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Research article

# Differential accumulation and distribution of natural gas and its main controlling factors in the Sinian Dengying Fm, Sichuan Basin

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**Abstract**

In order to disclose the genetic relationship between the hydrocarbon reservoirs and the transformation mechanism between ancient and modern gas reservoirs in the Sinian Dengying Fm in the Sichuan Basin, by using the drilling data, and geologic, geophysical and geochemical methods together, the differential accumulation and distribution of natural gas and its main controlling factors in this study area were identified following the idea of corroborating macroscopic, mesoscopic and microscopic results each other. The results demonstrate as follows. (1) The crude oil in the paleo-oil reservoirs of the Dengying Fm cracked into gas to form the early overpressure paleo-gas reservoirs 100 Ma. From 100 Ma to 20 Ma, the constant uplifting of the Sichuan Basin coupled with the shift of structural highs and the initial occurrence of Weiyuan anticline caused the adjustment of the early overpressure paleo-gas reservoirs into the late overpressure paleo-gas reservoirs. (2) With the increase of uplifting magnitude since 20 Ma, the formations overlying the Dengying Fm in Weiyuan structure experienced rapid erosion, resulting in decline of the caprock sealing ability and damage to the preservation conditions. Therefore, the natural gas in the Dengying Fm started to leak and dissipate from the eroded window of the Lower Triassic Jialingjiang Fm located on the top of the Weiyuan anticline, which is the beginning of the differential accumulation and dissipation of the natural gas in the Dengying Fm across the Sichuan Basin. During the process of the differential accumulation and dissipation, the gas below the spill point of the structural gas traps in Ziyang, Jinshi and Longnüsi−Moxi−Anpingdian−Gaoshiti areas migrated to the Weiyuan anticline along the unconformity of the Dengying Fm, and dissipated through the eroded window of the Jialingjiang Fm on the top of the Weiyuan anticline, resulting in a transformation of abnormal high pressure of gas reservoir to normal pressure in the Dengying Fm. The differential accumulation and dissipation mode in the Dengying Fm in the Sichuan Basin has both similarities with and differences from the classic hydrocarbon differential entrapment theory, and will give great inspiration to and guide the further gas exploration in the Sichuan Basin.


*Keywords:* Sichuan Basin; Sinian Dengying Fm; Natural gas; Differential accumulation; Controlling factors; Unconformity; Weiyuan anticline

The gas field, discovered in Upper Sinian Dengying Fm in Weiyuan, Sichuan Basin in 1964, was the first large gas field discovered after the foundation of PRC [1]. Although many researchers have conducted in-depth studies on it [2−12], they have not reached consensus on the reasons why only 25% of the closure height of the trap is filled with gas. Through the in-depth study of the gas field of Dengying Fm in Weiyuan, gas-bearing area of Dengying Fm in Ziyang, paleo-oil and gas reservoirs of Dengying Fm in Dingshan-Lintanchang, Liu Shugen et al. [13−16] considered that the natural gas reservoirs of Proterozoic Sinian Dengying Fm in the Sichuan Basin with deep buried depth had experienced a transformation process from gas generation center (paleo-oil reservoirs) to gas storage center (paleo-gas reservoirs, gas and dissolved gas enrichment region) and gas preservation center (present gas reservoirs). Gas generation center was the main "gas source"

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for gas storage center, which was in turn the main "gas source" for gas preservation center. The formation of gas generation center was controlled by the hydrocarbon generation center where source rocks were located (hydrocarbon kitchen). The formation of the gas reservoirs of Sinian Dengying Fm was determined by the coupling relationship among the four hydrocarbon centers (hydrocarbon generation center, gas generation center, gas storage center and gas preservation center) under the effect of multi-phase tectonic movements. The hydrocarbon generation center was controlled by the prototype of the basin, which would not change after its formation; while the other three centers were prone to change due to tectonic movements. The spatial distribution of "the three centers" determined the ultimate distribution of oil and gas. Through in-depth study on regional tectonics and structures, Liu Shugen et al. [17,18] proposed that the distribution of the marine oil and gas in the lower combinations of the Sichuan Basin was jointly controlled by the extensional intracratonic sags, paleo-uplifts and basin-and- orogen system. The extensional intracratonic sags controlled the distribution of hydrocarbon generation centers (hydrocarbon kitchen), paleo-uplifts controlled the distribution of gas generation centers (paleo-oil reservoirs) and gas storage centers (paleo-gas reservoirs), and the basin-and- orogen system controlled the distribution of gas preservation centers (present gas reservoirs). However, limited by available data, the previous studies mainly focused on the macroscopic description of local gas reservoirs, so the shifting process, mechanisms and controlling factors of "the three centers" need to be examined further.

The discovery and in-depth study of the gas reservoirs of the Sinian Dengying Fm in Gaoshiti−Moxi area made it possible to reveal the genetic relationship among the petroleum reservoirs of the Sinian Dengying Fm in Ziyang, Jinshi, Weiyuan, Gaoshiti, Moxi, Longnüsi and Guang'an in the Sichuan Basin, and the transformation mechanisms of paleo-gas reservoirs (gas storage center) to present gas reservoirs (gas preservation center). Gussow [19] proposed the hydrocarbon differential entrapment theory about traps formed with gradual elevation variation of spill points with genetic relations. On this basis, Sales [20] further proposed that seal strength and trap closure were a fundamental control over the hydrocarbon accumulation, dissipation and distribution and that traps can be divided into three types. Ohm et al. [21] advanced the hydrocarbon migration, accumulation and dissipation model in uplifted areas. According to the exploration results of Sinian Dengying Fm in the Sichuan Basin by far, it could be proposed that the traps in Weiyuan, Gaoshiti, Moxi, Longnüsi and Guang'an are the traps of Dengying Fm with gradually descending spill points during the regional uplifting of the Himalayan period, and the migration and distribution of natural gas might have followed the hydrocarbon differential migration and entrapment theory proposed by the researchers mentioned above. Based on the previous studies on the Sinian Dengying Fm of the Sichuan Basin, making use of geologic, geophysical and geochemical methods jointly, and the latest exploration data, the authors tried to find out the characteristics and main controlling factors of the differential accumulation and dissipation of the natural gas of the Dengying Fm in the Sichuan Basin, following the idea of corroborating microscopic, mesoscopic and macroscopic results with each other.

## 1. Present features of the gas reservoirs of the Sinian Dengying Fm in the Sichuan Basin

### *1.1. Features of the structural traps*

At present, the discovered underground structures of the Sinian Dengying Fm in the Sichuan Basin are mainly concentrated in and around Leshan-Longnüsi palaeouplift west of Huaying Mountain, including more than twenty small structural traps, such as Ziyang, Jinshi, Weiyuan, Gaoshiti, Anpingdian, Moxi, Longnüsi, Guang'an, Zhougongshan, Hanwangchang, Laolongba, Dawoding, Tiangongtang, Ziliujing, Panlongchang and Jinshi, of which Weiyuan structure is the biggest and highest (Fig. 1). Weiyuan structure, which can be easily identified from surface geology, is one of the structures in the Sichuan Basin where oil and gas exploration started at a very early time.

The first well drilled targeting Sinian Dengying Fm in Weiyuan structure was Well Weiji in 1956 [22], where the Sinian Dengying Fm trap is a giant dome in the southern flank of the central Leshan-Longnüsi Caledonian palaeouplift, with a closure area of 850 $km^2$, closure height of the 895 m, long axis of 51 km and minor axis of 27 km (Fig. 1). The gas field of the Dengying Fm in Weiyuan structure has a gas column height of 240 m and gas fullness of about 25%. In Weiyuan structure, the Sinian top surface has a buried depth of about 2500 m and an elevation of about −2200 m, while its trap spill point is located in the southwest side of the structure, with an elevation of about −3200 m.

Gaoshiti−Moxi buried structure is located in the east of Anyue county, where the structural top of the Denying Formation has a buried depth of about 4900 m and an elevation of about −4640 m, closure height of about 360 m and closure area of about 3474 $km^2$, while its spill point is located in the west, with an elevation of about −4940 m and gas fullness of over 100%.

Longnüsi buried structure is located in Wusheng county, where the drilling of the Dengying Fm dated back to Well Nüji in 1971 [22]. The Sinian structure has a structural top buried depth of about 5280 m, an elevation of about −4930 m, a closure height of 80 m, a closure area of 269 $km^2$ and a spill point elevation of −5010 m. The Sinian Deng 4 Member (depth:5197.92−5239.92 m) in Well Nüji had a tested gas production of $1.85 \times 10^4$ $m^3/d$ and water production of 11.8 $m^3/d$. However, its gas fullness has not been identified, and is still under exploration.

Guang'an structure is located in Guang'an county, where the Dengying Fm has a structural top buried depth of about 6020 m, an elevation of −5300 m, closure height of 250 m, spill point elevation of −5550 m and closure area of 210 $km^2$. This structure is still under exploration at present, with gas logging anomaly discovered in Deng 4 Member.

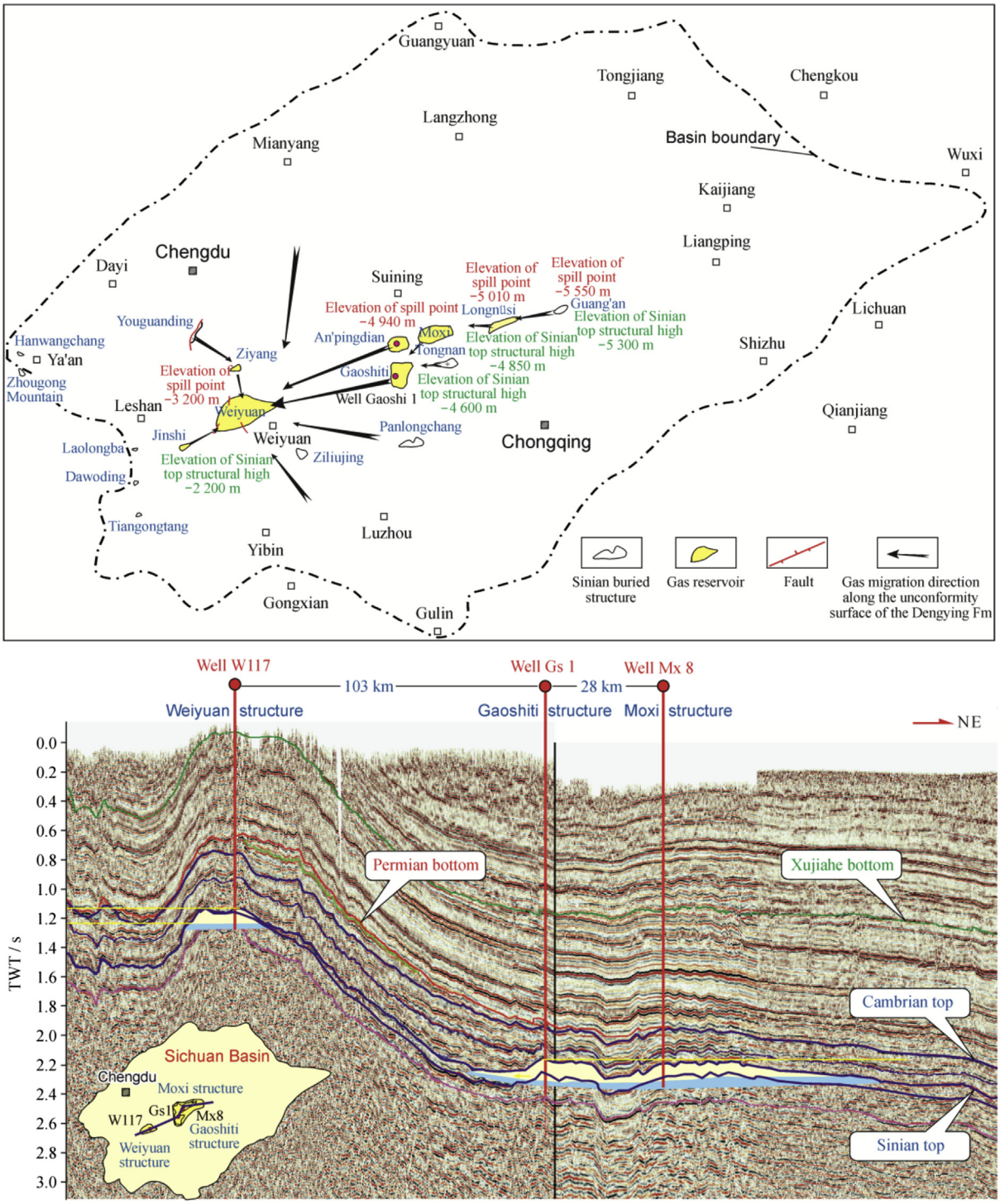


Fig. 1. Plane distribution of the main structures of the Dengying Fm in the Sichuan Basin and their profile features.

Jinshi structure trending NWW is in the west of Weiyuan structure, with a long axis of 8.2 km and minor axis of 4.1 km, closure height of about 90 m and closure area of 30.38 $km^2$, where exploration breakthrough has recently been made in Dengying Fm in Well Jinye 1 by Sinopec, with a tested gas production of $4.73 \times 10^4$ $m^3$/d.

In summary, from Weiyuan to Gaoshiti, Moxi, Longnüsi and Guang'an structure, the straight tectonic distance is from 110 km to 80 km then to 30 km, the total length is 220 km, the buried depth of the Dengying Fm structural top gradually deepens, from −2400 m to −4640 m, −4930 m and −5300 m; from Weiyuan to Guang'an structure, the drop height of the structural top is 2900 m; the spill point of the structural traps gradually deepens, from −3200 m to −4940 m, −5010 m and −5550 m, with drop height of 2250 m; meanwhile the fullness of gas reservoirs increases from 25% to 100% from Weiyuan to Gaoshiti.

### 1.2. Features of natural gas

Gas in the Dengying Fm gas reservoir in Weiyuan area with a stable methane content of 85−87% in volume, features high helium content (0.31−0.4%) and high sulfur content ($H_2S$) (2.5% on average) (Table 1).

Gas in the Dengying Fm gas reservoir in Gaoshiti−Moxi has a stable methane content of 86−90%, and a small amount of $H_2S$ (about 1% in volume fraction) (Table 1).

In Gaoshiti−Moxi area, gas in the Dengying Fm has ethane carbon isotope value ranging from −30‰ to −25‰ and gas in the Lower Cambrian Longwangmiao Fm from −33‰ to −30‰, indicating that gas reservoirs in the Dengying Fm and Longwangmiao Fm are two independent gas ones.

### 1.3. Features of formation water

The formation water of the Dengying Fm in Weiyuan structure is of $CaCl_2$ type, consistent in vertical and horizontal direction, with a relative density of about 1.055, pH value of 7−8, total salinity of 76−81 g/L. The water has a high content of $Ba^{2+}$, no $SO_4^{2-}$ and relatively high content of lithium, potassium, rubidium, strontium, boron and other trace elements (Table 2), which are the features of the Sinian formation water. The water type of the Dengying Fm in Ziyang area and Weiyuan area is basically the same.

### 1.4. Features of formation pressure

Gas reservoirs of the Dengying Fm in Weiyuan area belong to the same pressure system with the middle depth of the producing zone in Well Wei 12, −2291 m as their elevation. The initial formation pressure was 29.5 MPa, with a pressure coefficient from 1.03 to 1.04. Gas reservoirs of the Dengying Fm in Ziyang area have similar pressure with those in Weiyuan area (Table 3). The Sinian Dengying Fm of Well Jinye 1 in Jinshi structure has a pressure coefficient of 1.03, indicating normal pressure as well.

In Gaoshiti−Moxi area, gas reservoirs of Deng 4 Member takes the middle depth of the Deng 4 Member in Well Moxi 27 (−4500 m) as their elevation. The initial formation pressure of Deng 4 Member calculated thus is 55.4 MPa, with a pressure coefficient ranging from 1.06 to 1.14, representing normal pressure−weak overpressure. Deng 2 Member, with a pressure coefficient of 1.10 on average, is also normal in pressure.

Therefore, in terms of formation pressure, the entire Dengying Fm is normal with similar pressure coefficients in the whole basin. It can be seen from pressure coefficient alone that the entire Dengying Fm seems to have a unified pressure system; but from Weiyuan to Gaoshiti−Moxi, Longnüsi and Guang'an, the pressure coefficient of Dengying Fm increases slightly.

## 2. Features of the paleo-gas reservoirs (gas storage center) of the Dengying Fm

### 2.1. Palaeo-structure features

Although the Caledonian palaeouplift has experienced a long history of evolution, the structure of the Sinian top has slight variation. During Late Triassic Early Jurassic time, the paleo-oil reservoirs cracked into paleo-gas reservoirs in place, while Leshan-Guang'an area was still large palaeo-structural uplift, with axis in NE direction, long axis of 280 km and minor axis of 70 km. The uplift has two structural highs, one in Leshan-Ziyang area, and the other in Gaoshiti−Moxi−Longnüsi area. With a common closure elevation of −4400 m and a total closure area of 19600 $km^2$, the uplift is a large structural trap with a closure height of 850 m (Fig. 2).

### 2.2. Paleo-gas reservoir features

#### 2.2.1. Scale of paleo-gas reservoirs

The paleo-gas reservoirs of the Sinian Dengying Fm can be divided into two paleo-gas reservoirs by the saddle part in Lezhi-Anyue, namely Ziyang−Weiyuan paleo-gas reservoir and Gaoshiti−Moxi paleo-gas reservoir (Fig. 2). The high point of the Ziyang−Weiyuan paleo-gas reservoir was in Ziyang area, Weiyuan area was in the slope on the south flank of the paleo-structure, while the high point of Gaoshiti−Moxi paleo-gas reservoir is located in An'pingdian-Moxi area. The two paleo-gas reservoirs were connected macroscopically,

Table 1
Chemical properties of the Dengying Fm natural gas in Ziyang, Weiyuan, Gaoshiti and Moxi areas.

| Well | Formation | Gas producing interval/m | Gas components | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $CH_4$ | $C_2H_6$ | $C_3H_8$ | $H_2S$ | $CO_2$ | N | He | $H_2$ | Ar |
| Z1 | $Z_2dn^3$ | 3980.5−4081.0 | 91.52% | 0.12% | Trace | 5.940% | 1.143% | 1.22% | 0.042% | Trace | 0.009% |
| | | 3994.4−4044.0 | 93.59% | 0.12% | Trace | 0.785% | 4.313% | 1.22% | 0.040% | 0.007% | 0.002% |
| | | 3994.0−4067.0 | 89.71% | 0.11% | 0 | 1.231% | 7.411% | 1.53% | 0.037% | 0 | 0.014% |
| W27 | $Z_2dn^3$ | 2851.0−2950.0 | 87.07% | 0.09% | / | 6.51% | / | 6.02% | 0.310% | / | / |
| W30 | $Z_2dn^3$ | 2844.5−2950.0 | 86.57% | 0.14% | / | 5.4% | / | 7.55% | 0.340% | / | / |
| W86 | $Z_2dn^2$ | 3454.1−3660.0 | 86.7% | 0.07% | 0 | 0.22% | 3.297% | 9.35% | 0.307% | / | 0.056% |
| W117 | $Z_2dn^3$ | 3343.95−3457.54 | 83.69% | 0.06% | / | 0.154% | 0.045% | 15.46% | 0.404% | 0.213% | 0.134% |
| Apl | $Z_2dn^4$ | 5036.97−5187.00 | 94.69% | 0.03% | 0 | Trace | 4.31% | 0.59% | 0.025% | 0.349% | / |
| | $Z_2dn^2$ | 5396.97−5520.00 | 88.43% | 0.02% | 0 | 0.68% | 7.26% | 1.22% | 0.071% | 2.314% | / |
| Gs1 | $Z_2dn^3$ | 5130−5153 | 91.22% | 0.04% | 0 | 1% | 6.35% | 1.36% | 0.030% | 0.01% | / |
| | $Z_2dn^2$ | 5300−5390 | 82.65% | 0.04% | 0.11% | 0.85% | 14.19% | 2.12% | 0.040% | 0.01% | / |
| Mx8 | $Z_2dn^4$ | 5102−5172 | 92.16% | 0.04% | 0 | 1.04% | 5.9% | 0.81% | 0.050% | 0 | / |

Table 2
Chemical properties of the Dengying Fm water in Ziyang, Weiyuan, Gaoshiti and Moxi areas.

| Structure | Well | pH value | Content of common anions and cations/(mg* $L^{-1}$) | | | | | | | Water type | Salinity/(g $L^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $Na^+ + K^+$ | $Ca^{2+}$ | $Mg^{2+}$ | $Ba^{2+}$ | $Cl^-$ | $SO_4^{2-}$ | $HCO^{3-}$ | | |
| Ziyang | Z1 | 7.6 | 24898 | 2187 | 741 | 2051 | 44983 | 0 | 837 | $CaCl_2$ | 75.7 |
| Weiyuan | W51 | 7.7 | 27148 | 1952 | 342 | 979 | 46440 | 0 | 621 | $CaCl_2$ | 77.4 |
| Gaoshiti | Gsl | 4.1 | 7846 | 23715 | 12 735 | 1544 | 103945 | 315 | 0 | $CaCl_2$ | 156.3 |
| | Gs6 | 5.7 | 19496 | 22460 | 3 052 | 137 | 56788 | 0 | 0 | $CaCl_2$ | 102.1 |
| Moxi | Mx8 | 5.5 | 20582 | 18469 | 7 057 | 515 | 76079 | 0 | 0 | $CaCl_2$ | 122.8 |
| | Mx10 | 4.2 | 24697 | 15415 | 6 932 | 883 | 104956 | 0 | 0 | $CaCl_2$ | 153.4 |

The formation water of the Dengying Fm in Gaoshiti−Moxi area is also of $CaCl_2$ type, with a total salinity of 37−207 g/L, 85 g/L on average, a relative density of about 1.07, a PH value of 4−6. It has much higher salinity than that of Weiyuan−Ziyang area, and low $Ba^{2+}$ and $SO_4^{2-}$ content of the water suggests good sealing of the structure [23].

with a unified gas-water contact, a closure height of 500 m and a closure area of 16000 $km^2$. This paleo-gas reservoir was an overpressure gas reservoir, with paleo-pressure coefficient of up to 1.8 (see detail in the following section).

*2.2.2. Abnormal high pressure of paleo-gas reservoirs*

It is found from the observation of the cores and thin sections from the Dengying Fm in Well An'ping 1 and Well Gaoshi 1 that there are euhedral quartz and/or quartz + dolomite cavity-fillings formed after oil thermal cracking into asphalt, in which liquid methane inclusions are commonly seen. The study on the inclusions in the quartz formed during paleo-gas reservoir adjustment period after crude oil cracking (gas window) indicates that the inclusions in the quartz sampled at the depth of 4980.17−4981.87 m have a temperature distribution peak of 190−210 °C, and the inclusions sampled at the depth of 4958.40−4958.47 m have two temperature distribution peaks, 118−130 °C and 160−188 °C. Based on the homogeneous temperature obtained from the gas−liquid two-phase inclusions, the homogeneous temperature and density of the methane inclusions associated with the gas−liquid two-phase brine inclusions with simpler components were measured. Furthermore, the pressure when inclusions were captured was calculated by the method proposed by Duan [24]. The results show that the pressure of the Sample GS46 was 79.4−92.51 MPa at the temperature distribution peak of 200 °C, corresponding to a pressure coefficient of 1.35−1.57; the pressure of the Sample GS61 was 64.85−76.03 MPa at temperature distribution peak of 120 °C, corresponding to a pressure coefficient of 1.95−2.28, and 81.724−98.13 MPa at temperature distribution peak of 180 °C, corresponding to a pressure coefficient of 1.56−1.88.

The homogeneous temperature of the inclusions in quartz in the Sample A7 of the Dengying Fm in Well An'ping 1 during paleo-gas reservoir adjustment period after crude oil cracking (gas window) is 220−320 °C, mainly concentrating at 270−290 °C. According to the homogeneous temperature of the methane inclusions in quartz, the trapping pressure ranges from 101.6 to 228.52 MPa at 280 °C, mostly concentrating at 150.08−159.59 MPa, corresponding to a pressure coefficient of 1.77−1.88, while the rest pressure concentrates at 160.06−169.79 MPa, corresponding to a pressure coefficient of 1.88−2.00.

Thus, the paleo-gas reservoirs of the Sinian Dengying Fm not only had overpressure when oil cracked into gas (early paleo-gas reservoirs), but also had abnormal high pressure during early phase of adjustment (late paleo-gas reservoirs).

## 3. Evolution from the paleo-gas reservoirs of the Dengying Fm (gas storage center) to present gas reservoirs (gas preservation center)

### *3.1. Tectonic reworking and trap evolution*

*3.1.1. Breakup of large paleo-structural traps and formation of numerous small structural traps*

As was mentioned above, the paleo gas reservoirs of the Dengying Fm had a closure area of up to 19600 $km^2$ (Fig. 2). However, at present, there are more than 20 small structural traps in the Dengying Fm, including Ziyang, Jinshi, Weiyuan, Gaoshiti, An'pingdian, Moxi, Longnüsi, Zhougongshan, Hanwangchang, Laolongba, Dawoding, Tiangongtang, Ziliujing, Panlongchang and Jinshi etc, with a total closure area of no more than 4000 $km^2$, accounting for less than 1/3 of the total closure area of the paleo-traps of early phase, among which, Weiyuan structure is the largest, with a closure area of about 850 $km^2$ [25,26]. Present traps are generally high in the west and low in the east, with axial direction of NE and axis located along Laolongba, Weiyuan, Zizhong and Anyue area (Fig. 1). During the breakup of the paleo-structural traps, the closure changed significantly, for example, Weiyuan structure has a closure height of up to 895 m, but most of the other traps have small closure height, such as Ziyang, Jinshi, Gaoshiti, Moxi, Longnüsi and Guang'an structures, which are generally about 250 m in closure height.

Therefore, the breakup of large paleo-structural traps and the formation of dozens of small structural traps is one of the major products of the Himalayan tectonic reworking, during which, some structures were re-adjusted, such as Gaoshiti−Moxi structure, some were re-formed, such as Weiyuan structure, and some disappeared, such as Ziyang paleo-structure.

*3.1.2. Shifting of structural highs*

The axis of Leshan-Longnüsi palaeouplift has been shifting since Caledonian (early Paleozoic Era). During Caledonian, it

Table 3
Upper Sinian and Lower Cambrian formation fluid pressure in Weiyuan, Ziyang and Gaoshiti−Moxi areas.

| Area | Well | Formation | Middle depth of producing layer/m | Formation pressure/Mpa | Pressure coefficient |
|---|---|---|---|---|---|
| | Baolong 1 | Longwangmiao Fm | 4870.25 | 72.398 | 1.512 |
| | Moxi 11 | | 4728.50 | 75.922 | 1.638 |
| | Moxi 12 | | 4611.25 | 75.836 | 1.677 |
| | Moxi 13 | | 4612.00 | 75.871 | 1.679 |
| | Moxi 201 | | 4577.75 | 75.784 | 1.689 |
| Gaoshiti | Gaoke 1 | Deng 4 Member | 5011.25 | 55.857 | 1.140 |
| | Gaoshi 1 | | 5163.00 | 55.405 | 1.100 |
| | Gaoshi 1 | | 5024.75 | 52.276 | 1.060 |
| | Gaoshi 3 | | 5260.00 | 57.009 | 1.130 |
| | Gaoshi 6 | | 5210.50 | 57.779 | 1.130 |
| | Gaoshi 1 | Deng 2 Member | 5345.00 | 57.609 | 1.100 |
| Moxi | Moxi 8 | Deng 2 Member | 5440.50 | 58.617 | 1.080 |
| | Moxi 9 | | 5441.50 | 60.162 | 1.130 |
| Weiyuan | Wei 5 | Dengying Fm | / | 29.577 | 1.030 |
| | Wei 10 | | / | 29.400 | 1.030 |
| | Wei 30 | | / | 29.345 | 1.030 |
| | Wei 49 | | / | 27.533 | 1.010 |
| Ziyang | Zi 1 | Dengying Fm | 4099.00 | 41.650 | 1.030 |
| | Zi 2 | | 3722.10 | 37.670 | 1.010 |
| | Zi 3 | | 3847.00 | 40.020 | 1.010 |
| | Zi 7 | | 3961.60 | 40.630 | 1.030 |

The measured pressure data shows that the Lower Cambrian Longwangmiao Fm in Gaoshiti−Moxi area has overpressure in general, with the minimum pressure coefficient of 1.51 and the maximum pressure coefficient of 1.70, and 1.64 on average, which is quite different from the Dengying Fm, so gas reservoirs of Longwangmiao Fm and Dengying Fm are independent from each other, with independent pressure systems.

was nearly NEE, extending along Ya'an, Lezhi, Moxi and Guang'an. During Indosinian (Triassic to Jurassic), it shifted from north to south, with shifting distance decreasing from west to east. For instance, the shifting distance in Ziyang was 31 km, but only 6 km in Gaoshiti−Moxi area. During Himalayan (Cenozoic Era), Ziyang structural high migrated 25 km to Weiyuan, while Gaoshiti−Moxi structural high only migrated 3 km. Therefore, from Caledonian to now, the shifting distance gradually increases from east to west. For example, Ziyang−Weiyuan structural high migrated 56 km in

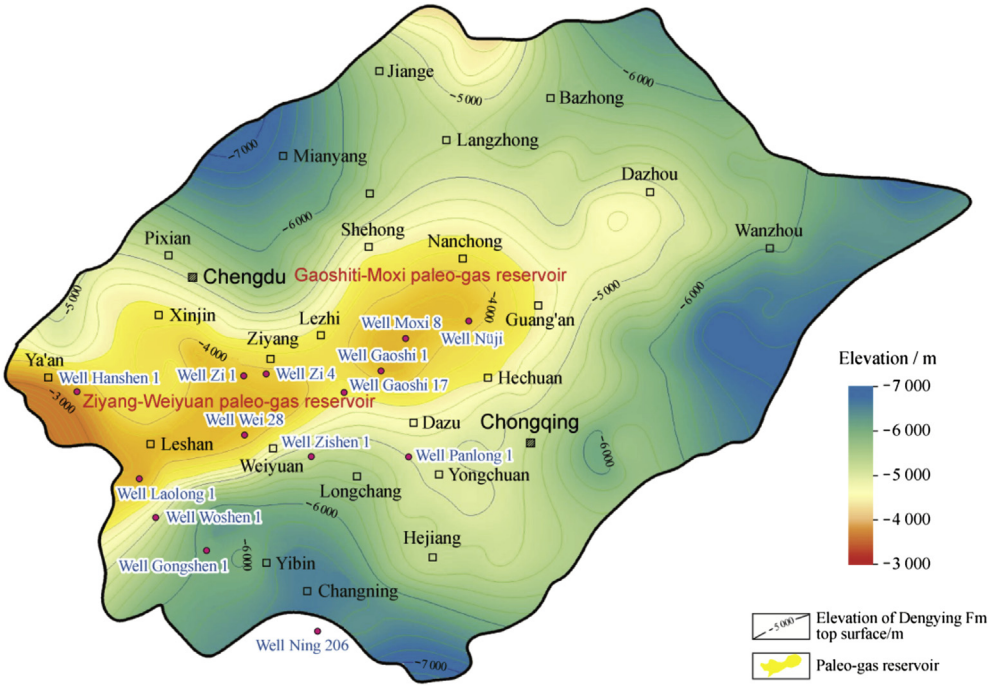


Fig. 2. Distribution of Yanshanian paleo-gas reservoirs formed by in-situ cracking of the paleo-oil reservoirs of the Sinian Dengying Fm in the Sichuan Basin. The base is the top structure map of the Dengying Fm before the deposition of middle Jurassic Shaximiao Fm

total, but Gaoshiti−Moxi structural high only migrated 9 km, which indicated that the structures of Ziyang and Weiyuan areas were less stable than that of Gaoshiti−Moxi area.

### 3.1.3. Uplifting and erosion

The fission track test analysis results of the 22 apatite samples from Weiyuan and Moxi areas indicate [27] that during Late Mesozoic−Cenozoic, Weiyuan area experienced fast and large magnitude uplifting, resulting in the erosion to Lower Triassic Jialingjiang Fm, and extensive exposure of carbonate rocks of Middle Triassic Leikoupo Fm in the core area, which formed the anticline with the largest surface area and oldest outcropped strata (carbonate rocks) west of Huaying Mountain in the Sichuan Basin [27,28].

Based on the modeling results of the apatite fission track, the uplifting and erosion (thermal history) of Weiyuan area can be divided into three types (Fig. 3): (1) Subsidence-uplifting type (Fig. 3a). After Late Cretaceous (100 Ma), deep burial and temperature rise happened and the maximum buried depth reached at Early Cenozoic (the general buried depth was greater than the apatite fully anneal isothermal surface). After a short period of retention, the formations uplifted rapidly and annealed to surface temperature. (2)Retained annealing-rapid uplifting type (Fig. 3b). During Late Cretaceous − Paleogene, the apatite fission track shows that some areas retained in partial annealing range, and experienced slow uplifting and cooling, since Neogene (20−15 Ma) these areas has gone through rapid uplifting and cooling to surface temperature. (3) Staged rapid uplifting (Fig. 3c). With staged rapid uplifting and cooling-slow uplifting-rapid uplifting and cooling again, this type of uplifting retained short in apatite fission track annealing period on the whole. During Late Paleocene−Early Eocene (60−45 Ma) and Neogene (20 Ma), rapid uplifting cooling and annealing occurred. Thus, in Weiyuan anticlinal area, uplifting cooling and annealing mainly occurred since Late Cretaceous and uplifting cooling mainly occurred since Cenozoic, especially since Neogene (20−15 Ma), rapid uplifting cooling and annealing was substantial. According to the calculation results of paleogeothermal field (the paleogeothermal gradient was 26.6 °C/km and surface temperature was 20 °C), conclusion can be drawn that the uplifting and denudation thickness of Weiyuan anticline is generally greater than 4000 m since Late Cretaceous and substantial denudation occurred in Neogene (with an average denudation thickness of 2000 m). Similarly, the fission track analysis results of the samples taken from Well Mo 24 and Well Mo 58 in Moxi area indicated that the uplifting and erosion thickness there was 1743−2030 m [29] since 60 Ma, causing the exposure of Jurassic Shaximiao Fm on the surface.

The available drilling data shows that Weiyuan area has similar strata overlying Dengying Fm with Gaoshiti−Moxi area. But nowadays, Lower Triassic Jialingjiang Fm is exposed in the highest point in Weiyuan area, and the strata overlying Jialingjiang Fm were eroded completely; while in Gaoshiti−Moxi area, the residual thickness of Leikoupo Fm and its overlying strata is about 2850 m, indicating that the maximum eroded amplitude of Weiyuan area is 2850 m higher than that of Gaoshiti−Moxi area.

In summary, Himalayan tectonic activities mainly included breakup of large structural traps, structural high migration and uplifting and erosion. Weiyuan area was characterized by large uplifting amplitude, strong tectonic deformation and strong trap reworking, while central Sichuan Basin was characterized by small uplifting amplitude, weak tectonic deformation and weak trap reworking. The evolution history can be divided into two phases: (1) compressional folding phase from 100 Ma to 20 Ma: this phase featured strong compression and weak uplifting and erosion, during which Weiyuan, Gaoshiti and Moxi structures took shape preliminarily, the early overpressure paleo-gas reservoirs formed by oil cracking adjusted into late overpressure paleo-gas reservoirs; and (2) rapid uplifting and erosion phase since 20 Ma: this phase mainly saw uplifting and erosion, which, fastest and most at the top of Weiyuan structure, led to further adjustment/damage to the late overpressure paleo-gas reservoirs into the present normal pressure gas reservoirs.

### 3.2. Evolution from early overpressure paleo-gas reservoirs to late overpressure paleo-gas reservoirs and present normal-pressure gas reservoirs

The study on the cavity filling sequence of Wells Gaoke 1, Gaoshi 1 and Anping 1 shows that there are multiple phases of fluids filling into the Dengying Fm reservoirs. Especially after

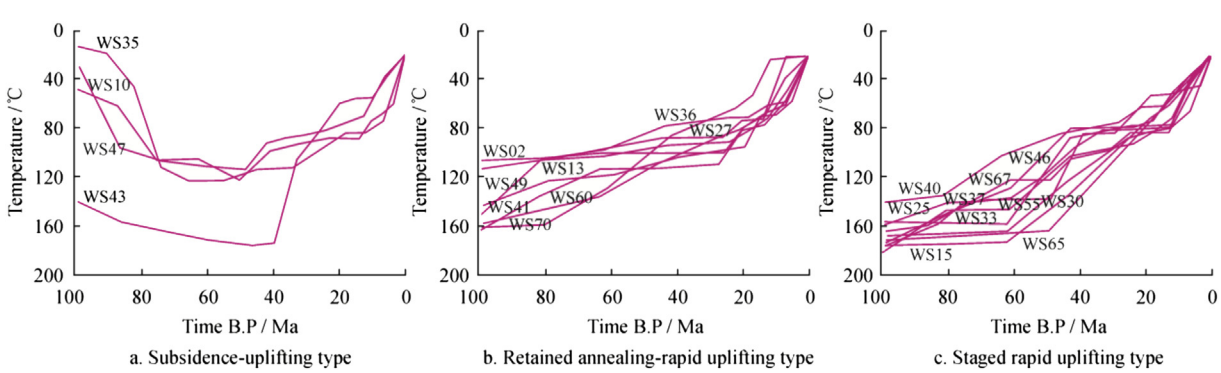


Fig. 3. Thermal evolution history simulated by the apatite fission track of Weiyuan anticline (ws35 et al. represent sample numbers).

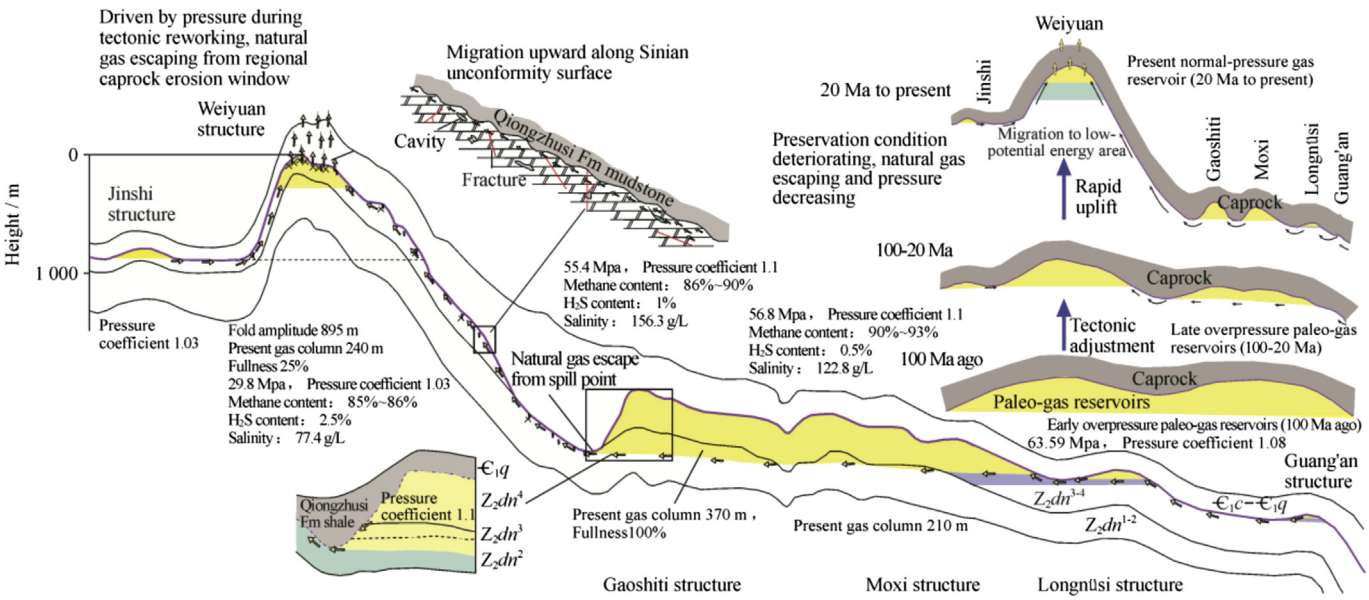


Fig. 4. Features of the differential accumulation and distribution of the natural gas in the Sinian Dengying Fm, Sichuan Basin.

crude oil cracking into gas and bitumen, some quartz or dolomite + quartz or calcite fillings continued to fill into reservoir pores, resulting in their coexistence with bitumen. For example, in the reservoirs of Deng 4 Member at different depth in Well Gaoshi 1 and Anping 1, coexistence of quartz + dolomite/quartz and asphalt or calcite and asphalt in one pore can be seen.

The previous study on the quartz-filled inclusions after crude oil thermally cracking into bitumen shows that the quartz is rich in liquid methane inclusions and gas−liquid two-phase brine inclusions, indicating that the fluid in which quartz formed had the properties of oilfield brine. Therefore, the location where quartz crystallized and precipitated represents the location of the bottom water or edge water of paleo-gas reservoirs, while the location of thermal-cracking bitumen represents the location of paleo-oil reservoirs, correspondingly, the gas-water contact of late paleo-gas reservoirs can be restored through the distribution of the bitumen and quartz. As was mentioned above, some of the quartz in the reservoirs of Gaoshiti and Moxi structure was formed after bitumen, and co-exist with thermal-cracking bitumen, indicating that the paleo-gas-water contact of the two structures migrated upwards and the space originally occupied by paleo-gas reservoirs had been occupied by edge water or bottom water.

1) The cracking of crude oil in paleo-oil reservoirs gave birth to early overpressure paleo-gas reservoirs (100 Ma), in which bitumen and gas co-existed; the volume variation and the pressure increase occurred during oil thermal cracking would inevitably lead to downwards pushing of ancient OWC (oil-water contact) to form new ancient gas-water contact (the mark of the gas-water contact has not been found so far); under the effect of overpressure, part of methane dissolved into water to form water-soluble gas.
2) The early overpressure paleo-gas reservoirs adjusted into the late overpressure paleo-gas reservoirs (100−20 Ma). The quartz filled in Deng 4 Member after crude oil cracking (gas window) occurs at the smallest depth of 4957.7 m, very close to the buried depth of the top Deng 4 Member (4954.5 m), which indicates that, after the formation of the early overpressure paleo-gas reservoirs, the paleo-gas reservoir at this location had been destroyed or migrated to other places, and the space originally occupied by paleo-gas reservoirs had been occupied by gasfield brine, but the formation water at this time still had overpressure.
3) The late overpressure paleo-gas reservoirs adjusted into the present normal-pressure gas reservoirs (since 20 Ma). Drilling results show that the present gas reservoir of Deng 4 Member is mainly at the depth of 4956−5093 m, indicating that natural gas has re-accumulated in this well.

The previous analysis shows that after the formation of the paleo-gas reservoirs of the Dengying Fm, the paleo-gas-water contact has been constantly changing till now. The variation of paleo-gas-water contact indicates paleo-gas reservoirs have been constantly adjusting themselves, which is also corroborated by the evolution from the overpressure paleo-gas reservoirs to the normal-pressure gas reservoirs now. The previous analysis on the fluid inclusions in quartz indicates that the fluid of the paleo-gas reservoirs of Deng4 Member in Gaoshiti−Moxi area had abnormal overpressure, with the pressure coefficient up to 1.56−2.00, while the fluid of the present Deng4 Member gas reservoirs has normal pressure, with a pressure coefficient of 1.06−1.14; Deng2 Member gas reservoirs are also normal in pressure, with a pressure coefficient of 1.10 (Table 3). The present Dengying Fm gas reservoirs in Weiyuan and Ziyang areas are also normal in pressure, with

the pressure coefficient of 1.01−1.03 (Table 3). Comparison of the pressure coefficient of the present gas reservoirs with that of paleo-gas reservoirs shows that the evolution from overpressure paleo-gas reservoirs to present normal-pressure gas reservoirs after crude oil cracking (gas window) is a pressure decrease process on the whole.

## 4. Differential accumulation and distribution of natural gas of the Dengying Fm and the main controlling factors

As was mentioned above, before the deposition of Jurassic Shaximiao Fm, a paleo-gas reservoir extending from Guang'an in the east to Ya'an in the west had been formed in the Sinian Dengying Fm of the Sichuan Basin, which was an overpressure gas reservoir, with a uniform pressure system at a pressure coefficient of about 1.8 (Fig. 2). During Late Yanshan − Early Himalayan stage, more than 20 small structural traps were formed in Dengying Fm due to tectonic movements, including Ziyang, Jinshi, Weiyuan, Gaoshiti, Anpingdian, Moxi, Longnüsi, Zhougongshan, Hanwangchang, Laolongba, Dawoding, Tiangongtang, Ziliujing, Panlongchang, etc (Fig. 1). It is reasonable that the structures formed within the scope of the early paleo-gas reservoirs were the most favorable for the re-accumulation of natural gas and the formation of late paleo-gas reservoirs. The fillings in reservoir pores and cavities and the composition of the inclusions in the fillings indicate that before the large-scale uplifting and erosion (20 Ma ago), the structures within the scope of the early paleo-gas reservoirs (such as Weiyuan, Gaoshiti, Anpingdian, Moxi and Longnüsi structure) had formed late overpressure paleo-gas reservoirs, with gas fullness greater than or equal to 100%.

At the start of uplifting100−60 Ma, Weiyuan trap, small in structure scale and closure amplitude, took shape preliminarily, the strata overlying the ancient gas reservoir was slightly eroded at this time. Although the paleo-gas reservoir had reformed, it still had abnormal high pressure since massive gas leakage hadn't happened yet due to good sealing conditions.

Since 20 Ma, as the uplifting intensified gradually and the strata overlying the ancient gas reservoir in Weiyuan area were eroded rapidly, especially at the structural core, where the erosion reached Lower Triassic Jialingjiang Fm at most and Leikoupo Fm was exposed in a large area, leading to significant reduction of caprock sealing capacity [21]; due to the joint action of the formation of fracture system and fluid abnormal pressure, the caprock was made unable to seal the over 240 m gas column in the Dengying Fm of Weiyuan structure anymore, so the natural gas of the Dengying Fm began to leak off and escape from the structural window of Lower Triassic Jialingjiang Fm, causing the degradation of Dengying Fm trap in Weiyuan area from type I to type III according to Sales's classification [20], and the initiation of differential accumulation and escape process of the natural gas of the Dengying Fm west of Huaying Mountain in the Sichuan Basin. In the process, the natural gas outside the spill point of gas reservoirs, such as Ziyang, Jinshi and Longnüsi−Moxi−Anpingdian−Gaoshiti gas reservoirs, which

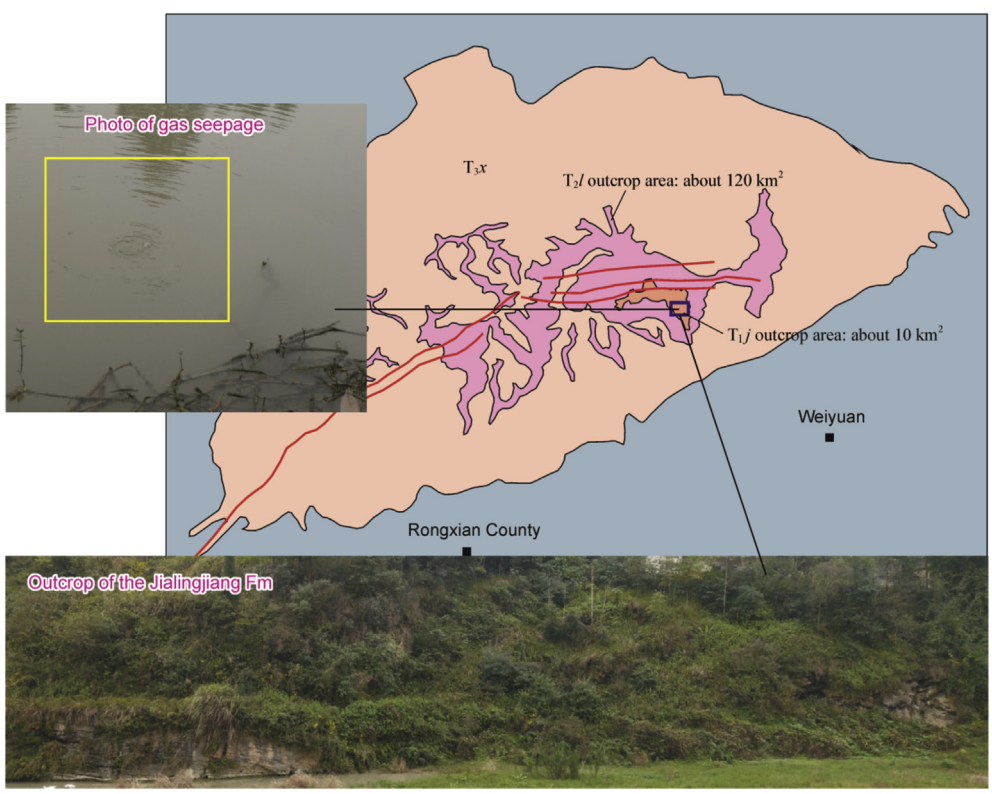


Fig. 5. Schematic diagram of the gas bubble spill point at the top of Weiyuan structure

migrated along the unconformity surface on the top of the Dengying Fm and accumulated in Weiyuan structure, then escaped through the structural window of Lower Triassic Jialingjiang Fm (Fig. 4), leading to the conversion of early structural-lithological gas reservoirs to structural gas reservoirs, gas-water contact migrating upwards, gas fullness of trap varying from over 100% to less than 100% in gas leaking off area, such as Weiyuan area (about 25%), and pressure coefficient transiting from abnormal high pressure to normal pressure, and approaching 1.0 near Weiyuan structure.

The reasons why the gas of the Dengying Fm can be migrated long distance in basin-wide and accumulated are as follows:

1) The gas source charging the Dengying Fm is sufficient (overfilled or over-supplied basin). The gas source rocks of the Dengying Fm includes Lower Cambrian Qiongzhusi Fm, Upper Sinian Doushantuo Fm and Deng 3 Member, among which, Qiongzhusi Fm is the best source rocks in the Sichuan Basin, with extensive distribution, large thickness and high content of organic matter [30]. The natural gas of the Dengying Fm now is mostly from the cracking of crude oil under high temperature, and the distribution of reservoir bitumen shows that the paleo-oil reservoirs of the Dengying Fm was large in area, so provided sufficient gas for the Dengying Fm [18,31].
2) During Himalayan, a series of structural traps with gradually ascending elevation of spill point were formed in Guang'an, Longnüsi, Moxi–Gaoshiti and Weiyuan areas from NE to SW.
3) The main migration pathway for natural gas, the unconformity surface on the top of the Dengying Fm is not only well-developed in pores and cavities and good in permeability, but also distributes stably across the basin [32,33].
4) Due to uplifting and erosion, a "window" for natural gas escape was formed at the top of Weiyuan structure.

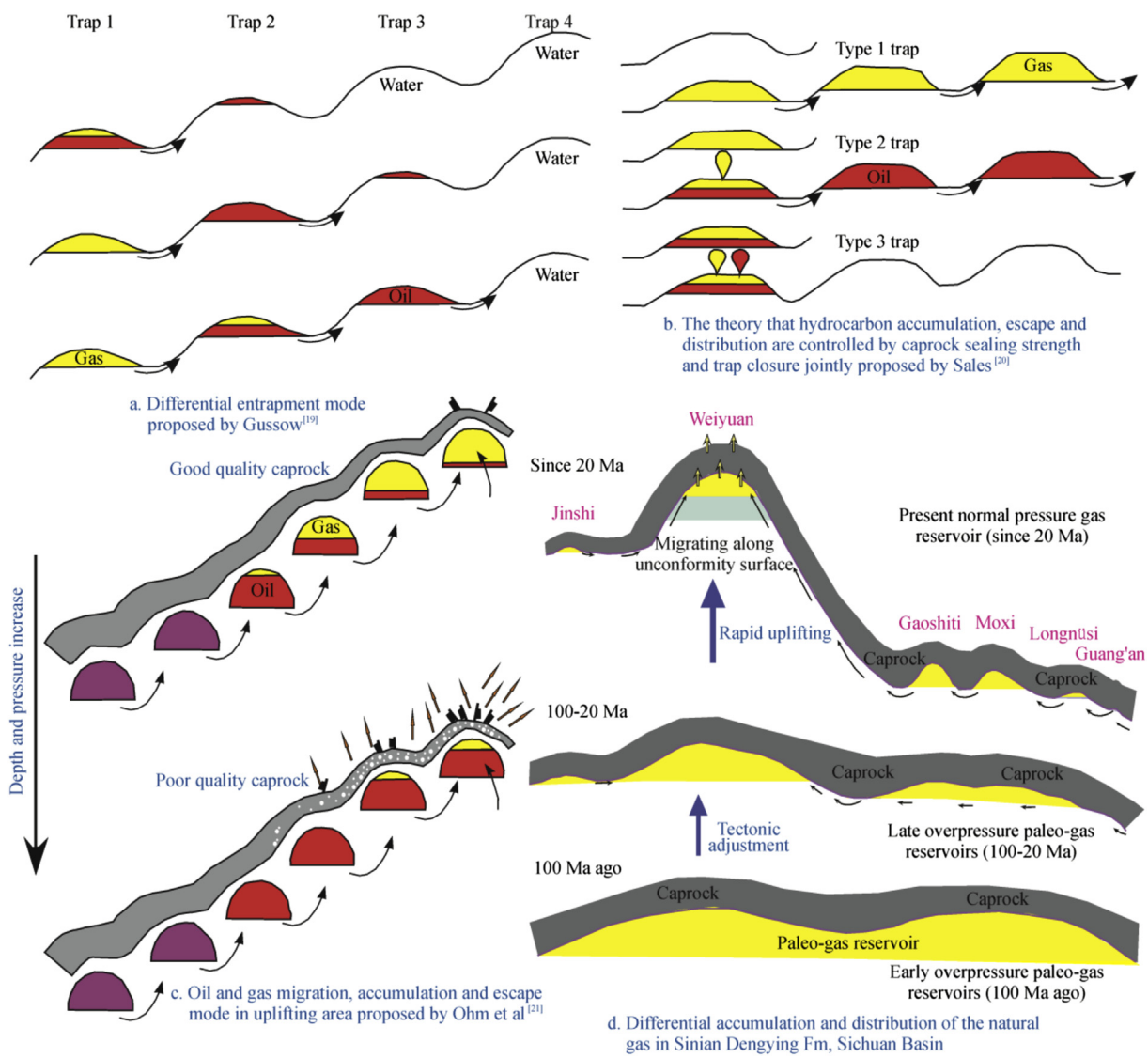


Fig. 6. Similarities and differences between the differential accumulation and distribution of the natural gas in the Sinian Dengying Fm, Sichuan Basin, and classical differential oil and gas entrapment theory.

Evaporite rocks of stable distribution in the Leikoupo Fm and the Jialingjiang Fm are the regional caprocks for marine oil and gas in the Sichuan Basin, which is one of the most important factors to preserve and stop the escape of gas there [34,35]. However, the Jialingjiang Fm at the top of Weiyuan structure outcrops (the only area where the Jialingjiang Fm is exposed in the Sichuan Basin in the west of Huaying Mountain) and the Lower Triassic−Jurassic continental strata, Middle Triassic evaporite rocks and part of evaporite rocks of the Jialingjiang Fm overlying it are already eroded away. In addition, there developed a number of faults in Weiyuan structure and its elevation is relatively higher in the Sichuan Basin (structural high buried depth of 902 m). Therefore, Weiyuan structure is the main escape pathway for the Dengying Fm gas in the central and western Sichuan. At present, the gas seepages discovered and are still leaking natural gas in the river near Laochang Village in Weiyuan structural center (Fig. 5), so the area has heavy $H_2S$ odor. Thus, it can be concluded that the long distance migration, adjustment and dissipation of natural gas of the Dengying Fm is still going on and the gas reservoirs of the Dengying Fm in the Sichuan Basin are still in dynamic state.

The straight distance from Weiyuan structure to Guang'an structure is about 210 km. The straight distance from Weiyuan to the southern basin boundary in Xuyong is about 190 km. And the distance from Weiyuan to Mianyang City of the north basin boundary is 210 km. It can be inferred that the adjustment of gas reservoirs at the late phase of the Sinian Dengying Fm in the Sichuan Basin (since 20 Ma) covers an area of $6 \times 10^4$ km in the west of Huaying Mountain, accounting for 1/3 of the whole Sichuan Basin area (Fig. 1).

## 5. Discussion

### *5.1. Similarities and differences between the differential accumulation and distribution of the natural gas in the Sinian Dengying Fm and classical differential oil and gas entrapment theory*

The classical differential oil and gas entrapment theory proposed by Gussow [19] holds that under hydrostatic condition, if a series of traps with spill point ascending from downdip direction to updip direction along the main hydrocarbon migration pathway, under buoyancy, they will be filled by oil, oil and gas, and gas respectively from downdip direction to updip direction when oil and gas source is sufficient and caprock sealing property is good (Fig. 6a). Sales [20] improved the classical differential oil and gas entrapment theory proposed by Gussow from the mutual relationship between trap closure height, caprock sealing intensity and gas column height [19] and divided the trap into three classes (Class 1, Class 2 and Class 3) (Fig. 6b). The traps discussed by Gussow [19] are Class 1 traps in Sales's theory [20].

Comprehensive analysis of all the references [19,20,36−38] shows that differential oil and gas entrapment requires the following four basic conditions: ① abundant oil and gas sources in regional downdip direction; ② good regional oil and gas migration pathway allowing long-distance migration of oil and gas; ③ a series of contiguous traps in the regional background, with spill point ascending in updip direction; and ④ static formation water filling the reservoirs.

Obviously, the differential accumulation and distribution of the natural gas of the Dengying Fm in the Sichuan Basin has the following differences: ① the initial driving force of them is different. The large-scale long-distance migration of the Denying Fm natural gas is driven by the natural gas leak-off and escape from Weiyuan structure rather than abundant oil and gas sources in downdip direction; ② the initial fluid in traps is different. Before large-scale long-distance migration, the traps of the Dengying Fm were filled with natural gas rather than formation water, with possible gas fullness of over 100%; ③ the results of gas differential accumulation are different. Classical differential oil and gas entrapment theory requires that source rocks continuously generate and expel oil and gas; as a result, there would be more and more gas in traps. In contrast, when large-scale long-distance migration and differential accumulation of natural gas happened in the Dengying Fm, the source rocks of the Dengying Fm and the Qiongzhusi Fm had almost stopped hydrocarbon generation and expulsion, and as the gas leaked off and escaped from the top of Weiyuan structure, the natural gas in the Dengying Fm decreases constantly.

But there are some similarities between the differential accumulation and distribution of the natural gas in the Sinian Dengying Fm, Sichuan Basin and classical differential oil and gas entrapment theory: ① they both have single migration and accumulation force. Buoyancy is the dominant continuous migration drive and the dynamic (buoyancy) process is only controlled by structural form (with ascending updipping spill point elevation). ② there is homogeneous conducting system. Permeable and connected pathway system (carrier bed) takes dominance, without break in spatial and temporal. For the Dengying Fm, it is the unconformity surface at its top. ③ Unified hydrodynamic system, i.e. formation pressure coefficient is equal to or changes regularly.

### *5.2. Implication of differential accumulation and distribution of the natural gas in the Sinian Dengying Fm to gas exploration in the Sichuan Basin*

The long-distance migration and differential accumulation of Dengying Fm natural gas basin-wide along the unconformity surface at its top give a great inspiration and guidance for oil and gas exploration in the Sichuan Basin.

1) The exploration of natural gas of the Dengying Fm should target at structural gas reservoirs. Since natural gas migrated long-distance along the unconformity surface at the top of Sinian strata, if there are no structural traps, gas can hardly accumulate and large-scale

stratigraphic-lithological gas reservoirs are unlikely to form.

2) The exploration of Dengying Fm natural gas should focus on the structural traps near Weiyuan area. The top of Weiyuan structure is the "window" for the escape of natural gas, so all the natural gas of the Dengying Fm migrate towards Weiyuan structure, and fill up the structural traps along migration pathway, before they can continue migrating and escaping from Weiyuan structure. Therefore, all the structural traps located on the gas migration pathway have reservoir-forming conditions. The unconformity at the top of the Dengying Fm is stably basin-wide with good continuity, so it can be inferred that all the structural traps of the Dengying Fm could form oil and gas reservoirs. Accordingly, the Dengying Fm in Tongnanba structure (the biggest underground structure in the Sichuan Basin) in northern Sichuan Basin is worthy of exploration. However, controlled by Early Cambrian Mianyang-Changning extensional intracratonic sag, Dengying source rocks and premium reservoir rocks are most abundant and most developed in and on both sides of the extensional sag [18,32], therefore, the structural traps of the Dengying Fm in and on both sides of Mianyang-Changning extensional intracratonic sag near Weiyuan structure are the most prospective exploration target.
3) The preservation conditions of shale gas at the bottom of Lower Cambrian are poor. The bottom of Lower Cambrian is generally above the top of Upper Sinian Dengying Fm, which has poor preservation conditions and connects with surface through Weiyuan structure to some extent (the pressure coefficient of Lower Cambrian Qiongzhusi Fm is 1.01 in Well Wei 201), this is quite different from Lower Silurian Longmaxi Formation in Jiaoshiba [39,40].
4) According to the theory proposed by Sales [20], the strata overlying Dengying Fm in Weiyuan structure have some exploration potential, but large gas reservoirs are unlikely to occur due to the limitation of preservation conditions.

## 6. Conclusions

1) From Weiyuan to Gaoshiti−Moxi, Longnüsi and Guang'an structure, the straight distance is from 110 km, 80 km and 30 km, with a total distance of 220 km. The elevation of Dengying Fm structural top gradually deepens, from −2400 m to −4640 m, −4930 m and −5300 m, with a drop height of 2900 m from Weiyuan to Guang'an structure. The spill point of the structural traps gradually deepens from −3200 m to −4940 m, −5010 m and −5550 m, with a drop height of 2250 m. The composition of Dengying Fm natural gas and formation water in these structures are similar and the formation pressure is normal.
2) Before 100 Ma, the crude oil in the paleo-oil reservoirs of the Dengying Fm cracked into early overpressure paleo-gas reservoirs in situ; during 100−20 Ma, continuous uplifting of the Sichuan Basin, together with the migration of structural highs and formation of Weiyuan structure made the early overpressure paleo-gas reservoirs adjust into late overpressure paleo-gas reservoirs; since 20 Ma, as the Sichuan Basin continuously uplifted, the overlying strata of Weiyuan structure were eroded rapidly, resulting in the significant damage to the sealing property of the caprock and deterioration of preservation conditions, subsequently, the natural gas of the Dengying Fm began to leak off and escape from the erosion window of Lower Triassic Jialingjiang Fm at the top of Weiyuan structure, when the differential accumulation and escape process of the natural gas of the Dengying Fm in the Sichuan Basin in the west of Huaying Mountain started. The natural gas outside the spill point of the structural traps in Ziyang, Jinshi and Longnüsi−Moxi−Anpingdian−Gaoshiti migrates along the unconformity surface at the top of the Dengying Fm and accumulates in Weiyuan structure, and escapes towards surface through the erosion window of Lower Triassic Jialingjiang Fm, resulting in the pressure coefficient transiting from abnormal to normal.
3) The differential accumulation and distribution of natural gas in the Sinian Dengying Fm, Sichuan Basin is consistent with classical differential oil and gas entrapment theory in terms of single migration and accumulation force (buoyancy), homogeneous conducting system and unified hydrodynamic force system, but is different from classical differential oil and gas entrapment theory in terms of the initial source force, initial fluids within traps and natural gas differential migration results.
4) The structural traps in and on both sides of Mianyang-Changning extensional intracratonic sag near Weiyuan structure are the most prospective exploration targets for the natural gas of the Dengying Fm.

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