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Discovery of Intracratonic Rift in the Upper Yangtze and Its Control Effect on the Formation of the Anyue Giant Gas Field

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Abstract—According to drilling and seismic data, the Late Sinian–Early Cambrian intracratonic rift was found in the Deyang–Anyue area of the Upper Yangtze craton. This rift is controlled by a tensional fault and extends in the N–NW direction with a N–S length of 320 km and an E–W width of 50–300 km. After three stages of the rift evolution, i.e., the formation stage, development stage, and dying stage, a favorable near-source accumulation assemblage formed. The research results indicate that: (1) the sedimentation stage of the Late Sinian Dengying Formation is the rift formation stage, during which trough-basin facies sedimentation is developed in the rift, while platform marginal-facies mounds and shoals are developed on both sides, controlling the formation and distribution of high-quality reservoirs in the Dengying Formation; (2) the sedimentation stage of the Early Cambrian Meishucun–Qiongzhusi Formation is the rift development stage, during which deep-water continental-shelf facies argillaceous rocks accumulated in the rift with a thickness of 500–1000 m, indicating the sedimentation of high-quality source rocks; (3) the sedimentation stage of the Canglangpu Formation is the rift dying stage, terminating the evolution history of the intracratonic rift by gap filling. The intracratonic rift is a key factor for the formation of the Anyue giant gas field, where the high-quality source rocks provide abundant gases for the giant gas field. A regional lateral sealing occurred during the rapid rise of the western paleouplift in Central Sichuan during the Late Yanshan–Himalayan period, favorable for the preservation of the Gaoshiti–Moxi giant gas field on the eastern wing of the rift. The intracratonic rift and its role in giant gas accumulation provide a significant reference for deep oil and gas exploration in paleocratonic basins.

Keywords: intracratonic rift; Sinian-Cambrian; paleouplift; giant gas field; near-source accumulation; Sichuan Basin

INTRODUCTION

The Sinian–Cambrian System is an important field for the natural gas exploration in the Sichuan Basin. For a long period, the paleouplift in Central Sichuan (Leshan–Longnvsi paleouplift) has drawn the most attention for its favorable zone of prospecting. However, since the discovery of the Sinian Weiyuan gas field in the upper region of modern formation of the paleouplift in 1964, no important breakthrough has been made through the exploration for more than 40 years. In 2011, the risk exploration well GS1 was tested, and high-yield natural gas for more than 1 million cubic meters was obtained from the Dengying Formation. Well GS1 is located in the Gaoshiti–Moxi area of the Leshan–Longnvsi paleouplift pitching end. The breakthrough opened the overall exploration in the Gaoshiti–Moxi area. At the end of 2013, the Anyue giant gas field was discovered (Du et al., 2014; Xu et al., 2014; Zou et al., 2014).

The research results indicate that the favorable conditions for the forming and distribution of the Anyue giant gas field (Du et al., 2014; Wei et al., 2015; Xu et al., 2014; Zou et al., 2014) include paleouplift background, abundant source, high-quality reservoir with large-scale distribution, macrostructure-stratum/lithology combination trap, and good storage conditions. It will be emphasized that the Late Sinian–Early Cambrian intracratonic rift found on the west side of the Anyue gas field is the key factor for the forming of the above-mentioned favorable conditions. Based on this, the paper mainly elaborates on the characteristics, formation and evolution of the intracratonic rift and its control effect on accumulation factors.

1. REGIONAL GEOLOGIC BACKGROUND

The Sichuan Basin is a superposed basin based on the Upper Yangtze craton. Its basement is folded, formed by the

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Jinning movement in the late Mesoproterozoic (Sichuan…, 1989). In the Neoproterozoic, influenced by the breakup of Rodinia, the Xingkai taphrogenic movement (Yong et al., 2009) occurred on the Yangtze paleocontinent, South China, forming a series of Neoproterozoic rift basins (Wang et al., 2006). The Nanhua and Kangdian Rifts, as the main rifts, were separately located at the southeast and west margins of the Yangtze block, South China (Wang, 1999; Wang et al., 2006). During the Sinian, the regional continental rifting ended and the evolutionary stage of the craton basin began. Represented by the Sinian Doushantuo and Dengying Formations, the combination of carbonate platform and clastic rock was developed in the Upper–Middle Yangtze area. The southeast margin of the carbonate platform was located in the Cili–Dayong area, Northwest Hunan, having a transition to the Hunan–Guizhou–Guangxi basin facies (Li et al., 2004).

The Tongwan movement (Li et al., 2014; Wang et al., 2014) occurred for three times in the Upper Yangtze area during the sedimentation stage of the Sinian Dengying Formation–Early Cambrian Meishucun Formation, being represented by regional uplifting and denudation and resulting in the scattered distribution of the Maidiping Formation stratum with a large residual stratum thickness in the Ziyang–Luzhou area. During the sedimentation stage of the Early Cambrian Qiongzhusi Formation, influenced by the rapid rise of the sea level, the silicon–phosphorus shale and carbonaceous shale were widely developed in the Upper–Middle Yangtze area, representing the deeper-water deposit during the stage of rapid rise of the sea level (Mei et al., 2006). During the middle Early Cambrian (sedimentation stage of the Canglangpu Formation), a great transformation occurred for the tectonic framework of the Upper Yangtze craton. The scope of vertical differential movement significantly decreased and the uplift–sag framework began to vanish (Liu and Xu, 1994). The Upper–Middle Yangtze area began the continuous evolutionary stage of carbonate platform, developing facies of onshore clastic rock, carbonate tidal flat, open platform, platform margin slope, and platform marginal basin, respectively, from the west basin margin to the southeast.

The discovery of the Anyue giant gas field drew the attention of a lot of scholars. Wide discussion and research were conducted by scholars in view of the disposition relationship between the large hydrocarbon production center of the Lower Cambrian Qiongzhusi Formation source rock and high-quality reservoir of the Longwangmiao Formation. Some scholars emphasized the denudation from the Tongwan movement in the late Sinian and the tensile function in the early Cambrian, putting forward tensile trough (Liu et al., 2013) and tensile erosion trough (Li et al., 2015), respectively. In fact, the high-quality reservoir of the Anyue gas field includes not only the Longwangmiao Formation but also the Sinian Dengying Formation, which has not been noted by the former researchers. The authors of this paper, through system research, believe that the Sichuan Basin was under a tensile environment during the Sinian. The intracratonic rift (Fig. 1), influenced by regional tensile function and fundamental fault activities, was formed during the Sinian in

Fig. 1. Basin prototype of the middle–upper Yangtze craton during the Sinian. *1*, intracratonic rift; *2*, Hunan–Guangxi continental margin basin; *3*, Upper Yangtze craton; *4*, Kangdian Oldland; *5*, Wudang block; *6*, basin boundary; *7*, place name.

the Sichuan Basin, which controlled the high-energy facies belt represented by rift marginal mounds and shoal facies belt. It continued developing during the early Early Cambrian and further controlled the developing of the Lower Cambrian Qiongzhusi Formation source rock. This rift died out in the late Early Cambrian and began the evolutionary stage of paleouplift, having control effect on the grain beaches distribution of the Longwangmiao Formation.

2. THE DISCOVERY OF INTRACRATONIC RIFT

The former research results indicate that the Sinian–Cambrian System in the Upper Yangtze area was stable in structure (Wang et al., 2002); the Dengying Formation was mainly composed of carbonate platform deposits (Tang et al., 1987; Liu et al., 2008); and the Qiongzhusi Formation was developed into shallow-water shelf facies clastic rock sediments (Ma et al., 2009). Along with the overall exploration for the Sinian–Cambrian System in the Gaoshiti–Moxi area of the paleouplift in Central Sichuan, a great quantity of firsthand data, such as drilling-geology and high-resolution three-dimensional seismic data, was obtained. Based on completing fundamental maps, such as stratum thickness and paleogeographic distribution of lithofacies, the Late Sinian–Early Cambrian intracratonic rift developed in the Anyue–Deyang area, Sichuan Basin, is put forward through making unique stratigraphic subdivision contrast for the Sinian–Cambrian well-seismic and precise explanation on its deep structure and combining sedimentary-facies and seismic-facies analyses.

2.1. THE BASIC CHARACTERISTICS OF INTRACRATONIC RIFT

The so-called intracratonic rift is a sag located within a cratonic basin and controlled by a synsedimentary fault. The Anyue–Deyang intracratonic rift is located at the hinterland of the Sichuan Basin, extending from West Sichuan to Central Sichuan and South Sichuan in the N–NW direction, with an E–W width of 50–300 km and a N–S length of 320 km; it occupies an area of 6×10^4 km^2 within the basin (Fig. 2). It can be seen from Fig. 2 that the stratum thickness map of the Lower Cambrian Maidiping and Qiongzhusi Formations shows a continuous decrease in stratum thickness from NW to SE. The stratum thickness near the area in front of Longmen Mountain might be 1200 m at most; that of the area to the east of Ziyang is 600–800 m; and that of the Zigong–Neijiang area is 300–500 m. The thickness of the lateral layers of the rift changes little, generally between 200 and 300 m, indicating that this rift was characterized by relative lower part in the north and relative high part in the south during the Early Cambrian.

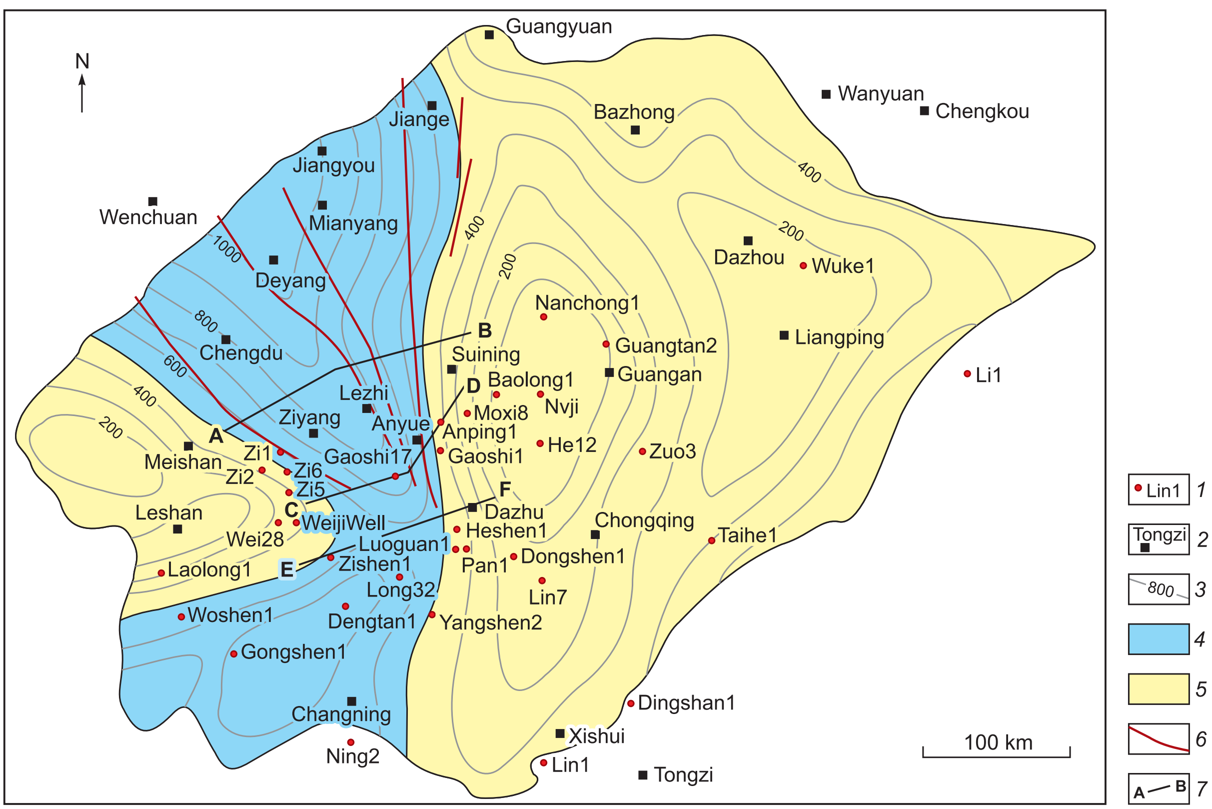

Fig. 2. Location and distribution of the Deyang–Anyue intracratonic rift. *1*, well; *2*, place name; *3*, thickness contour of the Lower Cambrian Maidiping and Qiongzhusi formations, m; *4*, intracratonic rift; *5*, craton sag; *6*, tensional fault; *7*, location of seismic section.

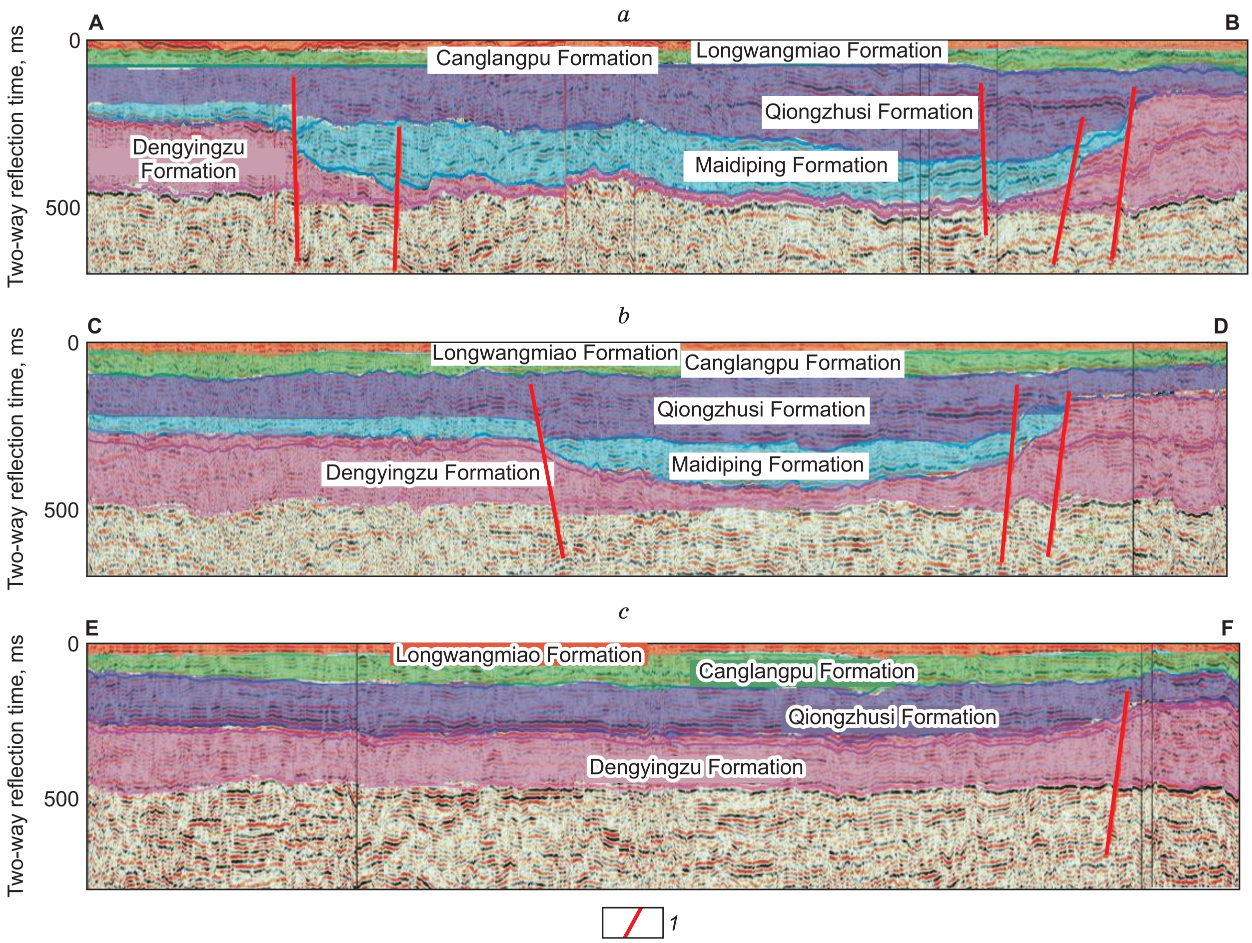

Fig. 3. Interpretation of the seismic section crossing the intracratonic rift (layer flattening by reflection top of the Canglangpu Formation, location see Fig. 2). *1*, fault.

The interpretation of seismic data indicates that the Anyue–Deyang intracratonic rift is distributed under the control of a fault. The extensional faults developed within the rift and its both sides in the NW direction indicate fault depression characteristics (Fig. 3). The boundary fault displacement is great with a trend of decreasing from north to south, and no faults are found to the south of Gaoshiti–Weiyuan. Vertically, the fault displacement of the Sinian and Lower Cambrian Qiongzhusi Formation is the largest with synsedimentary fault characteristics. The bottom fault displacement of Member 3, Dengying Formation (Deng Member 3), is 400–500 m, and that of the Cambrian System is 300–400 m. The fault displacement decreases from the bottom up to the Canglangpu Formation. Most of the faults except the boundary ones disappear at the Longwangmiao Formation. The above-mentioned characteristics indicate that the fault begins its activities during the sedimentation stage of the Late Sinian Dengying Formation, characterized by a continuous decline from NW to SE and from the basin margin to its inside. Then the fault activities died out during the sedimentation stage of the Canglangpu–Longwangmiao Formation during the middle and late Early Cambrian. Note that the boundary fault of the rift was still developed during the sedimentation stage of the Longwangmiao Formation with a great difference for the Longwangmiao Formation sedimentation on both sides of the fault and relatively undeveloped grain beaches within the rift area.

An obvious difference is found between the backfill stratum within the intracratonic rift and the platform area on its both sides. The stratum of the Sinian Dengying Formation within the rift is thin. The thickness of Deng Member 3–Dengying Formation Member 4 (Deng Member 4) is 50–100 m. The thickness of Dengying Formation Member 1 (Deng Member 1)–Dengying Formation Member 2 (Deng Member 2) is 100–300 m. The stratum thickness of the rift flank is great. The thickness of Deng Members 3–4 on the eastern limb of the rift, Moxi–Gaoshiti region, is 250–320 m, and that of Deng Members 1–2 is 400–600 m. The west limb (Ziyang area) underwent the denudation of the Tongwan movement with the full and complete denudation for the upper stratum (Deng Members 3–4) of the Dengying Formation. The stratum thickness of the Lower Cambrian Maidiping and Qiongzhusi formations within the rift is great with an accumulated thickness of up to 500–1200 m, while that of both sides area is generally 200–300 m. For the Lower Cambrian Maidiping Formation, the residual stratum thickness in the rift area is 100–200 m, and that of the rest of Sichuan basin is small, even stratum hiatus. Seeing from drilling statistics, the stratum thickness of the Maidiping Formation in the Moxi–Gaoshiti area is 0–30 m.

To sum up, the Anyue–Deyang intracratonic rift, Sichuan Basin, is a large intraplatform sag under the control of an extensional fault. The extensional activities are characterized by a decline trend from NW to SE. The stratum of the Dengying Formation within the Northwest rift in the adjacent area is small in thickness, while that of the Maidiping–Qiongzhusi Formation is great in thickness.

2.2. THE EVOLUTION OF INTRACRATONIC RIFT

The research results indicate that the formation and evolution of the Anyue–Deyang intracratonic rift proceeded in three stages: (1) the sedimentation stage of the Late Sinian Dengying Formation is the rift formation stage; (2) the sedimentation stage of the Early Cambrian Meishucun–Qiongzhusi Formation is the rift development stage; (3) the sedimentation stage of the Early Cambrian Canglangpu Formation is the rift dying stage (Fig. 4).

2.2.1. THE FORMATION OF THE RIFT DURING THE SEDIMENTATION STAGE OF THE LATE SINIAN DENGYING FORMATION

Regionally, the carbonate platform was developed during the sedimentation stage of the Late Sinian Dengying Formation in the Upper–Middle Yangtze area (Li et al., 2015; Wang et al., 2002), and mainly composed of dolomite, with an area of 75×10^4 km^2 and a thickness of over 1 km. Under the influence of regional extension, the west margin of the Upper Yangtze craton developed into a rift extending from the West Sichuan sea basin to the cratonic basin hinterland—the Anyue–Deyang rift (Fig. 1). The rift of the Dengying Formation sedimentation stage is mainly characterized by two features: (1) the normal fault activity in the rift area is obvious with the length of the Moxi–Gaoshiti west side fault (larger scale) up to 300 km, extending northward to the West Sichuan sea basin, namely the boundary fault controlling the rift. The west side fault of the rift is not obvious on the seismic cross section with little one visible, which is greatly related to the later stage compression and denudation in this area; (2) there is a remarkable difference between the rift and adjacent stratum and sedimentation. The Dengying Formation of the rift area develops deep-water trough-basin facies micritic dolomite and tumulous argil-

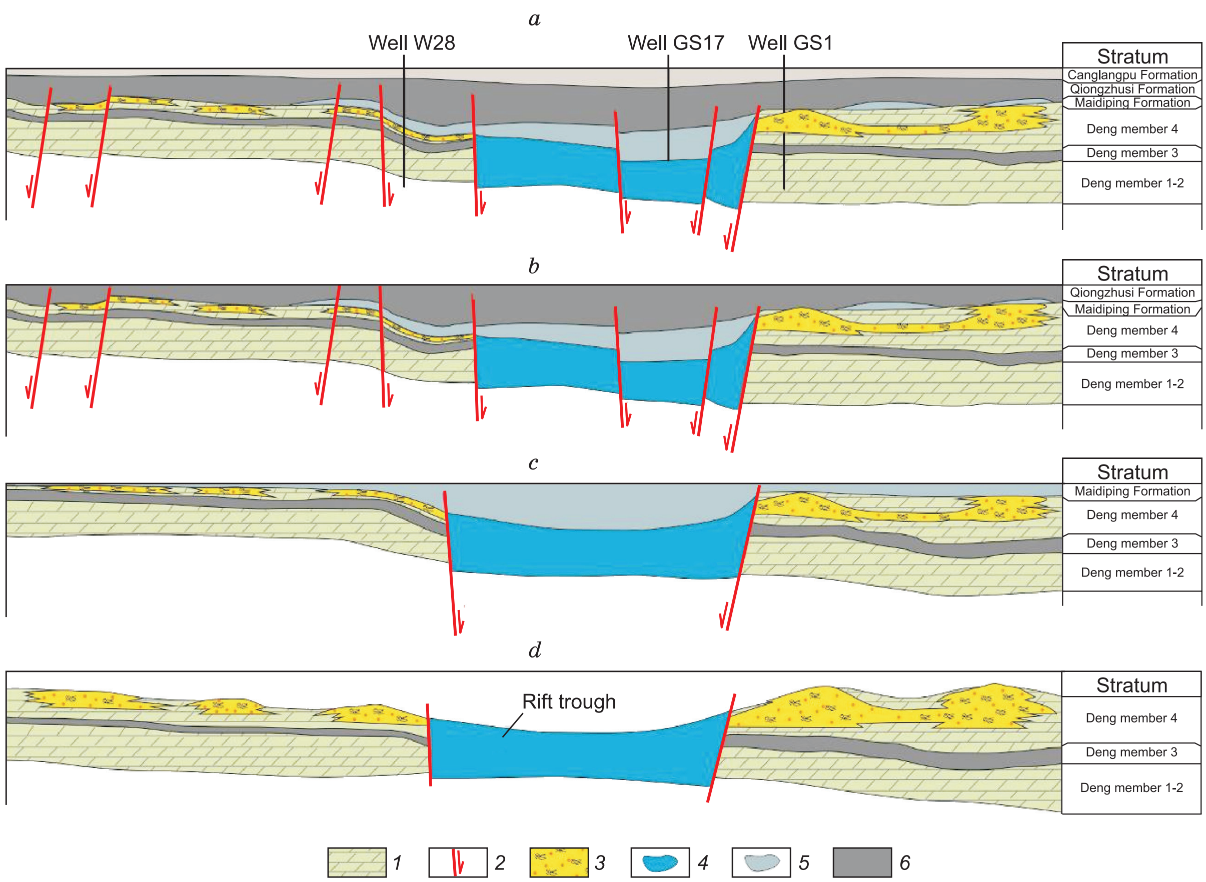

Fig. 4. Evolution model of the Deyang–Anyue intracratonic rift. *1*, dolostone; *2*, fault; *3*, algal mound; *4*, Dengyingzu Formation argillutite; *5*, Maidiping Formation marl; *6*, argillutite.

laceous dolomite with a smaller deposit thickness of 150–300 m. The platform marginal-facies mounds and shoal on the flank of the rift develop a larger thickness of 800–1000 m, characterized by microorganic framework dolostone and grain dolostone. The Dengying Formation in the other areas is platform-facies sedimentation with a thickness of generally 600–800 m.

2.2.2 THE EARLY CAMBRIAN DEVELOPING STAGE OF RIFT

During the sedimentation stage of the Early Cambrian Meishucun Formation, under the influence of regional tensional activities, the boundary fault of the intracratonic rift began its activities again. The thickness of the Maidiping Formation in the rift area can reach 100–200 m, which develops into the slope-basin facies, and its sedimentation areas in the outer ring of the rift develop into the carbonate-platform facies. Well GS17 in the rift area, drilled through the Maidiping Formation for 140 m, indicates slope-basin facies sedimentation with a facies sequences from bottom to top as basin-facies, slope-facies and basin facies, developing carbonaceous-siliceous mudstone argillaceous lamina nodular dolostone, dolomitic quartz sandstone, and carbonaceous-siliceous mudstone respectively (Fig. 5).

During the sedimentation stage of the Early Cambrian Qiongzhusi Formation, the Yangtze area widely developed into shelf-facies clastic rock sedimentation along with the continuous rising of sea level and regional transgression. During this period, the regional tensile activities were strong and the intracratonic rift and adjacent normal fault widely developed. The tectonic activities are characterized by “early rift and late sag”, and the sedimentation response shows early developed rift deep-water shelf facies persiliceous–phosphoric shale and mudstone and middle and late gradually

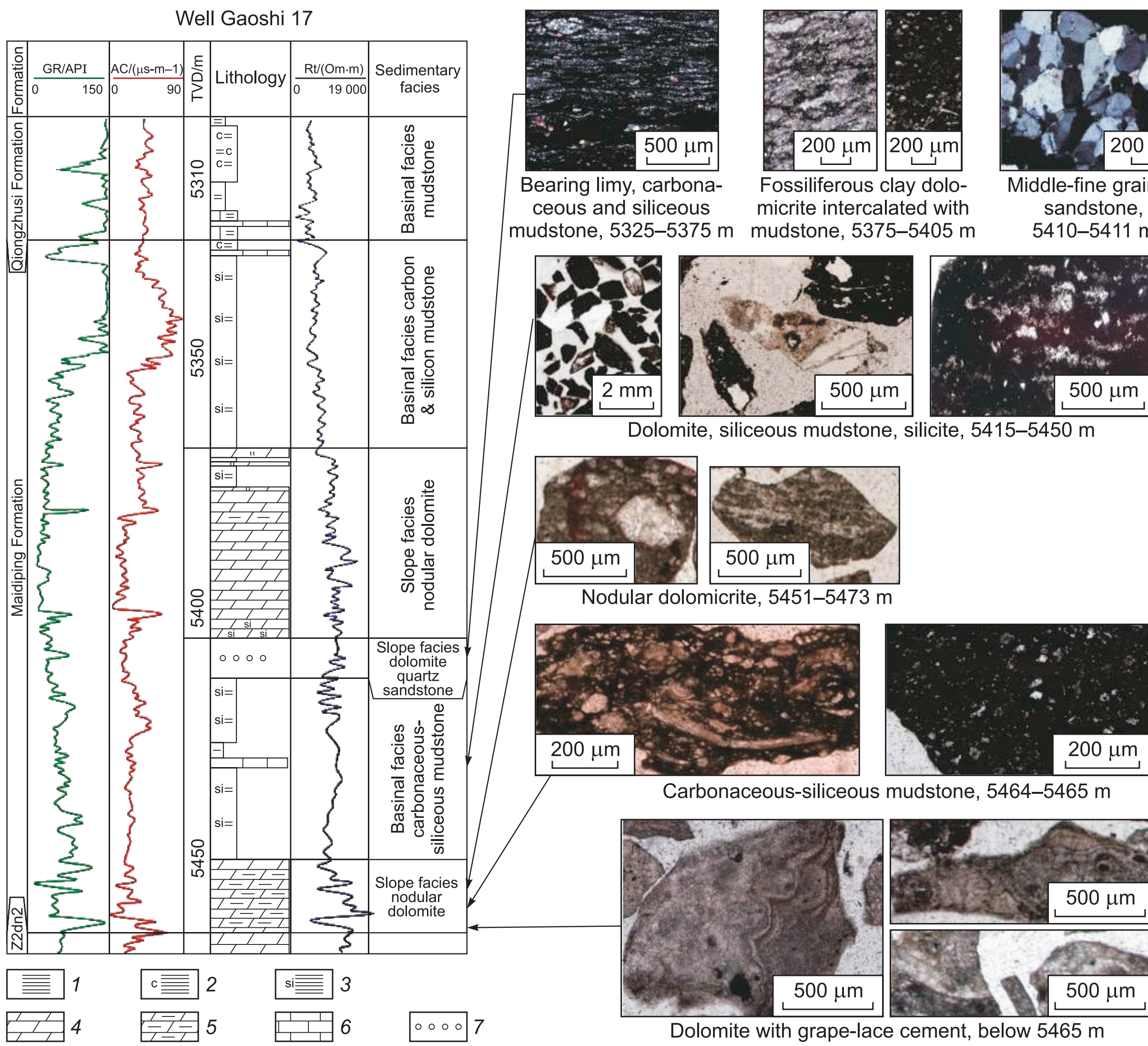

Fig. 5. Sedimentary facies sequences of the Maidiping–Lower Qiongzhusi Formations in Well GS17. *1*, shale; *2*, carbonaceous shale; *3*, siliceous shale; *4*, dolomite; *5*, argillaceous dolomite; *6*, limestone; *7*, sandstone.

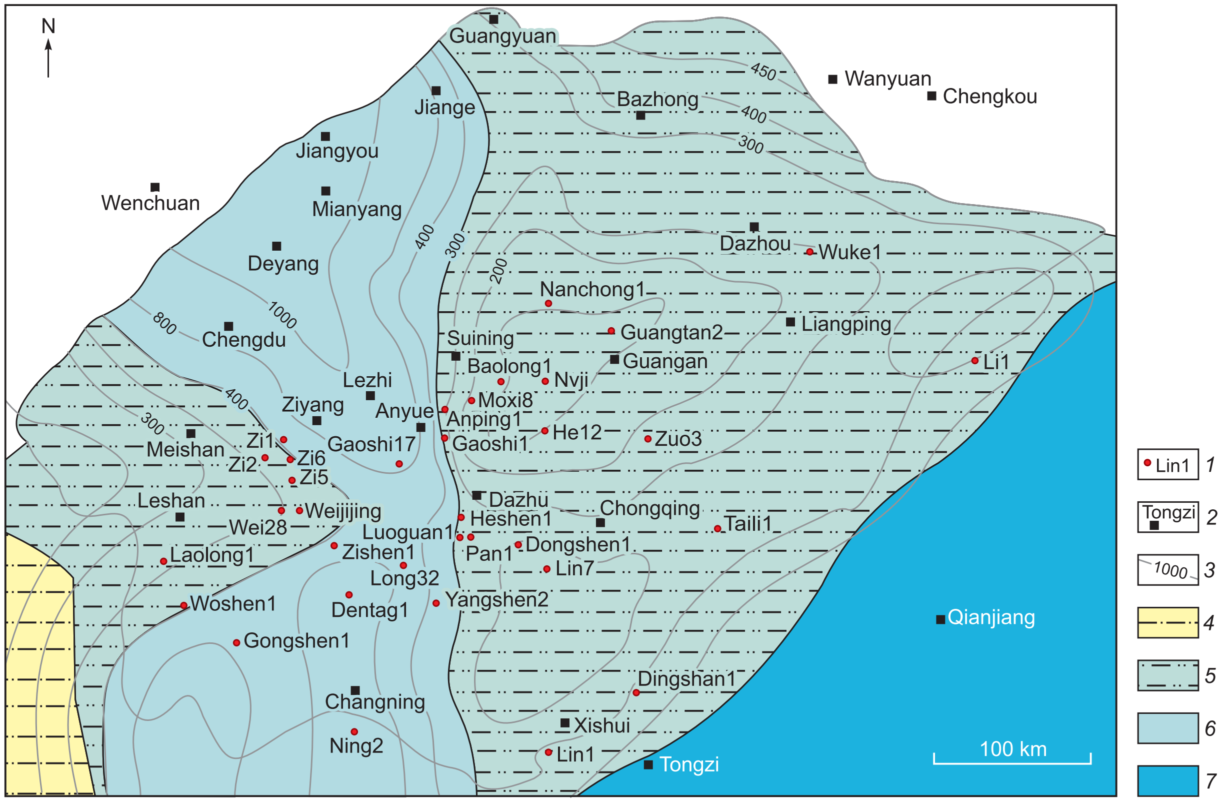

Fig. 6. Lithofacies paleogeography of the Lower Cambrian Qiongzhusi Formation. *1*, well; *2*, place name; *3*, thickness contour of Lower Cambrian Qiongzhusi Formation, m; *4*, littoral facies; *5*, shallow-water shelf facies; *6*, deep-water shelf facies; *7*, shelf-margin facies.

developed sag shallow-water shelf facies sandy mudstone. On the plane, the rift area westward passes through delta facies fine sand stone and eastward passes through shallow-water shelf facies argillaceous rock (Fig. 6).

2.2.3 THE MIDDLE AND LATE EARLY CAMBRIAN DYING STAGE OF RIFT

The study of regional structure shows that the middle and late Early Cambrian is an important period for structural transformation of the Upper Yangtze craton from early-stage tensile structure to compression structure. Under such influence, paleoland began forming at the west margin of the Upper Yangtze craton, such as the West Sichuan–Central Yunnan Oldland and Hannan Oldland, and became the main source area of terrigenous detritus sedimentation. Also, onshore delta facies sedimentation can be seen at the southwest margin of the Sichuan Basin. Meanwhile, the intracratonic rift gradually died out and began the evolutionary stage of the craton depression.

The dying stage of the Deyang–Anyue rift is the sedimentation stage of the Early Cambrian Canglangpu Formation. The drilling and seismic data indicate that the trend of variation of the Canglangpu Formation stratum in thickness is obviously different from that of the Qiongzhusi Formation stratum characterized "uplift–sag"; it wholly appears that the stratum distribution characteristics are controlled by the paleouplift in Central Sichuan; that is, there is a gradual increase in stratum thickness from west to east and from the paleouplift high member to the slope area. The stratum thickness in the paleouplift is 100–200 m; it is 200–250 m in the slope area; it increases to 300–400 m in the southeast margin and north of Sichuan basin. Being compared to those of the Qiongzhusi Formation, the lithology and lithofacies distribution also have an obvious difference: The former mainly consists of shelf-facies mudstone; the Canglangpu Formation lower member develops into diamictic platform facies mudstone intercalated with limestone, and its upper member develops into shallow-water continental-shelf mudstone intercalated with sandstone. The contrast between Well GS17 and the Moxi–Gaoshiti area drilling shows that the middle part of the Canglangpu Formation generally develops into limestone 30–40 m in thickness with obvious electrical property, distributional stability, and high contrast. It also indicates that the sedimentation during the sedimentation stage of the Canglangpu Formation is no longer under the control of the intracratonic rift, but shows more sedimentation characteristics of craton sag. This paleotectonic framework continues till the Ordovician.

3. CONTROL OF THE RIFT ON THE FORMATION OF ANYUE GIANT GAS FIELD

The Anyue giant gas field is located in the Gaoshiti–Moxi region in the downstructure location of the Central Sichuan paleouplift. Its west is adjacent to the Deyang–Anyue intracratonic rift, and the main target horizon consists of the Dengying and Longwangmiao formations. Studies show that the rift has controls over the reservoir-forming conditions, such as high-quality hydrocarbon source rock distribution, high-quality reservoir distribution in the platform edge of the Dengying Formation, favorable accumulation associations, as well as seal plugging in the updip direction of paleouplifts, and they are key geologic factors controlling the formation of giant gas fields. Note that two paleouplifts formed on both sides of the rift, influenced by partitioning of tongwan period rift stage and late sinian uplifting (Fig. 7). The eastern one was the Gaoshiti–Moxi paleouplift, and the western one was the Ziyang–Weiyuan paleouplift. Therefore, there were three paleogeomorphic units before Cambrian. The two paleouplifts had apparent controls over the later period deposition and uplifting.

3.1. CONTROLS ON THE HYDROCARBON GENERATION CENTER AND PROXIMAL SOURCE PLAY

As controlled by the intracratonic rift, three sets of high-quality hydrocarbon source rocks were developed in the rift: Z_2dn^3 and the Lower Cambrian Maidiping and Qiongzhusi formations. The analysis of the hydrocarbon source rocks with different depositional settings indicates that the thickness, organic carbon contents, and gas generation strength of the hydrocarbon source rocks in the rift are better than those in the neighboring areas. For instance, the thickness of the hydrocarbon source rocks of the Qiongzhusi Formation in the rift reaches 300–450 m, which is 2–3 times that in the neighboring areas; the organic carbon content (total organic carbon–TOC) in the rift is 1.8–2.8%, which is more than twice that in the neighboring areas; now the gas generation strength in the rift reaches $(60\sim140) \times 10^8$ m^3/km^2, which is more than three times that in the neighboring areas (Table 1). This shows that the intracratonic rift controlled the hydrocarbon generation center of Sinian to Cambrian.

As controlled by the segmentation of the intracratonic rift, the play of the Sinian–Lower Cambrian in the Central Sichuan paleouplift can be divided into three units planarly: the Deyang–Anyue taphrogenic trough, the Moxi–Gaoshiti paleohigh, and the Ziyang–Weiyuan paleohigh. There are differences between the play in different units (Fig. 8).

(1) The play of the intracratonic rift takes Z_2dn^1–Z_2dn^2 and the Longwangmiao Formation as reservoirs. The former is the “upper source–lower reservoir” play, and the latter “lower source–upper reservoir” play.

(2) Three sets of reservoirs (Longwangmiao Formation, Z_2dn^4, and Z_2dn^1–Z_2dn^2) are developed in the Moxi–Gaoshiti paleohigh. The Dengying Formation has the “upper source–lower reservoir”, “lower source–upper reservoir”, and “side source–side reservoir” play, with the plane of unconformity as the main migration pathway. The Longwangmiao Formation has the “lower source–upper reservoir” play, where faults are the main migration pathways. The area is close to the hydrocarbon generation center of the intracratonic rift with reservoirs developed and favorable conditions for near-source reservoir formation. The overburden Gaotai Formation of the Longwangmiao Formation with lithology of mudstone and tight carbonate rocks intercalated with salt gypsum consists of the direct cap rocks. The mud-

Table 1. Comparison of source rocks between the intracratonic rift and adjacent areas

Horizon	Evaluation parameter	Region				Note
		Western Weiyuan	Deyang–Anyue rift	Gaoshiti–Moxi–Longnvsi	Eastern Sichuan	
Qiongzhusi Formation	Thickness, m	100 ~ 200	350 ~ 450	150	200	Samples of outcrops from Eastern Sichuan (168) Others are drill core samples (458)
	Organic carbon content, %	0.8 ~ 2.0	1.8 ~ 2.8	0.8 ~ 1.2	0.8 ~ 2.4	
	Gas generation strength, 10^8 $m^3 \cdot km^{-2}$	20 ~ 40	60 ~ 140	10 ~ 20	20 ~ 30	
	Maturity, %	2.0 ~ 2.4	2.0 ~ 2.4	2.0 ~ 3.6	3.5 ~ 4.5	
Maidiping Formation	Thickness, m	0 ~ 25	50 ~ 100	0 ~ 5		Samples are drill cores (46)
	Organic carbon content, %	0.5 ~ 0.8	10 ~ 3.0			
	Gas generation strength, 10^8 $m^3 \cdot km^{-2}$	5 ~ 10	16 ~ 40			
	Maturity, %	2.0 ~ 2.4	2.2 ~ 2.4			
Z_2dn^3	Thickness, m	0 ~ 5	10 ~ 30	10 ~ 20	5 ~ 10	Samples of outcrops from Eastern Sichuan (38) Others are drill core samples (126)
	Organic carbon content, %	0.5 ~ 0.9	1.0 ~ 1.2	0.6 ~ 1.0	0.5 ~ 0.7	
	Gas generation strength, 10^8 $m^3 \cdot km^{-2}$	0 ~ 2	4 ~ 12	4 ~ 6	2 ~ 5	
	Maturity, %	2.0 ~ 2.4	2.8 ~ 3.0	3.2 ~ 3.6	4.0 ~ 4.4	

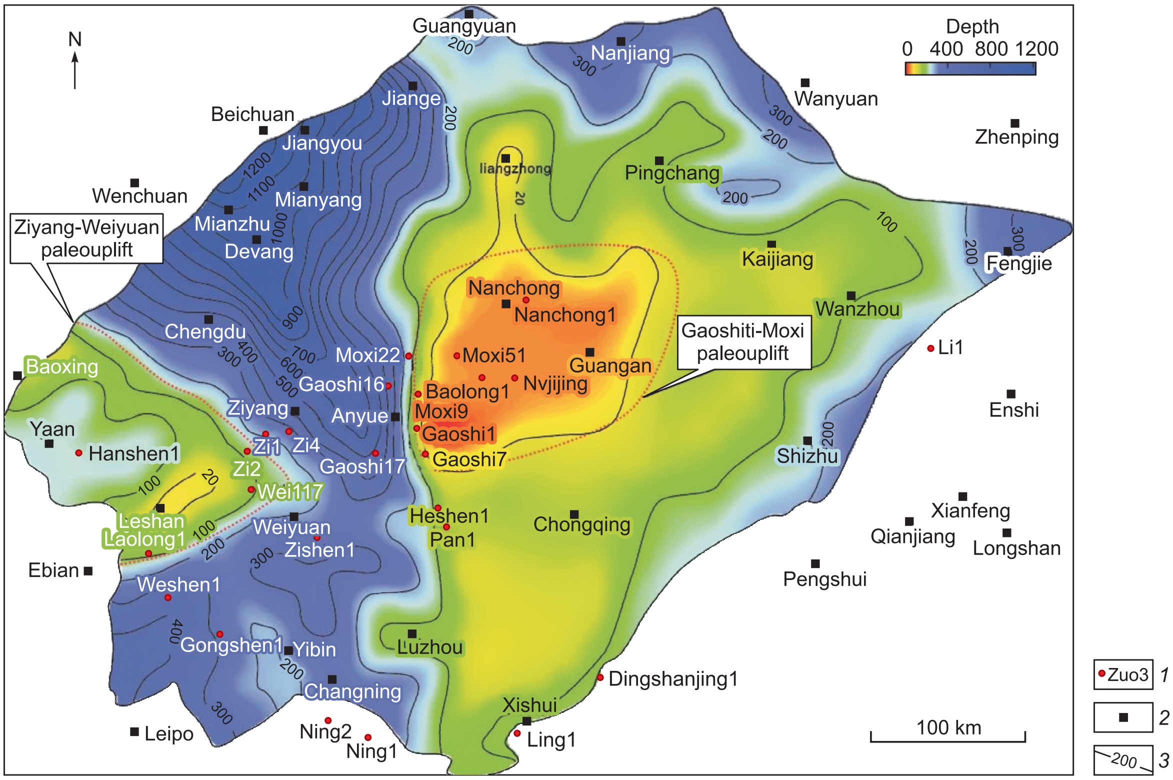

Fig. 7. Paleotectonic structure of the Sichuan Basin before the Cambrian. *1*, well name; *2*, place name; *3*, depth contour.

stone, sandstone, carbonate rocks, and salt gypsum from the Xixiangchi Formation of Cambrian to Triassic System with a thickness of several thousand meters are regional cap rocks with strong sealing capacity. The area is the most favorable for reservoir formation in the Longwangmiao Formation.

(3) The Ziyang–Weiyuan paleohigh experienced violent erosion of the Tongwan and Caledonian movements, with two sets of reservoirs (Z_2dn^1–Z_2dn^2) widely developed. The reservoirs of the Longwangmiao Formation are developed in the Weiyuan region; the Dengying Formation has the "upper source–lower reservoir, lower source–upper reser-

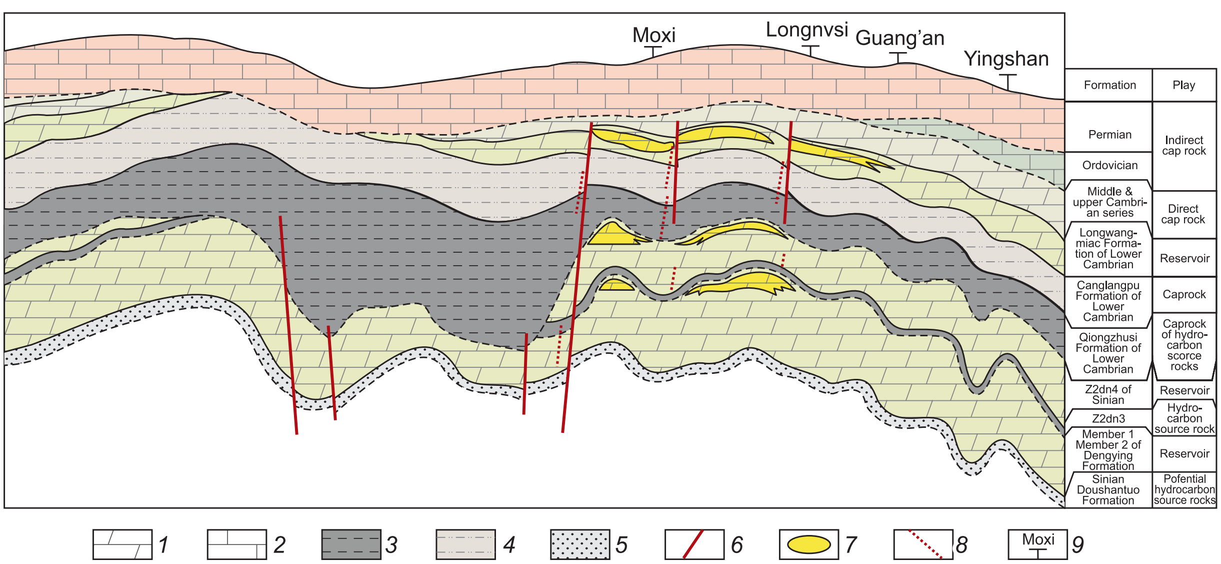

Fig. 8. Hydrocarbon accumulation play of the intracratonic rift and surrounding area. *1*, dolomite; *2*, limestone; *3*, shale; *4*, silty mudstone; *5*, sand mudstone; *6*, fault; *7*, reservoir; *8*, oil and gas channel; *9*, place name.

voir, and side source–side reservoir" accumulation associations, where the plane of unconformity is the main migration pathway. The Longwangmiao Formation has the "lower source–upper reservoir" accumulation association, where the faults are the main migration pathways.

3.2. CONTROLS ON FORMATION OF MOUND BEACH BODIES AND HIGH-QUALITY RESERVOIR DISTRIBUTION IN DENGYING FORMATION

3.2.1. PLATFORM-EDGE MOUND BODIES OF THE DENGYING FORMATION

Studies on sedimentary facies and lithofacies show that the main body of the Dengying Formation in the Sichuan Basin is a carbonate platform with platform-edge mound beach bodies developed along the edges of the platform (Figs. 9, 10), which was constructed by benthic microorganisms (such as viruses, mycoplasmae, rickettsiae, bacteria, actinomycetes, fungi, cyanobacteria, and algae) community and biochemical action constructions (Burne and Moore, 1987; Li et al., 2013). Simultaneously, for the presence of the Deyang–Anyue intracratonic rift in the hinterland of the basin, it resulted in obvious characteristics of sedimentary facies differentiation. Dolomicrite and nodular clay dolomicrite of the relatively deep-water basin facies are developed in the rift, such as Z_2dn^2 in Well Gaoshi 17 and Well Heshen 1 (Fig. 11, *a*). The hanging walls of boundary-controlling fault in both sides of the rift are shallow-water high-energy zones, which formed mound-beach complex bodies with a huge thickness of 650–1000 m and a U-mode distribution reaching 500 km on the plane. The lithology is characterized by microbian framework (such as thrombolite, foam sponge layers, and stromatolite) dolomite and granular dolomite (Fig. 11, *b*, *f*).

On the seismic section, the mound beach bodies in the platform edge are reflected by mound-shaped disordered reflections (Fig. 12) with a large thickness; the basin facies are reflected by layered continuous reflections with a small thickness.

Based on the above understanding, an intracratonic rift trough depositional model for the Sinian Dengying Formation is established (Fig. 13). Compared to the classical depositional models of rimmed platforms (Wilson, 1975; Tucker, 1985), the model takes the intracratonic rift as an axial line with intracratonic lagoon facies behind platform-edge, and open platform facies to half-localized and evaporation plat-

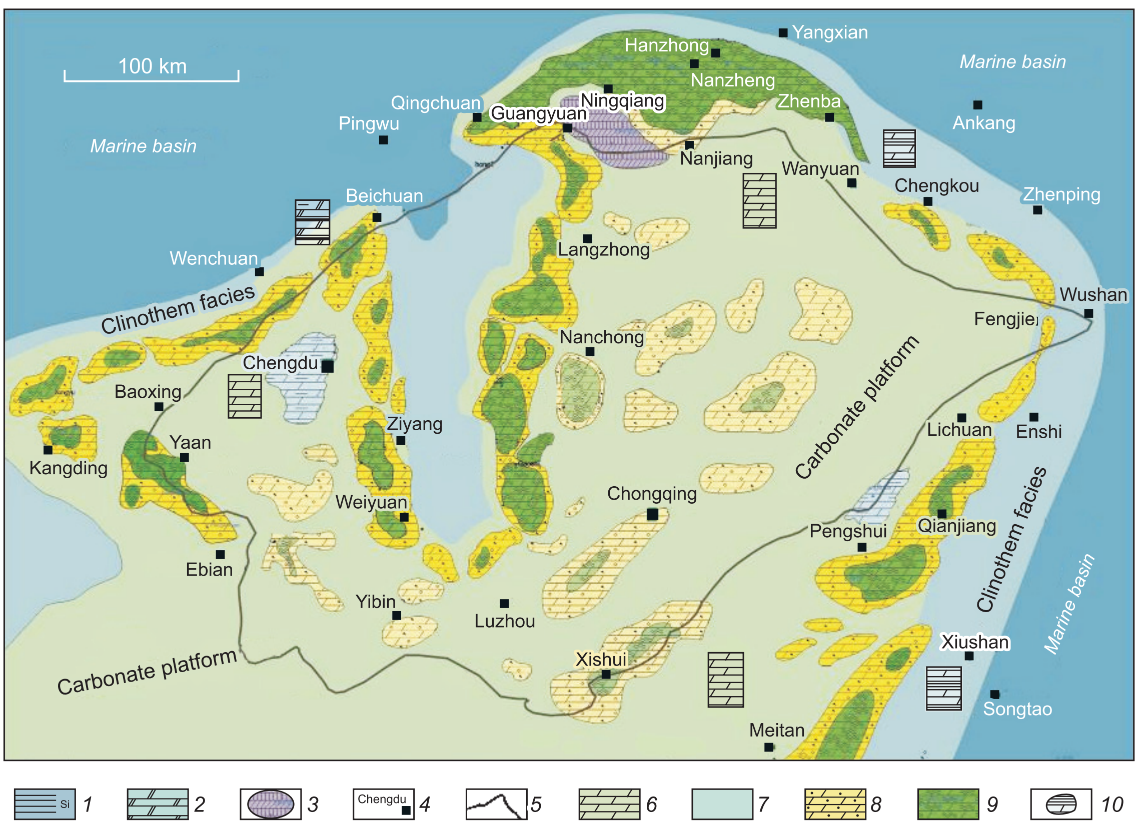

Fig. 9. Lithofacies paleogeography of Z_2dn^4 in the Sichuan Basin and neighboring areas. *1*, basin-facies siliceous shale; *2*, marble with siliceous slate interbed; *3*, evaporative lagoon gypsum-salt rock; *4*, drill site; *5*, basin border; *6*, partly restricted platform dolostone with kiesel bands; *7*, platform-margin slope dolostone with shale interbed; *8*, grain beach ooid doloarenite; *9*, algal-mound stromatolite; *10*, lagoon argilliferous micritic dolostone.

form facies as well as cratonic-margin platform-edge facies developed symmetrically on both sides. Two facies zones of trough-basin and intracratonic platform edge were added. Moreover, the model is different from that of the Changxing Formation of the upper Permian Series in the Sichuan Basin. The former belongs to the buildup of Cryptozoic microbial construction, and the latter belongs to the buildup constructed by Phanerozoic marine invertebrate frame-building organisms (such as sponges) (Du et al., 2010; Ma et al., 2014).

3.2.2. HIGH-QUALITY RESERVOIRS JOINTLY CONTROLLED BY SEDIMENTARY FACIES AND KARSTIFICATION

Weathering-crust karst reservoirs are widely developed in the Sinian Dengying Formation in the Sichuan Basin (Liu et al., 1991; Hou et al., 1999). Recent studies have shown that the platform edge zones by both sides of the Deyang–Anyue intracratonic rift have the characteristics of large reservoir thickness, good physical properties, and high single-good production rates. The formation of this set of high-quality reservoirs was controlled by both factors of sedimentary facies and karstification, characterized by the significantly better reservoir of the platform-edge mound beach body facies than the intraplatform facies zone. The reservoirs of the mound beach body facies mainly consist of algal clot dolomite, (algal) dolarenite, and algal stromatolite dolomite. The storage space is mainly of fracture and cavity type and fracture-solution cavity type with a thickness of 60–180 m and a porosity of 3.8–6.0%; the intraplatform facies zone is mainly of laminar algal dolomite and argillaceous dolomite with an average porosity of smaller than 2.0%, and the reservoir thickness is mainly 30–70 m.

Studies have shown that the benthic microbial community (such as spherical, silky, and foam sponge layer microorganisms) deposited in the depositional stage of the Dengying Formation and their biochemical actions could have built frameworks and pores (Fig. 14), which established a foundation for the formation of primary pores in the effective reservoirs of mound beach bodies. Large mound-beach complex bodies in rows and belts are developed in the platform edge (with a total thickness of more than 400 m). The primary pores, fractures, and caves are extremely developed. The uplifting and erosion of the Tongwan movement which occurred thereafter formed two planes of unconformity on the tops of Z_2dn^2 and Z_2dn^4. Fresh water in the atmosphere dissolved and enlarged the microbial framework pores, thrombolite framework pores, and granular rock intergranu-

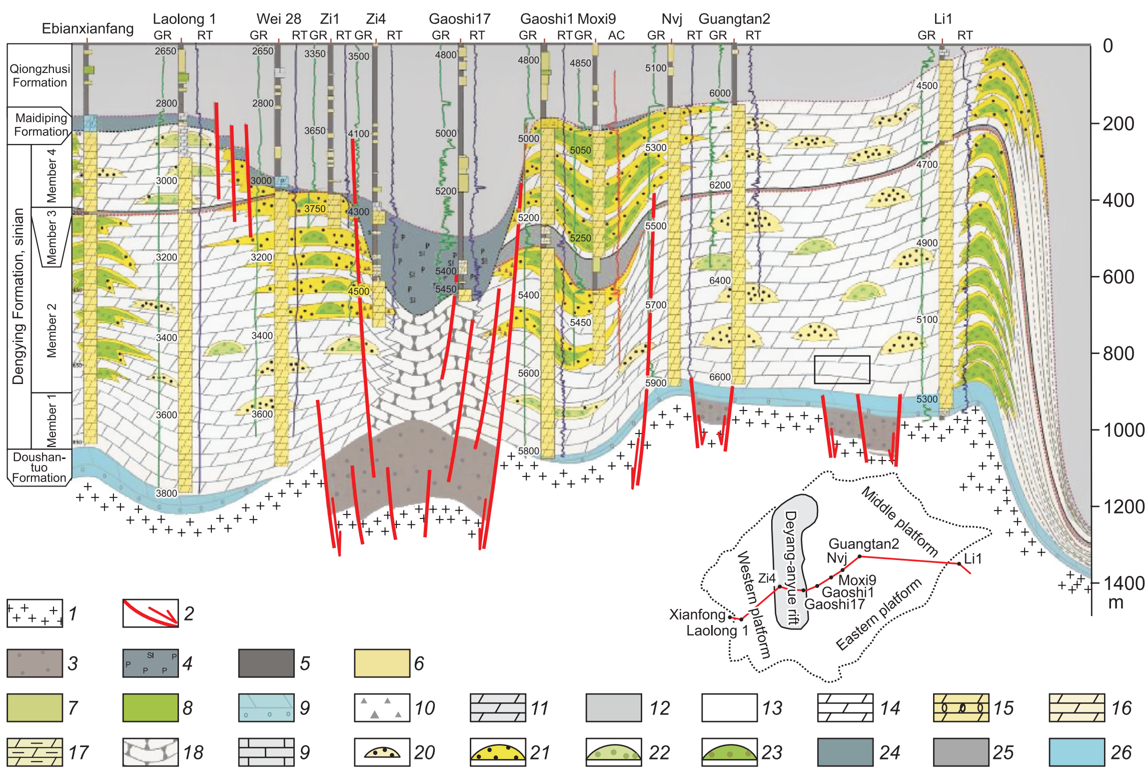

Fig. 10. Integrated outcrop-well-seismic deposition profile of the Dengying–Qiongzhusi Formations. *1*, basement; *2*, fault; *3*, coarse clastic rift infill; *4*, siliceous and phosphoric dolomitic mudstone; *5*, mudstone; *6*, silty mudstone; *7*, argillaceous siltstone; *8*, siltstone; *9*, phosphoric dolostone; *10*, slump deposits; *11*, limy dolomite; *12*, Qiongzhusi Formation; *13*, Members 1, 2, and 4 of the Dengying Formation; *14*, dolomite; *15*, breccia dolomite; *16*, siliceous dolomite; *17*, argillaceous dolomite; *18*, knobby dolomite; *19*, limestone; *20*, intraplatform beach; *21*, platform-margin beach; *22*, intraplatform mound; *23*, platform-margin mound; *24*, Maidiping Formation; *25*, Member 3 of the Dengying Formation; *26*, Doushantuo Formation.

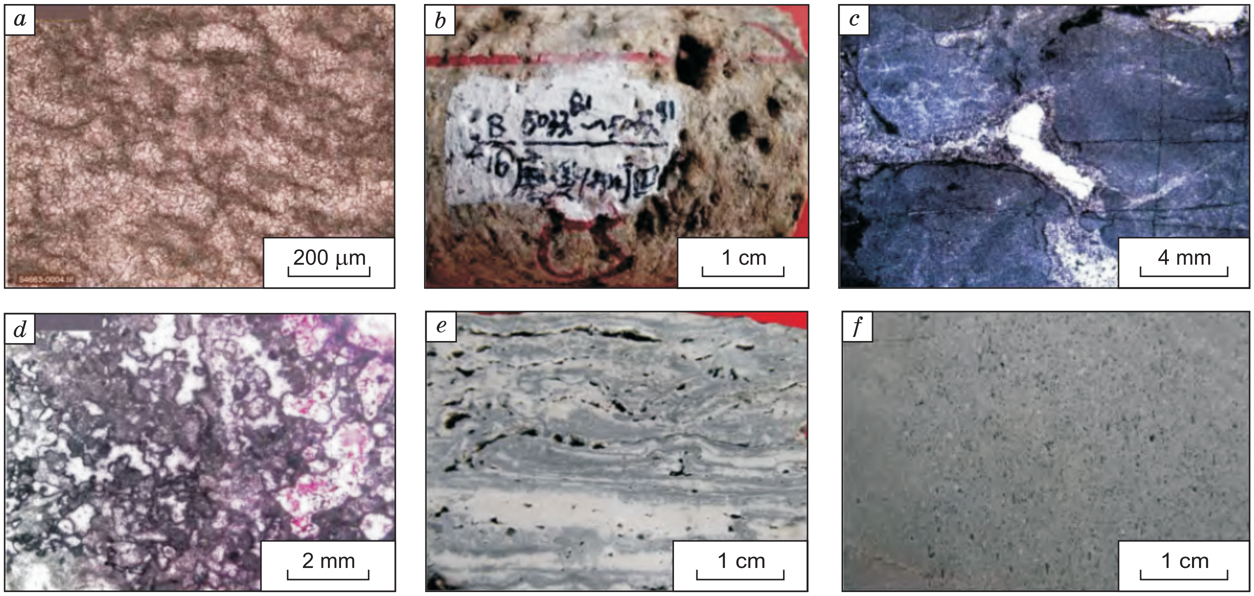

Fig. 11. Lithology, depositional features, and storage space types of the Dengying Formation, Sichuan Basin. *a*, Nodular clay dolomicrite, no reservoir, Z_2dn^2. A single polar core thin section of samples from 5465 m in well Gaoshi17; *b*, clotted limestone framework dolomite with framework-dissolved pores developed. Upper Z_2dn^4, Well Moxi 9; *c*, clotted limestone framework dolomite with framework-dissolved pores developed, Z_2dn^4. A single polar core thin section of samples from 5032 m in Well Gaoke 1; *d*, sponge framework dolomite with framework dissolution pores developed, Z_2dn^2. A (pink) casting body single polar core thin section of samples from 5446 m in Well Gaoke 1; *e*, stromatolite–crypt algal laminite framework dolomite with bedding-dissolved pores developed, Z_2dn^4; samples from the depth of 5158 m in Well Gaoke 1; *f*, dolarenite with dissolution pores developed, Z_2dn^2. Samples from the depth of 4533.1 m in Well Zi4.

lar pores in the dolomite of the Dengying Formation, which was the key factor for the formation of the effective reservoirs in that formation. In the exposure leaching-out period, the tops of mound beach bodies and wings of close rift in the platform edge were exposed to the surface, suffering erosion and eluviation of freshwater in the atmosphere, showing strong denudation. According to statistics in drilling information, the depth with influence of denudation in the mound beach bodies in the platform edge might be 200–360 m, whereas the depth with karstification in the platform is generally less than 100 m. Therefore, the distribution of high-quality reservoirs in the Dengying Formation has the characteristics of zonal distribution in the platform edge. According to seismic data prediction, the area of high-quality reservoir distribution in the platform edge of Z_2dn^4 in the eastern side of the Anyue–Deyang rift is about 2500 km^2.

3.3. CONTROLS ON LARGE STRUCTURAL-STRATIGRAPHIC COMPLEX TRAPS IN DENGYING FORMATION

The plane of unconformity formed by the Tongwan movement is widely distributed in the Sichuan Basin and neigh-

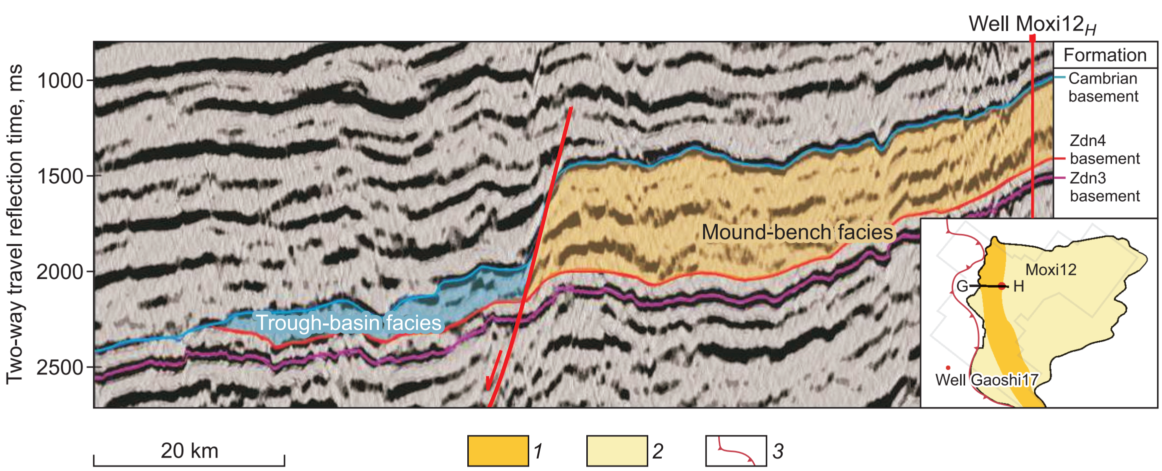

Fig. 12. Seismic section of the trough basin and platform marginal mounds and shoals beside the intracratonic rift of the Dengying Formation. *1*, platform edge; *2*, gas range; *3*, strata pinching-out line.

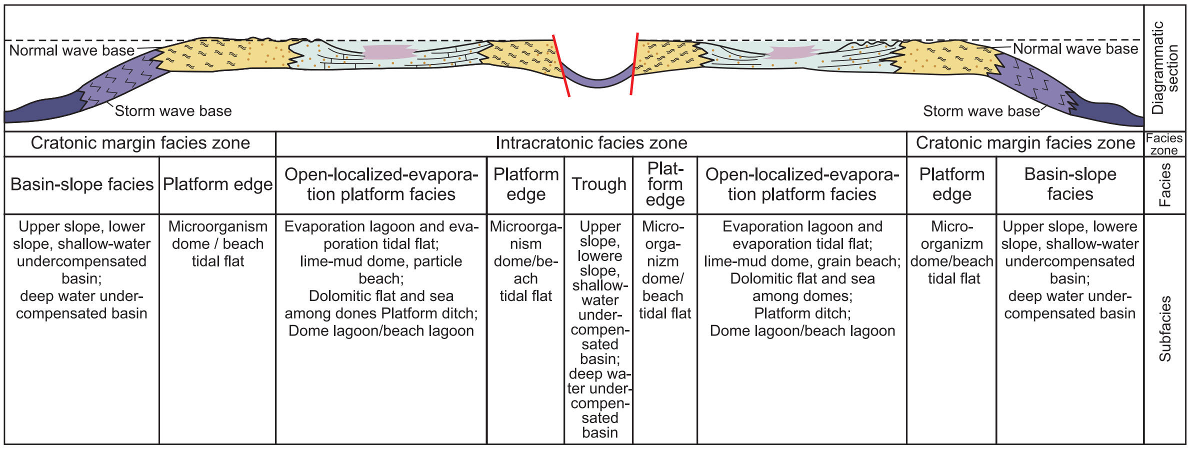

Fig. 13. Depositional model of the intracratonic rimmed platform of the Dengying Formation in the Sichuan Basin and surrounding area.

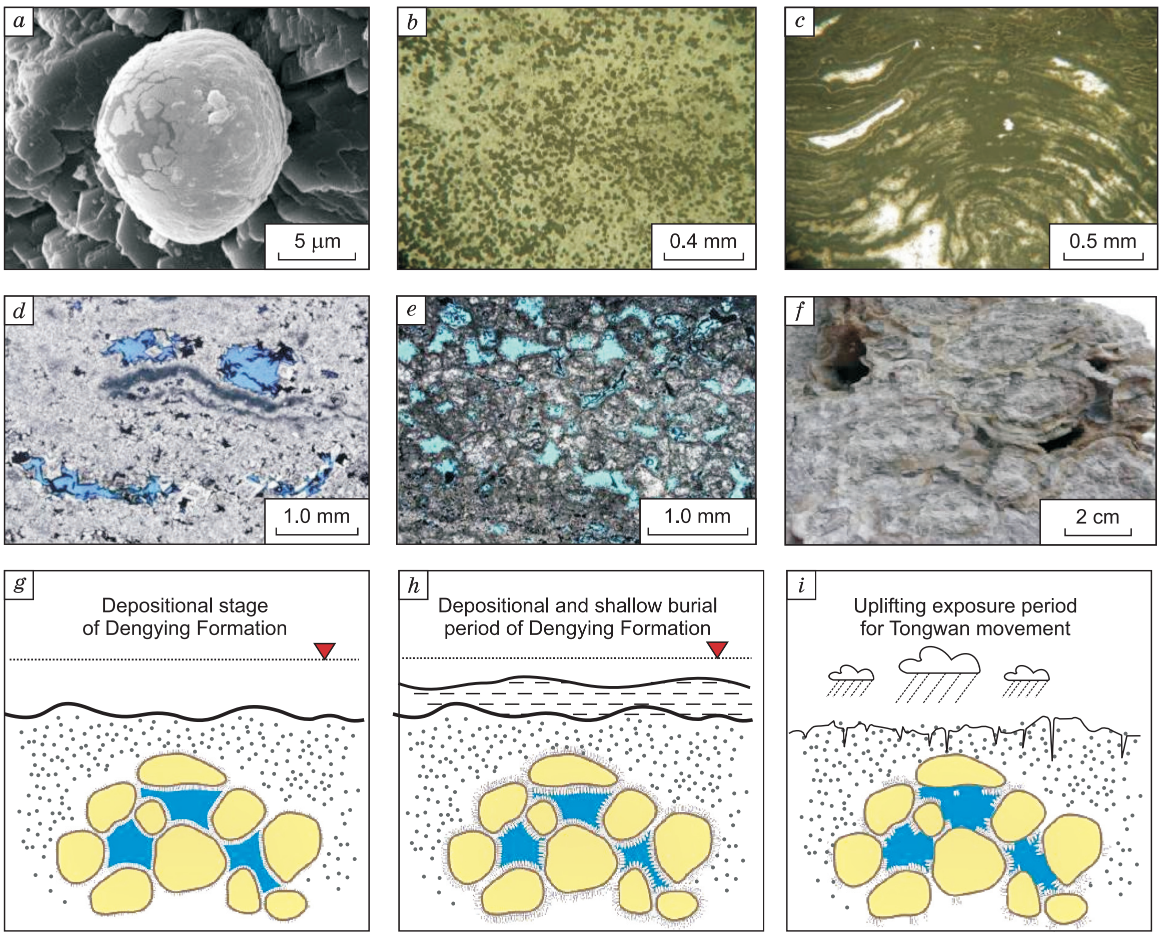

Fig. 14. Proof of microorganism frame pores and pore evolution in the Dengying Formation in the Central Sichuan exploration area in the Sichuan Basin. *a–c*, Microorganism proofs: *a*, bacteriogenic dolomite, Z_2dn^2, Xianfeng section, SEM; *b*, dolomite silicite containing spherical microorganisms, Z_2dn^4, Xianfeng section; *c*, laminated silky cyanobacteria microbial mat, Z_2dn^2, Xianfeng section. *d–f*, Proof of microorganism frame pores: *d*, silky cyanobacteria microbial mat frame pores. For strong dolomitization, only traces of the cyanobacteria microbial mat are left, Z_2dn^4, the samples were from the depth of 4967.10 m in Well Gaoshi 1, a (blue) casting body single polar core thin section; *e*, foam sponge layer microorganism frame pores, Z_2dn^2. The samples were from the depth of 5393.65 m in Well Gaoshi 2; *f*, microorganism genesis clotted limestone frame pores, with centimeter-level clotted limestone and framework fractures and caves developed, Z_2dn^2, Ebian Xianfeng section; *g–i*, Pore evolutionary proofs: *g*, in the process of sedimentation, it was half-filled with cement of subsea fiberlike rim dolomite cement. Primary pores were formed and kept; *h*, in the early diagenetic stage of shallow burial depth, it was filled with prismatic dolomite again; *i*, As the exposure erosion resulted from the Tongwan movement, mound beach facies-controlled karst reservoirs were formed with layered or quasi-layered distribution for the dissolution and enlargement of primary pores by fresh water in the atmosphere.

boring areas. The karst reservoirs of the Dengying Formation are developed below the plane of unconformity. The overburden formation of the plane of unconformity is a set of Lower Cambrian high-quality argillaceous cap rocks. Both of them are favorable for the formation of a stratigraphic trap. As controlled by the intracratonic rift, large structural-stratigraphic complex traps are developed in the platform edge of the Dengying Formation at the flank of the rift. According to the 3D seismic data interpretation for the Moxi–Gaoshiti, the west boundary of the complex trap atop the Sinian is blocked by the mudstone of the Qiongzhusi Formation; in the other directions, the –5010 m contour line is taken as a closed structural line with a trap amplitude of 370 m and a trap area of 3474 km^2. Beyond the closed structural line, gas source shows were obtained from Z_2dn^4 in multiple exploratory wells. Calculating according to the depth of the gas–water boundary of Z_2dn^4 in Well Moxi22 in the north of the trap, the gas-bearing area is 7500 km^2, and the gas column height is 590 m, both larger than the same circle area and trap amplitude (Fig. 15), which indicates that the gas reservoir of Z_2dn^4 in Moxi–Gaoshiti was controlled by the structural-stratigraphic complex trap.

3.4. CONTROLLING HYDROCARBON ACCUMULATION AND PRESERVATION

Paleotectonic reconstruction indicates that the development of the Central Sichuan paleouplift during the Tongwan tectonization was affected by two isolated paleohighs segmented by the NNW-trending intracratonic rift. Its formation was related to the buildup of the mound beach bodies in the platform edge in the depositional stage of the Dengying Formation. The Caledonian movement at the end of the middle Paleozoic formed NEE-trending paleouplifts. The overlapping of the second-phase paleostructures formed paleouplifts of the composite type, which experienced a long-term stable inherited development in the Hercynian–Yanshanian; with fast uplifting of the Weiyuan anticline in the Himalayan Period, the Central Sichuan paleouplift evolved into a large noselike structure high in the west and low in the east. The tectonic axis is located in the line of Weiyuan–Gaoshiti–Guang'an. The Gaoshiti–Moxi region is the low position of the large noselike structure.

Reservoir formation history analysis indicates that reservoir formation for the hydrocarbon of the Sinian–Cambrian in the Central Sichuan paleouplift experienced three stages: during the Permian–Middle Triassic, the paleoreservoir was formed (with a homogenization temperature of inclusions of 100–160 °C); during the Late Triassic–Cretaceous, it was a crude oil pyrolysis gas reservoir-forming period (with the homogenization temperature of inclusions of greater than 160 °C); during the Neogene, it was a period of gas reservoir adjustment and alteration.

The formation in the Gaoshiti–Moxi region was developed stably on a long-term basis. It is the most favorable region for hydrocarbon migration and accumulation. In the

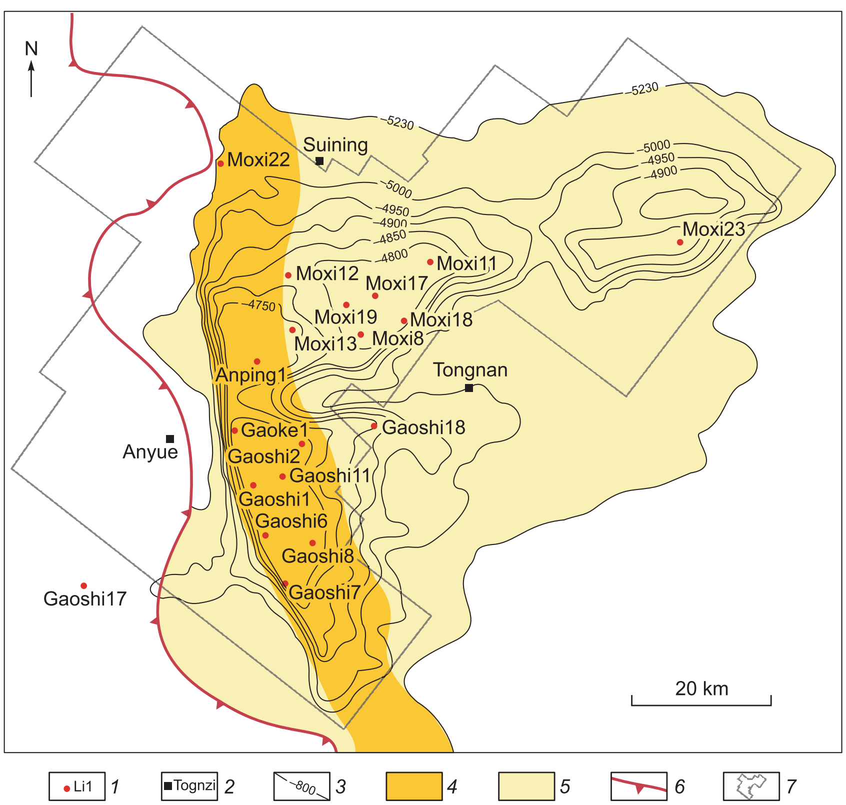

Fig. 15. Structural-stratigraphic trap and gas-bearing scope in Member 4 of the Dengying Formation, Gaoshiti–Moxi area. *1*, well drilled; *2*, place name; *3*, elevation contour, m; *4*, platform edge; *5*, gas range; *6*, strata thinning-out line; *7*, 3D seismic survey work area.

period of massive hydrocarbon generation, the liquid hydrocarbon generated by the hydrocarbon source rocks in the intracratonic rift migrated and accumulated in the Gaoshiti–Moxi region at the high position of the paleouplift through the unconformity surface and fault surface. As blocked laterally by the mudstone with a huge thickness in the rift, a large paleoreservoir was formed. It can be conjectured from the asphalt distribution the distribution range of paleoreservoirs. The reservoir bitumen content of Dengying Formation is 1.7–6.6%, and the distribution area of the paleoreser-

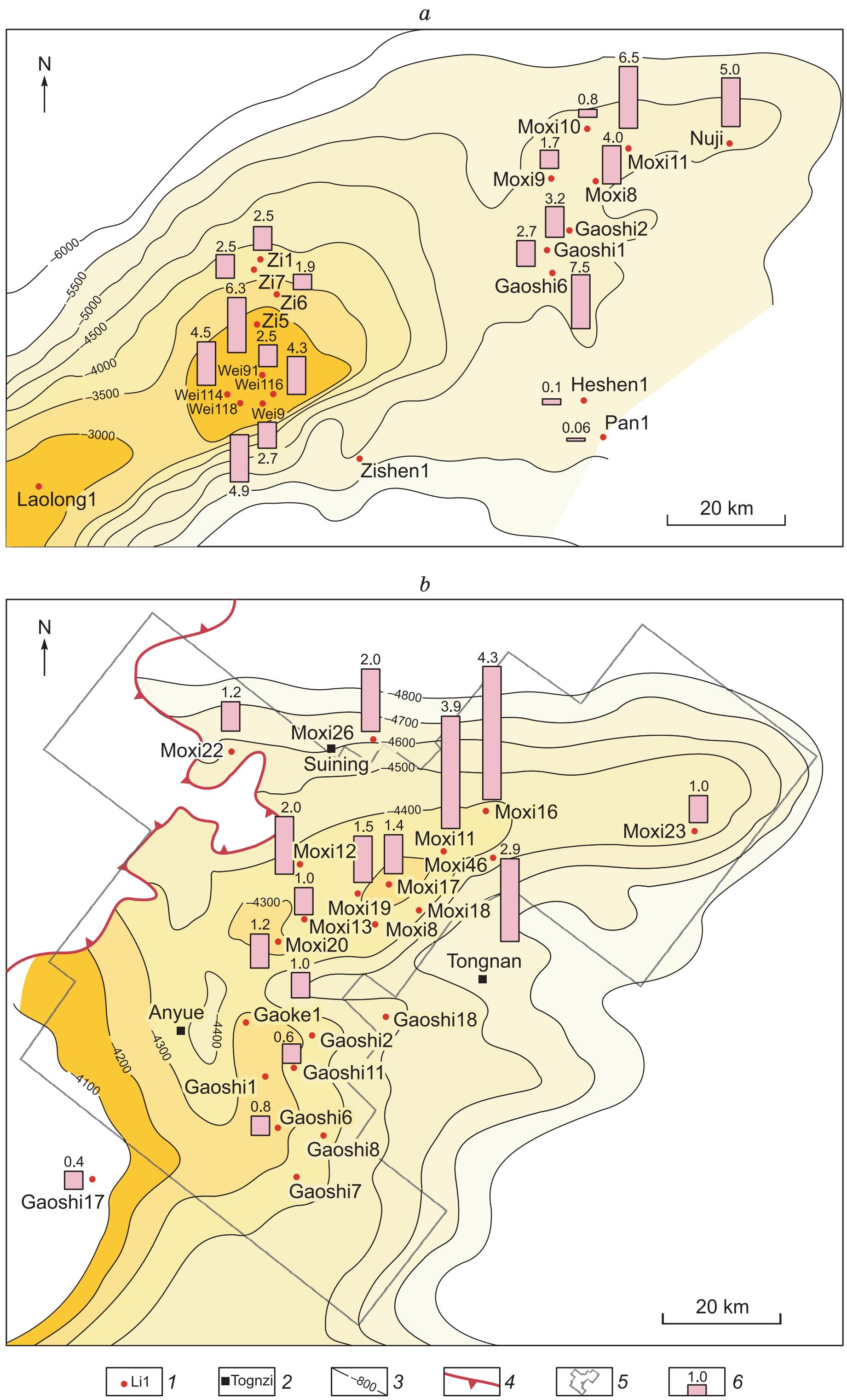

Fig. 16. Bitumen content and distribution of ancient oil reservoirs in the middle Sichuan paleouplift. *1*, well drilled; *2*, place name; *3*, depth contour, m; *4*, strata thinning-out line; *5*, 3D seismic survey work area; *6*, asphalt content.

voir is greater than 5000 km^2; the reservoir bitumen content of the Longwangmiao Formation is 0.9–4.3%, and the distribution area of the paleoreservoir is greater than 4000 km^2 (Fig. 16). During the Late Triassic, with the deposition of the Xujiahe Formation, the burial depth of the Sinian–Cambrian in the Central Sichuan paleouplift was increased, and the formation temperature reached 160 °C. By the end of the Cretaceous, the formation temperature had reached above 200 °C. In that period, kerogen and liquid hydrocarbon (including the paleoreservoir) went into a massive hydrocarbon generation to form a paleo-gas reservoir. In the late Cretaceous–Himalayan period, the formation was fast uplifted in the Weiyuan region; a large noselike structure with the features of a high in the west and a low in the east was formed in the Central Sichuan paleouplift, taking the Weiyuan anticline as high spots. The lateral sealling of mudstone in the rift prevented migration of natural gas to the Weiyuan direction effectively, making the natural gas reservoir in the Gaoshiti–Moxi region preserved.

CONCLUSIONS

(1) The Deyang–Anyue intracratonic rift in the Sichuan Basin was the product of regional extension activity during the Late Sinian–Early Cambrian, which experienced three stages of evolution. The sedimentary fill in the taphrogenic trough was controlled not only by the taphrogenic trough but also by the regional sedimentary environment. Under the sedimentary settings of a carbonate platform, trough-facies nodular dolomicrite was deposited and filled in the taphrogenic trough with a small depositional thickness, showing an obvious difference from that of the thick layered mound beach bodies in the flank; under the sedimentary settings of a clastic rock shelf, argillaceous rocks with a large thickness were filled in the taphrogenic trough, showing an obvious contrast with the thinner argillaceous rocks in the flank.

(2) The Deyang–Anyue intracratonic taphrogenic trough played a controlling role for the reservoir-forming conditions of the Sinian–Cambrian Anyue giant gas field, mainly reflected in controlling the hydrocarbon generation center, the distribution of mound beach bodies in the platform edge, near-source play, and structural-stratigraphic complex traps as well as blocking hydrocarbon from migrating and accumulating and dissipating in the updip direction at high positions in the paleouplift.

(3) The areas around the intracratonic rift are favorable places for deep stratum exploration in the craton basin in the future.

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