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Structural deformation characteristics and its influence on shale gas preservation of the Wufeng–Longmaxi Formation in the Wuxi area, Chongqing, China

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The Upper Ordovician Wufeng to Lower Silurian Longmaxi Formation has a good material basis for marine shale gas development, and the structural preservation condition is the key factor to control the rich and integrated shale gas reservoirs in the Wuxi area of Chongqing City, China. Based on the seismic-structural interpretation data, combined with the regional structural background and drilling effect, the structural deformation characteristics and shale gas structural preservation conditions are comprehensively analyzed in the study area. The Wuxi area is located at the structural junction of the Sichuan Basin and southern Dabashan along with strong structural deformations. Seven rows of NW to near EW structural belts are mainly developed. The fold styles and fault development degrees of different structural belts are different, and the difference in the structural preservation conditions of shale gas is also obvious. The study results reveal that the shale gas structure preservation conditions of the Wufeng–Longmaxi Formation in the Wuxi area are overall poor and only locally better. The structure preservation conditions for shale gas enrichment and accumulation are divided into four grades, such as the good Class I area, the general Class II area, the poor Class III area, and the very poor Class IV area. Among them, the Heiloumen structural zone and Huangcaoping buried structural zone nearby the Sichuan Basin have good preservation conditions and are classified as the good Class I preservation area. The macroscopic preservation type of shale gas in the Wufeng–Longmaxi Formation of the Wuxi area belongs to the complex structural preservation of the basin margin. Three structural preservation modes of shale gas in the study area have also been confirmed, including the lost destruction type, lost residual type, and trap preservation type. The trap preservation type is more conducive to the preservation of shale gas, which is the most favorable structural mode for shale gas exploration.

KEYWORDS

structural deformation characteristics, preservation mode, shale gas, Wufeng–Longmaxi Formation, Wuxi county of Chongqing city

Introduction

With the recently substantive breakthroughs and commercial development of marine shale gas in the Changning, Weiyuan, Fuling, Zhaotong, Fushun–Yongchuan, Pengshui, Nanchuan, and Dingshan areas from the Sichuan Basin and its surroundings, China's shale gas exploration and development has entered a very rapid pace, especially the exploration and development progress of shale gas in the complex structural regions at the margin of the Sichuan Basin (Jin et al., 2018; Potter, 2018; Ma et al., 2020; Liu et al., 2021a; Nie et al., 2021; Li et al., 2022; Wang et al., 2022). The Wuxi area of Chongqing city is situated in the transition zone between the northeastern margin of the Sichuan Basin and the Dabashan thrust belt, which belongs to the typical complex structural region of the basin margin. In this area, the black shale of the Upper Ordovician Wufeng to Lower Silurian Longmaxi Formation, which has the characteristics of large thickness, high organic matter abundance, and thermal evolution degrees, was widely developed in a similar sedimentary environment to shale gas fields today (Liu et al., 2016; Liu et al., 2018; Wang et al., 2018; Nie et al., 2019; Wang et al., 2019; Wu et al., 2019; Tang et al., 2020; Zhang et al., 2020). This also implies that the shale, as an important target stratum, has a good material basis for shale gas accumulation, and the Wuxi area is considered a favorable shale gas exploration area. Meanwhile, a number of shale gas geological survey wells have also been arranged in this area since 2012 and the WX2 well in the Wenfeng anticline deployed by PetroChina has obtained a good shale gas performance, with 2.32 and 8.39 m^3/t of mean and maximum gas-bearing contents, showing that the Wufeng–Longmaxi Formation in the area is of favorable shale gas exploration and developmental potential (Liang et al., 2015; Liu et al., 2017; Wu et al., 2017; Shi et al., 2018; Liu et al., 2021b; Zhao et al., 2021; Zhao et al., 2022). Although some shale gas exploration wells have achieved effective exploration results in this area, such as X202, X203, and X205 wells, none of them is up to the commercial production scale. Furthermore, the complex geological structural conditions have an important impact on the accumulation and preservation of shale gas in the Wufeng–Longmaxi Formation and deserve more attention. Due to the certain constraint of self-contained, self-sourced, and self-accumulating reservoirs, a detailed evaluation of structural deformation characteristics may be conducted through the comprehensive analysis of shale gas enrichment, accumulation, and preservation. This study will systematically analyze the structural deformation characteristics and shale gas structural preservation conditions of the Wuxi area in Chongqing city based on the seismic-structural interpretation in the study area, combined with the regional tectonic background and actual drilling results. This may provide the geological basis for favorable shale gas exploration and development of the Upper Ordovician Wufeng to Lower Silurian Longmaxi Formation in the area, which is of great significance for us to understand shale gas accumulation and preservation in the complex structural belts at the margin of the Sichuan Basin.

Geological setting

Multi-phase structural transformation went through the Wuxi area in geological history, and the structural deformation was much stronger than that within the Sichuan Basin (Chen et al., 2016; Yang et al., 2019). Due to the superimposed deformation of the southern Dabashan thrust-fold belt and the high-angle tectonic belt of the eastern Sichuan Basin, the overall structural style presented the complex fold of northwest (NW) to near east-west (EW) (Figure 1). Bounded by major deep-large faults, the area could be divided into three secondary structural units, such as the southern Dabashan ramp fault belt in the northeast, the southern Dabashan frontal fold belt in the middle, and the high-angle fold belt of the eastern Sichuan Basin in the southwest (Yu et al., 2018). In other words, from the inside to the outside of the Sichuan Basin, the magnitude of strata uplift and denudation, the intensity of fold deformation, and the degree of fault development all gradually increased. Towards the northern side of the Wanyuan–Wuxi fault, the structural mode mainly presented as a linear complex fold extending in an NW arc shape and anticlinoria and synclinore were arranged alternately (Figure 1). The fold often showed the branching and merging phenomenons, and the surfaced and underground faults were relatively developed, which have associated with back thrust and ramp fault combinations, respectively, and finally disappeared to the deep or merged with the main detachment fault belt. The Upper Cambrian to Middle Silurian strata occurred in the anticlinoria and the Permian and Triassic strata were exposed to the synclinore (Figures 2A–D). Towards the southern side of the Wanyuan–Wuxi fault and the northern side of the Shashi hidden fault, the intensity of structural deformation weakened and the structural mode transitioned into NNW complex closed-open folds with a relatively complete shape (Figure 2E). Surfaced faults in this location were not developed and there were many underground hidden faults according to the seismic and remote sensing image data. Towards the southern side of the Shashi hidden fault nearby the internal Sichuan Basin, the structural mode was relatively stable and wide with fewer faults, and the Triassic to Jurassic strata were exposed on the surface (Figure 2F). Under the structural superposed deformation, the fold style in this location changed complexly and focused on the wide-gentle fold and box-shaped anticline (Figure 3).

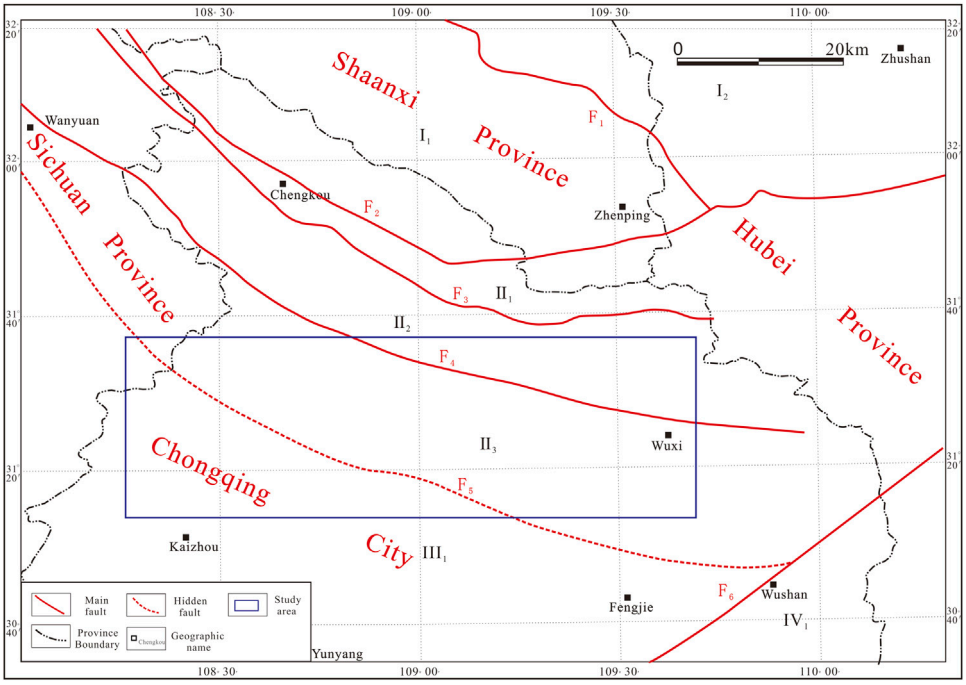

FIGURE 1
Geological structure of the study area. F_1, Hongchunba–Zengjiaba fault; F_2, Chengkou fault; F_3, Wuping fault; F_4, Wanyuan–Wuxi fault; F_5, Shashi hidden fault; F_6, Qiyaoshan basement fault; I_1, southern Dabashan linear synclinore–epimetamorphic belt; I_2, northern Dabashan dome-shaped anticlinoria–hypometamorphic belt; II_1, southern Dabashan imbricate fault belt; II_2, southern Dabashan ramp fold belt; II_3, southern Dabashan frontal fold belt; III_1, high-angle fold belt of eastern Sichuan Basin; IV_1, Qiyaoshan depression and fold belt.

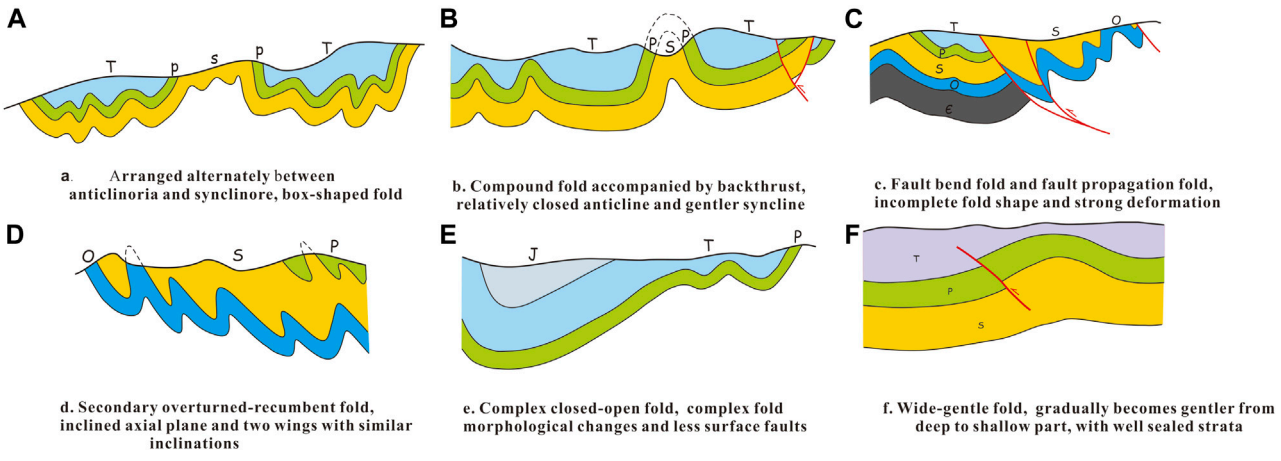

FIGURE 2
Main structural styles in the study area.

Structural partitioning and deformation characteristics

According to the interpretation results of seismic-structural data and regional structural distribution characteristics, taking the top boundary structures of Middle Ordovician as an example, the demonstration area can be divided into seven main NW to near EW structural belts from the north to south direction (Figures 3, 4). The detailed deformation characteristics of each structural belt are described as follows.

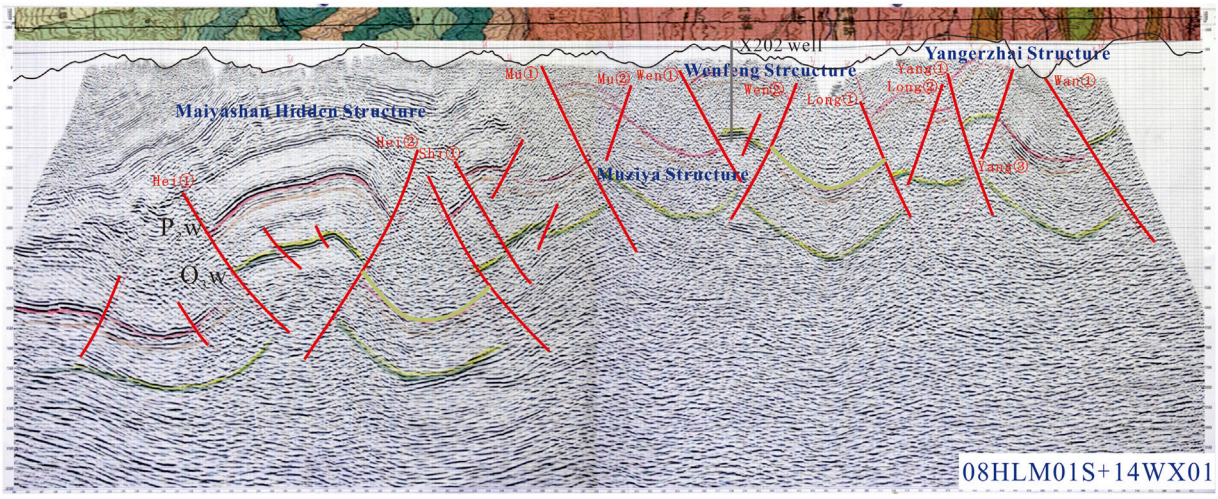

FIGURE 3
A–A′ seismic-structural profile in the study area.

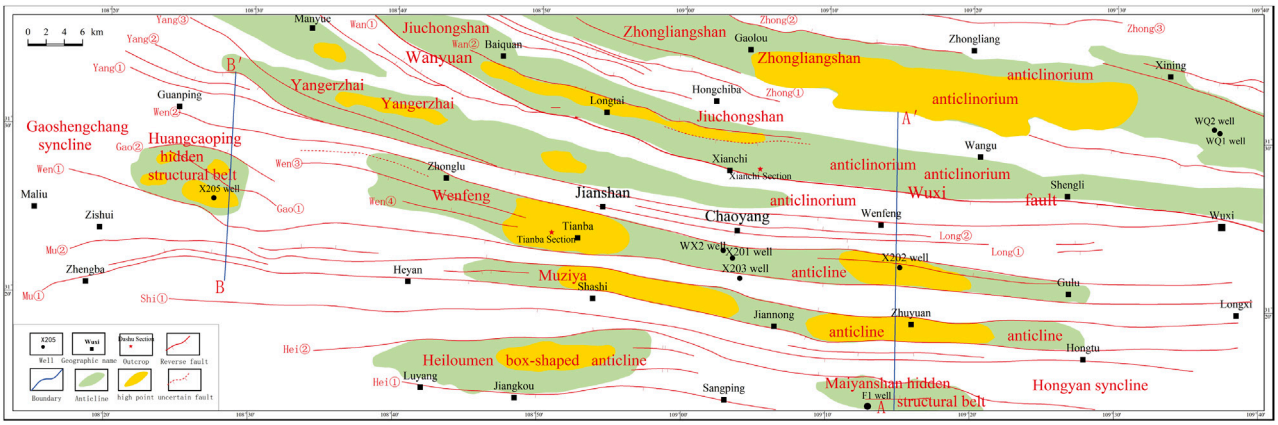

FIGURE 4
Top boundary of Middle Ordovician in the study area.

Heiloumen structural belt

The Heiloumen structural belt locates at the southern margin of the study area with the NWW to near the EW strike and mainly develops a box-shaped anticline. Its southern and northern flanks are controlled by the Hei① and Hei② faults, respectively. There are two structural high points, which are distributed on the eastern and western sides of the structural belt. The western high point belongs to the box-shaped anticline with a relatively gentle form and the Lower Triassic Jialingjiang Formation is exposed in the core of the anticline. The eastern high point is connected with the saddle of the Maiyanshan hidden structure, which is located in the southern part of the Hongyan syncline. The structural form of this point is relatively wide and gentle, and the Middle Triassic Leikoupo Formation is exposed along the axis of the anticline, and the secondary faults are well developed.

Muziya structural belt

The Muziya structural belt lies between the Mu① and Mu② faults, which is a strip-like anticline with an NWW direction. Its whole structural form is steep in the south and gentle in the north

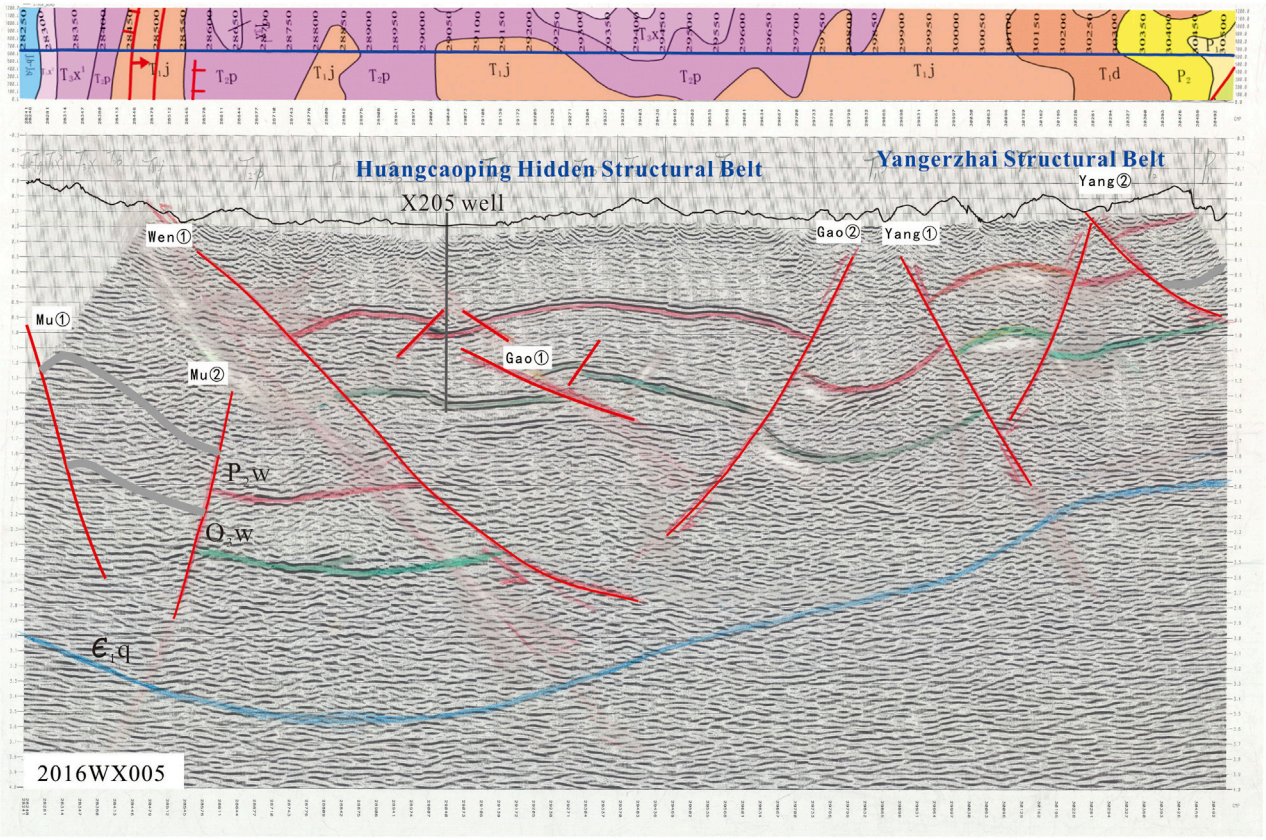

FIGURE 5
B–B′ seismic-structural profile in the study area.

and some secondary faults are developed along the axis of the anticline. The belt includes eastern and western structural high points, and the Lower to Middle Permian strata and Lower Triassic Jialingjiang Formations are exposed at the anticline core at the western and eastern high points, respectively.

Wenfeng structural belt

The Wenfeng structural belt distributes the hanging walls of Wen① and Wen② faults, which is classified as an NWW-trending strip-like anticline. The structural form is relatively stable as a whole steep in the south and gentle in the north. There are also some secondary faults in the axis zone of the anticline. The belt is divided into eastern and western high points, and its main high point is the Tianba anticline. The fluctuations of strata uplift and denudation in this belt are relatively large, so the exposed Lower Silurian Longmaxi shale formation is denuded and the oldest stratum on the surface is the Upper Cambrian. The Lower Triassic Feixianguan Formation is exposed at the core of the anticline in the eastern high point.

Huangcaoping hidden structural belt

The Huangcaoping hidden structural belt lies at the west-dipping end of the Wenfeng anticline, which is controlled by Wen① and Gao② faults, consisting of two rows of hidden high structural belts, namely, the southern and northern high structure zones (Figure 5). The general distribution of the two hidden zones is an NWW direction and its structural form has the characteristics of being relatively wide and gentle. In the southern hidden structural zone, there are two high structural high points, namely, Huangcaoping① and Huangcaoping② high points. The distribution of the northern hidden structural zone is very similar to that of the southern zone and there are also two high structural points, namely, Huangcaoping③ and Huangcaoping④. The belt is located at the structural transition zone and the extended distance and scale of the four high structural points are short and small. Furthermore, the buried depth of the two high structural points is superficial and the Lower to Middle Triassic strata are mainly exposed on the surface.

Yangerzhai structural belt

The Yangerzhai structural belt, occurring on the hanging wall of the Yang① fault and the footwall of the Wanyuan–Wuxi fault, is a typical NWW-trending anticlinorium. The two flanks of the anticline are very steep, with strong structural deformation, and develop secondary overturned recumbent folds and faults. The entire structural belt is wide in the west and narrow in the east, with two structural high points, and the Silurian is the oldest exposed strata in the core of the anticline.

Jiuchongshan structural belt

The Jiuchongshan structural belt locates the hanging wall of the Wanyuan–Wuxi fault, which is also an NWW-trending anticlinorium along with strong compression and deformation. The styles of secondary folds are complex, including fault bend fold and fault propagation fold, and most of their fold forms are closed and the formation occurrence changes repeatedly, mostly at high angles and locally reversed. The strata uplift and denudation in this belt are generally large and the local compression and fragmentation are also serious. The Upper Cambrian to Lower Triassic strata are exposed at the surface and the Wufeng–Longmaxi Formation is broadly denuded in the middle part of the structural belt.

Zhongliangshan structural belt

The Zhongliangshan structural belt lies at the northeastern margin of the Wuxi area and is arranged parallel to the Jiuchongshan anticlinorium. The strata are often strongly deformed with generally developed secondary folds and faults. Furthermore, the surfaced and underground structures are obviously inconsistent and the fold form changes significantly in the deep underground, with mostly high dip angles. On the surface of this structure belt, the Middle–Lower Silurian to Lower Triassic strata are exposed along with severe compression and fragmentation and multiple high-angle fractures.

Structural preservation conditions for shale gas enrichment

The influence of structure on the accumulation of shale gas

Generally, structural preservation conditions are the key factors controlling the enrichment and accumulation of conventional oil and gas. For the self-contained, self-sourced, and self-accumulating shale gas reservoir, due to the particular tight degree and adsorption mechanism of black shale itself, its anti-destructive ability is very strong so that whether or not the suitable structural preservation conditions remain uncertain, they are worthy of a deeper discussion (Hao et al., 2013; Nie et al., 2021).

According to the shale gas drilling data, the organic-rich black shale of the Wufeng–Longmaxi Formation is well developed in the Wuxi area and has a good material basis for shale gas enrichment, and the dark shale of the Wufeng–Longmaxi Formation is well developed in this area, with a thickness of more than 40 m and an organic carbon content of more than 2%, indicating the high over-mature evolution stage and well-developed organic micro-pores in the shale (Figure 6). Quartz contents generally reach more than 2%, with strong brittleness and good storage performance, representing a good material basis for shale gas development. But the gas-bearing differences are very obvious in the same shale layers from different structural locations in this area (Figure 7). For example, there are good shale gas-bearing properties of the Wufeng–Longmaxi Formation in the X205, X202, and WX2 wells, while that in X203, WQ2, and WQ1 wells are relatively poor. Thus, there is no absolute correlation between the organic matter abundance of black shale and the gas-bearing content. The X203 well is located on the southern flank of the middle section of the Wenfeng anticline. By drilling the core data from the upper part of the first bed of the Longmaxi Formation, strong compression and deformation occur in the well area and the formation dip angle changes greatly, locally with small crumpling, high-angle fractures, and a relatively broken core. This could imply that some secondary faults were encountered and no good gas-bearing properties were found during the drilling process of the Lower Longmaxi Formation, with less than 0.5 m^3/t and less than 0.8 m^3/t of natural desorption and total gas-bearing contents, indicating a large loss of gas in the shale layer that has already occurred, and further enrichment and accumulation of shale gas in the Longmaxi Formation were destroyed because of the poor structural preservation conditions (Figures 8A, B). The WQ1 and WQ2 wells are located in the eastern section of Zhongliangshan anticlinorium of the southern Dabashan ramp fold belt. The structural conditions are more complex than those of the southern Dabashan frontal fold belt. The drilling cores show that the favorable shale of the Longmaxi Formation is generally broken, with high-angle trending, strong structural deformation, and numerous fractures (Figures 8C–F). In addition, there are poor gas-bearing shale target layers from the two cores, which are less than 0.5 m^3/t and 0.8 m^3/t of gas-bearing contents in the WQ2 and WQ1 wells, respectively. In other words, good external structural preservation conditions can play a critical role in the gas-bearing properties of black shale layers in addition to the shale itself having a good material basis for shale gas enrichment and accumulation. Therefore, the quality of structural preservation conditions is the key factor controlling the enrichment and accumulation of shale gas in the Wuxi area.

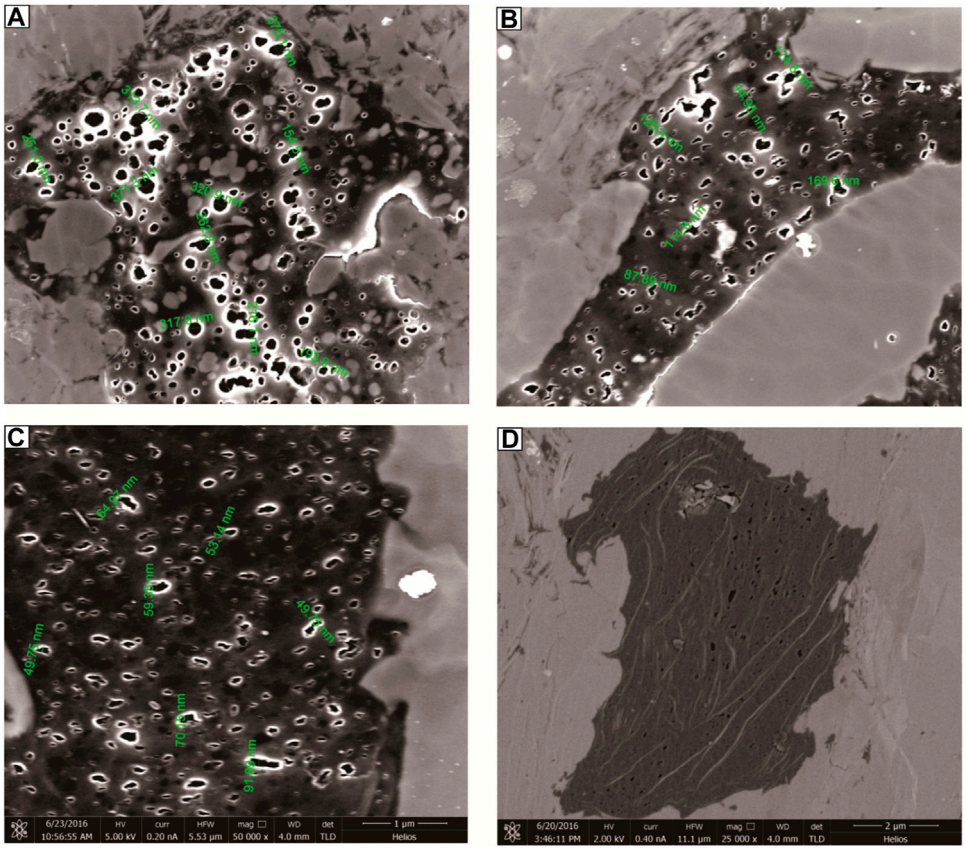

FIGURE 6
Development characteristics of organic micro-pores in the dark shale of the Wufeng–Longmaxi Formation in the Wuxi area. **(A)** Gray black shale, X202 (1888.99 m); **(B)** black carbonaceous shale, X202 (1955.85 m); **(C)** gray black silty shale, X203 (3,616.64 m); **(D)** black carbonaceous shale, X203 (3,634.83 m).

The partitioning evaluation of structural preservation conditions

The preservation conditions are one of the major controlling factors for shale gas enrichment, accumulation, and high gas production and an important aspect of shale gas geological evaluation (Liu et al., 2016; Feng et al., 2018; Wu et al., 2019). By the analytic results of a lot of previous research on the preservation conditions of shale gas (Tang et al., 2015; Xie, 2018; Sun et al., 2021), the structural condition is a major controlling factor for shale gas preservation, such as formation uplift and denudation, structural deformation intensity, faults and fractures, and capping conditions. At present, the evaluation of shale gas preservation depends on the combination methods of qualitative and quantitative analysis. Due to different regional tectonic backgrounds and differentiated degrees of research data, there is still no unified standard for the evaluation of shale gas preservation conditions. The Wuxi area is located in the basin-mountain coupling region and the macroscopic preservation type of shale gas is complex structural preservation of the basin margin. Through the detailed analysis of the structural conditions, the structural deformation is much stronger, so the structural preservation conditions are generally poor but are locally good and there are differentiated preservation conditions of shale gas in different regions.

By the deformation characteristics of each structural belt, combined with the actual drilling effect of shale gas, the structural preservation conditions of shale gas in the Wufeng–Longmaxi Formation can be evaluated in the area. Structure preservation conditions are divided into four grades, namely, the good Class I area, the general Class II area, the poor Class III area, and the very poor Class IV area (Figure 9; Table 1). In the compound fold belt at the northern side of the Wanyuan–Wuxi fault, the Jiuchongshan and Zhongliangshan structural belts have structural deformation, which is generally strong, and both the surfaced and underground faults are well developed. The shale target layer of the Lower Silurian has extensive exposure and denudation, with high-angle fractures and very poor structural preservation condition of shale gas, belonging to the Class IV area. In the Yangerzhai structural belt, Tianba anticline,

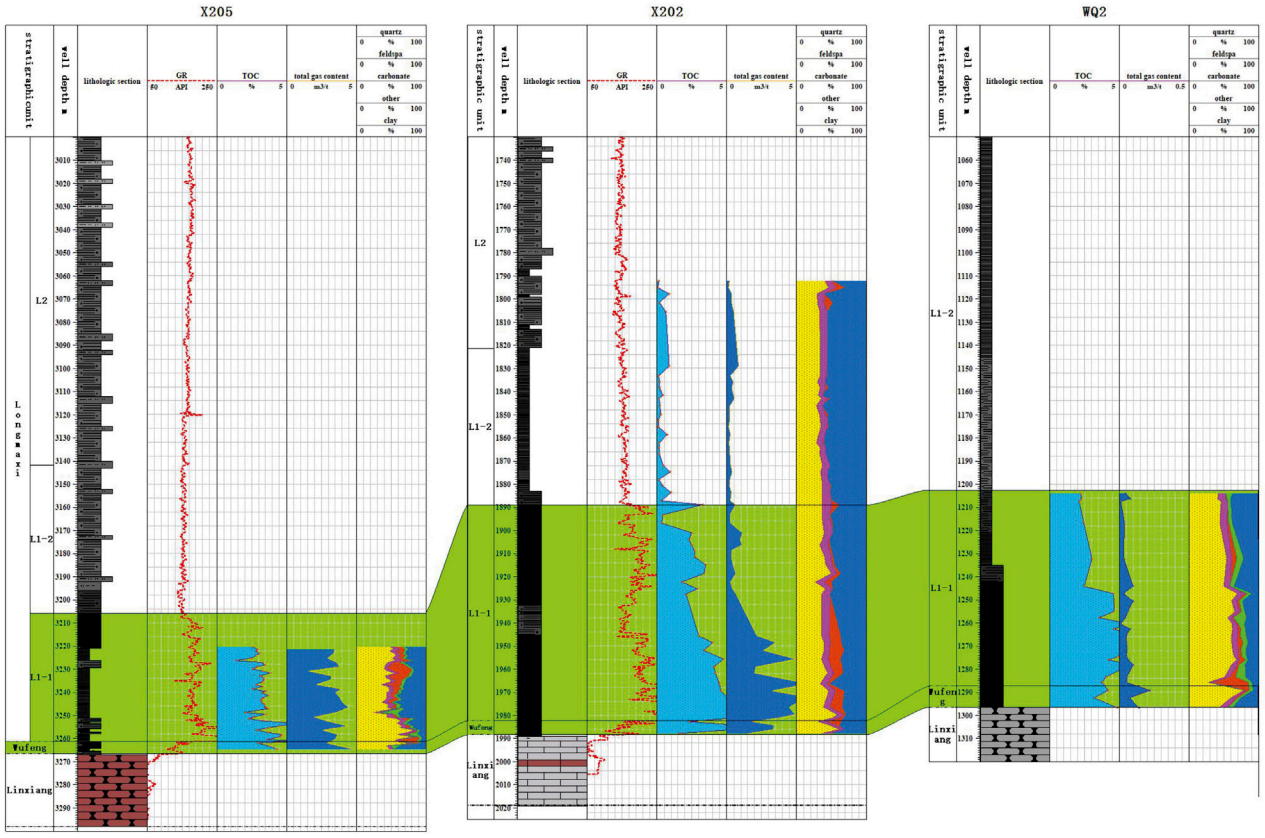

FIGURE 7
Connecting the well profile of shale target layers in the Wufeng–Longmaxi Formation.

and the western pinching end of the Muziya structural belt, the whole structural deformation is strong with relatively fragmented strata, mainly constructing anticlinoria and closed secondary folds. Faults are relatively well-developed with locally large faults, and the degree of formation uplift and denudation is rather large. The Permian to Lower Triassic strata are mainly exposed at the surface and the Lower Silurian is presented and denuded locally, such as the Tianba anticline. The capping condition of the region is generally poor, belonging to the Class III area. In the Muziya structural belt and fold region at the southern side of the Wenfeng structural belt, the structure form is rather stable, which is mainly composed of asymmetric folds and open folds. There is a low development degree of faults in this region, with relatively well-developed high-angle fractures larger than 3 km from the surfaced large fault. Moreover, the degree of formation uplift and denudation is rather small and the distance from the denudation zone of the shale target layer is more than 5 km. The Triassic strata are mainly exposed at the surface and partially exposed to the Lower Jurassic. The capping condition of the region in general belongs to the Class II area. In the Heiloumen structural region at the southern side of the Muziya structural belt and on the Huangcaoping hidden structure at the western pinching end of the Wenfeng structural belt, the structure form is stable, wide, and gentle, dominated by wide and gentle anticline. There is a relatively low development degree of faults in this region, larger than 5 km from the surfaced large fault. Moreover, the degree of formation uplift and denudation is rather small and the distance from the denudation zone of the shale target layer is more than 10 km. The Upper Triassic to Middle–Lower Jurassic strata are mainly exposed at the surface, and the capping condition of the region is good, belonging to the Class I area.

Structural preservation modes for shale gas enrichment

Through the comprehensive analysis of the structural preservation conditions of shale gas enrichment and accumulation in the Wufeng–Longmaxi Formation in the Wuxi area, the different structural preservation characteristics in different structural belts and their differences are very obvious.

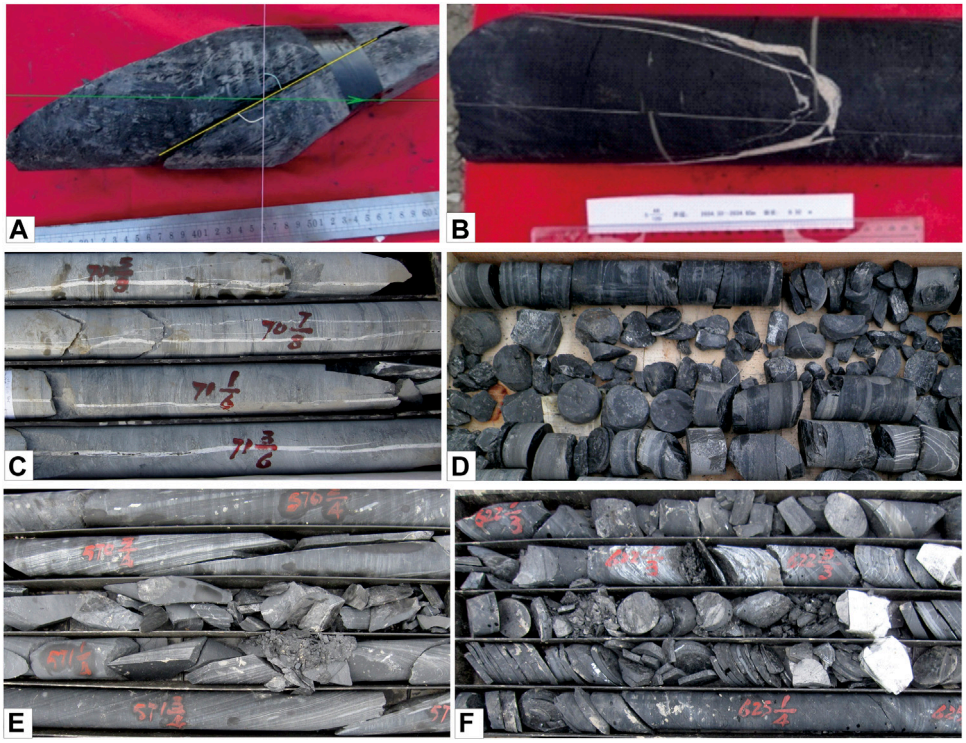

FIGURE 8
Typical drilling core photographs of the Longmaxi Formation. **(A)** X203 well, 3,553.50 m, with high-angle strata, and the red line direction is the stratum layer; **(B)** X203 well, 3,586.75 m, with high-angle fractures, and the fracture surface is filled with calcite veins; **(C)** WQ1 well, 258.35–261.20 m, with vertical fractures, and the fracture surface is filled with calcite veins; **(D)** WQ1 well, 343.75–348.62 m, with seriously broken strata and the core is broken into pieces; **(E)** WQ2 well, 1,174.50–1,177.64 m, with high-angle strata and light sandy lamina; **(F)** WQ2 well, 1,192.71–1,296.85 m, with a seriously crumpled and deformed strata, and the rock core is broken into pieces along the bedding plane.

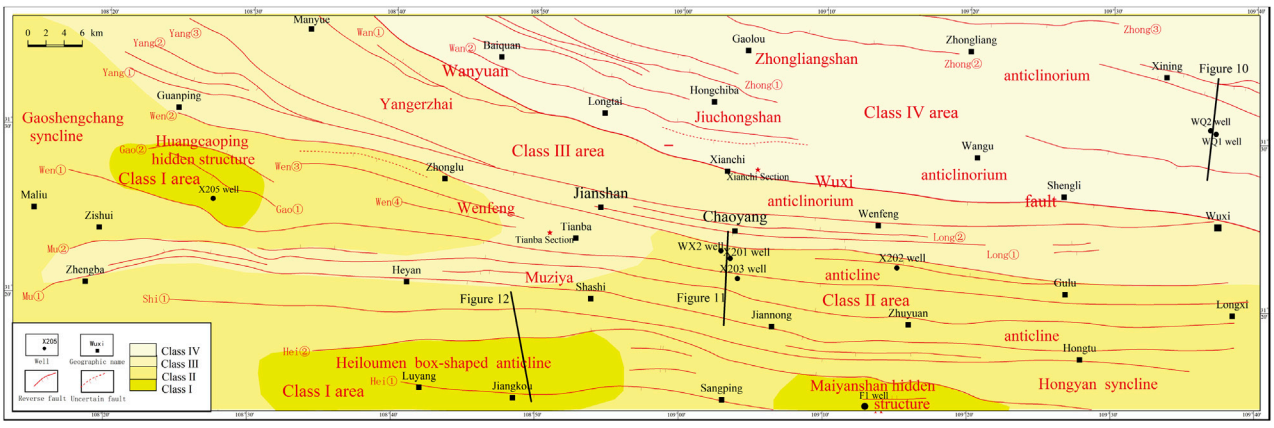

FIGURE 9
Partitioning evaluation of structural preservation conditions of shale gas enrichment and accumulation in the Wufeng–Longmaxi Formation.

TABLE 1 Grading evaluation of structural preservation conditions of shale gas enrichment and accumulation in the Wufeng–Longmaxi Formation.

Preservation type	Preservation condition grade	Structural location	Structural style	Development degree of faulted fractures	Uplift and denudation	Capping condition of the surfaced strata	Structural deformation	Evaluation of the preservation condition
	Class I area	Huangcaoping hidden structural belt and Heiloumen structural belt	Wide and gentle anticline	Relatively low development degree of faulted fractures larger than 5 km from the surfaced large fault	Weak formation uplift and denudation and the distance from the denudation zone of shale target layer more than 10 km	Middle–Upper Triassic to Lower–Middle Jurassic	Weak and stable	Good
Complex structural preservation of the basin margin	Class II area	Southern side of the Wenfeng structural belt and Muziya structural belt	Asymmetric fold and open fold	Relatively well-developed high-angle fractures larger than 3 km from the surfaced large fault	Relatively weak formation uplift and denudation and the distance from the denudation zone of shale target layer more than 5 km	Triassic	General	General
	Class III area	Yangerzhai structural belt, Tianba anticline, and the western pinching end of the Muziya structural belt	Anticlinoria and closed secondary folds	Relatively well-developed faulted fractures, with locally large faults	Rather strong formation uplift and denudation and the Lower Silurian denuded locally	Permian to Lower Triassic	Strong	Poor
	Class IV area	Jiuchongshan structural belt and Zhongliangshan structural belt	Compound fold	Cell developed surfaced and underground faulted fractures	Strong formation uplift and denudation and extensively exposed shale target layer of the Lower Silurian, with high-angle fractures	Upper Cambrian to Lower Triassic	Strong	Very poor

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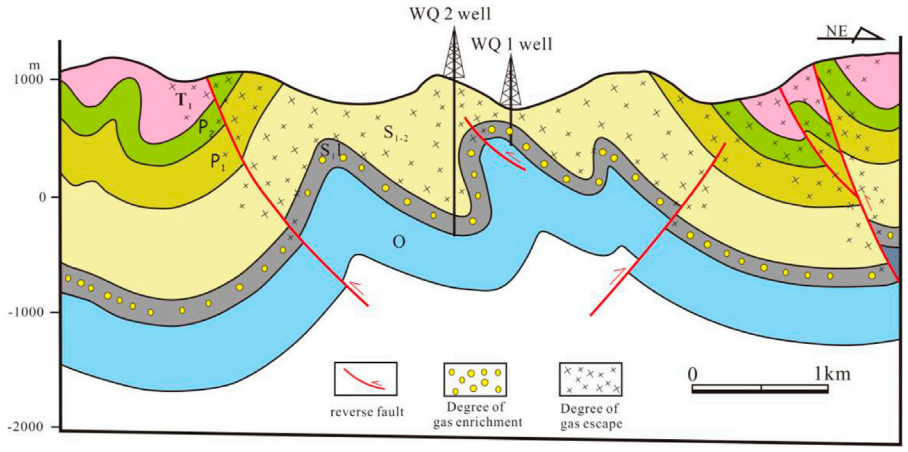

FIGURE 10
Structural preservation mode of shale gas enrichment and accumulation in the Wufeng–Longmaxi Formation-lost destruction type.

According to the differences in the structural styles and deformation intensity in the area, there are three structural preservation modes of shale gas enrichment and accumulation in the Wufeng–Longmaxi Formation. Its specific characteristics are as follows.

Lost destruction type

The lost destruction type focuses on the southern Dabashan ramp fault-fold belt with strong structural transformation. Intense structural compression deformation and formation uplift and denudation lead to complex fold changes in the Wuxi area, such as the development of faults and fractures, so that the formation capping condition becomes worse (Figure 10). The shale gas in the target layer of the Lower Silurian Longmaxi Formation has a large amount of it escape towards the superficial layers along the faulted fracture zones; especially the development of the enormous fault is directly connected with the surface. In most of the belts, the surface is dominated by the Lower Silurian and even the target shale layer is denuded. The direct release of overlying pressure leads to the vertical loss of shale gas, resulting in a low enrichment degree of shale gas in the target layer and the destruction of effective shale gas accumulation.

Lost residual type

The lost residual type mainly develops on the southern Dabashan frontal fold belt with weak structural transformation. The surfaced faults and fractures are of the non-development type, and the Permian to Triassic strata are exposed, which have certain capping conditions, but the deformation of underground folds is very complex and thrust faults are well-developed in this belt (Figure 11). The shale gas escapes to the superficial layers along the structurally weak regions such as faulted fracture channels. Even so, the most of shale adsorbed gas is effectively preserved due to the unique compactness and adsorption of the black shale interval itself. Although good gas-bearing properties have been found in some drilling wells because of the massive loss of free gas, which gives rise to lower formation pressure and insufficient energy; it is difficult to achieve commercial production with the scale of adsorbed gas. For example, the average gas content of the shale target layer in the X202 well is 2.07 m^3/t, but the formation pressure coefficient is only 0.67 and no industrial gas flow is obtained.

Trap preservation type

The trap preservation type mainly manifests in the Heiloumen structural belt and Huangcaoping hidden structural belt near the interior of the Sichuan Basin with stable, wide, and gentle structural forms and the weak development of faulted fractures. The structural style in this region is dominated by wide-gentle fold and suspected box-shaped fold, and the Triassic to Jurassic strata are exposed at the surface with good capping conditions (Figure 12). The overlying capping layers in the two structural belts are rather thick, especially the Middle Triassic gypsum-salt rock layer has played a very good capping effect on the shale gas reservoir. Although there are also some faults developed in the deep underground, they are only developed in the Lower Triassic strata, so the loss of shale gas is very limited and the mode is more

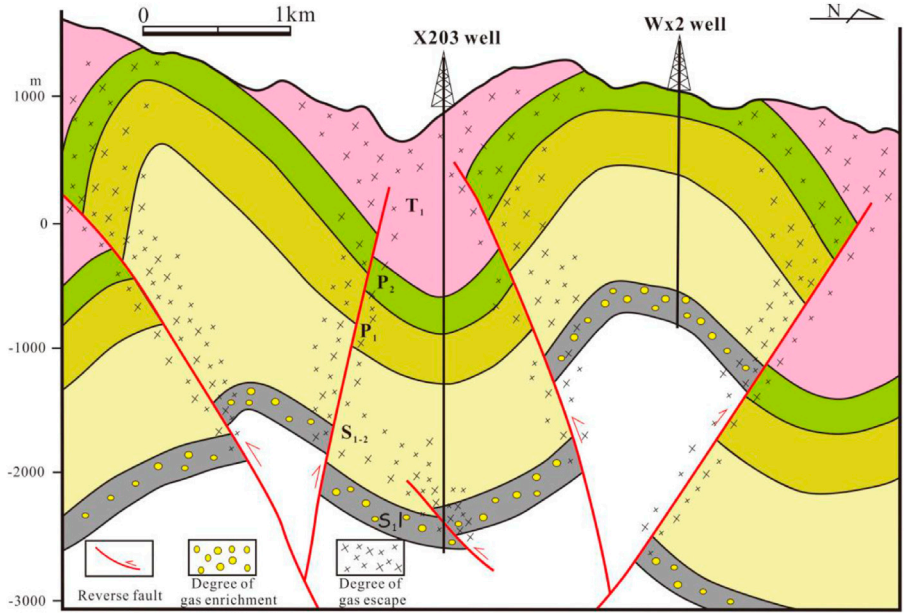

FIGURE 11
Structural preservation mode of shale gas enrichment and accumulation in the Wufeng–Longmaxi Formation-lost residual type.

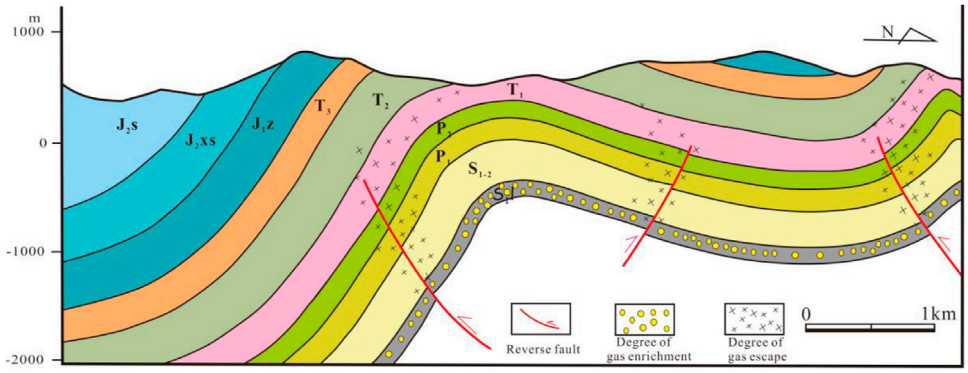

FIGURE 12
Structural preservation mode of shale gas enrichment and accumulation in the Wufeng–Longmaxi Formation-trap preservation type.

conducive to the enrichment, accumulation, and preservation of shale gas in the high structural points.

Conclusion

(1) The Wuxi area lies in the transition zone between the Dabashan thrust-fold belt and the Sichuan Basin, belonging to a superimposed transformation area with strong structural deformation. The area can be divided into seven structural belts, including the Heiloumen structural belt, Muziya structural belt, Wenfeng structural belt, Huangcaoping hidden structural belt, Yangerzhai structural belt, Jiuchongshan structural belt, and Zhongliangshan structural belt.

(2) The macroscopic preservation type of shale gas in the Wufeng–Longmaxi Formation of the Wuxi area belongs to the complex structural preservation of the basin

margin. The structural preservation conditions of shale gas enrichment and accumulation in the Wuxi area are divided into four grades, such as the good Class I area, the general Class II area, the poor Class III area, and the very poor Class IV area. Among them, the Heiloumen structural zone and Huangcaoping buried structural zone near the Sichuan Basin have good preservation conditions and are classified as good Class I preservation areas.

(3) Three structural preservation modes of shale gas in the Wuxi area have been identified, including lost destruction type, lost residual type, and trap preservation type. The trap preservation type is more conducive to the preservation of shale gas, which is the most favorable structural mode for shale gas exploration (Wang et al., 2006; Liu and Wang, 2016).

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

WL and TL: validation, writing—original draft, and investigation. CY, SW, ZZ, and JL: visualization. CY, XT, CY, WW, YZ, and JL: conceptualization, methodology, supervision, writing—review and editing, project administration, and funding acquisition.

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Conflict of interest

Authors WL, TL, CS, and ZZ were employed by Chongqing Shale Gas Exploration And Development Company Limited.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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