theory

Compared with worldwide Mesosoic and Cenozoic oil-rich marine strata, marine strata in China are mainly Paleozoic, in particular, Lower Paleozoic and Neoproterozoic. Because of multi-episodic tectonic movement in China, many marine strata are overlaid by Mesozoic and Cenozoic continental basinal strata, and are commonly deeply-buried below a depth of 5000 meters. Due to the characteristics of marine strata such as greater geological age and deep burial, source rocks therein typically have a high degree of thermal evolution and it is difficult to reconstruct the hydrocarbon generation and migration processes of the hydrocarbon kitchen. Reservoir rocks experience complex diagenetic processes following deep burial, and hence are highly heterogeneous and difficult to forecast. Multi-episodic tectonic evolution contributes to multiple phases of hydrocarbon accumulation and multiple stages of adjustment. The process of hydrocarbon generation, migration, accumulation, and adjustment is therefore quite complicated. As a result, since the 1930s, marine oil/gas exploration in China hardly achieved any breakthroughs. It was not until after 2000, with both research advances and the development of exploration technology, that a series of large-scale marine oil fields were discovered in the Sichuan, Tarim, and Ordos basins. The theory of marine oil/gas geology thus experienced a rapid development.

3.2.1 The mechanism of multi-source hydrocarbon generation of marine source rocks

The origin of oil and gas has always been one of the key scientific questions requiring an answer from research on hydrocarbon generation and accumulation. Through the study of the origin of oil and gas from newly discovered oil/gas fields in the Sichuan Basin and Tarim Basin, it has been revealed that oil and gas have multiple origins: some are hydrocarbons formed as products of thermal cracking of source rock kerogen from multiple sets of marine strata within marine sedimentary basins; some are associated with regenerated hydrocarbon sources formed as a result of later cracking, e.g., dispersed soluble organic matter within the original reservoir and source rocks; some are even contributed to by organic acid salts. For instance, natural gas produced from the Puguang gas field is primarily cracked gas from paleo-reservoir oil that formed at an earlier stage, and a product of kerogen of Permian and Lower Silurian source rocks that underwent thermal cracking. Bitumen in the paleo-oil reservoir as a secondary hydrocarbon source also contributed to the gas reservoir of the Puguang field, and is an important gas source for non-hydrocarbon gas (Ma et al., 2005c, 2007).

Through modeling of hydrocarbon expulsion from source rocks, and study of oil/gas source correlation, Chinese organic geochemists discovered that multiple phases of hydrocarbon expulsion from the same set of source rocks could occur during multiple episodes of tectonic movement. At the early stage of source rock evolution, kerogen is the major source for hydrocarbon generation, and so forms gaseous and liquid hydrocarbon.

Only a small portion of liquid hydrocarbon formed from kerogen degradation can be expelled from the source rocks, with the majority dispersed throughout them, and subsequent cracking occurring during the highly mature and over mature period (R_o >1.6%). This enables source rocks to have a high potential for gas generation and hydrocarbon accumulation. Therefore, cracking gas from liquid hydrocarbon dispersed within source rocks in a marine superimposed basin is considered to be an important gas source (Zhao et al., 2005, He et al , 2013).

Understanding of multi-source hydrocarbon generation and its associated conversion processes, as well as soluble organic matter that can form gas at a later stage, reflects that the gas generation period of source rocks can be continued to a higher evolutionary stage. To a certain extent, this explains the presence of large-scale oil/gas fields in source rock regions of high thermal evolution level.

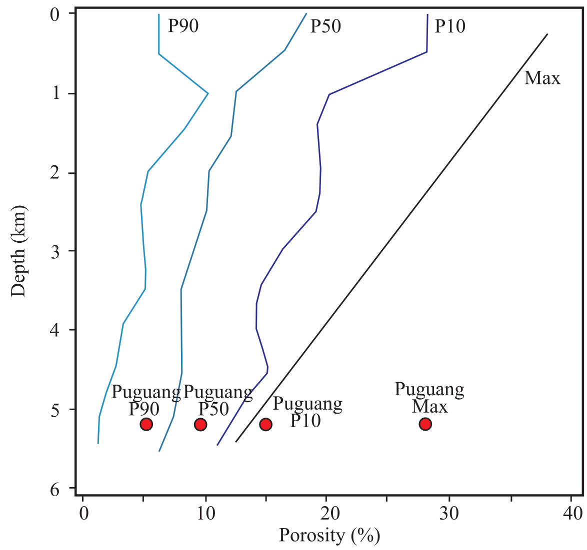

Fig. 2. Relationship between average porosity and depth for global petroleum carbonate reservoirs (Modified from Ehrenberg and Nadeau, 2005).

3.2.2 The formation mechanism of deep and ultra-deep marine carbonate reservoirs

China's marine carbonate reservoir is characterized by old age, deeply buried, with a complex diagenesis, high heterogeneity, various types of reservoir layers, and no apparent depth control on effective reservoir development. Taking the Puguang gas field in the Sichuan Basin as an example (Ma et al., 2010), porosity analyses of 300 cores and porosity-permeability samples from depths of 5000-5200 meters, carried out using S.N. Ehrenberg's method (Ehrenberg and Nadeau, 2005) of analyzing global carbonate porosities suggest that the porosities of the Puguang gas field are significantly higher than those of global carbonate reservoirs buried at the same depth (Fig. 2). In the more recently discovered Yuanba gas field, the reef and shoal dolomite reservoirs under an average burial depth of 6600 meters have an average porosity of 5.18%, and a maximum porosity of 23.59%. In Well Tashen 1 drilled in the north Tarim Basin, a high quality dolomite reservoir has been discovered at a depth of 8400 meters. Intercrystalline pores, corrosion-related fabric-selective intercrystalline solution pores, selective corroded pores and holes, and high-angle and horizontal solution fractures develop in these reservoir rocks (Meng et al., 2010). In high temperature and pressure environments at a burial depth of more than 8000 meters, with temperatures higher than 170℃, and pressures greater than 80 MPa, reservoir space development such as corroded pores, holes, and fractures are rarely observed worldwide. This observation refreshed Chinese petroleum geologists' early points of view on the preservation mechanism of effective reservoir pores of ancient carbonate reservoirs.

Ma et al. (2007, 2010, 2014) carried out detailed research on the formation mechanism of biogenic reef and shoal dolomite reservoirs, and suggested that the development and preservation of carbonate reservoirs are controlled by multiple factors such as (1) depositional and diagenetic environment, (2) tectonics, and (3) fluid flow (Fig. 3).

(1) Early depositional and diagenetic environment controls early pore development. Biogenic carbonate reef and shoal settings in which organisms developed under strong hydrodynamics are favorable depositional environments for the formation of high porosity carbonate rocks (Ma et al., 2005c). At the same time, high-energy biogenic reef and shoal settings can be exposed to the air easily, providing the potential opportunity for further corrosion by meteoric water. Development of primary pores is essential to the formation of dolomites through interaction between dolomitized fluid flow and the surrounding rock. Early dolomitization causes the replacement of early pores. Under conditions of deep-burial, dolomites have a stronger resistance to compaction than limestone and hence preserve more pore space (Ehrenberg, 2006). This paves the way for the preservation of high-porosity dolomites in a deep burial environment.

(2) The coupling of tectonics and fluid flow control fracturing and dissolution. The temperature of the diagenetic fluid, pressure variation, and the opening and closing of the diagenetic environment affected by the burial and uplift caused by tectonics controls the fluid-related dissolution. Tectonics control the formation and propagation of fractures, which control the extent of the development of fracture-related reservoir space.

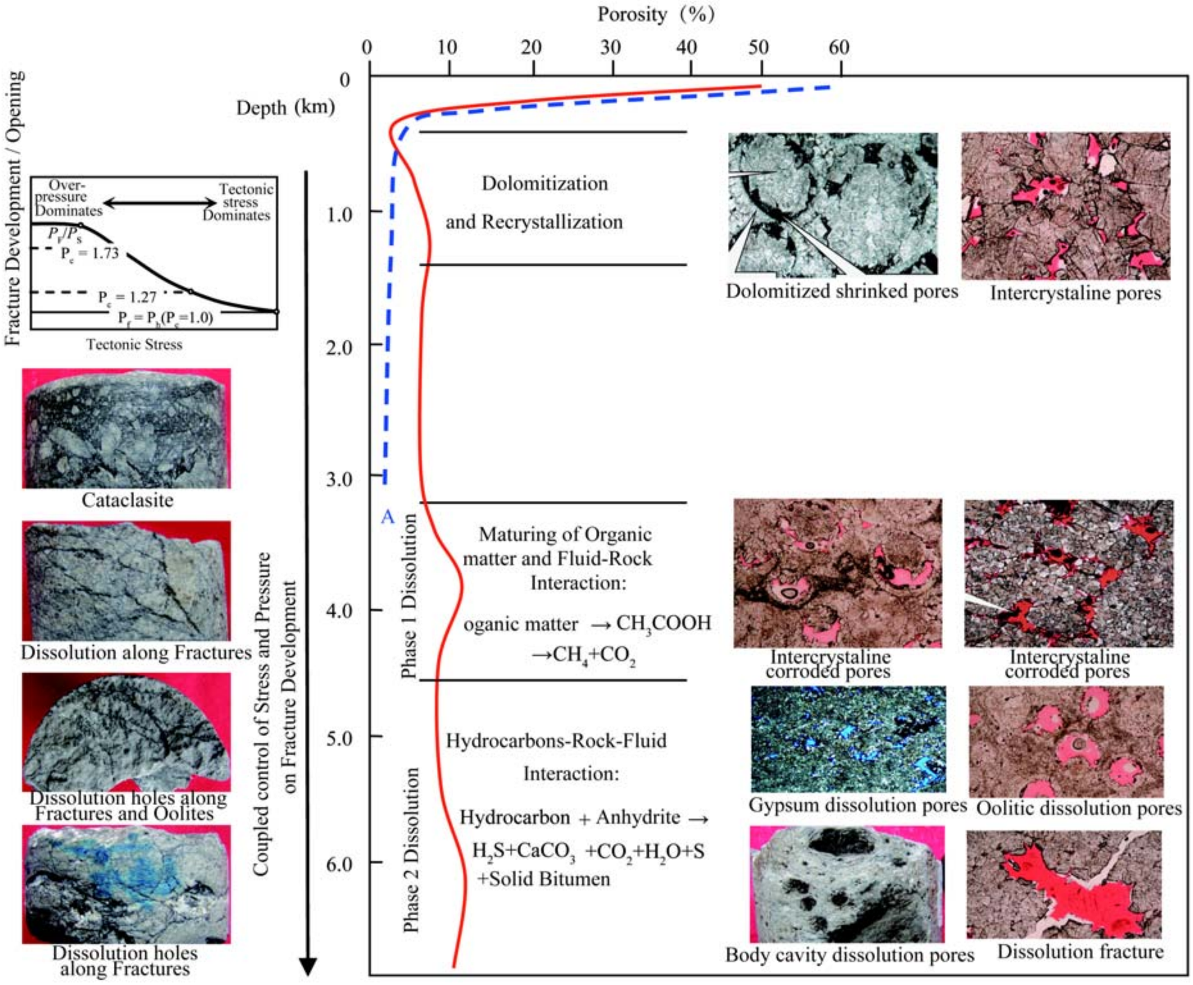

Fig. 3. The model of carbonate reservoir porosity evolution in deep carbonate formations (Ma et al., 2010).

Interconnected fractures act as conduits within rocks, providing favorable conditions for interaction between the rock and organic acids, CO_2 and H_2S (at later stages), etc., as well as sour fluids. Fracture formation periods and abundance control the degree of fluid-rock interaction.

(3) Fluid-rock interaction controls the dissolution and the preservation of porosities. Dolomitized fluid and CO_2 formed in meteoric water during early diagenesis, H_2S formed through interaction between the sulfides within the rock, and the organic acids and hydrocarbons decomposed from organic matter in middle-late diagenesis interact with the rock in the form of dissolution and precipitation. The temperature and pressure change of fluid-rock interaction, whether within an open or closed environment, determine the preservation and transformation of pore space. For the formation of deeply-buried high-quality reservoirs, depositional-diagenetic environments lay the fundamental foundations, tectonic stress-formation fluids coupled with fault-fracture systems serve as the prerequisites, and organic-inorganic reactions and hydrocarbon-rock-fluid interactions play the key roles.

3.2.3 Mechanism of superimposed multi-period marine hydrocarbon accumulation

China's marine carbonate oil/gas fields are primarily lithological (contain karst), and contain composite structural-lithological traps. In comparison with relatively stable marine cratonic basins in the Middle East and North America, China's marine basins have experienced multicyclic tectonic movement and strong late-stage transformation. Marine oil and gas reservoirs are characterized by multiple sources, multiple periods of oil/gas charges, and multiple stages of late-stage adjustments. Multiple modes of hydrocarbon accumulation of carbonate gas fields have therefore been identified, such as the deep burial of paleoreservoirs and oil cracked into dry gas pools, coal-derived gas mixed with cracking gas from liquid hydrocarbon together formed dry gas pools, and oil pools affected by dry gas emplacement thus formed condensate gas pools, etc.

Ma et al. (2005a, 2005b, 2006, 2007) carried out detailed studies using isotope analysis, fluid inclusion analysis, and paleostructure restoration on natural gas pools of the Changxing and Feixianguan formations in the Puguang gas field. Their studies suggested that the Permian source rocks of the Puguang gas field entered a liquid oil window in the Late Indosinian-Early Yanshanian, with liquid hydrocarbon then migrating into the trap and forming an oil pool. In the Middle and Late Yanshanian, continuous subsidence and burial induced the previously-formed oil to undergo high temperature thermal cracking and transform into a gas pool and reservoir with residual pyrobitumen left in the pores. At the same time, source rock kerogen underwent thermal cracking and formed gas migrating towards the gas pool. In the Late Yanshanian-Himalayan, strong tectonic compression and uplift transformed the paleotrap. The gas pool migrated from the structural high, experienced adjustments and transformation, and formed the present Puguang gas field (Fig. 4).

Wang et al. (2011) conducted geochemical research using lighter hydrocarbon, biomarkers, and isotope analysis on the Tazhong reef-shoal complex large-scale condensate gas reservoir. They suggested that the oil of

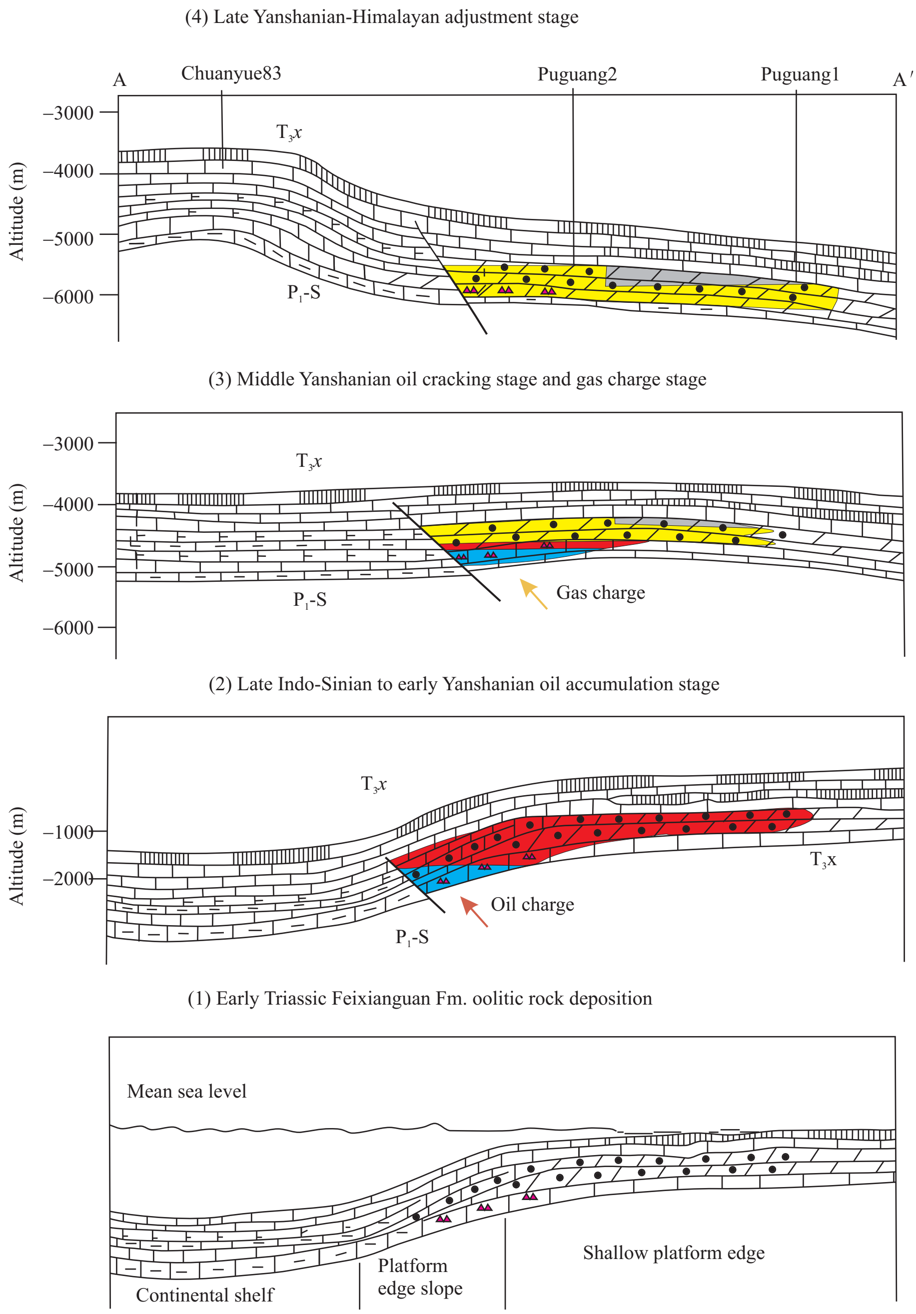

Fig. 4. Schematic models showing the evolution of the structure and reservoir fluids in the Puguang gas field (Ma et al., 2008).

Tazhong Lianglitage Formation reef-shoal reservoir mainly originated from the Middle-Upper Ordovician source rocks, and had mixed with Cambrian source rock generated oil. Natural gas was primarily the Cambrian oil cracking gas, which infilled along the Tazhong No. I slope-break fault zone. Three accumulation stages have been determined for this oil/gas reservoir. The first accumulation stage was Late Caledonian, during which the oil and gas were generated from Cambrian-Lower Ordovician source rocks. Due to the Early Hercynian tectonic movement, the reservoir was damaged. The second accumulation stage was Late Hercynian, which was the major accumulation stage. Oil originated from the Middle and Upper Ordovician source rocks. The third accumulation stage was Late Himalayan, during which the region experienced fast deep burial and the cracking of gas formed from the Cambrian oil. The gas was discharged into a shallow Ordovician oil reservoir from the deep fault zone, and thus a decrease in oil density was induced. With the increase of the gas-oil ratio, the condensate gas reservoir formed.

Yang and Bao (2011) and Yang et al. (2013) studied the Ordovician Jingbian gas reservoir in the Ordos Basin and proposed that Jingbian Ordovician natural gas is characterized by a mixed source, reflecting both the feature of coal-formed gas and that of liquid-hydrocarbon-cracked gas from the Ordovician sapropelic source rock. They considered that Ordovician source rocks reached the peak of oil generation in the Middle-Late Triassic. Magma intrusion occurred in the Late Jurassic-Early Cretaceous causing the thermal cracking of the liquid hydrocarbon formed in the Ordovician source rocks. At the same time, massive highly over-matured coal-generated-gas was formed in the Carboniferous-Permian and migrated along the erosion groove and nonconformity, discharging into Ordovician reservoirs. Under a high temperature regime, Carboniferous-Permian over-matured coal-formed gas and the liquid-hydrocarbon-cracked gas from the Ordovician sapropelic source rock mixed together and formed the Jingbian Ordovician gas reservoir.

4 Research Prospects of Oil and Gas Geological Theory of China

With the rapid development of the shale oil and gas industry in North America, the global oil industry is facing a new revolution, and entering into an era with conventional and unconventional resources being equally important. Driven by advances in nanometer testing technology as well as horizontal-well staged fracturing techniques, China's oil and gas geological theoretical research and understanding is evolving, and oil and gas exploration and development in China is expanding in eight directions: from oil/gas reservoir layers to oil/gas source layers, from local traps to large area basin-wide reservoirs, from structural lithological oil/gas reservoirs to conventional/unconventional oil/gas accumulations, from searching for oil/gas reserves at structural highs to exploration in low sags and depressions, from high-quality reservoirs to reservoirs of various types, from mid-depth and deep depth targets to middle, deep, and ultra-deep depth targets, from oil/gas resources of high-medium grades to resources of high-medium-low grades, and from shallow sea, mid-deep depth water to shallow sea, mid-deep depth water and deep sea. The current oil/gas geological theory of China is progressing forward in new directions as summarized in the sections below.

4.1 Integrated research on the regularity of formation of conventional-unconventional oil and gas

In recent years, Chinese petroleum geologists have noticed that unconventional resources such as shale oil and gas and conventional oil and gas can often occur within the same basin, suggesting a correlation in their genesis and a spatial relationship in their co-existence. With respect to the research on oil/gas geological theory, researchers have thus begun to pay attention to integrated study on the regularity of formation of conventional-unconventional oil and gas. Research on source rock related subjects has expanded from merely the hydrocarbon generation peak, to the whole hydrocarbon generation process. Research on reservoir layers has expanded to the application of nanometer testing technology to shale, sandstone, and carbonate rocks, and the description of petrophysical properties of reservoir rocks at the meter scale, centimeter scale, micrometer scale, and nanometer scale, etc., as well as the percolation characteristics of fluid at different pore diameters. In terms of research on the regularity of hydrocarbon accumulation, the coupling process of hydrocarbon expulsion from organic-rich source rocks with various types of reservoir bodies along with the burial evolution, as well as the control of reservoir bodies of different pore diameters on oil/gas types, have gained more attention. Through studies on the spatial distribution regularities and evolutionary processes of conventional-unconventional oil and gas at different stages of source-rock evolution, we have broken through the prior practice of only concentrating on conventional or unconventional oil/gas related research, exploration, and development.

4.2 Theoretical research of ultra-deep oil/gas geology

With greater exploration completed in shallow-middle depth layers, China's oil/gas exploration has been extending down towards deep and ultra-deep layers. A series of achievements have already been gained in the areas of ultra-deep continental clastic rocks and marine strata. Phenomena demonstrated by oil/gas exploration and development practices have countered traditional geological theory and understanding. Currently, Chinese geologists are carrying out research on the reservoir space revolution of carbonate and clastic reservoir layers during deep burial, the transformational effects of ultra-deep diagenetic fluid on reservoir petrophysical properties, brittle-ductile transition of the rock, and the regularities of fracture development in the ultra-deep environment. With respect to the research on source rocks, the following subjects have gained significant attention: the oil/gas generation mechanism, hydrocarbon phase behavior and oil gas resource potential under high-temperature and high-pressure conditions, hydrocarbon stability and maximum depth of oil/gas reservoir formation under high temperature and high pressure conditions, the introduction of deep earth fluids, such as CO_2 and H_2S, into oil/gas accumulations, etc.

It can be anticipated, as the technologies of nanometer testing and analysis, and big data, etc., are applied, that China's oil and gas geological research will shape new understandings in the formative relationships between conventional and unconventional oil and gas, as well as ultra-deep oil/gas geology. China's oil and gas geological theory will make further breakthroughs again in the near future.

5 Conclusions

In comparison to the worldwide oil/gas bearing beds that are mainly localized in the Mesozoic-Cenozoic marine strata, early oil and gas discoveries in China are distributed mainly in the Mesozoic-Cenozoic continental sedimentary basins. Terrestrial oil generation and the concomitant formation of large oil/gas fields in continental sedimentary basins is one of the major characteristics of China's oil and gas geological theory. Marine oil/gas fields in China have primarily been discovered in Lower Paleozoic strata (including Precambrian strata) in the Tarim Basin, Sichuan Basin, and Ordos Basin, which are tectonically stable. These strata are overlain by Mesozoic-Cenozoic deposits, and are characterized by old hydrocarbon-bearing layers and the deep burial of oil/gas fields.

With respect to the research on oil/gas geological theory, Chinese geologists have established the theory of hydrocarbon generation from terrestrial organic matter, such as terrestrial oil generation and coal-generated hydrocarbon. Significant progress has been made in the areas of continental sequence stratigraphy, the formation mechanisms of ultra-deep clastic reservoirs, and hydrocarbon accumulation of continental subtle reservoirs.

Regarding research on marine oil and gas geology in China, with respect to the major characteristics, such as deeply-buried reservoirs, old strata, and multiple phases of transformation, important understandings have been gained, such as in the multiple elements of hydrocarbon supply, the formation of reservoirs jointly controlled by deposition, tectonic activities, and diagenetic fluid-rock reactions, and oil/gas reservoirs forming through superimposed multi-stage hydrocarbon accumulation.

As the studies on unconventional oil and gas provide additional discoveries, Chinese petroleum geologists will continue to investigate the integrated formation mechanism of conventional-unconventional oil and gas, as well as the formation mechanism of ultra-deep oil and gas, and thereby will continue to shape our future understanding.

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About the first author

MA Yongsheng _Male; born in 1961 in Hohhot City, Inner Mongolia; Academician of the Chinese Academy Engineering; Vice President of China Petroleum & Chemical Corporation (SINOPEC); Research interests: Sedimentology, Petroleum and Natural Gas Geology.

Email: mays@sinopec.com ,yongshma@126.com