Superimposed pattern of the southern Sichuan Basin revealed by seismic reflection profiles across Lushan-Chishui，China*

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ABSTRACT：Sichuan Basin is a kind of typical intra-craton superimposed basin and rich in oil and gas resources in the different sets of sedimentary sequences. It had undergone multi-stage tectonic evolutions which resulted in different types of prototype basins. However, there are still many different opinions on the types and superimposed patterns of Sichuan Basin in different geological periods, which largely affect the understanding of the effective accumulation and preservation mechanism of oil and gas. This paper aims to re-recognize several prototype types of Sichuan Basin by discussing the prototype basin and their superimposed models, so as to further deepen the significance of basin superimposed evolution to hydrocarbon accumulation. By using the regional geological data and drilling data , seismic reflection profiles arcoss Lushan-Chishui are interpreted in detail, and then five regional unconformities are identified with an equilibrium profiles technique which is used to flatten the formation interface in different geological periods. According to the unconformities，the southern Sichuan basin is divided into six tectonic layers. Each tectonic layer is considered as a prototype basin, respectively, they are Pre-Sinian Crystal basement (AnZ), marine rift cratonic basin (Z-S), marine intracratonic sag basin (P_2l-T_2l), marine-continental downfaulted basin (T_3x^1-T_3x^3), continental depression basin (T_3x^4-J) and foreland basin (K-Q). The different prototype basins are vertically superimposed to form "layered block" geological structure of the multi-cycle basins. Affected by the late tectonic transformation, the geological structure of vertical stratification underwent a strong transformation, which had a profound impact on oil and gas accumulation with a characteristics of early accumulation and late adjustment.

Keywords: Southern Sichuan basin; Seismic reflection profiles; Prototype basin; Superimposed pattern

Introduction

As a negative tectonic units, basin records the process of basin subsiding as well as orogenic belt evolution at the same sedimentary period. While the appearance, morphology and their spatial configuration relationship of prototype basin reflected the direction and nature of regional dynamic action.

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The multi-stage prototypes are vertically superimposed in orderly to form a superimposed basin with various structures (Zhao Wenzhi et a., 2002; Wang Zecheng et al., 2002; Han Baoqing et al., 2007; He Dengfa et al., 2004-2010; Li Zhongquan et al., 2011). The superimposed relationship of different-period prototype basin also indicate regional tectonic evolution (Liu Shaofeng et al., 2005; Song Lijun et al., 2009). Sichuan Basin, a multi-cycle superimposed basin with rich oil and gas resources, is founded on the Upper Yangtze craton and composed of marine basin and terrestrial basin (Korsch et al., 1991; He Dengfa et al., 2011; Liu Shugen et al., 2011). However, the craton block was a long-term transition zone between the Gondwana land and Laurasia land (Ren Jishun, 1994). With the margin of craton being involved in deformation and thus undergone intense transformation in the later period (Ren Jishun et al., 1994&1999), its interior must exhibit different tectonic activities. Meanwhile, the Sichuan Basin , one of the earliest basins to find oil and gas resources in the world (Wei Guoqi et al.,2008; Liu Shugen et al.,2011) and the largest typical petroliferous superposed basin in southern China, has a long history of oil and gas exploration. After more than 60 years of exploration and development, 28 gas-bearing strata, 189 gas fields and 19 oil fields have been discovered from the Sinian system to the Jurassic system. Among them, there are 9 gas fields with proven geological reserves of over 100 billion cubic meters (Zheng Zhihong et al., 2017), showing that Sichuan Basin has a good prospects for oil and gas exploration in different strata. According to statistics, the conventional natural gas geological resources in Sichuan Basin were $20.69\times10^{12}m^3$ by 2017. From the perspective of regional distribution of the resources, the central Sichuan Basin had the most abundant resources, followed by the southern Sichuan Basin. In addition to the Weiyuan gas field in southern Sichuan Basin, there are more than 40 gas fields in Chongqing-Luzhou-Yibin areas. In fact, the study found that huge ancient oil fields and ancient gas fields were also formed in the geological history of these areas, but they were modified and destroyed by later differential structural uplift, as to some of the ancient gas reservoirs survived to form today's residual gas reservoirs (Sun Wei et al., 2007), while the preservation conditions of the ancient oil reservoirs were completely destroyed, leading gas accumulation rate to zero, only bitumen remained in the storage layer(Liu Shugen et al. , 2010). Thus, it can be seen that oil and gas accumulation had occurred in a large area of Sichuan Basin in the geological history, but the spatial distribution characteristics of the present (residual) oil and gas fields were formed due to the effect of multi-stage basin superimposition and late structural transformation(Liu Shugen et al., 2012). Such a long-term tectonic transformation has a profound impact on the mechanism of natural gas accumulation and preservation in Sichuan Basin. Therefore, it is particularly important to deepen the understanding of the formation and evolution process and the characteristics of each prototype basin in different stages of Sichuan Basin, which is located on Upper Yangtze craton block (Fig. 1a).

Although the prototypes of Marine basin have obtained a unified understanding, there are still many disputes on the prototypes of terrestrial basin since the late Triassic. First of all, one view holds that the southern Sichuan basin was an alternate marine and terrestrial basin in the sedimentary period of Xujiahe

FM Ⅰ of Upper Triassic, subsequently entering the stage of the development of foreland basin (Luo Qihou et al., 1983&2011; Hou Fanghao et al., 2005; Shi Zhensheng et al., 2008&2010&2012; Zhao Xiafei et al., 2008&2011). Furthermore, the second view holds that the Sichuan basin was an intra-cratonic depression basin in the sedimentary period of member1-3 of the Upper Triassic Xujiahe Formation, a foreland basin in the sedimentary period of member4-6 of the Upper Triassic Xujiahe Formation, and a continental depression basin in the Early- Middle Jurassic, since then entering the stage of the development of foreland basin once again (He Dengfa et al., 2011). Besides, another view is that the foreland basin began to develop in the Late Triassic continuing until the Cenozoic, then the basin tended to disappear, thus forming the current tectonic pattern (Xu Hanlin et al., 2001; Zhu Rukai et al., 2009; Chen Hongde, 2011; Zhu Min et al,2017).

Therefore, making clear the internal structure of Sichuan Basin, the prototype types of basins in different periods and their vertical superimposed relationship will not only lay a theoretical foundation for exploring the genetic mechanism of cratonic basins, but also provide an important clue for exploring the effective accumulation of oil and gas in strong tectonic environment. Combined with the regional geological data and based on the uncomformity, both the detailed analysis of the prototype type of basins in different stages and superimposed pattern of the prototype basins are re-recognized by analyzing the seismic reflection profiles corss Lushan to Chishui(Fig. 1b).

Geological setting

Sichuan basin is surrounded by Qinling orogenic belt, Jiangnan-Xuefeng orogenic belt, Sanjiang orogenic belt and Songpan-Ganzi orogenic belt, facing Micangshan-Dabashan tectonic belt in the north, Qiyueshan fault belt in the East and Daloushan and Daliangshan in the southwest, which has an obvious rhombic boundary (Fig. 1a), reflecting that the formation of Sichuan basin and its internal structure development are controlled by the evolution process of the deep-large faults which extended in a rhombic style (Luo Zhili, 1998). The research area lies in the south of Sichuan basin with the Yunnan-Guizhou Plateau on its south. Its western region is bordered by the southern section of Longmen Mountain, straddling Longmen mountain fault zone and facing Songpan-Ganzi folded belt. (Fig.1b).

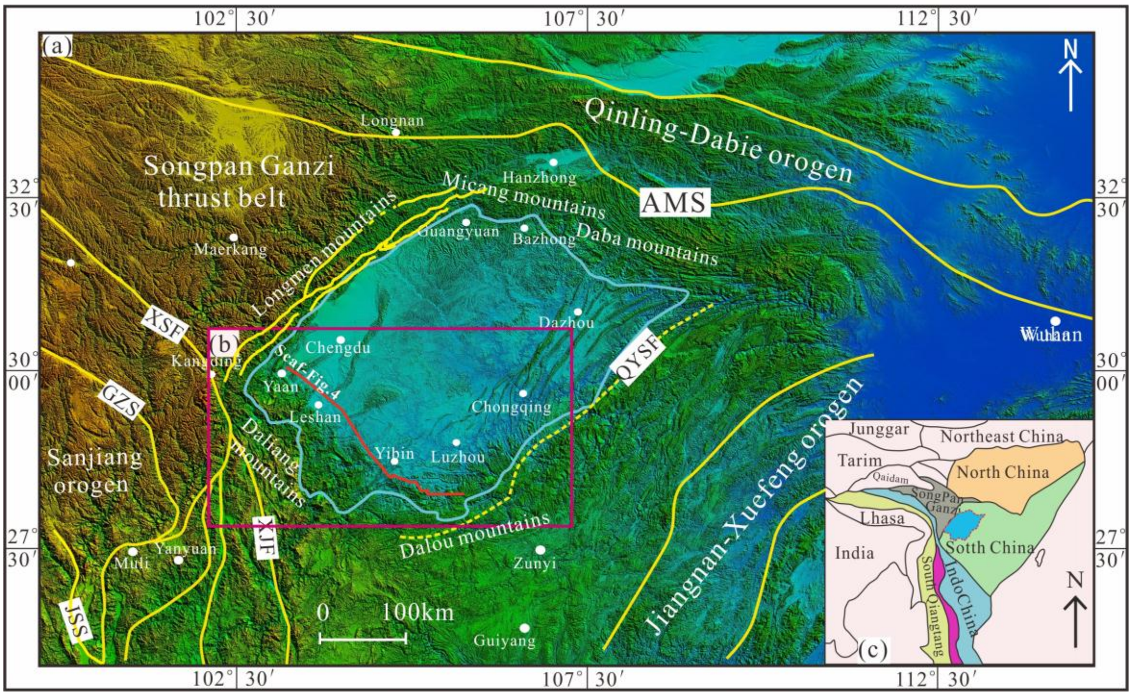

Fig.1. Tectonic outline of Upper Yangtze area(a) and (c)simplified geological map of the East Asia modified from Metcalfe(2013), location of study area(b);XJF=Xiaojiang fault； XSF=Xianshuihe fault； AMS=Animaqin-mianlue suture；GZS=Ganzi litang suture；JSS=Jinshajiang suture；QYSF=Qiyueshan fault

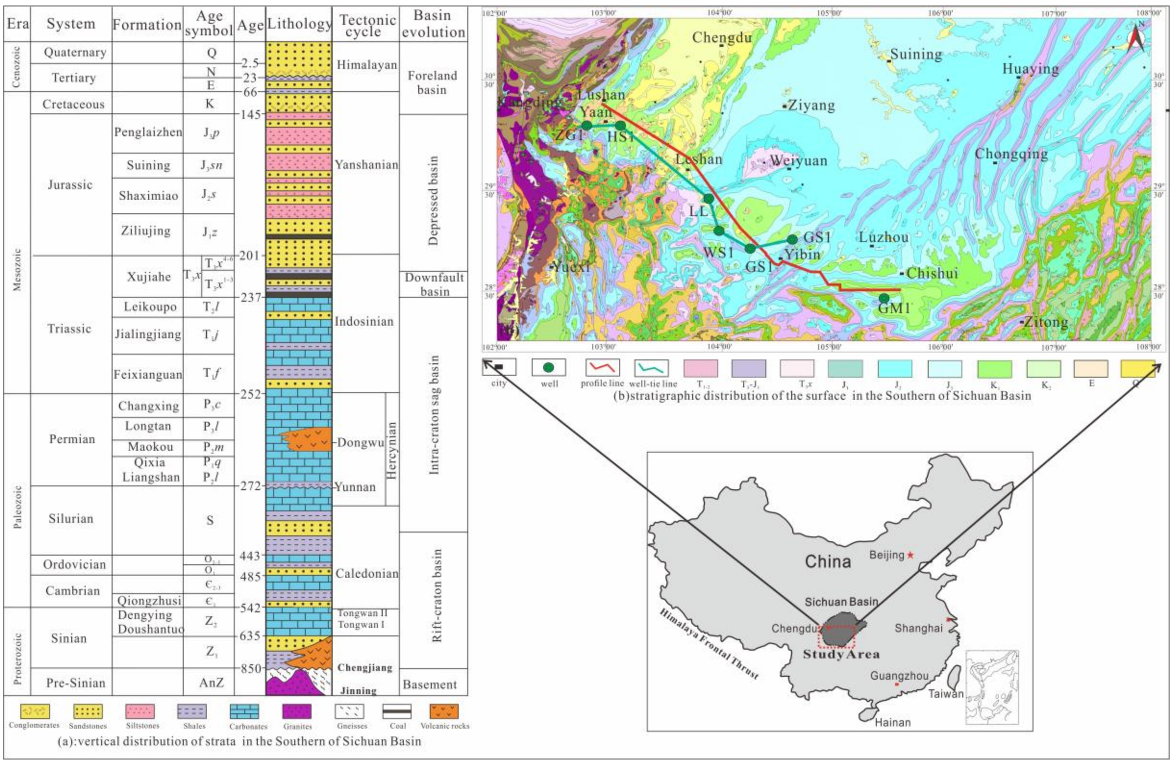

Fig.2 Stratigraphic column and tectonic sketch (a) , stratigraphic outcrop map(b) of the southern Sichuan basin

Basin texture revealed by the seismic reflection profiles

Basic geological characteristics of the seismic reflection profiles

The northwest end of the profiles in the southern Sichuan basin originates in Lushan Town and the southeast end terminates in Chishui City with a total length of 340km, successively passing through several structural units of Hanwangchang anticline, Xiongpo anticline, Longquanshan anticline, Weiyuan Dome, Datachang, Shuanghechang anticline, Laowangchang anticline and Wutongchang anticline and so on (Fig.4b).

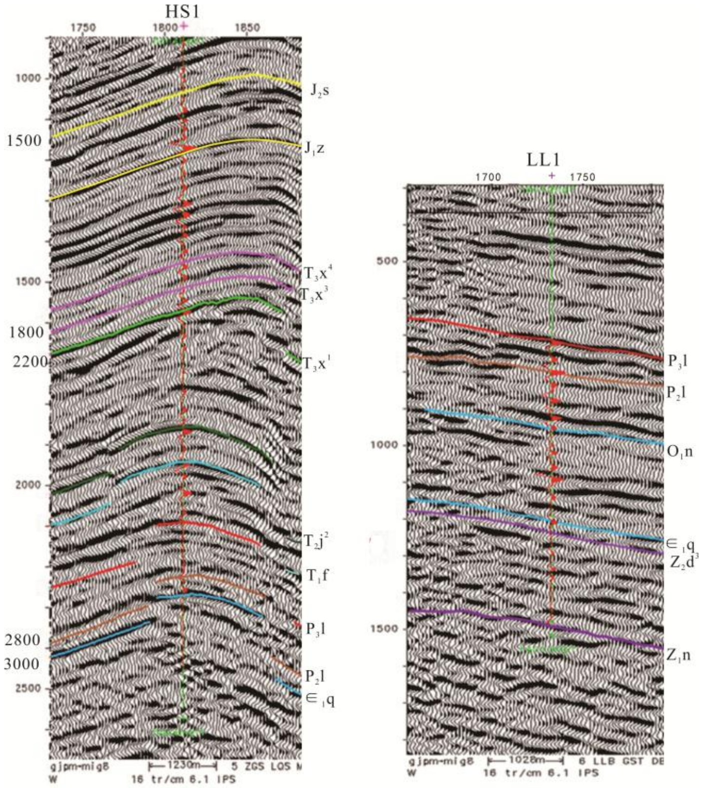

Fig.3 Synthetic records of HS1 well and LL1 well

With a comparison of regional stratum and by using the synthetic seismograms from HS1 well and LL1well (Fig.3) which is used to determine the major marker layers, the stratum interpretation of the profiles is eventually interpreted. According to the interpretation, the bottom boundary of eleven layers have been traced, and they are the Sinian System(Z), the third member of Sinian Dengying Formation(Z_2dn^3), the Qiongzhusi Formation of Cambrian System($Є_1q$), the Longwang miao of Cambrian System ($Є_1l$), the Nanjingguan Formation of Ordovician System (O_1n), the Siluric System(S), the Middle Permian Liangshan Formation (P_2l), the Upper Triassic Xujiahe Formation (T_3x^1), the fourth member of the Xujiahe Formation(T_3x^4), the Ziliujing Formation of Jurassic System (J_1z), and the Cretaceous System(K) ,respectively (Fig. 4b).

Combined with the interpretation（Fig.4b）, it can be seen that the basin is characterized by angular and parallel unconformities, strong fold deformation and fault displacement and most of the faults taper off the Cambrian and Silurian system. The most prominent features are the large anticline called Weiyuan Uplift in central Sichuan and the Jurassic fold and complex fault system in the east of Huaying Shan, where the strongest tectonic deformation occurred. From the standpoint of sedimentation, the thickness is thick on both sides of the basin and thin in the middle. Some stratum were eroded and flattened, for instance, the Cambrian, Ordovician and Silurian System were eroded and flattened in the western Sichuan depression, besides, the Devonian-Carboniferous System were largely absent, while the Permian-Middle Triassic System thickness is relatively stable. The member 1-3 of Xujiahe Formation is relatively thicker in the western than the eastern in which the thickness is only a few tens of meters. The thickness of member 4-6 of Xujiahe Formation-Jurassic system vary slightly in the regional basin, and the Cretaceous-Quaternary system forms a dustpan shape in front of Longmen Mountain near basin margin.

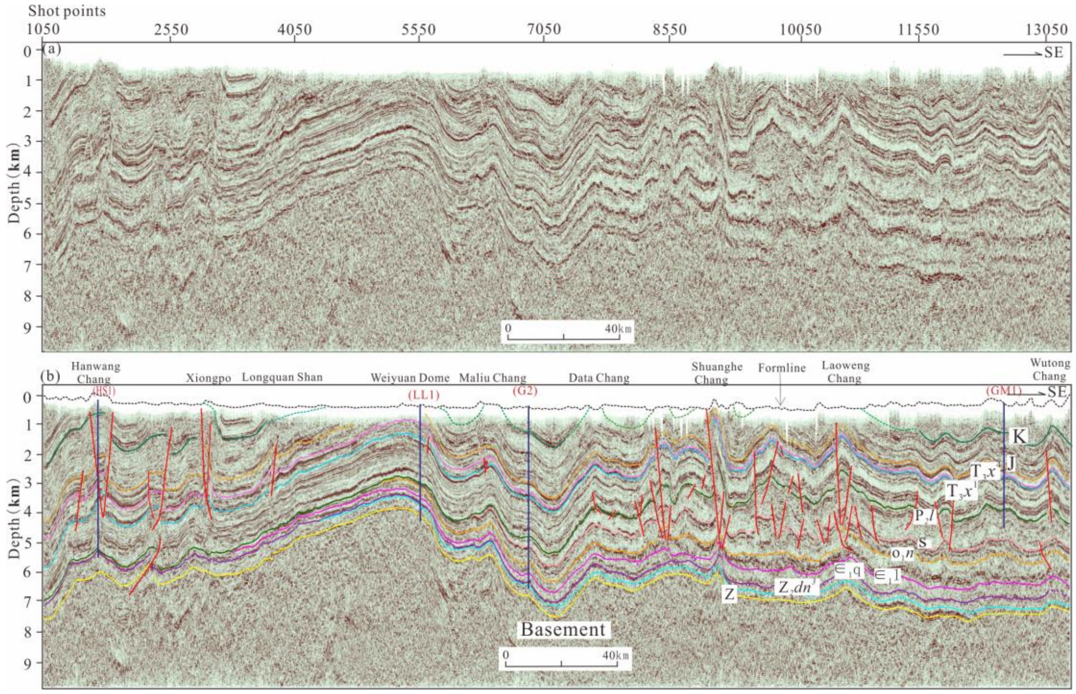

Fig.4 Geological interpretation of seismic reflection profiles in the southern Sichuan basin

Classification of unconformations and tectonic layers

Unconformity is the mark which is usually used to divide structural layers. According to the interpretation of the seismic profiles, five regional tectonic unconformities were identified with typical structures(Fig.5).

(1)Z/AnZ：The unconformity between the Sinian and the Pre-Sinian system. It is a basement unconformity formed between basement of archaean greenstone belt and gray gneiss and the Sinian system which overlay on the basement (Li Qigui et al, 2010). The drilling data of LL1 well also reveal this feature that the Sinian system directly covers on the epimetamorphic rocks of Pre-Sinian system.

（2）P/AnP：The angular unconformity between the Permian and Pre-Permian system. In the seismic profiles, it shows that the Cambrian, Ordovician and Silurian system are truncated by the Permian system (Fig.6). Even in the west of the Weiyuan dome, the middle Permian Liangshan Formation directly overlay on the weakly deformed Silurian, Ordovician or Cambrian system. For example, the LL1 well shows that the underlying stratum of the Liangshan Formation (P_2l) is the Middle Ordovician Nanjinguan Formation (O1*n*) (Fig. 3).

(3)T_3x^1/T_2l：The parallel uncomformity between the Upper Triassic Xujiahe Formation and the Middle Triassic Leikoupo Formaiton. It shows that the unconformity is parallel to the underlying Leikoupo Formation, Jialingjiang Formation or Feixianguan Formation in the seismic profiles, and micro-angle cut can be observed under the unconformity in southeastern Sichuan. (Fig. 8).

(4)T_3x^4/T_3x^3：The onlap sedimentary unconformity between the third and fourth members of the Xujiahe Formation is distributed only in western Sichuan. In the seismic profiles, it can be seen that some micro-angle cut are found at the top of the third member of Xujiahe Formation in the west of Weiyuan Uplift (Fig.10). and member1-3 of Xujiahe Formation are thick in the west and thin in the east like a wedge-shaped. Eastward, the thickness of the sediments is rapidly thinning, only tens of meters.

(5)K/J：The parallel unconformity between the Cretaceous and Jurassic. Although The Cretaceous appears less in the seismic profiles and the shallow seismic reflection characteristics is not ideal, the field geological survey in Longmen Mountain and drilling data of Gaomu 1 well reveal that the top of the Jurassic is a shallow sandy mudstone with argillaceous siltstone, otherwise the lower Cretaceous has a thick molasse formation. Great difference between these two sedimentary facies reflect a contact of parallel unconformity.

According to regional geological setting and these five unconformities stages, the southern Sichuan basin is divided into six tectonic layers in vertically(Fig.5): the pre-Sinian crystal-fold basement tectonic layer (AnZ), the Sinian-Silurian tectonic layer (Z-S), the Middle Permian-Middle Triassic tectonic layer (P_2l-T_2l), members 1-3 of the upper Triassic Xujiahe Formation tectonic layer（T_3x^1-T_3x^3）, the fourth member of the Upper Triassic Xujiahe Formation-Jurassic tectonic layer (T_3x^4-J) ,and the Cretaceous-Quaternary tectonic layer (K-Q). The order of the superimposed tectonic layers constitutes the texture of the Southern Sichuan Basin and reveals the superimposed evolution pattern of the prototype basins.

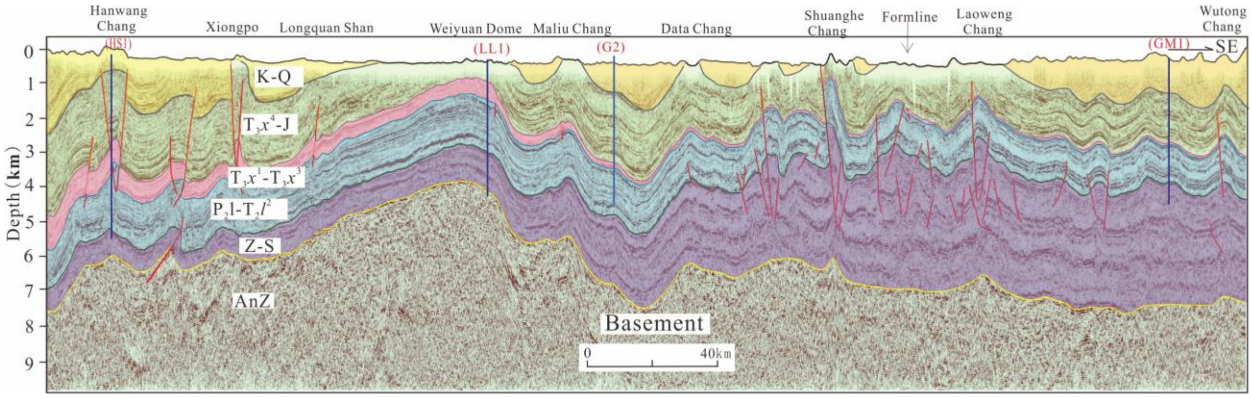

Fig.5 Classification of tectonic layers in the southern Sichuan basin

Characteristics of prototype basins in different geological periods

From the discussion of the above-mentioned classification of tectonic layers, it is believed that the southern Sichuan basin has undergone five stages of tectonic evolution since Sinian. Because of different tectonic dynamics, prototype basins formed in each evolution stage and then superimposed orderly in longitudinally influenced by the post-tectonic reconstruction. The characteristics of prototype basins in different geological periods are discussed in specifically.

Basin prototype in the Sinian-Silurian (Z-S)

After forming the Pre-Sinian Basement, the tectonic dynamic background changed from a compressive orogeny period to extensional basin-forming period. During the Sinian to Silurian, the entire Sichuan basin gradually exhibited a process of expanding and deepening (Wang Zecheng et al., 2002; Li Zhongquan et al., 2011&2014; He Dengfa, et al. 2011). Influenced by Caledonian movement at the end of the Silurian, the structural framework of Sichuan Basin had undergone significant changes. The differential uplift activities of large-scale Uplift, depression and fault block are particularly prominent (Li et al.,2004； Wu Saijun et al., 2015). Especially, the strong uplift of the Leshan-longnvsi paleo-uplift made the Lower Paleozoic stratum were exposed to denuded for a long time, and the Devonian-Carboniferous system were largely absent, forming an angular unconformity between the Permian and Pre-Permian system（Fig.7）. Based on this geological understanding, we flatten the bottom of the Permian stratum by using Landmark software. The results show that the southern Sichuan basin is characterized by high in the central and western while low in the eastern (Fig. 6a) . The bottom boundary of the Ordovician and Silurian stratum is truncated with high angle by the Permian System(Fig. 6b). On the southeastern slope of the Leshan-longnvsi paleo-uplift, not only the Ordovician system is superior to the Cambrian system but also the Silurian system overlap onto the Ordovician system (Fig.6c). These geological characteristics indicate that the Leshan-longnvsi paleo-uplift is a syn-sedimentary anticline during the Caledonian, and its wide and gentle structural form is the result of vertical uplift of the crust (Li Zhongquan et al., 2011), which is also supported by the normal faults developed in the Sinian and Cambrian (Fig.6cde). These characteristics of the seismic profiles reveal that the southern Sichuan basin represented a extensional environment in the Sinian-Silurian in a whole, and the uplift pattern in the basin should be a tectonic reflection for this environment.

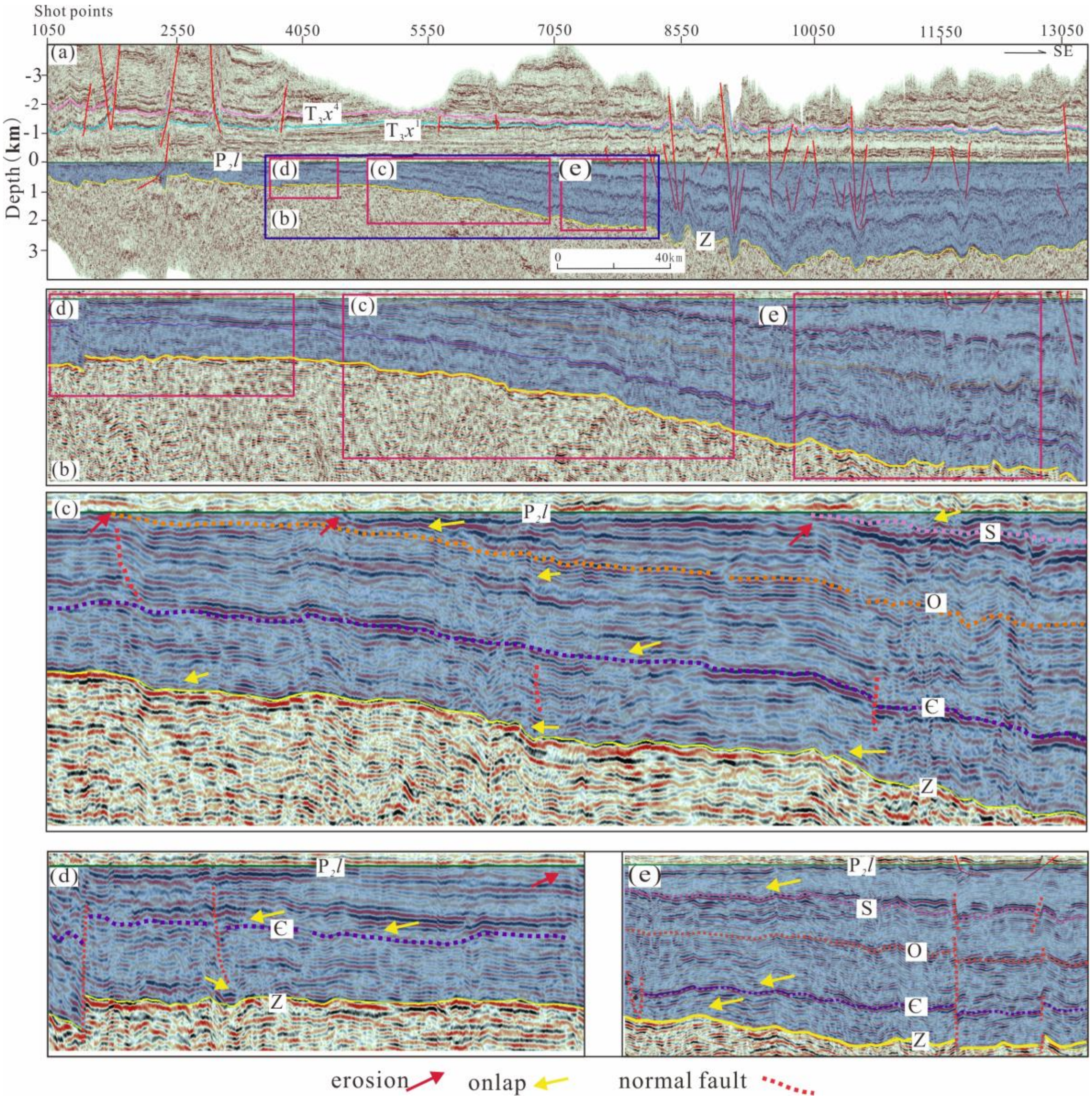

Fig.6 Prototype basin and key geological phenomena of the southern Sichuan basin in the Sinian-Silurian

In terms of sedimentary formation, the basement is composed of a set of granite in southern Sichuan basin. The first sedimentary Doushantuo Formation of the Sinian system（Ediacaran） deposited with a rhythmic neritic-lagoon carbonate, which resulted from the melting glacier of the Nantuo Ice Age in the Nanhua system and widely distributed in Yangtze Craton. From drilling data, the data of LL1 well show the subsequent sediments ,respectively, they were light gray limestone and dolomite of the Sinian Dengying Formation, a set of dark gray dolomite and argillaceous dolomite in the Cambrian system, an inter-bedded set of fine sandstone and siltstone shale, limestone and shale of the Ordovician stratum. These sediments record how the Sichuan basin gradually transformed from continent to marine sedimentation at an early stage. Since then, the Cambrian-Silurian showed that a process of sea basin gradually expand and deepen. Based on the characteristics of seismic profiles and regional sedimentary records, it is believed that the prototype basin in the Sinian-Silurian were in an extensional environment, belonging to a cratonic rift basins.

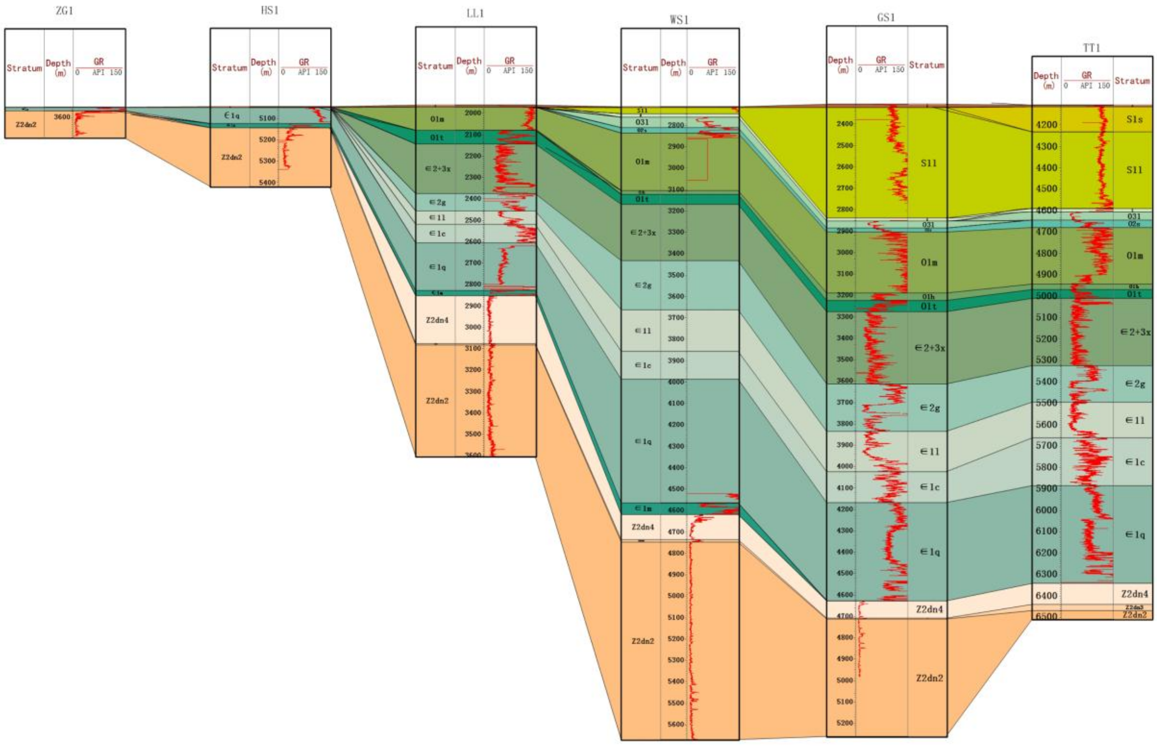

Fig.7 Sedimentary stratigraphic correlation before Permian in southern Sichuan Basin
(well-tie line shown in fig.2)

Basin Prototype in the Middle Permian-Middle Triassic (P_2l-T_2l)

The Middle Triassic is an important period of the evolution from marine to continental deposits in Sichuan Basin, especially at the end of the Middle Triassic(the early stage of the Indosinian movement). During the period, the basin was successively uplifted as a whole, experiencing the first large-scale regression since the Indosinian movement, and happening the eastern-westward "seesaw" transition (Li Ling et al., 2012), which caused the Luzhou-Kaijiang uplift to resulte in the denudation of Leikoupo Formation in Luzhou area, forming a regional unconformity denudation surface (T_3x^1/T_2^l) (Li Zhongquanet al., 2014; Wang Xuejun et al., 2015). The bottom boundary of the Upper Triassic Xujiahe Formation (T_3x^1) is flattened（Fig.8 and Fig.9）, showing that the stratum represent a Planar sediments during the Middle Permian-Middle Triassic System in the basin (Fig. 8a and Fig.9). There is almost no folds or thrust faults formed by large-scale horizontal compression, whereas the small-normal faults are relatively growing (Fig. 8b). The onlap phenomenon at the bottom of Leikoupo Formation (Fig.8c) indicates that the Luzhou Uplift had an embryonic form during the Jialingjiang sedimentary period in the southeastern of the basin. Meanwhile, the thinning and pinching of leikoupo formation towards the core of luzhou paleo-uplift and the truncation of the top of leikoupo formation indicate that luzhou paleo-uplift was a process of continuous development and broadening, existing with a form of underwater in that stage.

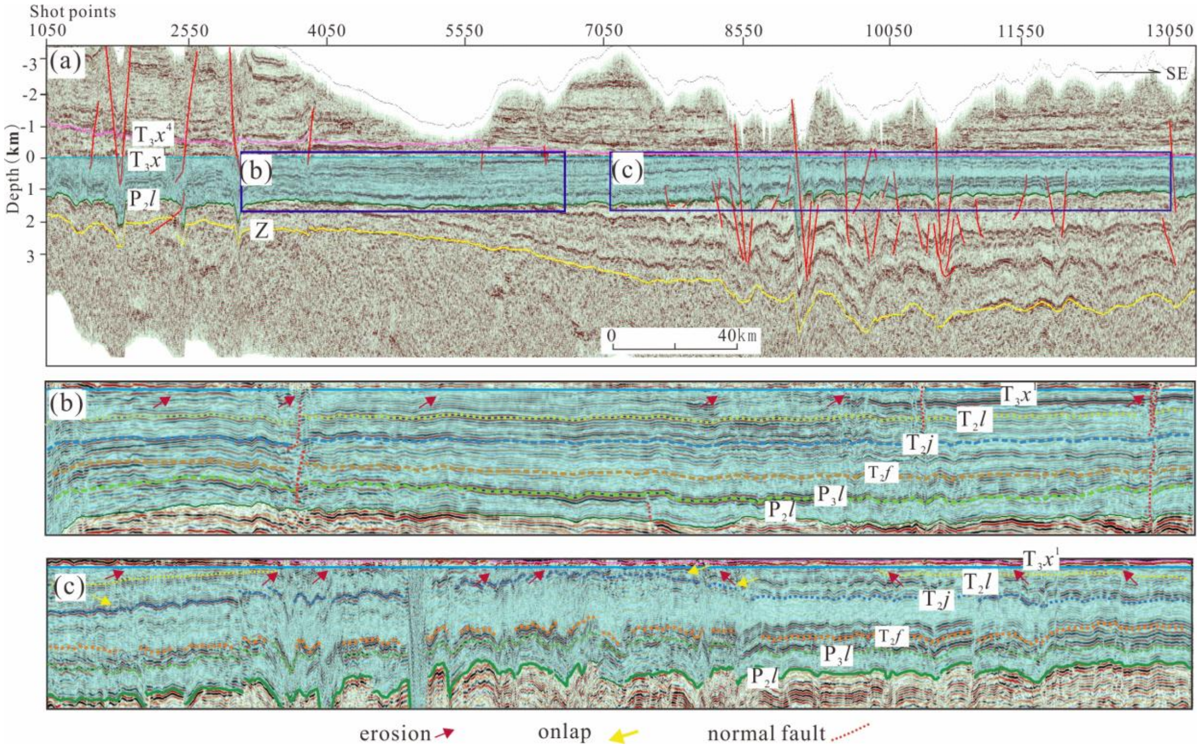

Fig.8 Prototype basin and key geological phenomena of the southern Sichuan basin

in the Middle Permian-Middle Triassic

From a standpoint of deposition, the basin began to subside and then experienced transgression in the early of Middle Permian, making the Liangshan Formation which were composed of a set of shallow gray mudstone and carbonaceous shale with coal line directly overlay on the Lower Paleozoic stratum (He Dengfa et al,2010；Huang Hanyu et al.,2017). Subsequently, the extensive transgression made the Yangtze area became a normal shallow-sea carbonate platform facies. In the longitudinally, the basin deposited the Qixia Formation and the Maokou Formation with platform facies and gentle slope facies. In the Late Permian, affected by the Emei taphrogenesis of the Dongwu movement, the basin uplifted again, accompanied by the eruption of a large area of basalt, making the formation of Emei basalt. Since then, the basin had been subsided as a whole, depositing the Upper Permian Changxing Formation composed of limestone, the Lower Triassic Feixianguan composed of off-white limestone and sand mudstone interbeds, the Jialingjiang Formation composed of dolomite sandwiched-cream salt rock, and the Middle Triassic Leikoupo Formation composed of dolomite. In the late Middle Triassic, the basin experienced the first large-scale regression，gradually ending the sedimentary facies from the sea to the land. Influenced by the Indosinian movement, the Sichuan basin was relative to the Longmen Mountain and Songpan-Ganzi region overall uplift, causing the eastern Sichuan basin were exposed to erosion successively and resulting in a parallel unconformity contact between Leikoupo and Xujiahe Formation (Huang Dong et al.,2011).

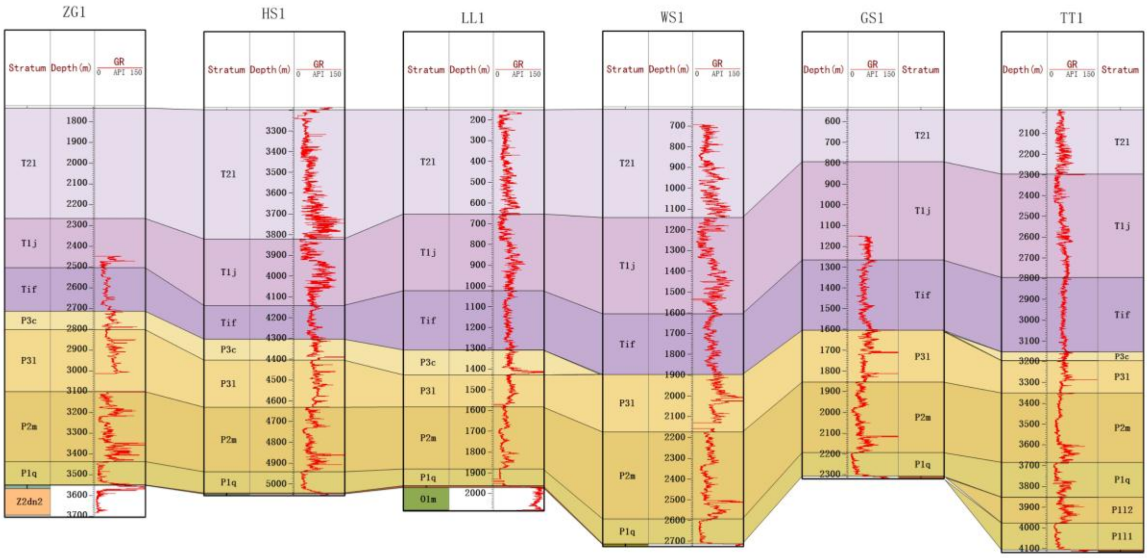

Fig.9 Sedimentary stratigraphic correlation before the late Triassic in southern Sichuan Basin (well-tie line shown in fig.2)

Both of the sequences of sedimentary-tectonic evolution and features of the seismic profiles record the transgression and regression which the Southern Sichuan basin had experienced, and further reveal that the basin was in the extensional tectonic dynamic environment. According to these characteristics, it is suggested that regional basin was an intra-craton sag basin under an environment of crustal oscillation during the Middle Permian to the Middle Triassic.

Basin Prototype in the Early Period of the Late Triassic (T_3x^1-T_3x^3)

The tectonic movement in the late Middle Triassic ended off the large area of marine sediments mainly composed by carbonate rocks over the Yangtze Plate. In the early period of the Late Triassic, due to the differential uplift rates between the blocks, Sichuan basin uplifted slowly relative to the Longmen Mountains , developing a large-scale normal fault inclined to the southeast side in the transitional zone between the two blocks (Li Zhongquan et al., 2014), which controlled the development of residual sea in the small area on the west side of southern Sichuan basin. By flattening the bottom boundary of the fourth member of the Upper Triassic Xujiahe Formation, it can be observed that the morphology of the western basin was asymmetrically wedge-shaped in transverse cross-section (Fig. 10a). On the other hand, the members 1-3 of the Xujiahe Formation onlapped onto the Leikoupo Formation, which was cut at a low angle by the bottom of Xujiahe Formation. Furthermore， small normal faults can be found in the residual sea of southern Sichuan basin (Fig. 10b、10c). These seismic profiles suggest that the basin was still in an extensional tectonic dynamic setting.

From the point of sedimentary, coastal-shallow marine sediments deposited in the western side of southern Sichuan basin during the Carnian-Norian age of the Late Triassic(T_3x^1-T_3x^3). Such as, the lower part of member 1of Xujiahe Formation is a platform facies（Zhu Ming et al.,2017）, the upper part is a bay facies, and member 2-3 of Xujaihe Formation are continental delta facies with a set of sandstone, mudstone interbedded siltstone and coal measure interbeds(Cui Bingquan et al., 1991; Zheng Rongcai et al., 2011). Due to the high topography of the Luzhou palaeo-uplift, the sedimentary succession is only 50~100m thick on the east side of the basin. According to the characteristics of seismic profiles and the sedimentary succession records，it is illustrated that the southern Sichuan basin should be a down faulted basin in the transitional environment between sea and land in the Carnian-Norian Period

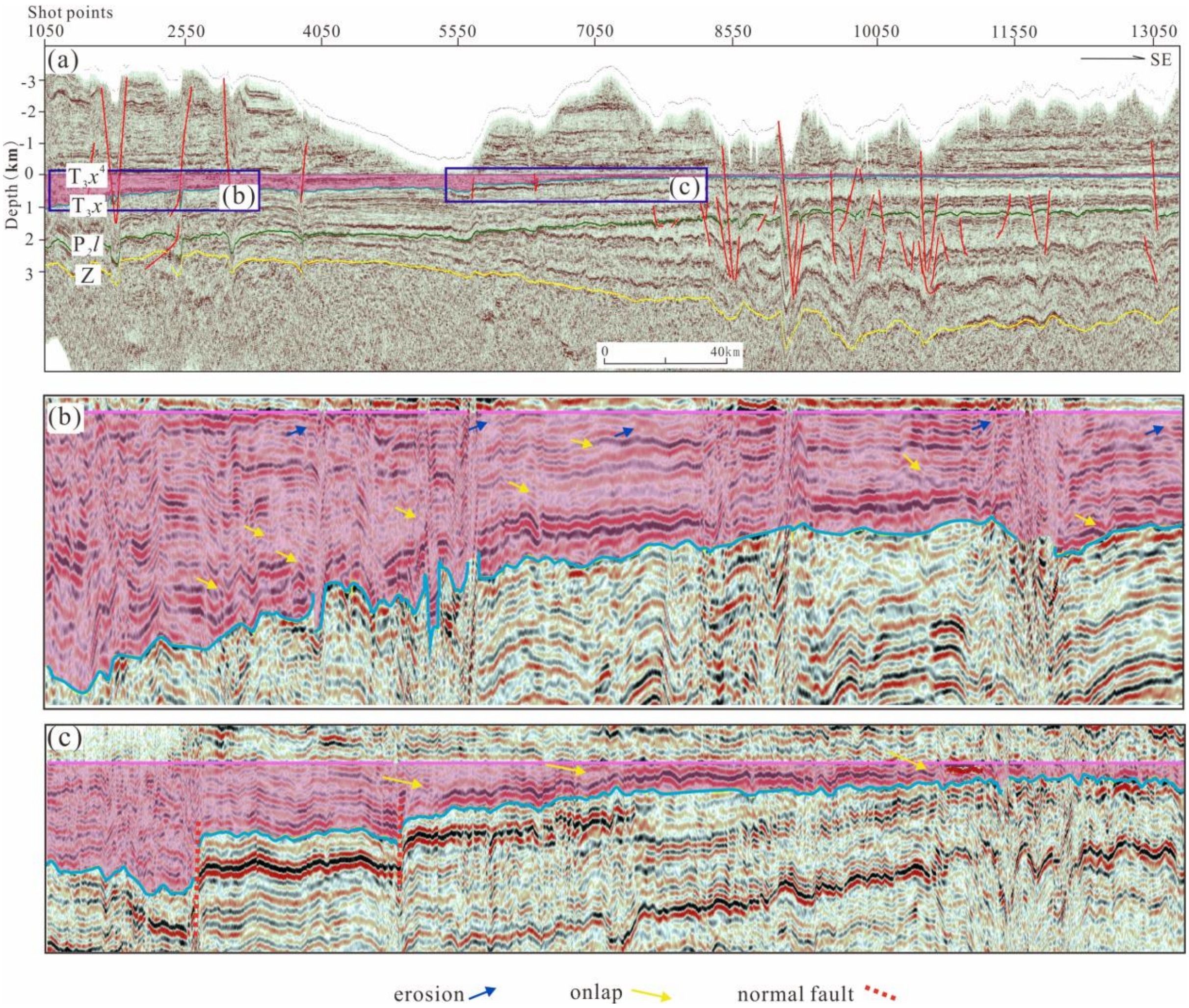

Fig.10 Prototype basin and key geological phenomena of the southern Sichuan basin in the Early Period of the Late Triassic (T_3x^1-T_3x^3)

Basin prototype in the late period of the Late Triassic-Jurassic (T_3x^4-J)

In the late of Late Triassic(the Rhaetian age of Late Triassic), the interior lake basin gradually formed with the recession of sea water on the west side of Longmen Mountain，making the main sedimentary areas in the Upper Yangtze area were confined to the interior of the craton. The sediments mainly consisted of continental fluvial and lake deposits(Fig. 11). In the late of Middle Jurassic , subsequently, the tectonic dynamic environment of the basin experienced alternating changes of strong and weak extensions, which made the basin undergone from rapid to slow to stable subsidence changes in Jurassic. Thus the basin gradually enlarged the sedimentary range，even deposited to Yichang-Guiyang area in the eastern of Qiyao Mountains (Li Zhongquanet al., 2011). The subsidence rate of Sichuan basin is much higher than the sedimentation rate of terrigenous clastic rocks, forming the largest lake basin in Sichuan Basin in the Jurassic with Coal-bearing clastic rock of Lacustrine marsh facies（Meng Qingren et al.,2005）. Fig. 8a and Fig.12 show that the whole basin deposited member 4 of the Xujiahe Formation-Jurassic system with equal longitudinal thickness and horizontal extension, showing a wide system of plate-like deposit. Combined with the seismic characteristics and sedimentary responses, consequently, it is indicated that the basin should have undergone an overall subsidence and still be in a relatively quiet extensional dynamic background during the late of Late Triassic to Jurassic period, thus ,the southern Sichuan basin at that time was a depression lake facies basin.

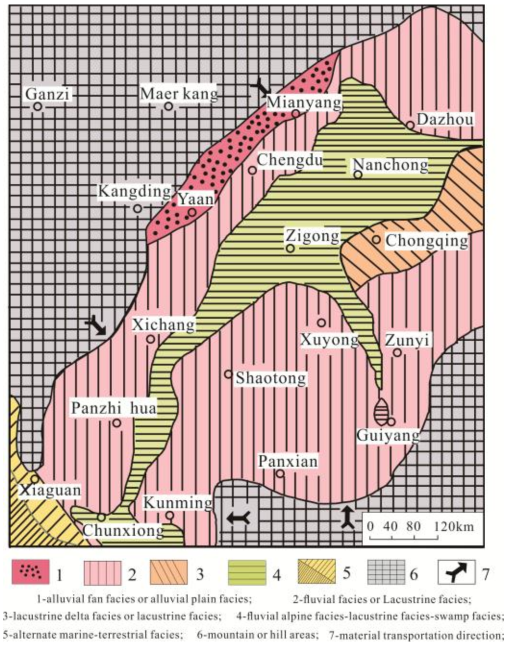

Fig.11 Paleogeographic map of the Jurassic sedimentary facies in southwest China, modified from Li et al. (2011)

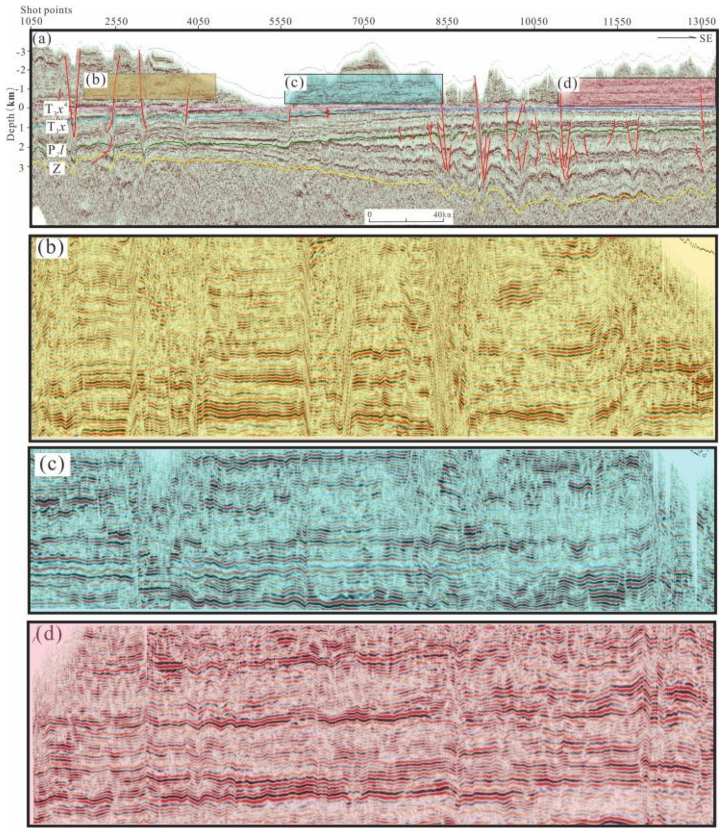

Fig.12 Prototype basin and key geological phenomena of the southern Sichuan basin in the late period of the Late Triassic-Jurassic (T_3x^4-J)

Basin prototype in the Cretaceous-Quaternary (K-Q)

According to the geological survey, there is a parallel unconformity between the Jurassic and Cretaceous system in western Sichuan basin (Wang Yongbiao et al.,2001；Long Ke et al.,2011；Li Yingqiang et al.,2016). Because of the clutter of shallow seismic in-phase axes and only small amount of Cretaceous stratum shown on the seismic profiles, it is difficult to flatten the bottom of the Cretaceous stratum to identify the internal characteristics of the stratum. The data of HS1 well shows that the lower cretaceous was eroded. On the one hand, it is shown that the Cretaceous Formation deposited with a shape like a wedge, thick in the west and thin in the middle, and obviously thicker on the side of the Longmen Mountanin on the seismic profiles(Fig.5).

In terms of sedimentary formation, the Early Cretaceous developed many alluvial fans in front of Longmen Mountain with quartz and limestone as the main gravel components, and fluvial sand and mudstone as the main ones in other areas of the basin. Additionally, the Cretaceous system which displayed a characteristic of thick at the bottom and thin at the top, indicate that the Longmen Mountains were greatly uplifted to the land being a source area, and the tectonic dynamic background of the basin was converted from stretching to extrusion in the Early Cretaceous. As a result, the Sichuan basin was gradually reversed from the depression basin to a foreland basin. The evolution of this basin continued until the Cenozoic. Compressed by the plates around Yangtze Plate, the basin was gradually shrinking so that the Paleogene-Quaternary stratum were distributed only in the southwest of the basin（Chen, Z,X et al.,2008；Chen Hongde et al., 2011; Zhu Rukai) (Fig. 2b). The thickness was only 100-500m^2,then the basin tended to disappear, forming the current tectonic pattern.

Discussion

evolution characteristics of prototype basins

Based on the characteristics of sedimentary filling and structural deformation, the types of prototype basin and its evolution in different stages are discussed by using equilibrium profiles technique.

（1）Z-S geological periods

Before deposition of Z_1dn^3（Fig.13a）. During the Sinian to Silurian, the entire Sichuan basin gradually exhibited a process of expanding and deepening (Wang Zecheng et al., 2002; Li Zhongquan et al., 2011&2014; He Dengfa, et al. 2011). The member 1-2 of the Dengying Formation were widely deposited in the basin, with the thickness decreasing slightly from the northwest side to the southeast side.

Before deposition of $Є_1q$（Fig.13 b-c-d）). Owing to the Tongwan I Movement , Sichuan basin was uplifted , making the second member of Dengying Formation subjected denudation at a large scale. Subsequently, member 3-4 of the Dengying Formation directly covered on the residual stratum of the member 1-2 of Dengying Formation, with the thickness thickening slightly from the northwest side to the southeast side (Fig. 13b). Affected by the Tongwang II Movement, Sichuan basin is mainly given with differential uplifting after the sedimention of Dengying Formation(Fig. 13c), having the stratum of the 3rd and 4th member of Dengying Formation denuded and flattened in the west of Longquan mountain, only remaining a thin unit in the east.

Before deposition of $\in_1 l$（Fig. 13e）. After the Tongwang II Movement, Sichuan Basin overall subsided and accepted deposits, making a unconformity between the Qiongzhusi Formation and the residual stratum of Dengying Formation, with the thickness increasing gradually from the west to the east of the basin. In this period, the Leshan-longnvsi paleo-uplift had become a miniature in the west of Weiyuan area.

Before deposition of $O_1 n$（Fig. 13f）. In this tectonic background, the Leshan-longnvsi paleo-uplift (Fig.13d)inherited the tectonic pattern in the early stage and continued to develop. Subsequently, the Middle -Upper Cambrian system was successively deposited on the Qiongzhusi Formation, forming a subsidence center in the field of Laolongchang-Wutongchang in the eastern , with the thickness of the stratum was generally thin from the west side to the east side.

Before deposition of the Silurian(Fig. 13g). During the Ordovician period, the tectonic environment of the basin was relatively calm. It is characterized by extensive and stable deposition with thin and uniform thickness.

Before deposition of the Permian(Fig.13h-i-j). In Silurian, the Leshan-longnvsi paleo-uplift(Fig.13d) continually upheaved in the west side of Sichuan Basin. As a result, it had deposited a huge sediments in the eastern basin whereas quiet a thin in the core of paleo-uplift（Fig. 13h）. At the end of the Silurian period, the Caledonian Movement entered its peak period, making the Leshan-longnvsi paleo-uplift strongly upheaved vertically（Fig. 13i）. Subsequently, the continuous differential uplift caused the Middle Sichuan and most of the Sichuan basin to be exposed at the surface, which experienced for long-term erosion and planation, leading to the extensive deletion of the Silurian, Ordovician and Cambrian stratum in the field of the Leshan-longnvsi paleo-uplift. On the other hand, the Leshan-longnvsi paleo-uplift basically took shaped during the period（Fig.13j）.

（2）$P_2 l$-$T_2 l$ geological periods

Before deposition of $T_3 x^1$（Fig.13j）. During the Late Paleozoic to Middle Triassic, the tectonic dynamics mainly manifested as the differential uplift of crust and epeirogenic movement in extensional environment, a process in which the sea basin gradually shrank and the land gradually expanded (Li Zhongquan, 2011). In the beginning of the Middle Permian, the crust entirely began to shake and sink, making the basin undergo a transgressive once again, and resulting a regional angular unconformity between the Middle Permian and the Lower Paleozoic stratum（Fig.8c）. In this period, the tectonic pattern of the Leshan-longnvsi paleo-uplift changed little, whereas the Luzhou Paleo-uplift(（Fig.13k）) was formed in this period, leading the sedimentary thickness of the Middle Permian to Middle Triassic gradually decreasing from the northwest side to the southeast (Fig. 13k). Combined with regional geological background, the evolution history and characteristics of seismic profiles, we believe that it is reasonable to classify the prototype basin of the Middle Permian and Middle Triassic into marine intra-cratonic sag basin.

（3）$T_3 x^1$- $T_3 x^3$ geological periods

Before deposition of $T_3 x^4$ (Fig.13*l*). Regionally, in the Carnian and Norian age of Late Triassic, there was no large-scale collision between Qiangtang Block and Yangtze craton which could not cause a horizontal compression geological background, and most area of Songpan-ganzi area in western Sichuan was still in passive continental margin (Meng Qingren et al,2007). There was a faulted basin in front of Longmen Mountain, with Member 1-3 of the Xujiahe Formation successively depositing on the Middle Triassic stratum. The stratum gradually became thinner from the west side to the east, with some small normal faults developing inside. Associated with the evolution history, sedimentary filling and deformation characteristics, therefore, it is believed that the basin is a Marine and continental faulted basin in the deposition period of member 1-3 of the Late Triassic.

（4）T_3x^4- J geological periods

Before deposition of the Cretaceous(Fig. 13m)**.** In the beginning of Rhaetian Age(T_3x^4-T_3x^6) of Late Triassic, Longmenshan and songpan-ganzi blocks continued to uplift (Liu et al.,1996), whereas the basin still subsided extensively (Li Zhongquan et al., 2011&2014). Before the deposition of the Jurassic system, the member 4-6 of Xujiahe Formation began to deposit continuously throughout the entire basin. In Jurassic, the tectonic movement displayed relatively weak, marked by widely depositing the lacustrine red sand mudstone intercalated with shell limestone deposition in the basin(Wang Yongbiao et al., 2001; He Dengfa et al. 2011), mainly forming a large depression basin in a weak intra-continental extensional environment (Li Yingqiang et al., 2014). Moreover，The sedimentary characteristics of member 4 of Xujiahe Formation to the Jurassic stratum likes a tabular shape indicated that no flexural subsidence occurred during the sedimentary period (Wang Erqi et al., 2008). That is to say, the foreland basin would not be formed at the front of Longmen Mountain in Jurassic. Therefore, it is reasonable to classify the prototype of regional basin as a continental depression basins in the late of Late Triassic-Jurassic.

（5）K-Q geological periods

Present day(Fig. 13n)**.** In the early of the Cretaceous, as to the subduction of Indian plate to Eurasian plate, the tectonic dynamic background of regional basin changed from extension to compression with an shortening from the northwest to the southeast (Ren Jishun,1987；Li Yingqiang et al,2016). The tectonic pattern of Longmen Mountain changed from the early tension ancient-island chain to the compressional fold thrust orogeny, making the west side of Sichuan Basin occurring flexural subsidence deposited huge thick Cretaceous stratum (Long Ke et al., 2011). Under the influence of the Xishan Movement, the Weiyuan dome gradually formed and became the highest structure in Present day, while the Leshan-longnvsi paleo-uplift changed into a lower structure located in the slope of Weiyuan dome. At the same time, the early prototype structures were further formed, such as the anticline Longquan shan in the west side of Weiyuan dome, the anticline of Data chang, Shuanghe Chang, Laoweng Chang ,Wutong Chang etc. in the east side of the southern Sichuan Basin. The prototype basins of five stages were superposed vertically in an orderly manner, forming the present tectonic pattern. Based on the tectonic dynamics and the evolution history of Sichuan basin , it reasonably considers that the foreland basin evolution period (K-Q) was beginning from the Cretaceous.

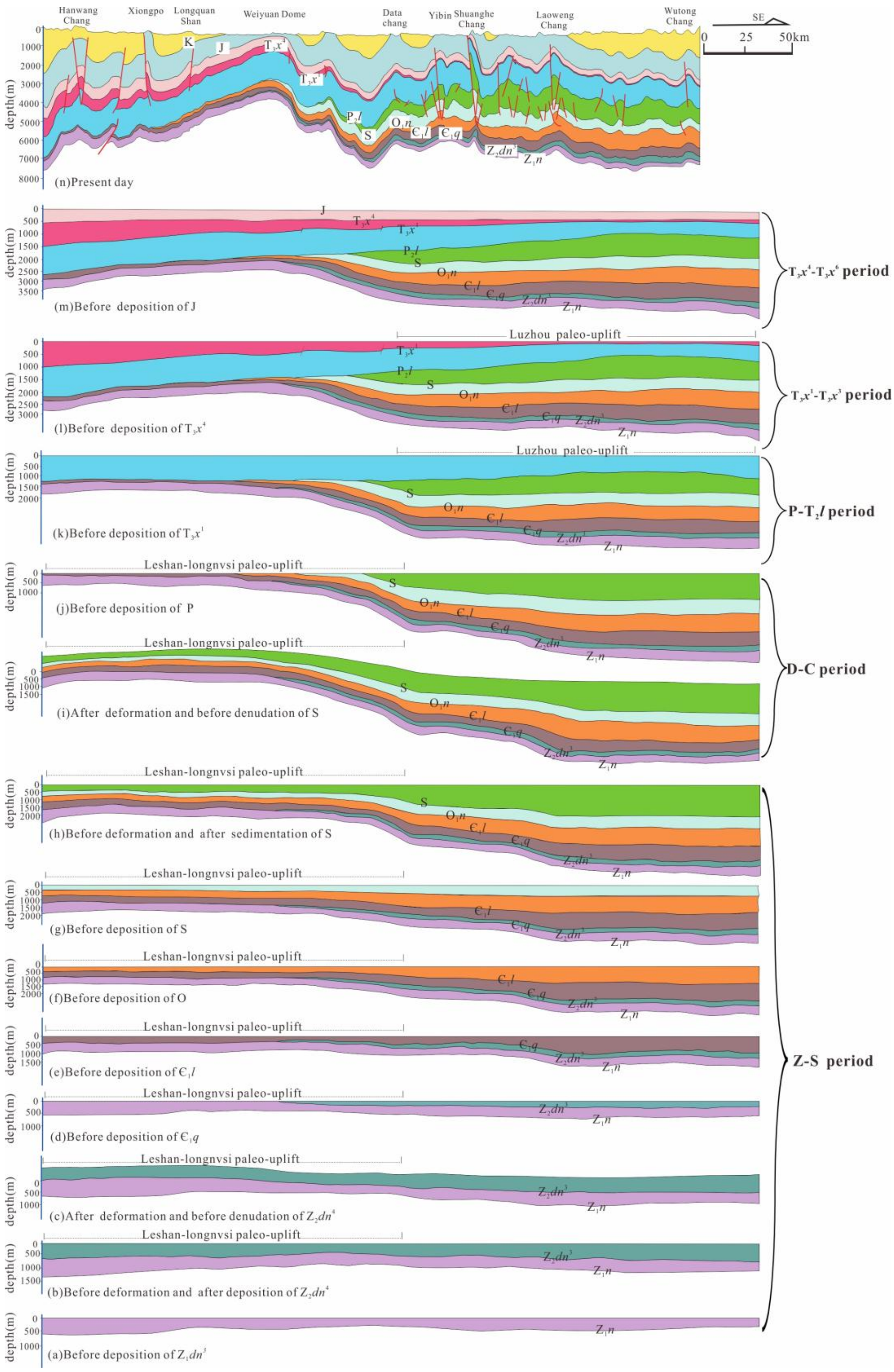

Fig.13 Geological evolution sections of Southern of Sichuan Basin

Superimposed pattern of prototype basins

Since Sinian, Sichuan basin has been involved into two evolution histories, including both marine and terrestrial facies（Ma Yongsheng et al., 2009；Liu Shugen et al.,2017）. At the end of Middle Triassic, Sichuan basin ended off the evolution of marine sedimentation gradually transforming into the evolution of terrestrial facies. Previous studies show that the transition from marine to terrestrial has a very close relationship with the structural coupling which come from the Longmenshan orogenic belt, Songpan-Ganzi belt and Sichuan basin (the coupling of basin-rang and basin-mountain), that is to say, the structural coupling of basin-rang is changed to basin-mountain in which the tectonic dynamics converted from stretching to extrusion (Li Zhongquan et al.,2011). During the long geological history, the sedimentary-tectonic evolution of Sichuan basin is comparatively complicated in that the changes of property and intensity of tectonic movement caused the crust quake of Sichuan basin.

Based on drilling data and the comprehensive analysis of seismic reflection profiles across Lushan-Chishui, the evolution sequence of the Sichuan Basin can be divided into five stages from the perspective of tectonic history, and these stages form a superimposition of five type of prototype basins longitudinally as follows (bottom up order) (Fig. 14): marine rift craton basin(Z-S), marine intra-craton sag basin (P_2l-T_2l), alternate marine and terrestrial downfaulted basin(T_3x^1-T_3x^3), terrestrial depressed basin(T_3x^4-J), and foreland basin(K-Q).These prototype basins of different properties are horizontally compounded and vertically superimposed to form the "layered block" geological structure of the multi-cycle basins. The superimposition of multiple prototype basins is a combined effect of multiphase sea-level fluctuation, multiphase tectonic activities and subsidence (He Dengfa et al., 2005), and its essence is to form a set of reservoir and cap assemblages on the superimposition interface. Due to the overlap of superposition interface, it not only forms the reservoir and cap assemblages, but also may lead to a superimposition of oil and gas reservoirs in different structural layers on space thus forming the hydrocarbon accumulation area. The Proterozoic-Middle Triassic sediments were mainly marine deposits with a thickness of 4000 ~7 000m in the southern Sichuan basin (Li Zhongquan et al., 2011). In the marine strata, there are several sets of high-quality source rocks in different structural-sedimentary environments, such as marine rift craton area, marine intra-craton sag area, and alternate marine and terrestrial downfaulted area, which are superimposed with the reservoirs longitudinally , forming multiple oil-gas systems from the bottom up. Affected by the late tectonic transformation, the hydrocarbon accumulation in southern Sichuan basin has a characteristics of early accumulation and late adjustment. with the geological characteristics of gas resource occurrence of "multiple strata, multiple types ", the prospect of oil and gas in southern Sichuan basin shows a huge potential of multi-layer three-dimensional exploration .

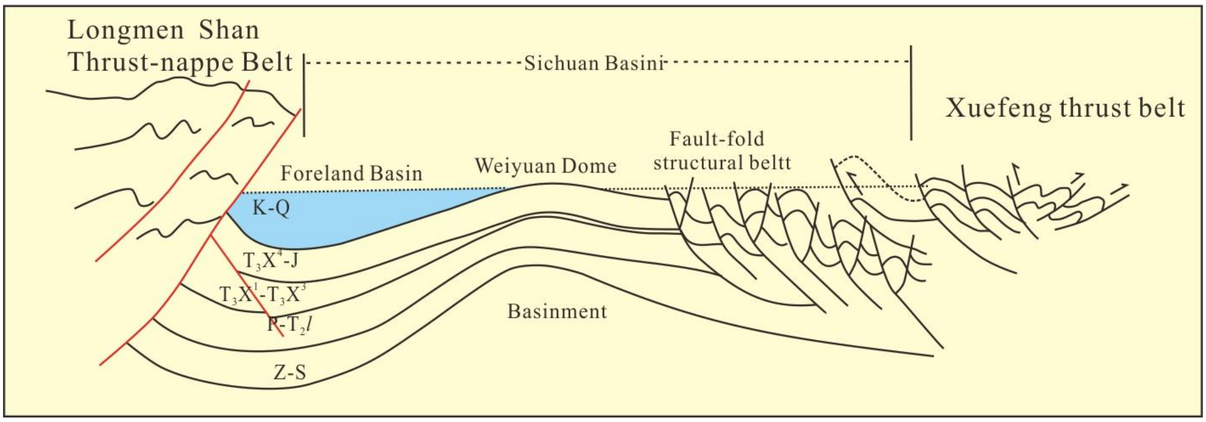

Fig.14 Sketch of the superimposed pattern of the prototype basins in the southern Sichuan basin

Conclusions

By detailedly analyzing the sedimentary and structural characteristics of seismic reflection profiles , closely combining with tectonic evolution of the plates around the Upper Yangtze, the geological structure, development history of prototype basins and their superimposed pattern of the southern Sichuan basin are discussed. Based on these, we present the following conclusions:

(1) Controlled by different vertical uplift of the crust and the activity of plates surrounded around the Upper Yangtze, the southern Sichuan basin underwent many tectonic movements with distinct deformations after the formation of its basement, resulting in five regional unconformities in the caprock.

(2) According to the regional unconformities we have identified , the sedimentary caprocks are divided into six tectonic layers vertically: the Pre-Sinian basement (AnZ), the Sinian-Silurian (Z-S), the Middle Permian System- Middle Triassic (P_2l-T_2l), member-3 of the Upper Triassic Xujiahe Formation (T_3x^1-T_3x^3), member4 of the Upper Triassic Xujiahe Formation-Jurassic (T_3x^4-J) and the Cretaceous –Quaternary (K-Q). These tectonic layers in different periods suggest that Sichuan basin has been involved into the development of prototype basins in an oscillating crustal environment, forming with an ordered superimposition from the bottom to the top, such as a marine rift craton basin(Z-S), marine intra-craton sag basin (P_2l-T_2l), alternate marine and terrestrial downfaulted basin(T_3x^1-T_3x^3), terrestrial depressed basin(T_3x^4-J), and foreland basin(K-Q). It is revealed the fact that the dynamic evolution of the southern Sichuan basin underwent a transformation from tension to compression, and eventually formed a multi-stage superimposed basin consisted of different prototype basins.

(3) The prototype basins of different properties are horizontally compounded and vertically superimposed, forming the "layered block" geological structure of the multi-cycle basins. The essence of superimposition is to form a set of reservoir and cap assemblages on the superimposition interface. Due to the overlap of superposition interface, it may lead to a superimposition of oil and gas reservoirs in different structural layers on space thus forming the hydrocarbon accumulation area. Affected by the late tectonic transformation, the hydrocarbon accumulation in southern Sichuan basin has a characteristics of early accumulation and late adjustment. With the geological characteristics of gas resource occurrence of "multiple strata, multiple types ", the prospect of oil and gas in southern Sichuan basin shows a huge potential of multi-layer three-dimensional exploration .

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