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The Anyue Giant Gas Field in the Sichuan Basin as the Largest Gas Field in Marine Carbonate Deposits from Domestic China

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Abstract—The Anyue gas field is located in the middle part of the Sichuan Basin, SW China. It occurs in the oldest marine carbonate strata and is characterized by the highest degree of thermal evolution and the largest gas reserves in China. A significant breakthrough was made with the Gaoshi-1 risk-taking exploration well deployed in 2011. As of 2015, the proven geologic reserves of natural gas were 657.4 billion m^3, and the total gas reserves including proven reserves, controlled reserves, and predicted reserves exceeded 1.5 trillion m^3. A total of three sets of gas-bearing strata are developed in the Anyue gas field in a descending sequence: The gas reservoir in the Cambrian Longwangmiao Formation ($Є_1l$) is treated as a structure-lithologic gas reservoir; the gas reservoir in Section No. 4 of the Dengying Formation (Z_2dn^4) is a structure-stratigraphic gas reservoir; and the gas reservoir in Section No. 2 of the Dengying Formation (Z_2dn^2) is a structural gas reservoir. A comparative analysis of the gas sources has shown that the gas Cambrian of reservoirs was mainly from mudshale of the lower Cambrian Maidiping and Qiongzhusi formations and the gas of the Dengying Formation reservoirs was from mudshale of the Qiongzhusi Formation and mudstone of Section No. 3 of the Dengying Formation. All gas reservoirs are referred to as reservoirs of dry gas with medium or low contents of sulfur and medium contents of CO_2. Gas reservoirs in $Є_1l$ are characterized by a large burial depth, a high temperature, and a high pressure, while the gas reservoirs in Z_2dn^2 and Z_2dn^4 are characterized by an ultralarge depth, a high temperature, and a normal pressure. The accumulation of gas reservoirs is controlled mainly by two factors. The distribution of hydrocarbon generation centers is controlled by the late Sinian–early Cambrian intracratonic rift, which acts as effective updip sealing conditions for gas reservoirs in the Dengying Formation. The late Sinian–early Cambrian Gaoshiti–Moxi paleouplift experienced a long-term inherited development, which controlled the generation and distribution of three sets of large-scale high-quality reservoirs in Z_2dn^4, Z_2dn^2, and the Longwangmiao Formation and the generation of three sets of high-quality reservoir–caprock assemblages. An inherited giant structural trap with a long-term stable development is always a favorable zone for petroleum accumulation.

Keywords: Anyue giant gas field; Sinian–Cambrian; marine carbonate rocks; intracratonic rift; Gaoshiti–Moxi paleouplift; geologic characteristics; Sichuan Basin; China

INTRODUCTION

There exist several supergiant oil and gas fields, which were explored and discovered in ancient strata at much earlier stages. For example, the Kuyumba and Yurubchen–Tokhomo oil and gas fields occur in the Upper Proterozoic carbonates of the Siberian Platform in the Lena–Tunguska Province (Kontorovich et al., 1981, 1982, 1988; Mel'nikov et al., 2011, 2017). The exploration of Sinian–Cambrian gas in the Sichuan Basin started from the 1940s (Song, 1987; Du, 1996; Zhang and Zhang, 2002; Ran, 2006). In 1964, the Weiyuan giant gas field was discovered in Sinian carbonates. Continuous research focused on the Leshan–Longnvsi paleouplift in the following 40 years. Fundamental work was undertaken in aspects of deposition, reservoir, structure, and gas accumulation, which showed that Sinian–Cambrian strata have favorable geologic conditions for hydrocarbon accumulation: widely developed ancient carbonate rocks, several sets of high-quality hydrocarbon source rocks, several reservoir–caprock assemblages, and prolific hydrocarbon resources (Hou et al., 1999; Li et al., 2000; Wang et al., 2002; Xu et al., 2002; Yang, 2002; Zhai et al., 2005). The exploration field was considered to be a great potential area, but no major breakthroughs were made. Since 2003, PetroChina has continuously carried out systematic research on Sinian–Cambrian oil and gas accumulation conditions in the Sichuan Basin. The Gaoshi-1 risk-taking exploration well was deployed in the Gaoshiti–Moxi area, where the development of inherited structures has been relatively stable since the Late Sinian. In 2011, a high-yield gas rate of 1.02 mil-

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lion m^3/d was obtained in the Sinian Dengying Formation in the Gaoshi-1 well. In 2012, a high-yield gas rate of 1.9 million m^3/d was obtained in the Longwangmiao Formation in the Moxi-8 well. Taken together, this indicates a significant breakthrough in exploration of the Sinian–Cambrian paleouplift (Wei et al., 2013; Du et al., 2014; Zou et al., 2014a,b). PetroChina developed the exploration arrangement concept of "overall study, overall planning, overall exploration, implementation by batches, and preferred selection of favorable zones" in the Gaoshiti–Moxi area and at its periphery. From a geological standpoint, the existence of an intracratonic rift and the Gaoshiti–Moxi paleouplift was proven (Wei et al., 2015c,d). In terms of oil and gas discovery, through the deployment of exploration and valuation wells within the Sinian–Cambrian Gaoshiti–Moxi paleouplift, the Anyue giant gas field was discovered. As of 2015, the proven geologic reserves of gas amounted to 657.4 billion m^3, and the total reserves (including proven, controlled, and predicted ones) exceeded 1.5 trillion m^3. Regarding the studies on hydrocarbon generation capabilities and contributions of gas source rocks to the Anyue giant gas field, some researches presumed that there exist five potential hydrocarbon source rocks and predicted their distribution (Zou et al., 2014a,b; Shi et al., 2018). The authors also dealt with the gas source rock issues (Wei et al., 2013, 2014, 2015a) and emphasized the controlling roles of the Tongwan Period (Late Sinian–Early Cambrian) intracratonic rift and Gaoshiti–Moxi paleouplift in the development of the main hydrocarbon source rocks of the Anyue giant gas field (Wei et al., 2015c–e). Based on a review of the discovery of the Anyue giant gas field, the geologic characteristics of the gas field were presented, and the major controlling factors of accumulation were discussed. This was done with a view to sharing the achievements of hydrocarbon exploration and promoting the exploration of ancient marine carbonate hydrocarbon reservoirs.

OVERVIEW OF THE ANYUE GAS FIELD

The Anyue giant gas field is located in the Gaoshiti–Moxi area (Fig. 1) in the central part of the Sichuan Basin, China, and the main reservoirs are in the Sinian Dengying and Cambrian Longwangmiao formations (Du et al., 2014, 2015; Wei et al., 2015c). Three sets of gas-bearing strata were developed in a descending sequence in the Anyue gas field. The gas reservoirs in the Cambrian Longwangmiao Formation belong to the structure-lithologic gas-bearing group, with an average gas-bearing thickness of 40 m, and the total reserves (including proven, controlled, and predicted ones) amount to 500 billion m^3. The gas-bearing area of the Moxi zone is 805.26 km^2, and the reserves amount to 440.38 billion m^3. The gas reservoirs in Z_2dn^4 are structure-strati-

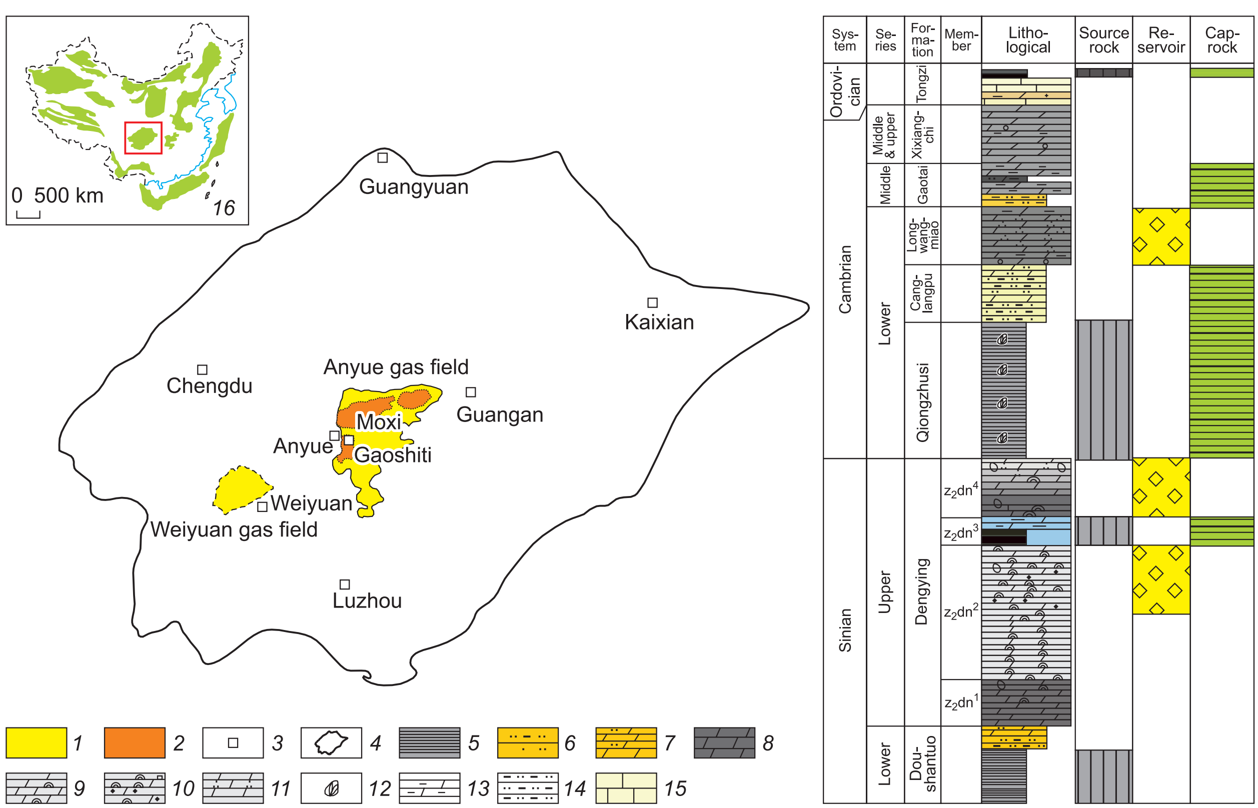

Fig. 1. Location and lithologic columnar section of the Anyue giant gas field, Sichuan Basin. *1*, Sinian gas reservoir; *2*, Cambrian gas reservoir; *3*, city; *4*, basin boundary; *5*, shale; *6*, argillaceous siltstone; *7*, silty dolomite; *8*, dolomite; *9*, algal dolomite; *10*, botryoidal dolomite; *11*, dolarenite; *12*, small shelly fossils; *13*, argillaceous dolomite; *14*, silty mud; *15*, limestone; *16*, the distribution of petroliferous basins in domestic China.

graphic, with a gas reservoir thickness in the range of 60 to 110 m and a gas-bearing area of 7500 km^2, among which 1500 km^2 is controlled by the platform margin belt, with proven reserves of 200 billion m^3. The gas reservoirs in Z_2dn^2 are structure-stratigraphic, with a thickness in the range of 5.1 to 69.1 m and a gas-bearing area of 2000 km^2. The sedimentary reservoir characteristics of the pay formations are as follows. The Cambrian Longwangmiao reservoir rocks are doloarenite, residual doloarenite, and fine–medium-grained dolomite, with the reservoir space composed of pores, caverns, and fractures, and the reservoir thickness values range from 20 to 70 m. The reservoir rocks in the Dengying Formation are mainly a mound-shoal complex: algal clotted dolomite, algal stromatolithic dolomite, and algal framework rock and doloarenite, with the reservoir space composed mainly of intergranular dissolved pores and intercrystal dissolved pores, and the reservoir thickness values range from 120 to 210 m. The gas sources of the pay formations are as follows. The Cambrian gas sources are mainly mud shale of the lower Cambrian Qiongzhusi and Maidiping formations, and the gas in the Sinian Formation is mainly from mud shale of the lower Cambrian and mudstones of Z_2dn^3. The caprocks developed in the area are favorable for the preservation of hydrocarbon. There are three sets of regionally distributed immediate caprocks, with respective thickness ranging from 5–25, 100–200, and 14–43 m. Indirect caprocks are widely developed, such as Permian mud shale, a little of coal series, and a thick gypsum bed in the Middle–Lower Triassic Jialingjiang and Leikoupo formations. As of 2015, the total disclosed reserves (including proven, controlled, and predicted ones) amount to 1.5 × 10^{12} m^3. Eleven billion m^3/y productivity was targeted in the Longwangmiao Formation, and 500 million m^3/y testing productivity was targeted in the Dengying Formation. The overall development scale may exceed 15 billion m^3/y.

DISCOVERY OF THE ANYUE GAS FIELD

The gas exploration of Sinian–Cambrian started in the 1940s. It can be divided into two stages: investigation of Sinian strata and exploration of the paleouplift, which might be subdivided into four stages: discovery of the Weiyuan gas field, investigation of the Caledonian paleouplift, risk-taking exploration of the Caledonian paleouplift, and overall exploration of the Tongwanian paleouplift.

Discovery of the Weiyuan gas field (1940–1964)

The exploration of Sinian strata in the Sichuan Basin was initiated in the 1940s, extending to 1964. Twenty-four years of efforts resulted in the discovery of the first big gas field in domestic China (Editorial…, 1989). In 1940, the Wei-1 well was drilled and completed in the Yangxin Series, with rare gas yield. In 1956, the Weiji well was drilled, with the completion stratum in the Lower Sinian Series, without commercial gas flow. In 1963, the Weiji well was started to drill deeper, and deepened to 2848.5 m in September 1964, and gas intrusion and lost circulation were detected on top of the Upper Sinian Dengying Formation. A gas yield rate of 7.98–14.5 × 10^4 m^3/d was acquired by a drill stem test, which is the first breakthrough in the Sinian strata. With gas then discovered in 12 wells, which proved a gas-bearing area of 216 km^2, with reserves amounting to 400 × 10^8 m^3, the first large-scale and integrated marine gas field in domestic China was proven (Fig. 1). The reservoirs in the Weiyuan gas field are targeted in the Sinian Dengying Formation; they are structural, with integrated bottom water and low gas saturation, up to only 25% of the trap amplitude.

Investigation of Caledonian paleouplift (1965–2005)

During the period of more than 40 years since the discovery of the Weiyuan gas field (1964–2005), the Sinian–Cambrian exploration potential of the Caledonian (middle Cambrian–Silurian) Leshan–Longnvsi paleouplift always attracted the attention of geologists (Hou et al., 1999; Wang et al., 2002; Xu et al., 2002; Yang, 2002), and continuous investigation was carried out. In the early 1970s, the Leshan–Longnvsi large noselike paleouplift (Song, 1987) was discovered through gravity, magnetic, and seismic survey. The burial depths of the Sinian range from 2500 to 5500 m; the paleouplift are 320 km in length and 160 km in width, with an area of 6.25 × 10^4 km^2 (Fig. 2). The lasting drilling outcomes and geological studies indicated that the long-term inherited development of the Leshan–Longnvsi paleouplift provides the basic geologic conditions for the forma-

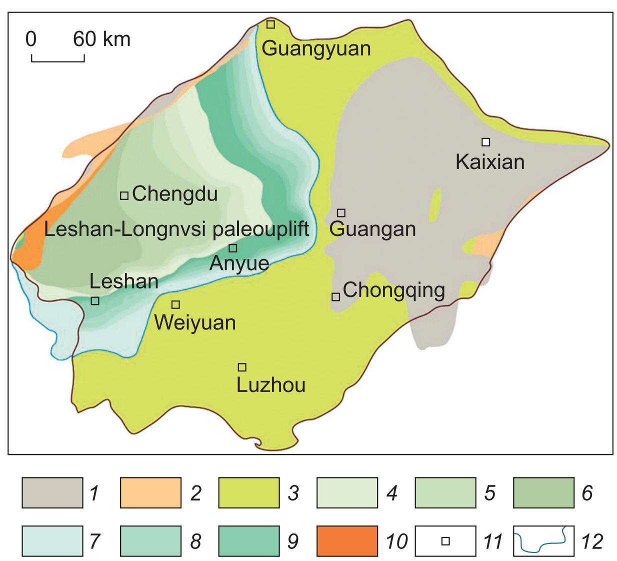

Fig. 2. Pre-Permian Paleogeological map of Caledonian paleouplift, Sichuan Basin. *1*, Carboniferous; *2*, Devonian; *3*, Silurian; *4*, upper Cambrian; *5*, middle Cambrian; *6*, lower Cambrian; *7*, Upper Ordovician; *8*, Middle–Upper Ordovician; *9*, Lower Ordovician; *10*, Sinian; *11*, city; *12*, Caledonian paleouplift range.

tion of a giant gas field. High-quality hydrocarbon source rocks are widely distributed in the lower Cambrian Qiongzhusi Formation. Dolomite cave reservoirs are widely developed in the Sinian Dengying Formation, with relatively strong heterogeneity. Within the wide area between Weiyuan and Longnvsi structures, gas-bearing strata were intercepted at different degrees. Commercial gas flow was obtained in the Ziyang paleotraps, and good shows of gas and oil were seen in some wells, such as the Gaoke-1, Anping-1, and Nvji wells. The research and exploration results proved that the paleouplift contained gas, with good exploration potential. However, no important discoveries on the paleouplift were made because of the shortage of geological knowledge, the lack of drilling or seismic data, and other factors.

RISK-TAKING EXPLORATION OF CALEDONIAN PALEOUPLIFT (2006–2011)

In 2006, based on the aforementioned statement that the Leshan–Longnvsi paleouplift generally has a gas-bearing potential, an analysis of drilled wells and a survey of outcrops were carried out. Besides the knowledge of the regional distribution of weathering crust cave reservoirs in the Dengying Formation, the results indicated that the granular dolomite reservoirs with good physical properties found in the Cambrian Longwangmiao Formation, with a thickness range of 20 to 30 m, make up the potential exploration targeted horizon. In view of the above, the exploration strategy was diverted, with emphasis both on the Dengying and Longwangmiao formations, and the Sinian–Lower Paleozoic strata of the Caledonian Leshan–Longnvsi paleouplift were determined to be the key areas of risky exploration.

Between 2007 and 2008, according to the strategy of large-scale exploration, three risk-taking prospect wells were drilled, which verified the wide distribution of gas-bearing strata in the Sinian Dengying Formation and Cambrian strata. The risk of exploration was whether the favorable reservoir development area could be effectively predicted and the inherited structures with good preservation conditions could be determined.

In 2009, in order to reduce the existent exploration risks, comprehensive geophysical and geological studies of the Sinian–Cambrian were initiated. It was concluded that though the Gaoshiti–Moxi area is located in the low part of the current structure of the Sinian–Cambrian, it is a favorable area for gas accumulation, where the structural traps inheritedly developed. The structural traps are developed with a complete trap structure, small closure, and large area. The hydrocarbon source conditions are good, with a potential of forming a medium- to large-scale gas field. Especially, with respect to the technical bottlenecks, including strong heterogeneity and difficult prediction as to the major target reservoirs in the Gaoshiti–Moxi structure, the reprocessing and interpretation of 215 km^2 3D seismic data and 1100 km 2D seismic data were done to determine the structural traps. Based on all the above conditions, the risk-taking wells were drilled, such as the Gaoshi-1 and Moxi-8 wells. A high-yield gas rate of 102.14×10^4 m^3 was obtained in the Gaoshi-1 well in Z_2dn^2, which means the significant breakthrough of the Sinian gas exploration in the paleouplift. On September 9, 2012, a testing gas rate of 107.18×10^4 m^3/d was acquired in the Moxi-8 well in the Lower Members of the Cambrian Longwangmiao Formation. On September 28, a gas rate of 83.5×10^4 m^3/d was acquired in the Moxi-8 well in the Upper Members of the Longwangmiao Formation. A commercial gas flow was acquired from the pay formation in the Longwangmiao Formation of the Moxi-8 well, which became the discovery well of the gas reservoir in the Longwangmiao Formation of the Anyue gas field. The exploration of the Longwangmiao Formation made a historical breakthrough.

OVERALL EXPLORATION OF THE TONGWANIAN PALEOUPLIFT (2012–PRESENT)

Following the major findings in the Gaoshi-1 well, important geological results were achieved, with the discovery of the SN-distributing late Sinian–early Cambrian intracratonic rift and the Gaoshiti–Moxi Tongwanian (Late Sinian–early Cambrian) paleouplift in the east of the rift (Wei et al., 2015c,d) (Fig. 3). The favorable exploration area was diverted to the Gaoshiti–Moxi paleouplift from the Caledonian Leshan–Longnvsi paleouplift, and the strategy of integrated research and integrated deployment and implementation by steps was initiated in the Tongwanian paleouplift.

From July 2011 to December 2014, the exploration purpose was to ascertain the gas-bearing scale of the Gaoshiti–Moxi paleouplift area in the Sinian Dengying and Cambrian Longwangmiao formations. After four rounds of integrated deployment, the gas-bearing scale of the Dengying and

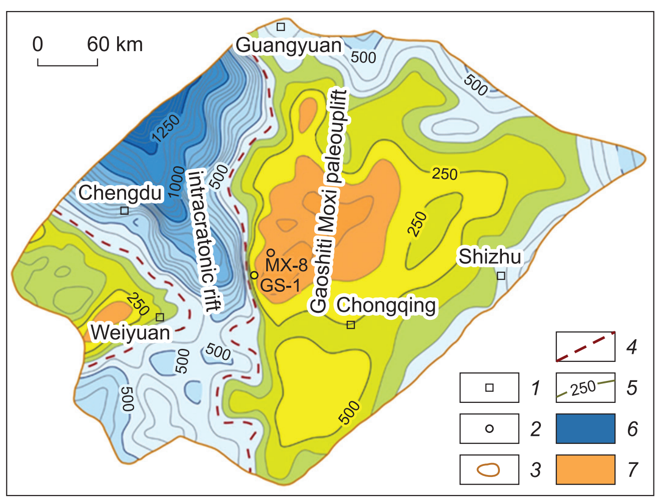

Fig. 3. Distribution of Sinian–early Cambrian paleostructures in the Sichuan Basin. *1*, city; *2*, wells; *3*, basin boundary; *4*, boundary of intracratonic rift; *5*, Tongwanian paleogeomorphology contour; *6*, lower part of paleogeomorphology; *7*, high part of paleogeomorphology.

Longwangmiao formations was basically ascertained. As of December 2014, a total of 67 wells were drilled in the Gaoshiti–Moxi paleouplift area, with 51 wells tested and commercial gas flow acquired in 38 wells, indicating a comprehensive exploration success rate of 75%. With the discovery of the Anyue giant gas field, the reserves amounted to 1.3×10^{12} m^3. Here, the gas-bearing area controlled by the Sinian Dengying Formation is 7500 km^2, with controlled gas reserves of 8000×10^8 m^3. Three gas reservoirs were discovered in the Cambrian Longwangmiao Formation: Moxi, Gaoshiti, and Longnvsi. The gas-bearing area of the Moxi block is 805.26 km^2, with proven geologic reserves of 4403.83×10^8 m^3, which is categorized as a large-scale integrated gas reservoir.

As of 2015, based on the integrated valuation on the gas-bearing scale of the Anyue gas field, the proven geologic reserves reached 657.4 billion m^3, and the total reserves (including proven, controlled, and predicted ones) exceeded 1.5 trillion m^3.

GEOLOGIC CHARACTERISTICS OF THE GAS FIELD

Characteristics of traps and gas reservoir types

Diverse traps were developed in the Sinian Dengying and Cambrian Longwangmiao formations, which comprised different gas reservoirs. The Longwangmiao Formation is a structure-lithologic trap, and the gas reservoirs formed inside are of the structure-lithologic type; Z_2dn^4 is a structure-stratigraphic trap, and the gas reservoirs formed inside are structure-stratigraphic; Z_2dn^2 is a structural trap, and the gas reservoirs formed inside are structural.

In the Gaoshiti–Moxi area of the Anyue gas field, there are mainly three regional structural traps (SN-, NE-, and E-trending) in the top surface structures of the Longwangmiao Formation, with a trap distribution area of 124, 195, and 316 km^2, respectively (Wei et al., 2015c). In terms of the distribution of gas reservoirs, the Longwangmiao gas reservoir belongs to a group composed of three independent reservoirs (Fig. 4). In the depositional environment, large-scale grain beaches are developed in the Longwangmiao Formation, and the development of grain beaches is controlled by micropaleogeomorphy. Grain beaches are mainly distributed over a relatively high terrain, and the grain beach dolomite is marked by good physical properties (including reservoir porosity, permeability, etc.); argillaceous dolomite and clay-bearing fine-grained dolomite are developed between the beaches, with a relatively high argillaceous content and bad reservoir properties. The distribution of the grain beaches and discrepancies between their physical properties and those of the surrounding rocks created an objective basis for the formation of lithologic traps. In terms of the test results, the gas/water contact altitude of the Moxi-27 well is –4459 m; the gas/water contact altitude of the Moxi-47 well is –4385 m; the gas/water interface altitude of the Moxi-51

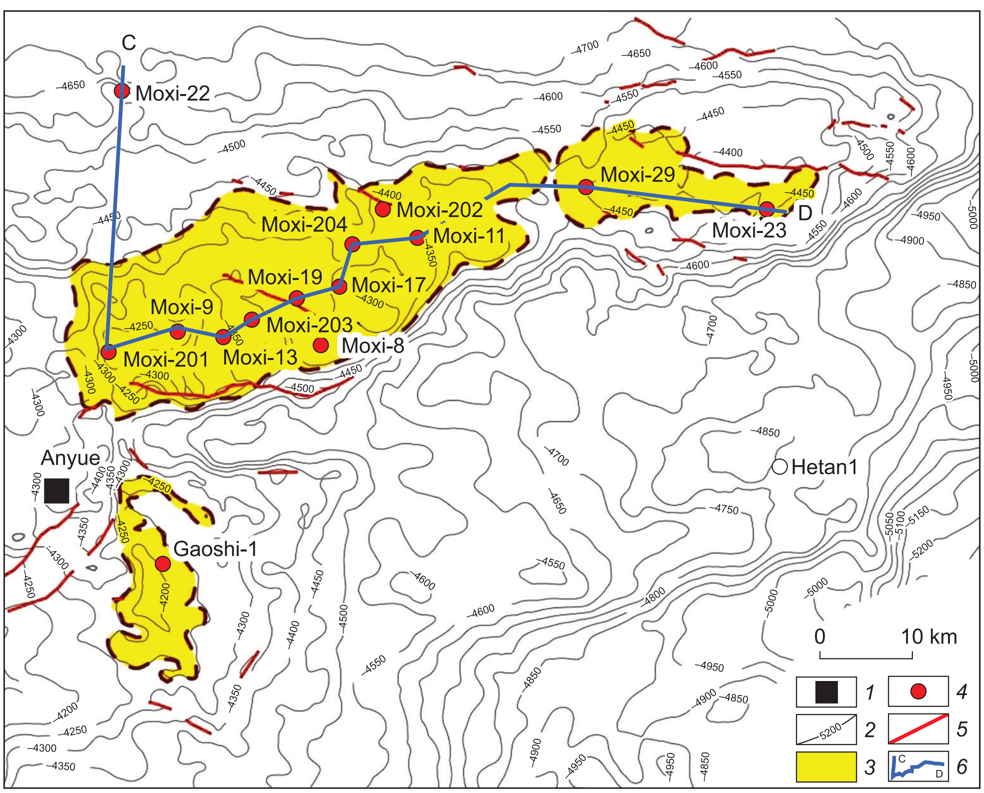

Fig. 4. Gas reservoirs distribution in the Cambrian Longwangmiao Formation of the Anyue gas field. *1*, city; *2*, structural contour; *3*, Longwangmiao Formation gas reservoirs; *4*, wells; *5*, faults; *6*, Longwangmiao Formation gas reservoir section location.

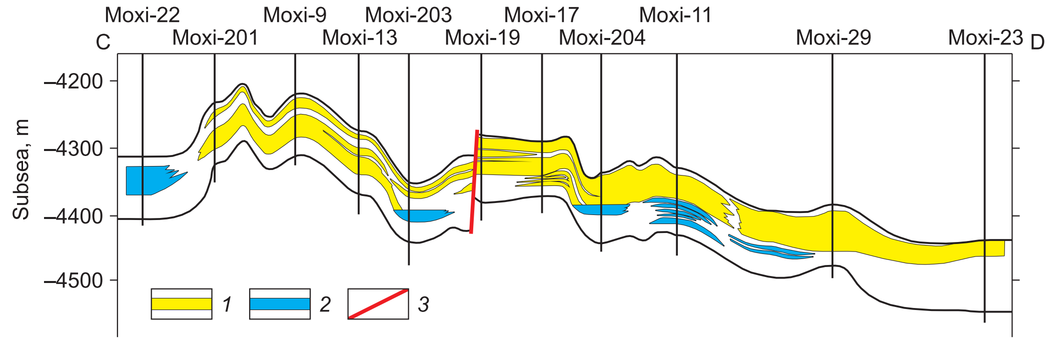

Fig. 5. Gas reservoir sections of the Longwangmiao Formation in the Anyue gas field (see location in Fig. 4). *1*, gas reservoir; *2*, water-bearing bed; *3*, fault.

well is –4593 m. This indicated that the nearby lower parts of the structure of the Longwangmiao Formation are generally water-bearing areas, with different gas/water contacts. So, the Longwangmiao gas reservoirs are structure-lithologic, and they are characterized as isolated beach reservoirs. The figure presents the gas reservoir section of the Moxi block (Fig. 5). It shows that there are several gas/water contacts, and the gas reservoirs are controlled by grain-beach traps, with lateral heterogeneity, and mutually overlain vertically. Besides, the gas column height of the Longwangmiao Formation in the Moxi block is 232 m, and the gas-bearing area exceeds the lowest structural trap line. In the west of the gas reservoir there exists a lithologic sealing belt formed by a tight reservoir. Hence, the Longwangmiao Formation gas reservoirs are of the structure-lithologic type.

The top area of Z_2dn^4 has shown characteristics of weathering crust and is unconformable with the Cambrian System, with the overlying stratum of lower Cambrian mudstone and overlapping on top of Z_2dn^4, which is composed of good stratigraphic traps (Fig. 6). As shown on the top structural map of the Sinian in the study area (Fig. 7), structural traps formed in the area of Gaoshiti, Moxi, Longnvsi, etc. The closed line of the Sinian top structural trap is –5010 m, with a trap range of 370 m, and the closed area reaches 3474 km^2, which is a large-scale structural trap. The drilling outcomes indicated that the Moxi-22 well in the north of the Anyue gas field contains a gas reservoir in the upper part of Z_2dn^4 and a water-bearing layer in the lower part of Z_2dn^4. The Z_2dn^4 gas/water contact altitude is –5230 m, with a gas column height of 590 m, which indicated that the closure of the gas reservoir is larger than the closure of the structural trap. The gas reservoir area delineated with the gas/water contact is predicted to reach 7500 km^2, larger than the structural closed area. As mentioned above, the Z_2dn^4 zone of the Anyue gas field is a structure-stratigraphic gas reservoir.

The gas reservoirs of Z_2dn^2 are of the structural type with bottom water. The upper part of Z_2dn^2 in the Gaoshiti–Moxi area consists of gas-bearing beds, and the lower part consists of water-bearing layers, with the gas-bearing area controlled by structural closure. The Moxi and Gaoshiti blocks have relatively integrated gas/water contacts, respectively (Fig. 8).

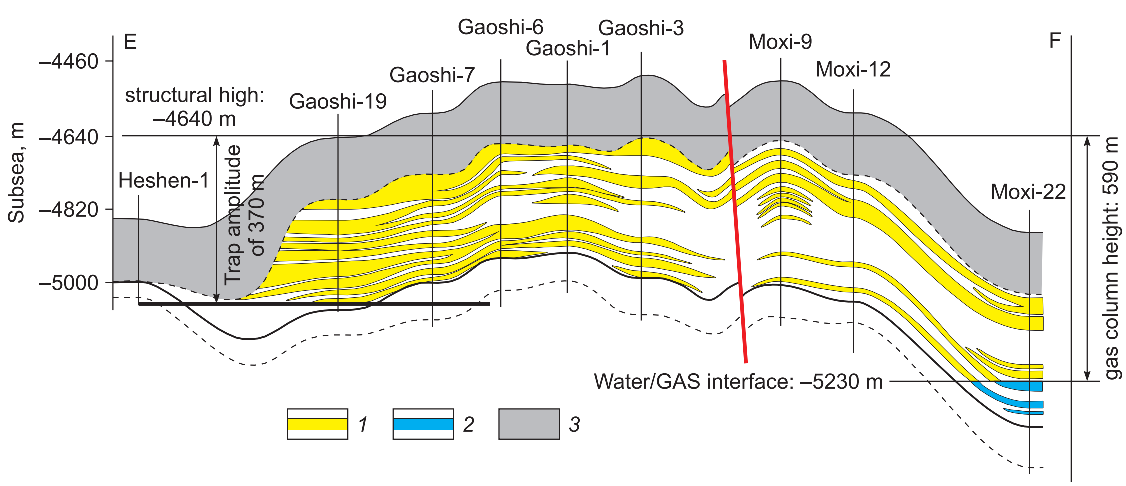

Fig. 6. The Z_2dn^4 gas reservoir sections of the Anyue gas field (see location in Fig. 7). *1*, gas reservoir; *2*, water-bearing bed; *3*, shale/mudstone.

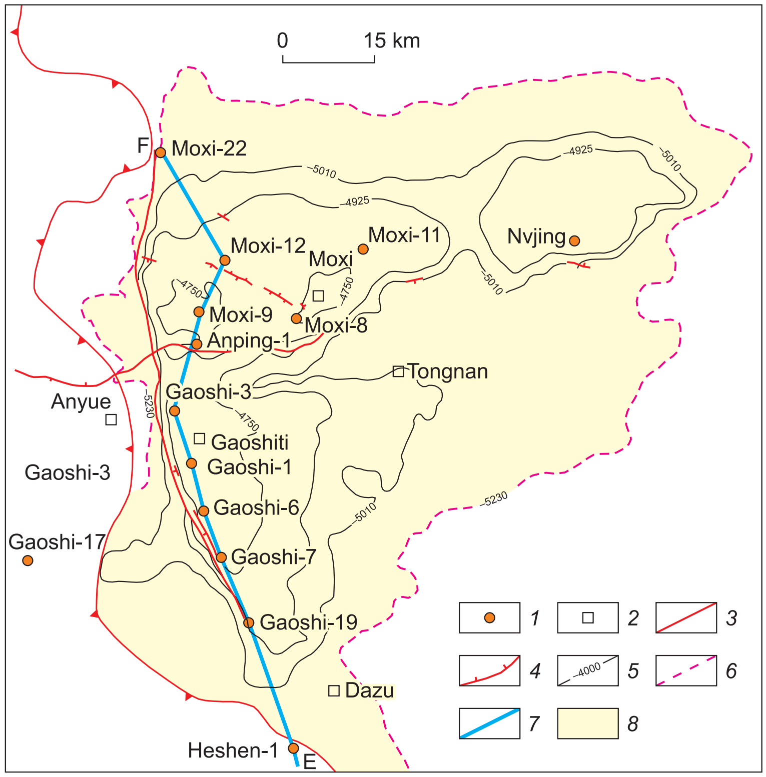

Fig. 7. Gas reservoirs distribution of the Sinian Dengying Formation in the Anyue gas field. *1*, wells; *2*, city; *3*, faults; *4*, Z_2dn^4 pinch line; *5*, structural contour; *6*, gas–water contact; *7*, Z_2dn^4 gas reservoir section location; *8*, gas reservoir range.

CHARACTERISTICS OF GAS SOURCE ROCKS

The source rocks of the Anyue gas field can be categorized into two types: argillaceous and carbonate source rocks, namely, the mud shale of the lower Cambrian Qiongzhusi Formation, the mudstone of the Maidiping Formation, the mudstone of Z_2dn^3, and the algae-rich carbonate source rocks of the Dengying Formation (Wei et al., 2013, 2014, 2015b; Zou et al., 2014a,b). The source rocks of the Qiongzhusi Formation are mainly black mudstones, rich in organic matter, with total organic carbon (TOC) ranging from 0.50 to 8.49% and an average of 1.95%. Their distribution was obviously controlled by the Mianzhu–Changning large-scale intracratonic rift, which developed from Sinian to early Cambrian (Wei et al., 2015c,d). The thickness range of the source rocks of the Qiongzhusi Formation along the direction of the rift is generally 300–450 m, and that in the adjacent area is 100–150 m. Moreover, the high-abundance source rocks are developed both inside and outside the rift. For example, the TOC values of 35 core samples from the Gaoshi-17 well in the rift are ranging from 0.37 to 6.00%, with an average of 2.17%. Nearly 10 m of black carbonaceous mudstone was intercepted in the Moxi-9 well in the Gaoshiti–Moxi paleouplift on the east side of the rift with TOC values ranging from 2.49 to 6.19%, with an average as high as 4.4%. The basin simulation results indicate that the gas generation intensity values of the source rocks of the Qiongzhusi Formation exceed 20×10^8 m^3/km^2 in the whole

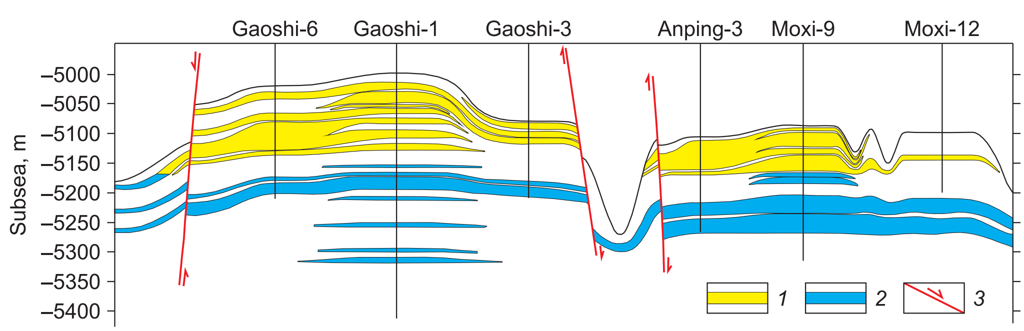

Fig. 8. The Z_2dn^2 gas reservoir sections in the Anyue gas field. *1*, gas reservoir; *2*, water-bearing bed; *3*, fault.

basin, and the gas generation intensity in the rift zone is generally greater than 60×10^8 m^3/km^2, which is fully qualified with the source rock conditions for the accumulation of a large gas field (gas generation intensity greater than 20×10^8 m^3/km^2 (Dai et al., 1997, 1999, 2003)).

The source rocks of the Maidiping Formation are mainly siliceous shale, carbonaceous mudstone, etc., mainly distributed in the intracratonic rift zone (Zou et al., 2014b), with thickness values ranging from 50 to 100 m and TOC values ranging from 0.52 to 4.00% with an average of 1.68%. The gas generation intensity is generally 12–30 × 10^8 m^3/km^2. The source rocks of Z_2dn^3 are mainly black shale, locally intercalated with thin-layer gray dolomite-bearing mudstone, mainly distributed in the Central Sichuan Basin (Zou et al., 2014b), with thickness values ranging from 10 to 30 m, TOC ranging from 0.50 to 4.73%, with an average of 0.87%, and the source rocks with TOC > 0.5% account for 59.8%. The gas generation intensity is relatively high, generally 6–12 × 10^8 m^3/km^2. These two sets of source rocks provided an important gas source supplement for the formation of the Anyue giant gas field.

Algae-rich dolomite, which is commonly developed in the Sinian System, is also an important set of source rocks. The TOC values of 415 algae-rich dolomite samples analyzed in this study range from 0.20 to 3.67%, with an average of 0.61%. The samples with TOC values ranging from 0.2 to 0.5% account for 54.4%. The samples with a TOC of 0.5 to 1.0% account for 31.8%, and the samples with TOC values greater than 1.0% account for 13.8%. Thermal simulation experiments on the algae extracted from the rocks show that the maximum total gas yield rate is 3471 L/ton algae. Thermal simulation results for the algae-rich dolomite show that the total gas yield rate is 69 L/ton rocks. It can be seen that the overmature algae-rich dolomite still has a high hydrocarbon generation potential. The comparison of carbon isotopes in natural gas and kerogen shows that the carbon isotopes in the kerogen in the algae-rich dolomite make up –33.7 to –23.8‰, with an average of –27.8‰, while the average carbon isotope content in the natural gas from the Sinian gas reservoir is 28.1‰. According to the carbon isotope fractionation rule for hydrocarbon generating (Tissot and Welte, 1984), it is believed that the algae-rich carbonate source rocks made an important contribution to the Sinian natural gas. Moreover, the algae-rich dolomite is large in thickness, generally between 100 and 400 m in the basin, with a wide distribution range (Zou et al., 2014b). Based on simulation calculation, the gas generation intensity in the basin reaches $40–70 \times 10^8$ m^3/km^2, so the algae-rich dolomite developed in the Sinian System basin proved to be a set of important source rocks.

It can be seen that the mudstone of the Qiongzhusi Formation and the algae-rich carbonate rocks of the Dengying Formation, which were widely developed in the whole basin, provided not only sufficient gas sources for the formation of the Anyue giant gas field but also necessary hydrocarbon source conditions for the extended exploration of the Sinian–Cambrian system in other areas of the basin.

RESERVOIR ROCK TYPES AND PROPERTIES

The reservoir rocks of the Longwangmiao Formation are mainly doloarenite, residual doloarenite, and fine–medium-grained dolomite. The reservoir space involves pores, caves, and fractures, which are dominated by intergranular dis-

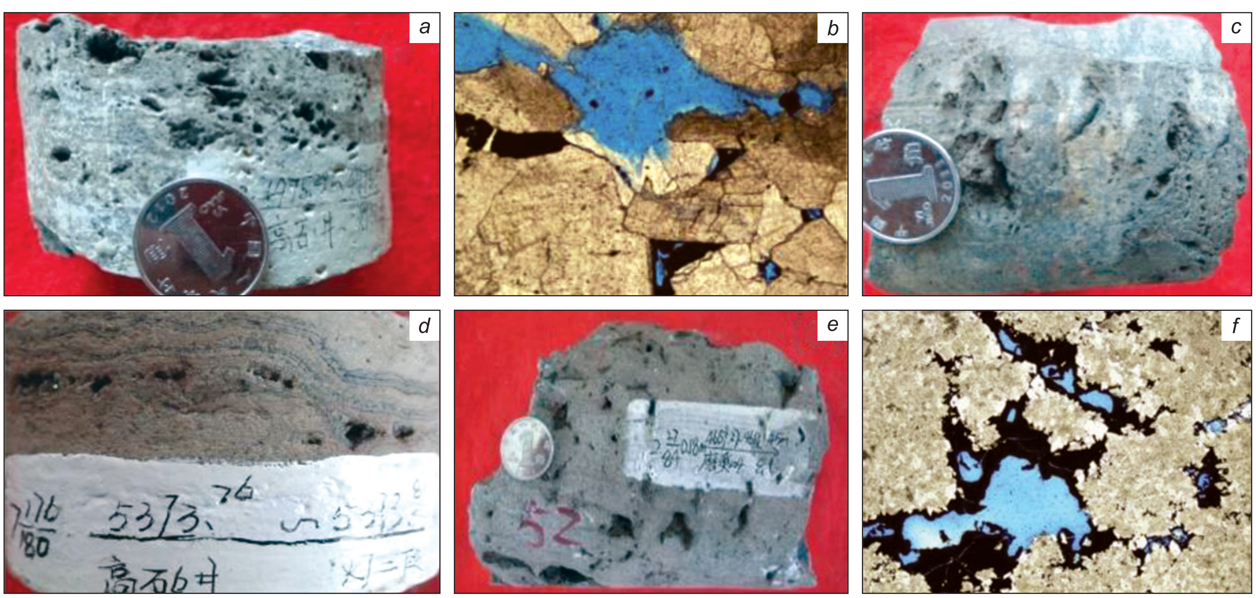

Fig. 9. Reservoir properties of the Dengying and Longwangmiao Formations of the Anyue gas field. *a*, Gaoshi-1 well, Sinian Dengying Formation Member 4, karstification cavity; *b*, Moxi-9 well, Sinian Dengying Formation Member 2, intergranular pore; *c*, Gaoshu-7 well, Sinian Dengying Formation Member 4, karstification cavity; *d*, Gaoshi-6 well, Sinian Dengying Formation Member 2, karstification cavity; *e*, Moxi-204 well, Cambrian Longwangmiao Formation, karstification cavity; *f*, Moxi-12 well, Cambrian Longwangmiao Formation, intergranular pore.

Table 1. Reservoir properties of the Anyue gas field (Wei et al., 2015a)

Horizon	Thickness / well/layer, m	Accumulated thickness for a single well, m	Average porosity for a single well, %	Average permeability for a single well, mD	Rock type	Reservoir space	Reservoir type
Longwangmiao Formation	0.1–8.9 /1.2	10.8–61.1 /39.5	3.35–5.83 /4.28	0.008–6.777 /0.966	Doloarenite, residual doloarenite, and fine–medium-grained dolomite	Pores (inter-granular, inter-granular dissolved, inter-crystal dissolved, and residual intergranular), caves, and fractures	Mainly pore-type, regional fracture–pore (cave) type
Z_2dn^4	0.25–18.80 /2.17	1.38–101.40 /24.40	2.21–3.95 /3.22	0.0005–6.320 /0.593	Algal binding doloarenite, algal doloarenite, algal clotted dolomite, algal stromatolithic dolomite, algal framework rock and doloarenite	Mainly intergranular (dissolved) pores, then inter-crystal pores, inter-crystal dissolved pores, caves, and fractures	Mainly fracture–pore (cave) type
Z_2dn^2	0.13–26.80 /3.66	5.64–63.00 /32.96	3.26–3.74 /3.35	0.00155–13.20 /1.16	Mainly mound-shoal complex: algal clotted dolomite, algal stromatolithic dolomite, algal framework rock and doloarenite	Inter-granular dissolved pores and then inter-crystal dissolved pores	Mainly fracture–cave type

solved pores and intercrystalline dissolved pores, then the intercrystalline pores. Caves and fractures are relatively developed in some well intervals. The average reservoir porosity is 4.28%, with an average permeability value of 0.966 mD (Fig. 9; Table 1). The thickness values of the reservoir range from 10 to 60 m, with the maximum value in the Moxi block, and then followed by the Gaoshiti block. The reservoir formation is mainly divided into two periods. In the early stage of the reservoir formation, grain beaches that contained frame-building pores by coelomate experienced penecontemporary dolomitization and the eluviation process of the fresh water, and lots of early dissolved pores were produced and preserved. In the late stage, the pores formed in the early stage experienced polyphase karstification during the Caledonian and Hercynian Periods (Liu et al., 2014; Tian et al., 2015), with the formation of cellular-pore and vug-superposed fractures, forming fracture–pore and fracture–cave high-quality reservoirs, with thickness ranging from 20 to 70 m and an area of 8000 km^2.

The reservoir rocks of Z_2dn^2 and Z_2dn^4 are generally developed in a mound-shoal complex, and they are dominated by algal clot dolomite, algal stromatolithic dolomite, and algal framework rock and doloarenite, with the reservoir space being composed mainly of intergranular dissolved pores and intercrystal dissolved pores. Besides, small–medium vugs and fractures are the main reservoir space in the Dengying Formation. Vertically, dissolved vugs may reach 300 m below the erosion surface of the Sinian top surface. The average porosity of Z_2dn^4 is 3.22%, with an average permeability of 0.593 mD. The average porosity of Z_2dn^2 is 3.35%, with an average permeability of 1.16 mD (Fig. 9; Table 1). The reservoir thickness values of Z_2dn^4 of the Dengying Formation range from 60 to 110 m. The reservoirs are developed in the upper part of Z_2dn^2 and show a relatively stable lateral distribution. The reservoirs mainly developed in a mound-shoal complex with microorganism framework pores in the platform edge of the Sinian Dengying Formation. The mound-shoal complex experienced penecontemporary dissolution and polyphase weathering karstification. The vugs enlarged and formed a quasi-layered large-scale dolomite reservoir, including two types of reservoirs: fractural–vug and fractural–vug–cave ones [Luo et al., 2015]. The reservoir thickness values range from 120 to 210 m, and the reservoir area reaches 6000 km^2 along the platform margin belt of the Sinian Dengying Formation.

PROPERTIES OF NATURAL GAS

The gas reservoir in the Z_2dn^4 zone of the Anyue gas field is categorized as dry gas reservoir, with a medium–low sulfur content, a medium CO_2 content, and trivial propane, He, and N. The relative density of natural gas is 0.6079–0.6336, and the natural gas is mainly composed of methane, with content values of CH_4 ranging from 91.22 to 93.77%, H_2S content ranging from 1.00 to 1.62%, and CO_2 content ranging from 4.83 to 7.39%.

The gas reservoirs of Z_2dn^2 belong to the dry type, with a medium–high sulfur content, a medium CO_2 content, and trivial propane, He, and N. The relative density of natural gas is 0.6265–0.6326, and the average methane content value is 91.03%, with H_2S content ranging from 0.58 to 3.19%, and CO_2 content ranging from 4.04 to 7.65%.

The gas reservoirs of the Longwangmiao Formation of the Anyue gas field are dry, with a medium–low sulfur content and a medium–low CO_2 content. The natural gas is mainly composed of methane, with content values ranging from 95.10 to 97.19%, ethane content ranging from 0.12 to

0.21%, H_2S content ranging from 0.26 to 0.77%, with an average of 0.531%, and CO_2 content ranging from 1.83 to 3.16%, with trivial propane, He, and N contents.

TEMPERATURE AND PRESSURE PROPERTIES OF GAS RESERVOIRS

The gas reservoirs of the Longwangmiao Formation are characterized by a deep burial horizon, a high temperature, and a high pressure, with a burial depth exceeding than 4600–4700 m. The formation pressure in the central gas reservoir in the Moxi block is 75.7 MPa, with a pressure coefficient of 1.65. The average formation pressure in the Gaoshiti block is 68.3 MPa, with a pressure coefficient of 1.5. The average formation pressure in the Gaoshiti block is 78.0 MPa, with a pressure coefficient of 1.67. The average temperature in the central gas reservoir ranges from 140.3 to 150.4 °C.

Gas reservoirs in Z_2dn^2 and Z_2dn^4 are characterized by an ultradeep burial horizon, a high temperature, and an atmospheric pressure. The gas reservoir depth of the Deng4 Section ranges from 5000 to 5100 m, and the formation pressure in the central production horizon ranges from 56.57 to 56.63 MPa, with a gas reservoir pressure coefficient of 1.06 to 1.13. The average temperature in the central gas reservoir ranges from 149.6 to 161.0 °C. The burial gas reservoir depth of Z_2dn^2 ranges from 5300 to 5400 m, and the formation pressure in the central production horizon ranges from 57.58 to 59.08 MPa, with a gas reservoir pressure coefficient of 1.06 to 1.10. The average temperature in the central gas reservoir ranges from 155.82 to 159.91 °C.

MAJOR CONTROLLING FACTORS FOR GAS RESERVOIR FORMATION

The Anyue gas field is mainly controlled by two factors: late Sinian–early Cambrian intracratonic rifts and Gaoshiti–Moxi paleouplift (Fig. 3). The intracratonic rifts controlled the development of the hydrocarbon generation center, and the filled mud shale of the Qiongzhusi Formation could be the effective sealing conditions for the Dengying Formation gas reservoirs. The Gaoshiti–Moxi paleouplift controlled the formation and distribution of three sets of large high-quality reservoirs: Z_2dn^4, Z_2dn^2, and Longwangmiao Formation. Furthermore, the paleouplift controlled the formation of three sets of high-quality reservoir–caprock assemblages. The integrated and inherited giant trap structures, characterized by a long-term independent and stable development, are always the most favorable directing zones (Wei et al., 2015c).

LATE SINIAN–EARLY CAMBRIAN INTRACRATONIC RIFT

(1) Control of the hydrocarbon generation center. The research found that a SN-extending intracratonic rift developed in the late Sinian–early Cambrian Sichuan Basin, lower Cambrian high-quality hydrocarbon source rocks, and mudstone of the Qiongzhusi and Maidiping Formations. The subsidence center controlled the lower Cambrian high-quality hydrocarbon source rocks center (Fig. 9), and the thickness of the hydrocarbon source rocks of the Qiongzhusi Formation reaches 300–450 m, which is three times larger than that of the other areas; the TOC values are usually higher than 1.0%, belonging to high-quality hydrocarbon source rocks. In addition, the argillaceous hydrocarbon source rocks of the Maidiping Formation are developed inside the intracratonic rifts, with thickness values ranging from 5 to 100 m, and they are thin or even pinched out in the other regions. The gas generation strength of these hydrogenation source rocks reaches 100–180 × 10^8 m^3/km^2, which is four times larger than that in the other regions. Hence, no matter judging from the thickness of hydrocarbon source rocks or gas generation intensity, this intracratonic rift is the hydrocarbon generation center of lower Cambrian high-quality source rocks, with a distribution of 5.0×10^4 km^2. From the resource valuation results, the hydrocarbon generation of the source rocks inside the intracratonic rift contributes nearly 61% to the Sinian–Cambrian resources;

(2) Construction of lateral sealing conditions. The lower Cambrian mud shale which fills the intracratonic rifts extending in the Central Sichuan basin provides good lateral sealing conditions for large gas reservoir accumulation of the Dengying Formation in the Gaoshiti–Moxi area to the east of the intracratonic rift (Fig. 10). As stated above, the gas reservoirs of Z_2dn^4 in the Moxi–Gaoshiti area are of the structure-lithologic type. Although the current structure occupies a narrow range, the exploration proved that the gas column height of Z_2dn^4 exceeded the range of a structural trap. In combination with the distribution characteristics of mudstone of the Qiongzhusi Formation, one of the main causes of the large area of reservoir accumulation in Z_2dn^4 is the lower Cambrian thick argillaceous rocks filling the intracratonic rift, which provide good lateral sealing conditions for the formation of traps along the upper dip direction of Z_2dn^4 in the Anyue gas field (Figs. 6, 10).

LATE SINIAN–EARLY CAMBRIAN GAOSHITI–MOXI PALEOUPLIFT

(1) Control of the formation of three sets of high-quality reservoirs. The western part of the Gaoshiti–Moxi paleouplift is superposed by the gentle-slope platform margin belt of Z_2dn^2 and the steep-slope platform margin belt of Z_2dn^4. The intraplatform grain bank is developed in the central and eastern parts of the paleouplift. Overall cratonic uplifting corrosion of Late Z_2dn^2, Late Z_2dn^4, and Late Maidiping Formation formed two sets of large weathering karst reservoirs of Z_2dn^2 and Z_2dn^4. Besides, the relatively high land of the Gaoshiti–Moxi paleouplift of the Late Canglangpu Period controlled the large area development and distribution of high energy grain banks and experienced superposition of karstification at the synsedimentary, supergene, and burial

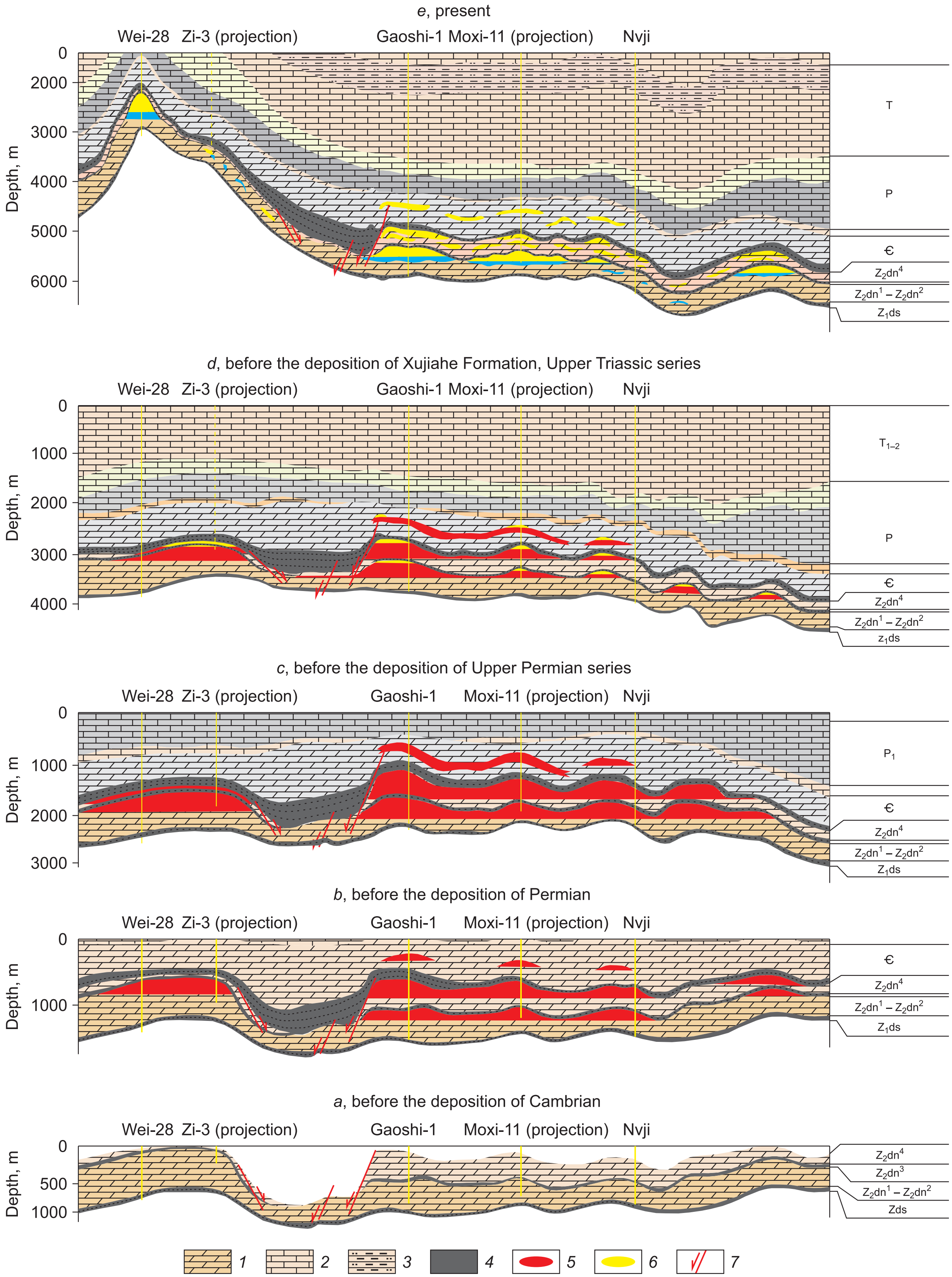

Fig. 10. Natural gas accumulation modes in the Sinian–Cambrian of the Anyue gas field in the Sichuan Basin. *1*, dolomite; *2*, limestone; *3*, silty mudstone; *4*, mudstone; *5*, paleo-oil reservoirs; *6*, paleogas reservoir; *7*, faults.

stages, forming a set of high-quality doloarenite reservoirs belonging to the pore and fracture–pore (cave) types. The reservoir properties of the Dengying and Longwangmiao formations are shown in Table 1;

(2) Control of the formation of three sets of high-quality reservoir–caprock assemblages. Three sets of regionally distributed mud shale immediate caprocks in the Gaoshiti–Moxi paleouplift are developed in a ascending sequence (Z_2dn^3, Qiongzhusi Formation, and Gaotai Formation), and the thickness reached 5–25, 100–200, and 14–43 m, respectively. In addition, the indirect caprocks are widely developed, such as Permian mudstone, a little of coal series, and a thick gypsum bed in the Middle–Lower Triassic Jialingjiang and Leikoupo formations. These high-quality caprocks, together with three sets of large high-quality reservoirs (Z_2dn^2, Z_2dn^4, and Longwangmiao Formation), form three sets of high-quality reservoir–caprock assemblages (Fig. 1): (1) dolomite reservoir of Z_2dn^2–mudstone caprocks of Z_2dn^3; (2) dolomite reservoir of Z_2dn^4–mud shale caprocks of the lower Cambrian Qiongzhusi Formation (including the Maidiping Formation); and (3) dolomite reservoir of the lower Cambrian Longwangmiao Formation–caprock assemblage of middle Cambrian sand shale and Permian mud shale. From Dengying Formation to Cambrian Longwangmiao gas reservoirs, the pressure coefficient increases from normal (1.1–1.2) to ultrahigh (1.5–1.6), which indicates that, in addition to immediate caprocks, the regional distributed indirect caprocks (Permian mud shale, Middle–Lower Triassic Jialingjang Formation, and Leikoupo Formation gypsum rock) play a very important role for the preservation of Sinian–Cambrian gas reservoirs;

(3) The most favorable hydrocarbon accumulating zone. In the Gaoshiti–Moxi paleouplift area, a long-term independently integrated and inherited giant trap structure has developed since the Sinian Period. It has shown a stable development, which always is the most favorable hydrocarbon accumulating area, with vertical and lateral migration and accumulation, from the Maidiping Formation, the Qiongzhusi Formation in the western rifts, and Dengying and Qiongzhusi Formation hydrocarbon source rocks in the paleouplift. The inherited giant trap also provided favorable conditions for paleo-oil reservoir forming *in situ* cracking and the formation of giant gas reservoir. The study of evolution of the hydrocarbon generation source rocks proved that the Sinian hydrocarbon source rocks began to generate hydrocarbon in the middle–late Cambrian (Fig. 10*a*). Influenced by the Caledonian movement uplifting, the hydrocarbon generation process ceased. A second burial happened in the Permian, and secondary hydrocarbon generation began. The oil generation stage lasted until the Triassic Period, during which the liquid hydrocarbon generated from the source rocks migrated at the core of the Gaoshiti–Moxi paleouplift and formed the oil reservoir. This suggests that the Permian–Triassic periods are the main stage of the formation of the Gaoshiti–Moxi giant paleooil reservoir (Fig. 10*b*, *c*). Before the deposition of Upper Triassic strata, some crude oil in the reservoir began in-situ cracking, and a hydrocarbon reservoir was formed (Fig. 10*d*); further cracking continues in the Late Triassic–Cretaceous oil reservoir, forming lots of cracking dry gas reservoirs (Fig. 10*e*). The periods of both hydrocarbon generation from Cambrian hydrocarbon source rocks and crude oil cracking are slightly later than the Sinian, and the main cracking period of crude oil is the Middle Jurassic–Cretaceous.

CONCLUSIONS

(1) The Anyue gas field is located in the Gaoshiti–Moxi area in the Central Sichuan Basin in China, the exploration of which might be divided into two general stages: investigation of Sinian strata and exploration of paleouplifts, which might be then subdivided into four stages: discovery of the Weiyuan gas field (1940–1964), Caledonian paleouplift investigation (1965–2005), Caledonian paleouplift risk-taking exploration (2006–2011), and overall exploration (2012–present) of the paleouplift in the Tongwan Period. In 2011, the Anyue giant gas field was discovered in the Gaoshiti–Moxi area. As of 2015, the proven geologic reserves of natural gas amounted to 657.4 billion m^3, and the total reserves (including proven, controlled, and predicted ones) exceeded 1.5 trillion m^3. The Anyue gas field occurs in the oldest marine carbonate strata and is characterized by the highest degree of thermal evolution and the largest reserves for a single gas field ever discovered in domestic China;

(2) A total of three sets of gas-bearing strata are developed in the Anyue gas field in a descending sequence. The gas reservoir of the Longwangmiao Formation is determined as a structure-lithologic reservoir forming the Gaoshiti–Moxi–Longnvsi gas reservoir group of the Longwangmiao Formation. The gas reservoir of Z_2dn^4 is determined as structure-stratigraphic, and the gas reservoir of Z_2dn^2 is determined as a structural gas reservoir with bottom water. The gas sources of Cambrian gas reservoirs are mainly generated from mud shale of lower Cambrian hydrocarbon source rocks, and the Dengying Formation is characterized by mixed gas sources of Sinian and Cambrian hydrocarbon source rocks. The gas reservoirs are all of the dry gas type, with a medium–low sulfur content and a medium CO_2 content. The gas reservoir of the Longwangmiao Formation is characterized by a deep horizon, high temperature, and high pressure. The gas reservoirs of Z_2dn^2 and Z_2dn^4 are characterized by an ultradeep horizon, high temperature, and normal pressure;

(3) The accumulation of the Anyue gas field is mainly controlled by two major factors: the late Sinian–early Cambrian intracratonic rift and the synchronous Gaoshiti–Moxi paleouplift. The intracratonic rift controlled the development of the hydrocarbon generation center, and the infilled mud shale of the Qiongzhusi Formation acted as the effective sealing conditions for gas reservoirs in the Dengying Formation. The Gaoshiti–Moxi paleouplift controlled the accumulation and distribution of three sets of large-scale high-quality reservoirs and the formation of three sets of high-quality reservoir–caprock assemblages. The long-term,

independent, and stably developed integrated and inherited giant trap structures are always the most favorable accumulation zones for oil and gas.

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