TYPE Original Research
PUBLISHED 09 January 2024
DOI 10.3389/feart.2023.1301302

OPEN ACCESS

EDITED BY
Lawrence H. Tanner,
Le Moyne College, United States

REVIEWED BY
Hossain Rahimpour-Bonab,
University of Tehran, Iran
Longyi Shao,
China University of Mining and Technology, China

*CORRESPONDENCE
Xiucheng Tan,
tanxiucheng70@163.com

RECEIVED 24 September 2023
ACCEPTED 15 December 2023
PUBLISHED 09 January 2024

CITATION
Yang W, Tan X, Tang D, Zhang Z, Hu X, Li M, Zeng Z and Xiao D (2024), Sequence lithofacies paleogeography evolution of the Middle Permian Maokou Formation in the northwest margin of the Sichuan Basin.
Front. Earth Sci. 11:1301302.
doi: 10.3389/feart.2023.1301302

Sequence lithofacies paleogeography evolution of the Middle Permian Maokou Formation in the northwest margin of the Sichuan Basin

Wenjie Yang[1,2], Xiucheng Tan[1,2]*, Dahai Tang[3], Zhaokun Zhang[4], Xin Hu[3], Minglong Li[1,2], Zixuan Zeng[1,2] and Di Xiao[1,2]

[1]State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, China, [2]Division of Key Laboratory of Carbonate Reservoirs, China National Petroleum Corporation, Southwest Petroleum University, Chengdu, China, [3]Northwest Sichuan Division, PetroChina Southwest Oil and Gas Field Company, Jiangyou, China, [4]Research Institute of BGP Inc., PetroChina, Chengdu, China

Due to the present tectonic and stratigraphic distribution characteristics in the northwest margin of the Sichuan Basin are complex, which restricts the understanding of sequence lithofacies paleogeography of the Middle Permian Maokou Formation. To investigate the process of tectonic–sedimentary evolution, basin-margin outcrop and intra-basin well and seismic data were used. The results show two structural sequences, namely, SSQ1 and SSQ2, and five third-order sequences, namely, SQ1–SQ5, in the Middle Permian Maokou Formation. SSQ1, with stable formation thickness, shows a slow transgression–fast regression sequence structure. SSQ2 shows a fast transgression–slow regression sequence structure in the area with large thickness and a sustained transgression–fast regression sequence structure in the area with small thickness owing to thickness differentiation caused by tectonic subsidence. Sedimentological analysis shows that sequences SQ1–SQ2 mainly consist of carbonate-ramp sediments, the sedimentary facies of which change from intermediate ramp to outer ramp as the area depressed topographically from south to north. Sequences SQ3–SQ5 mainly consist of rimmed carbonate platform sediments; the platform margin turned up along Shuangyushi–Jian'ge–Yuanba, and the region to the north subsided rapidly to form slope-basin facies. Lithofacies paleogeography in the Middle Permian epoch shows that the northwest margin of the Sichuan Basin was dominated by extensional stresses in northeast and northwest directions. Tectonic activities have a dominant control on the distribution of two structural sequences and the evolution of carbonate platform types in the Maokou Formation, and the sea-level change has a dominant control on third-order sequence boundaries and sedimentary facies migration. Thus, the Middle Permian tectono-sedimentary evolution model of the northwest margin of the Sichuan Basin is established.

Research findings may offer new ideas and theoretical support to promising facies exploration in the Maokou Formation in the northwest margin of the Sichuan Basin.

KEYWORDS

lithofacies paleogeography, sequence stratigraphy, sedimentary evolution, Middle Permian epoch, Maokou Formation, Sichuan Basin

1 Introduction

The northwestern Sichuan Basin, lying at the intersection of the Upper Yangtze Block and Songpan–Ganzi and Qinling orogenic zones, experienced multi-phase tectonic activities in geologic history. Thus, the process of tectonic evolution and sedimentary formations is very complicated (Yang et al., 2023). Tectonic activities, ancient landforms, and sea-level changes are the basic factors that control sedimentary facies type and distribution. The Middle Permian epoch is the period with maximum extensional tectonic activities, the multi-phase responses of which inevitably affected sedimentary processes, sedimentary features, and facies migration; however, research studies on this area are not sufficient to provide further information. This means that the complex tectonic stress system should be integrated with tectonic evolution to restore lithofacies paleogeography in each phase and analyze the evolutionary rules so as to provide further guidance for a deeper understanding of the paleogeographic framework and high-energy facies distribution in the Middle Permian of the Sichuan Basin. In addition, it was difficult to perform isochronal stratigraphic correlation between surface outcrops and subsurface formations drilled because available data were deficient before and research studies mainly focused on the inner basin, which further restricted the restoration of sequences and lithofacies paleogeography in this area. As a consequence, there are different opinions on the paleogeographic framework in the Middle Permian Maokou Formation, northwestern Sichuan for a long period of time, including rimmed carbonate platform and carbonate ramp (Hu et al., 2012; Liu et al., 2017; Song, 2018; Zhong et al., 2021).

The Middle Permian Maokou Formation is an important series of strata for exploration in the Sichuan Basin, but previous exploratory drilling and research studies focused on the central and southern parts of the basin (Shen et al., 2015; Zhong et al., 2021). The breakthroughs in intra-platform shoal-facies dolomite exploration by drilling wells JT1 and PY1 close to northwestern Sichuan (Yang et al., 2021; Xiao et al., 2023) indicated a promising prospect of exploration in the study area. On the other hand, the complexities of hydrocarbon accumulation caused by tectonic–sedimentary differentiation in the Middle Permian epoch and different opinions on lithofacies paleogeography have, for a long period of time, restricted shoal-facies dolomite reservoir exploration in this area. This means sequence lithofacies paleogeography restoration is of scientific significance for the understanding of tectonic–sedimentary evolution and sedimentary formations, and it may offer theoretical support to promising prospect optimization in northwestern Sichuan.

The data used include high-precision GR logs from wells and outcrops in northwestern Sichuan. Based on the isochronal correlation of sequence boundaries, we restore the paleogeographic framework and process of tectonic–sedimentary evolution in the Middle Permian epoch and discuss sedimentary responses in the context of complicated tectonic activities and their geologic significance to hydrocarbon accumulation. Our research findings may set a course for future large-scale hydrocarbon discoveries in the Maokou Formation in the Sichuan Basin.

2 General geology

The study area lies in the northwest margin of the Yangtze Plate and is next to the Longmenshan fault zone in the northwest, which changes outward into the Songpan–Ganzi folded zone, and the Qinling folded zone in the northeast (Yang et al., 2023) (Figure 1A). The Sichuan Basin experienced multi-phase marine deposition alternating with continental deposition in the Paleozoic era; mass transgression in the initial Permian Period almost flooded the whole Middle–Upper Yangtze regions and gave rise to the Liangshan, Qixia, Maokou, Wujiaping, and Changxing formations in the study area (Hu S. et al., 2020). As gradual transgression continued at the initial stage of the Qixia Formation, the littoral-swamp facies in the Liangshan Formation changed into a carbonate platform system. The Maokou Formation with thick carbonate rocks, which are mainly bioclastic limestones and marls, is divided into four members from Mao1 to Mao4. The upper Maokou Formation in the Wangcang area also includes the Gufeng Member, which is composed of siliceous rocks and shales (Fu et al., 2021). Owing to intense denudation caused by the uplift resulting from the Dongwu movement after Maokou deposition, only formations below Mao3 were preserved in most areas (Jiang et al., 2018). The overlying strata are Wujiaping marine carbonate rocks. It evolved into the Changxing Formation, which is composed of normal carbonate deposits at paleogeomorphic highs, and the Dalong Formation, which is mainly composed of deep-water deposits in the ocean trough zone.

The whole Sichuan Basin experienced an extensional tectonic environment during the Middle Permian due to the continuous extensional cracking in the Hercynian period. The Longmenshan rift basin and the South Qinling rift basin were formed in the western and northern margins of the basin. The tectonic stress of the Middle Permian Maokou stage was mainly derived from the extensional cracking of the passive continental margin of the Upper Yangtze north and the passive continental margin of the Upper Yangtze west (Zhang et al., 2019; Yan et al., 2020; Huang et al., 2023), which resulted in the tension stress in the NW and NW directions. In addition, the distal tensioning caused by the mantle plume uplift of Mount Emei further strengthens the NNE tensile stress (Su et al., 2020).

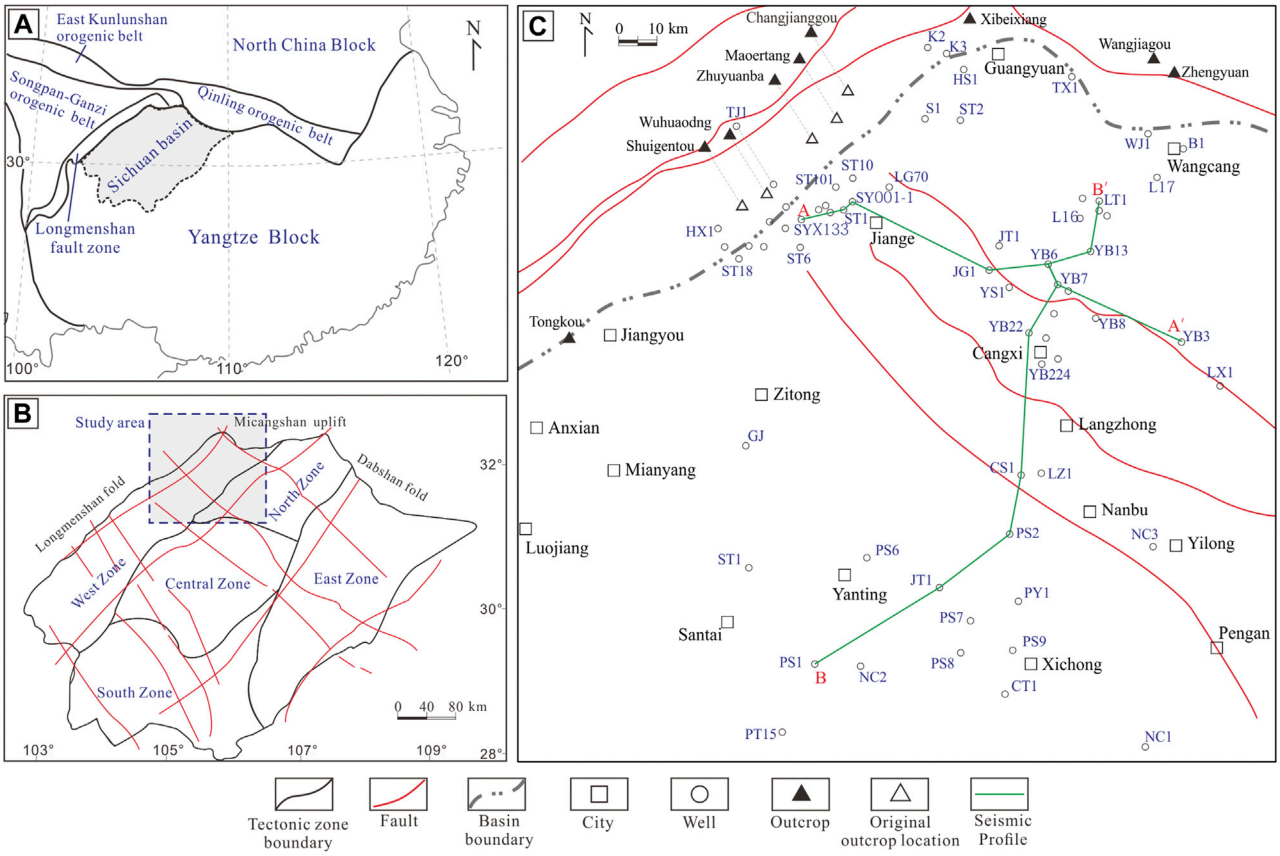

FIGURE 1
Regional geology in the northwest margin of the Sichuan Basin. **(A)** Yangtze plate tectonic area map; **(B)** tectonic provinces in the Sichuan Basin; and **(C)** distribution map of wells and outcrops in the northwest margin of the Sichuan Basin.

Many basement faults in the northeast and northwest directions formed in the Sichuan Basin, which experienced an extensional structural environment. These basement faults created a strong impact on later regional tectonic deformation and sedimentation, among which the Longmenshan fault made a great impact on northwestern Sichuan (Figure 1B). The Longmenshan fault zone consisted of normal faults generated by extensional stress during the Permian Period, which were extruded into reverse faults in Indonesia, leading to typical thrust-nappe structures in the Longmenshan area (Liang et al., 2022). A number of shovel-like faults, steep in the upper part and gentle in the lower part, penetrating the basement exhibit the properties of syndepositional normal faults before structural inversion (Zou and Yin, 2009). Basement faults penetrating the Permian System were also discovered in the Micangshan piedmont zone; the faults may be extensional structures in a northeast-southwest direction during the Permian Period and are mostly reverse faults now (Chen et al., 2019). To accurately restore the stratigraphy and sedimentation in the Middle Permian epoch in northwestern Sichuan, we referred to the preceding study on the thrusting distance of the Longmenshan fault zone (Xiong et al., 2019) and extrapolated well and retrieved the outcrop data at the hanging wall 20–40 km toward the northwest to establish the map of well sites and outcrops in the study area (Figure 1C).

3 Data and methodology

Based on the comprehensive analysis of outcrop, core, log, and seismic data, we investigated the sedimentary features of the Maokou Formation in the northwest margin of the Sichuan Basin and restored the process of tectonic–sedimentary evolution. Sequence boundaries were identified using high-precision GR logs and lithofacies change characteristics acquired at 3 outcrops: Changjianggou, Xibeixiang, and Zhengyuan. Sedimentary facies types were defined by observing thin sections that were prepared using the samples from 3 outcrops, drilling cores from 3 wells, and drilling cuttings from 12 wells. The slowness-time thickness of a sequence calculated using 2D and 3D seismic data was combined with well data to map sequence thickness. Based on the development features of cross-well and plane facies, the coupling mechanism of tectonic–sedimentary evolution is discussed.

4 Sequence stratigraphic framework restoration

4.1 Sequence boundary identification

Core data on the Maokou Formation in northwestern Sichuan are insufficient, and it is difficult to accurately identify and correlate

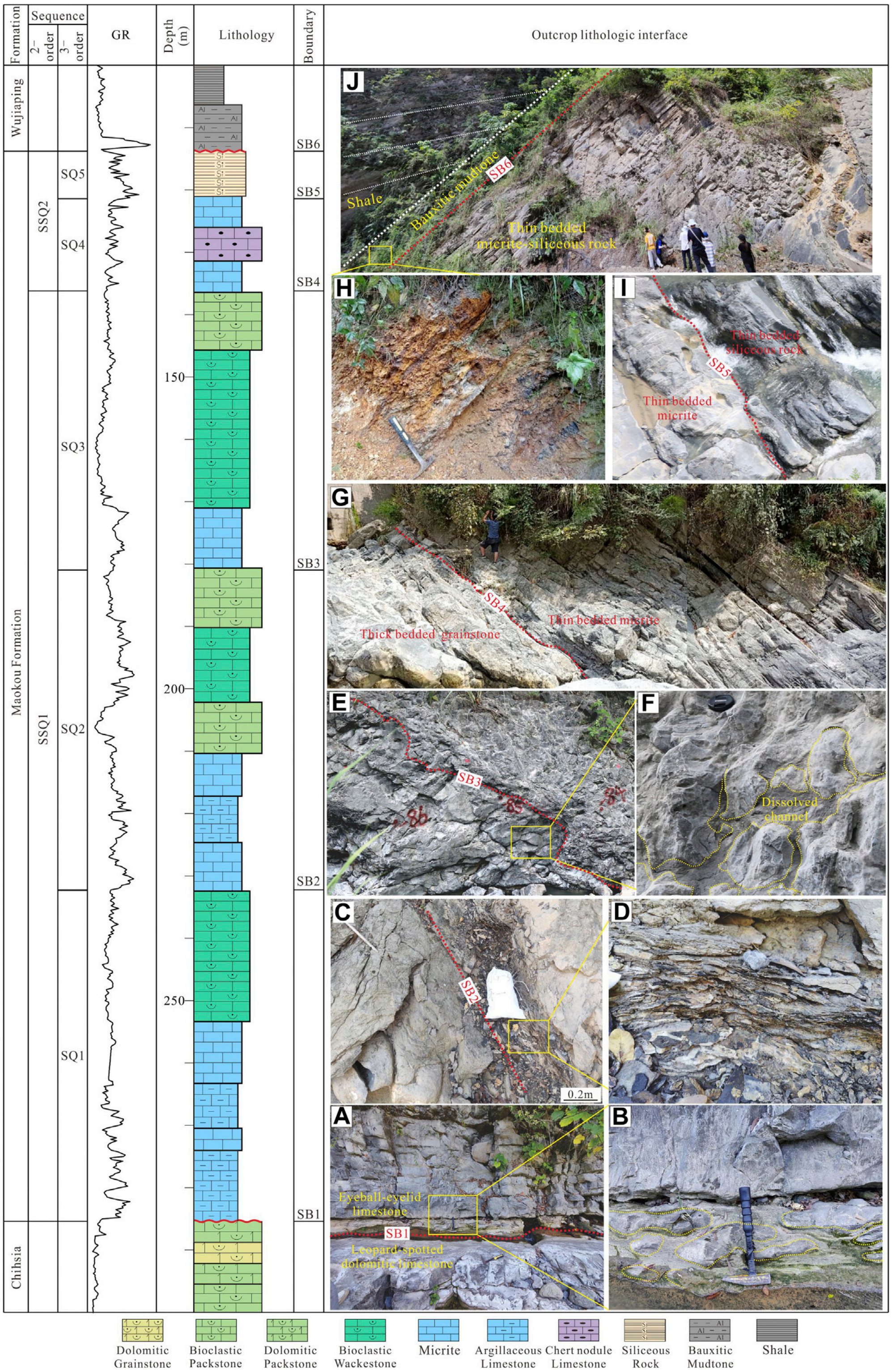

FIGURE 2
Sequence boundary identification marks on the Changjianggou section. **(A)** SB1 outcrop photograph, leopard-spotted dolomitic limestones below the boundary, "eyeball–eyelid" limestones above the boundary; **(B)** Photographs of the eyelid limestone of the bottom eyeball of SQ1; **(C)** SB2 outcrop photograph, wackestones below the boundary, calcareous mudstones above the boundary; **(D)** Photograph of the very thin layer of calcareous mudstones at the bottom of SQ2; **(E)** SB3 outcrop photograph, grainstones below the boundary, wackestones above the boundary; **(F)** The top of SQ2 was exposed and the dissolved channels could be seen; **(G)** SB4 outcrop photograph, grainstones below the boundary, thin bedded micrites above the boundary; **(H)** Photograph of corresponding position in Figure 2, brown bauxitic mudstones; **(I)** SB5 outcrop photograph, micrites below the boundary, siliceous rocks above the boundary; **(G)** SB6 outcrop photograph, thin bedded limestones or siliceous rocks below the boundary, bauxitic mudstones above the boundary.

sequence boundaries by merely using log data. Outcrop data provide abundant first-hand petrologic information for sequence boundary identification, and high-precision GR logs of outcrops could be used for identifying a credible sequence correlation between outcrops and subsurface strata drilled. Hence, the identification and correlation of Maokou sequence stratigraphic boundaries in the whole area were performed based on outcrops with high-precision GR logs to establish a unified sequence stratigraphic framework. For example, on the Changjianggou section in Jian'ge, six sequence boundaries from SB1 to SB6 were identified from the bottom up in the Maokou Formation, which was then divided into two second-order sequences and five third-order sequences.

SB1 and SB6, corresponding to the bottom and top boundaries of the Maokou Formation (Figures 2A, H, J), respectively, are the regionally exposed unconformable surfaces (Jiang et al., 2018; Su et al., 2020). There is an abrupt change from Qixia leopard-spotted grainstones experiencing intense karstification below SB1 to Maokou "eyeball–eyelid" limestones above SB1 (Figures 2A, B). SB6 is an exposed boundary at the top of the Maokou Formation and often marked by Wangpo shales (Figures 2G, H). There is the consensus of opinion about the top and bottom boundaries of the Maokou Formation; thus, the key to isochronal sequence stratigraphic correlation is how to identify sequence boundaries inside the Maokou Formation.

Below SB2, grayish black thin-to-medium-layered wackestones (Figure 2C) with distinct argillaceous components and testa and bivalve fossils are visible under a microscope. Above SB2, khaki thin calcareous mudstones of 10–20 cm thick (Figures 2C, D) with oriented calcareous strips and little biogenic debris are visible under a microscope, which indicates low-energy deposition at the initial stage of a transgressive cycle.

Below SB3, medium-to-thick grainstones (Figure 2C) with a lot of corroded grooves and karstic breccia at a depth ranging 2–5 m owing to intense karstification are observed (Figure 2F). Many *Dasycladus* fragments and various biogenic debris materials are visible under a microscope. Above SB3, there are remarkably different thin wackestones or micrite (Figure 2E) with very low microorganism content and micritic interstitial materials, which indicates low-energy transgressive deposition.

Below SB4, there are thick blocky grayish white grainstones (Figure 2G) with exposed karst features, e.g., small corroded grooves and dissolved cavities. Above SB4, there are significantly different thin micrites and limestones with siliceous strips (Figure 2G). Bioclastic particles are rare, which indicates a rapid transition from shallow-water platform facies to deep-water facies.

From micrites to siliceous rocks, both of which are deep-water deposits, the rock particle size does not significantly change at SB5 on the Changjianggou section (Figure 2I); however, there is a positive shift in outcrop GR logs above this boundary (Figure 2).

4.2 Sequence stratigraphic correlation

Based on sequence boundaries identified on outcrops, we developed the scheme of outcrop-well sequence correlation using high-precision outcrop GR logs. Some key boundaries, e.g., SB1, SB4, and SB6, could be identified on 2D and 3D seismic sections across the northwestern Sichuan Basin. Thus, the sequence stratigraphic framework of the Middle Permian Maokou Formation in northwestern Sichuan was built by jointly using well and seismic data to describe stratigraphic distribution and filling laws.

As shown in the cross-well sections of Changjianggou-YB3 and PS1-Zhengyuan, high-precision outcrop GR logs could be well correlated (Figures 3, 4). There are two second-order sequences and five third-order sequences on the SE cross-well correlation section. Sequence SSQ1 is relatively thick in Shuangyushi–Jian'ge and thin in Yuanba, and the sequence structure of long-term sustained transgression–fast regression in the whole area indicates a process of slow transgression in a long period of time at the early depositional stage. Sequence SSQ2 exhibits different structures, i.e., fast transgression–slow regression in Shuangyushi and YB7 well block and sustained transgression–fast regression in Changjianggou and JG1–YB6 and YB3 well blocks. SSQ2 thickness in the above well blocks decreases both on well drilling and seismic sections (Figure 3).

The NE cross-well correlation section shows similar features. SSQ1 with stable thickness is a long-term slow transgression–fast regression sequence; SSQ2 thins rapidly toward the north and exhibits a structure of sustained transgression–fast regression in the area with small thickness. In addition, the well correlation section and seismic section together reveal a large topographic slope break between wells YB22 and YB13 during SSQ2 (Figure 4). Different structures of SSQ1 and SSQ2 imply that local areas in northwestern Sichuan may subside rapidly at the depositional stage of SSQ2, which led to the sustained rise of relative sea level.

4.3 Sequence thickness distribution

The thickness of each sequence in SQ1–SQ5 in northwestern Sichuan was restored using formation thickness at well sites and outcrops in the whole area. The spatial trend was constrained using the slowness-time thickness derived from seismic data.

SQ1 is thin in Shuigentou–Changjianggou and Yanting–Cangxi and to the north of Wangcang, particularly in the southwest margin, and thick in other areas (Figure 5A). SQ2 shows some features inherited from SQ1, particularly in Yanting–Cangxi. Small thickness also occurs in the southwest and Shuigentou–Changjianggou and to the north of Wangcang, but the areas with small thickness extend toward the south or southeast (Figure 5B). SQ3 thickness indicates the features in late SSQ1. The southern area with small thickness shows some features that have been inherited from the early and middle phases (SQ1–SQ2). Sequence thickness becomes large in Jiangyou–Jian'ge and Guangyuan–Wangcang in the north and small in the northwest and northeast margin. There is a small-thickness belt extending in the northwest direction between Langzhong and Wangcang (Figure 5C). SSQ1 features large thickness in northwestern Sichuan and small thickness in central Sichuan.

SQ4 shows distinct thickness differentiation: thin to the north of Jiangyou–Jian'ge–Cangxi and thick in the south. Thick areas alternate with thin areas in a northwest direction (Figure 5D). The thickness differentiation may be related to the extensional tectonic activities in the Middle Permian epoch, which led to the rapid subsidence of the northern area. SQ5 thickness shows some features inherited from SQ4. A large thickness increase in JG1–YB7 well blocks in front of the area with thick SQ4 may be related to the insufficient accommodation space and small deposition thickness of the platform at the end of regression. On the other hand, the slope zone

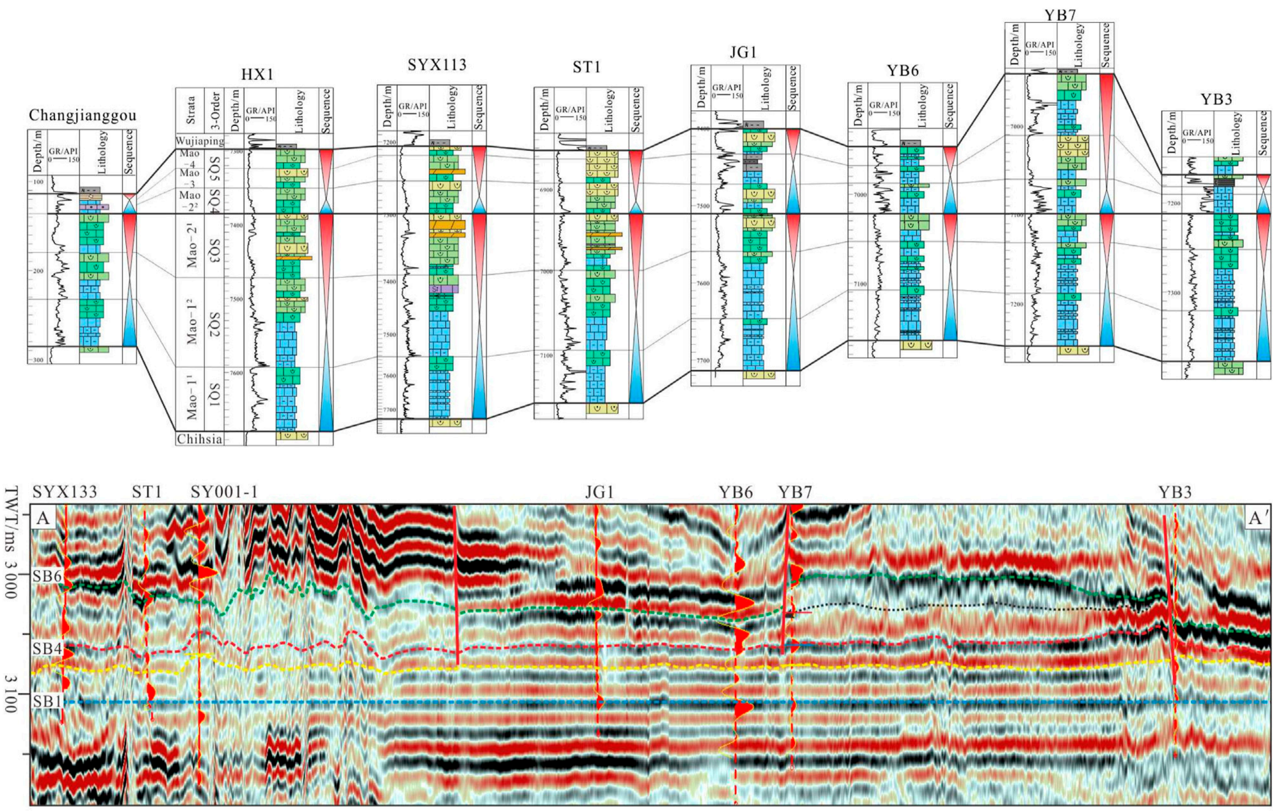

FIGURE 3
SE sequence stratigraphic correlation section across an outcrop and wells in the northwest margin of the Sichuan Basin (see Figure 1 for section location).

was in over-compensatory deposition, which gave rise to a product similar to a progradational wedge (Hu et al., 2017) (Figure 5E).

5 Sedimentary features

5.1 Dominant sedimentary facies types and features

The Maokou Formation comprises limestones, marls, dolomites, siliceous limestones, siliceous rocks, and mud shales with abundant *Fusulina*, gasteropod, *Brachiopoda*, alga, and bivalve fossils. Through the detailed study of sedimentology based on the latest drilling and outcrop data and preceding research findings, we concluded that the northwest margin of the Sichuan Basin experienced a sedimentary environment with a carbonate ramp and rimmed carbonate platform in the Middle Permian epoch (Table 1).

5.1.1 Carbonate ramp

Topographically depressed land surface and increasing formation thickness from central Sichuan to northwestern Sichuan, owing to the influence of the Caledonian paleohigh at the initial stage of the Middle Permian epoch, reflect the features of a gentle slope before deposition. Mass low-energy rocks in SQ1–SQ2 in northwestern Sichuan are the depositional product of the ramp platform below the wave base. Sedimentation mainly occurred in a middle-ramp environment with outer ramps locally; high-energy environments, such as the inner ramp, were not observed (Su et al., 2021; Liu et al., 2022b).

(1)Intermediate ramp

The intermediate ramp with low energy occurred between a normal wave base and a storm wave base, where there are various fossil organisms and low-energy bioclastic shoals. The intermediate ramp is lithologically dominated by wackestones, packstones, and marls. The Mao1 Member in northwestern Sichuan mainly comprises wackestones with a low content of unevenly distributed poorly sorted biogenic debris (Figure 6A), which indicates a plausible low-energy neritic environment forming below the normal wave base. Affected by the action of the storm wave, storm shoals with positive grain sequence bedding developed locally. Storm shoals are mainly sandy or bioclastic shoals formed due to storm wave disturbance. The lithology is mainly packstones (Figure 6B), which is distributed in static water mud with a lenticular shape (Liu et al., 2022b).

(2)Outer ramp

The outer ramp occurred below a storm wave base and thus was little affected by wave and storm actions, where deep-water low-energy carbonate rocks, including marls and micrite, were deposited. Biogenic debris is rare. Micrites with a very small content of organisms (Figure 6C) mainly formed in a low-energy lentic environment, such as the outer

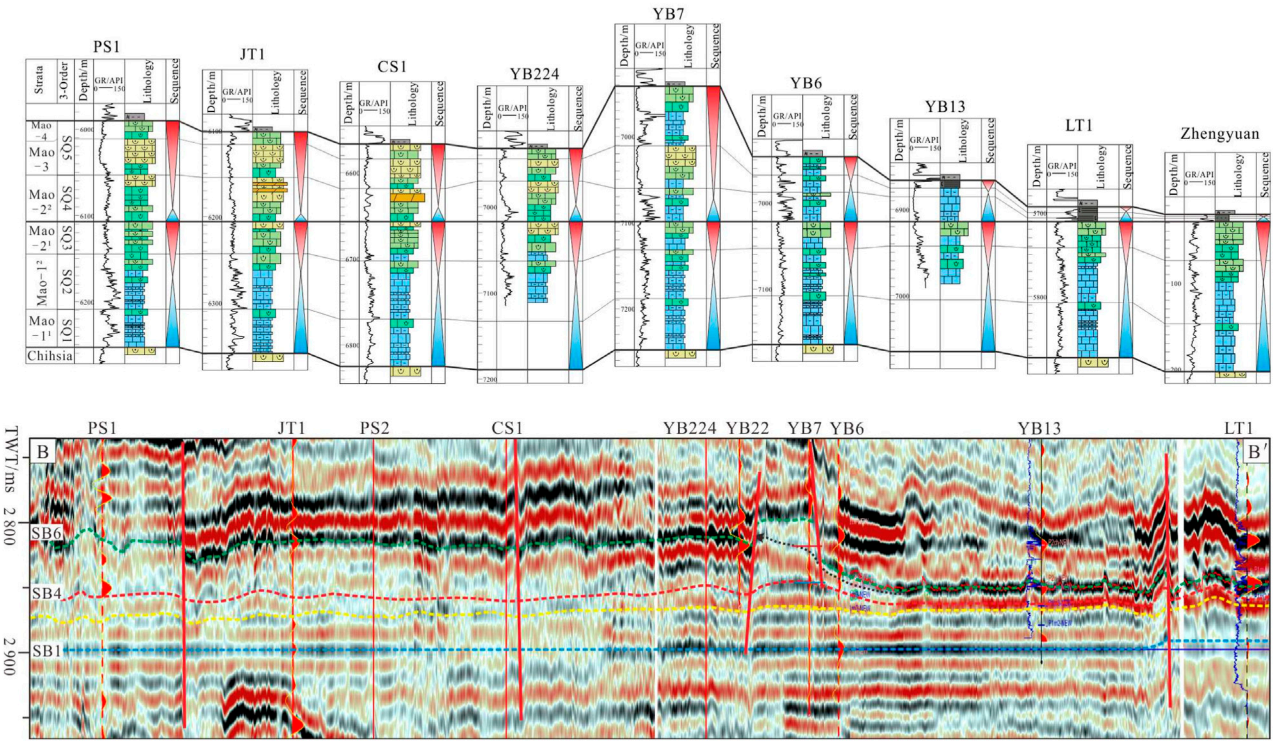

FIGURE 4
NE sequence stratigraphic correlation section across the northwest margin of the Sichuan Basin (see Figure 1 for section location).

ramp below a storm wave base. Owing to extensive transgression at the early depositional stage of the Maokou Formation, thick marls were deposited at the bottom of the Maokou Formation (Figures 6D, E). Siliceous organisms that are occasionally visible in marls may indicate the occurrence of an upward flow in the ramp (Tian et al., 2021). Outer ramps are mainly distributed in upper and lower SQ1 and correspond to medium-to-high box-shaped GR responses.

5.1.2 Carbonate platform

(1)Platform margin

The platform margin facies feature small water depth and strong hydrodynamic condition, and it is classified into two intrafacies: platform margin shoal and interbank sea. A platform margin shoal was observed in the high-energy area of a platform margin, where high-energy grainstones were deposited (Figure 6F), and reef-building organisms may also occur (Zhong et al., 2021). Dolomites with a residual grain pattern are another important rock type in the platform margin shoal; most virgin rocks of dolomites are grainstones with considerable original porosity, which indicates high-energy shoal-facies sedimentation. The interbank sea occurred in the low-energy area of a platform margin. Owing to geomorphic barriers, such as platform margin shoals, the interbank sea features restricted water body and low energy.

(2)Semi-restricted platform

The intrafacies of intra-platform shoal were observed inside the semi-restricted carbonate platform, which features the strongest hydrodynamic condition in the semi-restricted platform. Intra-platform shoals in the Maokou Formation in the study area mainly comprise packstones with interstitial lime mud between bioclastic particles that were not greatly filtered and transported by waves, which indicates weak wave energy and a sedimentary environment rich in organisms in the vicinity of a wave base. In addition, grainstones are common in the intrafacies of intra-platform shoal.

The intra-platform depression is the lowest area in a semi-restricted carbonate platform and features large depth, weak hydrodynamics, and low water energy. These intrafacies mostly comprise marls and micrites with little biogenic debris.

The semi-restricted sea, with platform margin shoals and intra-platform shoals as the barriers, features quiet water body and small relief, where fine-grained gray-to-dark gray argillaceous limestones, micrites, and wackestones were deposited. The bioclastic content is low, and such biogenic debris such as algae and testa could be observed. The restricted sea occurred in central Sichuan. Shoal-facies dolomites that are related to a restricted water environment were discovered in SQ3 in intra-platform highlands at wells JT1 and PY1 (Xiao et al., 2023).

(3)Slope-basin

The slope facies usually occurred between a normal wave base and the average storm wave base; on the one side, there are basin deposits with lower energy in deeper water, and on the other side, there are shallow-water carbonate platform deposits with higher energy in shallower water. Bioclastic particles in such a reducing

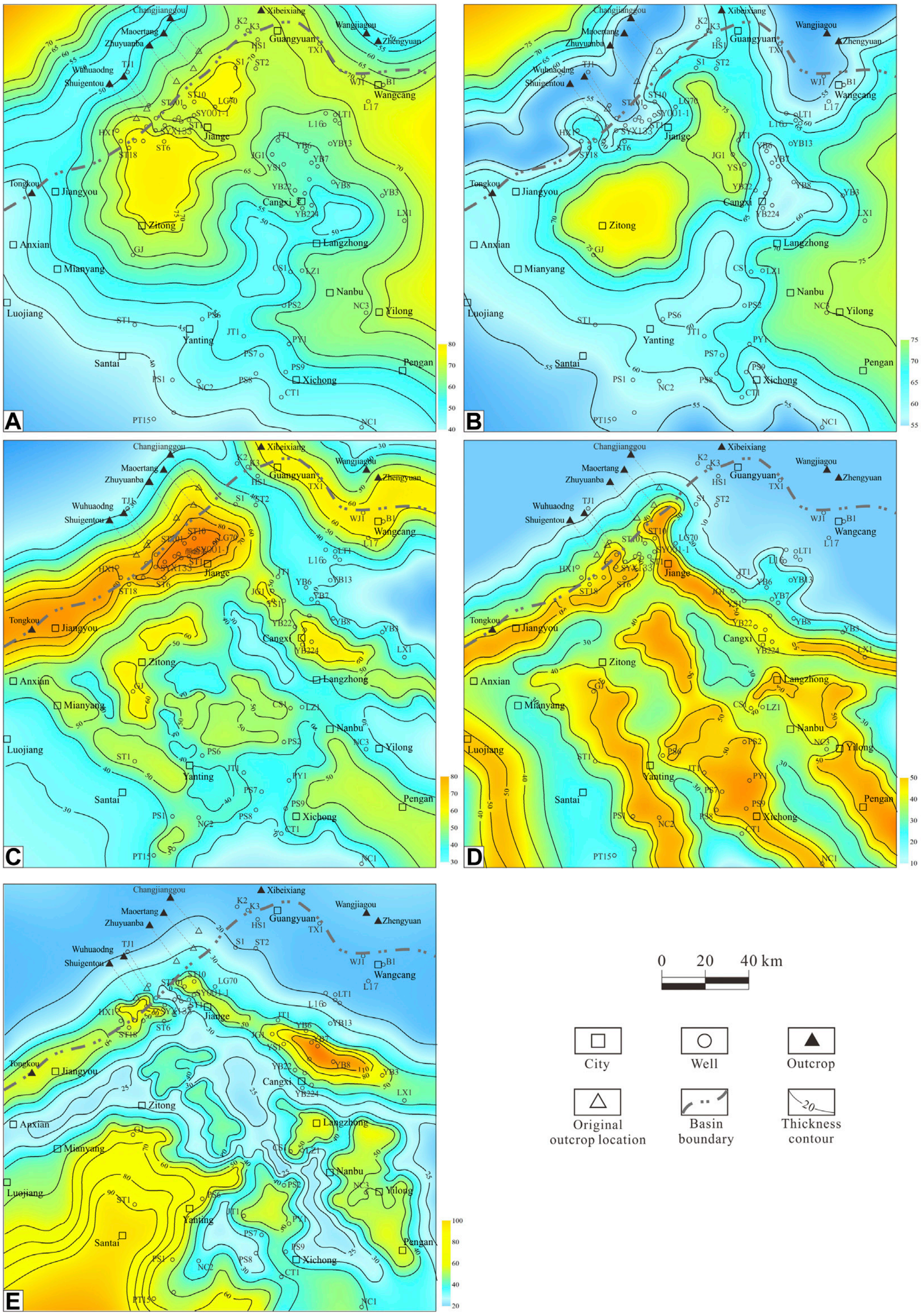

FIGURE 5
Thickness maps of third-order sequences in the Maokou Formation in the northwest margin of the Sichuan Basin. **(A)** SQ1 thickness map; **(B)** SQ2 thickness map; **(C)** SQ3 thickness map; **(D)** SQ4 thickness map; and **(E)** SQ5 thickness map.

environment are rare in sediments and may be more densely distributed toward the platform margin. Owing to the action of storm waves, there may be normal-grading storm shoals in the slope facies (Figure 6I). The basin facies indicate an extremely low-energy environment, with water depths exceeding tens to hundreds of meters and below the storm wave base (Zhu, 2008). Low-energy sediments are deposited in the basin facies, which consist of mainly mudstones and micrites and few bioclasts. There are mass deep-water organisms, such as *Radiolaria* (Figures 6J, K).

TABLE 1 Dominant sedimentary facies type in the northwest margin of the Sichuan Basin.

Platform type	Facies	Intrafacies	Sequence
Carbonate ramp	Intermediate ramp	Low-energy shoal and open sea	SQ1–SQ2
	Outer ramp	Storm shoal and static water mud	
Rimmed carbonate platform	Semi-restricted platform	Intra-platform shoal, intra-platform depression, and semi-restricted sea	SQ3–SQ5
	Platform margin	Platform margin shoal and interbank sea	
	Slope-basin	Storm shoal and static water mud	

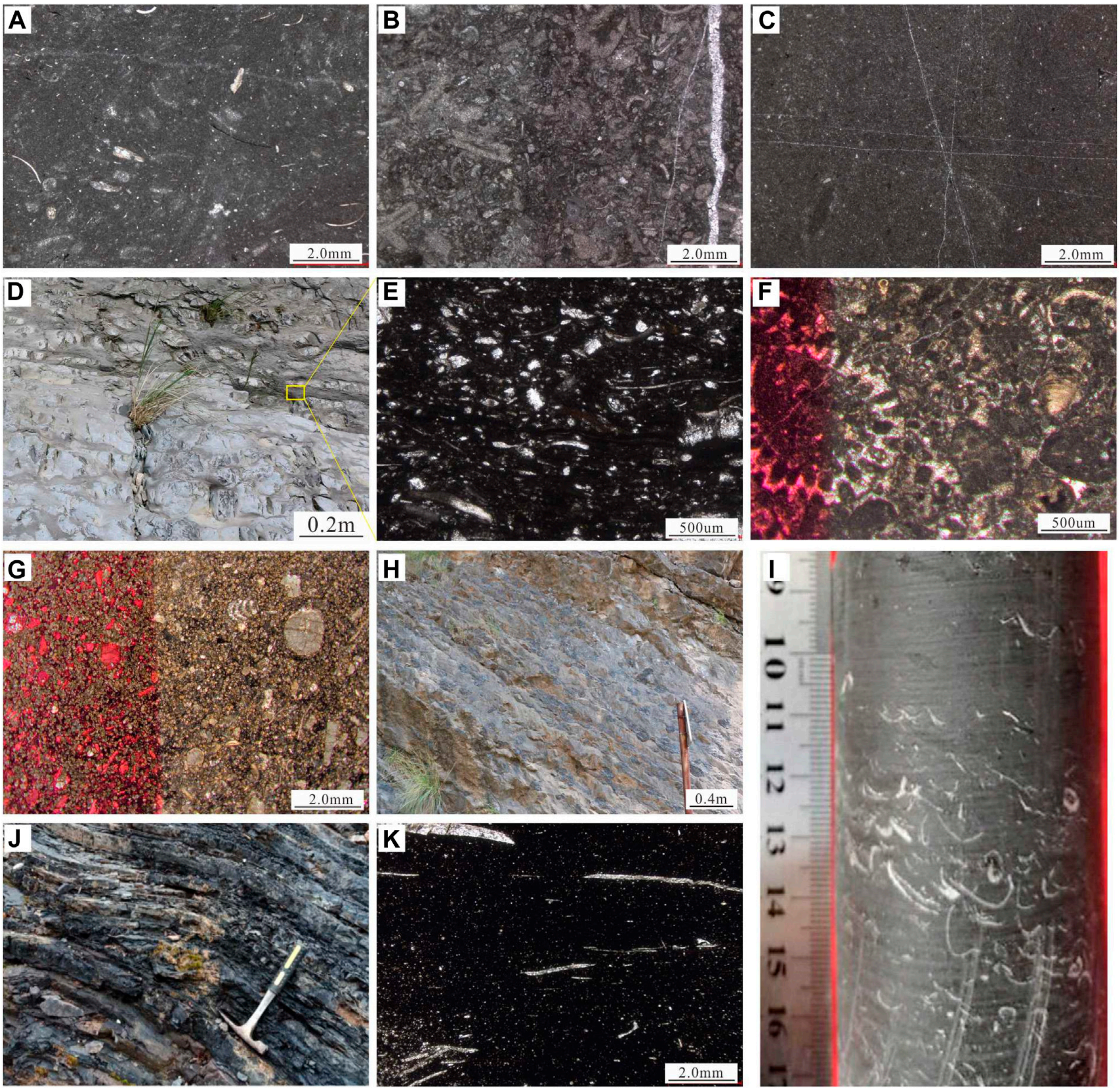

FIGURE 6
Macroscopic and microscopic photographs of microfacies. **(A)** Wackestones, plane-polarized light, Changjianggou section, SQ2; **(B)** packstones, plane-polarized light, Changjianggou section, SQ3; **(C)** micrite, plane-polarized light, Changjianggou section, SQ4; **(D)** limestone-marl rhythmic bedding, Changjianggou section, SQ1; **(E)** marls, plane-polarized light, Changjianggou section, SQ1; **(F)** bioclastic grainstone, plane-polarized light, well B1, SQ3; **(G)** calcite dolomites with mass undolomitized bioclastic particles, plane-polarized light, well B1, SQ4; **(H)** siliceous rocks with siliceous concretions, Chejiaba section, SQ5; **(I)** packstones in the lower part and wackestones in the upper part, normal-grading storm shoal, well JG1, SQ5; **(J)** siliceous mudstones, Xibeixiang section, SQ5; and **(K)** black shales, plane-polarized light, Changjianggou section, SQ5.

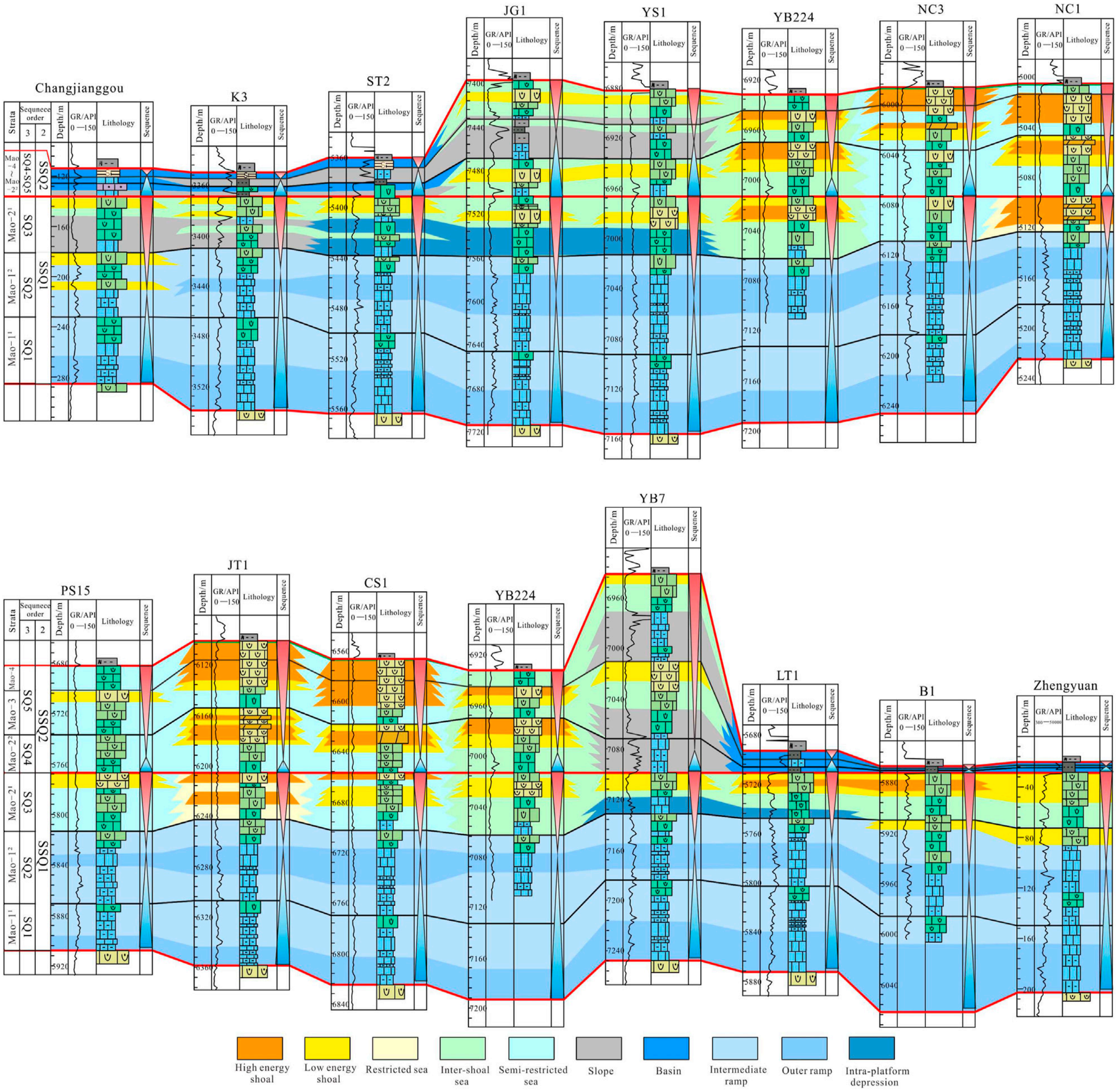

FIGURE 7
Cross-well sections showing sedimentary facies correlation in northwestern Sichuan.

5.2 Vertical and lateral distribution of sedimentary facies

As shown in the NW–SE cross-well section for sedimentary facies correlation, SQ1 and SQ2 comprise ramp facies; thick areas mainly correspond to outer ramp facies, and thin areas mainly correspond to intermediate ramp facies. Low-energy shoal sediments occurred in SQ2, Changjianggou well block. Ramp deposition changed into a rimmed carbonate platform depositional system in SQ3. As the relative sea level dropped, local areas in the south inherited the geomorphic highs in the intermediate ramp, and open-sea and high-energy bioclastic shoal sediments were settled in open water. Sediments of platform–deep bottom land–slope-basin facies was observed in the northern and central area. The NC3 well block was settled with intra-platform shoal and semi-restricted sea deposits, and the YB224 well block was settled with platform margin deposits. Deep bottom land and slope deposits occurred toward the northwest. At the depositional stage of SQ4, semi-restricted platform, platform margin, slope, and basin deposits were settled in turn toward the northwest with distinct facies differentiation. The YB224 well block was deposited with thick platform margin shoals; Changjianggou, K3, and ST2 well blocks were settled with thin slope and basin deposits; dolomitized shoals mainly occurred inside the platform. SQ5 shows the inherited depositional features of SQ4, particularly in platform-margin areas. The change lies in low-energy slope-facies deposits in JG1 and YS1 well blocks with enlarged shoals (Figure 7).

As shown in the SW-NE section from well PS15 to Zhengyuan, SQ1 and SQ2 were settled with ramp deposits. SQ3 was settled with semi-restricted platform deposits with a lot of shoals, well JT1 in the southwest margin was settled with open-sea and high-energy bioclastic shoal deposits on the inherited geomorphic highs, and YB7 and LT1 well blocks were settled with deep bottom land deposits. Large intra-platform shoals in SQ4 and SQ5, which are mainly high-energy bioclastic shoals, indicate a high-energy sedimentary environment in shallow water. Thick sediments of slope facies in the YB7 well block, as well as those in JG1 and YS1 well blocks in the above cross-well section, belonged to low-energy progradational wedges, which change into basin deposits toward the northeast (Figure 7).

6 Lithofacies paleogeography of Middle Permian sequences

SQ1 and SQ2, mainly comprising micrite and argillaceous limestones, were deposited in the period with high sea level. According to sequence sedimentation, the areas with large deposition thickness were supposed to be geomorphic lows and classified as outer ramps; the areas with small deposition thickness were supposed to be geomorphic highs and classified as intermediate ramps. The overall sedimentary framework of SQ1 is a ramp that gradually deepens to the north, and the shoal subfacies are less developed. Except for the southwestern area, Shuigentou–Changjianggou, and the area to the north of Wangcang with intermediate ramp deposits, the other areas were covered with outer ramp deposits. SQ2 shows inherited depositional features. The areas with outer ramp deposits were somewhat shrank, and low-energy shoals began to occur in Shuigentou–Changjianggou (Figures 8A, 10A). Due to the background of continuous transgression in the early stage of the Maokou Formation, the strata were overlapped from north to south, so the storm shoals gradually migrated to the south.

The SQ3 sedimentary framework of transitional ramp-rimmed platform system shows distinct differentiated facies in the south and north margins (Figure 10B). The southern area inherited previous geomorphic highs and experienced a sedimentary environment with restricted to semi-restricted sea; the northwestern area and northeast margin were settled with slope-basin deposits; the ST2–YB13–LX1 well area was settled with deep bottom land deposits; Jiangyou–Jian’ge–Cangxi areas were deposited with platform margin facies; intra-platform areas were settled with semi-restricted sea and intra-platform shoal deposits due to the existence of barriers in the marginal platform areas. Shallow-water facies areas were deposited with thick belt-like platform margin shoals and intra-platform shoals; deep-water facies areas dominated by extensional faults had an undercompensated deposition of slope-basin facies (Figure 8B). Due to the insufficient accommodation space, the southeastern area, inheriting the geomorphic highs of SQ2, was settled with thin restricted sea and intra-platform shoal deposits. SQ3 dolomites were well developed in such a restricted environment, for example, at wells JT1 and PY1.

The SQ4 sedimentary framework of the rimmed carbonate platform system shows distinct differentiated facies in the south and north margins (Figure 10C). Platform deposits occurred to the south of Jiangyou–Jian’ge–Cangxi, and slope-basin deposits occurred to the north. Shallow-water facies areas were deposited with belt-like platform margin shoals and belt-like intra-platform shoals in the northwest direction; deep-water facies areas experienced starved deposition of slope-basin facies (Figure 8C).

The lithofacies paleogeographic features of SQ5 were similar to those of SQ4, but small grain-formation thickness ratio and its relationship with formation thickness of progradational wedges in JG1–YB7 well blocks demonstrated different depositional features from those in other areas (Figure 8D). Based on these depositional features and sequence thickness variation, progradational wedges were supposed to be low-energy slope deposits in the outside of the platform margin with a low grainstone-formation thickness ratio. The SQ5 sedimentary framework shows some inherited features, i.e., differentiated facies in the south and north margins. Platform deposits occurred to the south of Jiangyou–Jian’ge–Cangxi, and slope-basin deposits occurred to the north (Figure 8D).

7 Discussion

7.1 Restoration of sedimentary paleogeomorphology

The restoration of paleogeomorphology in the depositional period is of great significance to clarify the sedimentary evolution process and favorable karst zones in the early diagenetic stage. However, early studies mainly restored the late paleogeomorphology of the Maokou Formation based on the thickness of the entire Maokou Formation (Tang et al., 2016; Chen et al., 2021), with a lack of characterization of sedimentary paleogeomorphology.

SSQ1 is the inner structural sequence of the Maokou Formation, which has not suffered obvious weathering and denudation, and the strata are well preserved. In the early stage of the Maokou Formation, the Sichuan Basin generally showed a geomorphic pattern of “high in the middle and low in the periphery” (Li et al., 2022), that is, the geomorphic pattern gradually decreased from the middle to the northwest margin. This study reveals that the formation thickness of SSQ1 has a negative correlation with the ratio of granular rocks to strata (Figure 9A), that is, the ratio of granular rocks to strata is low in the formation thickness area and high in the formation thin area, and the thickness area is mainly distributed in the northern geomorphic lowland of the study area (Figure 5). The SSQ1 sequence reflects a low-energy compensation deposition process, and the sequence thickness has filling and replenishing characteristics. SSQ1 paleogeomorphology was recovered through sedimentological analysis (Wang et al., 2023). The SSQ1 thick value area represents the landform lowland during the sedimentary period, and the SSQ1 thin value area represents the landform upland during the sedimentary period. Therefore, the paleogeomorphology of SSQ1 is generally “low in the west and high in the east and low in the middle and high in the north and south” (Figure 9B), and the distribution range of the southern landform highland is consistent with the moderate slope facies belt of the SQ1–SQ2 period (Figure 8A). During the SQ3 period, due to the sea-level decline at the end of the sequence, the sea water limitation in the southern highlands increased, forming a restricted marine environment (Figure 8B). In addition, the Jiulongshan area in SSQ1 is a relatively high landform, which is conducive to karst

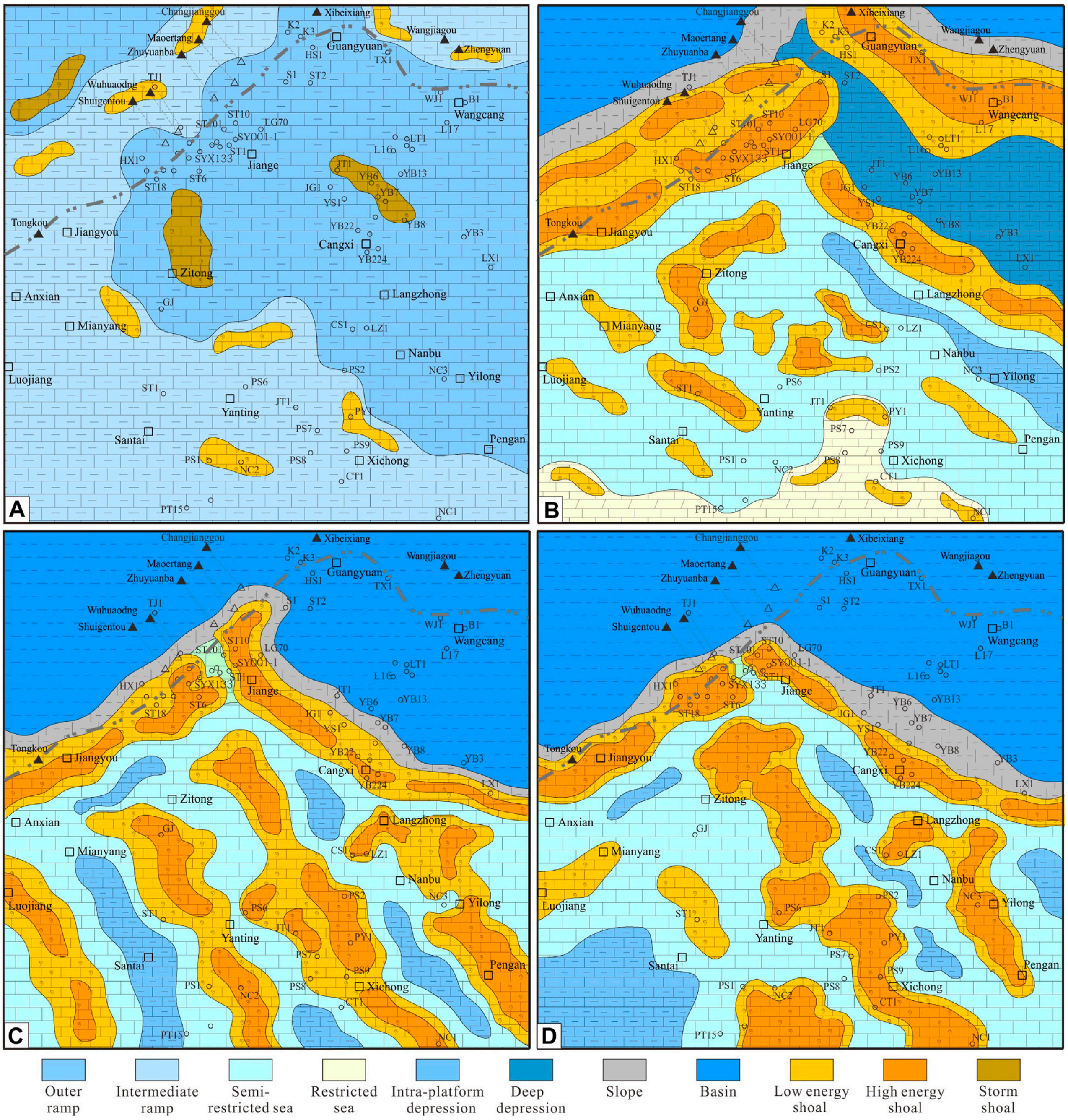

FIGURE 8
Lithofacies paleogeography of each sequence in the Middle Permian epoch. **(A)** Lithofacies paleogeography of SQ1–SQ2; **(B)** lithofacies paleogeography of SQ3; **(C)** lithofacies paleogeography of SQ4; and **(D)** lithofacies paleogeography of SQ5.

development in the early diagenetic stage, and is a favorable development area for karst limestone reservoirs (Wen et al., 2021).

There is a positive correlation between the thickness of the SSQ2 sequence and the proportion of granular rocks, that is, the ratio of granular rocks to strata is high in the thick value area and low in the thin value area (Figure 9C). In addition, the sequence filling characteristics are different in the study area, and the north is thin in thickness and has a low ratio of granular rocks to strata, which has the characteristics of deep-water undercompensated sedimentation. In the south, the thickness is large and the ratio is high, which is a typical feature of shallow-water granular beach deposition (Tan et al., 2011). In addition, stratigraphic dating studies in the Xibeixiang section show that the top layer of the Maokou Formation has a small amount of denudation (Hu C. et al., 2020), which reflects that the thickness of the residual strata of the Maokou Formation in the northwest margin of Sichuan Basin is relatively complete, and can be used to indicate the stratigraphic distribution characteristics during the depositional period. Therefore, the paleogeomorphology of the SSQ2 deposition period is recovered through the residual formation thickness. The

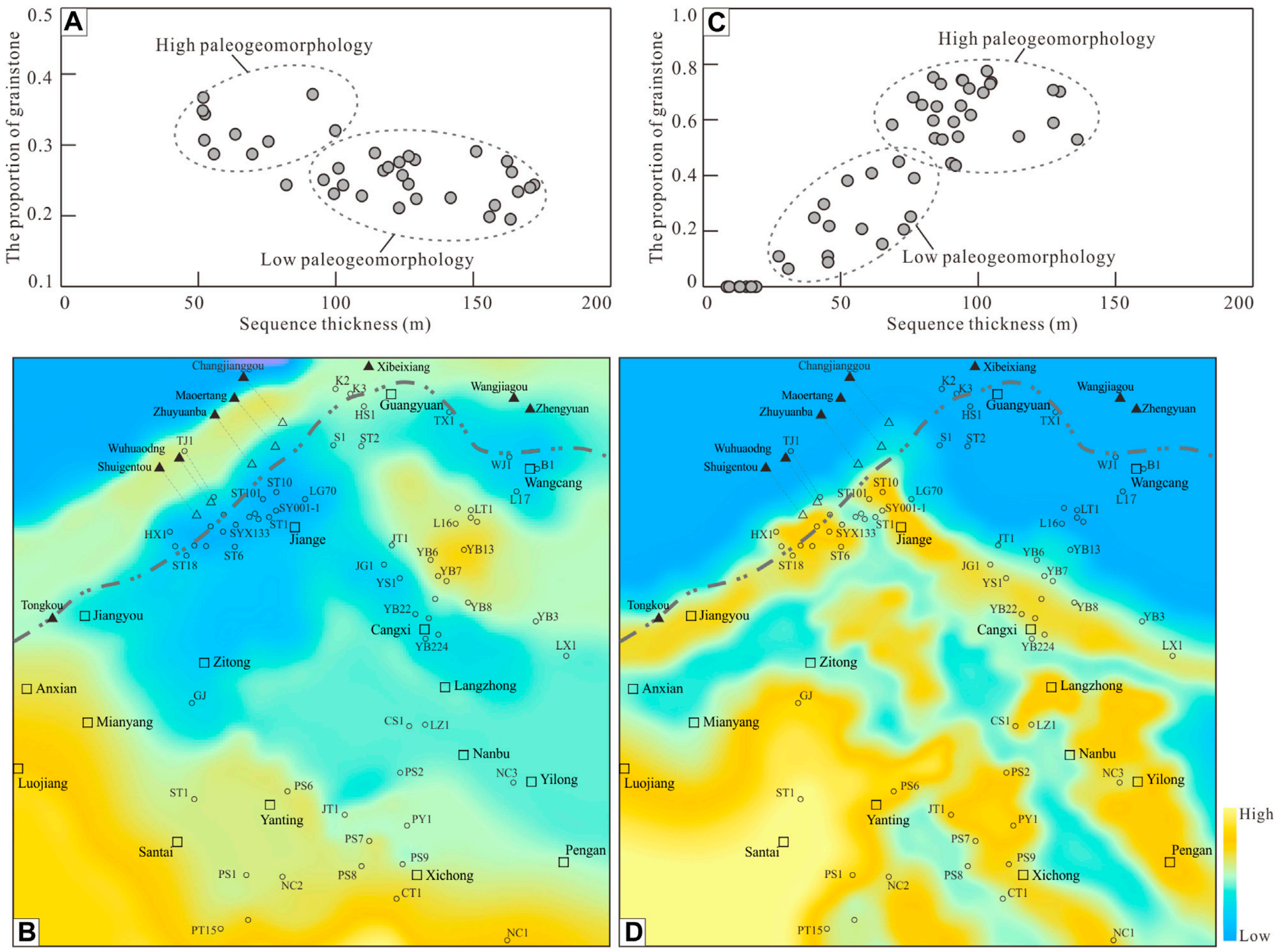

FIGURE 9
Paleogeomorphology of the depositional period of the Maokou Formation in the northwest margin of the Sichuan Basin. **(A)** Cross-plot of SSQ1 thickness and proportion of granular rocks; **(B)** paleogeomorphology of the SSQ1 depositional period; **(C)** cross-plot of SSQ2 thickness and proportion of granular rocks; and **(D)** SSQ2 paleogeomorphology.

SSQ2 formation thickness area can represent the shallow-water platform facies area with relatively high geomorphology, while the formation thin value area can represent the deep-water basin facies area with low geomorphology (Figure 5). The sedimentary paleogeomorphologic pattern shows that the area to the west of Jiangyou–Shuangyushi and north of Jian'ge–Cangxi during SSQ2 is generally geomorphic lowland, and deep-water low-energy sediments with under-compensated deposits are developed. As a whole, the southern part of the study area is a shallow-water carbonate platform with relatively high energy granular rock sediments (Figure 9D).

7.2 Tectonic–sedimentary evolution

7.2.1 Sedimentation at a quasi-stable tectonic stage

At the early depositional stage (SQ1–SQ2), the Maokou Formation inherited the ancient landform at the end of the Qixia Formation. Tectonic activities were stable in the Sichuan Basin, and sedimentation was dominated by early ancient landforms in the quasi-stable tectonic setting. Paleogeomorphology in the study area is generally high in the south and low in the north (Figure 9B), and the strata are gradually overlying from north to south. The deposition thickness in the north is large, and the deposition thickness in the south is thin. Carbonate ramp deposits were settled stably. Owing to geomorphic lows and early depositions, an asymmetrical sequence structure was observed in the study area, and the deposition thickness of the transgressive system tract was larger than that of the highstand system tract. Owing to extensional tectonism in the northwest-southeast direction, the Jiangyou–Zhuyuanba area was tilted and uplifted (Ran et al., 2023), where belt-like discontinuous shoals were deposited. Scattered shoals occurred in the Guangyuan–Wangcang area with inherited Qixia geomorphic highs (Figure 10A).

7.2.2 Sedimentation at the initial active tectonic stage

The Maokou Formation at the middle depositional stage (SQ3) inherited the landform which was filled and leveled up in SQ1–SQ2. As the Mianlue Ocean in the northern margin of the Upper Yangtze region continued to expand, extensional stress started to dominate

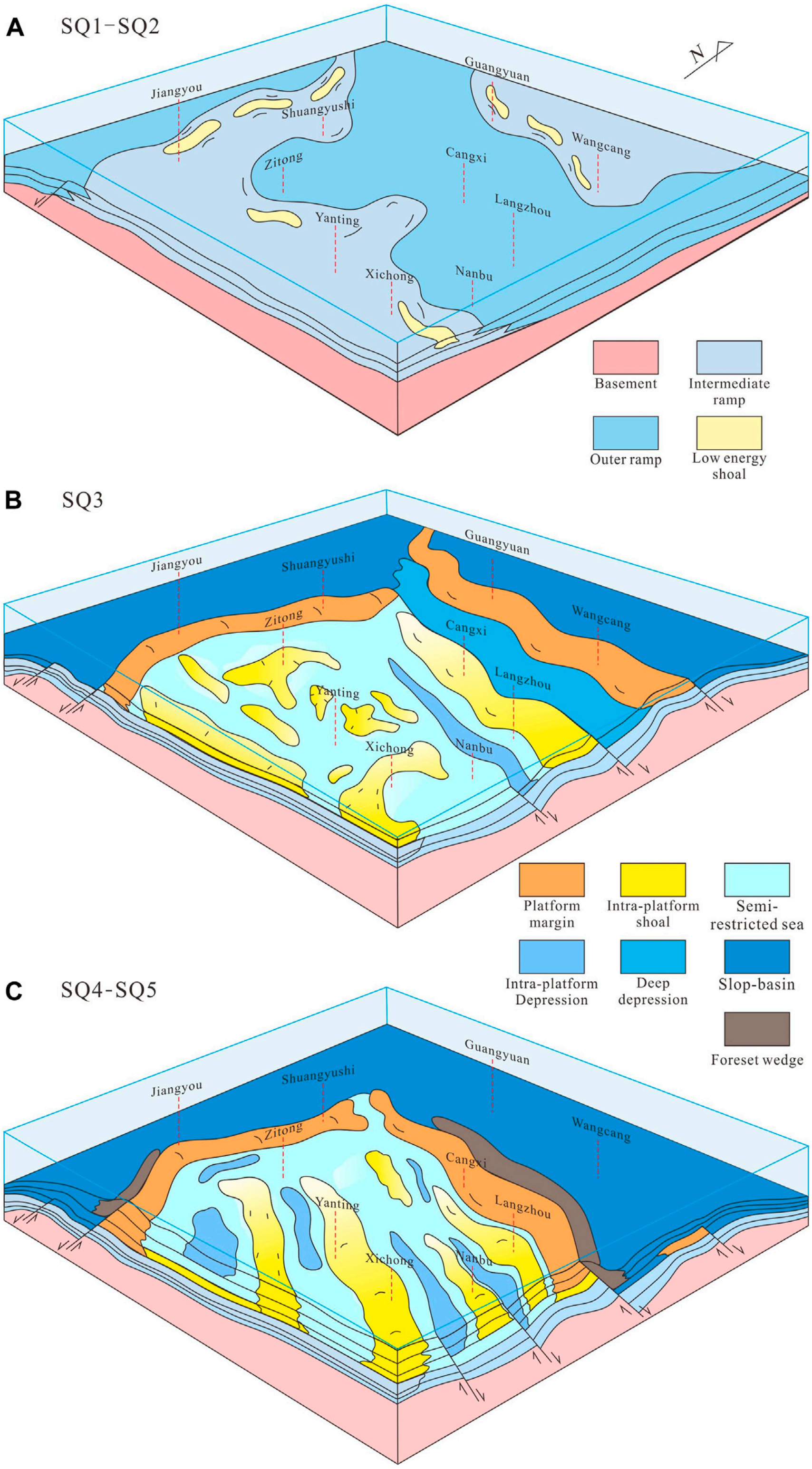

FIGURE 10
Tectonic–sedimentary evolution models in the northwest margin of the Sichuan Basin. **(A)** Sedimentary model at a quasi-stable tectonic stage; **(B)** Sedimentary model at the initial active tectonic stage; **(C)** Sedimentary model at the increasingly active tectonic stage.

the northern part of the study area (Zhang et al., 2019; Li et al., 2022). The area to the north of Guangyuan subsided quickly to form a slope-basin, and Guangyuan–Wangcang became the platform margin dominated by NW-SE faults. SQ3 occurred in the late period of the highstand system tract in SSQ1, when the sea level declined gradually. The global sea level also dropped continuously at the middle and late depositional stages of the Maokou Formation (Haq and Schutter, 2008). Hence, the platform margin in Guangyuan–Wangcang experienced a shallow-water high-energy environment, where belt-like high-energy shoals were deposited continuously; northwestern Sichuan changed into a rimmed carbonate platform as a whole. This means that differential tectonic subsidence and sea-level change are crucial to the differential evolution of carbonate platform margin structures of the Maokou Formation in the northwest margin of the Sichuan Basin. The outer edge of a rimmed carbonate platform is different from a carbonate ramp as the former is usually connected to the basin in an obvious gradient, while the latter generally transforms into a platform in the process of sedimentary evolution (Santantonio et al., 2013; Liu et al., 2022a).

In addition, the area between Guangyuan and Cangxi began to subside to form deep intra-platform bottom lands, around which high-energy marginal shoals were deposited. Separated by platform margin shoals and bottom-land marginal shoals, the intra-platform experienced a semi-restricted sea environment due to a limited water body. The southern part of the study area inherited the geomorphic highs in the preceding intermediate ramp and was deposited with shallow-water high-energy sheet-like intra-platform shoals. Due to sea-level change, a restricted sea environment occurred, in which penecontemporaneous infiltration backflow dolomitization occurred (Yang et al., 2022; Xiao et al., 2023). Formation thickness was large in the north and small in the south in this period, and the ancient landform at the initial depositional stage of the Maokou Formation was basically filled and leveled up. Geomorphic relief in the wide intra-platform was further reduced, indicating stable extensional tectonic activities that mainly affected tectonic–sedimentary differentiation in the northern part of the area (Figure 10B).

7.2.3 Sedimentation at the increasingly active tectonic stage

Intensified extensional tectonic activities in northeast and southwest directions at the late depositional stage of the Maokou Formation (SQ4–SQ5) further dominated the intra-platform area in northwestern Sichuan, according to high-angle basement fractures in the platform margin and intra-platform bottom-land margin shown on the seismic section perpendicular to Jian'ge–Langzhong (Figure 1C; Figure 4). Guangyuan–Wangcang in the north subsided quickly beneath the surface of water, and the platform margin moved toward Jiangyou–Jian'ge–Cangxi. Tectonic–sedimentary responses to NE extensional tectonic activities began to emerge in the intra-platform area, and activated high-angle basement fractures dominated the sedimentary framework comprising a series of NW-SE intra-platform depressions and intra-platform shoals. Such a sedimentary framework may be the incipient form of the Kaijiang–Liangping trough and a series of intra-platform depressions in the Sichuan Basin during the Changxingian period.

A large rate of tectonic subsidence in the basin facies in this period led to a sustained rise in the relative sea level and an asymmetrical sequence structure with the deposition thickness of the transgressive system tract larger than that of the highstand system tract; the sequence structure with fast transgression–slow regression mainly occurred in the relatively stable platform facies (Figure 4). Owing to the sustained uplift of the Emeishan mantle plume (Li et al., 2019), the Upper Yangtze region was uplifted extensively at the end stage of the Maokou Formation. In addition, SQ5 was in the period with the maximum regression in the Maokou Formation (Su et al., 2020), leading to a low sea level and insufficient accommodation space in the study area. As a result, intra-platform deposition thickness is generally small in the Mao4 Member (at the late stage of the highstand system tract in SQ5) in northwestern Sichuan; thick wedge-like deposits settled in the slope zone on the outside of the platform margin, for example, in JG1–YB7 well blocks (Figure 10C). On the other hand, far-end extension caused by the Emeishan mantle plume led to topographic depression and consequent relatively sufficient accommodation space at the depositional stage of SQ5 in the southwest of the study area, where deposition thickness is large in the Mao4 Member (at the late stage of the highstand system tract in SQ5).

7.3 Geologic significance to hydrocarbon accumulation

Promising targets for exploration in each period were determined based on the restored tectonic–sedimentary evolution in the Maokou Formation in the northwest margin of the Sichuan Basin. SQ1 and SQ2 were settled with low-energy ramp deposits in the context of sustained transgression, and shoal-facies reservoirs were generally underdeveloped. Thick "eyeball–eyelid" limestones formed in a sub-oxidizing to reducing environment have shown good source properties and could function as source rocks (Gao et al., 2020). The environment of platform-margin high-energy shoal facies produced by initial extension in SQ3 was favorable for the occurrence of reservoirs. It is worth noting that grain banks at inherited geomorphic highs in the southern area were dolomitized in the shallow-water restricted environment to form shoal-facies dolomite reservoirs, which could be correlated with the dolomite reservoirs in the lower Mao2 Member in central Sichuan (Yin et al., 2023). Hence, the potential of exploration may be large. SQ4 and SQ5 at the increasingly active tectonic stage were deposited with large thick platform margin shoals that are promising for exploration. Large-scale intra-platform shoals as the product of intra-platform extension are also important targets for exploration.

Ocean troughs formed in the extensional tectonic setting at the depositional stages of SQ4–SQ5 of the Maokou Formation in northwestern Sichuan. Black siliceous rocks and mudstones generally of 10–30 m thick in the northern and northwestern areas could be correlated with the Gufeng Member in the Middle and Lower Yangtze regions (Zhang et al., 2019). As water became shallow toward the south, the thickness of the Gufeng Member decreased, and lithofacies almost completely changed into limestones in Shuangyushi–Yuanba. The Gufeng Member in northwestern Sichuan is the product of contemporaneous heterotopic deposition at the late stage of the Maokou Formation. The study area was in a passive continental margin environment at the depositional stages of SQ4–SQ5, and such a sedimentary environment in the deep-water rift generated by extensional stress was favorable for the deposition of source rocks. There are two factors: one is high paleoproductivity in the Maokouan age resulting from thriving organisms in the Permian Period for the formation of promising source rocks, and the other factor is the strong reducing environment in ocean troughs, which is favorable for the preservation of source rocks, both of which jointly dominated the occurrence and distribution of high-graded source rocks in the Gufeng Member. Our findings lay the foundation for the study of source rock distribution in the northwest margin of the Sichuan Basin. In addition, high-energy platform margin shoals adjoined the Gufeng Member at the depositional stages of SQ4–SQ5, and thus, they may constitute a promising source-reservoir assemblage in the lateral direction.

8 Conclusion

(1) Two structural sequences, namely, SSQ1 and SSQ2, were identified in the northwest margin of the Sichuan Basin. SSQ1 is dominated by the sequence structure of slow transgression and rapid regression, which is a process of "filling and replenishing" sedimentary filling in the quasi-stable tectonic period. SSQ2 is mainly controlled by the stretching stress in NNE and NNW directions, and the sequence thickness and structure are significantly different. The sedimentary thickness is large in the stable platform facies area, which is characterized by a rapid transgression–slow regressive sequence structure. The rapid tectonic subsidence area has thin deposition thickness and is characterized by continuous transgression and rapid regressions.

(2) SQ1 and SQ2 were settled with a carbonate-ramp depositional system, which features overlap sedimentation comprising the outer ramp and intermediate ramp facies thinning from north to south, in the quasi-stable tectonic setting. Owing to extensional tectonism, steep slope breaks began to occur at SQ3 carbonate ramps. As the global sea level dropped, thick continuous high-energy shoals were deposited on breaks and then evolved into the rimmed carbonate platform; the region to the north of the platform margin subsided quickly to form slope-basin facies. The domination of extensional tectonism in the intra-platform region intensified at the depositional stages of SQ4 and SQ5. Tectonic activities and sea-level change are two key controls on Maokou carbonate platform types and platform margin evolution in the study area.

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

WY: writing–original draft. XT: writing–review and editing. DT: project administration and writing–review and editing. ZZ: writing–original draft. XH: project administration and writing–review and editing. ML: writing–review and editing. ZZ: writing–review and editing. DX: writing–review and editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This work was supported by the National Natural Science Foundation of China (No. 42172166) and China National Petroleum Corporation Upstream Field Basic Forward-looking Project (No. 2021DJ0501). The funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article or the decision to submit it for publication.

Conflict of interest

Authors DT and XH were employed by PetroChina Southwest Oil and Gas Field Company. Authors WY, XT, ML, ZiZ, and DX were employed by China National Petroleum Corporation. Author ZZ was employed by the Research Institute of BGP Inc., PetroChina.

Publisher's note

References

Chen, W., Chen, Y., Xu, F., Li, S., Li, Y., Zeng, L., et al. (2021). Stratigraphic division and correlation and karst palaeogeomorphology restoration of the middle permian Maokou Formation in the eastern Sichuan Basin. *Nat. Gas. Ind.* 41, 27–36. doi:10.3787/j.issn.1000-0976.2021.06.003

Chen, Z., Li, W., Wang, L., Lei, Y., Yang, G., Zhang, B., et al. (2019). Structural geology and favorable exploration prospect belts in northwestern Sichuan Basin, SW China. *Petroleum Explor. Dev.* 46, 413–425. doi:10.1016/s1876-3804(19)60022-4

Fu, X., Chen, Y., Luo, B., Li, W., Zhang, J., Wang, X., et al. (2021). Characteristics and petroleum geological significance of the high-quality source rocks in the Gufeng member of the middle permian Maokou Formation in the northern Sichuan basin. *Acta Geol. Sin.* 95, 1903–1920. doi:10.19762/j.cnki.dizhixuebao.2021128

Gao, G., Cao, J., Bing, L., Xiao, D., Zhang, Y., and Cong, C. (2020). Evidence of the Middle Permian marine mixed type source rocks in the northwestern Sichuan Basin and its contribution to large gas reservoirs in Shuangyushi area. *Acta Geol. Sin.* 41, 433–445. doi:10.7623/SYXB202004006

Haq, B. U., and Schutter, S. R. (2008). A chronology of Paleozoic sea-level changes. *Sci. Am. Assoc. Adv. Sci.* 322, 64–68. doi:10.1126/science.1161648

Hu, C., Hu, G., Zhang, X., Chen, C., Peng, H., Gao, Z., et al. (2020). Sedimentary environment, hydrocarbon potential and development of black rocks in upper Maokou Formation, northwestern Sichuan. *Petroleum Geol. Exp.* 42, 202–214. doi:10.11781/sysydz202002202

Hu, M., Hu, Z., Wei, G., Yang, W., and Liu, M. (2012). Sequence lithofacies paleogeography and reservoir prediction of the Maokou Formation in Sichuan Basin. *Petroleum Explor. Dev.* 39, 45–55. doi:10.1016/S1876-3804(12)60014-7

Hu, S., Tan, X., Luo, B., Zhang, B., Zhang, Y., Su, C., et al. (2020). Sequence stratigraphic characteristics and geological significance of the permian Qixia stage in northwestern Sichuan Basin. *J. Palaeogr. Ed.* 22, 1109–1126. doi:10.7605/gdlxb.2020.06.075

Hu, X., Pei, S., Zhang, B., Chen, H., Wang, Y., and Yang, X. (2017). Stratigraphic sequence evolution of lower triassic feixianguan Formation in jiange-jiulongshan area, the Sichuan Basin. *Nat. Gas Explor. Dev.* 40, 8–15. doi:10.12055/gaskk.issn.1673-3177.2017.03.004

Huang, H., Xue, Z., Dan, Z., Yu, X., Peng, Q., Zhou, H., et al. (2023). Permian-triassictectonicevolution of the ganzi-litang ocean basin, sichuan: evidence from thegeochronology andgeochemistry ofbasicrocks in the ophiolite mélangebelt. *Geoscience*, 1–18. doi:10.19657/j.geoscience.1000-8527.2023.042

Jiang, Q., Hu, S., Jiang, H., Zhai, X., Ren, M., Chen, X., et al. (2018). Calculation and inducement of lacuna in the mid-permian Maokou Fm of the Sichuan Basin. *Nat. Gas. Ind.* 38, 21–29. doi:10.3787/j.issn.1000-0976.2018.01.003

Li, D., Chen, H., Hou, M., Xu, S., Pang, C., and Guo, H. (2019). Lithofacies and paleogeographic characteristics of middle permian Qixia and Maokou periods in Sichuan Basin and the geodynamic mecheanism. *Chin. J. Geol.* 54, 1114–1134. doi:10.12017/dzkx.2019.063

Li, M., Tan, X., Yang, Y., Ni, H., Luo, B., Wen, L., et al. (2022). Sequence-Iithofacies paleogeographic characteristics and petroleum geological significance of Lower Permian Qixia Stage in Sichuan Basin and its adjacent areas, SW China. *Petroleum Explor. Dev.* 49, 1119–1131. doi:10.11698/PED.20220088

Liang, H., Wen, L., Ran, Q., Han, S., Liu, R., Chen, K., et al. (2022). Structural characteristics and implications on oil/gas accumulation in north segment of the Longmenshan piedmont, northwestern Sichuan Basin, SW China. *Petroleum Explor. Dev.* 49, 546–559. doi:10.1016/s1876-3804(22)60045-4

Liu, X., Liu, C., Li, N., Feng, M., Wang, X., Zhang, B., et al. (2017). Depositional characters and framework of differential carbonate ramp in Qixia and Maokou formation, the middle Permian of western Sichuan Basin. *J. XI'AN Univ. Sci. Technol.* 37, 242–250. doi:10.13800/j.cnki.xakjdxxb.2017.0215

Liu, Y., Hu, M., and Zhang, S. (2022a). Types, structural evolution difference and petroleum geological significance of CambrianOrdovician carbonate platforms in Gucheng-Xiaotang area, Tarim Basin, NW China. *Petroleum Explor. Dev.* 49, 1019–1032. doi:10.1016/s1876-3804(22)60329-x

Liu, Y., Hu, M., Zhang, S., Zhang, J., Gao, D., and Xiao, C. (2022b). Characteristics and impacts on favorable reservoirs of carbonate ramp microfacies: a case study of the Middle-Lower Ordovician in Gucheng area, Tarim Basin, NW China. *Petroleum Explor. Dev.* 49, 107–120. doi:10.1016/s1876-3804(22)60008-9

Ran, Q., Lei, C., Chen, K. Z. B., Liang, H., Han, S., Zeng, M., et al. (2023). Structural styles, evolution and their oil-gas geological significance in the northwestern Sichuan Basin. *Chin. J. Geol.* 58, 18–35. doi:10.12017/dzkx.2023.002

Santantonio, M., Scrocca, D., and Lipparini, L. (2013). The ombrina-rospo plateau (apulian platform): evolution of a carbonate platform and its margins during the jurassic and cretaceous. *Mar. Petroleum Geol.* 42, 4–29. doi:10.1016/j.marpetgeo.2012.11.008

Shen, P., Zhang, J., Song, J., Hong, H., Tang, D., Wang, X., et al. (2015). Significance of new breakthrough in and favorable targets of gas exploration in the Middle Permian system, Sichuan Basin. *Nat. Gas. Ind.* 35, 391–398. doi:10.1016/j.ngib.2015.09.014

Song, X. (2018). Sedimentary characteristics and sedimentary facies model of the middle Permian Maokou formation in northwestern Sichuan. *J. Northeast Petroleum Univ.* 42, 66–74. doi:10.3969/j.issn.2095-4107.2018.04.006

Su, C., Li, R., Shi, G., Jia, H., and Song, X. (2021). Reservoir characteristics of the first member of Middle Permian Maokou Formation in Sichuan Basin and its periphery and inspirations to petroleum exploration, SW China. *Petroleum Explor. Dev.* 48, 1329–1340. doi:10.1016/s1876-3804(21)60290-2

Su, W., Hu, S., Jiang, Q., Zhang, J., Huang, S., Jiang, H., et al. (2020). Sedimentary responses to the Dongwu movement and the influence of the Emeishan mantle plume in Sichuan Basin, Southwest China: significance for petroleum geology. *Carbonates evaporites* 35, 108. doi:10.1007/s13146-020-00638-w

Tan, X., Nie, Y., Liu, H., Zhou, Y., Li, L., Zhao, L., et al. (2011). Research on the method of recoverying microtopography of epeiric carbonate platform in depositional stage: a case study from the layer A of jia 22 member in moxi gas field, Sichuan Basin. *Acta Sedimentol. Sin.* 29, 486–494. doi:10.14027/j.cnki.cjxb.2011.03.018

Tang, D., Xiao, D., Tan, X., Li, H., Xie, J., Liu, H., et al. (2016). Restoration of paleokarst landform and its geological significance: a case from middle permian Maokou Formation in northwestern Sichuan Basin. *Petroleum Explor. Dev.* 43, 751–758. doi:10.1016/s1876-3804(16)30090-8

Tian, X., Shi, J., and Dong, J. (2021). New understanding of sedimentary facies of the first member of Maokou Formation based on the latest drilling in central Sichuan Basin. *Nat. Gas. Geosci.* 32, 1646–1655. doi:10.11764/j.issn.1672-1926.2021.05.001

Wang, X., Zhou, L., Wu, Y., Zhang, X., Li, S., Li, Y., et al. (2023). Restoration of palaeogeomorphology and its petroleum-geological significance: transitional-facies deposition during the early Permian in the southeastern Ordos Basin, North China. *J. Petroleum Sci. Eng.* 221, 111310. doi:10.1016/j.petrol.2022.111310

Wen, X., Yuan, B., Xu, B., Zhang, Z., and Luo, Q. (2021). Identification of seismic response characteristics of the Maokou Formation in the Jiulongshan area, Sichuan Basin based on for ward modeling of wave equation. *Geol. Explor.* 57, 402–412. doi:10.12134/j.dzykt.2021.02.015

Xiao, Q., Yuan, H., Ye, Z., Chen, C., Zhang, X., and Xu, T. (2023). Genetic mechanism of dolomite reservoir in Maokou Formation of permian in bajiaochang structure in north central sichuan. *Nat. Gas. Geosci.* 34, 1218–1236. doi:10.11764/j.issn.1672-1926.2023.02.009

Xiong, L., Yao, G., Xiong, S., Shen, A., and Hao, Y. (2019). A method of stratum restoration for fault belt based on balanced cross-section: a case study of the middle devonian guanwushan Formation in the longmenshan area, western Sichuan Basin, China. *Geotect. Metallogenia* 43, 1079–1093. doi:10.16539/j.ddgzyckx.2019.06.001

Yan, S. T., Tan, C. H., Qin, M., Li, H., and Duan, Y. H. (2020). Geochemical characteristics and geological significance of permian-triassic siliceous rocks in litang area, sichuan province(article). *Acta Geosci. Sin.* 41, 504–514. doi:10.3975/cagsb.2020.042001

Yang, W., Tan, X., Li, M., Xia, J., Long, H., Ni, J., et al. (2022). Development characteristics and genesis of thin layered dolomite of the middle permian Qixia Formation in the platform in weiyuan-gaoshiti area, Sichuan Basin. *China Pet. Explor.* 27, 75–90. doi:10.3969/j.issn.1672-7703.2022.04.006

Yang, Y., Bai, X., Yi, H., Liu, R., Ma, H., Han, S., et al. (2023). Progress and potential of natural gas exploration in the complex tectonic belt of Longmen Mountain: learning from drilling achievements of Well Hongxing 1. *Nat. Gas. Ind.* 43, 1–14. doi:10.3787/j.issn.1000-0976.2023.02.001

Yang, Y., Xie, J., Zhao, L., Huang, P., Zhang, X., Chen, C., et al. (2021). Breakthrough of natural gas exploration in the beach facies porous dolomite reservoir of Middle Permian Maokou Formation in the Sichuan Basin and its enlightenment: a case study of the tridimensional exploration of Well JT1 in the central-northern Sichuan Basin. *Nat. Gas. Ind.* 41, 1–9. doi:10.3787/j.issn.1000-0976.2021.02.001

Yin, C., Shi, J., Zheng, J., Wang, X., Tian, X., Ju, L., et al. (2023). Characteristics, controlling factors and exploration significance of shoal facies dolomite reservoirs in 2nd member of Maokou Formation in Hechuan-Tongnan area of Sichuan Basin. *Petroleum Geol. Oilfield Dev. Daqing* 42, 1–10. doi:10.19597/j.issn.1000-3754.202209036

Zhang, X., Chen, C., Huang, J., Wen, L., Xie, C., Xu, S., et al. (2019). The discovery of Middle Permian Guangyuan-Bazhong extensional trough in the Sichuan Basin and its petroleum geological significance. *China Pet. Explor.* 24, 466–475. doi:10.3969/j.issn.1672-7703.2019.04.007

Zhong, Y., Yang, Y., Wen, L., Luo, B., Xiao, D., Li, M., et al. (2021). Reconstruction and petroleum geological significance of lithofacies paleogeography and paleokarst geomorphology of the Middle Permian Maokou Formation in northwestern Sichuan Basin, SW China. *Peyroleum Explor. Dev.* 48, 95–109. doi:10.1016/s1876-3804(21)60007-1

Zhu, X. M. (2008). *Sedimentary petrology*. Beijing: Petroleum Industry Press. (in Chinese).

Zou, F., and Yin, H. (2009). Analysis on the patterns and M echanisn of inversion structuresin longmen Shan region, sichuan, China. *Geotect. Metallogenia* 33, 321–333. doi:10.16539/j.ddgzyckx.2009.03.001