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ORIGINAL ARTICLE

The Caledonian paleokarstification of Longwangmiao Formation, Lower Cambrian in the central Sichuan basin, China

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Abstract Longwangmiao Formation in Lower Cambrian is one of the key petroleum systems in Sichuan basin. The reservoir is well developed in the Longwangmiao Formation which was deposited in the restricted carbonate platform. It is indicated that the karstification occurred in the reservoir of Longwangmiao Formation during the Caledonian tectonic movement on the basis of seismology, petrology, sedimentology and geochemistry. Distinguishable markers of the paleo-karstification include: the lost strata and unconformable contact occurring between Middle-Upper Cambrian carbonates and Lower Permian Liangshan Formation; the occurrence of collapse breccias and fillings in caves and karrens; the evident difference between cave fill dolostones and matrix dolomite in the Sr/Ba ratio; and the log response of cavernous formations. The karstification lasted for a long time. According to the residual thickness between the top of Longwangmiao Formation and the bottom of the Permian, paleo-geomorphology during the Caledonian karstification had been recovered. In that time, Longwangmiao Formation was not directly exposed to the surface in central Sichuan basin; lots of meteoric fresh water flowed through faults and cracks from Gaotai Formation and a series of vertical dissolved caverns and karrens were formed. Meanwhile, due to the denudation window of Leshan-Longnvsi paleo-uplift lying in the west of the study area, meteoric fresh water flowed from the denudation window and the Longwangmiao Formation became a karstic confined aquifer. Under the pressure, diagenetic fluid migrated along the formation. Consequently, elongated dissolved pores and vugs formed and bedding karst reservoir developed in Longwangmiao Formation. The intensity of the karstification weakened with the distance from the paleo-uplift increasing, which indicates that the karstification was deeply influenced by the paleo-uplift. Finally, the supergene karstification model of Longwangmiao Formation has been established on the basis of the synthesis of the above-mentioned research results.

Keywords Supergene · Paleo-karstification · Reservoir · Karst model · Longwangmiao Formation · Caledonian · Central Sichuan Basin

Introduction

Cambrian is the most potential petroleum system in Sichuan basin. In the bottom of Lower Cambrian, a stable and thick source rock development is widespread (Li 1992; Dai et al. 1999; Xiao et al. 2006; Ran et al. 2006; Jin and Cai 2006), and its prospective resources occupies the first place in the lower Paleozoic (Huang et al. 2011). In Middle-Upper Cambrian, 1000 m of carbonate rocks developed, in which some good reservoirs formed (Zhu et al. 2006; Huang et al. 2009; Li et al. 2013). Petroleum exploration in Lower Cambrian Longwangmiao Formation has not achieved a breakthrough so that the related research is not well-known. However, with a significant gas

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exploration of Longwangmiao Formation in central Sichuan basin, especially in Moxi area, natural gas production uses several new wells with high production rates. Moxi Longwangmiao gas field has been the biggest gas field found in china. Longwangmiao Formation is a new important hydrocarbon reservoir in addition to Changxing Formation and Feixianguan Formation, and it shows great exploration potential. Previous studies indicate that the Longwangmiao reservoir develops very well. The reservoir spaces are mainly some widespread dissolved pores and caverns that are closely related to karstification.

Karstification is considered as a group of dissolution of soluble rock and its products (Yuan 1993). In general, carbonate karstification can occur in atmospheric fresh water environment and submerged environment (Moore, 2001; Esteban and Klappa 1983; Du et al. 2011; Pan et al. 2009; James and Choquette 1988). The dissolved pores and vugs formed by karstification may act as good reservoir spaces and have a significant meaning in huge hydrocarbon reservoirs (Chen et al. 1994; Jia et al. 1995; Wang et al. 1996; Dai and Wang 2000; Jin et al. 2001; Zhang, 2001; Lin 2002; Zhao et al. 2012, 2013). The understanding of karst is based on the observations of modern karst landform. Because supergene karstification is in symbiosis with unconformity, it is feasible to investigate the karst development of the overlying strata by looking for regional unconformity. Most karstic reservoirs are directly related to the direct exposure and erosion on the unconformity.

The reservoir of Longwangmiao Formation is mainly composed of grain dolomite and crystalline dolomite. The dissolved pores and caverns are extremely developed, especially the elongated dissolved pores and vugs, which were related to the exposure and erosion of the Leshan-Longnvsi paleo-uplift during the Caledonian. Research aimed at the Caledonian karstification of Longwangmiao Formation in the central Sichuan basin has not been very clear. Caledonian karstification which occurred after Cambrian and before the Permian and developed in central Sichuan basin are reviewed in this study. Research on the influence of the karstification on the Longwangmiao Formation is reviewed. A theoretical basis for petroleum exploration is provided.

Regional geological background

The Moxi area is located in the central low flat belt of the Sichuan basin, trending roughly in northeast to southwest (Fig. 1a). It is a secondary structure lying in the Leshan-Longnvsi paleo-uplift (Song 1996). The study area has experienced several periods of Syndepositional uplift as well as denudational uplift after the Sinian deposition. Influenced by the Caledonian and Hercynian tectonic movements, the study area generally lacks the Carboniferous, Devonian, Silurian and practically Ordovician strata due to exposure and erosion for a long time. Simultaneously, the carbonate formation below the regional unconformity was strongly transformed by the supergene karstification. Gas exploration here follows the principle that the Caledonian paleo-uplift was conducive to the accumulation of oil and gas exploration.

Cambrian is well developed in the study area (Li 1992; Feng et al. 2002). It is composed of Qiongzhushi Formation, Canglangpu Formation, Longwangmiao Formation, Gaotai Formation and Xixiangchi Formation from the bottom upwards (Li et al. 2012) (Fig. 1c). Qiongzhushi Formation, the favorable regional hydrocarbon source rock, is composed of thick gray–black shale, mudstone and silty mudstone. Canglangpu Formation developed a set of gray or mauve sandstone, sandy dolomite and dolomitic siltstone. The lithology of Gaotai Formation is similar to that of Canglangpu Formation. Longwangmiao Formation developed between Canglangpu Formation and Gaotai Formation and is composed of a set of grain dolomite and crystalline dolostone. Xixiangchi Formation developed a set of dolomite and limy dolomite.

In Longwangmiao period of the early Cambrian, Sichuan basin was located in the northwest of the upper Yangtze carbonate platform (Feng et al. 2002). Limited by the peripheral ancient land and underwater uplift, a restricted-evaporative carbonate platform has developed in central Sichuan basin (Yao et al. 2013). Two stages of four grade eustatic cycles occurred in Longwangmiao period. As a consequence, two sets of regressive deposition product have formed.

According to the fluctuation of the sea level, Longwangmiao Formation can be divided into upper Longwangmiao Formation and lower Longwangmiao Formation by a set of politic micrite dolomite containing gypsum pseudocrystal in middle section (Fig. 1c). The reservoirs are developed in the middle and upper part of the two submembers, and the main lithology is the dolarenite with dissolved pores and caves, residual dolarenite, as well as crystalline dolostone.

Methodology

The samples used in the lithological identification and geochemical analysis of the research were from the newly drilling and coring in central Sichuan basin. About 300 m cores and 1000 thin sections were studied to describe the petrology of the Longwangmiao Formation. The 3D seismic profile has been investigated to reflect the unconformity interfaces and geologic background. The cave fillings were sampled to study its geochemistry characteristics,

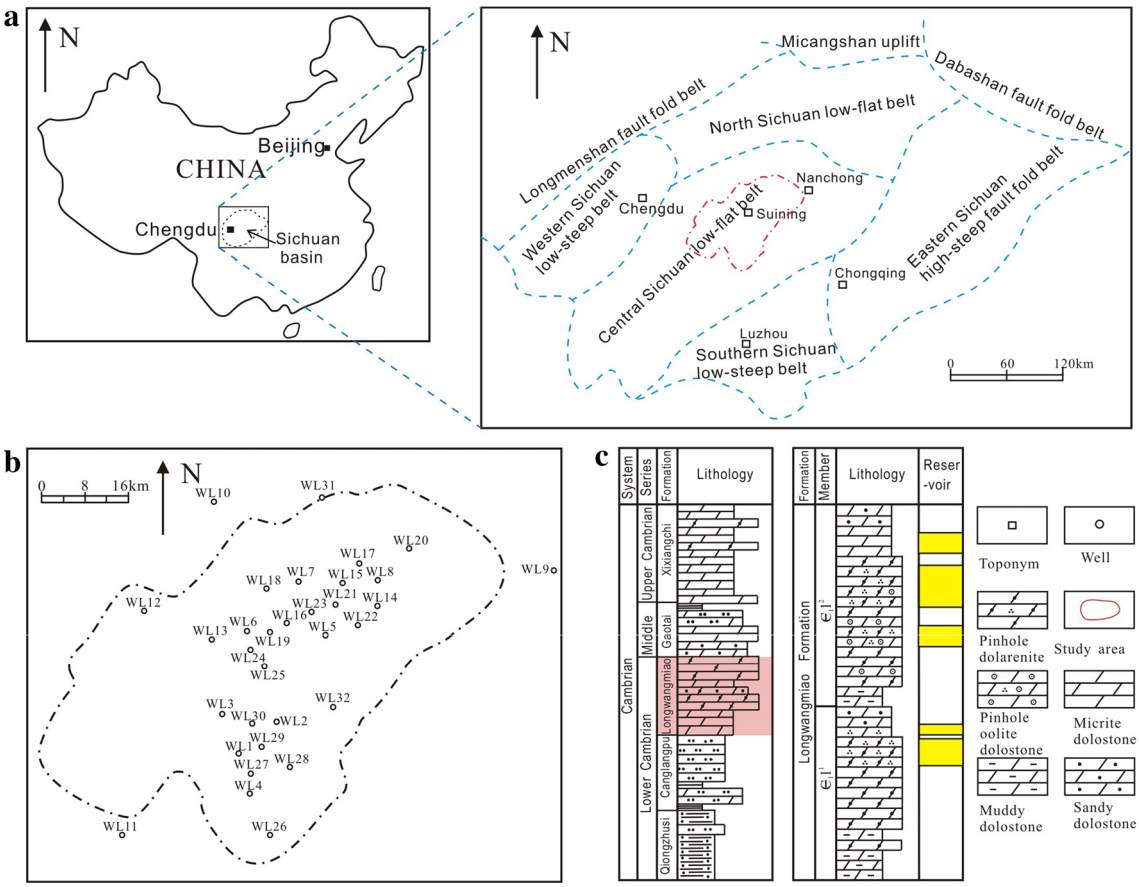

Fig. 1 **a** Tectonic units in the Sichuan basin and the location of the Moxi area. **b** Some representative wells and out crops in the Moxi area. **c** Generalized stratigraphy of the Longwangmiao Formation

including 19 specimens of matrix dolomite and eight specimens of dolomite filled in caves and fissures were selected to analyze for trace elements, especially Sr and Ba. Trace element analyses were carried out with an Axios X-ray fluorescence spectrometer after grinding the samples, with the error less than 2 %, in the state key laboratory of Oil and Gas Reservoir Geology and Development Engineering.

Logging trace including GR, AC, DEN, RS and RT were used to identify the cave and its fillings, which have different characteristics from the matrix dolomites in the Longwangmiao Formation. The reservoir property and reservoir thickness were also analyzed to discuss the karstification influence. Porosity and permeability of reservoir were all tested in the analysis laboratory center of petroleum exploration and development institute, Southwest oil and gas branch, China Petroleum Group Co., Ltd. Residual thickness between the top of Longwangmiao Formation and the bottom of the Permian can be used to recover the paleo-geomorphology. Combined with the paleo-geomorphology, the karstification model of the Longwangmiao Formation during the Caledonian has been established.

The evidences of karstification

Petrology

Vertical corrosion characteristics

In central Sichuan basin, especially in Moxi-Gaoshiti area, caves and fillings caused by karstification are found. For example, black mud as well as the vadose silts filled in karren in Longwangmiao Formation of WL20 well (Fig. 2c); about 2 m of collapse breccias and black mud filled in Longwangmiao Formation WL17 well (Fig. 2d); black mud filled in between the collapse breccias in deep 4657 m of WL16 well (Fig. 2e); breccias and vadose silts under the microscope (Fig. 2f). It can be concluded from all these phenomenons that the supergene karstification was intense and lasted a long time.

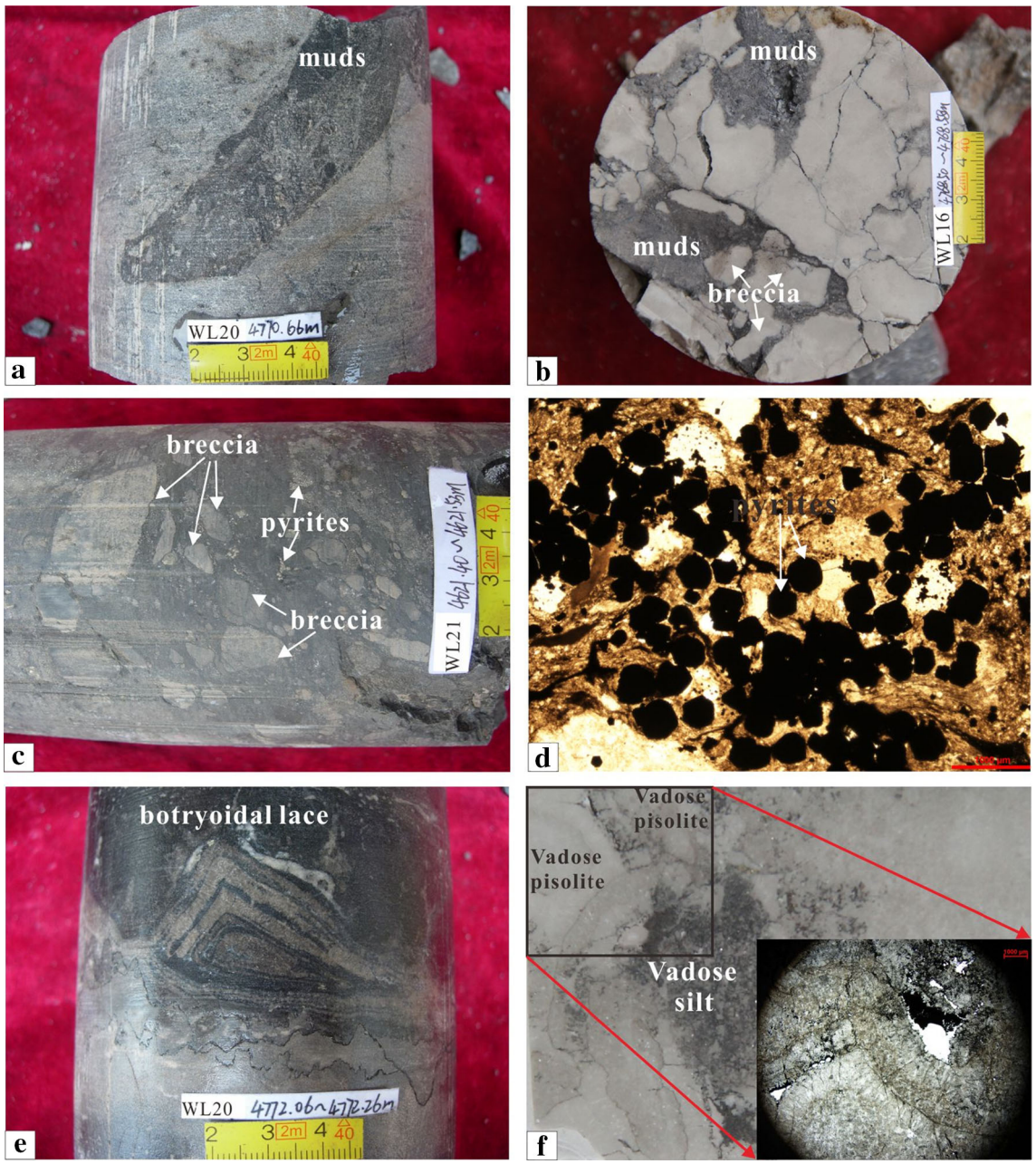

Fig. 2 Lithology evidence of karstification in Longwangmiao Formation, central Sichuan basin (**a** karren filled with *gray black* mud and vadose silts, 4770.66 m, Well WL20; **b** *black* mud filled in between the collapse breccias in deep 4768.50 m of Well WL16; **c** cave filled with collapse rubbles and *gray black* mud, 4621.40–4621.53, Well WL21; **d** Pyrites and mud filled in the cave, plane light, 4619.67–4619.78, Well WL21; **e** botryoidal lace in the cave, 4772.06–4772.26, Well WL20; **f** Vadose pisolite filled in caves, plane light, 4668.45–4668.52, Well WL17)

Bedding erosion characteristics

Beside the caves, karrens and fillings, lots of dissolved pores and vugs also formed in the karstification (Fig. 3a). The core observation shows that the elongated dissolved pores and vugs were oriented in horizontal direction with very few vadose slit and other fillings including some dolomite crystals and the asphalt (Fig. 3b, c). This kind of the dissolved pores and vugs developed well in Longwangmiao Formation in the study area on a large scale (Fig. 3e). According to statistics, the development degree of the dissolved pores and caves is inversely proportional

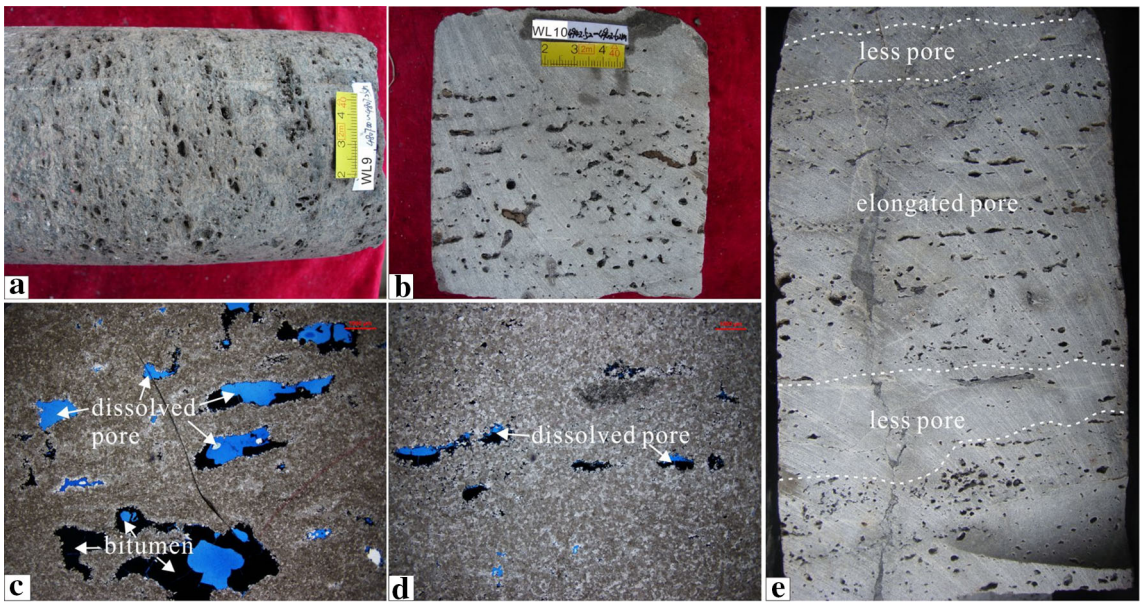

Fig. 3 Karstification phenomenon of Longwangmiao Formation in study area. **a** Elongated dissolved pores and vugs, 4807.25 m, Well WL9; **b** elongated dissolved vugs, 4942.52 m, Well WL10; **c** elongated dissolved pores and vugs filled with bitumen under the microscope, 4656.45 m, Well WL15; **d** dissolved pores filled with bitumen, 4649.12 m, Well WL17; **e** elongated dissolved pores and vugs oriented in horizontal direction, 4944.50 m, Well WL10)

to the distance from the paleo-uplift, which indicates that the dissolution was strong and the pores were well developed near the paleo-uplift.

Seismology

According to three dimensional seismic profile which is across well WL18 from the western to eastern area (Fig. 4), it is indicated that the bottom of the Permian is in uncomfortable contact with middle-upper Cambrian. There is an absence of the formation of Carboniferous, Devonian, Silurian and Ordovician. Longwangmiao Formation pinched out westward and the distance from the unconformity surface increased from west to east, which demonstrates that Leshan-Longnvsi paleo-uplift has experienced a long and intense exposure and erosion in Caledonian.

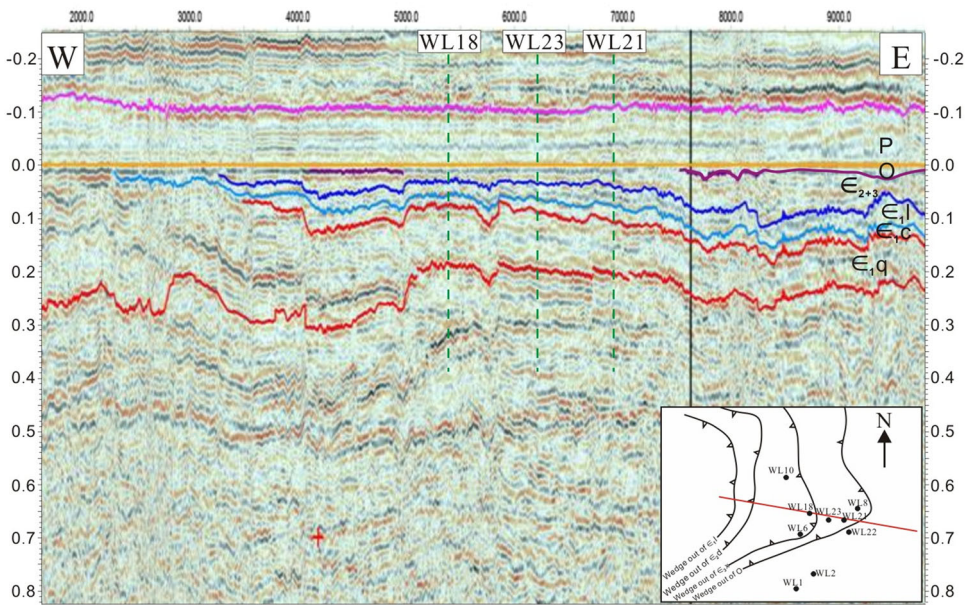

Fig. 4 The west-east profile through WL18–WL23–WL21 well in the central Sichuan basin ($\in_1 q$ represents Lower Cambrian Canglangpu Formation and Qiongzhushi Formation, $\in_1 c$ represents Lower Cambrian Canglangpu Formation, $\in_1 l$ represents Lower Cambrian Longwangmiao Formation, $\in_{2+3}$ represents the middle-upper Cambrian, *O* represents the Ordovician, *P* represents the Permian)

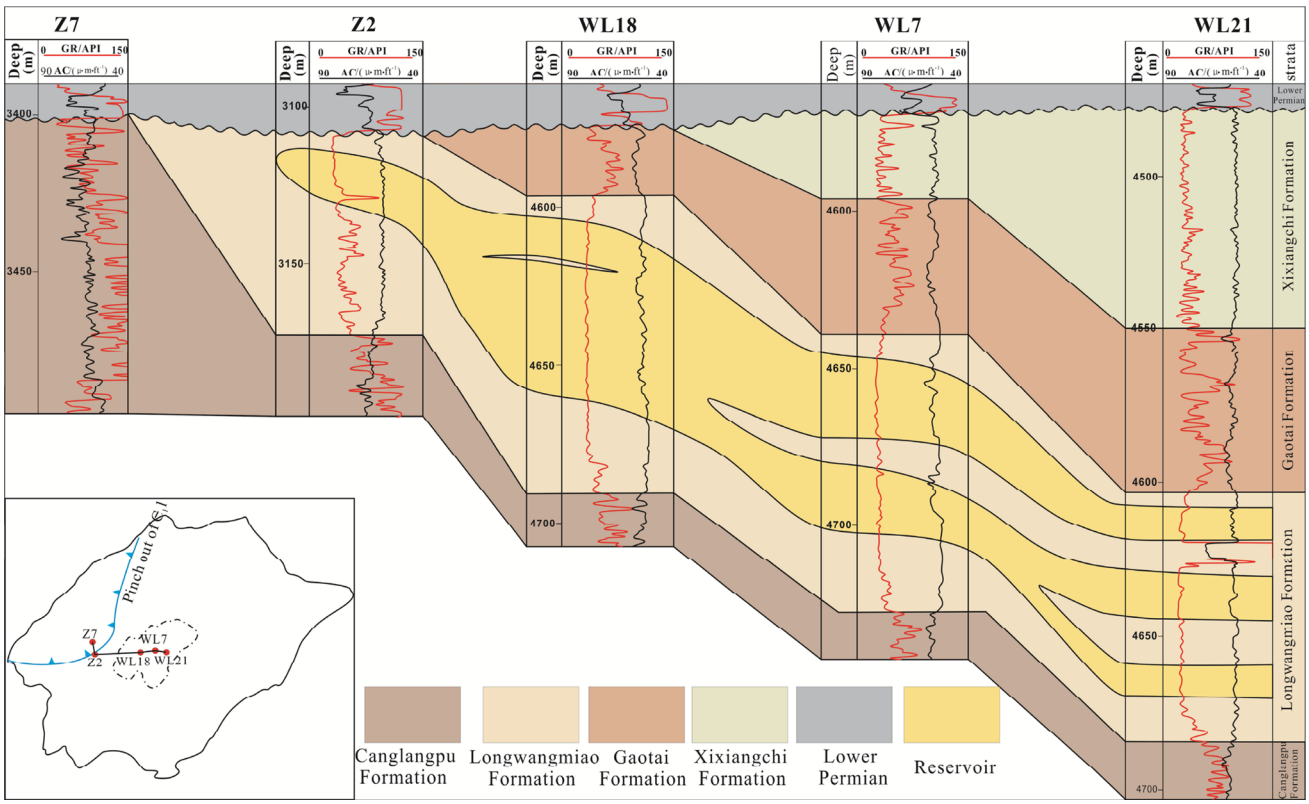

Fig. 5 The stratigraphic correlation of Longwangmiao Formation from Z7 Well to WL21 Well

Stratigraphy

From the Fig. 5, the distance between the unconformable surface and Longwangmiao Formation increases from west to east in the study area. Longwangmiao Formation is directly contacted with the Permian in well Z2, which demonstrates that the western area was located in the high point of the paleo-uplift. Longwangmiao Formation suffered from supergene weathering crust karstification due to the intense erosion of the formation. In the eastern area, it lies in the slope of the paleo-uplift so that the overlying Gaotai Formation remained. It is obvious that the tectonic uplift has a direct influence on the Longwangmiao Formation in the west, but the influence weakens eastward because of the water barrier function of Gaotai Formation.

Geochemistry

About 27 samples of Longwangmiao Formation were tested for geochemical dating (strontium isotopic, carbon isotopic, ratio of Sr/Ba). Taking an example of the ratio of Sr/Ba in trace element, it is commonly thought that Sr/Ba ratio in marine sediment is always more than 1, while that in land sediment is always less than 1 (Yang et al. 2014).

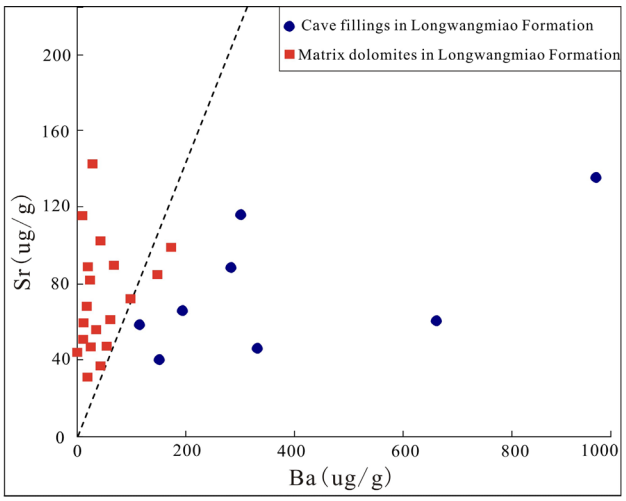

Fig. 6 The distribution of Sr–Ba in the Longwangmiao Formation in the central Sichuan basin

This research analyzed 19 specimens of matrix carbonate, 8 specimens of cave or fissure fillings. There were 10 specimens including all of the cave fillings locating in the band where Sr/Ba ratio was less than 1, which were proved to be fillers of Caledonian karstification (Fig. 6).

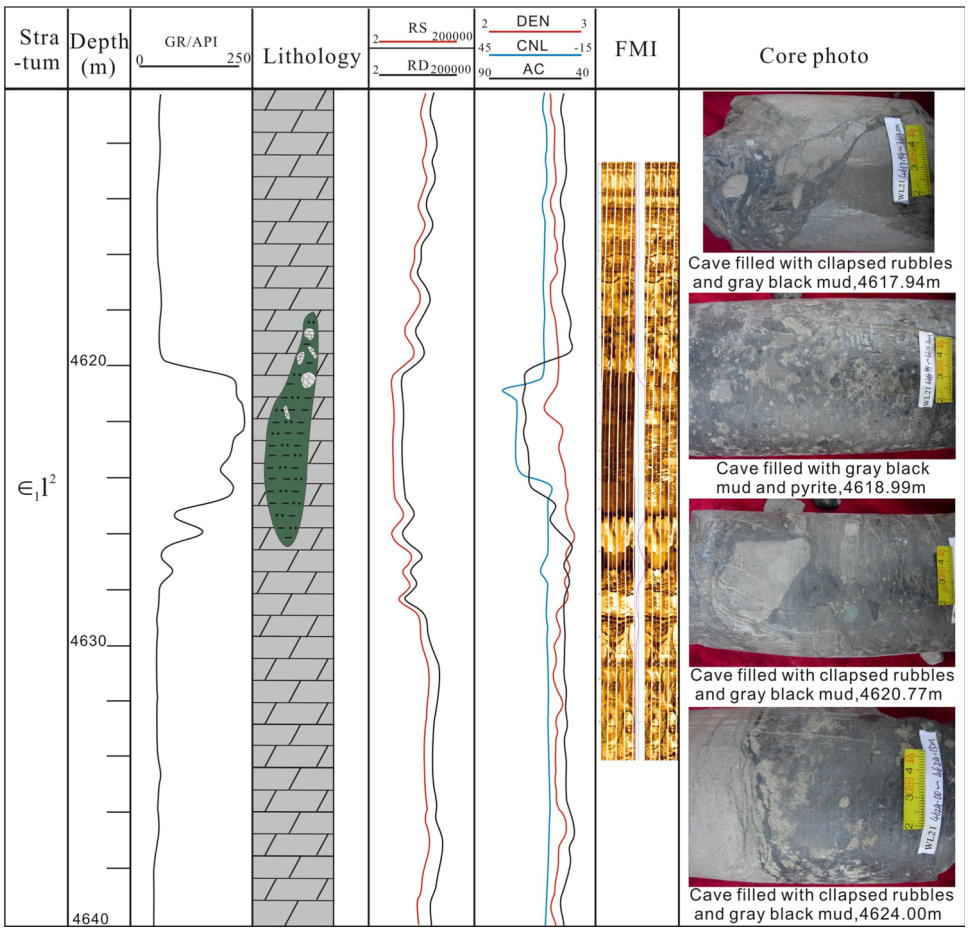

Fig. 7 Log response to cave filling of WL21 well. ($\in_1 l^2$ represents upper Longwangmiao Formation in the Lower Cambrian)

Logging response

It is confirmed by coring of WL21 well that the particular characteristic of log response between 4617 and 4628 m acted as caves filling with arenaceous mudstones and collapsed breccias (Fig. 7). Caused by corroded colluviation, CAL value, AC value and CNL value accreted partly while DEN value decreased. Because arenaceous mudstones filled in caves, GR value in this interval obviously got higher, and RS and RD degraded, indicating that the filler in the cave had high clay content.

Karst reservoir property

In the study area, Longwangmiao Formation is composed of kinds of dolomites, including grain dolomite, argillaceous dolomite and crystalline dolomite. The reservoir is closely related to the dolarenite as well as the crystalline dolomite that is chiefly powder-fine crystal. The reservoir spaces are mainly produced by corrosion pores, vugs and dissolved fractures, etc. According to the analytical and testing results of the conventional physical properties of 769 samples from the six wells in the study area (Fig. 8), it

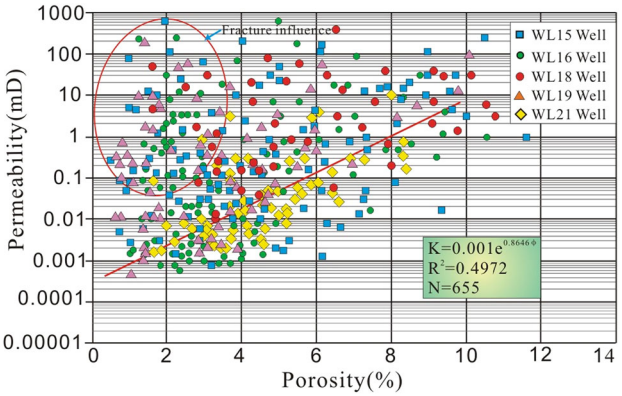

Fig. 8 Porosity–Permeability characteristics of Longwangmiao reservoir in study area

can be concluded that Longwangmiao Formation belongs to the medium porosity and the low permeability reservoir. On the whole, the permeability increases with the porosity increases. Simultaneously, some samples located in the same porosity, but there permeability exhibit considerable variation. Combining with the microscope observation, it can be seen that some mud powder crystal dolomite with

little pores developed in the fractures which can connect the isolated dissolved pores and vugs so as to improve the permeability. It can be concluded that the fractures have great effects on the permeability. The reservoirs of Longwangmiao Formation are mainly the vuggy reservoir and the porosity fractured reservoir.

According to the characteristics of karstification and the rule of the reservoir distribution, it can be concluded that karstification was mainly affected by the tectonic denudation window. Under the pressure, meteoric fresh water from the denudation window was easier to migrate laterally and dissolve the formation along Longwangmiao Formation. Some pores and caves formed in the dissolution caused by the meteoric water through the overlying Gaotai Formation; they were filled totally and unavailable to act as a reservoir. With the corrosion decreasing gradually from the uplift core to the wing, the reservoir porosity tends to decrease (Fig. 8) and thickness tends to thin gradually (Fig. 5). Therefore, the lateral dissolution has an important significance on the reservoir.

Paleo-geomorphology

Before the deposition of Liangshan Formation in the lower Premian, the geological structure suffered from long time denudation during the Caledonian tectonic deformation. Liangshan Formation is a typical chronohorizon, which is the depositional product in reginal maximum transgression after the Caledonian tectonic movement, with a set of stable and widespread black shale and carbonaceous mudstones. At the top of Longwangmiao Formation is another chronohorizon. When the Gaotai Formation was deposited, the sedimentary environment was a regional gentle tidal flat, with widespread gray or mauve sandstone. The residual thickness between the two chronohorizons represents the relative height of the ancient tectonic appearance before the early Premian. The residual thickness in Sichuan basin was from 0 to 2000 m, but in central Sichuan basin was concentrated in 0–500 m (Table 1).

According to the residual formation thickness between the bottom of Liangshan Formation and the top of Longwangmiao Formation, the paleo-topography during the Caledonian karstification (Fig. 9) can be defined as: karst highland (lack of Longwangmiao Formation), I-level karst slope (residual thickness more than 0 and less than 200 m), II-level karst slope (residual thickness more than 200 and less than 400 m), and karst basin (thickness more than 400 m). In the I-level karst slope, a lot of dissolved pores and vugs formed, and less dissolved pores and vugs were formed in II-level karst slope.

Karstification model

According to the research of regional tectonic history (Li, 1992; Feng et al. 2002; Li et al. 2012), Sichuan basin influenced by the Caledonian movement underwent a long-term uplift that resulted in extremely intense erosion of the Carboniferous, Devonian and Silurian in part of the area, and experienced a long-term transformation caused by the meteoric water with enriched CO_2. Leshan-Longnvsi paleo-uplift is an inherited paleo-uplift. Its characteristics were being formed since the Sinian. In the Caledonian, it had developed into a paleo-uplift inclining from southwest to northeast after a strong tectonic movement. In central Sichuan basin, Longwangmiao Formation is not directly exposed to the surface, but influenced by the Leshan-Longnvsi paleo-uplift. The study area was located in the eastern of the tectonic denudation window. Meteoric fresh water dissolved the formation along the fracture and drainage system related to "denudation window", which has resulted in the supergene bedding karstification (Fig. 10).

With the tectonic uplifting and the overlying strata being denuded, the meteoric water dissolved the overlying soluble rock firstly and then moved downward along the fractures and the cracks. Gaotai Formation, as a barrier to water, consisted of mudstone and lime mudstone with a lower permeability, so it was difficult for meteoric freshwater to get through this strata and dissolve the underlying

Table 1 Residual thickness between the top of the Longwangmiao Formation and the bottom of the Liangshan Formation in the Premian, central Sichuan basin

Well	Residual thickness (m)	Well	Residual thickness (m)	Well	Residual thickness (m)
Z2	0	B1	283	WL19	127
Z7	0	WL28	296	WL3	164
WL18	21.44	WL4	327	Z6	171
Z4	33	Z5	454	WL25	206
WL6	42	L1	486	WL3	231.02
WL7	70	WH101	540	AP1	234.5
WL8	109	W28	559	WL5	240
WL21	125	WH1	582.5	W2	625.5
WS1	923.5	H1	1172.4	GS1	1439
P1	1684	ZS1	1799	YS2	2835

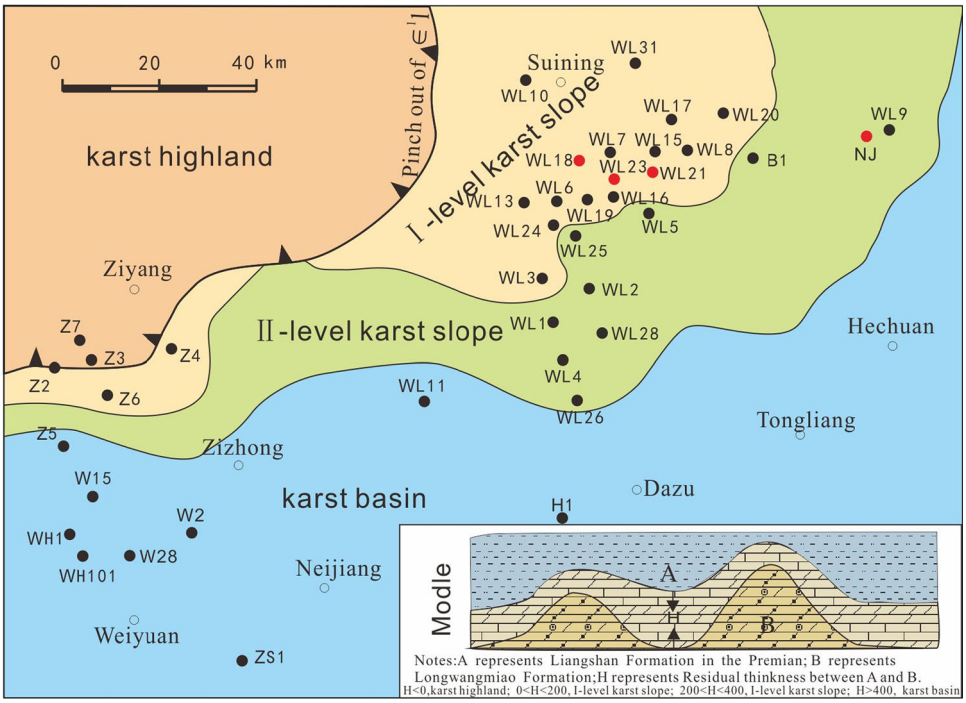

Fig. 9 Paleo-topography during the Caledonian karstification in central Sichuan basin

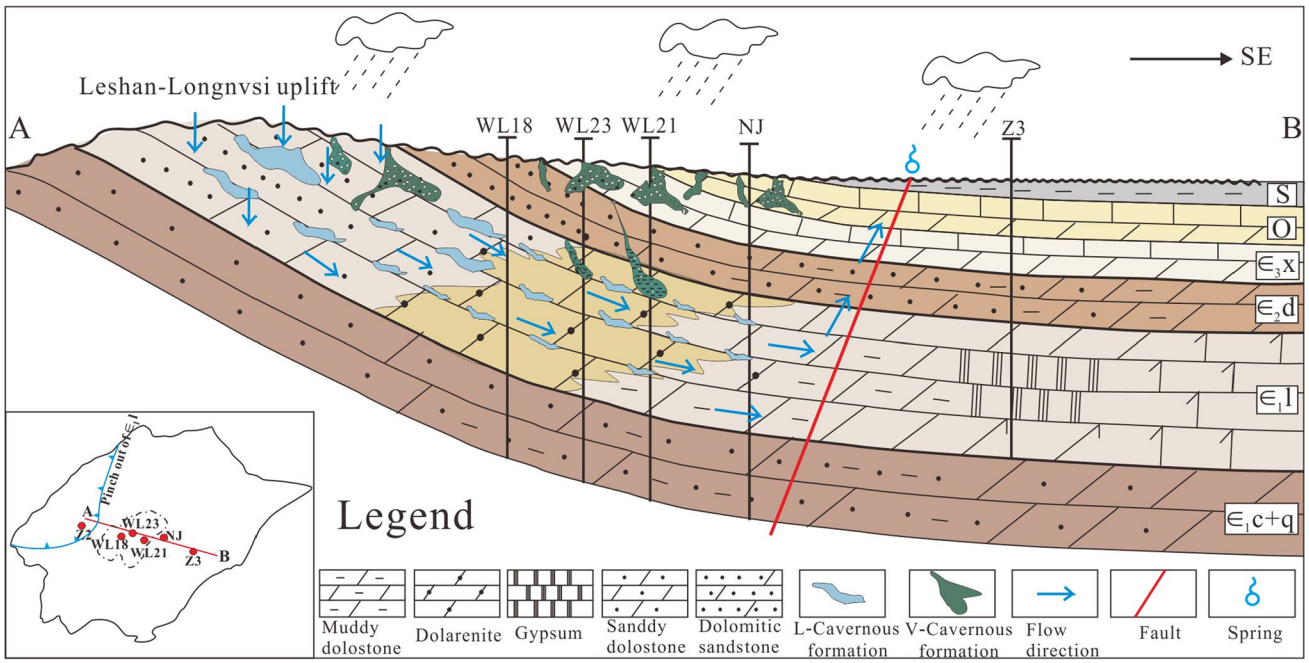

Fig. 10 Karstification model of Longwangmiao Formation during the Caledonian tectonic movement

strata. But there is still some meteoric karst collapses directly from the overlying strata along fractures and fissures. Limited by the water barrier function of Gaotai Formation, it was difficult for meteoric freshwater to dissolve Longwangmiao Formation by getting through Gaotai Formation, but easier to enter permeable Longwangmiao Formation directly. In this process, a lateral dissolution related to the meteoric water from the tectonic denudation window has occurred, which resulted in many elongated dissolved pores and caves in the cores.

Conclusion

1. The evidences of the seismic, stratigraphy, geochemistry and logging indicate that karstification occurred in central Sichuan basin after long-term uplift and erosion influenced by the Caledonian movement. The Lower Cambrian Longwangmiao Formation was about 100 m from the unconformity, and it was easily affected by unconformable surface weathering karst.
2. Longwangmiao Formation was not directly exposed to the surface; there are still some traces of fillings in dissolved caverns and karrens related to fracture and fissures. Simultaneously, influenced by the tectonic denudation window of Leshan-Longnvsi paleo-uplift, a lot of meteoric water entering into the Longwangmiao Formation took a lateral migration to form the directionally elongated pores and vugs.
3. In the plane, the reservoir physical property of Longwangmiao Formation decreased slightly from west to east, and the thickness obviously shows the same decreasing trend, which further indicates the intensity of the karstification is related to the distance from the paleo-uplift.

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