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Theoretical Progress and Key Technologies of Onshore Ultra-Deep Oil/Gas Exploration

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ABSTRACT

Oil/gas exploration around the world has extended into deep and ultra-deep strata because it is increasingly difficult to find new large-scale oil/gas reservoirs in shallow–middle buried strata. In recent years, China has made remarkable achievements in oil/gas exploration in ultra-deep areas including carbonate and clastic reservoirs. Some (ultra) large-scale oil and gas fields have been discovered. The oil/gas accumulation mechanisms and key technologies of oil/gas reservoir exploration and development are summarized in this study in order to share China's experiences. Ultra-deep oil/gas originates from numerous sources of hydrocarbons and multiphase charging. Liquid hydrocarbons can form in ultra-deep layers due to low geothermal gradients or overpressures, and the natural gas composition in ultra-deep areas is complicated by the reactions between deep hydrocarbons, water, and rock or by the addition of mantle- or crust-sourced gases. These oils/gases are mainly stored in the original high-energy reef/shoal complexes or in sand body sediments. They usually have high original porosity. Secondary pores are often developed by dissolution, dolomitization, and fracturing in the late stage. The early pores have been preserved by retentive diageneses such as the early charging of hydrocarbons. Oil/gas accumulation in ultra-deep areas generally has the characteristics of near-source accumulation and sustained preservation. The effective exploration and development of ultra-deep oil/gas reservoirs depend on the support of key technologies. Use of the latest technologies such as seismic signal acquisition and processing, low porosity and permeability zone prediction, and gas–water identification has enabled the discovery of ultra-deep oil/gas resources. In addition, advanced technologies for drilling, completion, and oil/gas testing have ensured the effective development of these fields.

1. Introduction

After many years of petroleum exploration and exploitation, it is becoming increasingly difficult to find oil or gas in middle–shallow buried strata. Globally, with the development of theory and technology, more and more oil and gas have been found in deep (4500–6000 m) to ultra-deep (> 6000 m) buried strata. Since 2008, production of oil and gas from reserves in ultra-deep buried strata has increased greatly.

The potential for ultra-deep petroleum exploration is huge. Globally, the six basins with the most enriched ultra-deep oil and gas reserves are the Mexican Bay Basin (USA), the Tarim Basin (China), the South Caspian Basin (Russia), the Arab Basin (Middle-East), the Santos Basin (South America), and the Sichuan Basin (China). In these basins, 120 ultra-deep oil or gas fields have been found with tremendous proven, probable, or possible deep reserves.

Ultra-deep strata are also important targets of petroleum exploration in China, and several oil or gas fields have been found. In this paper, these discoveries are introduced with specific cases. In addition, key features of these oil/gas fields, including the oil/gas sources, reservoir, petroleum accumulation mechanisms, and major technologies in ultra-deep petroleum exploration and exploitation, are discussed.

2. Recent exploration discoveries in ultra-deep areas in China

Ultra-deep petroleum exploration in China is mainly concentrated in the Sichuan Basin and the Tarim Basin. In recent decades, several ultra-deep giant oil or gas fields, such as the Yuanba

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Gasfield in the Sichuan Basin, and the Tahe Oilfield and Keshen–Dabei Gasfield in the Tarim Basin, have been found. At present, a total of 2.55 Gt (oil equivalent) of reserves has been proven, accounting for 11.6% of the proven, probable, and possible reserves (Fig. 1). These achievements were listed in Table 1 as major progresses in science and technology on an annual basis over a ten-year period in China by the China National Petroleum Corporation (CNPC), Geological Society of China (GSC), and Chinese Petroleum Society (CPS). However, considering the tremendous reserves in ultra-deep strata, most of the ultra-deep petroleum is unexplored.

According to these discoveries, ultra-deep petroleum could be stored in various reservoirs, including carbonates, clastic rocks, and volcanic rocks. Among these, carbonates deposited in marine environments and clastic rocks sedimented in terrestrial delta facies are the most important (Table 2).

2.1. Carbonate reservoirs

The ultra-deep carbonate reservoirs in China are mainly distributed in the Paleozoic to Proterozoic strata in the Sichuan Basin and the Tarim Basin. In the Sichuan Basin, only natural gas is produced in the ultra-deep buried strata, and the potential reservoirs are distributed throughout the basin. To date, the Yuanba Gasfield has been discovered in this region in addition to some minor discoveries in the Longgang area (Fig. 2).

The Yuanba Gasfield is located in the northern depression of the Sichuan Basin. The gas is reserved in marine strata of the Upper Permian Changxing to the Lower Triassic Feixianguan Formations. The reservoir, buried at 6500–7110 m, is a lithological reef-shoal complex with an average porosity of 5.2%. The total proven gas reserve is 2.19×10^{11} m^3. The natural gas was composed of 88.35% methane (CH_4), 5.22% hydrogen sulfide (H_2S), and 6.8% carbon dioxide (CO_2) [1]. Tens of kilometers to the southeast of the Yuanba Gasfield, the Longgang reef-shoal gas field was discovered, with a shallower burial depth and a proven reserve of about 4.1×10^{10} m^3 in the ultra-deep strata.

In the piedmont zone of the western depression of the Sichuan Basin, high-producing gas flow was also found in the top reservoir of the Leikoupo Formation, with a depth of more than 6000 m. The daily gas production of Well Yangshen-1 in the fourth member of the Leikoupo Formation reached 0.6×10^6 m^3, thus demonstrating great exploration potential.

In the Tarim Basin, the ultra-deep large oil/gas fields are mainly distributed in the Tabei and Tazhong areas (Fig. 3). The main production strata are the Middle–Lower Ordovician; the Cambrian also has a certain degree of exploration potential.

Table 1
Major progresses in science and technology related to ultra-deep petroleum exploration in China since 2010.

Year	Major progresses in ultra-deep petroleum exploration	Awarded organization
2010	(Ultra-) deep exploration technology from China used in the shallow sea region promoted the discovery of a giant gas pool in the mature exploration area in the Gulf of Mexico	CNPC
2011	The Yuanba exploration project, a sub-project of Marine Exploration in northeastern Sichuan Basin, found the deepest large gas field in China	GSC
2012	The hydrocarbon supply theory for deep stratum was widely promoted	CNPC
2012	A giant gas field was found in the carbonate strata with a depth greater than 6500 m in the Hanilcatam (Halahatang) area, Tarim Basin	GSC
2014	A natural gas exploration project was undertaken in Kelasu, Tarim Basin	GSC
2015	The tolerance temperature of downhole tools broke the record and reached 200 °C	CNPC
2016	High and stabilized production technology was developed for big reef gas fields with ultra depth and high sulfur content in the Yuanba Area	GSC
2016	Ultra-deep horizontal well drilling and completion technology were developed	CPS

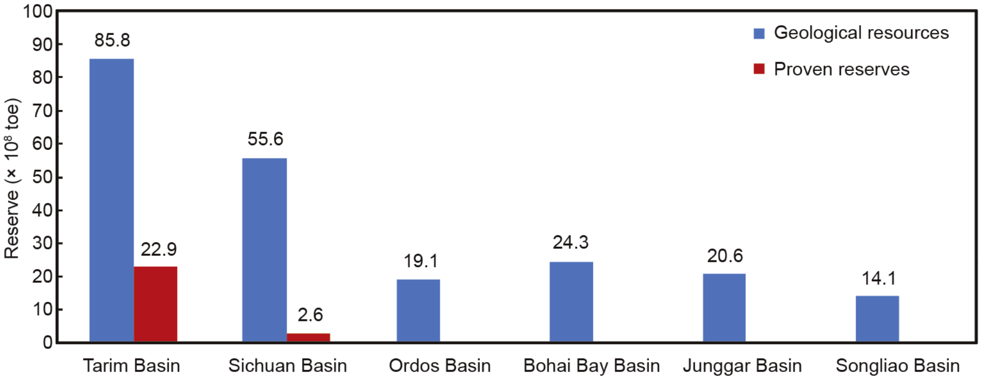


Fig. 1. Bar charts showing geological resources and proven reserves of ultra-deep petroleum in six main onshore basins in China. toe: tonne of oil equivalent.

Table 2
Ultra-deep reservoir rock types and major discoveries.

Reservoir types	Sedimentary facies	Major discoveries with formations and locations
Carbonates	Marginal platform reef-shoal	Upper Permian Changxing Formation and Lower Triassic Feixianguan Formation (Yuanba, Sichuan Basin) Ordovician (Tazhong No. 1 structure, Tarim Basin)
	Shoal (grain beach)	Carboniferous (Tazhong No. 4 structure, Tarim Basin)
	Dolostone	Carboniferous (Sichuan Basin)
	Karstic weathering crust	Ordovician (Tahe, Hanilcatam, Lunnan and Lungu, Tarim Basin)
	Fault/fracture	Ordovician (Shunbei, Tarim Basin)
Clastic rocks	Delta deposits	Cretaceous (Keshen–Dabei Gasfield, northern Tarim Basin)

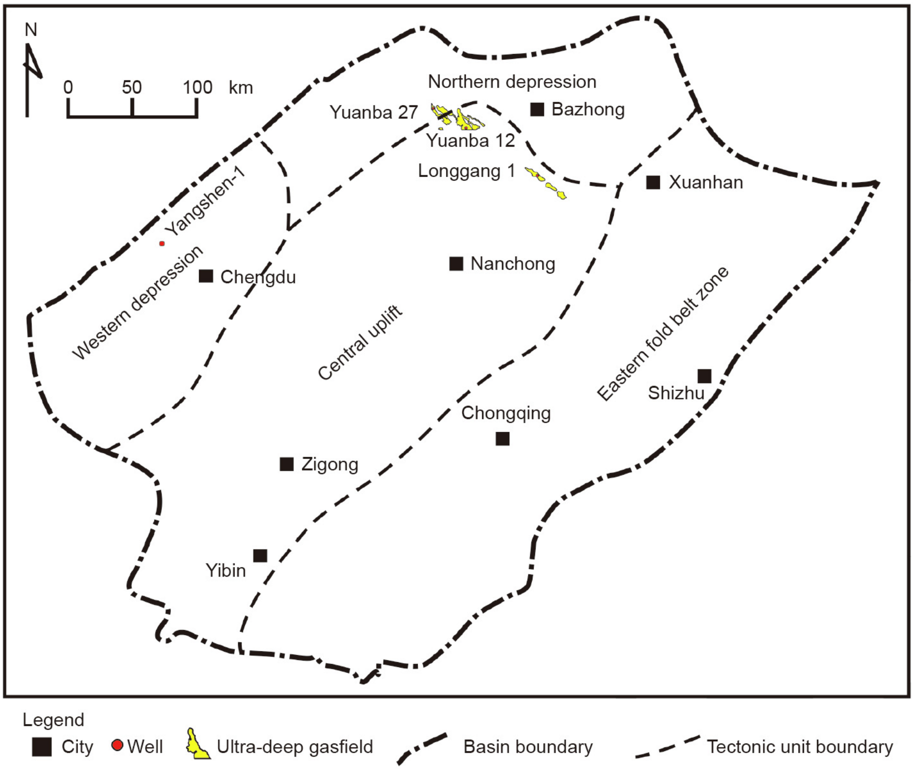


Fig. 2. Ultra-deep gas fields in the Sichuan Basin.

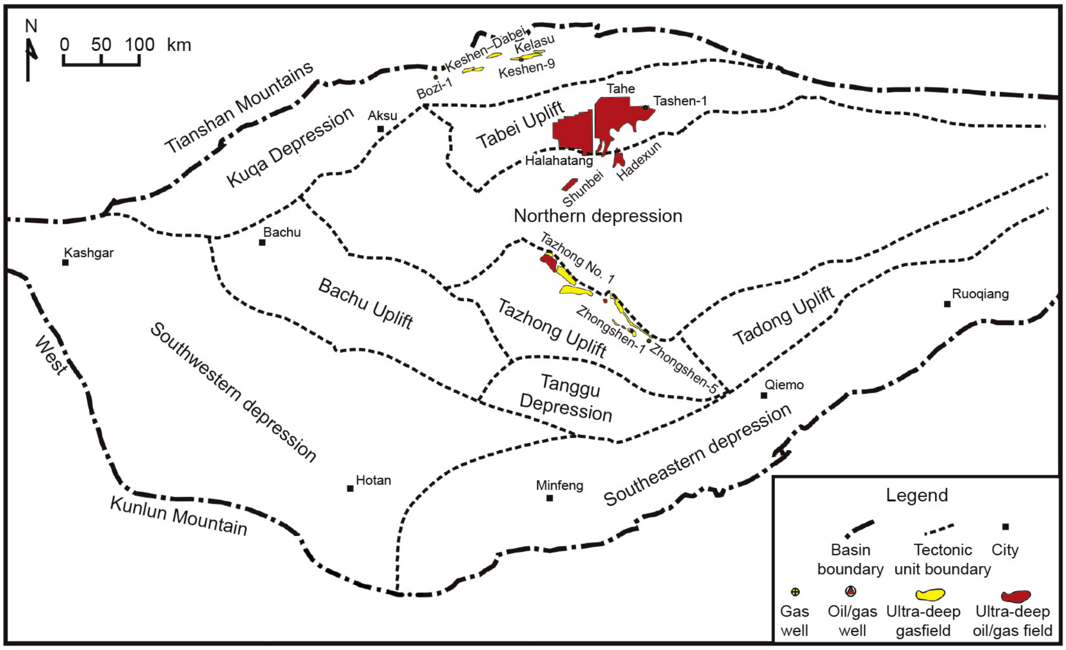


Fig. 3. Ultra-deep oil and gas fields in the Tarim Basin.

The largest oil field discovered in the Tabei area is the Lunnan–Tahe karst fracture-cavity field. Its oil-bearing area is 2800 km^2, consisting of more than 100 karst fracture-cavity oil storage units of various sizes. Even in the buried strata more than 6000 m deep, these epigenetic karst fracture-cavities are still well preserved. In 2006, Well Tashen-1, which is 8408 m deep, was drilled in the southeastern part of the Akekule Uplift in the northern Tarim Basin, and liquid hydrocarbons were found in Cambrian high-quality dolostone reservoirs. At the end of 2014, the drilling depth of a single well of the Middle–Lower Ordovician in the Well Tashen-3 field was 6168.24–6724.00 m. A fracture-cavity beneath the weathering crust with a thickness of 160–350 m was subsequently discovered, and high-yield oil flow was obtained. As of the end of 2014, the Tahe Ordovician has yielded 1.377×10^9 t of proven reserve.

In Tazhong, the ultra-deep oil and gas are mainly distributed along the Tazhong No. 1 fault zone. In 2013, there were also breakthroughs from Well Zhongshen-1 in the Middle–Lower Cambrian

Xiaoerblak Formation at 6861–6944 m, with 158 500 m^3 of natural gas produced per day. Subsequently, liquid hydrocarbons were found in Well Zhongshen-5 at 6562–6671 m. After acid fracturing, the highest daily oil and gas production were 24.17 and 11 804 m^3, respectively, with a 6 mm nozzle [2]. In the Shuntuoguole Lower Uplift area of the Tazhong No. 1 fault zone, the reservoir depth is generally 6600–8000 m, with a formation pressure of 82–172 MPa and a stratum temperature of 184–207 °C. Well Shuntuo-1, with a depth of 7874 m, produced 388 000 m^3 of natural gas per day in the Ordovician reservoir. In the southern part of Tazhong—that is, the Shunnan area—2.6×10^5–1.1×10^6 m^3 of natural gas per day was drilled to a well depth of 6300–6700 m in the Ordovician. In the northern part of Tazhong—that is, the Shunbei area—ultra-deep oil with a burial depth of more than 6300 m was also discovered in the Ordovician. Well Shunbei-1CX produced 132 m^3 of oil and 45 000 m^3 of gas per day.

2.2. Clastic rock reservoirs

To reach ultra-deep layered clastic reservoirs, China has drilled multiple ultra-deep wells. These wells include: Well Keshen-1 (8023 m), Well Keshen-902 (8038 m), and Well Bozi-1 (7014 m) targeting the Cretaceous; Well Adong-1 (7680 m) targeting the Upper Ordovician in the Tarim Basin; and Well Niudong-1 (6027 m) targeting the Paleocene in the Bohai Bay Basin. The Keshen–Dabei Gasfield is currently the only found gas pool in the Kuqa Depression of Tarim.

The Keshen–Dabei Gasfield is located in Kelasu Subsalt in the Kuqa Depression in the Tarim Basin. Its clastic rock reservoirs are rich in natural gas resources. A Cretaceous high-quality delta sand reservoir was found in the ultra-deep buried strata with a burial depth of 6000–8000 m, stratum pressure of 88–136 MPa, stratum temperature of 120–184 °C, and reservoir thickness of 200–300 m. The reservoir is vertically stacked and is laterally connected with an area of 18 000 km^2; it has a porosity of 5.7%–7.9% [3]. A total industrial oil flow of 466 000 $m^3 \cdot d^{-1}$ was obtained in the 6573–6696 m Cretaceous interval from Well Keshen-2 drilled on August 28, 2008, which marked the discovery of the Keshen Gasfield. The test of Well Keshen-9 in the 7445–7552 m section revealed a daily output of 1.13×10^6 m^3 of high-yield industrial gas. The gas reservoir pressure is 127.4 MPa with a wellhead oil pressure of 100 MPa. Thus far, 14 gas pools have been found by the end of September 2018, these included five large-scale gas reservoirs (Keshen-8, Keshen-9, Keshen-6, Keshen-13, and Bozi-1) with a total proven gas reserve of 8.3×10^{11} m^3 and probable and possible reserves of 3×10^{11} m^3.

In addition, in the Songliao Basin, ultra-deep clastic rock reservoirs have been industrially developed. In the Qikou sag area of the Bohai Bay, ultra-deep buried strata have also been identified as a potentially profitable exploration area.

3. Oil/gas sources in ultra-deep reservoirs

The first major issue to be solved in ultra-deep oil/gas exploration is the origin of the oil/gas. The classic "kerogen pyrolysis and hydrocarbon generation theory" [4] uses a kerogen-generating-hydrocarbon geochemical diagram to establish an oil/gas genesis model. However, this model is too general [5–7], and it is becoming increasingly difficult to explain complicated ultra-deep oil/gas sources. After long-term geological evolution, the composition of ultra-deep oil/gas is becoming extremely complex and often shows the characteristics of mixed and multistage formation from multiple sources. This is because ultra-deep oil/gas reservoirs often have multiple supplies of hydrocarbons and multistage charging mechanisms.

3.1. Multiple supplies of hydrocarbons

There are two major sources of ultra-deep gas. One is the cracking of crude oil, which includes the direct cracking of crude oil into gases and the cracking of bitumen—the byproduct of crude oil cracking—into gases. The other is the cracking of hydrocarbon source rocks (kerogen) after maturation.

3.1.1. Crude oil-cracked gases

After being deeply buried for a long time, the source rocks became mature and began to generate hydrocarbons. As they were transported, these hydrocarbons accumulated in effective traps and formed ancient reservoirs. As the burial depth further increased, the temperature rose above 160 °C and the ancient oil reservoir began to crack. An ancient gas reservoir was thus formed. Under the effects of later tectonic adjustment and re-aggregation, the current gas reservoir was then formed. Another product of crude oil cracking was solid bitumen, which could generate hydrocarbons again under the effect of heat. This constituted another important source of natural gas [8,9].

Therefore, paleo-oil or bitumen cracking may be an important source of ultra-deep natural gas. With respect to sapropelic organic matter, most of the natural gas comes from the cracking of crude oil produced by kerogen in the early stage, and only a small part of natural gas originates from kerogen cracking [10].

The marine reef-shoal gas field of the Changxing Formation in the Yuanba area, Sichuan Basin and the Cambrian subsalt gas reservoir of Well Zhongshen-1 in the Tazhong area of the Tarim Basin are typical reservoirs composed of gases cracked from crude oil [11–13]. Analyses of $\ln(C_2/C_3)$–$\ln(C_1/C_2)$ and the relationship between ($\delta^{13}C_2$–$\delta^{13}C_3$) and $\ln(C_2/C_3)$ of natural gases from the marine reef-shoal reservoir of the Changxing Formation in the Yuanba area show that this natural gas comes from the Upper Permian hydrocarbon source rocks. The ratio of C_2/C_3 obviously increases, and the change in C_1/C_2 is relatively small. This demonstrates that natural gas of the Changxing Formation is mainly sourced from the cracking of crude oil (Fig. 4) [1]. A large amount of pyrobitumen can be seen in the reservoir. Isotopes show that natural gas from Well Zhongshen-1 in the Tazhong area is also mainly derived from crude oil cracking [13].

3.1.2. Hydrocarbon source rock (kerogen)-cracked gases

With respect to humic organic matter, most natural gas comes from the cracking of kerogen [10]. The Cretaceous sandstone reservoir of the Keshen–Dabei Gasfield in the Tarim Basin is filled with kerogen-cracking gas sourced from the Triassic. The current vitrinite reflectance of the source rock is 1.5% Ro (reflectance in oil) or higher, which meets the conditions for the formation of cracked gas [14].

Overall, the proposed mechanism of polygenic hydrocarbon generation breaks through the theoretical framework of "kerogen degradation to generate hydrocarbon" [12]. By theoretically proving that ultra-deep buried strata are rich in hydrocarbon sources and have huge exploration potential, this mechanism has important guiding significance for oil/gas exploration in areas with over-matured source rocks.

3.1.3. Reworking of gas compositions by thermochemical sulfate reduction

H_2S content is one of the most distinctive characteristics of the gas composition of different ultra-deep gas reservoirs. The H_2S in natural gas reservoirs generally originates from the following sources: ① pyrolysis of sulfur compounds in kerogen or crude oil; ② bacterial sulfate reduction (BSR) by bacteria or microorganisms; and ③ thermochemical sulfate reduction (TSR). It is gener-

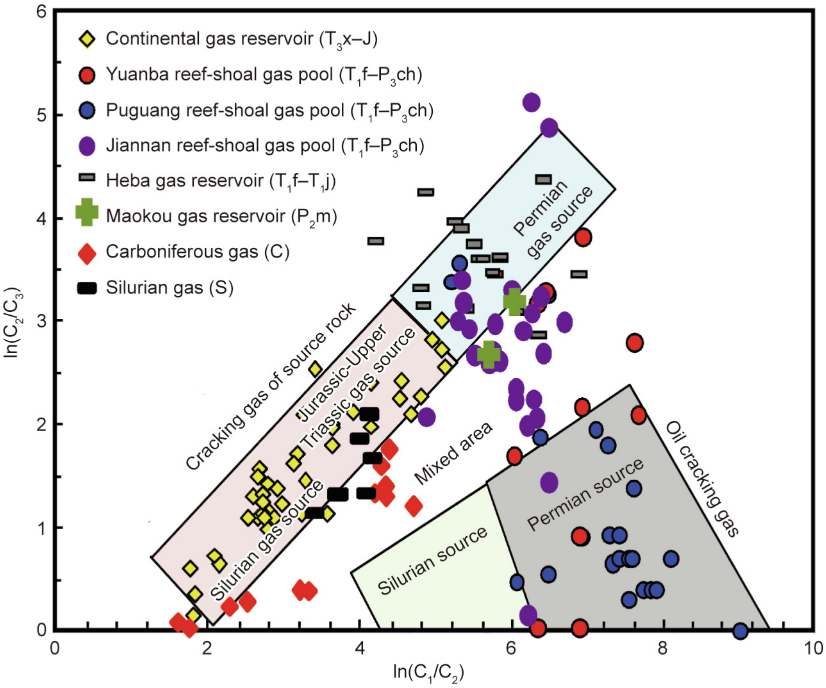


Fig. 4. Relationship between $\ln(C_2/C_3)$ and $\ln(C_1/C_2)$, showing sources of natural gas in the Sichuan Basin. Reproduced from Ref. [1] with permission of Marine Origin Petroleum Geology, © 2014.

ally believed that high concentrations of H_2S (> 5%) in ultra-deep natural gas indicate a contribution from TSR [15–18]. The reaction occurs between sulfate (gypsum/anhydrite) and hydrocarbons:

$$CaSO_4 + \text{hydrocarbon} \rightarrow CaCO_3 + H_2S + H_2O \pm S \pm CO_2 \quad (1)$$

The content of H_2S and CO_2 in the ultra-deep natural gas of the Changxing Formation in the Yuanba area is relatively high. Statistics show that the content of H_2S in the Yuanba I block is generally greater than 5.0% with a maximum of 12.0%–15.0%, and that the CO_2 content is generally between 5.0% and 20.0%. The H_2S content of the Yuanba II block is generally between 1.0% and 6.0%, and the CO_2 content generally ranges from 2.5% to 12.5%. Although the content of non-hydrocarbon gases in wells of blocks I and II has changed significantly, there is a significant positive correlation between the content of H_2S and CO_2 in each well [19], indicating that both are products of the TSR, a chemical reworking of the natural gas in this area.

3.1.4. Mantle- or crust-sourced gases

The injection of mantle- or crust-sourced gases, such as helium (He), nitrogen (N_2), and CO_2, makes the composition of deep gases even more complicated. Those mantle- or crust-sourced non-hydrocarbon gases may be economically producible, as has been shown globally by many cases. Among them, the reservoirs found in China are mainly distributed in the central and eastern areas near and along the Tanlu Fault Zone, including the Songliao Basin, Liaohe Basin, Huanghua Depression, Jiyang Depression, northern Jiangsu Basin, and Sanshui Basin. Some of the gas wells have a He gas concentration of more than 0.05% or a CO_2 content of 80% or as high as nearly 100% [20]. Examples include: ① the Permian CO_2 gas field in the Huangqiao area, northern Jiangsu Province, with a CO_2 purity of 99.9% with proven reserve of $1.42 \times 10^{10}\ m^3$; ② gases from the Wanjinta structure in the Songliao Basin and Well Jie-3 in the Liaohe Basin, which are rich in He gas; ③ the Weiyuan Gasfield, western Sichuan Basin, the He content in which ranges from 0.1% to 0.34%; and ④ Well Yang-1 and Well Shuang-1 on the northern margin of the Nanpanjiang Basin, the He contents in which are as high as 1.28% and 0.1%–1.28%, respectively.

Mantle- or crust-sourced gases generally migrate along deep faults. After entering the gas reservoirs, non-hydrocarbon gases becomes abnormally high in content, which changes the original composition of the gases. Conversely, the complication of gas reservoir composition has made it difficult to recognize the source of ultra-deep oil/gas and to understand the gas accumulation mechanism.

3.2. Development of ultra-deep liquid hydrocarbons

Formation temperature increases as the depth of burial increases, and hydrocarbon formation and evolution are closely related to temperature. Not only does the hydrocarbon generation process of source rocks tend to stop above a certain temperature limit, but liquid hydrocarbons are often cracked into gas under high-temperature condition. Therefore, there are "oil-generation windows" and "hydrocarbon generation deadlines" for oil/gas exploration [21]. Most oil and gas are stored in the zone where the formation temperature is 60–120 °C [22]. However, in ultra-deep buried strata, the temperature is often higher than 120 °C. Therefore, it was believed that the chance of finding liquid hydrocarbons would be very low.

Nevertheless, exploration has confirmed that liquid hydrocarbons can still be found in ultra-deep buried strata. Liquid crude oil has been found in the Cambrian below 6000 m in Well Zhongshen-1 and below 8000 m in Well Tashen-1 in the Tarim Basin, and in the Mesoproterozoic Jixian Group in Well Niudong-1 in the Bohai Bay Basin. These examples show that the liquid oil window may change with geological conditions. In particular, the low geothermal gradient and overpressure effect are often the main factors for the development of ultra-deep liquid hydrocarbons.

3.2.1. Low geothermal gradient

Ultra-deep strata are commonly characterized by high formation temperature. However, basins with a low geothermal gradient are controlled by low heat-flow values. Their stratum compaction is often relatively weaker than that of basins with a high geothermal gradient. To a certain extent, the maturing of source rocks postpones and hence the time of hydrocarbon generation lags behind, which is beneficial to the generation of ultra-deep oil/gas in cold basins. Due to the rapid and deep burial at the late stage, the Tarim Basin in western China has a low geothermal gradient (15–25 °C·km^{-1}) and is capable of generating hydrocarbons even in the ultra-deep buried strata. However, in regions in the east of China, such as the Songliao Basin, which has a high geothermal gradient (38–42 °C·km^{-1}), there is basically no hydrocarbon generation capacity [23]. Recently, exploration findings from the Shuntuoguole Uplift in the northern part of Tazhong indicate that the Lower Cambrian source rocks were still in the condensate oil and natural gas generation stage during the Himalayan period due to a long period of low formation temperature [24]. Furthermore, as for marine crude oil in the Tarim Basin with a low geothermal gradient background and a fast burial history in the late stage, some researchers believe that the lower limit of the depth of liquid petroleum degradation due to cracking is below 9000–10 000 m, and the corresponding reservoir temperature is greater than 210 °C. Above this depth, liquid petroleum can exist in large quantities [25].

3.2.2. Overpressure effect

Most ultra-deep reservoirs are characterized by overpressure [26]. Under overpressure conditions, the thermal maturation of organic matter would be resisted. Therefore, hydrocarbon generation and oil cracking would be postponed [27]. Hence, oil could be generated or preserved in ultra-deep strata.

3.3. Multistage charging

In superimposed basins, the superimposition of multistage tectonic movements controls the multistage hydrocarbon generation process of multicomponent parent materials. Affected by this, ultra-deep hydrocarbon reservoirs often have the characteristics of multiphase charging.

Ultra-deep gas reservoirs often originate from the cracking of aggregated crude oil. The pyrolysis and multiphase (primary, secondary, or even tertiary) hydrocarbon generation of bitumen in different evolutionary stages and with different occurrences including *in situ* reservoir bitumen, offsite reservoir bitumen, and source rock-dispersed bitumen residual, often constitute the main accumulation mechanism for deep/ultra-deep natural gas [28]. Oil/gas geochemistry and fluid-inclusion data from the Cretaceous ultra-deep sandstone reservoir in the Dabei Gasfield of the Kuqa Foreland Basin show that there are two-stage oil and one-stage natural gas charging in the Dabei area, which is an important factor for the high yield and enrichment of the Dabei Gasfield [29,30] (Fig. 5).

4. Key controlling factors of reservoir formation

The development of reservoir and its size are two of the key factors that affect the successful exploration of ultra-deep oil/gas. Under deep-burial conditions, the strata are generally under high-temperature and high-pressure conditions, and generally have undergone long-term, multiphase tectonic movements and diageneses. The pores of reservoir rocks often disappear due to destructive diageneses such as compaction, pressure dissolution, and cementation [31].

The key factors for the development of ultra-deep reservoirs can be explained from three aspects: the development of primary pores, the formation of secondary pores, and the effective preservation of reservoir pores.

4.1. Original pores controlled by high-energy sedimentary facies

Large-scale high-energy deposits are the basis for the formation of large oil and gas reservoirs. As for carbonates, high-energy deposits are mainly marginal-platform reef-shoal complexes and inner-platform shoals. These are characterized by large depositional areas and abundant original pores. For example, we found

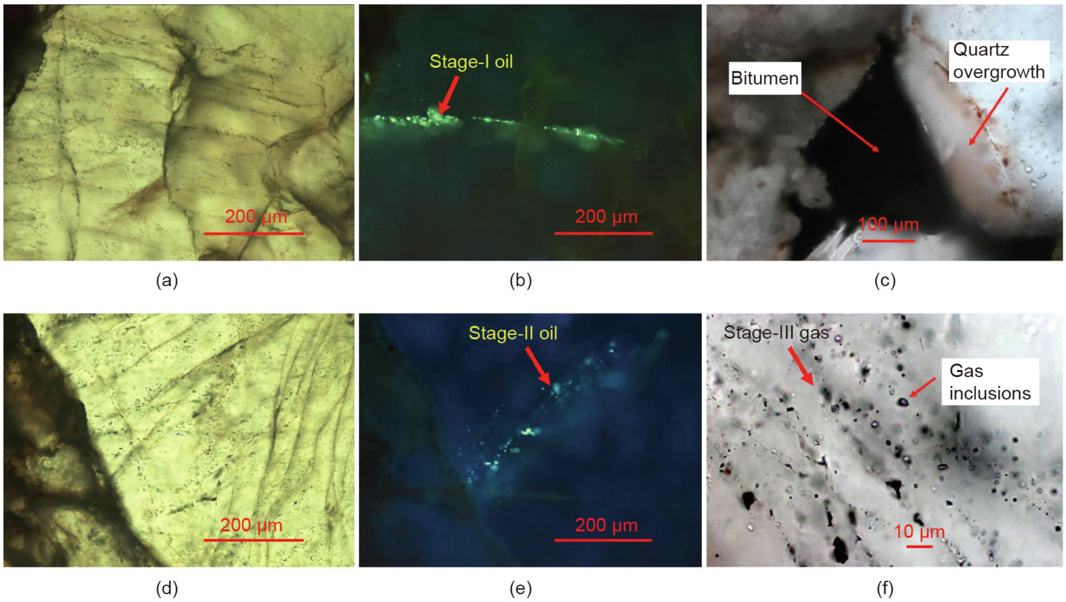


Fig. 5. Three stages of hydrocarbon filling as indicated by fluorescence observation in Well Dabei-1. (a) Single polarized light; (b) fluorescence, where the yellow fluorescent oil inclusions represent the crude oil filling with relatively low maturity in the first phase; (c) single polarized light, pyrobitumen (cracking product from crude oil); (d) single polarized light; (e) fluorescence, where the blue-white fluorescent oil inclusions represent the crude oil filling with relatively high maturity in the second phase; and (f) fluid inclusion, where the black gas inclusions represent natural gas filling in the late third phase. Reproduced from Ref. [29] with permission of China University of Geosciences, © 2010, and from Ref. [30] with permission of China University of Mining and Technology, © 2015.

a 350 km^2 reef-shoal complex in the Yuanba area (Fig. 6) [12]. The original porosity of this kind of reef-shoal complex is estimated to be as high as 40% [32].

As for clastic rocks, high-energy deposits are mainly delta sand bodies and channel sand bodies. Rocks of the Middle–Late Triassic strata with petroleum reservoir potential, located in eastern Svalbard, are expected in both the delta front and channelized sandstone deposits [33]. In China, we found the delta sand bodies of the Keshen–Dabei Gasfield in the North Tarim Basin to be 200–300 m thick with porosities of 5.7%–7.9% (Fig. 7) [3].

4.2. Secondary reservoir spaces

Secondary pores often develop in carbonate and clastic reservoirs. In most cases, the pores of carbonate reservoirs are dominated by secondary pores [31,34].

The formation of secondary pores in reservoirs is often associated with dissolution, dolomitization, and fracturing.

4.2.1. Dissolution

Dissolution is key to the formation of secondary pores. In Earth's long geological history, dissolution often occurs when the strata are exposed to contact with seawater, fresh water, formation water, or deep hydrothermal fluids (hot water).

Penecontemporaneous dissolution is common in reef-shoal complex reservoirs. The marginal-platform reef-shoal complexes and inner-platform shoals are sensitive to the rise and fall of the sea level due to their high paleo-geomorphic locations. During the process of frequent sea level rise and fall, reefs and shoals are easily exposed, leached, and dissolved by meteoric water. Those processes have been recorded in carbon and oxygen isotopes and abundant fabric-selective pores in the reservoir sections [11].

The epigenetic karstification associated with large-scale unconformity is often the key to the development of karst reservoirs or buried hill reservoirs. Massive dissolution occurs in carbonates beneath large-scale unconformities. This process will form karst reservoirs. There are many oil/gas fields associated with large unconformities in China, of which the Tahe Oilfield is the largest [35].

Deep burial dissolution is the common mechanism for the formation of effective reservoirs of deep and ultra-deep clastic rocks. It is generally believed that organic acids and inorganic acids produced through the maturation of organic matter commonly dissolve intergranular carbonate cements and soluble components such as feldspar and rock debris, thus forming secondary pores [36]. However, with the occurrence of dissolution, authigenic clay minerals and siliceous cements are also formed. If these products are left near the dissolution site and cannot be effectively carried out, the pores will be occluded [37].

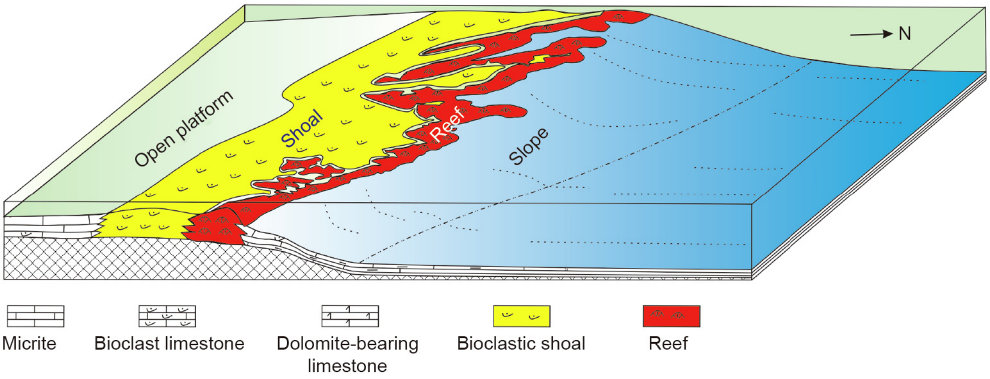


Fig. 6. Sedimentary models of the reef-shoal complex in the Yuanba area. Reproduced from Ref. [12] with permission of Research Institute of Petroleum Exploration & Development, PetroChina, © 2018.

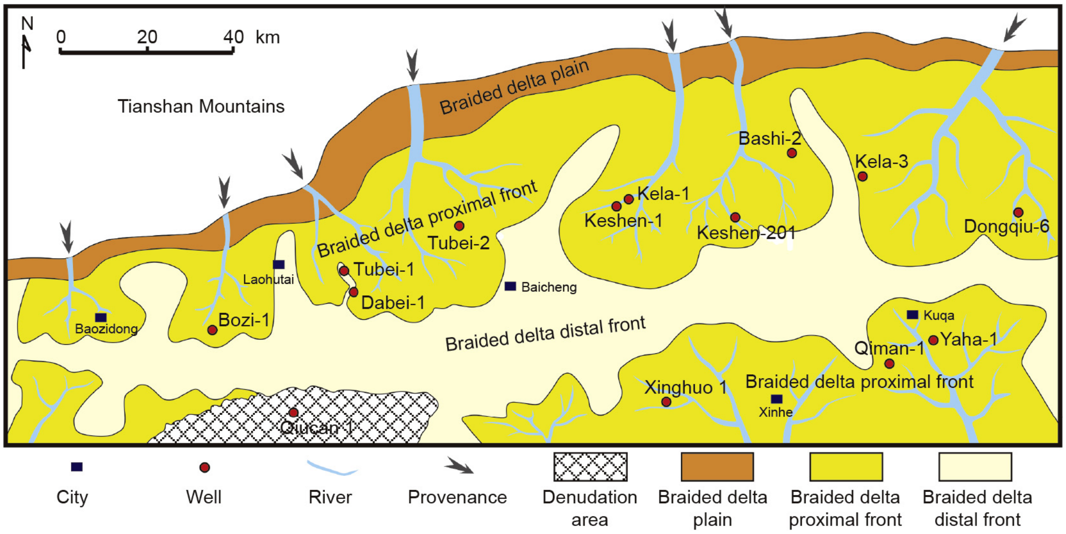


Fig. 7. Map of sedimentary facies of the Cretaceous in the Keshen–Dabei area. Reproduced from Ref. [3] with permission of Natural Gas Geoscience, © 2014.

The contribution of deep burial dissolution in carbonate reservoirs has long been controversial. Many researchers believe that organic acid dissolution [38], CO_2 dissolution [39], H_2S dissolution [40], and hydrothermal fluid dissolution [41] often occur under deep burial conditions, and are critical to the development of deep reservoirs. However, Ehrenberg and Nadeau [31] have stated that differences in pore development in carbonate reservoirs are related to sedimentation (controlling rock composition and structure), early diagenesis, burial history, and thermal history. Although burial dissolution may occur, it will have a small contribution.

4.2.2. Dolomitization

Lower Paleozoic limestone is dense, while the pores of the dolostone are well developed in many parts of the world [42,43]. Dolomitization involves mol-to-mol replacement of Ca^{2+} by Mg^{2+} in the early open system, so that the crystal volume is decreased and the pore space is increased. In addition, after dolomitization, the composition and texture of the rock are changed. Dolostone is more resistant to physical and chemical compaction than limestone, so the pores within dolostone can be better preserved. In addition, dolostone is more soluble and more prone to fracturing than limestone in deep areas, which means that more pores may develop in dolostone. Therefore, the quality of ultra-deep dolostone reservoirs is generally better than that of limestone reservoirs [44]. A typical example is the ultra-deep buried dolostone reservoir of the Changxing Formation in the Yuanba Gasfield in the Sichuan Basin. We have proposed that shallow burial dolomitization occurred, and that it controlled the development of ultra-deep high-quality reservoirs [11].

4.2.3. Fracturing

Tectonic fracture not only directly increases the reservoir space and greatly improves the permeability, but also serves as a channel for many kinds of fluids. These channels can bring dissolution fluid to the reservoir and form dissolution pores at certain stages. However, they may also lead to cementation or filling of pores by over-saturated fluids along faults and fractures. In this case, pores will be occluded and porosity of the reservoirs will be reduced.

Crude oil cracking always leads to overpressure. A large number of micro-fractures will be formed under overpressure conditions. These fractures are critical in improving reservoir permeability [11]. The Yuanba Gasfield is located at the junction of the northern Sichuan Depression and the Middle Sichuan low and gentle tectonic zone. It is a negative structural zone confined by the Jiulongshan anticline structural belt, the Tongnanba structure belt, and the Middle Sichuan low and gentle tectonic zone, showing weak deformation by tectonic stress extrusion, which is not beneficial to the development of fractures and cracks. However, the dolostone reservoir section in the Changxing Formation has developed dense micro-fractures that are mainly at low angles, and the directions are not strongly related to regional tectonic stress fields. The directions tend to be dendritic, radial, or cross-shaped, and most are filled with pyrobitumen. In contrast, fractures have not developed in the non-reservoir limestone section. The micro-fractures in dolostone are related to overpressure caused by crude oil cracking, with the highest pressure coefficient reaching 2.19 during the Late Jurassic–Early Cretaceous, leading to the development of hydraulic fractures (Fig. 8).

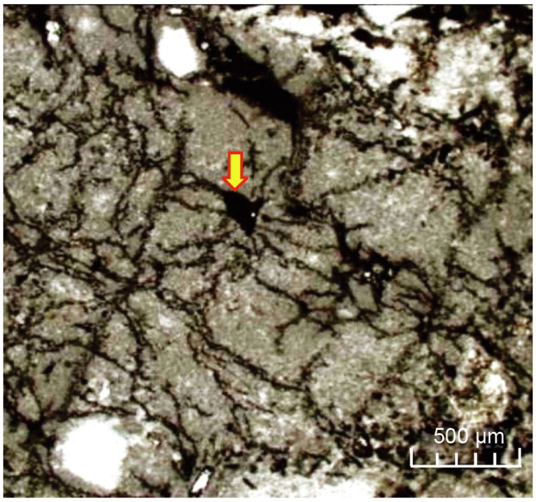


Fig. 8. Hydro-pressure micro-fractures caused by oil cracking. The arrow points to the pore filled with pyrobitumen, around which micro-fractures have developed; P_3ch, Well Yuanba-204, 6550 m.

4.3. Preservation of primary and secondary reservoir spaces

Primary pores and early secondary pores are easily destroyed by diageneses such as compaction, pressure dissolution, and cementation. Therefore, ultra-deep strata must undergo effective reserving diageneses so as to form ultra-deep high-quality reservoirs [44]. With respect to carbonate rocks and clastic rocks, the factors that help effectively maintain the porosity of ultra-deep reservoirs include low geothermal gradients, an early long-term shallow-burial and late rapid deep burial process, early clay/carbonate mineral cementation, abnormally high pressures, gypsum/salt effects, and early hydrocarbon charging [36,44,45].

Hydrocarbon charging in the early stage has important significance for the maintenance of reservoir pores. Hydrocarbon filling, accompanied by a large number of organic acids and fluids containing CO_2 and H_2S in the reservoir, not only makes the existing pores be further dissolved and expand, but also makes the pore fluid weakly acidic, which inhibits cementation, and thus effectively preserves the pores and protects the reservoir. Moreover, the filling of hydrocarbons in the reservoir changes the wettability of the reservoir rocks (from hydrophilic to lipophilic) and forms an oil film on the pore surface of the reservoir, which will be cracked into pyrobitumen. This oil or pyrobitumen film effectively prevents contact between rocks and formation fluids, thus inhibiting water–rock reactions in the pores and the over-growth and recrystallization of dolomites or the cementation of calcite and quartz.

5. Petroleum accumulation mechanisms

Understanding the oil/gas accumulation mechanisms in ultra-deep reservoirs is the key to determining the target of oil/gas exploration. The most important mechanisms for the accumulation of ultra-deep oil/gas are the “near-source accumulation” and “sustained preservation” mechanisms.

5.1. Near-source accumulation

Statistical results show that large and medium-sized ultra-deep oil/gas fields are generally distributed near the hydrocarbon generation center. When the reservoir is in close proximity to the hydrocarbon source rock, the migration path is short, and the oil/gas charging intensity is high. In areas with good reservoir and favorable preservation conditions, large to medium-sized oil/gas fields may form. The marginal-platform reef-shoal gas field of the Changxing Formation in Yuanba is adjacent to high-quality hydrocarbon source rocks in the Permian Wujiaping and Dalong Formations [12]. Among these, the Wujiaping Formation has a hydrocarbon source rock thickness of about 30–80 m and a total organic carbon (TOC) content higher than 2%. The organic matter is dominated by aquatic organisms, and the type is IIA. This set of hydrocarbon source rocks is characterized by large thickness, high abundance, and good type. The hydrocarbon source rocks are at the peak of hydrocarbon generation during the Early Jurassic and are vertically adjacent to the marginal-platform facies reservoir of the Changxing Formation, which is beneficial to the filling of hydrocarbons first expelled from the Wujiaping source rocks. At the same time, the gas field is horizontally adjacent to the Dalong Formation hydrocarbon source rock, which was sedimented in different facies during the Changxing Formation deposition. The total hydrocarbon generation intensity of these two sets of high-quality hydrocarbon source rocks is as high as 3×10^9–7×10^9 $m^3{\cdot}km^{-2}$ [12], which makes Yuanba a favorable accumulation area for oil/gas accumulation. In the Tarim Basin, the Cretaceous sandstone reservoir in the Keshen–Dabei area is also adjacent to the Triassic high-quality hydrocarbon source rocks in the Kuqa Depression [3].

5.2. Sustained preservation

Sustained preservation of an oil/gas reservoir requires good capping conditions and a relatively stable tectonic background. Caprock is one of the key factors for oil/gas accumulation and determines whether there is a prospect for exploration in a basin or depression. The size (e.g., distribution area, thickness, and continuity) and quality of the caprock directly determine the formation, preservation, and scale of oil/gas reservoirs. In particular, after multiple stages of uplifting denudation and tectonic fracture activities, the effectiveness of the caprock is decisive. In addition to the macroscopic lithology, thickness, distribution range, and continuity, the nature of the caprock depends on petrological properties such as mineral composition (especially clay minerals and illite-montmorillonite mixed minerals), diagenesis, porosity, permeability (especially pores and seepage conditions under formation conditions), specific surface area, breakthrough pressure, capping height, and diffusion coefficient. The Changxing Formation gas field in Yuanba in northeastern Sichuan Province developed a direct caprock of tight limestone in the Feixianguan Formation and thick (300–600 m) gypsum caprock in the Jialingjiang Formation–Leikoupo Formation. The Paleogene of the Keshen–Daibei Gasfield developed a thick layer (100–1000 m) of regional caprock consisting of evaporites and mudstone [29]; this caprock is dense and has a good quality with a breakthrough pressure of up to 60 MPa, indicating excellent capping ability.

A relatively stable tectonic background ensures that the early formed ultra-deep hydrocarbon reservoirs can be preserved until the present day. Yuanba Gasfield is located at the front of the northern section of Longmenshan and is a low and gentle tectonic zone affected by the Longmenshan, Micangshan, and Dabashan orogenic belts. The weak overall tectonic deformation [12] is key to the sustained preservation of cracked gas from crude oil. The tectonics of the Keshen–Dabei Gasfield in the Kuqa Foreland Depression Belt is also relatively stable, so that gas reservoirs formed in the late stage by rapid one-time filling are also well preserved.

Overall, good capping conditions combined with a relatively stable tectonic background were key accumulation factors for the formation of the Yuanba Gasfield and the Keshen–Dabei Gasfield.

6. Key technologies in ultra-deep petroleum exploration and exploitation

Ultra-deep reservoirs have large burial depths and strong concealment. In addition, they are often located in mountainous regions. Both the ground topography and underground tectonics are complex. The greatest difference on a ground elevation map can reach more than 1000 m. Conventional seismic methods often have low recognition rates in identifying ultra-deep reservoirs. In addition, ultra-deep petroleum exploration suffers greatly from deep drilling, multiple layers identification, complex pressure systems, high well temperatures, complex well wall stability, and large heterogeneity of the strata. These factors often cause slow drilling speed, more complex accidents, difficulties in quality control, large safety risks, insufficient drilling capacity, and other issues affecting ultra-deep drilling. Therefore, for ultra-deep oil/gas exploration, it is necessary to use the latest and most appropriate seismic exploration technology along with drilling, completion, and testing technologies.

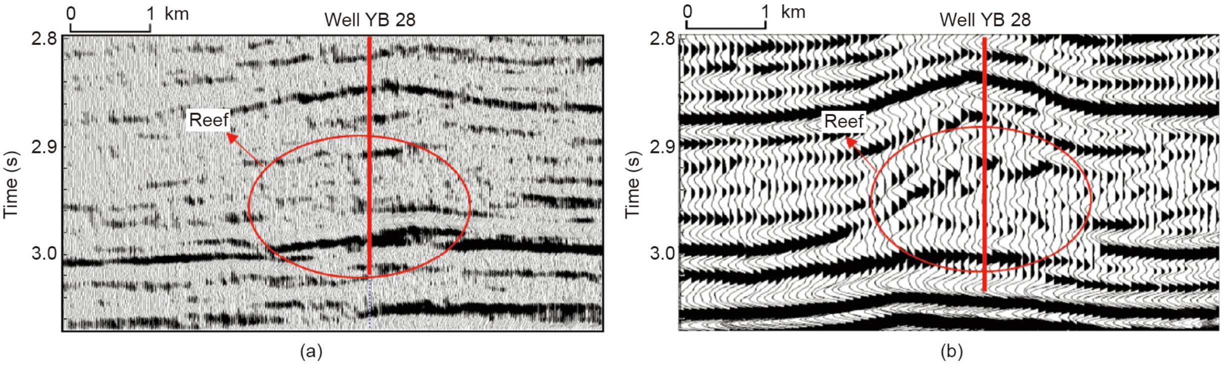
6.1. Seismic exploration technology

6.1.1. Seismic signal acquisition and processing technology

To accurately identify reservoirs, the first step is to improve the quality of seismic signals during acquisition and processing.

Application of the “saturation excitation” theory [46] during data acquisition increases the effective energy of the ultra-deep target layer. A method combining tomography static correction with frequency division static correction was used to solve the problem of near-surface effects in complex mountainous terrain. At the same time, weak signal extraction and compensation technology for ultra-deep reservoirs based on an anisotropic and absorbing-attenuating media model were established.

The combination of new seismic acquisition and processing technologies led to a breakthrough in the seismic high-precision and high-resolution imaging of ultra-deep reef-shoal reservoirs in complex mountainous regions. Taking Yuanba as an example, in comparison with the old data, the effective energy of the target layer with a depth of more than 6500 m increased by more than 70%. The frequency band range extends from 8–50 Hz to 4–80 Hz, and the main frequency increased by 15–18 Hz (Fig. 9) [12].



(a) (b)

Fig. 9. Comparison of (a) old and (b) new seismic profile. YB: Yuanba. Reproduced from Ref. [12] with permission of Research Institute of Petroleum Exploration & Development, PetroChina, © 2018.

6.1.2. Prediction technology for zones with low porosity and high permeability

The reserve ability of ultra-deep reservoirs is largely influenced by the burial depth. As for carbonate reservoirs, diageneses such as dolomitization, dissolution, compaction, and cementation could intensively change the pore structure and pore volume. Therefore, most deep-buried carbonate reservoirs are dense or strongly heterogeneous, and the relationship between pore structure and pore permeability is always complicated. About 83.5% of the samples from the Changxing Formation in the Yuanba area have porosities lower than 2%. However, due to the high permeability, high-yield gas flows were also obtained. Therefore, the prediction of low-porosity and high-permeability reservoirs is an important aspect of ultra-deep oil/gas exploration.

Traditional one-dimensional prediction models such as the Wyllie model and the Raymer model have large errors in the prediction of ultra-deep carbonate reservoirs. According to core rock physics test data, Sun's model [47–49] is simplified to obtain a "frame flexibility factor" that describes the pore structure [11]. The higher the frame flexibility factor, the more fractures develop in the core; hence, the higher the permeability. Different relationships between porosity and velocity, porosity and permeability, and permeability and frame flexibility factor are established according to their discrepant distributions on the cross-plot of compressional velocity versus porosity (Fig. 10) [12,50]. This has improved the porosity prediction accuracy and led to successful prediction of high-permeability reservoirs.

6.1.3. Gas–water identification technology

Exploration practice shows that the distribution of gas and water in ultra-deep reservoirs is complex, and often difficult to accurately identify. In the Yuanba area, absorption attenuation attributes extracted from post-stack seismic data were mainly used for prediction previously, and there was always a great discrepancy between the drilling results and the prediction results. During the exploration and development of the Yuanba gas field, a rock physics test of reef-shoal complex carbonate rocks was carried out. It was found that the Lamé constant multiplied by the density value ($\lambda\rho$) of the gas-bearing dolostone reservoir decreased by 31.59% compared with that of the water-bearing dolostone reservoir [51]. Prestack seismic inversion should be carried out to obtain the $\lambda\rho$ volume. However, the average burial depth of the reef-shoal gas reservoir in the Yuanba gas field is about 7000 m, and it is difficult to obtain large-angle seismic information. The incident angle of the prestack seismic gather is generally about 27° with a maximum lower than 30°. The prestack polynomial elastic wave impedance inversion method [52] can be used to identify reservoir fluids and overcome the problem associated with the lack of large-angle data. Finally, the area of the high-yield and enrichment belt in the Yuanba gas field was predicted to be 98.5 km^2. Ten exploration wells were drilled in this area, and each achieved a gas flow of around 1×10^6 m^3·d^{-1} (Fig. 11).

6.2. Drilling, completion, and test technology

Since the 1990s, considerable development and progress have been achieved in ultra-deep well-drilling technology, ranging from theory to craftsmanship, based on practical research in the Tarim and the Sichuan Basins in China. In the Yuanba area, with continuous advancements in drilling equipment and supporting process technologies, the drilling depth has gradually increased, and a new geological level that the previous generation failed to reach has been achieved. Due to the complexity of geological conditions for the engineering of ultra-deep wells, it is difficult to use traditional methods to design well structures to ensure smooth and safe completion of drilling. By applying design techniques that are normally used in unconventional well structures, the structure of ultra-deep wells has been optimized (Table 3). The casing level has been increased. In order to increase the drilling speed, the drilling fluid has been replaced with gases in the shallow layers. Dur-

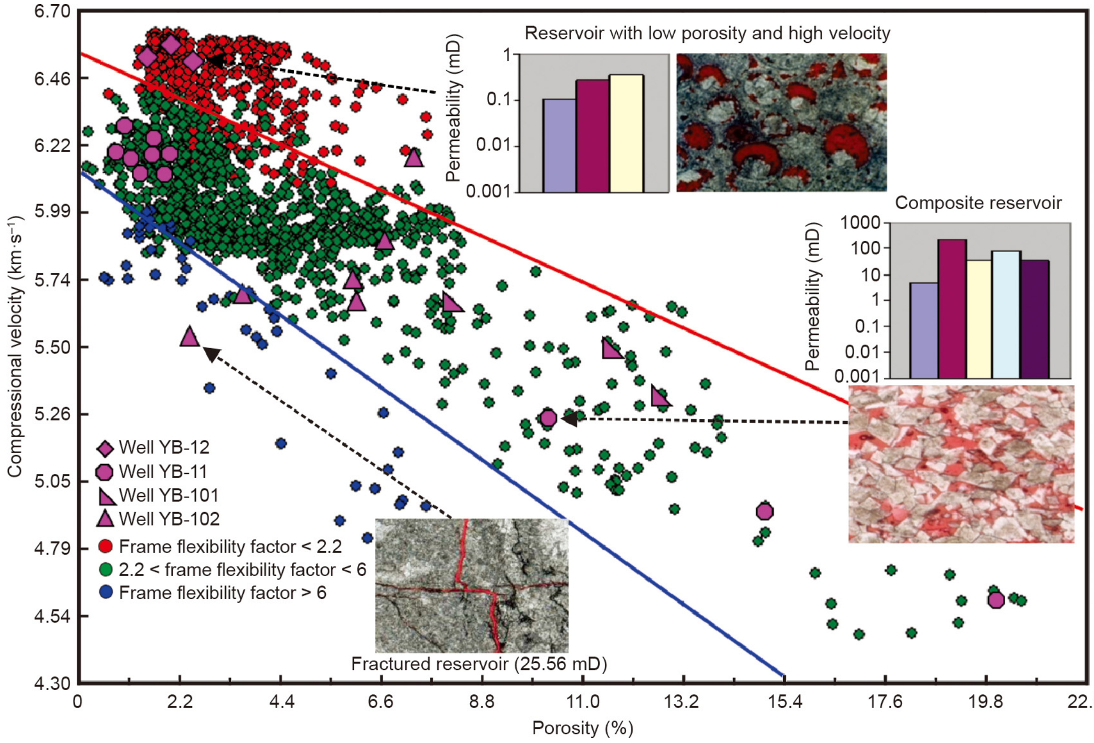


Fig. 10. The pore structure parameter-velocity model for identifying reservoir pore structure in the Yuanba area. 1 mD = 0.9869233 μm^2. Reproduced from Ref. [12] with permission of Research Institute of Petroleum Exploration & Development, PetroChina, © 2018.

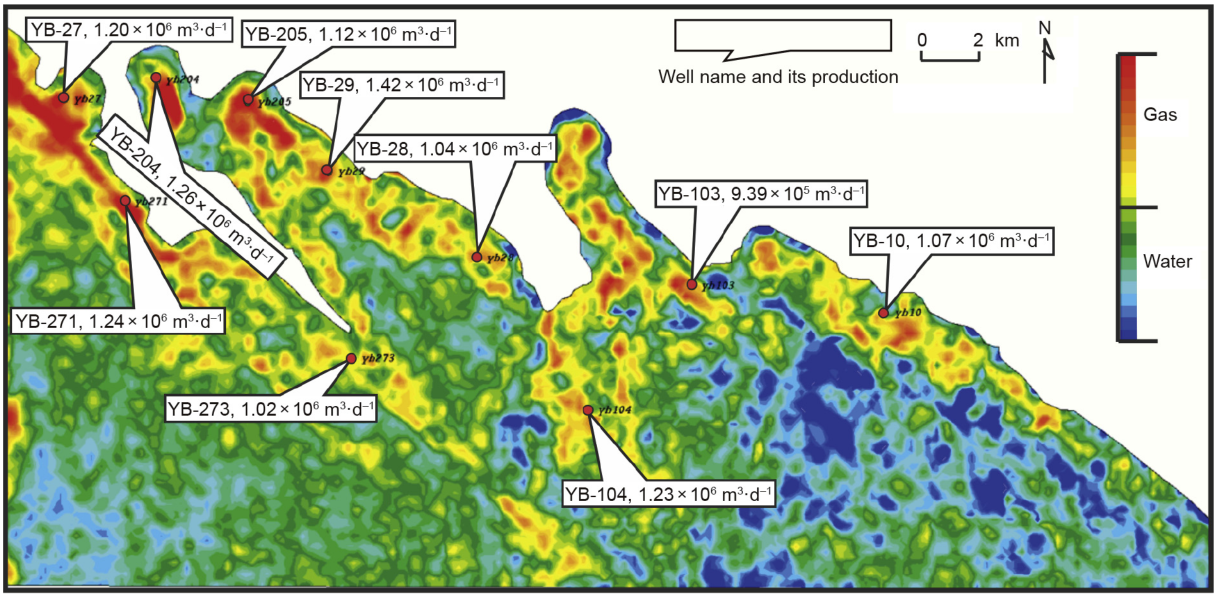


Fig. 11. Gas–water prediction map of the reef-shoal reservoir of the Changxing Formation in Yuanba, showing drilling wells and production.

Table 3
The well body data for a well under actual drilling in Yuanba area.

Spudding	Bit size (mm)	Well depth (m)	Casing size (mm)	Landing depth (m)	Cement return depth (m)
Conductor pipe	914.4	50	720.0	50.00	Ground
1st spudding	660.4/609.6	961	482.6	959.64	Ground
2nd spudding	406.4	4295	346.1/339.7	4292.85	Ground
3rd spudding	311.2	6204	282.6/273.1/284.2	6203.50	Ground
4th spudding	241.3	7699	206.4/193.7	7699.00	Ground
5th spudding	165.1	8418	146.1/139.7	7481.92–8418.00	7481.92

ing drilling from the middle layers to the deep layers, a facilitating polycrystalline diamond compact (PDC) bit with a screw, an impregnated diamond bit with a high-speed turbine, a torsional impact generator, a rotary drilling tool, and a mixed drill were used [12], which greatly increased the drilling speed. The success of drilling was further ensured by using the latest plugging and cementing technologies. In fact, the application of these key technologies for drilling and completion solved many problems that made ultra-deep well drilling impossible in the past. Well Yuanba-3 was successfully drilled and holds the record for the deepest vertical well in Asia.

Petroleum exploration and exploitation work are still far from complete after drill completion. The challenge of how to test safely and efficiently is present for ultra-deep layers. In the northeastern Sichuan Basin, marine facies are generally characterized by "four-highs and one-ultra"—namely, high temperature, high pressure, high sulfur content, high yield, and ultra-deep burial depth. Normally, annular pressure-responsive (APR) tools and related technologies are used to test these kinds of reservoirs. However, it was shown that traditional APR technologies could not be used in the northeastern Sichuan Basin until it was improved. We upgraded the APR test tubes and developed a new safe and high-efficiency testing technology named by "ultra-high pressure-perforating acid-fracturing testing" [12].

By using a new triple-working process (Fig. 12) [12], the testing was completed with safety and efficiency while the reservoir was well protected and effectively reformed. Moreover, the construction period and test cost were effectively reduced. We used acid with a higher density (1.8 g·cm^{-3}) relative to the normal one in Well Yuanba-1. As a result, we obtained the highest record for liquid exacerbation at the bottom pressure (212 MPa). At the same time, the reservoir was effectively reformed, and high yield was obtained. Moreover, ground safety-control technologies for testing ultra-deep gas with high sulfur content have been developed to control the hazards of high-content H_2S gas in gas reservoirs. An

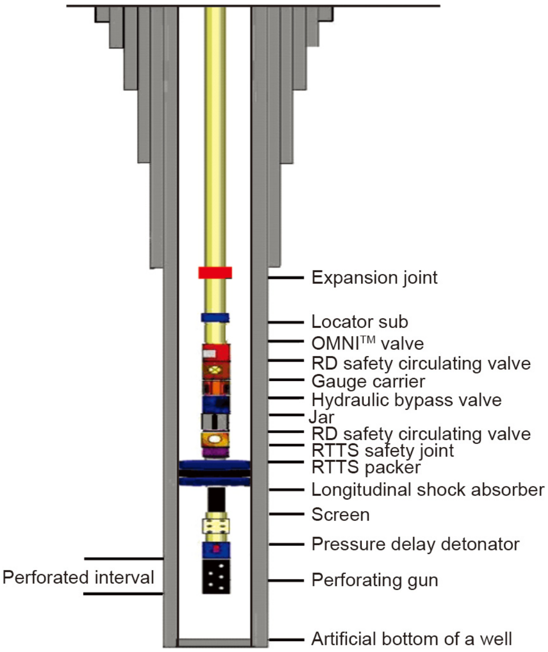


Fig. 12. Tube diagram of the triple-working process in the perforated acid fracturing testing. RD: rupture disk; RTTS: retrievable test-treat-squeeze. Reproduced from Ref. [12] with permission of Research Institute of Petroleum Exploration & Development, PetroChina, © 2018.

integrated anti-sulfur structure and high-pressure anti-sulfur gas wellheads made of FF-grade stainless steel with multiple sealing technologies have been developed. A hydraulically controlled "four-gate" anti-sulfur high-pressure blowout-preventer combination and a safety interlocking device have been designed. High-pressure dynamic wellhead-sealing technology and automatic acquisition equipment have been developed to ensure the safe and efficient development of the Yuanba gas field.

7. Conclusions and perspective

It is conclusive that the potential for petroleum exploration in ultra-deep buried strata is considerable. (Ultra) large oil/gas fields in ultra-deep carbonate rocks and clastic rocks have been discovered in China. The oil/gas originates from multiple supplies of hydrocarbons by multi-phase charging. Due to a low geothermal gradient or overpressure, liquid hydrocarbons can still be developed in ultra-deep strata. The composition of ultra-deep natural gas is complicated because of the deep hydrocarbon–water–rock reaction or the addition of mantle- or crust-sourced gases. These oil and gas resources are mainly stored in the original high-energy reef-shoal or sand body sediments which have high original porosity. Dissolution, dolomitization, and fracturing in the later stage often lead to the development of secondary pores, while retentive diagenesis such as early filling of hydrocarbons helps to preserve early pores until the present. Ultra-deep oil/gas accumulation generally presents the characteristics of near-source accumulation and sustained preservation. The effective exploration and development of ultra-deep reservoirs cannot be separated from the support of key technologies such as seismic exploration, drilling, completion, and oil/gas testing.

Ultra-deep oil and gas exploration was developed recently, and many problems in science and challenges in technology remain. These problems always exist when we face new formations in new regions. Issues to be solved may include the following: ① identifying favorable reservoir types and key controlling factors; ② determining hydrocarbon accumulation mechanisms in low-porosity and low-permeability ultra-deep strata; ③ predicting techniques for diverse reservoirs; and ④ drilling and testing technologies and equipment under conditions of high temperature and high pressure. Despite these challenges, we believe that ultra-deep regions will be a strategic substitution for further exploration and exploitation.

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Compliance with ethics guidelines

Xusheng Guo, Dongfeng Hu, Yuping Li, Jinbao Duan, Xuefeng Zhang, Xiaojun Fan, Hua Duan, and Wencheng Li declare that they have no conflict of interest or financial conflicts to disclose.

References

[1] Guo XS, Guo TL, Huang RC, Duan JB. Cases of discovery and exploration of marine fields in China (part 16): Yuanba gas field in Sichuan Basin. Mar Origin Pet Geol 2014;19(4):57–64. Chinese.

[2] He ZL, Jin XH, Wo YJ, Li HL, Bai ZR, Jiao CL, et al. Hydrocarbon accumulation characteristics and exploration domains of ultra-deep marine carbonates in China. China Petro Explor 2016;21(1):3–14. Chinese.

[3] Wang ZM. Formation mechanism and enrichment regularities of Kelasu subsalt deep large gas field in Kuqa Depression, Tarim Basin. Nat Gas Geosci 2014;25(2):153–66. Chinese, URL: http://www.nggs.ac.cn/EN/10.11764/j.issn.1672-1926.2014.02.153.

[4] Tissot BP, Welte DH. Petroleum formation and occurrence. 2nd ed. Berlin: Springer Verlag; 1984.

[5] Dahl B, Speers GC. Geochemical characterization of a tar mat in the Oseberg Field Norwegian Sector, North Sea. Org Geochem 1986;10(1–3):547–58.

[6] Behar F, Vandenbroucke M, Teermann SC, Hatcher PG, Leblond C, Lerat O. Experimental simulation of gas generation from coals and a marine kerogen. Chem Geol 1995;126(3–4):247–60.

[7] Behar F, Vandenbroucke M, Tang Y, Marquis F, Espitalie J. Thermal cracking of kerogen in open and closed systems: determination of kinetic parameters and stoichiometric coefficients for oil and gas generation. Org Geochem 1997;26(5–6):321–39.

[8] Qin JZ, Fu XD, Liu XC. Solid bitumens in the marine carbonate reservoir of gas field in the northeast area of the Sichuan Basin. Acta Geol Sin 2007;81(08):1065–71. 1161. Chinese.

[9] Li HL, Shao ZB, He ZL. Hydrocarbon generation characteristics and potential of bitumen in the Tarim Basin. Pet Geol Exp 2009;31(04):373–8. Chinese.

[10] Burnham AK. A simple kinetic model of petroleum formation and cracking. Report. Livemore: Lawrence Livermore National Lab; 1989. Report No.: UCID-21665.

[11] Guo XS, Hu DF, Huang RC, Duan JB, Ji CH. Developing mechanism for high quality reef reservoir (Changxing Formation) buried in ultra-depth in the big Yuanba gas field. Acta Petrol Sin 2017;33(4):1107–14. Chinese.

[12] Guo XS, Hu DF, Li YP, Duan JB, Ji CH, Duan H. Discovery and theoretical and technical innovations of Yuanba gas field in Sichuan Basin, SW China. Pet Explor Dev 2018;45(1):14–26.

[13] Zhang JZ, Wang ZM, Yang HJ, Xu Z, Xiao Z, Li Z. Origin and differential accumulation of hydrocarbons in Cambrian sub-salt dolomite reservoirs in Zhongshen Area, Tarim Basin, NW China. Pet Explor Dev 2017;44(1):40–7. Chinese.

[14] Sun NF, Guo FX. Natural gas identification under evaporite bed of Dabei–Kelasu tectonic belt. Compl Hydroc Reserv 2014;7(3):20–3. Chinese.

[15] Orr WL. Changes in sulfur content and isotopic ratios of sulfur during petroleum maturation—study of Big Horn Basin Paleozoic oils. AAPG Bull 1974;58(11):2295–318.

[16] Orr WL. Geologic and geochemical controls on the distribution of hydrogen sulfide in natural gas. Adv Org Geochem 1977:571–97.

[17] Krouse HR, Viau CA, Eliuk LS, Ueda A, Halas S. Chemical and isotopic evidence of thermochemical sulphate reduction by light hydrocarbon gases in deep carbonate reservoirs. Nature 1988;333(6172):415–9.

[18] Worden RH, Smalley PC, Oxtoby NH. The effects of thermochemical sulfate reduction upon formation water salinity and oxygen isotopes in carbonate reservoirs. Geochim Cosmochim Acta 1996;60(20):3925–31.

[19] Duan JB, Li PP, Chen D, Feng C. Formation and evolution of the reef flat facies lithologic gas reservoir of Changxing Formation in Yuanba gas field, Sichuan Basin. Lith Res 2013;25(3):43–7. 91. Chinese.

[20] Tao MX, Xu YC, Han WG, Gao B, Ma JL, Wang WC. Active characteristics and accumulative effects of mantle-derived fluids in eastern china. Geotecton Metallog 2001;25(3):265–70. Chinese.

[21] Tissot BP, Welte DH. Petroleum formation and occurrence: a new approach to oil and gas exploration. New York: Springer-Verlag; 1978. p. 185–8.

[22] Zhang GY, Ma F, Liang YB, Zhao Z, Qin YQ, Liu XB, et al. Domain and theory–technology progress of global deep oil & gas exploration. Acta Petrolei Sinica 2015;36(09):1156–66. Chinese.

[23] Jia CZ, Pang XQ. Research processes and main development directions of deep hydrocarbon geological theories. Acta Petrolei Sinica 2015;36(12):1457–69. Chinese.

[24] Qi LX. Oil and gas breakthrough in ultra-deep Ordovician carbonate formations in Shuntuoguole Uplift, Tarim Basin. China Pet. Explor. 2016;21(03):38–51. Chinese.

[25] Zhu GY, Yang HJ, Su J, He K, Han JF, Gu LJ, et al. True exploration potential of marine oils in the Tarim Basin. Yanshi Xuebao 2012;28(3):1333–47. Chinese.

[26] Wang WY, Pang XQ, Wu LY, Chen DX, Huo ZP, Pang Y, et al. Pressure distribution features of deep and middle-shallow hydrocarbon reservoir in global oil and gas-bearing basins. Acta Petrolei Sinica 2015;S2(36):194–202. Chinese.

[27] Lu SF, Wang M, Wang YW, Xu LH, Xue HT, Li JJ. Comparison of simulation results from the closed and open experimental systems and its significance. Acta Sedimentol Sin 2006;24(02):282–8. Chinese.

[28] Ma YS. Geochemical characteristics and origin of natural gases from Puguang gas field on eastern Sichuan Basin. Nat Gas Geosci 2008;19(1):1–7. Chinese.

[29] Cao LY. The hydrocarbon accumulation mechanism of Dabei–Kelasu structural zone in Kuqa Depression [dissertation]. Beijing: China University of Geosciences; 2010. Chinese.

[30] Mao YK, Zhong DK, Neng Y, Zhang CW, Liu YL, Wang A, et al. Fluid inclusion characteristics and hydrocarbons accumulation of the Cretaceous reservoirs in Kuqa foreland thrust belt, Tarim Basin, Northwest China. J China U Min Techno 2015;44(6):1033–42. Chinese.

[31] Ehrenberg SN, Nadeau PH. Sandstone vs. carbonate petroleum reservoirs: a global perspective on porosity-depth and porosity-permeability relationships. AAPG Bull 2005;89(4):435–45.

[32] Heydari E. Porosity loss, fluid flow, and mass transfer in limestone reservoirs: application to the Upper Jurassic Smackover Formation, Mississippi. AAPG Bull 2000;84(1):100–18.

[33] Haile BG, Klausen TG, Czarniecka U, Xi K, Jahren J, Hellevang H. How are diagenesis and reservoir quality linked to depositional facies? A deltaic succession, Edgeøya, Svalbard. Mar Pet Geol 2018;92:519–46.

[34] Choquette PW, Pray LC. Geologic nomenclature and classification of porosity in sedimentary carbonates. AAPG Bull 1970;54(2):207–50.

[35] Kang YZ. Cases of discovery and exploration of marine fields in China (part 4): Tahe oilfield in Tarim Basin. Mar Orign Pet Geol 2005;10(4):31–8. Chinese.

[36] Feng JR, Gao ZY, Cui JG, Zhou CM. The exploration status and research advances of deep and ultra-deep clastic reservoirs. Adv Earth Sci 2016;31(7):718–36. Chinese.

[37] Chen Y, Wang CJ, Sun XF, Wang M, Han Y, Yan SY. Progress on mineral solubility and mechanism of dissolution secondary porosity forming in clastic reservoir. Bull Mineral Petrol Geochem 2015;34(4):830–6. Chinese.

[38] Surdam RC, Boese SW, Crossey LJ. Role of organic and inorganic reactions in development of secondary porosity in sandstones: abstract. AAPG Bull 1982;66(66):635.

[39] Druckman Y, Moore Jr CH. Late subsurface porosity in a Jurassic grainstone reservoir, Smackover Formation, Mt., Vernon field, southern Arkansas. In: Roehl PO, Choquette PW, editors. Carbonate petroleum reservoir. New York: Springer–Verlag; 1985. p. 371–83.

[40] Hill CA. H_2S–related porosity and sulfuric acid oil-field karst. AAPG Mem 1995;37:301–5.

[41] Jin ZJ, Zhu DY, Hu WX, Zhang XF, Wang Y, Yan XB. Geological and geochemical signatures of hydrothermal activity and their influence on carbonate reservoir beds in the Tarim Basin. Acta Geol Sin 2006;80(2):245–53. Chinese.

[42] Warren J. Dolomite: occurrence, evolution and economically important associations. Earth-Sci Rev 2000;52(1–3):1–81.

[43] Zhang XF, Hu WX, Zhang JT. Critical problems for dolomite formation and dolomitization models. Geol Sci Tech Info 2006;25(5):32–40. Chinese.

[44] Zhang XF, Shi KB, Liu B, Yang YK, Wang JQ. Retention processes and porosity preservation in deep carbonate reservoirs. Geol Sci Tech Info 2014;33(02):80–5. Chinese.

[45] Guo XS, Guo TL, Huang RC, Chen ZQ. Reservoir development characteristics and predication technologies of large Puguang–Yuanba gas field. Eng Sci 2010;12(10):82–90. Chinese.

[46] Yang GX, He ZH, Zhu X. Research on seismic acquisition methods for lower assemblage of marine strata in South China. Geophy Pros Petrol 2006;45(1):158–68. Chinese.

[47] Sun YF. Core-log-seismic integration in hemipelagic marine sediments on the eastern flank of the Juan de Fuca Ridge. ODP Sci Results 2000;168:21–35.

[48] Sun YF. Seismic signature of rock pore structure. Appl Geophys 2004;7(1):42–8.

[49] El-Wazeer FA, Vizamora A, Hamedi AA, Al-Housam H, Abram P, Busman S. Integrating rock physics, seismic reservoir characterization and static modeling of carbonates: a case study from the UAE. In: Proceedings of the AAPG 2010 Middle East Geoscience Conference; 2010 March 7–10; Manama, Bahrain. Houten: EAGE Publications; 2010.

[50] Zhang HR, Sun YF, Dou QF, Zhang TT. Preliminary application of the frame flexibility factor in Puguang gas field. Oil Gas Geol 2012;33(6):877–82. Chinese.

[51] Yin ZW. Gas-water identification technologies for ultra deep reef reservoirs in the Yuanba gas field, Sichuan Basin. Nat Gas Idn 2014;34(5):66–70. Chinese.

[52] Lu SM, McMechan GA. Elastic impedance inversion of multichannel seismic data from unconsolidated sediments containing gas hydrate and free gas. Geophysics 2004;69(1):164–79.