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Preface

Sichuan Basin is a large superimposed petroliferous basin developed above the Yantze craton with two evolution stages: craton basin and foreland basin. Sinian-Triassic marine carbonate rocks are widely developed in the basin, with a thickness of more than 6000 m. The Central Sichuan area is located in the central Sichuan Basin, with stable structures and well-developed marine strata and favorable petroleum geological conditions and exploration potential. At present, strata of Sinian, Cambrian, Permian, and Triassic in the Central Sichuan area have been explored, which indicates that the multiple marine strata in Central Sichuan area have good exploration prospects.

The study of lithofacies paleogeography is the base of oil and gas exploration, and it is of great significance for oil and gas exploration and development. The predecessors have done a lot of effective researches relating to marine strata in Sichuan Basin, such as the series of lithofacies paleogeography in southern China (Xia Wenjie, et al., 1994), lithofacies paleogeography map of Sinian-Triassic in Yangtze Region (Ma Yongsheng, et al., 2007), lithofacies paleogeography map of Cambrian-Ordovician in Sichuan Basin (Yang Wei, et al., 2012), lithofacies paleogeography map of Permian-Triassic complied by sequence stratigraphic units (Zhao Zongju, et al., 2012), lithofacies paleogeography map of Sinian-Cambrian in Sichuan Basin (Du Jinhu, et al., 2016). These studies play an important role in oil and gas exploration by clarifying the Sinian-Triassic lithofacies paleogeographic patterns of Sichuan Basin. With the development of exploration and the deepening of understanding, there are many problems restricting exploration and research, such as how to depict lithofacies paleogeographic pattern of different periods more precisely by combining seismic data with drilling and outcrop data, and how to make detailed reservoir research under the constraints of lithofacies paleogeography.

In 2018, PetroChina Exploration and Development Research Institute began to carry out fine lithofacies paleogeography research and natural gas exploration evaluation for multiple marine strata in the Central Sichuan area. After three years of research, the project team built a more detailed paleostructure restoration and evolution of multiple marine strata in Central Sichuan area with comprehensive application of outcrop data and 2D, 3D seismic data finely calibrated by drilling and well logging

data, clarified the paleogeographic pattern of each sedimentary period in the basin, reconstructed the fine Sinian-Triassic lithofacies paleogeographic pattern, revealed the genesis and distribution characteristics of reservoirs under the control of the paleogeographic pattern, and evaluated the key exploration areas and favorable zones, which provided detailed basic geological evidence for oil and gas exploration.

The book is divided into six chapters. The preface was written by Wang Tongshan and Li Qiufen, Chap. 1 Outline of "Regional Geological Setting" was written by Bian Congsheng, Li Qiufen, Lin Tong, Zhao Jie, and Dong Jinghai, Chap. 2 Structural Characteristics and Evolution was written by Wang Tongshan, Li Qiufen, Lan Xiaodong, Lu Weihua and Tan Cong, Chap. 3 Lithofacies Paleogeography and Sedimentary Evolution was written by Li Qiufen, Wang Tongshan, Chen Xuan, Hu Zhonggui, Zhang Baomin, Zhai Xiufen, Huang Shiwei and Zhang Xiaorong, Chap. 4 Reservoir Characteristics and Distribution Prediction was written by Li Qiufen, Wang Tongshan, Zhang Baomin, Chen Yanhu, Wei Hengfei, Tian Xiaobin and Xu Anna, Chap. 5 Evaluation of Natural Gas Accumulation Conditions was written by Bian Congsheng, Li Qiufen, Wang Tongshan, Huang Shipeng, Qin Shengfei and Xu Zhaohui, Chap. 6 Recent Key Exploration Fields and Zones was written by Wang Tongshan, Li Qiufen, Bian Congsheng, Li Jun, Lintong and Sun Qisen. The whole book was edited by Li Qiufen and Wang Tongshan.

The book was strongly supported by PetroChina Exploration and Development Research Institute, PetroChina Daqing Oilfield Company, PCL Southwest Oil and Gas Branch, Changjiang University, China University of Geosciences, Beijing, Research Institute of Zhongheng Lihua Petroleum Technology, Beijing. At the same time, it received guidance and help from Prof. Hu Suyun, Prof. Li Jianzhong, Prof. Luoping, and Prof. Bi Jianjun. We would like to express our heartfelt thanks.

This book contains the latest achievements in the petroleum geology research of multiple marine strata in the central area of Sichuan Basin in recent years. It has both scientific and practical significance for exploration guidance that may help advance basic geological research. This book is a reference book integrating teaching, production, and scientific research. It is liable to mistakes or omissions, so we welcome suggestions and criticisms.

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Contents

Chapter 1
Outline of Regional Geological Setting

Sichuan Basin is located in the northwest margin of the Yangtze plate, bordered by Longmenshan Mountains in the west, Qiyaoshan Mountains in the east, Micangshan-Dabashan Mountains in the north, and Daliangshan-Daloushan Mountains in the south. The basin area is about 18×10^4 km^2. Sichuan Basin is developed with strong tectonic activities as it has long been in the transition-transform zone between Gondwana and Laurasia. Multiple regional unconformities are developed in the craton of Sichuan Basin, and the craton margin was strongly transformed due to orogenic deformation in the later stage.

The Leshan-Longnvsi paleo-uplift is located in the Central and Western Sichuan Basin, and the plunging zone is located in the gentle structural belt in Central Sichuan. It is the most prominent structural unit in Sichuan Basin, with an irregular shape. The core of the paleo-uplift is formed by the absense of Silurian, covering an area of 6.25 $\times$ 10^4 km^2. The outcrops in Central Sichuan are mainly composed of Middle and Upper Jurassic, in Weiyuan and Laolongba anticline they are mainly composed of the Triassic, which are relatively old, and in Western Sichuan are mainly composed of Cretaceous and Quaternary. This study focuses on the Central Sichuan at the eastern end of the Leshan-Longnusi paleo-uplift, located on the west side of Huayingshan tectonic belt.

1 Regional Geotectonics

Geographically, the research area is located within the inner Upper Yangtze craton. The development and evolution of marine sedimentary sequences in the study area must be consistent with the whole Upper Yangtze craton. According to the theory of "basin controlled by tectonics", the analysis of characteristics and influence of

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regional and areal tectonic movements is an important link in the process of sedimentary sequence filling. The following is a phased summary of the regional tectonic characteristics of the craton evolution stage in the Middle and Upper Yangtze Region.

The basement of Yangtze platform was formed by the Jinning movement in the Late Neoproterozoic, which made the Yangtze landmass enter the evolution stage of craton basin under plate movement mechanism since the Nanhua period. The evolution and development are closely related to the expansion and contraction evolution stages of the Tethys ocean during the reconstruction process of the mainland China and the interaction of the adjacent landmasses. In general, from the Early Paleozoic to Middle Triassic, the Yangtze landmass experienced the development and evolution history of differential action with adjacent landmarks (Cathaysian landmass, North China landmass, Indosinian landmass, etc.) in different periods of the process of South-to-North rotational drift in the proto-Tethys and paleo-Tethys ocean (Fig. 1). The Late Indosinian movement lasted to the Middle Triassic resulted in the closure of the paleo-Tethys ocean, the withdrawal of seawater, the tectonic inversion and the foreland orogeny, which ended the development and evolution stage of the Yangtze craton basin. As a result, the Yangtze landmass has entered a new stage of basin evolution, which includes intracontinental orogeny and foreland basin formation.

(1) Stage of Jinning-Tongwan movement. The accretive fold belts in the southeast margin of the Yangtze landmass and the trench-arc-basin system in the margin of the Cathaysia continent were formed by the subduction of South China Sea to the Yangtze landmass. About 850–880 Ma ago, between the Cathaysia and the Yangtze, the ancient South China Sea in the eastern part of the Yangtze landmass disappeared after the movement of the Jinning II episode, and the South China residual Sea basin in the western part remained to the Caledonian period. The basement of the Yangtze platform was formed after the Jinning movement. During the period of Chengjiang-Tongwan movement, the Rodinia supercontinent began to break up (Fig. 2), and the Yangtze block was under the influence of extensional tectonic action. The rift trough in the platform margin and the intercontinental rift developed together with the Sinian sedimentary caprock.

(2) The stage of the Caledonian movement. It is said to be the development stage of plate movement, including the extension-rifting stage and the convergence-matching stage, corresponding to the development of rifting-passive continental margin basin, the Formation of “great uplift to big depression” and foreland basin on the Yangtze craton.

The Caledonian period tectonic movements are mainly composed of the Tongwan movement, Xingkai movement, Yunan movement, and Duyun movement (Beiliu movement). Among them, ① Tongwan movement at the end of Sinian had a great impact on the Western Yangtze landmass, resulting in the uplift of the Western Sichuan Basin, which formed the prototype of paleo-uplifts in Leshan-Longnvsi, Longmenshan, Hannan-Dabashan, Xuefeng, and Central Guizhou. At that time, the Deyang-Anyue rift trough had begun to develop on the west margin of the Yangtze landmass. During the development period of

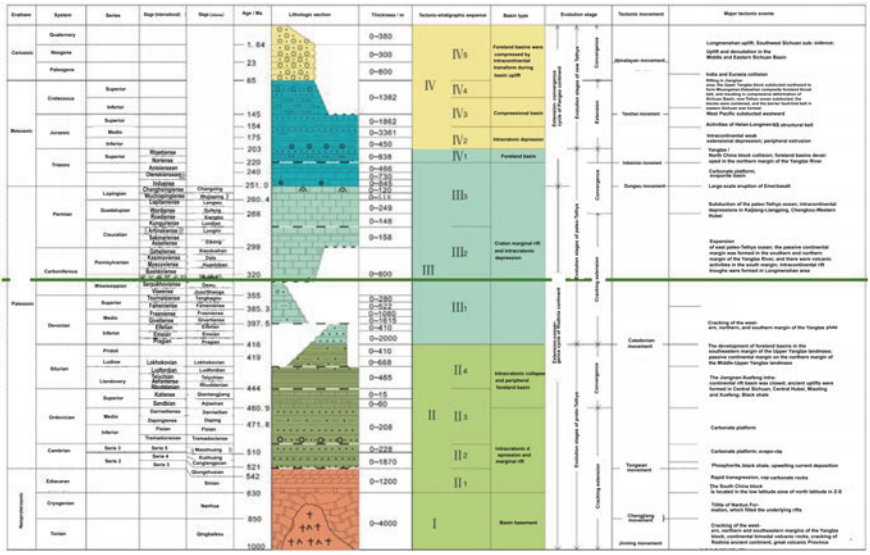

Fig. 1 Tectonic-stratigraphic sequences and evolution stages of Sichuan Basin (He et al., 2011)

the Dengying Formation, the mound-bank bodies in the platform margin were developed on both sides of the rift trough. ② The Xingkai movement at the end of the Early Cambrian had little effect on the Yangtze Region, characterized by uplift. ③ The Yunan movement at the end of Cambrian also had no significant influence on the Yangtze Region, and it was mainly developed as uplift, resulting in local unconformity. ④ The Duyun movement at the end of Ordovician was relatively strong, with intense activity in the west and weak in the east, strong in the margin and weak in the interior. Leshan-Longnvsi area uplifted early and intensely, Hannan and Dabashan uplifts developed inherently, and then Xuefeng and Central Guizhou uplifts rose sharply, which changed the tectonic pattern of the Yangtze Region from high in the west and low in the east to the uplift of the southeast margin. ⑤ Under the background of early tectonic pattern, at the end of Silurian, the Guangxi movements were dominated by uplifts, and caused the main uplift of the whole region to form a unified South China uplift.

Overall, the tectonic characteristics during the period of Caledonian movement were affected by the subduction of the paleo-Asian Ocean and the branches of proto-Tethys ocean, as well as the matching and collision of Chinese landmasses after the first expansion. Affected by the northward subduction of the proto-Tethys ocean, the northern margin of the Yangtze landmass formed a back-arc expansion zone and affected by the northward subduction of the ancient South China Ocean in the southern margin in the Yangtze landmass, the Hunan-Guangxi landmass overlapped on the Yangtze continental margin in the form of flexure basin.

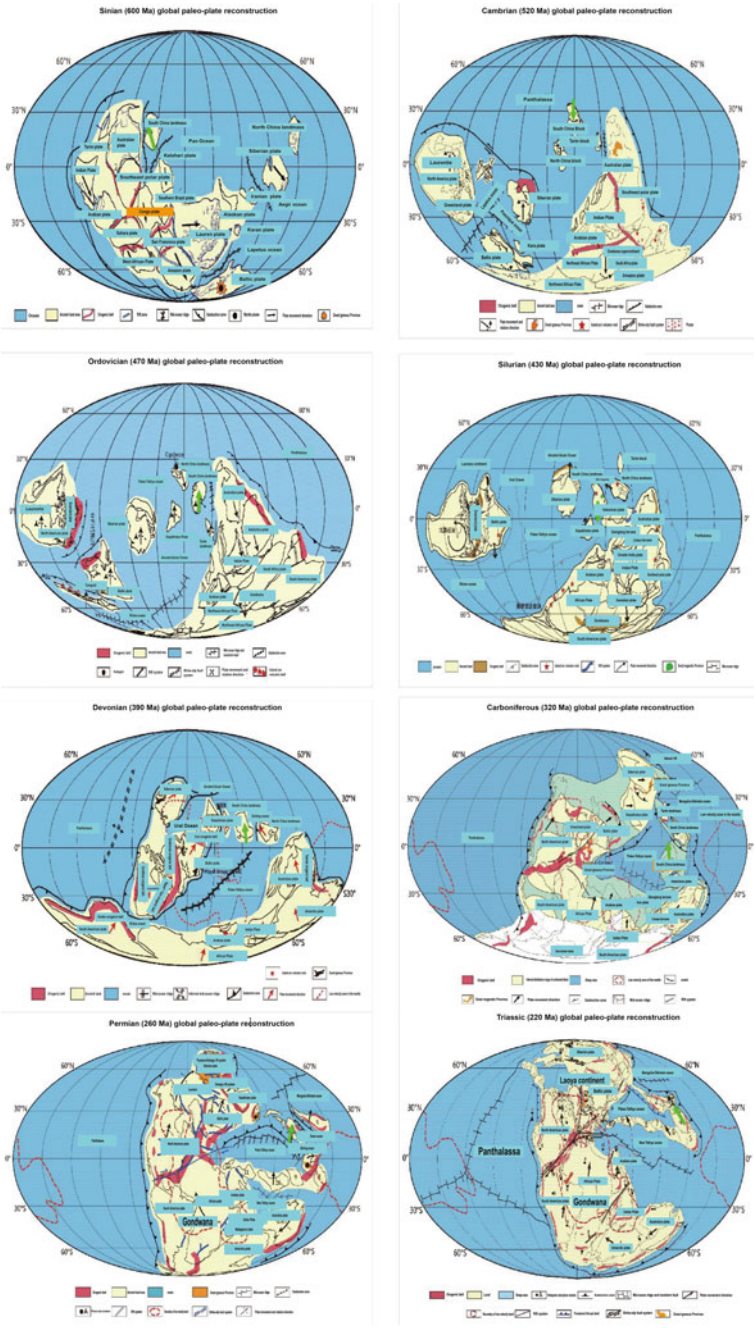

Fig. 2 Tectonic-stratigraphic sequences and evolution stages of Sichuan Basin (Li et al., 2014)

(3) Hercynian-Indosinian period (D-T_2). It is the development stage of intraplate activities, which includes the two geotectonic stages of convergence-extension and convergence orogeny-extension. In the stage of convergence-extension, the Nanpanjiang Basin, Hunan-Guangxi-Jiangxi rift basin and small Mianlue ocean basin were formed by the continental rifting. In the late stage, the Qinfang Trough closed. In the convergent orogeny -extension stage, a continental rift formed in the early period was further developed. In the late stage, the intracontinental convergence occurred, and the whole region changed from sea to land. In the Hercynian-Indosinian period, under the tectonic background of the Guangxi movement, many tectonic movements were further developed, including Ziyun movement, Yunnan movement (Sichuan-Hubei movement), Guizhou-Guangxi movement, Dungwu movement and the first episode of Indosinian movement. Among them, ① Guangxi movement (the end of Silurian): had a profound impact on the development and evolution of the whole Middle and Upper Yangtze Region in the late stage. The tectonic pattern of relatively stable main uplift and relatively active marginal rifting was remained until to the late Early Permian. ② Early Hercynian (D-C): most of the Yangtze platform continued to uplift into the land, and the platform margin (the front of Longmenshan) was sharply rifted and received stable-transitional sediments with huge thickness. The Ziyun movement (at the end of Devonian) occurred in this period, which was active in the Sichuan-Hubei area, resulting into unconformities and overlapping between Carboniferous and Devonian. In the late Early Carboniferous, the unconformity between the Late and the Early Carboniferous was formed by the Yunnan movement (Sichuan-Hubei movement), and the Wudang uplift was formed. At the end of the Carboniferous, the Guizhou-Guangxi movement was dominated by the vertical movement, resulting in interval unconformities. ③ Dungwu movement (the end of P_2): the tectonic environment was relatively stable in the Middle and Early Permian. A large-scale gentle carbonate slope was developed and intensely stretched during the late stage. Under the influence of "Emei Taphrogenesis" at the end of the Middle Permian, the paleo-Tethys was opened, and the Emei hot mantle plume uplifted. In the early Late Permian, large-scale basalt magmatic effusion occurred in the Wolong-Panxi rift, forming an erosion gap between the Late and the Middle Permian, and the South China region had been raised and turned into a denudation zone. ④ Early Indosinian (T_1–T_2): Songpan-Ganzi trough was developed with back-arc extension, subsidence and uncompensated active sediments. Beach islands were arranged around the platform margin, and the stable marine evaporation deposition of the Upper Yangtze was received in the platform.

In short, in the Hercynian-Indosinian period, the Yangtze landmass's tectonic characteristics were affected by the expansion and contraction of the paleo-Tethys ocean. The effects are shown as: ① two EW sub-branch oceans, Mianlue ocean and Qinfang trough, were developed by the expansion of northern and southern margin of Yangtze platform in Carboniferous; ② in Late Permian, the Mianlue ocean in northern margin subducted to North China, the Yuehai Ocean

in the southern part subducted from east to west and south, and the paleo-Tethys ocean subducted from west and south to north. ③ In the Middle Triassic, by inheriting the previous tectonic background, the Yangtze landmass was shown as a subducting collision in whole. Foreland basins and foredeep basins were formed around South China landmass, and Xuefengshan, Dabashan, Jiangnan orogenic belt and corresponding foreland uplift areas developed in the landmass. That is, the northern margin of the landmass was affected by the northward collision of the Mianlue ocean to the North China landmass, the southern part was affected by the southward subduction of Yuehai ocean, and the western margin was affected by the west to east subduction of small Ganzi-Litang ocean basin.

(4) Late Indosinian period (T_3): it belongs to the Indosinian-Yanshan-Himalayan cycle. Paleo-Tethys ocean closure: in the northern part, the South China and North China landmass collided and converged into one piece; in the southern part, South China landmass and Sanjiang region were unified as shallow sea area; in the western part, Songpan-Ganzi trough and Longmenshan platform margin depression returned, tectonic inversion was developed, orogeny basins were formed. The foreland basin in T_3x of Western Sichuan was formed and evolved and entered a new intracontinental orogeny and foreland basin development stage.

The above analysis shows that from Sinian to Middle Triassic, the Middle and Upper Yangtze Region was developed with multi-stage structural evolutions, the transformation of multi-period tectonic movement, multi-type basin superposition, multi-cycle sedimentary filling, and multi-stage hydrocarbon accumulation.

2 Stratigraphic Development Characteristics

The drilling wells reveal that the sedimentary caprocks in Central Sichuan are Sinian, Cambrian, Ordovician, Silurian, Carboniferous, Permian, Triassic and Jurassic from old to new, without Devonian. The basement stratum is the pre-Sinian crystalline rock (Fig. 3). The Sinian unconformity overlays on the granite basement of pre-Sinian.

(1) Pre-Sinian. The pre-Sinian strata in Central Sichuan are mainly developed metamorphic rocks and magmatic rocks. According to drilling data of Well Nvji, the pre-Sinian volcanic rocks developed in the basement of Longnvsi anticline, with the lithology of dacite. Well Wei 15 in the Weiyuan area reveals that the basement was developed with biotite quartz diorite, while Well Wei 28 and Wei 117 reveal that the basement was composed of granite mixed with thin diabase.

(2) Sinian. It is the oldest sedimentary overlying layer in Sichuan Basin, which is unconformable overlaid on the pre-Sinian. Doushantuo and Dengying Formation developed in Sinian, and Doushantuo Formation mainly developed in the Lower Sinian. The sedimentary sequence of Sinian can be divided into four

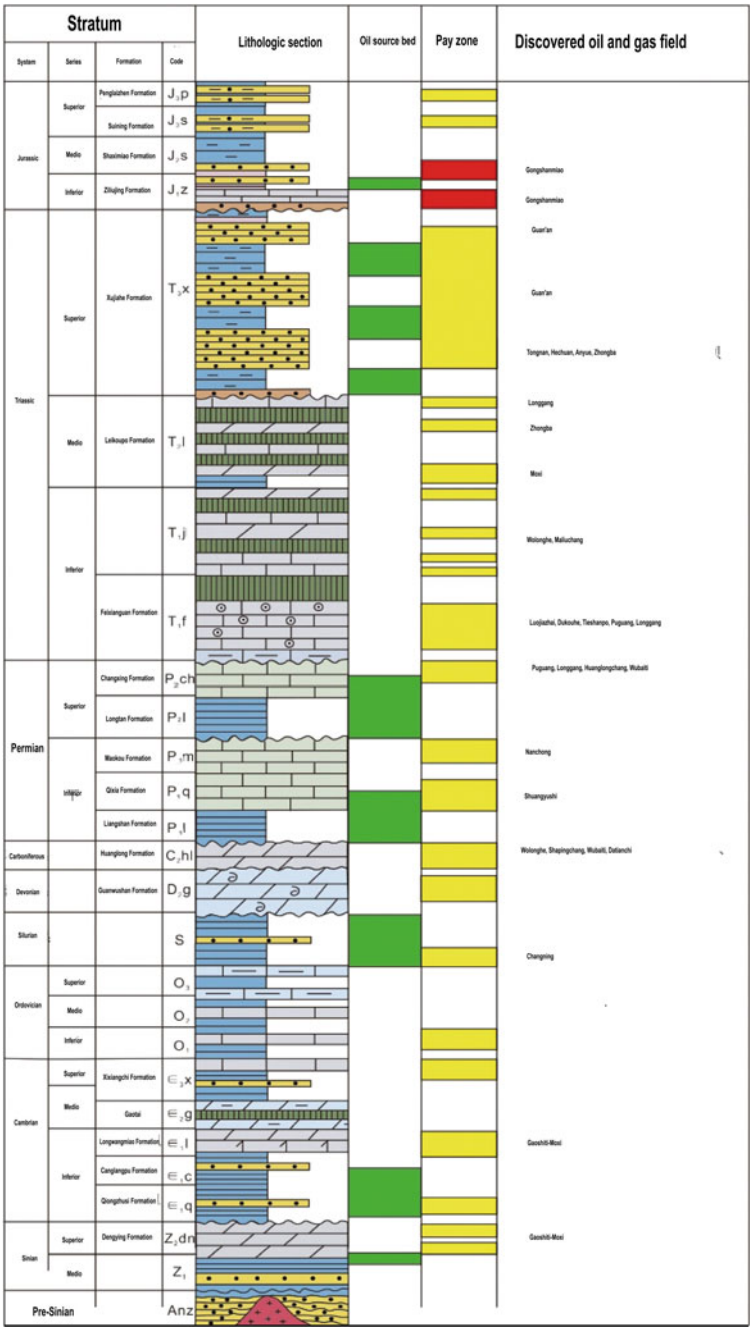

Fig. 3 Comprehensive stratigraphic column of the study area

segments. The first and third segments are mainly composed of gray-white and white carbonate rocks. The second and fourth segments are black shales, commonly known as “two white and two black”. The Dengying Formation of the Upper Sinian is mostly composed of carbonate rocks, with a considerable amount of algal dolomites and grain dolomites overlain by a thin layer of sand, shale, and siliceous rocks. It can be divided into four sections by the lithology. The Deng1 Member is the product of early marine transgression of the Late Sinian, and the lithology is mainly layered silty dolomite of light–dark gray, containing sandy dolomite and alginate, locally mixed with siliceous bands and chert. The Deng 2 Member is mainly composed of light-gray and gray-white algal dolomites and silty dolomites, with laminated, snowflake, block and grape structures, paleoalgaes are developed in the stratum with siliceous dolomites. The Deng3 Member is mainly composed of dark-gray and gray layered fine silty dolomites, and dark-gray mudstones are developed in the bottom of Central Sichuan. The Deng 4 Member is mainly composed of layered, pore-dissolved silty dolomites, sand-bearing dolomites and algal dolomites, locally intercalated with siliceous bands and cherts. Under the influence of Tongwan movement in Sinian Dengying period, the Deng 2 and Deng 4 Member were weathered and denuded to form regional pore and cave layers, which are the main production layers of platform marginal zone in Gaoshiti-Moxitai.

(3) Cambrian. It is a set of relatively stable layers mainly composed of marine carbonate rocks intercalated with clastic rocks, and it can be compared regionally. The Tongwan movement uplifted the structures in the Upper Yangtze Region, strata denudation, and then resulted into the formation of non-uniform landform. The Maidiping and Qiongzhusi Formation of the Lower Cambrian were deposited on this uneven ancient landform. The Maidiping Formation is mainly distributed in the Deyang-Anyue rift trough, and the Well Gaoshi 17 in the western study area reveals this statum. It was developed under the sedimentary background of large-scale transgression. It is mainly composed of dark fine-grained sediments, including laminar interbedding argillaceous dolomites, silicophosphate dolomites and phosphorus black shale. The Qiongzhusi Formation, which is mostly composed of transgression sediments with fine grains, is a major source rock in the Sichuan Basin. The lithology of Qiongzhusi includes fine sandstones and sandy shale mixed with fine sandstones. In the lower part of the study area, Canglangpu Formation is mainly composed of fine-coarse-grained quartz sandstones, and in the upper part, it is mainly composed of gravel quartz sandstones with high roundness. The stratum is developed with relatively high mineral maturity and composition maturity, and it deposits gravel sandy tidal-flat. The Longwangmiao Formation is mainly developed with oolitic limestones, lime dolomites and dolomites, most of which are striped and mottled, and mixed with wavy argillaceous bands. Fossils are relatively rare in Longwangmiao Formation. The stratum deposits shallow water gentle slope. The reservoirs in the gas field of the Longwangmiao Formation in the Moxi-Gaoshiti area are mainly composed of a set of porous dolomites in beach facies,

and the reservoir spaces are mainly intergranular solution pores and intergranular solution pores. The reservoirs are porous reservoirs with good reservoir performance. The lithology of the Gaotai Formation in the Middle Cambrian is divided into upper and lower sections: the lower part is mainly composed of a set of argillaceous dolomites with aubergine mudstones, and the upper part is a set of aubergine argillaceous siltstones and dolomitic siltstones mixed with aubergine mudstones. The lithology of Xixiangchi Formation of Middle and Upper Cambrian is relatively single, which is a large set of thick massive fine-grained dolomites and silty dolomites, bioclastic dolomites, and dissolved dolomites can be seen in some layers with conodont fossils.

(4) Ordovician. It is mainly composed of terrigenous clastic rocks and carbonate rocks. The Ordovician on the uplift was denudated in varying degrees by the Caledonian movement. In the high part of the uplift, the Ordovician was denudated and missing, and the residual thickness in the two wings of the paleo-uplift increased. The middle and lower part of the Lower Ordovician Tongzi Formation is argillaceous shale with bioclastic limestones of thin layer, and the upper part is shale. Honghuayuan Formation is mainly composed of thick massive coarse-grained bioclastic limestones. Meitan Formation is mainly composed of a set of shale and siltstones, occasionally intercalated with limestones. The lower part of the Middle Ordovician Shizipu Formation is mainly composed of limestones, where as the upper part is dominated by argillaceous shale mixed with argillaceous limestones, containing conodonts, chitins and other fossils. Baota Formation and Linxiang Formation of Upper Ordovician are mainly composed of limestones with more mud. The former is characterized by unique "turtle crack" and the latter is characterized by "pimple limestone". The Wufeng Formation is mainly developed with a set of black carbonaceous shale, and the upper part is siliceous shale.

(5) Silurian. It comprises deposited black and grayish-green shale, intercalated with thin layers of siltstones, biological limestones and calcareous shale. The Silurian was denuded entirely in the high portion of the Leshan-Longnvsi uplift, and the residual thickness progressively thickened to both sides and the lower section of the uplift. The Silurian consists of Longmaxi Formation, Xiaoheba Formation, Hanjiadian Formation, jintaiguan Formation and Chejiaba Formation from bottom to top. The lithological characteristics are as follows: the lower part of Longmaxi Formation of Lower Silurian is black graptolite shale, which contains a large amount of graptolites with varying thickness, and the upper part is mainly composed of gray, grayish-yellow, or greenish-yellow shale mixed with siltstones or lime tumor cores, containing a small amount of graptolites and it is a continuous deposit with the overlaying Wufeng Formation. The lower part of the Xiaoheba Formation is mainly composed of medium and thick green-gray siltstones, locally intercalated with thin layers of bioclastic limestone, and the upper part is yellow-green, gray-green shale and silty shale, intercalated with thin layers of biological limestone or limestone lens. The lower part of Shiniulan Formation (i.e. Qiaogou section) is interbedded with black lime shale, thin layers of nodular limestone and limestone, and the upper part (i.e. Shiniulan

section) is mainly composed of gray nodular marlites and argillaceous limestones, occasionally intercalated with yellow-green mudstones. The Hanjiadian Formation in Middle Silurian is mainly developed with a set of gray-green and blue-gray mudstone and silty mudstone, and the lower part is mainly developed with yellow-green and blue-gray mudstones.

(6) Carboniferous. The study area's Carboniferous layers are concentrated mostly in the eastern part. They are mainly developed with Huanglong Formation composed of thick dolomites, superimposed on the Silurian and pseudo-integrals under the Permian Liangshan Formation. They contain fusulinid belts, which are generally tens of meters thick. The Carboniferous is an important natural gas reservoir in the study area.

(7) Permian. The Permian strata are draped on Leshan-Longnvsi paleo-uplift. In Central Sichuan, the lower part of Liangshan Formation in Lower Permian is mainly composed of light gray and purple clay shale and iron-bearing chlorite clay rocks. It is locally enriched with oolitic and pisolitic hematites. The middle part is mainly composed of gray and gray-white ferrolite mudstones, dense and bean-shaped bauxites. The upper part is mainly composed of grayish-brown and black carbonaceous shale, which is mixed with coal lines or thin anthracite coal seams. Qixia Formation of Middle Permian is mainly deposited by carbonate platform comprising a large set of dark-gray bioclastic micrite limestones intercalated with argillaceous rocks and bioclastic limestones. Maokou Formation is mostly composed of dark-gray, gray and gray-white thick to massive micritic limestones, micritic bioclastic limestones and algal limestones, with a small amount of dolomites containing more flint limps and strips. Longtan Formation in Upper Permian is mainly developed with a set of black-gray shale and brown-gray limestones interbedded by unequal thickness. The lower part of Changxing Formation is mainly developed with gray thick-layer micritic limestones, skeletal fragment limestones and algal limestones, and the middle and upper parts are mainly developed with gray-white medium-thick layer strip limestones containing flints, dolomitic limestones and biological limestones. The top is mainly developed with a thin layer of micritic limestones, dolomitic limestones and clay rocks interbedded with unequal thickness, intercalated with siliceous layers and tunnel flints.

(8) Triassic system. It is parallel integrated above the Permian. The Lower Triassic includes Feixianguan Formation and Jialingjiang Formation, the Middle Triassic is mainly developed with Leikoupo Formation and the Upper Triassic is mainly developed with Xujiahe formation. The Feixianguan Formation of the Lower Triassic is a set of alternating deposition of open sea platform facies limestones and intertidal-supratidal red clastic rocks. Carbonate rocks and evaporite rocks are deposited in the closed bay of Jialingjiang and Leikoupo Formation. The Leikoupo Formation was denudated by the Indosinian movement that occurred at the end of the Middle Triassic, and the denudation degree gradually intensified from northwest to southeast. Xujiahe Formation in Late Triassic is a set of sand and mudstone deposits of marine-continental alternative deposition.

3 Tectonic Evolution

In general, a set of extremely thickened sedimentary caprock was developed above the Presinian basement in Sichuan Basin, which further divided into two sets of marine and continental strata, with a total thickness of 6000–12,000 m. The Middle Triassic Xujiahe Formation and above are mainly developed as clastic rock strata with a thickness of 2000–5000 m. The strata of the Sinian-Middle Triassic are dominated by marine carbonate rocks, with a thickness of 4000–7000 m, among which, the study area is located above the Central Sichuan paleo-uplift, and the east transition area is the Luzhou paleo-uplift (Fig. 4). The sedimentation and structures in the study area are controlled by the evolution of Central Sichuan paleo-uplift and Luzhou paleo-uplift. According to the development characteristics of strata above the paleo-uplift in Central Sichuan, 7 regional unconformities are mainly developed in the marine strata. (1) Sinian/pre-Sinian: Is the product of Jinning movement, and the Sinian sedimentary rocks are unconformable on the pre-Sinian metamorphic rocks or intrusions. (2) Cambrian/Sinian: It represents the Tongwan movement. The Cambrian and Sinian are in parallel unconformity contact. From the East and west sides, the strata of Cambrian are thinned towards the direction of Leshan-Longnvsi paleo-uplift in Central Sichuan. The bottom boundary of Lower Cambrian is onlapping, and the top boundary of Cambrian is eroded. It shows that Leshan-Longnuvsi paleo-uplift is developed with both synsedimentary and denudation characteristics. The Leshan-Longnvsi paleo-uplift is surrounded by a depression area, and the altitude difference between uplift and depression is about 3000 m, indicating that Sichuan Basin has presented the structural pattern of great uplift and depression in Cambrian. (3) Ordovician/Cambrian: It is the product of the middle Caledonian movement, which is mainly characterized by the onlaping deposition on strata of Ordovician in the slope. The top of Ordovician was truncated from east to west. (4) Silurian/Ordovician: The onlap of Silurian strata can be seen on both sides of Leshan-Longnvsi uplift. (5) Permian/pre-Permian: there is a regional angle unconformity interface between Permian and pre-Permian, which resulted due to late Hercynian movement. The lower Permian is missing in a large range of the basin, and the Middle Permian mainly overlaps above the Carboniferous, Silurian or Ordovician. (6) Upper Permian/Middle Permian: The Middle and Upper Permian is also a parallel unconformity contact, which is called the Dungwu movement in the Upper Yangtze Region. In the Late Permian, affected by the activity of “Emei mantle plume”, Emeis basalt erupted on a large scale and normal faults in the basin were frequently developed. (7) Upper Triassic/Middle Triassic. It is the angular unconformity interface between the Middle and Upper Triassic and is the product of early Indosinian movement, indicating the end of marine sedimentation in the basin. The top Leikoupo Formation of the Middle Triassic was truncated, and the thickness of Leikoupo Formation in the whole study area was increased from southeast to northwest.

3.1 Tectonic Evolution of Central Sichuan Paleo-Uplift

(1) Original stage. The basement of Sichuan Basin was formed after the Jinning movement and before the Sinian sedimentation, where as for tillites were deposited in Nantuo period of pre-Sinian, which was got distributed in Northeast Sichuan, Longmenshan, Dabashan and Xichang-Ganluo areas. This set of tillite sedimentation is missing in Sichuan Basin. After the glacial period, the deposition of black shale, siltstone and thin-layer carbonate rock of Doushantuo Formation was received by Sichuan Basin, with the thickness of 0–250 m. However, the stratum thickness in Weiyuan-Longnvsi and other Central Sichuan areas is only 9–20 m, which is the thinnest developed area in the basin, indicating that the Central Sichuan area may have been the uplift at that time, and the uplift is developed with low tectonic amplitude, which is mainly related to the basement activity.

Dengying Formation was deposited after Doushantuo Formation, and at the initial stage of deposition, transgression occurred in Sichuan Basin. Dengying Formation is mainly deposited with a large set of algal dolomite, a series of onlap pinchout points were developed in the southeast wing of the paleo-uplift in the Deng1 Member. Combined with the comprehensive well data and seismic data, during the deposition period of Dengying Formation, the southeast wing of Leshan-Longnvsi paleo-uplift was relatively low, and the Central Sichuan may be the uplift. Well Nvji and Well Gaoshi 1 are located on the slope of the uplift. At the end of the deposition of the Deng1 Member, the sea flooded the study area and further extended to the Longmenshan area. In this period, the Sichuan Basin received the deposition of the Deng2 Member. The Deng 2 Member was relatively stable with large deposition thickness. At the end of the stratigraphic deposition, the first episode of Tongwan tectonic movement began to move, the paleo-uplift was differentially uplifted, and the denudation thickness gradually increased from east to west. After the tectonic movement, the paleo-uplift subsided again, and the Deng 3 Member was deposited. The gentle slope was developed inside the basin. There were only two onlap pinchout points in the Deng 3 Member on the southeast wing. After the deposition of the Deng 4 Member, the overall uplift could be lifted again and denudated by the

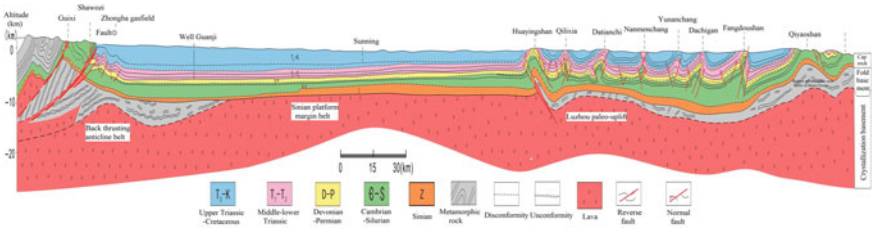

Fig. 4 Structural cross section of Sichuan Basin

second episode of Tongwan movement. Well Gaoshi 17 may be located at the high part of the paleo-uplift, the third and the Deng4 Member were completely denuded.

Based on the above analysis, the paleo-uplift was lifted on large-scale during the Tongwan movement, and the stratum was strongly denuded. The residual thickness of Dengying Formation in the Weiyuan-Quxian area was 500–700 m, and it could be 800–1200 m to both sides, indicating that the paleo-uplift was characterized by both sedimentation and uplift denudation during the deposition of Sinian Dengying Formation, which was the original development period of the paleo-uplift.

(2) Development stage. After the Tongwan movement, a nearly NS rift trough was developed in Central Sichuan, resulting in the uneven shape of the paleogeomorphology of the paleo-uplift. A series of onlap pinchout points were identified on the southeast wing of the paleo-uplift, as well as inside the rift trough. The Central Sichuan was mainly developed as filling-leveling up sedimentation in the NE-SW section. A rift trough developed in the Weiyuan-Gaoshiti area with near NS direction. Maidiping and Jianzhusi Formation of Lower Cambrian with large thickness deposited in the trough. At the end of the Early Cambrian, the paleo-uplift of Leshan-Longnvsi was uplifted again, and denudation pinchout points were developed in the northwest wing, while the denudation in Central Sichuan was affected by the late Caledonian movement. After the tectonic movement of this period, transgression occurred. The onlap pinch points can be identified in the Middle and Upper Cambrian at the margin of the paleo-uplift. Under the influence of the late Caledonian movement, in most parts of the core in the paleo-uplift, the Middle and Upper Cambrian were denuded. The tectonic activities in the Late Cambrian may have occurred only in Longmenshan area and Western Sichuan. These areas were uplifted, as a result, the Cambrian was seriously denuded, while the southeast wing of the paleo-uplift was still underwater, so that the Ordovician continued to deposit. From the well correlation section, the thickness of the Middle and Lower Cambrian was significantly decreased towards the Central Sichuan, indicating the existence of transgression. The structural form of the paleo-uplift at the end of the Cambrian was inherited by Ordovician, which later became an uplift in the northwest part, highpoint in the central part, and depression in the southeast part. At the same time, the sediments were coarse in the northwest and fine in the southeast. The Ordovician in the core of Leshan-Longnvsi paleo-uplift had been denuded, which is only distributed at the core margin. The southeast wing of the paleo-uplift is relatively intact, and multiple onlap pinchout points can be identified on the section. From the well data, only the Lower Ordovician remains at the well location on the paleo-uplift. However, the Ordovician is relatively intact at the wing of the paleo-uplift, especially the southeast wing. It can be seen that the thickness of the stratum gradually decreases from the southeast wing to Central Sichuan. It is judged that the paleo-uplift of Leshan-Longnvsi area may be a synsedimentary uplift during the deposition of the Ordovician. In

the Late Ordovician, the study area was uplifted again, and the amplitude in the southeast was the smallest, only the Upper Ordovician was denuded. From the seismic section, it can be seen that, in most areas, the Lower Ordovician was basically in direct contact with the Silurian, indicating that the Middle and Upper Ordovician may be denuded in this period.

After the tectonic action of the Late Ordovician, the paleo-uplift subsided again and received sedimentation. In the seismic section, there is an overlapping phenomenon in the Silurian, indicating that the strata of the study area have entered the stage of slow transgression again.

(3) Stage of strong uplift and denudation. At the end of Silurian, large-scale uplift and strong denudation occurred in the Upper Yangtze Region, and the core of Leshan-Longnvsi uplift was seriously denuded. The denudation continued until to the Sinian Dengying Formation in Southwest Sichuan, and was relatively weak in the wings of the paleo-uplift. The denudation period may last until before the deposition of Permian.

In summary, the Leshan-Longnvsi paleo-uplift developed on the pre-Sinian basement, and the original form was developed at the end of Sinian through the Tongwan movement. Then the multicycle tectonic uplift and subside was developed in the paleo-uplift. Finally, the paleo-uplift was flattened after the strong uplift and denudation of the Late Caledonian movement and was finalized as an inherited paleo-uplift of the Caledonian period before the deposition of Permian.

(4) Stable burial stage. After the deposition of Permian, Leshan-Longnvsi paleo-uplift entered the tectonic stage of later adjustment and transformation. In Permian, Sichuan Basin entered the stable craton basin development stage, and the paleo-uplift received stable deposition. At the end of the Early Permian, the paleo-uplift was lifted and short-term denudated again by the Soochow movement. Subsequently, the thickness of the strata in the paleo-uplift was stable by the Middle and Lower Triassic deposition. By the end of the Middle Triassic, tectonic inversion occurred in Sichuan Basin, Luzhou and Kaijiang paleo-uplift developed, under the effect, the southeast Leshan-Longnvsi paleo-uplift was uplifted, and the northwestern part was subsided. The structural axes of the Paleozoic strata in the paleo-uplift migrated to the southeast, and the Ziyang paleo-uplift was formed at this time. The Middle Triassic of Permian in the paleo-uplift was developed as monoclinic, and the Leikoupo Formation was strongly denuded in the southeast of the study area.

(5) Development stage of West Sichuan Foreland Basin. Until the Late Triassic, the tectonic pattern in Sichuan Basin is still developed as depression in West Sichuan, relative uplift in Southeast Sichuan, and foreland basin in West Sichuan. The pre-Sinian detachment layer of the paleo-uplift was developed, the structure axes of the Paleozoic strata continued to migrate to the southeast, and the monoclinic structure of Permian-Middle Triassic was more prominent. The detachment layer of the Jialingjiang formation was only developed in the

front of Longmenshan area, and the tectonic stress was not transmitted to the Middle Sichuan paleo-uplift on the west side of Huayingshan.

(6) Adjustment and finalization stage. At the end of the Jurassic, the structural layer under the detachment layer of the Jialingjiang Formation inherited the characteristics of previous structural deformation, and the Western Sichuan area was still developed as a depression basin. In the Himalayan period, the tectonic stress continued to transfer to Central Sichuan through the gypsum detachment layer of the Jialingjiang Formation, and Longquanshan continued to uplift. A series of thrust faults and recoil faults were also developed on the gypsum detachment layer in Central Sichuan. During the period of 8–13 Ma, affected by the expansion and uplift of the eastern margin of the Qinghai Tibet Plateau, a large-scale structural wedge was developed in the deep layers of the study area, resulting in the rapid uplift of Longmenshan. The Southwest Sichuan was compressed and deformed. The paleo-uplift axes continued to migrate to the southeast, the Weiyuan anticline uplifted rapidly, and the paleo-uplift of Leshan-Longnvsi evolved into the current structural form.

3.2 Tectonic Evolution of Luzhou Paleo-Uplift

The development period of Luzhou paleo-uplift crosses almost the whole Triassic period, with sustainable development and change. As we all know, the Middle-Late Triassic is the period for the transformation of the Sichuan Basin from the stage of craton basin to the stage of compressional or foreland basin, especially the sedimentary period of Leikoupo Formation in the Middle Triassic, which is the last period of marine sedimentation in Sichuan Basin and the prelude to the formation of foreland basin. The Sichuan Basin in this period was dominated by marine carbonate deposits. Influenced by the paleogeographic pattern of the basin by the NE-SW trending of Luzhou Kaijiang paleo-uplift belt, the sedimentary filling of the basin was developed with prominent differentiation characteristics. In the uplift area, barrier island sedimentation was the main sedimentary environment, evaporation platform and calcareous lagoon were the main sedimentary environment on the northwest side of the paleo-uplift, and carbonate rocks were widely developed While in the southeast side of the paleo-uplift, tidal basin was the main sedimentary environment. From the Southeast to Sangzhi area on the northwest side of Jiangnan Xuefeng paleo-uplift, the strata were mainly gray, aubergine mudstones, silty mudstones and cinereous silty-fine sandstones. It shows that the content of clastic particles gradually increases from northwest to southeast.

From the perspective of geotectonic background, the southeast margin of Sichuan Basin is the Jiangnan-Xuefeng orogenic belt, which was comprehensively affected by plate matching, intracontinental deformation and deep power in the Middle Triassic, and continued to advance to the northwest, forming a series of thrust nappes. The Jiangnan-Xuefeng orogenic belt gradually expanded and uplifted in the Middle Triassic and became an important provenance area in the Sichuan Basin, which led to

the formation of a piedmont depression on the southeast side of Luzhou paleo-uplift, with an overall terrain of high in the east and low in the west, and the sedimentary center gradually migrated to the west. Longmenshan area in the west of Sichuan Basin was still dominated by tensile environment in the Middle Triassic. It was a low and gentle underwater uplift area controlled by normal faults, mainly developed in the sedimentary environment of the salinized shallow sea and rich in algae. The west of Longmenshan was developed as the Songpan-Ganzi passive continental margin basin, which was still dominated by the tensile environment. A series of alternating rift zones and tilted uplift fault blocks were developed. Generally, it was developed with the geomorphic characteristics of low in the west and high in the east, and was a set of marine carbonate formation. The Songpan-Ganzi area was developed with strong tectonic activities in the early-middle period of the Late Triassic, and deposited a large thickness of flysch formation, mainly in the passive continental margin deep-sea slope and shallow sea shelf environment. Until the late period of Late Triassic, the strong compression of the rift zone was developed in this area by the closure of the paleo-Tethys ocean. Under the regional dynamic metamorphism, the fold deformation was developed in the early strata. As a result, the Western Sichuan foreland basin was formed by compression and matching between the rift zone and Eastern Sichuan basin in Longmenshan area.

On the NW–SE seismic section of the core area of Luzhou paleo-uplift, the Middle Triassic was generally characterized by high in the middle part and low on both sides. It is close to the margin of the basin. Above the pre-existing Paleozoic strata with weak deformation, Early and Middle Triassic strata were deposited, especially Leikoupo Formation, which remained on both sides of the paleo-uplift with thin thickness. By the Late Triassic, compressive tectonic activities were developed in a large scale of the Upper Yangtze Region, especially the compressive stress from the Jiangnan-Xuefeng area in the southeast, which gradually lifted the southeast region to form a terrain low in the west and high in the east. In the Late Triassic, the thickness of the Xujiahe Formation gradually decreased from west to east, and the strata in Lower Cambrian composed of mudstone, shale and gypsum salt were folded and deformed under the influence of tectonic activities. Thrust faults occurred along the Cambrian detachment layers in some areas, cutting through the upper Cambrian strata and spreading upward. It can be seen that the dynamic origin of Luzhou paleo-uplift mainly comes from the Jiangnan-Xuefeng belt on the southeast margin. The front uplift belt on the west side of its piedmont depression was developed by the long-distance stress transmission effect resulted due to the Early Indosinian orogeny. At that time, the Western Sichuan was not developed as a foreland basin, while it was characterized by a depression basin.

During the Jurassic-Early Cretaceous sedimentary period, the basin was developed with weakened stress in the eastern part, entered the evolution stage of the inner craton depression basin, and deposited thicker Cenozoic strata. The eastward propagating faults along the Cambrian detachment layer were developed by the tectonic compression transmitted eastward from the western margin of the basin. In the Late Cretaceous, the tectonic compression activities were strengthened again, and the Jurassic and Late Cretaceous deposited in the early stage were uplifted and denuded

in large scale. The fault activities developed along the Cambrian detachment layer were strengthened. The faults cut through the Silurian mud and shale layers continued to spread upward, as a result, the fold shape in the early period was formed. After the Late Cretaceous, affected by the continuous action of tectonic compressive stress from the EW direction, the faults spread upward, and the folds continued to uplift and expand. This resulted, in the current tectonic pattern to be gradually formed under the long-term weathering and denudation.

4 Regional Paleogeographic Pattern

4.1 Sinian Lithofacies Paleogeography in Sichuan Basin and Around Areas

A large-scale transgression occurred in the deposition period of the Deng1 Member, and an epicontinental sea deposit was formed. In this period, with the gentle slope of the basin, there was little difference in the depth of the sedimentary water body. A set of argillaceous dolomite was deposited, and a small amount of algal sheet dolomites can be seen locally. Leshan, Mianzhu, Guangyuan and other areas in the west of the basin near the land margin were mainly deposited with mud-dolostone flat deposits, while the central and eastern parts of the basin were deposited with algal-dolostone flat and grain beach. The distribution range of grain beach was relatively limited. Gypsum salt flat was deposited in Changning area of the southern basin, and a large set of gypsum rocks were deposited in Well Ning 1, reflecting the relatively restricted environment of the Deng1 Member. The basin is close to Xiaoji of Yuqing, Guizhou to Nangao of Danzhai, and was deposited by muddy lime flat. It was mainly deposited by micrite limestones, dolomitic limestones and mudstones with obviously decreased thickness. During the deposition period of the Deng 2 Member, large-scale regression occurred, the water depth was shallow, and algal dolomites were developed in a large scale. Tidal flat sedimentary structures such as bird eye and pane can be seen on the field outcrops. The sediments were mainly composed of grape algal dolomites, laminated dolomites, granular dolomites and muddy to micritic dolomites. The basin was characterized by the large-scale distribution of algal mounds and grain beaches, among which the grain beach subfacies were mostly developed in the Weiyuan and Gaoshiti-Moxi areas. The Well Dingshan 1 and Well Lin 1 in the southeast of the basin revealed that the thickness of Dengying Formation was large, and the algal laminar dolomites and algal arenaceous dolomites were developed, and the strata were developed with grain beach facies, especially on the sections of Qingzhen, Jinsha Yankong and Songlin Zunyi. Gaomo area in Central Sichuan was mainly deposited as algal mound facies in platform marginal, and eastern Gaomo area was deposited by algal mound inner the platform.

During the deposition of the Deng 4 Member, the water depth was relatively shallow as a whole. Due to the influence of the Tongwan movement, the basin uplifted

in the west and subsided in the east, showing a regressive process. Mud-dolostone flat facies were deposited in the west of the basin, algal mound and grain beach facies were deposited in the middle part of the basin, and slope-basin facies were deposited in the east of the eastern margin of the basin. Gaomo area in Central Sichuan were mainly developed with algal mound facies of platform marginal, and eastern Gaomo area was developed with algal mound deposition of inner platform.

4.2 Lithofacies Paleogeography of the Cambrian Longwangmiao Formation in Sichuan Basin and Around Areas

Based on lithofacies paleogeographic pattern study, the grain beach produced in the Weiyuan-Gaoshiti-Moxi-Yilong area has a direct connection with the development of gypsum lagoon. The grain beach was located between the mixed tidal flat and gypsum lagoon, that is, the development area of grain beach was far away from the interference of terrigenous materials and lagoon. In addition, the sedimentary environment of grain beach was formed as a result of strong hydrodynamic force, it can be observed in the lithofacies paleogeographic map, in development location of grain beach between the mixed tidal flat and the gypsum Lake (Bao et al., 1998; Chen & Li 1994). In Gaomo area, the grain beach was distributed from NE to SW. Large-scale grain beaches were distributed in the Moxi area, and there were back beach lagoons between some grain beaches. The back beach lagoons were developed from reservoirs with relatively poor scale. For example, Well Moxi 205, Well Moxi 18 and Well Moxi 203 are located in the development area of the back beach lagoon. The development scale of grain beach in Gaoshiti area is slightly worse than that in the Moxi area, however, grain beach in the direction of Well Gaoshi 6-Well Gaoshi 10 is still relatively developed. Between the structures of Moxi and Gaoshiti, there is an intertidal sea developed with the direction of NE-SW, which is mainly developed with muddy argillaceous dolomite and poor reservoirs. For example, Well Moxi 21, Well Gaoshi 3 and Well Gaoshi 2 are located in intertidal subfacies, and reveal relatively poor reservoirs. Well Anping 1 and Well Moxi 20 are located at the intertidal sea margin and reveal the slightly poor reservoirs (Dai et al., 1999; Li ei al., 2012; Zhang et al., 2010). In general, the Longwangmiao Formation of Gaomo gas field in Central Sichuan is a large-scale continuous platform grain beach facies, with small distribution and thickness of grain beach in the east.