Chapter

Structural Differentiation and Sedimentary System of the Permian Sichuan Cratonic Basin

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Abstract

The Sichuan Basin located in the western region of the Yangtze block was a stable craton basin in the Permian. The structural differentiation caused by the Dongwu movement and the Emei rifting activity controlled the sedimentary system and the Permian carbonate gas reservoirs in the Sichuan Basin. In this study, we have investigated the stratigraphic characteristics of each Permian formation, studied the depositional systems of each period of the Permian stage, and discussed the overall tectono-sedimentary evolution of the sedimentary basin. During the Permian, the Sichuan Basin experienced an intense tectonic activity, controlling the variations of the sedimentary environments occurring in the basin. The depositional systems of the basin were controlled by the tectonic setting of the intra-cratonic depression and marginal rifts during the period. Therefore, this is an important period in the tectono-sedimentary evolution of the study area, which can be divided into the following stages: (1) From the Late Carboniferous to the Early Permian, the Sichuan Basin was dominated by tectonic uplift and denudation. In the Middle Permian, a regional transgression occurred in the whole upper Yangtze region, and the sedimentary environments of the Sichuan Basin and its adjacent areas gradually changed to the carbonate platform. (2) In the early phase of the Late Permian (the Wujiaping period), being influenced by the Emei rift, the Sichuan Basin and its adjacent areas formed a complex pattern of structural highs and adjacent depressions, controlled by a differential subsidence. (3) In the late phase of the Late Permian (the Changxing period), with the cessation of the volcanic activity and the enhancement of the regional extension, the pattern of structural highs and depressions is more obvious, and the relatively calm structural environment makes the carbonate sedimentary environment tending to dominate.

Keywords: Yangtze block, Permian, structural differentiation, sedimentary system, tectono-sedimentary evolution

1. Introduction

The Yangtze block is located in South China, with the Qinling-Dabie-Sulu orogenic belt in the north and the Songpan-Ganzi fold belt in the west [1].

The Sichuan cratonic basin located in the western region of the Yangtze block has experienced multiple tectonic movements during its evolution. During the

Permian, the structural differentiation caused by the Dongwu movement and the Emei rifting activity controlled the sedimentary system [2].

Moreover, the depositional systems controlled the distribution of the Permian carbonate gas reservoirs in the area, where several new gas fields have been discovered in recent years. The platform margin reef-shoal facies of the Upper Permian Changxing Formation is one of the favorable sedimentary facies belts for the formation of favorable reservoirs in the Puguang and Yuanba gas fields [3, 4]. Besides, the high-energy granular beach sedimentary facies belt of the Middle Permian is also considered as a reasonable basis for the development of natural gas reservoirs with the discovery of several high-yield gas fields in the northwestern and central part of the Sichuan Basin [5, 6]. On the other hand, shales with high organic matter content widely developed in the Wujiaping period of Upper Permian in the Sichuan Basin are the suitable hydrocarbon-generating beds [7]. Therefore, it is of considerable significance for natural gas exploration to analyze and study the structural differentiation and sedimentary system of the Permian Sichuan cratonic basin.

Although many different opinions have been put forward on the genetic mechanisms of the structural differentiation pattern of the Sichuan Basin [2, 5, 8, 9], these opinions lack a complete analysis on the basin sedimentary filling processes. The previous study lack a detailed discussion on the relationships between the structural differentiation and the depositional processes in the basin, which is precisely the basis and key of structural sedimentary evolution in the Sichuan Basin.

In this study, we focus on the structural differentiation, on the sedimentary systems, and on the tectono-sedimentary evolution of the Sichuan cratonic basin during the Permian.

2. Geological setting

2.1 Tectonic evolution of the Yangtze block and the formation of the Sichuan Basin

The Sichuan Basin is a superimposed basin developed on the upper Yangtze craton [8] (**Figure 1**). However, the craton block has long been in the transitional position between Gondwana and Laurasia [10, 11], showing a vigorous tectonic activity. During the later stage there are many regional unconformities in the craton. The cratonic margin was involved in orogenic deformation and was strongly re-shaped. The processes of basin formation and evolution were quite complicated.

At the end of Mesoproterozoic (1000 Ma), the island arc and accreted continental crust in the margin of the Yangtze Paleocontinent were spliced onto the Yangtze block. The Yangtze, Cathaysia, and North China blocks were combined to form a part of Rodinia ancient land [11, 12]. Since 850 Ma, it has experienced (1) the early cracking, the formation of rifted sag, passive continental margin basin, and composite basin of intra-cratonic depression in 850–460.9 Ma (Nh-O_2), and (2) the late convergence, the establishment of intra-continental foreland basin and large-scale tectonic uplift in 460.9–416 Ma (O_3-S) [12]. In the Tethys Ocean evolutionary stage from Sinian to Silurian, the inner plate tension between the Yangtze block and the Cathaysia block resulted in the formation of the Xianggui continental rift basin and in the internal and marginal rifting of the middle and upper Yangtze craton. Then the compression orogeny in the Caledonian stage resulted in the formation of the South China continent. In the Late Paleozoic, it turned into the Paleo-Tethys Ocean evolution stage.

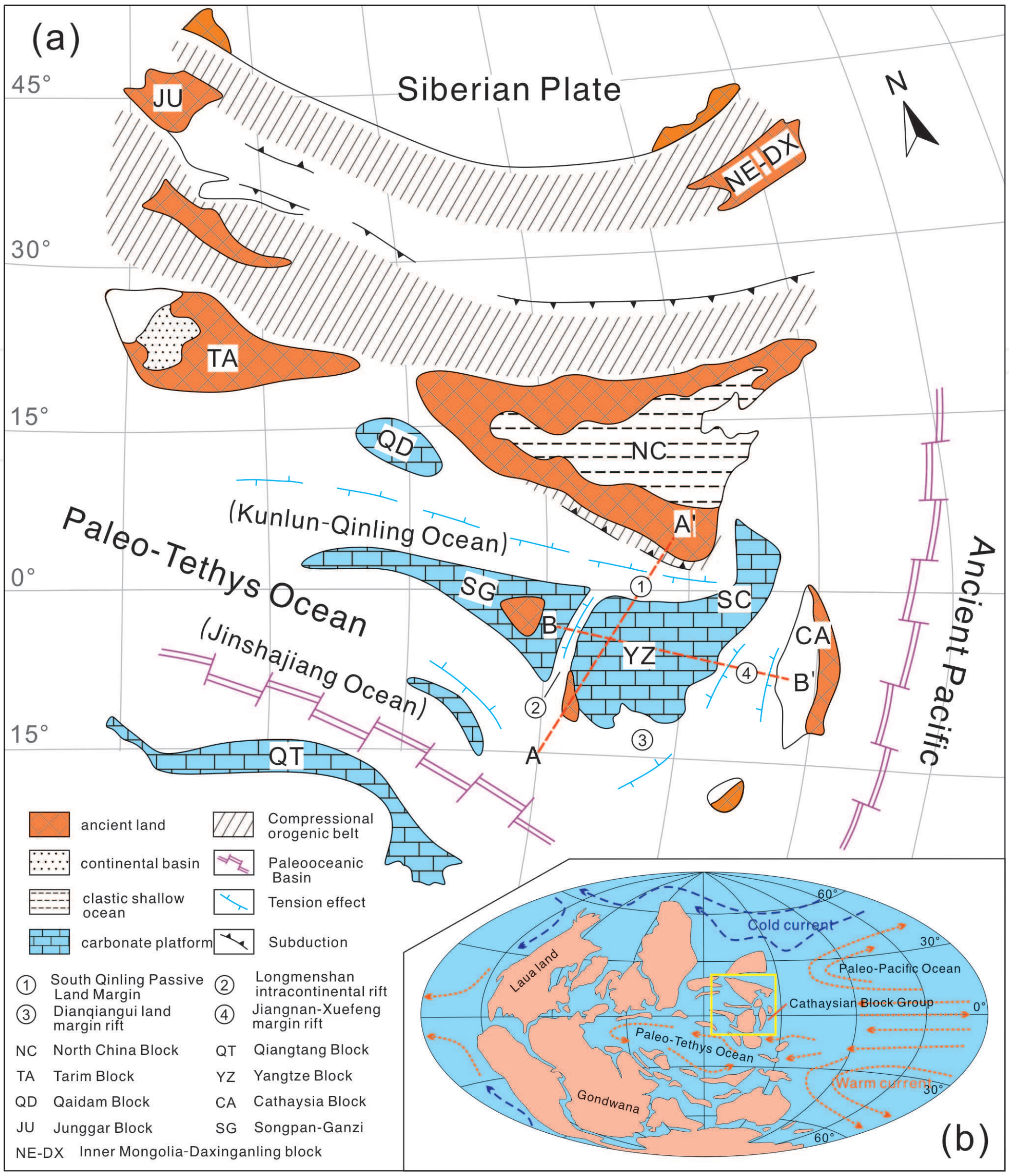

Figure 1.
(a) Location of the Yangtze block and its relationships with other tectonic units in Permian; (b) the restoration of Permian global paleogeography (modified from Huang et al. [45]).

From the Late Paleozoic to the Middle Triassic, the formation and evolution of the Sichuan Basin was genetically related to the geological process of South China block splitting and drifting from the northern margin of the Gondwana continent. The southwestern and northern margin of the Yangtze block became passive continental margins facing on different branches of the Paleo-Tethys Ocean. The middle and upper Yangtze block experienced a relatively short convergence and compression process from Devonian to Permian, forming the inner depression, the marginal depression, the passive continental margin, and the foreland basin of the middle and upper Yangtze craton [12–15].

After the development of the foreland basin in the Late Triassic, the middle and upper Yangtze were involved in an extensional and convergent cycle, closely related to the development of the Neo-Tethys Ocean, which included (1) the short-term extension from the Early Jurassic to the Early-Middle Jurassic (199.6–167.7 Ma) and (2) the long-term compression and transformation from the Late-Middle Jurassic to the Quaternary (167.7–0 Ma) [12, 16].

Above all, the basin prototypes of the Sichuan Basin were controlled by the activities of the surrounding plates in different phases. The basement of the basin was formed in the Pre-Nanhua Period; the rift basin was established in the Nanhua Period; the cratonic margin rift and the cratonic inner depression were created in the Sinian-Ordovician; the cratonic inner depression and the peripheral foreland basin were developed in the Silurian; the cratonic margin rift and the cratonic inner depression were developed from the Devonian to the depositional period of the third member of the Xujiahe Formation in the Late Triassic (D-T_3x^3); the foreland basin was established in the depositional period of the upper Xujiahe Formation (T_3x^{4-6}); the large-scale cratonic depression was developed in the Early to the Middle Jurassic; the compressional basin was developed in the Late Jurassic-Early Cretaceous; the depression basin was established from the Late Jurassic to the Early Cretaceous; and from the Late Cretaceous to the Quaternary, a transitional compressional foreland basin was formed. As a whole, the Sichuan Basin shows the characteristics of an alternating development of extensional basin (Z-O, D-P-T_3x^3, J_{1-2}) and compressional basin (S, T_3x^{4-6}, J_3-K_1) [12].

2.2 The tectonic stages of the Permian

In the Early Permian the striped continents composed of the Cimmerian block, Qiangtang block, and Sibumasu block were separated from the northern margin of Gondwana. Then the back part was extended to form the new Tethys Ocean. In the Middle Permian the transgression reached its maximum in South China, leading to the development of a wide southward-dipping carbonate platform. At that time, the Jiangnan-Xuefeng area was a submerged structural high and was separated by the southern and northern sedimentary regions. On the north side of the Yangtze block, the sedimentary environments were the shallow slope and deepwater basin southward of the Qinling Ocean, where deepwater dark limestones with nodular cherts and bedded cherts were deposited. The southern Qinling Ocean crust was subducted northward under the Qinling micro-block at the end of the Early Permian and developed corresponding island arc volcanic rocks, while the passive continental margin on its southern side was still growing (**Figure 1**).

In the Sichuan Basin, the Middle Permian strata include the Liangshan Formation (P_2l), the Qixia Formation (P_2q), and the Maokou Formation (P_2m), with a thickness of 400–500 m. In the early transgression stage of the Middle Permian sandstones, mudstones, marls, and marshes were deposited. In the middle period, the deposits evolved to shallow platform limestones and shaly limestones interlayered with sandy limestones. Massive limestones, dolomites, and black shales developed in the late Middle Permian, during which Leshan-Luzhou biological shoals grew.

At the end of the Middle Permian characterized by the Emei rift movement, the region was uplifted, and the Maokou strata were denuded in different degrees. The event of the Emei rift may be related to the subduction of the Jinshajiang-Mojiang ocean basin from the south to the north, and a large-scale extension occurred in the back of the arc (**Figure 1**). Longmenshan, Kaijiang-Liangping, and Chengkou-Exi rifts developed in the Yangtze craton block [12, 17].

3. Structural differentiation of the Sichuan cratonic basin during the Permian

3.1 Tectonic characteristics of plate margin rift

During the Permian, the Yangtze block was generally located in the low-latitude area near the equator [18, 19], in the transitional position between the

Gondwana and the Laurasia supercontinents. From the Early Permian to the Late Permian, the Yangtze platform was surrounded by the Paleo-Tethys Ocean and the Paleo-Pacific Ocean [20]. It rotated mainly anticlockwisely and formed the South China block, together with the Cathaysia block in the southeast (**Figure 2**). In the Late Permian the North China block was located northward of the South China block.

The paleomagnetic data showed that both the North China block and the South China block had the trend of northward movement and their latitudinal changes showed a certain degree of synchronicity, which may be related to the first collision of the two blocks in the east [21]. The South Qinling Ocean was located between the two blocks, opening toward the west in the form of scissors, with an angle of 70–80° [21]. Because of the continuous northward subduction, the North Qinling orogenic belt was formed at the southern margin of the North China block, while a passive continental margin emplaced at the north margin of the Yangtze block [22].

The southwest margin of the South China block was Simao-Indosinian block, which was located in the low-latitude area near the equator [23]. Between the two blocks was Jinshajiang Ocean, a branch of the Paleo-Tethys Ocean. The ocean basin rapidly expanded from the Early Permian to the Late Permian [24]. The subduction of the Jinshajiang Ocean to the Simao-Indosinian block in the southwest reflected a strong tectonic compression, while the South China block was a passive continental margin in the overall extensional setting [25]. The South China block was connected with the Songpan-Ganzi Ocean in the west, while the Jiangnan-Xuefeng intra-continental rifting zone was connected with Youjiang rifting zone, mainly in deepwater shelf environment, with isolated carbonate platform sporadically developed [26]. During the Permian, the tectonic setting of South China block was mainly of regional extension, showing the characteristics of a strong tension at the margins of the block.

3.2 Characteristics of block internal structure differentiation

In the Permian period, the tectonic setting of the South China block was mainly of regional extension, showing the characteristics of strong extension at the margin of the block and of a weak tension within the block and developing a set of marginal rift basins, intra-continental depression basins, and rift basins. In the Kangtien ancient land area, located on the southwestern margin of the block,

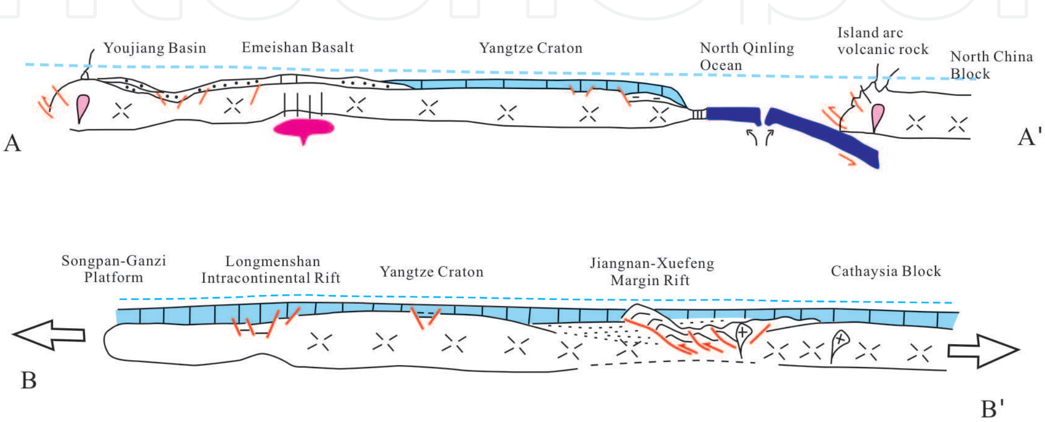

Figure 2.
Structural differentiation profile of the middle and upper Yangtze plate in the Permian (A-A', NW-SE direction; B-B′, NE–SW direction, location in Figure 1(a); modified from He et al. [12]).

a basalt eruption was considered to be a stratigraphic marker of the extensional process. The exposed area of basalt could reach 250,000 square kilometers, with a wide range of influence [9, 27]. During the Permian, the upper Yangtze block had the characteristics of a structural high to the south and of a depression to the north. The Kangtien ancient land was the main source area supplying terrigenous clastic in the upper Yangtze craton [28, 29]. To the north, it was dominated by the shallow sea carbonate environment and graded into the passive continental margin basinal environment.

The Sichuan Basin is a typical cratonic basin located in the western margin of the Yangtze block, which has recorded many geological events during the Permian. Several geological events occurred in the Permian, including the Emeishan Large Igneous Province [30–32], the Paleo-Tethys Ocean expansion and evolution [19, 33–35], and the end of the Permian biological extinction, have been widely of concern by scholars [36–39]. During recent years, according to the field outcrop data and to the stratigraphic records of drilling data, it was found that from the southwest to the northeast of the basin, the Sichuan Basin has deposited a wide range of marine carbonate rocks during the Permian. However, in the central and northern sectors of the basin, there were many deepwater sedimentary areas toward the carbonate platform margins. This unique sedimentary filling pattern reflects that the Sichuan Basin had the unique structural differentiation characteristics during the Permian [40].

4. Sedimentary system of the Permian

Permian strata widely developed in the eastern sectors of the Sichuan Basin during the early depositional stages, when carbonate rocks are dominant. During late stages, the difference between the eastern and the western sectors increased. In the Panxi area, the continental basic volcanic rocks were dominant, while the eastward transition was represented by continental clastic rocks. On the contrary, in the eastern Sichuan Basin, thick marine carbonate rocks were dominant [41]. In the Sichuan Basin, the Permian strata can be divided into the Middle Permian Liangshan Formation, Qixia Formation, Maokou Formation, and Upper Permian Wujiaping Formation and Changxing Formation (**Figure 3**).

4.1 Stratigraphic characteristics of the Liangshan formation

In the late Early Permian, the tectonic movement uplifted the northwestern region of the upper Yangtze to land, controlling variable degrees of denudation of the Paleozoic strata [42]. Until the Middle Permian, transgression occurred from south to north, and the Liangshan Formation was the product of the land-sea transformation at the beginning of this transgression [41, 43, 44]. The Liangshan Formation, widely developed in the Sichuan Basin and its adjacent areas, which is a coal-bearing deposit dominated by clastic rocks, and the contact between Liangshan Formation and underlying strata (e.g., Carboniferous or older layers) are disconformable [41, 43–45].

In the Sichuan Basin and Panxi areas, the lithology and the thickness of the Liangshan Formation considerably vary [41, 44]: (1) The sandstone content of the Liangshan Formation deposited in the western region is relatively large, with a thickness generally ranging from 10 to 42 m and finally reaching 88 m (e.g., Gan Luo). (2) The sedimentary thickness of the Liangshan Formation rapidly decreases

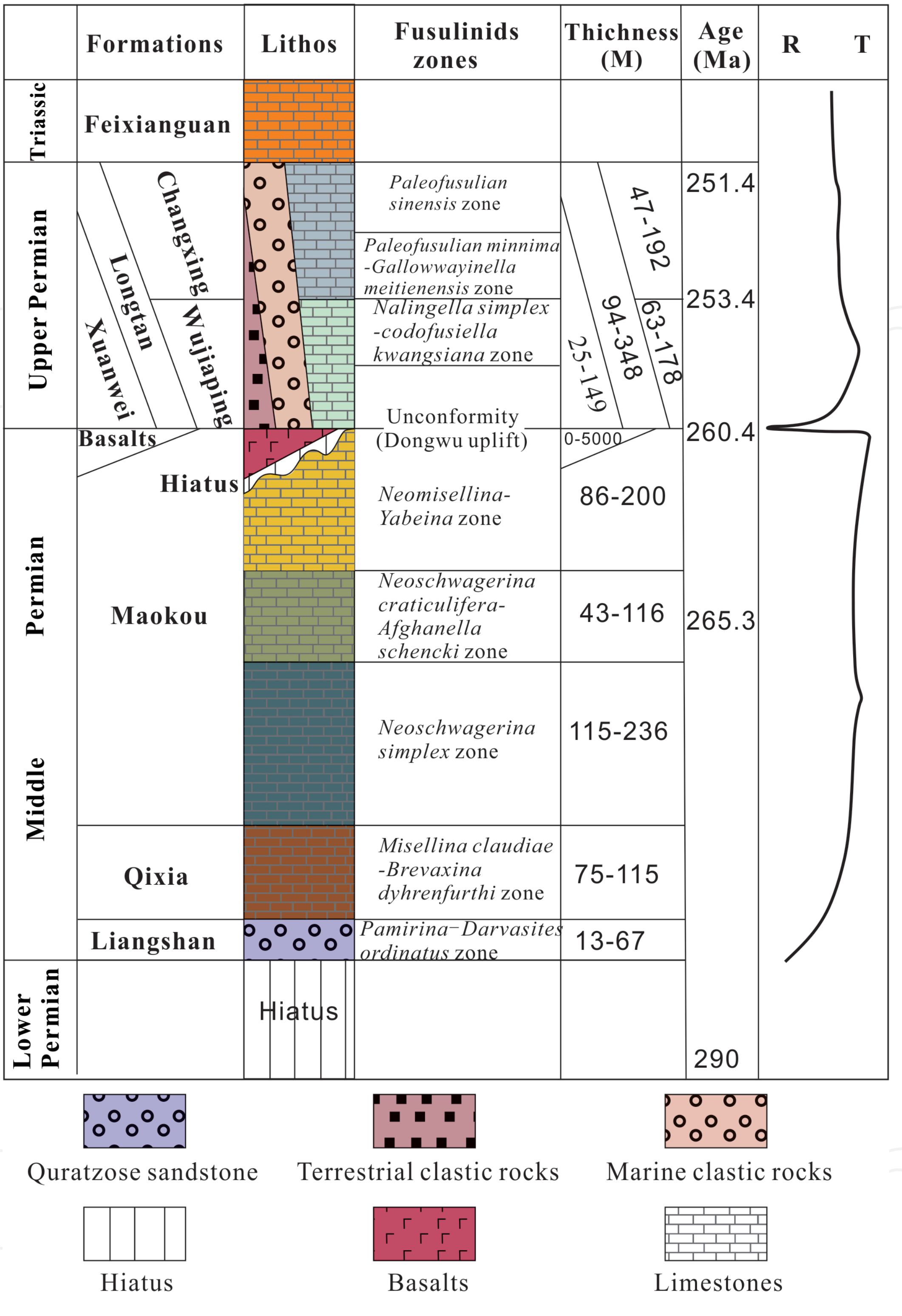

Figure 3.
Generalized Permian stratigraphy and division of fusulinid zones in SW China (after He et al. [54]).

eastward to 5–15 m in the area of Emeishan and Leshan, which is often dominated by carbonaceous shales. (3) The Liangshan Formation in the south of Sichuan is 4–17 m thick and is mainly composed of carbonaceous shale and clay rock, containing bauxite and hematite. (4) The Liangshan Formation in eastern Sichuan is dominated by coal-bearing claystone and sandstone and occasionally contains oolitic and bean-shaped hematite, with a thickness of 4–8 m, reaching 21 m. (5) The Liangshan Formation in the north of Sichuan and Longmenshan is 3–30 m thick, thinning eastward, and is mainly composed of aluminum clay rocks, bauxite, and weak coal seams. The Liangshan Formation contains plant fossils (e.g., *Lepidodendron,* *Problemocumnum wongii, Taeniopteris multinervis*), brachiopods (e.g., *Orthotichia indica*), and bryozoans [44].

4.2 Stratigraphic characteristics of the Qixia formation

During the deposition period of the Qixia Formation, the crustal subsidence was stable and seawater intruded on a large scale. As a result, the early sedimentary environment dominated by clastic rocks was transformed into carbonate platform sedimentary environment [41, 45].

Qixia Formation is widely distributed in the middle and eastern sectors of the Sichuan Basin. It is mainly composed of dark gray-black limestone, with a massive and micrite structure, locally mixed with bioclastic limestone, siliceous limestone, siliceous bands, and siliceous concretion [41, 44]. The limestones of the Qixia Formation generally contain high asphaltene and siliceous components and show dolomitization, and abundant eyeball-shaped structures (e.g., Huayingshan area) occur locally [46]. The Qixia Formation is interlayered above the Liangshan Formation, and its stratigraphic thickness ranges from tens of meters to more than 300 meters, gradually thickening from west to east [41].

According to the observation results of the outcrop in the wild, the Qixia Formation can be divided into two types [44]. One is called "White Qixia," which is distributed in the northern section of Micangshan and Longmenshan. It is mainly composed of light gray-black limestone with dolomitic limestone and dolomite and with shale at the bottom. The other is called "Black Qixia," which is distributed in other areas of the Sichuan Basin, with shale and siliceous layer at the bottom, dark gray thick layer of biological limestone, micritic shell limestone in the lower part, and light gray biological limestone in the upper part.

The Qixia Formation contains many types of fossils, mainly including fusulinids (e.g., *Nankinella orbicularia*, *N. nankingensis*, *N. discoides*, *N. regularis*, *Pisolina excessa*, *Schwagerina tshernyschewi*), corals (e.g., *Hayasakaia yunnanensis*, *Wentzellophyllum denticulatum, Polythecalis chinensis*), brachiopods, and conodonts [41, 44].

4.3 Stratigraphic characteristics of the Maokou formation

In the Sichuan Basin, the lithology of the Maokou Formation is relatively uniform with shallow marine, light gray, thick micritic fossiliferous limestone, including siliceous concretions and thin siliceous layers, ranging in thickness from 50 m to 600 m. Due to the influence of the Dongwu tectonic movement, the Maokou Formation was involved by various degrees of erosion, and the integrity of the strata gradually improved from west to east. In the southern part of the Sichuan Basin, basalts erupted in the middle sedimentary period of the Maokou Formation. The Maokou Formation can be divided into two members in the northeastern Sichuan Basin and into three members in the central Sichuan Basin.

The lower member of the Maokou Formation is composed of dark gray muddy micritic limestones, bioclastic limestones with black calcareous shales, and a thin siliceous layer at the top. Microbial rocks and storm rocks can be seen in southern Sichuan, eastern Sichuan, and Longmenshan areas. The Maokou Formation contains brachiopods (e.g., *Cryptospirifer omeishanensis*, *C. striatus*) and fusulinids (e.g., *Schwagerina quasibrevipola*, *S. declinata*, *Chusenella sinensis*, *Neoschwagerina*, *Pseudodolina*).

The middle member of Maokou Formation consists of light gray and dark gray thick layer massive micritic bioclastic limestone and micritic limestones with siliceous concretions. In the northwest and south of Sichuan, tempestite is relatively developed. There are abundant organisms, including fusulinids (e.g., *Neoschwagerina craticulifera*, *N. colaniae*, *N. sphaerica*, *Verbeekina heimi*, *Pseudodoliolina ozawai*, *Chusenella conicocylindrica*), corals (e.g., *Wentzelella elegans*), brachiopods, and conodonts.

The upper member of the Maokou Formation consists of gray-white micritic limestone with siliceous concretion, gray-black micritic limestone, and bioclastic limestone, including fusulinids (e.g., *Yabeina*, *Neomisellina*) and ammonoids (e.g., *Altudoceras*, *Paraceltites*, *Shouchangoceras*).

The Maokou Formation in Dabashan, Wushan, and southeastern Sichuan only remains lower and middle members. Parts of the lower, middle, and upper members of the Maokou Formation are preserved in Micangshan, Longmenshan, and Huayingshan. The Maokou Formation is well preserved in southern Sichuan (such as Gongxian).

4.4 Stratigraphic characteristics of the Wujiaping formation

The Wujiaping Formation is mainly distributed in the northeastern Sichuan Basin and can be subdivided into two members according to lithology differences. The lower member (formerly known as Wangpo shale) is a coal-bearing stratum at the intersection of land and sea. Its lithology is an aluminous clay rock, carbonaceous shales with coal seam or coal lines, oolitic hematite, and monohydrallite.

The upper member of the Wujiaping Formation (limestone section) has little change in lithology, which is micritic limestone, limestone with calcareous, siliceous, carbonaceous shale, and coal lines, with a siliceous layer at the top. From west to east, the dolomite content of deposits increased. In Mianzhu and Youyang, there are thin micritic limestone, limestone with shale, and multilayer coals. To the west of the line of Mianzhu-Daxian-Nanchuan-Gulin, Wujiaping Formation gradually changed into Longtan Formation.

In the Sichuan Basin, Wujiaping Formation consists of fusulinids (e.g., *Codonofusiella*), brachiopods (e.g., *Dictyoclostus*), and corals (e.g., *Waagenophyllum*).

4.5 Stratigraphic characteristics of the Changxing formation

As a lithostratigraphic unit at the top of the Permian, the Changxing Formation usually refers to the carbonate formation of platform facies sedimentary under the Lower Triassic in the Sichuan Basin, which is roughly equivalent to the sedimentary period of the Dalong Formation, and the difference between them is the sedimentary environment [47].

The Changxing Formation is mainly composed of shallow water carbonate, while the Dalong Formation primarily consists of deepwater siliceous rock and shale. Therefore, the sedimentary area of the Dalong Formation is also called "siliciclastic rock basin" [48].

The Dalong Formation is defined as the layer dominated by black and gray-black thin-layer siliceous rocks and siliceous shales in Sichuan and Chongqing area, with relatively stable sedimentary thickness, generally 15–42 m. The Dalong Formation is interlayered with the underlying Wujiaping Formation and the overlying Feixianguan Formation, and there is no apparent stratigraphic division between them [41]. In the Sichuan Basin, the distribution of the Dalong Formation is strictly controlled by the paleogeographic pattern, which is distributed in the north deep-water trough or basin facies area, roughly along the line of Guangyuan- Wangcang-Chengkou-Wushan. The lithology of the Dalong Formation is dominated by siliceous rock, siliceous shales, and siliceous limestones with tuff, mudstone, shales, and siltstones, and the siliceous composition is gradually reduced from the bottom to the top. There are abundant fossils, mainly including fusulinids (e.g., *Palaeofusulina*, *Codonofusiella*), ammonoids (e.g., *Pseudotirolites*, *Pseudogastrioceras*), brachiopods (e.g., *Spinomarginifera*), conodonts (e.g., *Clarkina changxingensis*, *C. meishanensis*), and radiolarians (e.g., *Neoalbaillella*, *Albaillella*).

The lithology of the Changxing Formation is mainly composed of medium-thick bioclastic limestones, micritic limestones, reef limestone, and dolomites, containing siliceous bands and concretions. The sedimentary thickness of the Changxing Formation varies from tens of meters to more than 100 m, and in some places, it can be as thick as 200–300 m. The fossils of the Changxing Formation are extremely rich, including algae (e.g., *Tubiphytes*, *Archaeolithoporella, Permocalculus*), fusulinids (e.g., *Palaeofusulina*, *Codonofusiella*), foraminifers (e.g., *Nodosaria*, *Colaniella*, *Pseudoglandulina*, *Pachyphloia*, *Geinitzina*), brachiopods (e.g., *Oldhamina*, *Enteletina*, *Orthothetina*, *Leptodus*), gastropods, bivalves (e.g., *Aviculopecten*), coral (e.g., *Lophophyllidium*, *Plerophyllum*, *Waagenophyllum*, *Huayunophyllum*), bryozoon (e.g., *Fistulipora*, *Fenestella*, *Polypora*), sponge (e.g., *Sphinctozoa*, *Inoza*, *Sclerospongiae*), trilobite (e.g., *Pseudophilipsia*), and conodonts (e.g., *Clarkina changxingensis, C. meishanensis, C. yini*).

Coral reefs and sponge reefs in the Changxing Formation is very well developed. Due to the tectonic control of faults within the platform, the shallow water area around the trough is deposited to form a platform margin reef. The most developed reef is located eastward of Sichuan, such as Wujiti, Huanglongchang, Damaoping, Gaofeng, and Laolongdong. The high-quality reservoir formed by the Changxing reef also provides favorable conditions for the formation of a reef gas reservoir [4].

5. Tectono-sedimentary evolution

After the small-scale transgression in Late Carboniferous, the Sichuan Basin experienced tectonic uplift in the Early Permian, controlling a wide stratigraphic gap, as shown by the lacking of Lower Permian strata in the basin filling. At the beginning of the Middle Permian, a new transgression occurred in the Sichuan Basin, which extended to the west of Hunan. As a result, the pre-existing ancient land around the basin was submerged by seawater. Only the Kangtien ancient land in the southwest of the basin and the Xuefeng ancient land in the east of the basin remained, which controlled the source supply in the basin and around the basin [41].

5.1 Liangshan period

During the Middle Permian, the Liangshan Formation, the Sichuan Basin, and its surrounding areas were generally characterized by clastic shore deposits, as controlled by the relatively shallow water body and by the high siliciclastic supply [45]. In the area around the paleo-uplift, the sediments were mainly medium-grained or fine-grained quartz sandstone, which represented the near-source coastal sedimentary environment. In the central Sichuan area, due to its high structural position, the lithology was mainly composed of sandy carbonate sediments, which showed a sedimentary environment of sand flat. In other areas of the basin, due to the relatively deepwater and lower water energy, the sedimentary environment was mainly muddy flat (**Figure 4**).

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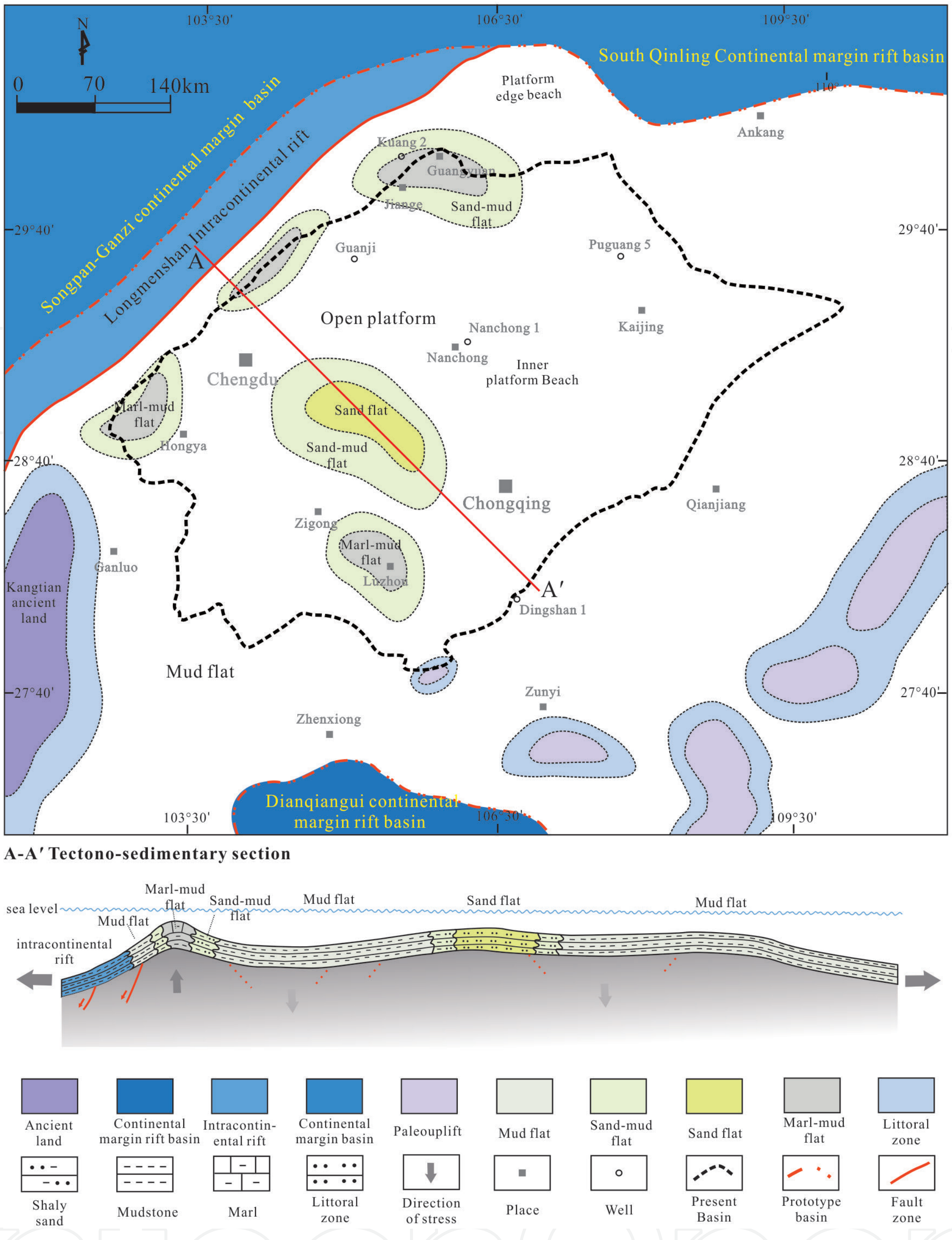

Figure 4.
Tectono-sedimentary system of the Liangshan period in the Sichuan Basin and its adjacent areas (modified from Huang et al. [45]).

5.2 Qixia period

During the deposition of the Qixia Formation, the sea level gradually decreased. At this time, the overall topography of the basin was high in the west and low in the east. With the relative shallowness of the water depth, as well as the subsidence of the depression in the basin and the extensional rifting of the basin margin, the sedimentary environment changed accordingly [45].

In the periphery of the Kangtien ancient land, it was still shoring facies. In the southwest of the basin, the lithology was mainly characterized by dolomites, dolomitic limestones, sandy limestones, and marls, with a low biological content, showing a typically restricted platform facies deposition. To the east of the restricted platform was an open platform facies area with good circulation of seawater, dominated by micrites and locally developed bioclastic limestones. The platform margin was established in the northwestern Sichuan Basin, roughly along the line of Mianzhu-Guangyuan. The sediments of the platform margin facies were mainly composed of thick bioclastic limestones, which were rich in species and high in abundance, and dolomitization locally occurred. In the northern part of the Sichuan Basin, influenced by Longmenshan ancient fault in the west, the terrain was sharply reduced, and the sediments were mainly mudstone, limestones, and shales, representing slope deposits (**Figure 5**).

5.3 Maokou period

During the deposition of the Maokou Formation, the southwestern margin of the upper Yangtze block was the Kangtien ancient land, and the northeastern margin was the passive continental margin environment, which was connected with the South Qinling continental margin basin. The northern part of the basin was mainly extensional. In contrast, the southern part of the Kangtien ancient land was continuously uplifting, and the basin was distributed in the pattern of uplift and depression [49]. From the southwest to the northeast, the seawater gradually deepened, and the sedimentary environment slowly changed from the continental environment to the marine one. The terrigenous shore facies, the restricted platform facies, the open platform facies, the platform margin facies, and the slope deepwater shelf facies then developed.

The restricted platform facies is distributed in Leshan-Emeishan-Zigong and other places in the southwest of the basin, and bioclastic beach facies is locally developed. The open platform facies area is located in the vast area to the east of the restricted platform facies area, where bioclastic banks are widely deposited in the higher ground, and micrite representing a low-energy environment was widely deposited in other places. The platform margin shoals were developed in the northwest of the basin, generally along the line of Qionglai-Anxian-Jiangyou-Guangyuan. In the area west of the platform margin, the seawater was steeply deepened, and the sedimentary environment also changed into slope deep shelf (**Figure 6**).

5.4 Wujiaping period

In the Late Permian the Sichuan Basin was located eastward of the Paleo-Tethys Ocean, with a high relief in the southwest and a low relief in the northeast. During the deposition of the Wujiaping Formation, the seawater transgressed from the northeast of the basin, and the provenance was mainly from the Kangtien ancient land [41, 50]. From the southwest to the northeast, due to the deepening of the ocean, the Sichuan Basin and its surrounding areas successively developed terrigenous shore facies, restricted platform facies, open platform facies, platform margin facies, and slope facies.

Shoreline facies extended from the southwest to the southeast of the basin, being composed mainly of coal-bearing terrigenous clastic deposits. In the area of Chengdu, Suining, Guangan, Chongqing, Nanchuan, and Zunyi, the poor circulation of seawater controlled the deposition of restricted platform facies. The area located eastward of the restricted platform was an open platform facies, where micrite and bioclastic limestones deposited. In the north and east Sichuan, a series of bioclastic shoals were developed along the line of Guangyuan-Dazhou-Wanyuan-Shizhu, which together form the platform margin. On the west side of the range of Guangyuan-Dazhou-Wanyuan-Shizhu,

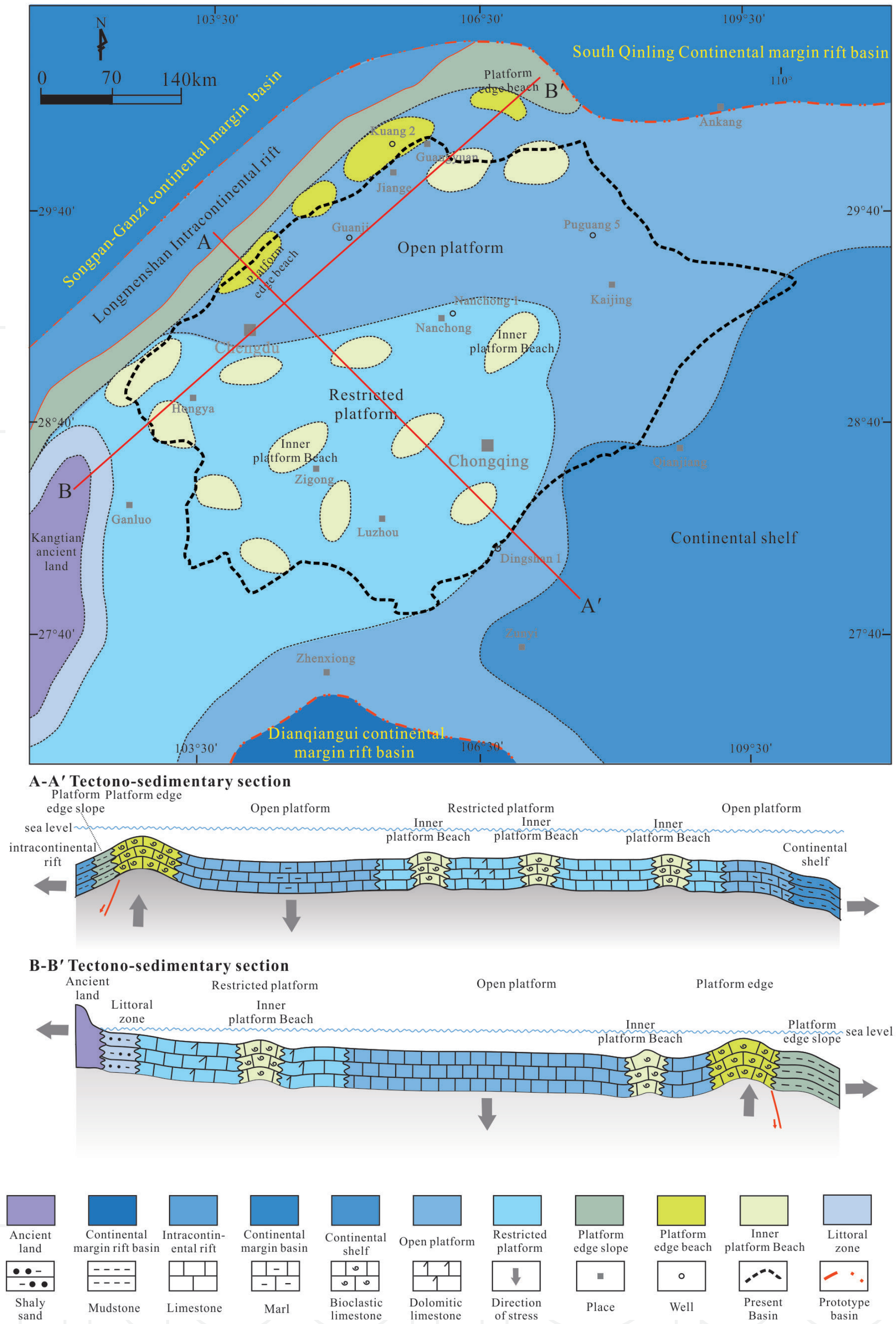

Figure 5.
Tectono-sedimentary system of the Qixia period in the Sichuan Basin and its adjacent areas.

there were slope and deepwater shelf sedimentary environments, and the sediments are mainly mudstone and siliceous rock (**Figure** 7).

5.5 Changxing period

During the deposition of the Upper Permian Changxing Formation, the paleogeographic pattern of the Sichuan Basin and its surrounding areas was controlled by the Longmenshan-Kangdian ancient land in the west [51]. Its structural lithofacies paleogeographic pattern features can be summarized as strong tectonic activity (e.g., "Emei ground fissure movement" [27]), obvious lithofacies

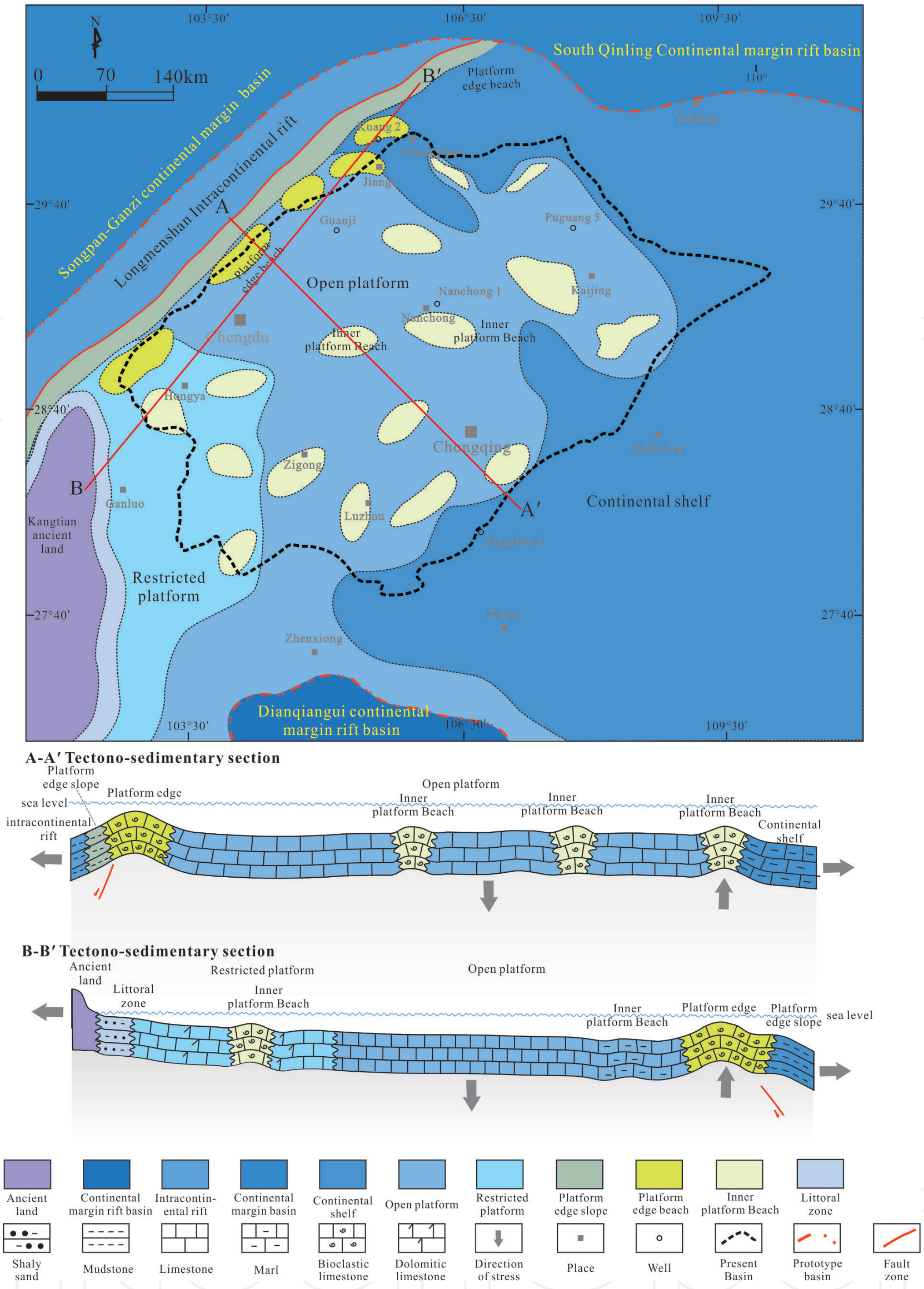

Figure 6.
Tectono-sedimentary system of the Maokou period in the Sichuan Basin and its adjacent areas.

differentiation (e.g., siliceous clastic lithofacies and shallow marine carbonate lithofacies), and relatively rich and complex paleogeomorphic types (e.g., trough and uplift) [50].

During the Late Permian, the eruption of Emei basalts reached its peak due to the strong ground fissure movement, which was called the "Emei ground fissure movement" [27]. This volcano-tectonic activity had a profound impact on the paleogeographic pattern of the Late Permian and Early Triassic in the upper Yangtze region. Wang et al. believed that a series of the northwest and southeast deepwater troughs developed in the Late Permian in the upper Yangtze region, such as "Guangyuan-Wangcang trough," "Kaijiang-Liangping trough" in the west, and "Chengkou-Exi trough" in the east. The formation of these

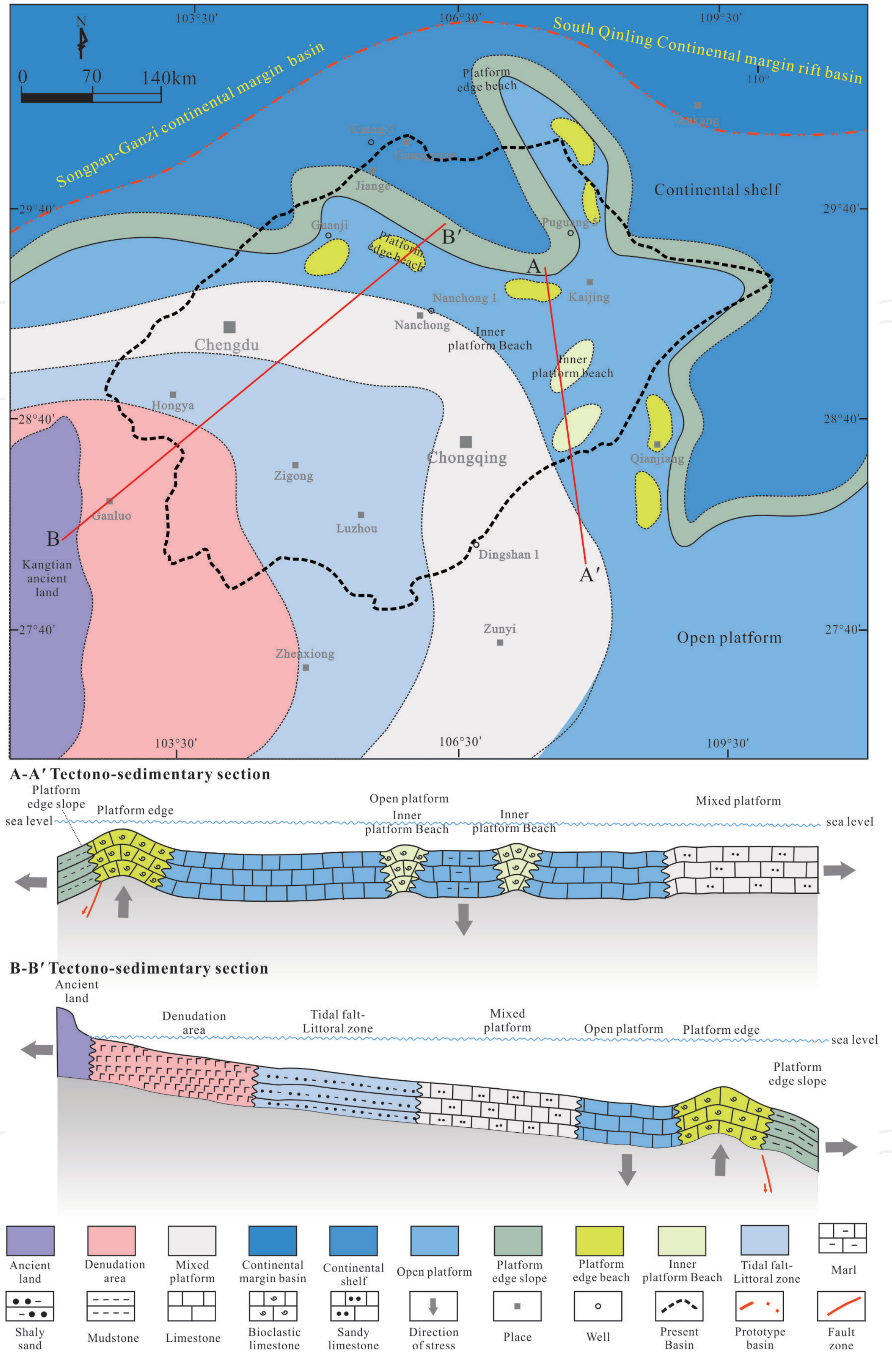

Figure 7.
Tectono-sedimentary system of the Wujiaping period in the Sichuan Basin and its adjacent areas.

troughs was controlled by the extensional movement of the southern Qinling Ocean in the north and the "Emei rift movement" in the west [27, 52]. In the Late Permian, the sedimentary facies belts in the upper Yangtze area were obviously different. The dark thin siliceous rocks, siliceous mudstones, and siliceous limestones were mainly deposited in the deepwater trough facies area, and the bioclastic limestones and reef limestones were mainly deposited in the shallow water platform facies area [53].

The sedimentary characteristics of the Late Permian can be summarized as follows: the sedimentary facies belt was generally distributed in the east–west direction and was controlled by the north–south direction structure and differentiated; reef and beach deposits are generally distributed in a belt along the trough to form the platform margin. On the west side of the platform margin, open platform, restricted platform, and terrigenous shore facies were developed, respectively, and on the east side, slope facies and deepwater shelf facies are developed (**Figure 8**).

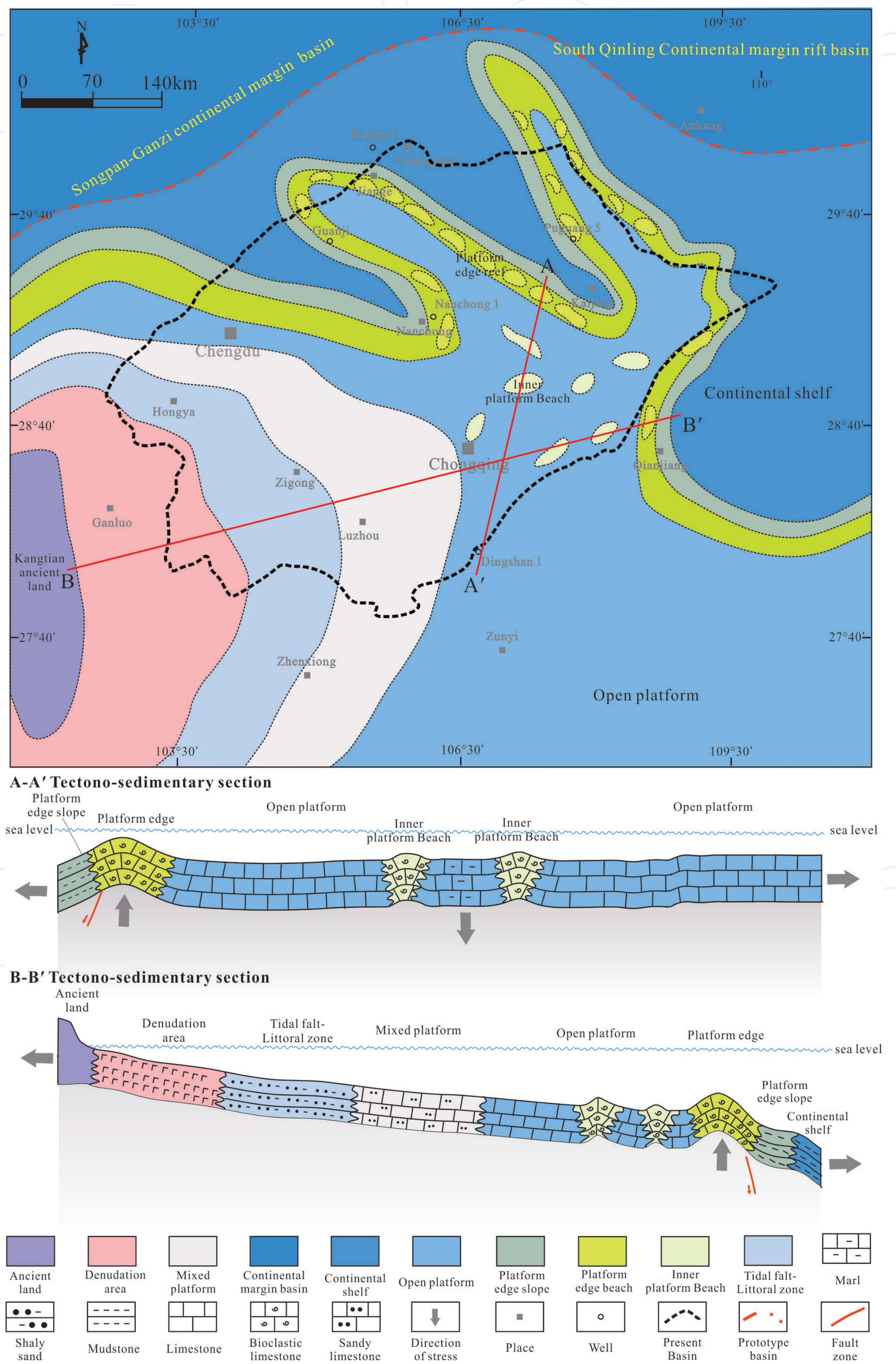

Figure 8.
Tectono-sedimentary system of the Changxing period in the Sichuan Basin and its adjacent areas.

6. Conclusions

The northern and western margins of the Yangtze block were passive continental marginal environments, while the southern and southeastern margins were continental marginal rift basins with deepwater settings.

During the deposition of the Liangshan and Qixia formations, the northern and western margins of Sichuan cratonic basin were discrete passive continental margin environments, while the south and southeast margins were continental margin rift basins with deepwater sedimentary characteristics. The sedimentary environment in this period gradually changed from the early shore tidal flat to the stable carbonate platform, which was generally characterized by east–west differentiation and north–south gradual change.

The tectonic setting of the basin was relatively stable in the Maokou period. The Kangtien ancient land in the south of the basin showed a trend of continuous uplift. The basin presented a pattern of alternating structural highs and depressions. The development of sedimentary facies belts in each sedimentary stage had obvious inheritance and migration. From southwest to northeast, the sedimentary facies included shore facies, limited platform facies, open platform facies, continental shelf facies, platform margin facies, and slope facies. These are the characteristics of a carbonate platform system.

Being influenced by the regional extension controlled by the Emei rifting, the tectonic subsidence of the basin in the Late Permian gradually increased from southwest to northeast. In the early stage, the basin was controlled by the thermal effect of deep materials, and then the northern part of the basin was mainly affected by the superimposition of regional extensional phases and finally formed the sedimentary pattern of platform shelf structural differentiation. At the same time, the sea level changes and the development of reefs and beaches at the platform edge had an important impact on the filling sequence. In the study area transgression gradually occurred from NE to SW, forming a sequence of shelf, slope, platform margin, carbonate platform, mixed platform, tidal flat, and volcanic facies.

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