

# Study on Development Characteristics and Reservoir Formation Model of Lower Ordovician Reservoirs in Central Sichuan

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**Abstract.** Sichuan Basin is a large superimposed petroliferous basin, which has experienced multi-stage extension-convergence cycle and has great potential of oil and gas resources. In recent years, the lower combination oil and gas exploration in the middle Sichuan area has made great breakthroughs in the Sinian Dengying Formation and the Lower Cambrian Longwangmiao Formation, but has not achieved good results in the Ordovician. At present, a number of Wells in the middle Sichuan area show varying degrees of oil and gas in the Lower Ordovician strata, suggesting that the Ordovician strata in this area have the basic conditions for the formation of large-scale oil and gas reservoirs. However, no consensus has been reached on the paleogeographic pattern of Ordovician lithofacies and the distribution of favorable facies zones in this area, and the understanding of reservoir types and reservoir properties is quite different. Therefore, the weak basic research on the geological conditions of reservoir formation has severely restricted the hydrocarbon exploration of the Ordovician in this area. In this paper, the Lower Ordovician lithofacies paleogeography reconstruction and reservoir characteristics analysis are carried out by systematically combing the drilling and field profile data in the central Sichuan area, combined with core observation, thin section identification and reservoir analysis, and finally the Ordovician oil and gas accumulation model is established. The results show that the lithofacies paleogeography distribution of the Lower Ordovician Tongzi-Honghuayuanstage in the central Sichuan area is from the paleo-uplift to the east in the order of platform tidal flat to platform shoal to limited platform. The Lower Ordovician reservoir types in the middle Sichuan area include karst reservoir and dolomite reservoir, among which the karst reservoir is heavily filled and the reservoir performance is limited. The Ordovician reservoir-forming model in the middle Sichuan area reveals a new exploration model of dolomite superimposed bedding under karst in the epicontinental platform, which provides important geological basis for the new breakthrough of Ordovician oil and gas exploration.

**Keywords:** Karst reservoir; Dolomite reservoir; Reservoir forming model; Lower Ordovician Series; Middle Sichuan region.

## 1. Introduction

The Marine strata of Sichuan Basin is rich in oil and gas resources, and the carbonate rocks are about 3000-5000m thick. It has many advantages, such as good hydrocarbon source conditions, multiple reservoir series, multiple reservoir assemblages, and wide regional cap layers. It also faces many problems, such as large burial depth, strong structural transformation, poor reservoir physical properties, and high development cost. Since the beginning of the 21st century, remarkable achievements have been made in Marine carbonate oil and gas exploration in Sichuan Basin. Several large Permo-Triassic gas reservoirs have been discovered successively in Puguang, Longgang and Yuanba. In recent years, the dolomites of the Canglangpu and Longwangmiao formations of the Cambrian in central Sichuan have regenerated high-yield industrial gas flows, respectively, which marks another important discovery of new strata in the Lower Paleozoic Marine carbonate field. However, compared with the rich results of Permian-Triassic, the exploration degree of Lower Paleozoic Marine carbonate rocks in Sichuan Basin is obviously lower.

Previous studies have shown that the Ordovician is a potential successor system for Lower Paleozoic Marine carbonate oil and gas exploration in Sichuan Basin (Guo Tonglou, 2014; Li Boyuan, 2016; Zhang Dianwei et al., 2020). Rich bitumen can be seen in the Ordovician carbonate rock system of Anpingdian-Gaoshiti structure in central Sichuan (Zhao Zeheng et al., 2008; Huang Wenming et al., 2011; Sun Dongsheng et al., 2015), indicating that large-scale oil and gas accumulation had occurred in Ordovician carbonate rocks. The Nyuji and Moshen 1 Wells in central Sichuan gained gas  $3.6 \times 10^4 \text{ m}^3/\text{d}$  and  $4220 \text{ m}^3/\text{d}$  in Tongzi Formation, respectively (Wang Zecheng et al., 2002). The Wells Anping 1 and Gaoke 1 and Hehe 12 also showed gas influx and gas gushing in Lower Ordovician carbonate formations (Wang Zecheng et al., 2002; Chen Zong-Qing, 2010). Although a series of studies have shown that the Ordovician carbonate system has abundant oil and gas, due to the lack of clear understanding of the lithofacies paleogeographic characteristics and reservoir development laws of the Lower Ordovician Series in the middle Sichuan area, no substantial breakthrough has been made in oil and gas exploration, and no large-scale oil and gas reserves have been discovered so far. Based on the typical drilling and profile data in the middle Sichuan area, this paper rebuilds the lithofacies paleogeography of the Lower Ordovician Tongzi Formation and Honghuayuan Formation in this area, defines the reservoir types and development characteristics, establishes the hydrocarbon accumulation model of the Ordovician system, and provides basic data and theoretical support for the next oil and gas exploration in this area.

## 2. Regional Geological Background

Located in the northwest margin of South China Plate, Sichuan Basin is a superposition basin developed on the basis of Yangtze craton after multiple tectonic evolution (Wang Zecheng et al., 2002; Liu Shugen et al., 2011; Wu Saijun et al., 2015). The Ordovician strata are widely distributed in Sichuan Basin. Outcrop drilling and seismic data reveal that the Ordovician strata are fully developed in other areas of the basin except in central, north and southwest Sichuan, where they are missing to varying degrees due to denudation (Huang Fuxi, 2011; Li Jiao et al., 2015; Liu Wei et al., 2017). In addition, the Ordovician was an important period of change in the Caledonian tectonic cycle, and the successive Yunnan movement and Duuniformality movement greatly affected the development degree and distribution law of strata, resulting in diverse lithology, varying thickness and complex contact relations of the Ordovician strata (Ma Yongsheng et al., 2009; Yang Wei et al., 2012; Zhao Kaili et al., 2022).

According to the differences in sedimentary material composition, sedimentary environment, paleontological features and tectonic setting, the Ordovician strata in the Sichuan Basin can be divided into four major petrostratigraphic divisions (Liu Wei et al., 2017), namely, Longmen Mountain, central Sichuan, eastern Sichuan-Northern Guizhou and Hubei Sichuan-Guizhou (FIG. 1a). This research area is located in the central Sichuan area, and the research is mainly carried out based on the actual drilling data of Nanchong 1, Anping 1, Guangtan 2 and Gaoshi 16 Wells, as well as the Liziya and Shizhu Qiliao profiles of Huaying Mountain (FIG. 1b). The lithostratigraphic division scheme of "three series and seven groups" was adopted in the Ordovician strata (FIG. 1c) : The lower Ordovician strata are divided into dolomite of Tongzi Formation and dolomitic limestone or limestone of Honghuayuan Formation, the Middle Ordovician strata are black mudstone laminated thin siltstone or limestone of Meitan Formation, and the Upper Ordovician strata are divided into mudstone shale of Crosspu Formation, limestone of Baota Formation, marl of Linxiang Formation and black shale of Wufeng Formation.

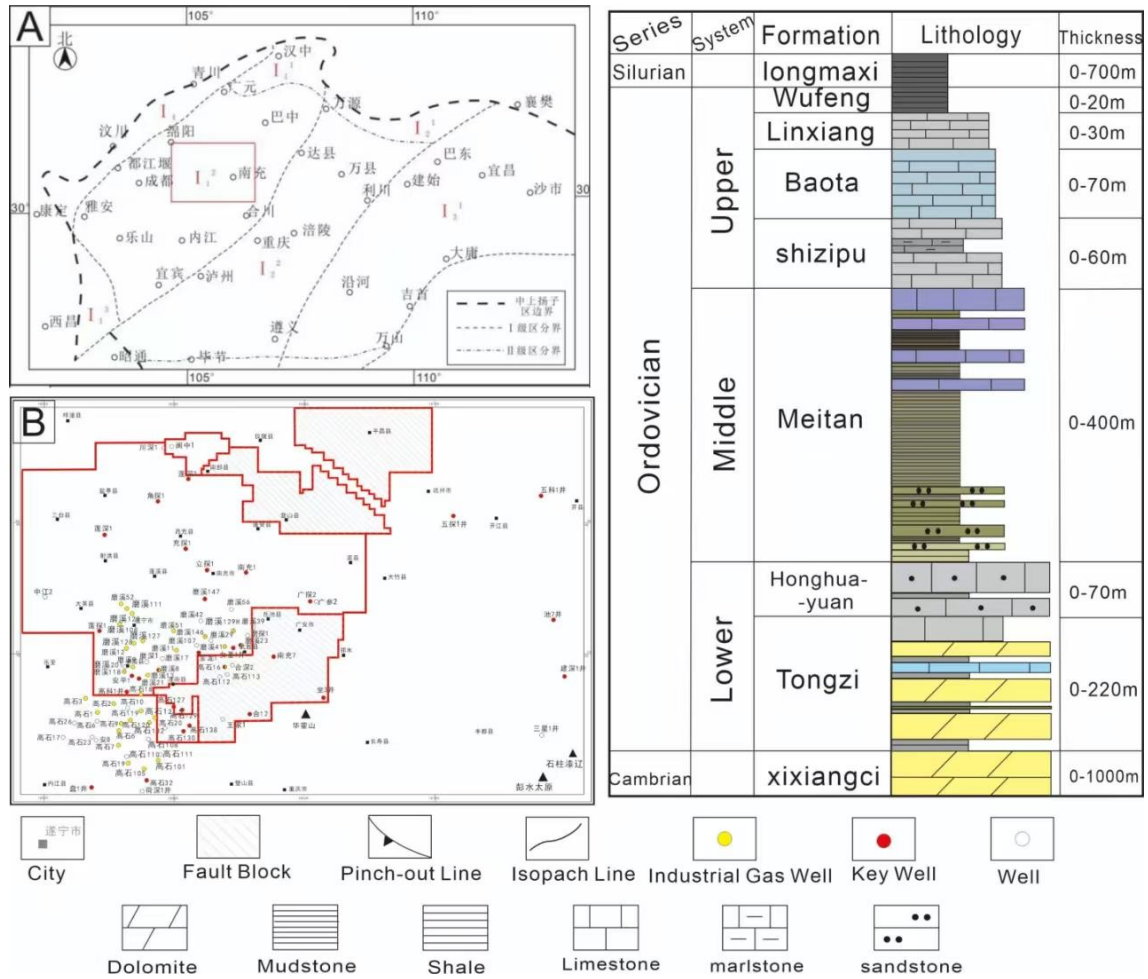


Fig. 1 Ordovician stratigraphic division, distribution of drilling profile and sequence of rock strata in the study area in Sichuan Basin

### 3. Lithofacies Paleogeographic Characteristics of Lower Ordovician

This study of lithofacies paleogeography first defines the lithofacies paleogeographic evolution process of Sichuan Basin from the whole basin scale, and then analyzes the paleouplift changes and the sedimentary facies of more than 30 single Wells in the central Sichuan area in detail (FIG. 1b). The single factor data such as formation thickness, dolomite thickness, limestone thickness and mudstone thickness of Lower Ordovician Wells and sections in the central Sichuan area are counted. Finally, through comprehensive analysis of single factor maps, strata denudation lines, sedimentary facies characteristics, sedimentary evolution and regional paleogeography pattern, the boundary of each sedimentary environment is determined, and the Lower Ordovician lithofacies paleogeography map in central Sichuan is finally compiled, which provides important geological basis for the next step of reservoir distribution prediction.

The Sichuan Basin inherited the carbonate platform pattern of the Late Cambrian during the Tongzi-Honghuayuan Stage of the Lower Ordovician (Guo Tonglou, 2014; Hu Huarui et al., 2019), the distribution of sedimentary facies was obvious. Hannan ancient land, Leshan-Longnusi ancient uplift and Kangdian ancient land developed in the west of the basin, and the sedimentary pattern along the edge of the ancient land was characterized by east-west zonation and north-south distribution. The basin as a whole is dominated by shallow Marine carbonate deposits, and the spatial distribution of lithofacies from west to east is successively shore-tidal flat - limited platform - slope-basin. The spatial distribution of lithofacies in the middle of Sichuan is successively from paleo-uplift to the east as platform tidal flat-internal shoal-limited platform (FIG. 2). The tidal flat facies are mainly developed on the northern flank of the paleo-uplift. The lithology is mainly





#### 4.1 Karst Reservoir

The Caledonian movement after Silurian deposition led to the exposure of Ordovician uplift in the central Sichuan area, and the Ordovician strata developed a ring Caledonian exposed denudation belt along the periphery of the central Sichuan Paleouplift (Huang Fuxi, 2011; Yang Wei et al., 2012; Li Wenjie, 2021), to create favorable geological conditions for the development of karst reservoirs. The core of the Middle and Upper Ordovician has been most seriously denuded, and the karst reservoir development belt of the Lower Ordovician Tongzi Formation and Honghuayuan Formation is distributed around the paleo-uplift in a ring belt.

Previous studies have confirmed that karst reservoirs are commonly developed in Lower Ordovician strata in central Sichuan (Huang Wenming et al., 2011; Zhu Dongya et al., 2015; Sun Dongsheng et al., 2015). Semi-filled vertical dissolution and expansion fractures were found under the unconformity of Tongzi Formation in Nyujijing, and karst caves developed along the fractures. Rich bitumen can be found in the ancient weathering crust reservoir of Tongzi Formation in Gaoke 1 well, and only bitumen or other minerals are often filled in the stratified weathering karst caverns. In Sanquanwan section, Nanchuan, the sedimentary discontinuity of Honghuayuan Formation can be seen under the development of solution holes in bedding (FIG. 3a). Karst caves filled with breccia (FIG. 3b) in Nushen5 Jingtongzi Formation vary in size, with a maximum of 5.9×9.1cm. Coring fractures and caves are developed, and the depth of karst action is greater than 30m. Karst breccia of Anping 1 Jingtongzi Formation is relatively developed (FIG. 3c), vertical cracks can be seen, and karst caves are developed along the cracks.

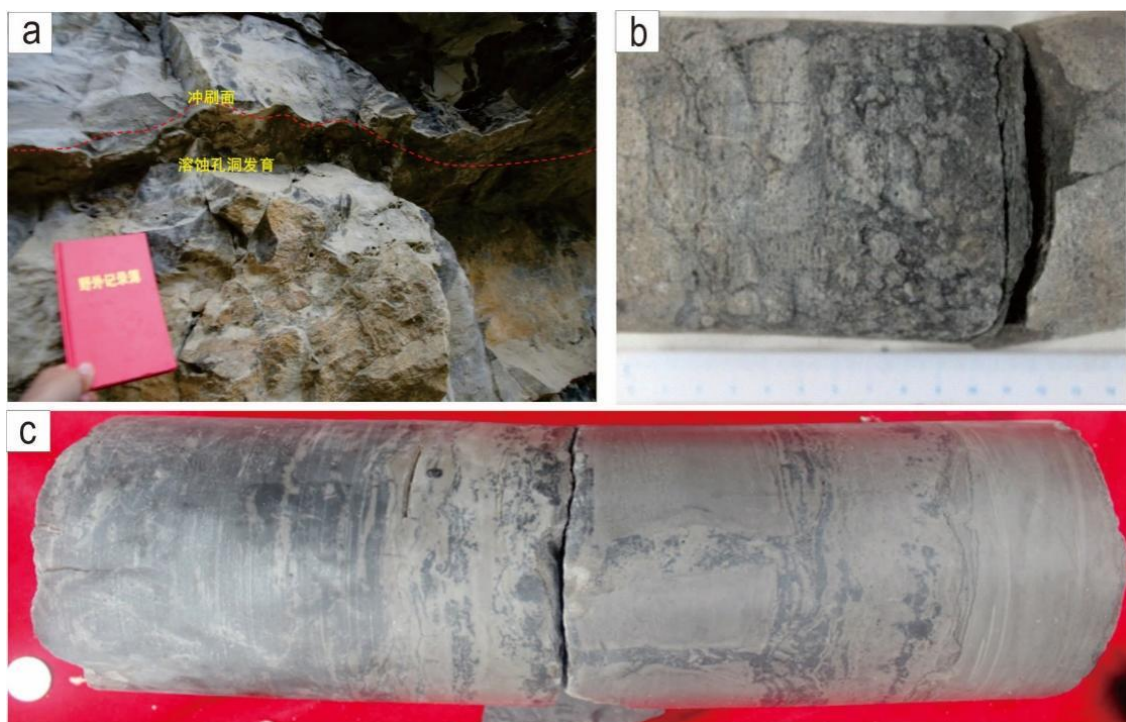
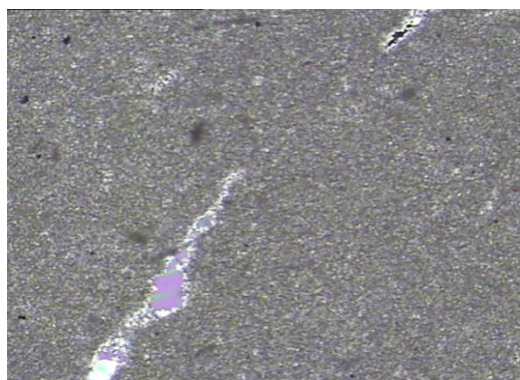


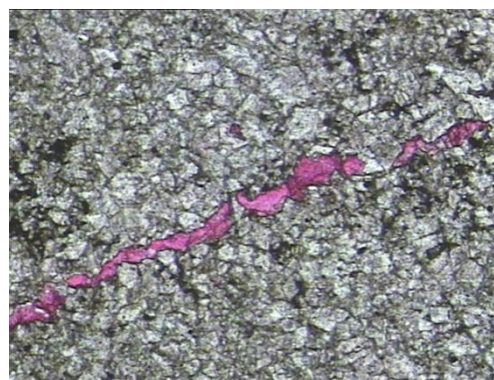
Fig. 3 Lower Ordovician karst characteristics in central Sichuan.

a, Sanquanwan Section, Honghuayuan Formation, karst cave; b, Nushen 5 Jing, Tongzi Formation, Karst breccia; c, Anping Well 1, Tongzi Formation, karst breccia

In addition, a large number of idiomorphic (fine to coarse crystalline) dolomites, bitumen and a small amount of siliceous filling were developed in the dissolution holes and dissolution expansion fractures of the dolomites of the Ordovician Tongzi Formation in the Nyuji Well, He 12 well and Mosheng 1 well distributed around the denudation zone (FIG. 4), which all reveal the widespread existence of Lower Ordovician karst reservoirs in the middle Sichuan region. However, due to the serious karst filling, the reservoir performance of the karst reservoir is relatively general.



(a) The fine powdery dolomite of Tongzi Formation in Well He12 and the dissolution joint are filled with gypsum



(b) Nyujijing, Tongzi Formation powdery dolomite, dissolution joint filled with calcite

Fig. 4 Lower Ordovician karst reservoir characteristics in central Sichuan

## 4.2 Dolomite Reservoir

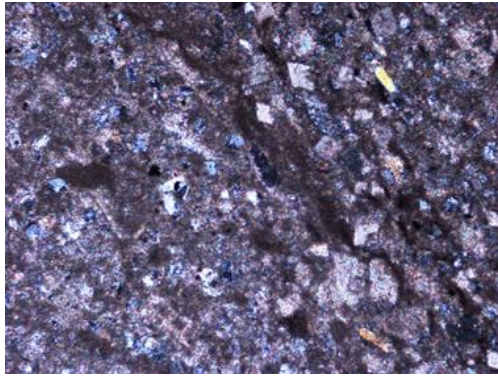
Dolomite reservoir is the most important reservoir type in Lower Ordovician Series in central Sichuan (Guo Tonglou, 2014; Liu Wei et al., 2017; Liu Zhibo et al., 2021), the favorable position for dolomite reservoir development is between the restricted platform where gypsum layer is usually developed and the paleo-uplift, and most areas of central Sichuan are located above this favorable facies belt. Dolomite reservoir consists of granular dolomite whose original sedimentary structure can be identified and crystalline dolomite whose original sedimentary structure cannot be identified. Compared with karst reservoirs with more serious filling, dolomite reservoirs develop a large number of intercrystalline pores, dissolution pores, micro-fractures and other pore space types. This type of reservoir is usually located in the part where karst is not developed and has a certain distance from the top unconformities of the Ordovician system, and the dissolution phenomenon is more obvious, which may be due to the superposition of bedding karstification on the slope of the paleo-uplift.

### 4.2.1 Granulated dolomite

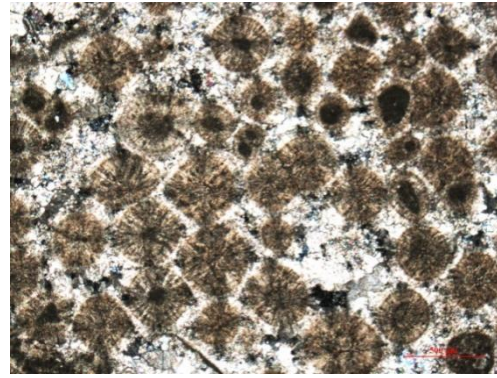
Granular dolomite is formed in the shallow environment of the platform, and the particles include sand, gravel, oolitic and algal sand, etc., and may contain a small amount of terrigenous clastic quartz. The particle content is 50 ~ 97%, the particle size of gravel is generally 2 ~ 15mm, the particle size of other particles is generally 0.16 ~ 0.4mm, in addition to the irregular shape of algal sand, other particles are more regular, sub-round ~ circular.

The rock characteristics of the Lower Ordovician strata in central Sichuan show that the granulated dolomites are mostly sparry cementation (FIG. 5), and the intergranular powder-fine dolomite and mesocrystalline dolomite are 2 ~ 3 stages of cementation, with intergranular pores, intergranular dissolved pores and a small number of intra granular dissolved pores, and the face rate is generally about 3%. When the granular dolomites undergo strong late dolomitization, only residual phantoms can be seen in most of them. For example, the residual granular dolomite of Zao3 well has a maximum of 6-8% intergranular pores (FIG. 5d).

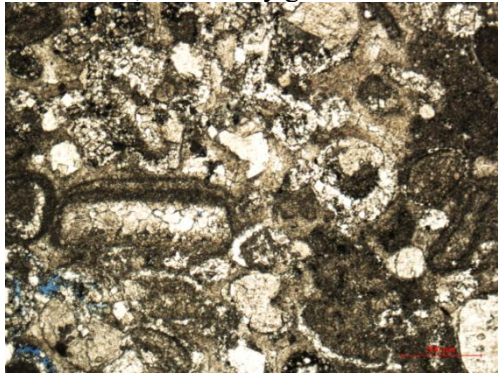




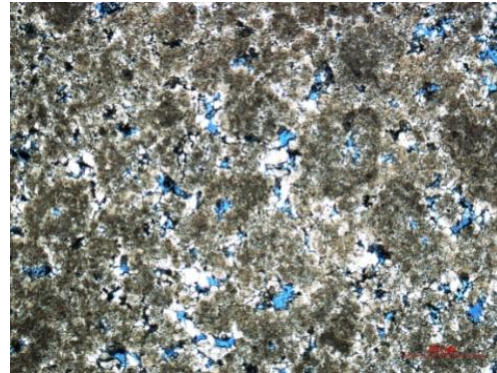
(a) Qiliao section of stone pillar, Honghuayuan Formation, with sandy granular dolomite



(b) Chi7 Well, Tongzi Formation, oolitic dolomite



(c) Biogenic oolitic dolomite, Tongzi Formation, Well Weihai 1

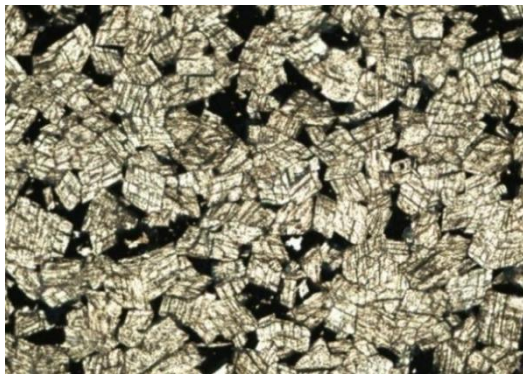


(d) Zao 3 Well, Tongzi Formation, residual granular dolomite

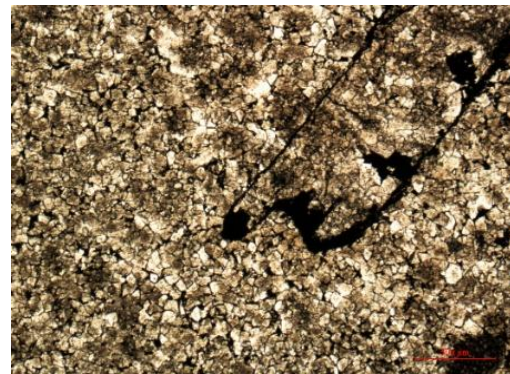
Fig. 5 Characteristics of Lower Ordovician granulated dolomite in central Sichuan

#### 4.2.2 Granular dolomite

Mostly formed in confined platform or platform tidal flat, grain dolomite is usually associated with granular dolomite to form compound reservoir. According to the division of grain size, the reservoirs can be formed by powdery, fine, mesocrystalline and coarse-grained dolomite (FIG. 6). Among them, powder-fine dolomite is the main rock, and particle phantoms can be seen, which indicates that the primary rock is granular limestone. The intercrystalline pores are not developed if the grains are of other shape and closely Mosaic, and the visible intercrystalline pores and intercrystalline dissolved pores of the grains have semi-idiomorphic - idiomorphic, and the face rate is generally less than 3%, and the high can reach 5 ~ 8%.

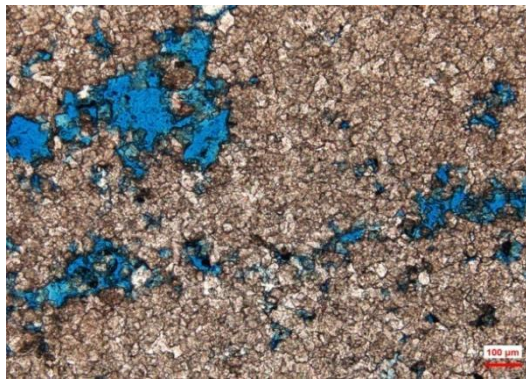


(a) Nushen 5 well, fine-grained dolomite of Tongzi Formation

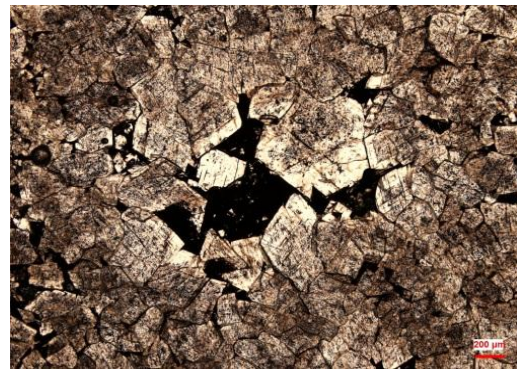


(b) Block 3 well, fine-grained dolomite of Tongzi Formation





(c) Xishui section, fine powdery bioclastic dolomite of Tongzi Formation



(d) He12 Well, fine-grained dolomite of Tongzi Formation

Fig. 6 Characteristics of Lower Ordovician grain dolomite in the middle Sichuan area

## 5. Hydrocarbon Accumulation Model of Ordovician in Central Sichuan Area

Based on a comprehensive analysis of the spatial association of lower Paleozoic source rock, reservoir and cap layer in Sichuan Basin, two sets of hydrocarbon accumulation assemblage developed in the Ordovician in central Sichuan, namely the lower assemblage (Tongzi Formation - Honghuayuan Formation) and the upper assemblage (Baota Formation - Linxiang Formation), and the two sets of assemblage were separated by the Meitan Formation of Middle Ordovician. Due to the limited hydrocarbon generation potential of the source rocks of the Ordovician system, the accumulation of the Ordovician system mainly depended on external hydrocarbon sources. The source rock of the lower part is the Lower Fuhanwu Qiongzhusi Formation and the cover layer is Meitan Formation. The source rock of the upper combination is Meitan Formation, and the cover layer is Wufeng Formation-Longmaxi Formation. Due to the relatively stable structure, there is no structural condition of overlying source rock underlying in the middle Sichuan area, which is not conducive to the development of fractured reservoir in the dense upper combination limestone. Therefore, the potential reservoir-forming assemblage in central Sichuan is mainly concentrated in the lower assemblage, which has high organic matter abundance, sapropelic organic matter type, high thermal evolution degree and strong hydrocarbon generation ability. According to the existing discoveries of natural gas in the Ordovician, the gas source of the Qiongzhusi Formation can supply hydrocarbon upwards through faults across layers (Xu Guosheng et al., 2007; Jinhuang Liang et al., 2012; Yang Yu et al., 2021), providing hydrocarbon source conditions for Ordovician reservoirs. At the same time, the Middle Cambrian did not develop the salt-and-paste layer in the middle Sichuan area, which also avoided the unfavorable factors for the oil and gas combination.

Previous exploration of Ordovician oil and gas in central Sichuan mainly focused on karst reservoirs distributed in a ring belt along the periphery of the central Sichuan paleouplift (Caledonian exposed denudation area) (Huang Wenming et al., 2011; Zhu Dongya et al., 2015; Sun Dongsheng et al., 2015). The typical three-layer karst structure is not shown on the drilling rig, and the karst reservoir is seriously filled, and the dissolution cavity is mostly blocked. In addition, the dolomite strata of Tongzi Formation and Honghuayuan Formation mainly show the upper superstructure, which is basically covered by the overlying Meitan Formation, and the karst time is relatively short. Therefore, these unfavorable factors seriously restrict the reservoir performance of the Lower Ordovician karst reservoirs in the middle Sichuan area.



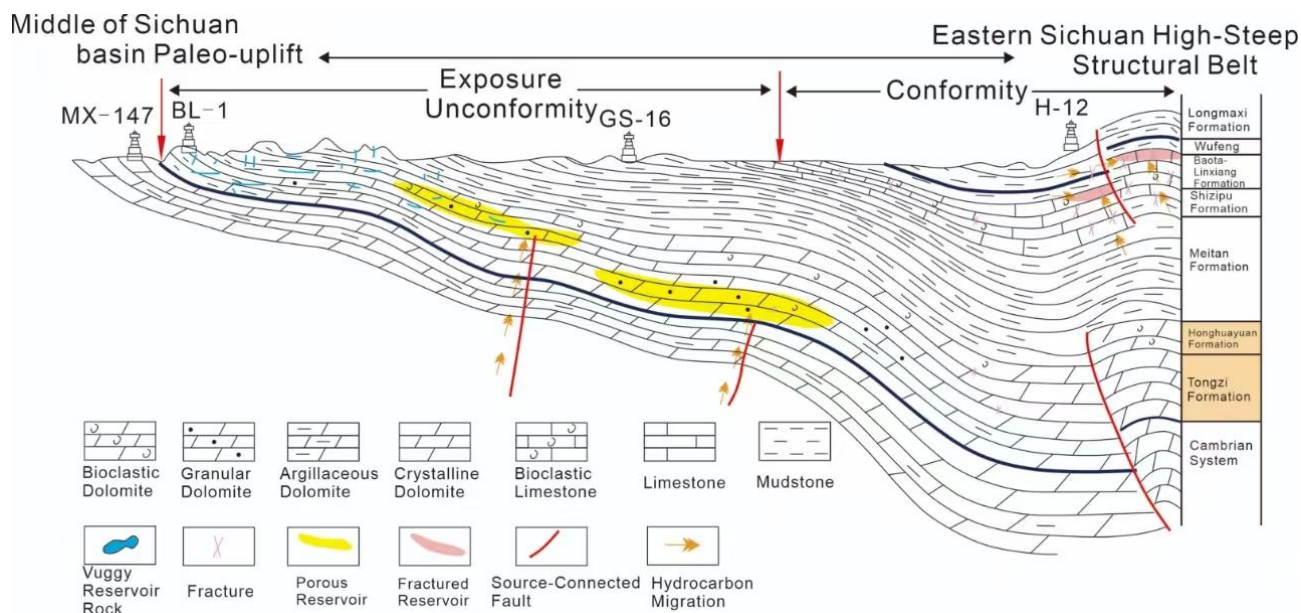


Fig. 7 Reservoir formation model of Lower Ordovician in central Sichuan

The Lower Ordovician Tongzi Formation and Honghuayuan Formation developed a large area of beach facies dolomite reservoir distributed in rows, especially in the Moxi-Guang'an area. Because the beach facies reservoir of the dolomite has a good natural storage space, which is conducive to the later dissolution transformation, the bedding karstification is very likely to give full play to the constructive transformation of the dolomite reservoir. The well profile data in the central Sichuan area show that the dolomite reservoirs of Tongzi-Honghuayuan Formation in the Meitan Formation coverage area on the east side of the karst exposed area have good reservoir performance. The dolomite reservoir of Tongzi-Honghuayuan Formation communicated with the source rocks of lower Cambrian Qiongzhusi Formation through faults, and was capped by Meitan Formation, forming a good source-reservoir-cap configuration combination (FIG. 7).

In summary, the Lower Ordovician oil and gas exploration in central Sichuan should shift from the previous exploration model of karst reservoir (Caledonian exposed denudation area) to the complex model of dolomite sheet + bedding karst in epicontinental platform (covered area of Meitan Formation to the east of Caledonian exposed denudation area), and the type of gas reservoir should shift from the previous single structural gas reservoir to the search for structure-lithology complex gas reservoir.

## 6. Conclusion

(1) The spatial distribution of lithofacies in the middle Sichuan area during the Tongzi-Honghuayuan stage of Lower Ordovician Series is successively from paleo-uplift to the east, from platform tidal flat to platform shoal to limited platform.

(2) The reservoir types of the Lower Ordovician strata in the middle Sichuan area include the karst reservoir distributed in a ring band around the paleo-uplift and the dolomitic rock beach reservoir located between the limited platform and the paleo-uplift.

(3) The performance of Lower Ordovician karst reservoirs in the middle of Sichuan is general, which may be related to the serious filling of karst reservoirs and the short karst exposure time. In contrast, the dolomite reservoir has a large number of intergranular pores and dissolution pores, and the combination of bedding karstification makes its reservoir performance better.

(4) The exploration idea of Ordovician carbonate rocks in central Sichuan area should be changed from conventional karst reservoir exploration to a new exploration model of shoal dolomite superimposed bedding karst in epicontinental platform.

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