



## Tectonic evolution and accumulation characteristics of Carboniferous shale gas in Yadu-Ziyun-Luodian aulacogen, Guizhou Province, South China

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### ABSTRACT

The Yadu-Ziyun-Luodian aulacogen (YZLA) developed into being NW-trending in the Late Paleozoic, and was considered as an important passive continental margin aulacogen in Guizhou Province, South China. This tectonic zone is considered a large intracontinental thrust-slip tectonic unit, which has undergone a long period of development. It was ultimately determined in the Yanshanian, where the typical Upper Paleozoic marine shales were deposited. In 2021, Well QSD-1 was deployed in the Liupanshui area at the northwest margin of the aulacogen, and obtained a daily shale gas flow of 11011 m<sup>3</sup> in the Carboniferous Dawuba Formation. It thus achieved a breakthrough in the investigation of shale gas in the Lower Carboniferous in South China, revealing relatively good gas-bearing properties and broad exploration prospects of the aulacogen. Being different from the Lower Paleozoic strata in the Sichuan Basin and the Yichang area of the Middle Yangtze, the development of the Carboniferous Dawuba Formation in the aulacogen exhibits the following characteristics: (1) The Lower Carboniferous shale is thick and widely distributed, with interbedded shale and marlstone of various thickness; (2) The total organic carbon (TOC) content of the shale in the Dawuba Formation ranges from 1% to 5%, with an average of 2%, and the thermal maturity of organic matter ( $R_o$ ) varies from 1% to 4%, with an average of 2.5%, indicating good hydrocarbon generation capacity; (3) The main shale in the aulacogen was formed during the fault subsidence stage from the Middle Devonian to the Early Permian. Although the strong compression and deformation during the late Indosinian-Himalayan played a certain role in destroying the formed shale gas reservoirs, comparative analysis suggests that the area covered by the current Triassic strata has a low degree of destruction. It therefore provides good conditions for shale gas preservation, which can be regarded as a favorable area for the next exploration.

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## 1. Introduction

With the continuous and rapid advancement of shale gas exploration and development (Zou CN et al., 2021), an effective development of shale gas resources has been

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achieved in China, which makes it become the largest shale gas producer outside North America (Pan JP, 2021; Teng JW et al., 2021; Zheng ZX et al., 2021). The Upper Ordovician-Lower Silurian Wufeng-Longmaxi Formation in the Sichuan Basin has become the major target of shale gas production in China (Li SZ et al., 2022). In addition, shale gas discoveries and breakthroughs have also been made in the Sinian-Cambrian strata in the Yichang area of the Middle Yangtze (Zhai GY et al., 2017, 2019; Chen XH et al., 2017; Li H et al., 2019; Liu GH et al., 2019; Cai QS et al., 2021). However, due to the high degree of hydrocarbon source rock thermal evolution, complexed reservoir diagenesis (Jia CZ, 2017;

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Dong DZ et al., 2016; Zhang JC et al., 2008; Yang YR et al., 2019), and complicated topographic and geological conditions, no significant oil and gas breakthroughs have been made in Yunnan-Guizhou-Guangxi region of South China until recently.

The Yadu-Ziyun-Luodian aulacogen (YZLA) is an important tectonic unit in the Yunnan-Guizhou-Guangxi region. Xia BD (1992) described it as a branch at the southwest margin of the Yangtze block. Zeng YF (1992), Chen HD (1994), and Xia WC (1995) discussed the “northernmost inter-platform basin of the Youjiang composite basin” from the perspectives of sedimentary features, tectonic evolution, and lithofacies paleogeographical evolution. Qin JH (1996) took the Ziyun-Yadu Fault as an important fault in the Nanpanjiang Basin and analyzed the tectonic evolution and geological features during the Hercynian-Indosinian periods. Based on it, Qin JH (1996), Wang SY and Zhang H (2006) summed up and put forward the concept of “Yadu-Ziyun-Luodian Late Paleozoic aulacogen” and made a detailed study on its stratigraphic filling, paleontological evolution, and the controlling of mineralization.

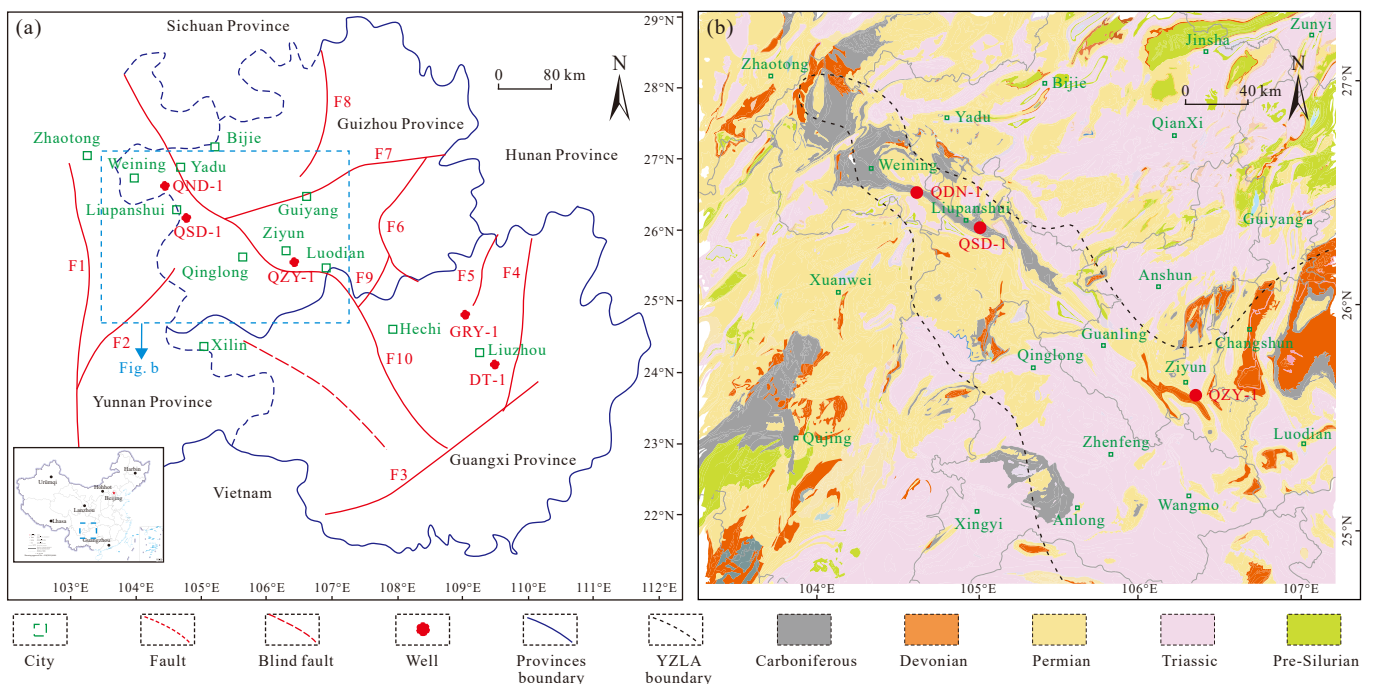
Based on previous studies on oil and gas geological conditions, China Geological Survey selected YZLA as the target of Carboniferous shale gas exploration in 2014, and implemented a series of explorations of the 2D seismic and wide-field electromagnetic method (Yuan K et al., 2022). Shale gas wells have been carried out successively in different sites in YZLA, and obtained important discoveries and breakthroughs recently (Yuan K et al., 2017, 2018; Li XF et al., 2022). In 2021, well QSD-1 obtained a shale gas flow with an average daily output of 11011 m<sup>3</sup> in the vertical well fracturing test of the Dawuba Formation, which was a

breakthrough in the investigation of the Carboniferous shale gas in South China (Yuan K et al., 2021). On the Basis of analyzing the sedimentary characteristics and tectonic evolution of the YZLA, the Lower Carboniferous Dawuba Formation is analyzed from the aspects of accumulation conditions, preservation conditions, and gas-bearing properties. Additionally, the shale gas accumulation of the Upper Paleozoic marine strata in YZLA is discussed. The results of this study may play a certain role in promoting the deeper understanding of shale gas accumulation in South China and accelerating the pace of shale gas exploration.

## 2. Geological background

The YZLA is located in the southeastern part of the Yangtze block, which derived from the NW-trending tectonic zone along the lines of Yadu, Ziyun, and Luodian in Guizhou (Wang XW et al., 2013) (Fig. 1). As an important passive continental margin aulacogen in the Yunnan-Guizhou-Guangxi region of China, the deformation zones on both sides of the aulacogen have significant variations in deformation direction, style, and intensity (Wang SY, 2016; Chen HD et al., 2000).

The northwest margin of YZLA starts near Zhaotong, Yunnan Province, and the southeast margin is located in the area of Ziyun and Wangmuo, Guizhou Province. As a Paleozoic aulacogen basin with a strike of 300°–310°, YZLA is long in NW direction, but short in NE direction. The opening area is in the southeast sector (Fig. 1b), and reached its maximum, 400 km long and 10–80 km wide, in the middle period of the Early Devonian (Wang SY et al., 2006). The northeastern part of the aulacogen is bounded by two



**Fig. 1.** Location map and tectonic outline map of YZLA and its periphery (a); Regional geological characteristics of YZLA (b). F1–Xiaojiang fault; F2–Shizong fault; F3–Pingxiang-Dali fault; F4–Yongfu fault; F5–Longsheng fault; F6–Tongren-Sandu fault; F7–Guiyang-Zhenyuan fault; F8–Zunyi fault; F9–Libo fault; F10– Ziyun-Luodian-Nandan-Du’an fault

synsedimentary faults, the Yadu-Ziyun Fault and the Ziyun-Luodian Fault, but the fault controlling effect in the southwest is not obvious (Mei MX et al., 2005). The width of the aulacogen varies to a certain extent due to the influence of different stages of tectonic activities (Wang SY et al., 2006). For example, there are northeastern secondary aulacogens with 120 km long and 50 km wide that are perpendicular to the trend of the aulacogen in place such as Qinglong and Ziyun. The overall area of the aulacogen is about 28000 km<sup>2</sup>.

Multiple sets of strata in the aulacogen are well developed from the Sinian to Ordovician, Devonian to Middle Triassic, Upper Triassic, Tertiary, Quaternary (Zhao MJ et al., 2006; Liu JP et al., 2006; Wang YF et al., 2021; Ma K et al., 2022). The Devonian strata of the Upper Paleozoic conform with the Cambrian and Ordovician strata. The lithological combinations are different because of various depositional environments. The platform facies mainly developed carbonate assemblages, and the lithological units correspond to Dushan Formation, Gaopochang Formation, and Gelaohu Formation; while the slope-basin facies are mainly composed of shale, siliceous rock and carbonate rock, and the lithological units are Guanziyao Formation, Huohong Formation, Liujiang Formation, Rongxian Formation, and Wuzhishan Formation. Among them, the Huohong Formation is the section, where the dark mudstone of Devonian is concentrated (Zhong YJ et al., 2011). Similarly, in different parts of the Carboniferous system, the sedimentary lithology is also different. The Tangbagou Formation, Xiangbai Formation, Jiushi Formation, Baizuo Formation, Huanglong Formation, and Weining Formation are mainly developed as platform carbonate rocks and organic reef bank limestone, while the Dawuba Formation and the Nandan Formation consist of slope-basin facies. Among them, the Dawuba Formation is characterized by enrichment of shale and is the main target strata for shale gas exploration in the study area. The Permian strata are composed of the Xuanwei Formation of fluvial-lacustrine facies, the Longtan Formation of littoral facies, the Changxing Formation, Dalong Formation, Heshan Formation, Wujiaping Formation of platform margin facies, and the Linghao Formation of slope-platform basin facies. Among them, the coal-bearing strata of the Longtan Formation and shale strata of the Linghao Formation constitute the main hydrocarbon-generating strata. The open sea sedimentary rocks of the Early-Middle Triassic are widely distributed (Wang SY et al., 2006), including the Feixianguan Formation, Jialingjiang Formation, Luolou Formation, and Xinyuan Formation (Fig. 2).

The regional variation characteristics of the Upper Paleozoic strata generally show a process of shrinkage from the Zhaotong area of Yunnan Province to the southeast. In the middle period of the Early Devonian, the area of the slope-platform facies was the largest, then retreated eastward to the vicinity of Weining, Guizhou Province, during the Carboniferous period. The strata were distributed in Shuicheng and the southeast of Panxian County in Guizhou Province in the Middle Permian and retreated to the south of

Guanling in the Upper Permian (Zhang N et al., 2016).

### 3. Tectonic evolutionary features

The Caledonian orogeny made most areas of Yunnan, Guizhou, and Guangxi uplift into land, which then was suffered denudation, and became the base of YZLA (Wang SY et al., 2006). Since the late Early Devonian, under the influence of crustal stretching and thinning, seawater invaded from the Qinfang Trough in the southeast, and then the aulacogen was gradually formed and continued to develop and evolve (Mei MX et al., 2005). By the Late Triassic, all the seawater was withdrawn, and the aulacogen was uplifted as land (Yuan K et al., 2018; Mei MX et al., 2005). The carbonate, clastic, and volcanic rock strata developed in the Devonian, Carboniferous, Permian, and Triassic periods were deposited in the aulacogen. Afterwards, under the influence of the south-to-north extrusion during the Yanshanian and Himalayan periods, the aulacogen experienced strong uplift and strike-slip deformation (Wang SY et al., 2006; Peng J et al., 2000). Eventually, the asymmetrical shape with steep gradient in the northeast and gentle gradient in the southwest was formed. Combined with factors, such as structure, sedimentation, magmatism and the evolution process of the aulacogen. Therefore, it can be divided into five stages and several secondary stages (Zeng YF et al., 1992; Peng J et al., 2000; Wang SY, 2006; Zhang N et al., 2016) (Fig. 3).

(1) Folded basement formation stage (Pre-Devonian). The Caledonian basement was the direct underframe of the YZLA (Fan YR and Tong JF, 1997). The Guangxi Movement at the end of the Early Paleozoic Silurian made the collision of Yangtze and Cathaysian blocks into a unified entirety in the South China plate (Qin JH et al., 1996). The crust was transformed into a continental crust, and four trunk faults, which are the Ziyun-Shuicheng, Shuicheng-Panxian, Xingyi-Guiyang, Weng'an-Hezhang (Wang XW et al., 2013). They constituted the basic framework of the Pre-Devonian basement and became the important basis for the development of YZLA. In addition, due to the impact of the collision, the thermal expansion in the Early Devonian caused the crust to uplift and suffered from strong fissures and denudation (Fig. 3D<sub>1</sub>), which resulted in different degrees of denudation for the Silurian and Ordovician strata in the rift trough (Zhou MH, 1999).

(2) Crustal stretching and thinning stage (Early Devonian). In the middle and late Early Devonian, under the continuous action of thermal expansion of the crust, the study area entered the tectonic extension stage (Wang SY et al., 2006). The crust continued to rise, stretch and thin during this stage (Fig. 3D<sub>2-3</sub>). The extent of the continental shelf expanded and some lowlands appeared in the thinning area (Wang SY et al., 2006). Seawater was invaded from the southeastern Qinfang Trough (Peng J et al., 2000), and the area received marine mud deposits.

(3) Fracture subsidence stage (Middle Devonian to Late Carboniferous). As the most important stage in the

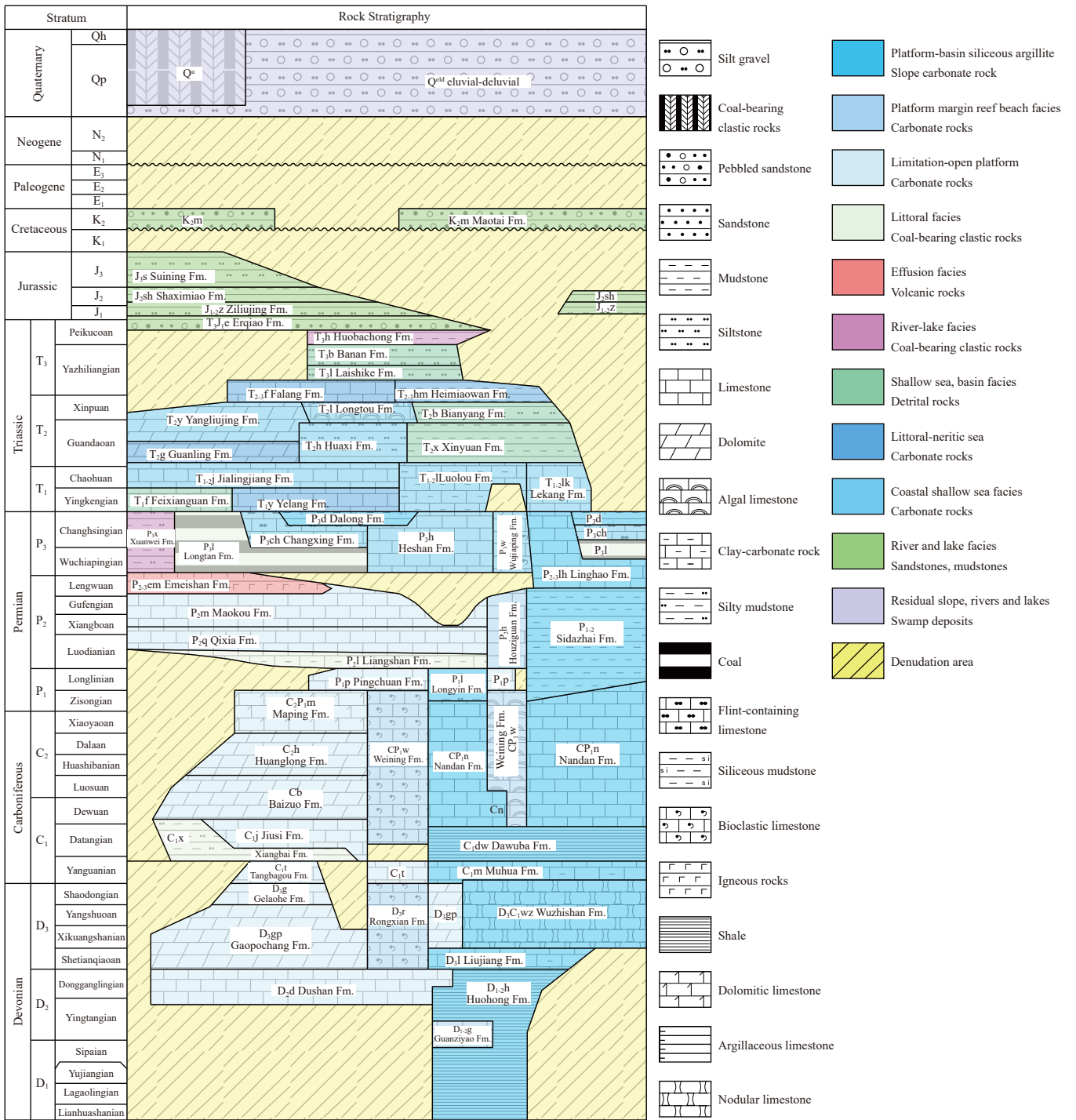


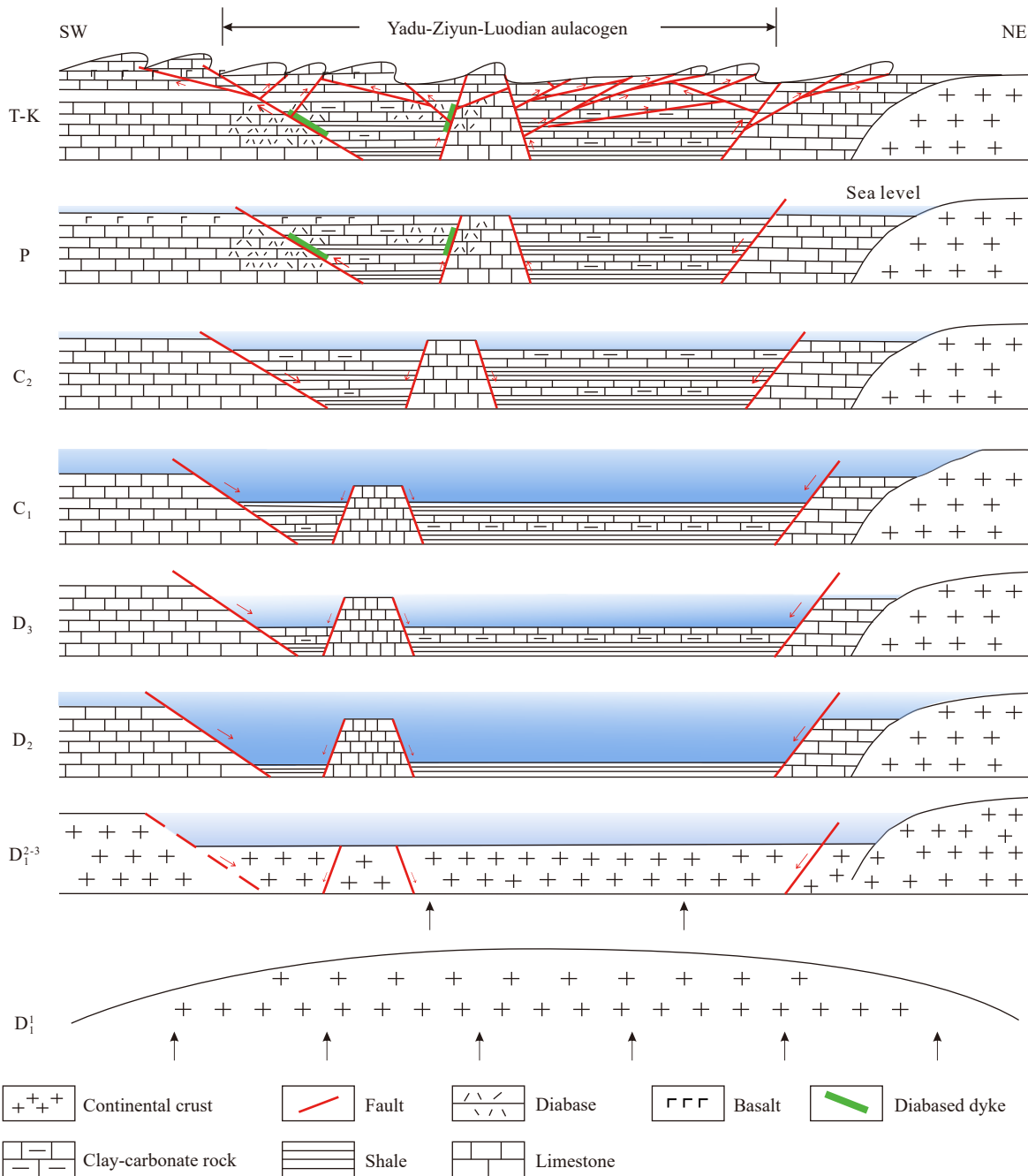
Fig. 2. Comprehensive stratigraphic characteristics of YZLA.

development of the YZLA, this stage lasted from the Middle Devonian to the Early Permian (Wang SY et al., 2006). According to the different characteristics of the sediments, it can be divided into five sub-stages.

From the late Early Devonian to the Middle Devonian, the strong extensional rifting caused great changes in the sedimentary environments. The scope of transgression expanded, and based on the shallow-water shelf, the aulacogen began to appear in the rudiment of platform and basin division (Cheng GF and Xu AQ, 1998), forming a NW-trending sub-deep-water basin. In the aulacogen, due to the

uneven subsidence of fault blocks, shallow-water carbonates developed on high fault blocks, deep-water carbonaceous mudstone and siliceous deposits developed on low fault blocks, and gravity flow and olistostrome developed in the slope belt of the platform margin (Peng J et al., 2000).

From the late Middle Devonian to the early Late Devonian, the regional transgression reached the maximum (Zhou MH, 1999) (Fig. 3D<sub>2</sub>). With the intensification of sedimentation, the syn-sedimentary fault activity was significantly enhanced, and the platform-basin facies deposited in the marine shale strata of the Middle Devonian



**Fig. 3.** Tectonic evolution pattern of YZLA (modified from Wang SY et al., 2006).

Huohong Formation (Wang SY, 2016). The slope facies deposits characterized by slump breccia and clastic flow developed at the junction of the platform basin. At this time, the YZLA reached the largest extent on the plane, starting from Zhaotong in Yunnan Province in the west, passing through Weining and Ziyun in Guizhou Province, fanning out to the southeast in Luodian, and extending to Liucheng and Luzhai in Guangxi Province in the east. In this area, a pattern of alternating troughs and platforms with a NW length of about 400 km was formed, and the shallow-water carbonate platforms were isolated in the deep water (Chen HD et al., 1994).

Affected by the Late Devonian regression, a large number of terrigenous debris was injected into the northwest end of

the YZLA, which gradually filled the boundary and became shallower (Fig. 3D<sub>3</sub>), and retreated southeast to the vicinity of Weining and Liupanshui. In the Early Carboniferous, the appearance of the aulacogen basically inherited the characteristics of the previous period. Under the influence of the Ziyun movement, the rifting activity of the fault increased, the seawater became deeper, and the secondary inter-platform basin changed from the platform facies to the platform-basin facies (Mei MX et al., 2015) (Fig. 3C<sub>1</sub>). During this period, the Dawuba Formation of siliceous rock, chert nodule limestone, shale, and marl interbedded rock assemblages were deposited; some small isolated platforms merged into large ones, and the northwest end of the aulacogen was mostly coastal swamp facies deposition.

In the Late Carboniferous, the rifting and strike-slip of synsedimentary fault zones in the region tended to be stable due to the weakening of the expansion of the Paleo-Tethys Ocean. Affected by the regression, the seawater in the aulacogen became shallower, the coastal marshes and limited platforms became wider, and then the aulacogen was filled with a large number of sediments and shrank to the southeast (Fig. 3C<sub>2</sub>). The deep-water secondary basins were gradually filled up, which is different from the surrounding water bodies. The shallow-water areas gradually expanded. Under the continuous activity of faults, the NE-trending secondary rifts with a length of about 120 km and a width of about 50 km were developed in Qinglong and Ziyun that were perpendicular to the strike of the aulacogen. Since then, under the long-term denudation and flattening, the surrounding ancient continents lacked terrigenous debris (Zhou MH, 1999). Only the Pu'an-Qinglong area could receive terrigenous supply from the northwest (Fig. 4). A combination of calcareous mudstone and marl interbedded was deposited

in Ziyun, Wangmo, and other places far away from the terrigenous source. In the late Early Permian, under the influence of the Qiangui epeirogeny, the platform in the aulacogen gradually rose to land and suffered denudation (Wang SY, 2016).

(4) Mantle plume stage (Permian). After the Dongwu Movement, the Qinfang Trough, which had been in deep water for a long time, folded into mountains, and the pattern of mutual encirclement of shallow-water areas and deepwater areas reappeared in the basin (Fig. 3P). The range of the platform-basin facies changed significantly, and the aulacogen shrank eastward to the south of the Guanling-Zhenxiong area (Wang SY et al., 2006). The emergence of basic volcanic eruptions formed a large area of volcanic rocks. The main lithology of the Late Permian in the aulacogen was continental overflow tholeiitic basalt and basaltic pyroclastic rock (Gao JB et al., 2017).

(5) Thrust retrofit stage (Triassic to Cretaceous). Since the Triassic, the Yuebei block and the Yangtze block collided, the

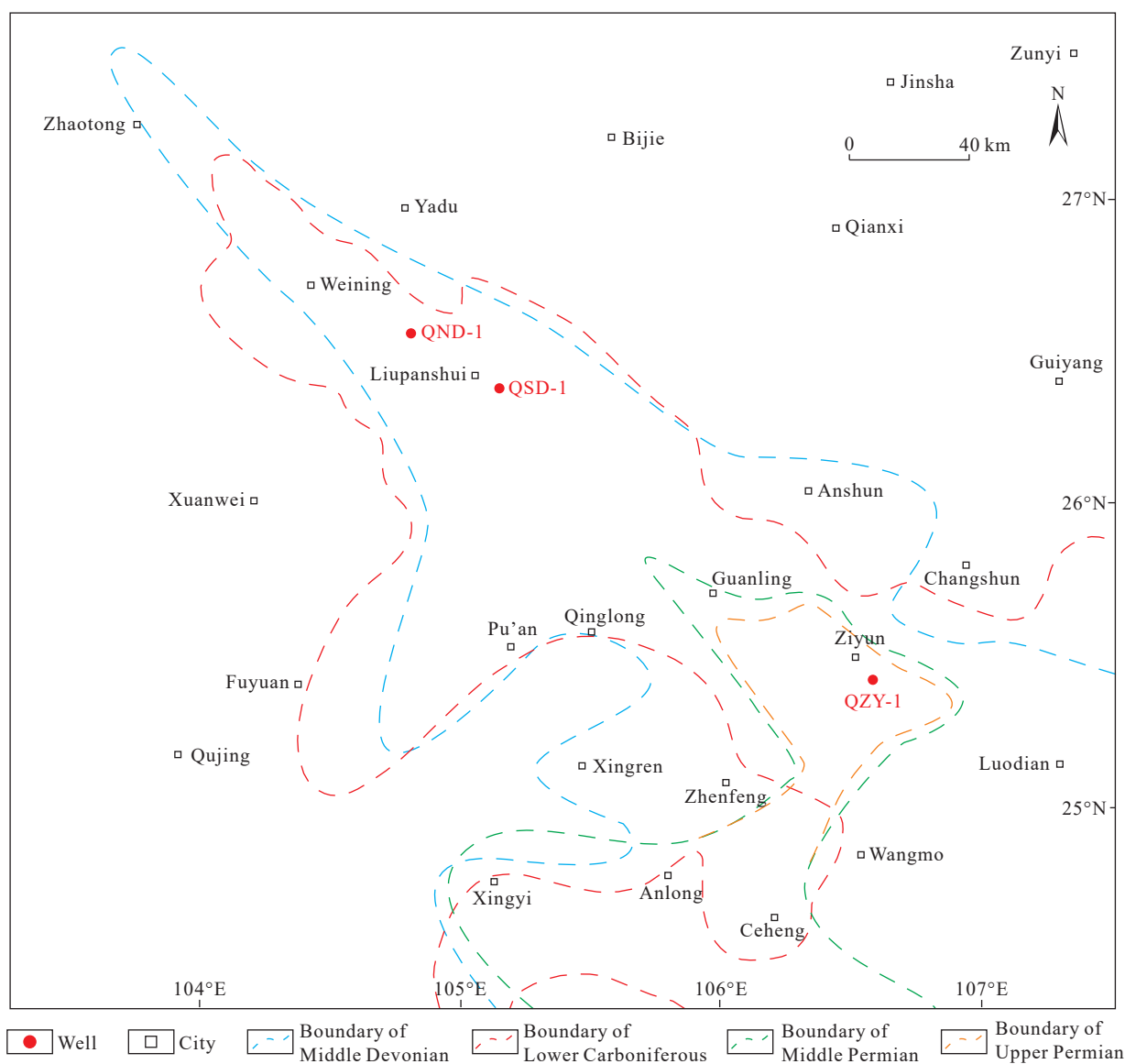


Fig. 4. Range of deepwater deposition in different periods in YZLA (modified from Wang SY et al., 2006).

direction of stress in the through began to change, and the Paleo-Tethys subducted to the northeast, causing severe depression in the aulacogen (Wang SY et al., 2006). At the end of the Late Triassic, the seawater was completely withdrawn, the aulacogen was uplifted into land, forming a fold-fault belt with a NW-trending tectonic line (Fig. 3T-K). From the Yanshanian to the Himalayan period, under the strong intracontinental compression from south to north, the aulacogen was strongly folded and uplifted, and finally, the present topographical features were formed (Wang SY et al., 2006).

#### 4. Sedimentary features of Carboniferous shale

After the large-scale transgression in the Early Devonian, the YZLA developed a paleogeographical pattern of platform-basin-mound-trough (Zeng XF et al., 1992; Yuan K et al., 2021). The Early Carboniferous inherited the sedimentary pattern of the Late Devonian. But the range of the aulacogen had shrunk to the vicinity of Weining, Guizhou Province (Wang SY et al., 2006).

As an important sedimentary facies transition zone, the Shuicheng-Ziyun zone controls the northern boundary of the platform facies. During the Early Carboniferous, a sedimentary pattern with multiple trough enclosures and inter-trough platforms was formed (Zeng XF et al., 1992). The range of platform-basin facies extends from the direction of Leye and Luodian to Liupanshui and Weining, where organic-rich shale and siliceous rocks of the Lower Carboniferous are deposited. In addition, the platform-basin facies were affected by the influence of NW-trending extension, and a secondary rift perpendicular to the strike of the aulacogen was formed in the Qinglong-Panxian area. In the aulacogen, isolated platforms of different sizes were developed. For example, platforms with a diameter of more than 50 km were developed near Xingren County, and a series of isolated platforms with small coverage were also developed in Ceheng, Leye, Luoping, west of Ziyun, and south of Liupanshui. The segmented shallow-water carbonate rock platform was isolated and surrounded by deep-water deposits, and the interbedded slope facies of carbonate rock and shale were deposited at the transition part. It was integrated by the slope and connected to the platform in the south of Luoping and Longlin (Fig. 5).

To the north of the Weining-Liupanshui-Ziyun-Luodian area, near the Qianzhong uplift, the platform-basin facies transition into slope, platform, and coastal facies (Peng J et al., 2000; Zhang N et al., 2016). Sediment gravity flow and olistostrome developed on the slope. Affected by the Caledonian tectonic extension, the northeast side of the YZLA is characterized by a steep slope. That is, the slope and platform range is narrow, and the transition is rapid when entering the platform basin; on the southwest side of the aulacogen, the slope becomes gentle and the depositional range of slope facies increased (Fig. 6), connecting the Nanpanjiang Depression from the Shizong and Luoping areas.

In the late Early Carboniferous, the seawater continued to deepen and the sea was expanded (Wang SY et al., 2006). Based on the previous deposition, accreted thin siliceous rocks, dark thin to medium-thick limestones, flint nodule limestones, and claystones were formed (Lower part of Nandan Formation).

In the Late Carboniferous, due to the weakening of fault activity in YZLA, the seawater retreated to the southeast, and the Nandan Formation strata of micrite limestone, flint limestone, marl limestone intercalated with gravel limestone, and siliceous rock were deposited in the aulacogen.

#### 5. Characteristics of shale gas accumulation

##### 5.1. Accumulation conditions

The YZLA has a NW-trending narrow and long distribution shape, with a large spatial span, complex geological evolution, large lateral changes in strata lithology, strong vertical heterogeneity, and the Lower Carboniferous strata are less exposed on the surface. In this study, combined with the 2D seismic and wide-field electromagnetic method work deployed in the area, the underground low-resistivity strata were identified, and the distribution regularities of Carboniferous shale were predicted.

##### 5.1.1. Shale thickness

From the distribution of Carboniferous shale (Fig. 7), the changes of sedimentary facies and major faults in the Early Carboniferous played a major role in controlling the shale deposition in the aulacogen (Yuan K et al., 2017; Mei MX et al., 2005). Platform-basin and slope facies are favorable facies for Carboniferous shale development, and the axis of the aulacogen is the most favorable area for shale deposition. The Lower Carboniferous shale is distributed in the NW direction, with a thickness of 100–350 m. The deposition center is located in the Weining-Liupanshui-Guanling-Ziyun line, and the thickness decreases in the direction of Xingren, Nayong, and Anshun. In addition, shale-bearing strata are also relatively developed in the footwall of the synsedimentary normal fault in the aulacogen, while in some structural high parts and the peripheral areas of the aulacogen, the deposition thickness of shale is thinner, even pinched out (Wang SY et al., 2006).

##### 5.1.2. Content of organic carbon

The kerogen type of the Dawuba Formation shale in the aulacogen have complex changes, generally showing a transformation from type III close to the provenance area to type II<sub>1</sub> and type I in the aulacogen. In addition, the organic carbon content (TOC) in the aulacogen varies widely, ranging from 1% to 5%, and it mainly distributed in the range of less than 2.0% (Fig. 8a). From the core of the aulacogen (Shuicheng-Qinglong-Luodian area), TOC gradually decreases to the northeast and southwest; the change of TOC also gradually decreases from the southeast of the aulacogen (Luodian) to the northwest (the Weining-Liupanshui area).

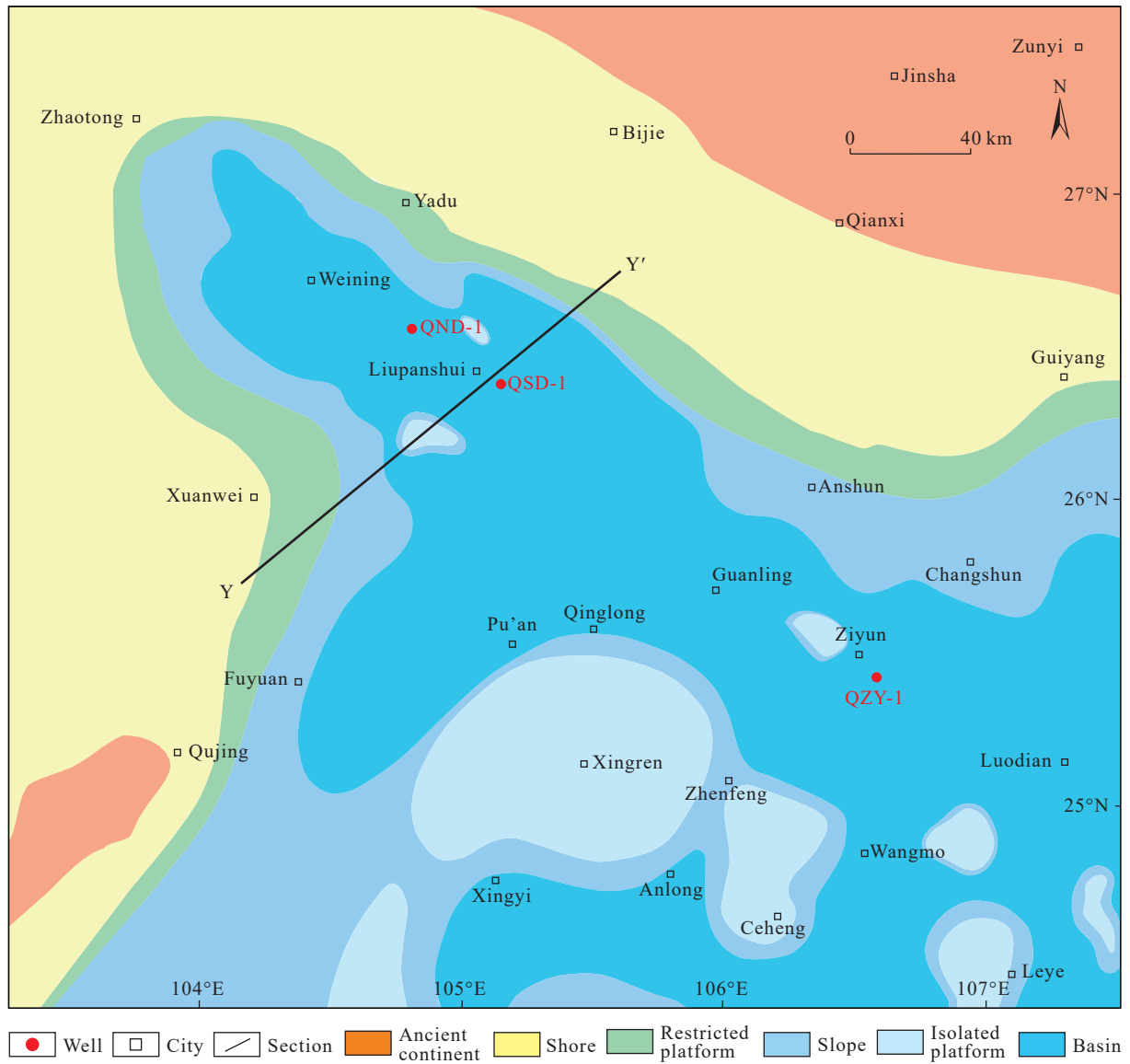


Fig. 5. Early Carboniferous sedimentary facies map of YZLA. Note: YY' means section line.

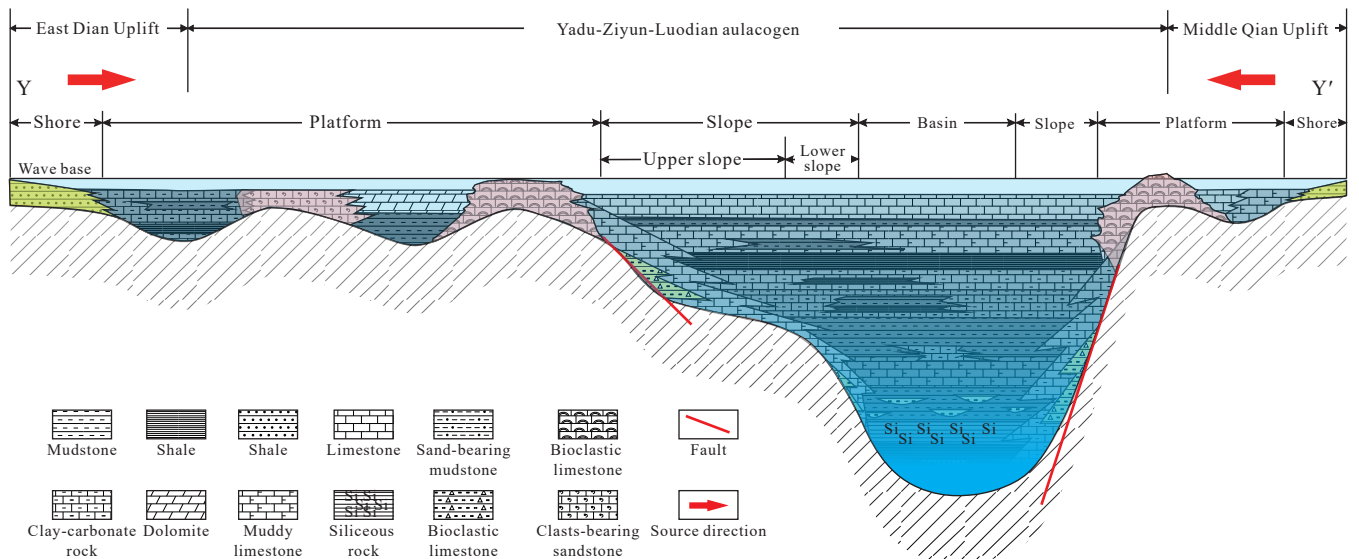


Fig. 6. Early Carboniferous sedimentary model of YZLA. Note: The section location is shown in Fig. 5.

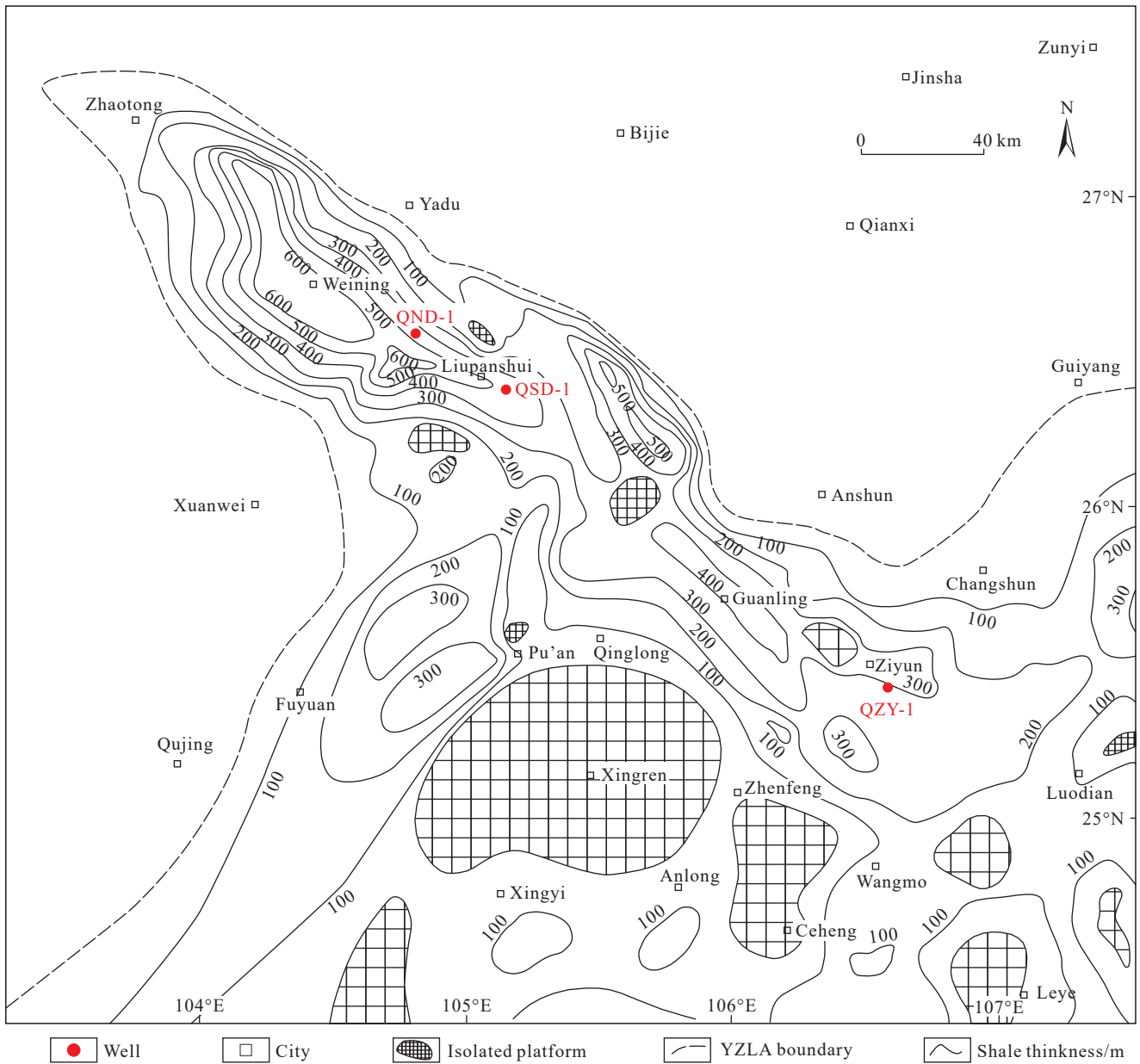


Fig. 7. Isopach map of the Lower Carboniferous shale in YZLA .

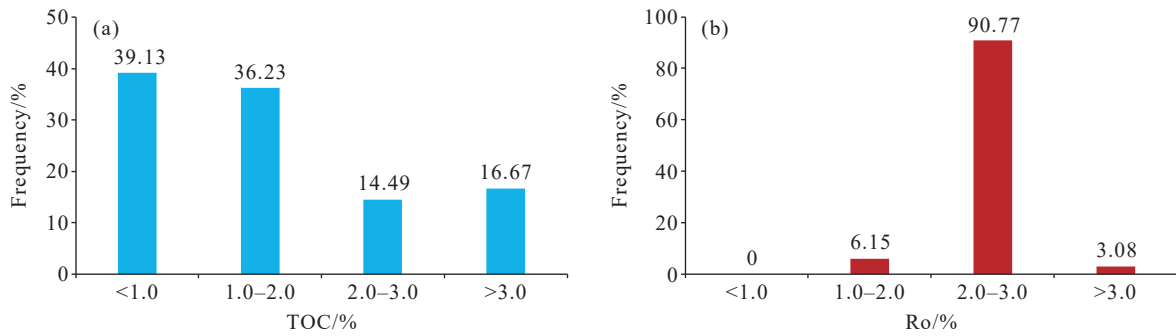


Fig. 8. TOC frequency distribution (a) and  $R_o$  frequency distribution (b) of Dawuba Formation in YZLA.

The Luodian area, as a part of deep water in the Early Carboniferous, is also located in the core of the aulacogen. It corresponds to the area with the highest TOC in the Dawuba Formation, and the average TOC can exceed 5%. The TOC in Qinglong-Ziyun area is 2% to 4%, and the TOC in Weining-

Liupanshui area is 1% to 3%.

### 5.1.3. Thermal evolution degree

Most of the Carboniferous shales in YZLA are in the high over-mature stage, the thermal evolution degree ( $R_o$ ) is

distributed from 1.0% to 4.0%, mainly distributed in 2.0% to 3.0% (Fig. 8b). Qinglong-Ziyun-Luodian area is the area with a high degree of thermal evolution, in areas with strong strike-slip effects such as Ziyun,  $R_0$  can reach more than 4.0% (Yuan K et al., 2018).  $R_0$  in the Xingyi-Anlong-Ceheng-Wangmo area is less than 2.0%,  $R_0$  in the Weining-Liupanshui area is 2.0% to 3.0%, and the  $R_0$  is 1.5% to 2.5% in other areas.

5.2. Preservation conditions

The faults of YZLA are well developed, and the NW-trending faults play a major role in controlling the formation and evolution of YZLA. Most of these faults are normal faults formed in the extensional environment during rifting and depression period, and maintain a certain degree of inheritance in the long-term evolution process (Wang XW et al., 2013; Liu GH et al., 2022).

The Yadu-Ziyun fault and the Ziyun-Luodian fault are boundary synsedimentary faults that control the aulacogen.

This group of contemporaneous normal faults was formed in the Guangxi Movement and has a length of more than 250 km (Fig. 9). They were active in multiple stages, controlled the formation of NW-trending sedimentary depressions and uplifts on both sides of the fault, and have obvious control over the depositional environment of the aulacogen (Wang XW et al., 2013). The Guiyang-Zhenyuan fault was initially formed during the Duyun Movement, and had several activities during the Guangxi Movement and the Devonian period. This fault played a certain role in controlling the sedimentary evolution in the north-south direction of YZLA. During the Indosinian, Yanshanian and Himalayan periods, most faults in YZLA were activated for several times, and underwent a tectonic inversion. The present Ziyun-Luodian fault is characterized by an obvious left-lateral strike-slip.

Two shale gas accumulation models are summarized combined with the typical wells in the aulacogen and the characteristics of Carboniferous shale in the study area. One of them is the lower slope facies syncline structural accumulation model represented by well QZY-1, and the

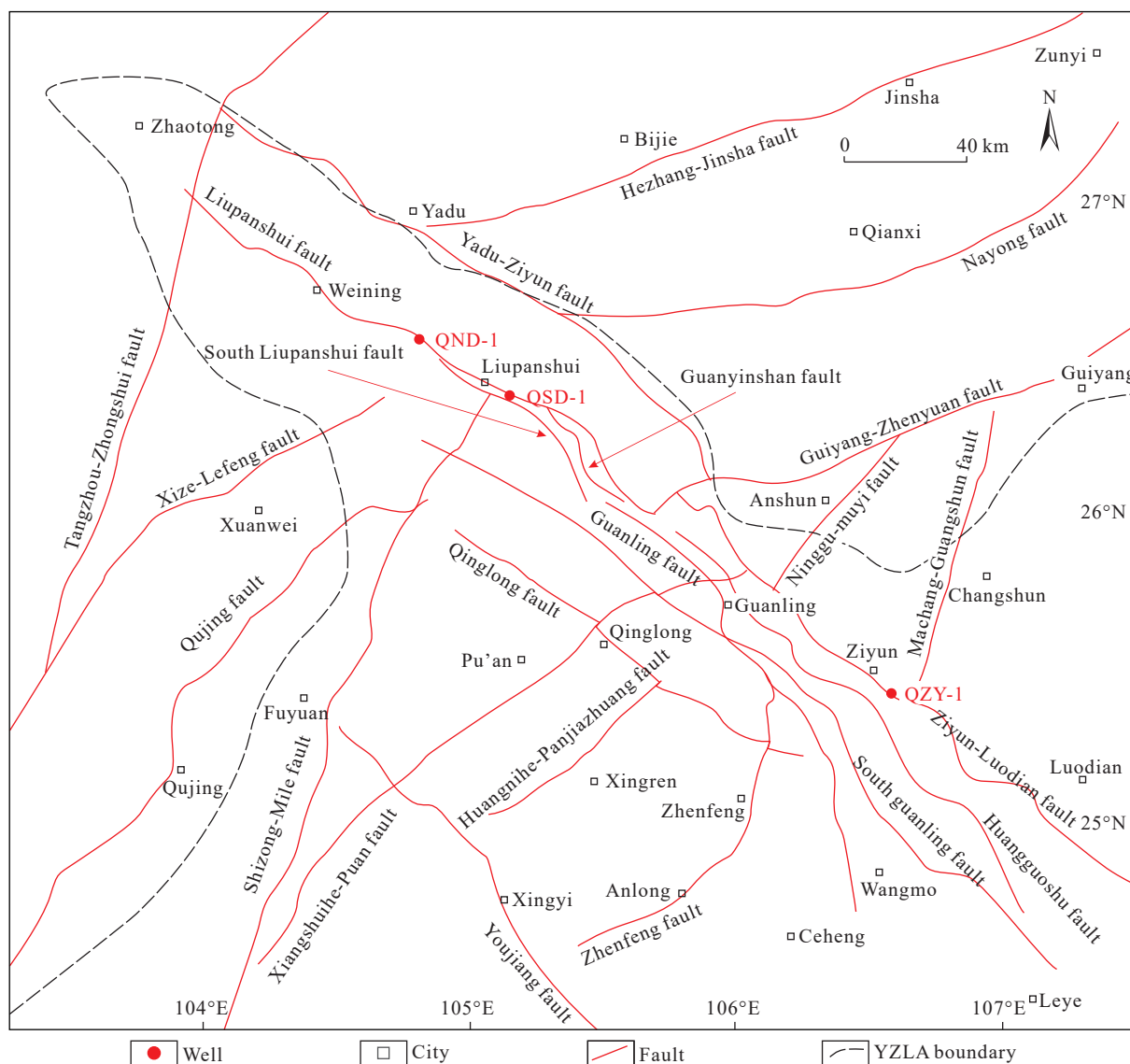


Fig. 9. Distribution of main faults in the YZLA from Early Devonian to Triassic (modified from Liu JP et al., 2006; Wang XW et al., 2013).

other is the platform-basin facies tightly closed anticline model represented by well QSD-1. (1) Well QZY-1 is located in the Ziyun area of Guizhou Province. This area is located in the middle of the aulacogen, and the lithological assemblage of the lower slope facies was deposited during the Early Carboniferous period. Under the tectonic background of compression, the internal syncline faults are relatively undeveloped. Due to the large burial depth of the Lower Carboniferous strata, the scale of the surrounding faults is small and most of them are reverse faults. Therefore, after the shale gas was generated, a good shale gas reservoir will be formed during this stage of shale formation (Fig. 10). (2) Well QSD-1 is located in the Liupanshui area of Guizhou Province, which is located in the west of the aulacogen. The sedimentary facies developed in this model is platform-basin facies. The shale in the bottom of the Early Carboniferous is thick, and the interlayers of shale and marl gradually increase upward, with good hydrocarbon generation conditions. Structural morphological features are mainly dominated by compression and deformation in this model. Under the superimposition of multi-phase tectonic movements, structural forms of fold and fault combination can be seen in the field and on cores. Affected by compressive-torsional reverse faulting in the Indosinian period, the structure in this model has a good relationship with the configuration of shale gas accumulation. Besides, it is easy to form reverse faults to block shale gas, which controlled the accumulation of shale gas (Fig. 11).

### 5.3. Gas bearing characteristics

According to the statistics on the gas-bearing properties of multiple shale gas wells in the YZLA, the wells in YZLA in the Early Carboniferous show good gas-bearing properties

(Yuan K et al., 2017). (1) Well DT-1 (1224.65 m) located at the eastern part of YZLA, encountered a total thickness of 1171.5 m in the Lower Carboniferous Luzhai Formation. The highest value of total hydrocarbon in gas logging is 26.55%, the gas content is  $0.45 \text{ m}^3/\text{t}$ – $1.67 \text{ m}^3/\text{t}$ , the type of kerogen is type  $\text{II}_2$ , the average TOC is 1.13%, and the average  $R_o$  is 2.04%. (2) Well GRY-1 (3305 m) in the northeast of YZLA shows good gas-bearing performance in the first member of the Lower Carboniferous Luzhai Formation. The formation thickness is 288.5 m, and 8 gas-bearing layers with a cumulative thickness of 193.5 m were comprehensively interpreted, the highest total hydrocarbon measured by gas is 2.88%, the gas content is  $0.71 \text{ m}^3/\text{t}$ – $2.61 \text{ m}^3/\text{t}$ , the shale kerogen type is mainly type II, the average TOC is 1.63%,  $R_o$  average 2.62%. (3) Well QZY-1 (3050 m) in the middle of YZLA encountered 319 m of the Lower Carboniferous Dawuba Formation. A total of 16 gas-bearing layers with a cumulative thickness of 95.97 m were comprehensively interpreted, and the highest total hydrocarbon measured by gas was 2.58%. The gas content is  $0.37 \text{ m}^3/\text{t}$ – $4.37 \text{ m}^3/\text{t}$ , the type of shale kerogen is type  $\text{II}_2$ , the average TOC is 1.7% and the average  $R_o$  is 3.99%. (4) Well QSD-1 (2500 m) located in the west part of YZLA, encountered 1009 m of Carboniferous Dawuba Formation, and 53 gas-bearing layers, which generally contain gas. The total hydrocarbon value was all greater than 2%, the highest total hydrocarbons is 76.27%, the gas content is  $0.66 \text{ m}^3/\text{t}$ – $3.79 \text{ m}^3/\text{t}$ , the kerogen type of shale is mainly  $\text{II}_1$ , the average TOC is 1.0%, and the average  $R_o$  is 2.2%. (5) Well QND-1 (1133.05 m) at the northwest part of YZLA encountered 783 m of the Lower Carboniferous Dawuba Formation. The highest total hydrocarbon measured by gas is 5.80%, the analytical gas volume is  $0.14 \text{ m}^3/\text{t}$ – $3.31 \text{ m}^3/\text{t}$ , and the shale kerogen type is  $\text{II}_1$ , with an average TOC of 1.3% and average  $R_o$  of 2.1%.

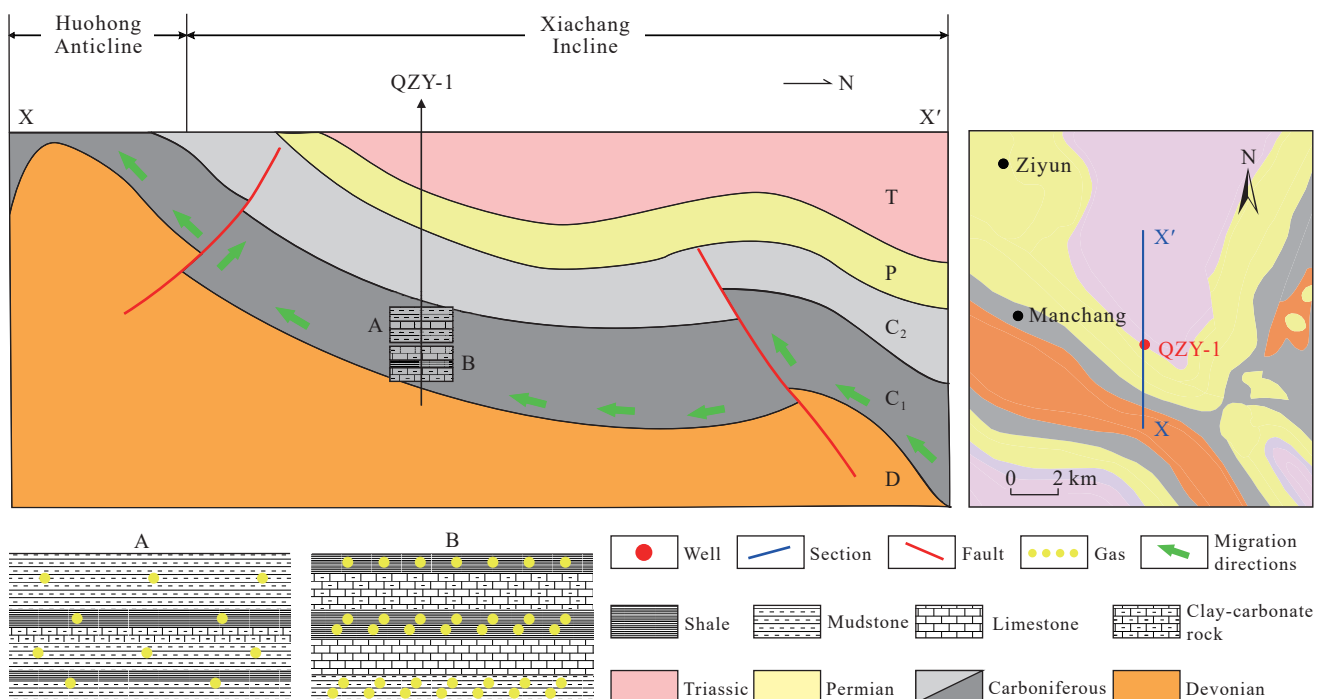
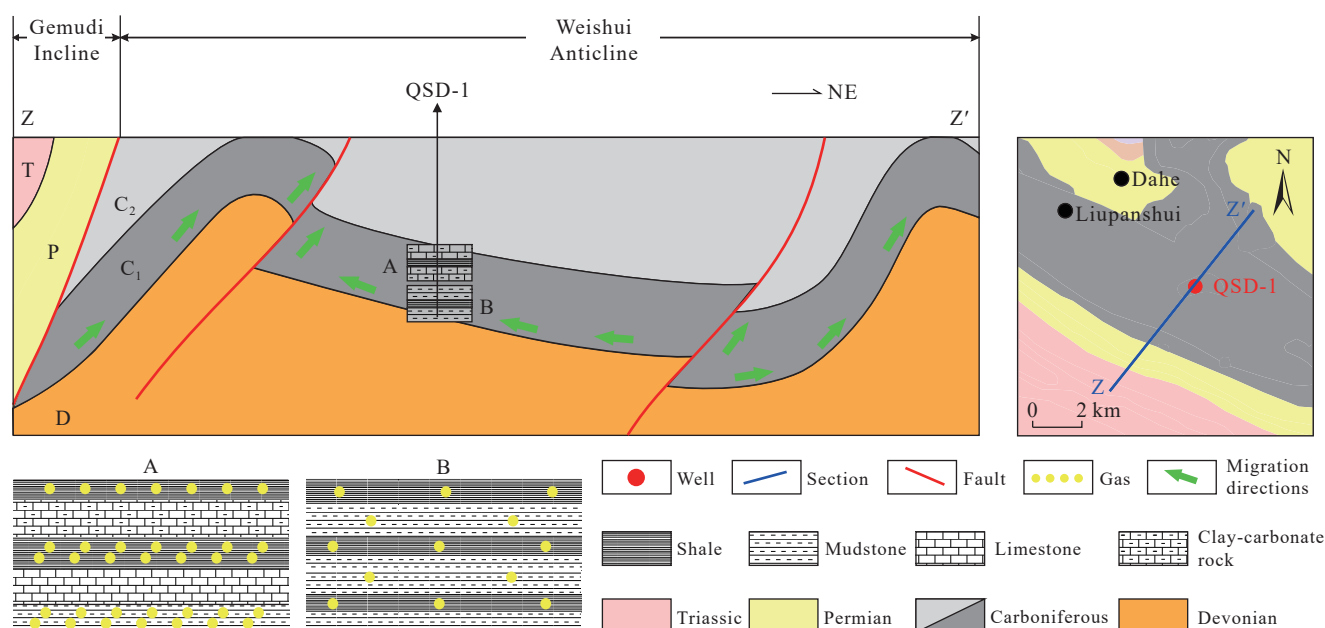


Fig. 10. Shale gas enrichment model of lower slope in syncline structure (Ziyun Area).



**Fig. 11.** Shale gas enrichment model of platform-basin facies in closed anticline (Liupanshui Area).

By comparing the gas-bearing conditions of wells in different parts of YZLA, it is concluded that a good positive correlation appears between the gas-bearing properties of the Early Carboniferous shale and the lithologic association characteristics. In the interbedded lithological section, the gas content increases correspondingly in the parts with high TOC, which indicates a positive role of the lithological interbedding of the Carboniferous in the preservation of shale gas. In addition, in the area covered by the Triassic, the damaging effect of the late structure on shale gas reservoirs is weak.

Based on the shale organic carbon content, thermal evolution degree, reservoir physical properties, formation pressure, it is considered that the YZLA has a good material basis for shale gas accumulation.

## 6. Conclusions

(i) According to the tectonic evolution of YZLA and the characteristics of Carboniferous shale deposition in the aulacogen, it can be divided into five evolution stages: a Pre-Devonian folded basement formation stage, an Early Devonian crustal stretching and thinning stage, a Middle Devonian to Late Carboniferous fault subsidence stage, a Permian mantle plume stage and a Triassic to Cretaceous thrusting transformation stage. The last stage has a significant impact on the preservation of shale gas in the area.

(ii) The Carboniferous sedimentation of YZLA is characterized by the sedimentary pattern with multiple trough enclosures and inter-trough platforms formed. The asymmetric platform-basin pattern shows that from the continental margin to the interior of the basin, it is steep in the northeast and gentle in the southwest, and there are multiple isolated plateaus of different sizes in the basin.

(iii) The Early Carboniferous shale has the following favorable conditions for shale gas accumulation: The Dawuba Formation has a typical rhythmic interbedding feature of shale

and marl with unequal thickness, and the stratum is stable and thick. The static index elements of the Dawuba Formation are well-matched, the shale gas in the area covered by the Triassic strata is well preserved, and the dynamic evolution is conducive to the large-scale accumulation of gas, which can be the focus of the next exploration.

(iv) There are obvious differences between the development of the Upper Paleozoic Carboniferous shale and the Wufeng-Longmaxi formation. Well QSD-1 in the aulacogen obtained a high-yield shale gas flow of daily output of 11011 m<sup>3</sup>, which confirms that the Lower Carboniferous shale in the aulacogen has good shale gas hydrocarbon generation potential, revealing a new set of high-quality shale gas reservoirs different from the Longmaxi Formation. Furthermore, it shows that the YZLA and its eastern extension of Rongshui and Hechi areas in Guangxi Province may become one of the important areas for realizing a substantial breakthrough in the industrialization and commercialization of shale gas in the Yunnan-Guizhou-Guangxi region of South China, which is worthy of further in-depth study.

## CRedit authorship contribution statement

Kun Yuan and Wen-hui Huang conceived the presented idea. Shi-zhen Li and Ting Wang conceived and planned the experiments. Xiang-can Sun carried out the experiments. Kun Yuan, Ting Wang, and Xin-xin Fang wrote the manuscript in consultation. All authors discussed the results and contributed to the final manuscript.

## Declaration of competing interest

The authors declare no conflicts of interest.

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