УДК 534.647(510)
Геология и геофизика, 2021, т. 62, № 6, с. 843—860

ХАРАКТЕР НАЛОЖЕНИЯ В ЮЖНОЙ ЧАСТИ СЫЧУАНЬСКОЙ ВПАДИНЫ ПО ДАННЫМ СЕЙСМИЧЕСКОГО ПРОФИЛЯ ЛУШАНЬ–ЧИШУЙ (*Китай*), ПОЛУЧЕННОГО МЕТОДОМ ОТРАЖЕННЫХ ВОЛН

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Сычуаньская впадина — типичный внутрикратонный наложенный бассейн. Она богата ресурсами нефти и газа, локализованными в толщах различных осадочных серий. Для Сычуаньской впадины характерна многоэтапная тектоническая эволюция, в результате которой сформировалось несколько типов протобассейнов. Тем не менее, вопрос о типе и характере наложения Сычуаньской впадины в разные геологические периоды остается дискуссионным, что определяет точку зрения на механизм эффективного накопления и сохранения нефти и газа. В данной статье пересмотрены типы протобассейнов для Сычуаньской впадины и модели их наложения, подчеркивается важность эволюции наложенных впадин для накопления углеводородов. Авторы приводят подробную интерпретацию сейсмических профилей Лушань–Чишуй, полученных методом отраженных волн, с использованием региональных геологических данных, а также данных бурения. Затем выделяются пять региональных несогласий методом равновесных профилей с целью выравнивания границы пластов в разные геологические периоды. На основе данных несогласий южная часть Сычуаньской впадины подразделяется на шесть тектонических слоев, каждый из которых рассматривается как протобассейн: досинийский кристаллический фундамент (AnZ), морской рифтовый кратонный бассейн (Z–S), морской внутрикратонный прогиб (P_2l–T_2l), континентально-морская сбросовая впадина (T_3x^1–T_3x^3), континентальная депрессия (T_3x^4–J) и форландовый бассейн (K–Q). В результате вертикального наложения протобассейнов формируется слоисто-блочная геологическая структура полицикличных впадин. Под влиянием поздних тектонических преобразований геологическая структура вертикальной слоистости подверглась значительной трансформации, которая оказала большое влияние на накопление нефти и газа и дальнейшую перестройку нефтегазовых пластов.

Сейсмические профили, полученные методом отраженных волн, протобассейн, характер наложения, южная часть Сычуаньской впадины

SUPERIMPOSED PATTERN OF THE SOUTHERN SICHUAN BASIN REVEALED BY SEISMIC REFLECTION PROFILES ACROSS LUSHAN–CHISHUI, CHINA

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The Sichuan Basin is a typical intracraton superimposed basin. It is rich in oil and gas resources in the different sets of sedimentary sequences. It underwent multistage tectonic evolution, which resulted in different types of prototype basins. However, there are still many different opinions on the types and superimposed patterns of the Sichuan Basin in different geologic periods, which largely affect the understanding of the mechanism of effective oil and gas accumulation and preservation. This paper aims to re-recognize several prototype types of the Sichuan Basin by discussing the prototype basins and their superimposed models to deepen the significance of superimposed basin evolution for hydrocarbon accumulation. The regional geological and drilling data are used for a detailed interpretation of seismic reflection profiles across Lushan–Chishui. Then, five regional unconformities are identified with the equilibrium profiles technique, which is used to flatten the formation interface in different geologic periods. Based on the unconformities, the southern Sichuan Basin is divided into six tectonic layers, each of which is regarded as a prototype basin: a pre-Sinian crystalline basement (AnZ), a marine rift cratonic basin (Z–S), a marine intracratonic sag basin (P_2l–T_2l), a marine–continental downfaulted basin (T_3x^1–T_3x^3), a continental depressed basin (T_3x^4–J), and a foreland basin (K–Q). The different prototype basins are vertically superimposed to form a “layered block” geologic structure of the multicycle basins. Affected by the late-stage tectonic transformation, the geologic structure of vertical stratification underwent a strong transformation, which had a profound impact on oil and gas accumulation with the characteristics of early accumulation and late adjustment.

Seismic reflection profiles, prototype basin, superimposed pattern, southern Sichuan Basin

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DOI: 10.15372/GiG2020126

INTRODUCTION

As a negative tectonic unit, the Sichuan Basin reflects the process of basin subsiding and orogenic belt evolution in the same sedimentary period. At the same time, the appearance, morphology, and the spatial configuration relationship of the prototype basin reflected the direction and nature of regional dynamic action. The multistage prototypes are vertically superimposed to form a superimposed basin with various structures (Wang et al., 2002a; He et al., 2004, 2010; Han et al., 2006; Li et al., 2011). The superimposed relationship of different-period prototype basins also indicates regional tectonic evolution (Liu and Zhang, 2005; Song, 2009). The Sichuan Basin, a multicycle superimposed basin with rich oil and gas resources, is localized on the Upper Yangtze craton and comprises a marine basin and a terrestrial basin (Korsch et al., 1991; He et al., 2011; Liu et al., 2011a). However, the craton block was a long-term transition zone between Gondwanaland and Laurasia (Ren, 1994). As the margin of the craton was involved in deformation and thus underwent intense transformation in the later period (Ren, 1994; Ren et al., 1999), its interior must exhibit different tectonic activities. Meanwhile, the Sichuan Basin, one of the earliest basins with found oil and gas resources in the world (Wei et al., 2008; Liu 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 Sinian to Jurassic systems. Among them, there are nine gas fields with proven geologic reserves of over 100 billion cubic meters (Zheng et al., 2017), showing that the Sichuan Basin has good prospects for oil and gas exploration in different strata. According to statistics, the conventional natural gas geologic resources in the Sichuan Basin had been 20.69×10^{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 the southern Sichuan Basin, there are more than 40 gas fields in the Chongqing–Luzhou–Yibin areas. In fact, the study found that huge ancient oil fields and ancient gas fields also formed in the geologic history of these areas, but they were modified and destroyed by later differential structural uplift. Some of the ancient gas reservoirs survived to form today's residual gas reservoirs (Sun 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 et al., 2011). Thus, oil and gas accumulation occurred in a large area of the Sichuan Basin in the geologic history, but the spatial distribution characteristics of the present (residual) oil and gas fields were formed by multistage basin superimposition and late structural transformation (Liu et al., 2012). Such a long-term tectonic transformation has a profound impact on the mechanism of natural gas accumulation and preservation in the

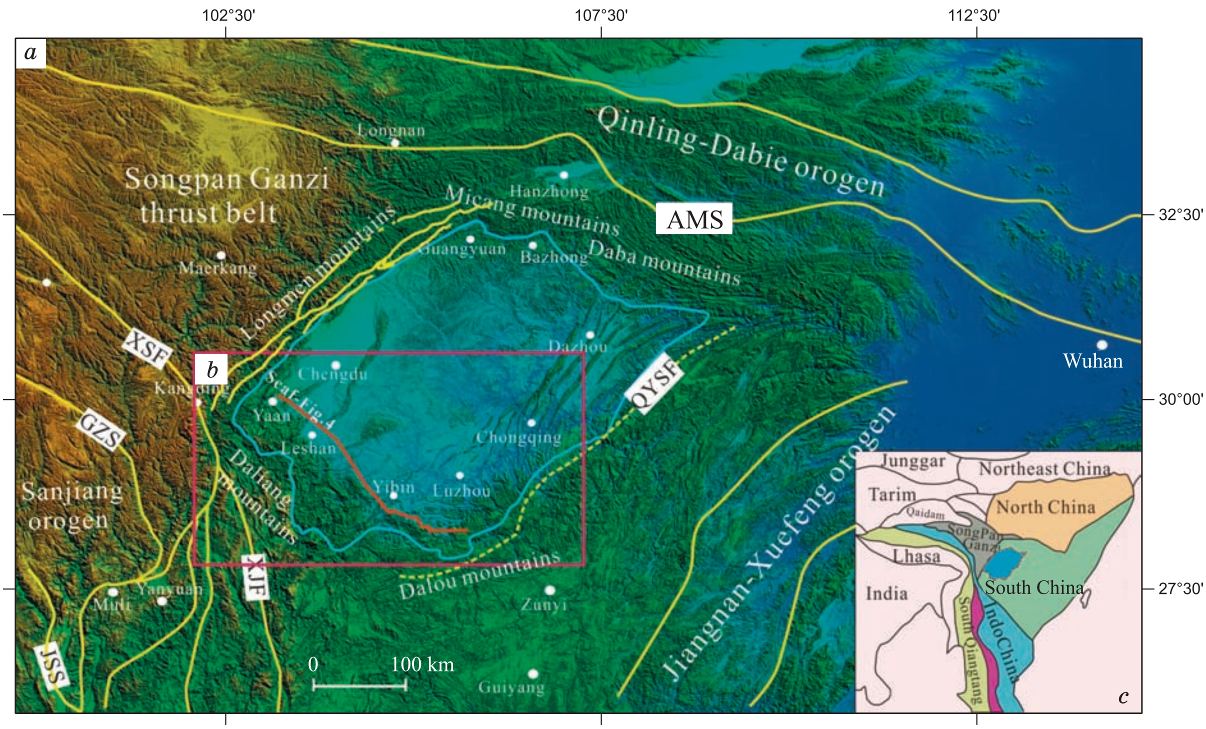

Fig. 1. Tectonic outline of the Upper Yangtze area (*a*) and (*c*) simplified geologic map of East Asia, modified from Metcalfe (2013), location of study area (*b*); XJF, Xiaojiang fault; XSF, Xianshuihe fault; AMS, Animaqin–Mianlue suture; GZS, Ganzi–Litang suture; JSS, Jinshajiang suture; QYSF, Qiyueshan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

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 the Sichuan Basin, which is located on the Upper Yangtze craton block (Fig. 1*a*).

Although the prototypes of the marine basin have obtained a unified understanding, there is still a heated discussion on the prototypes of the terrestrial basin since the Late Triassic. One view is that the southern Sichuan Basin was an alternate marine and terrestrial basin in the sedimentary period of Xujiahe Fm I of the Upper Triassic, subsequently entering the stage of the development of foreland basin (Luo, 1983, 2011; Hou et al., 2005; Shi et al., 2008, 2010, 2012; Zhao et al., 2008; Zhao and Zhang, 2011). The second view is that the Sichuan Basin was an intracratonic depression in the sedimentary period of Members 1–3 of the Upper Triassic Xujiahe Formation, a foreland basin in the sedimentary period of Members 4–6 of the Upper Triassic Xujiahe Formation, and a continental depression in the Early–Middle Jurassic, since then entering the stage of the development of foreland basin once again (He et al., 2011). Still 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 et al., 2001; Zhu et al., 2009; Chen et al., 2011; Zhu et al., 2017).

Therefore, making clear the internal structure of the 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 a 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 across Lushan to Chishui (Fig. 1*b*).

GEOLOGIC SETTING

The Sichuan Basin is surrounded by the Qinling orogenic belt, Jiangnan–Xuefeng orogenic belt, Sanjiang orogenic belt, and Songpan–Ganzi orogenic belt, facing the Micangshan–Dabashan tectonic belt in the north, the Qiyueshan fault belt in the east, and Daloushan and Daliangshan in the southwest, which has an obvious

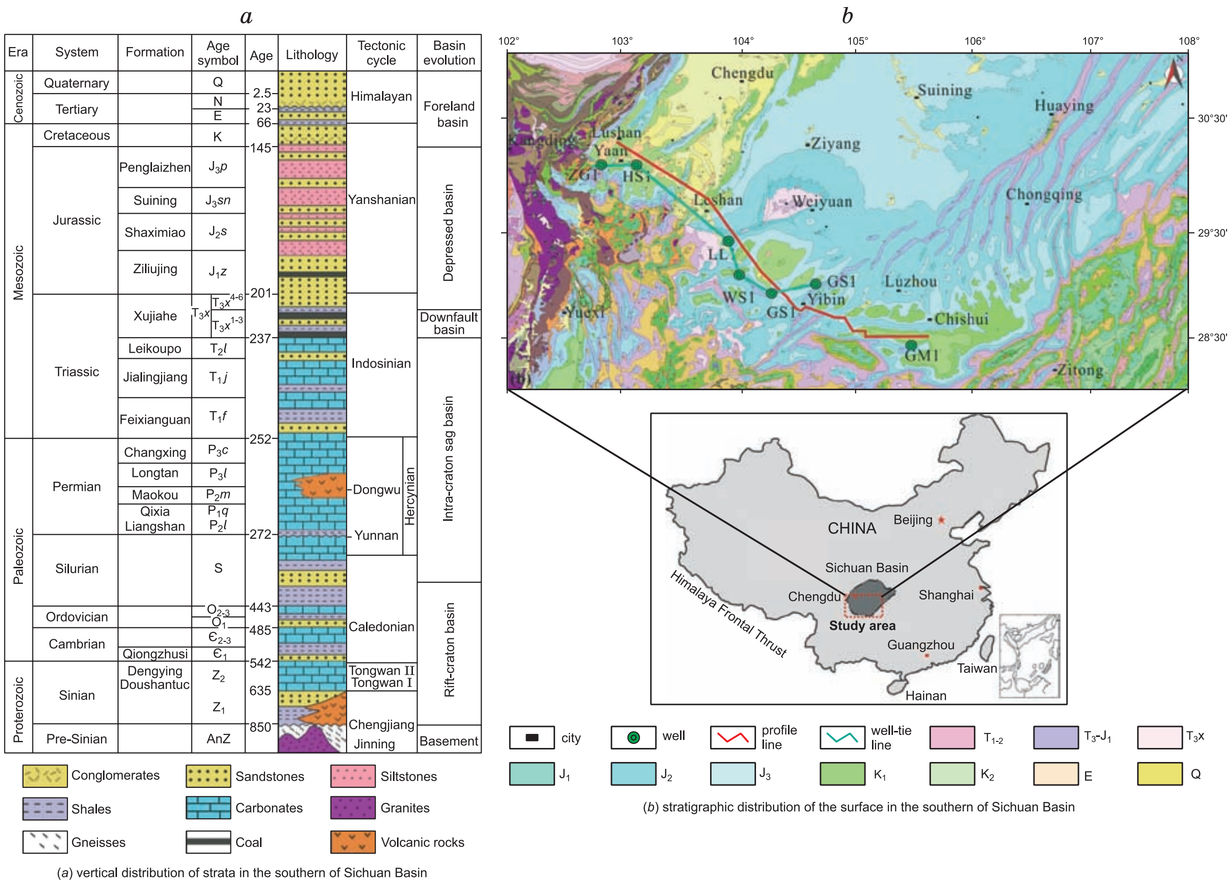

Fig. 2. Stratigraphic column and tectonic sketch (*a*), stratigraphic outcrop map (*b*) of the southern Sichuan Basin.

rhombic boundary (Fig. 1*a*), reflecting that the formation of the 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, 1998). The research area lies in the south of the Sichuan Basin with the Yunnan–Guizhou Plateau in its south. Its western region is bordered by the southern section of Longmen Mountain, straddling the Longmen Mountain fault zone and facing the Songpan–Ganzi folded belt (Fig. 1*b*).

BASIN TEXTURE REVEALED BY THE SEISMIC REFLECTION PROFILES

Basic geologic 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 340 km, successively passing through several structural units of the Hanwangchang anticline, Xiongpo anticline, Longquanshan anticline, Weiyuan Dome, Datachang, Shuanghechang anticline, Laowangchang anticline, Wutongchang anticline, and so on (Fig. 4*b*).

With a comparison of a regional stratum and by using the synthetic seismograms from the HS1 and LL1 wells (Fig. 3), which is done to determine the major marker layers, the stratum interpretation of the profiles is eventually obtained. According to the interpretation, the bottom boundary of eleven layers has been traced, and they are the Sinian System (Z), the third member of the Sinian Dengying Formation (Z_2dn^3), the Qiongzhusi Formation of the Cambrian System ($Є_1q$), the Longwangmiao Formation of the Cambrian System ($Є_1l$), the Nanjingguan Formation of the Ordovician System (O_1n), the Silurian 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 the Jurassic System (J_1z), and the Cretaceous System (K), respectively (Fig. 4*b*).

Combined with the interpretation (Fig. 4*b*), 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 systems. The most prominent features are the large anticline called the 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 large on both sides of the basin and small in the middle. Some strata were eroded and flattened. For instance, the Cambrian, Ordovician, and Silurian systems were eroded and flattened in the western Sichuan depression; besides, the Devonian–Carboniferous systems were largely absent, while the Permian–Middle Triassic systems thickness is relatively stable. Members 1–3 of the Xujiahe Formation are relatively thicker in the west than in the east, where the thickness is only a few tens of meters. The thickness of Members 4–6 of the Xujiahe Formation–Jurassic System vary slightly in the regional basin, and the Cretaceous–Quaternary systems forms a dustpan shape in front of Longmen Mountain near the basin margin.

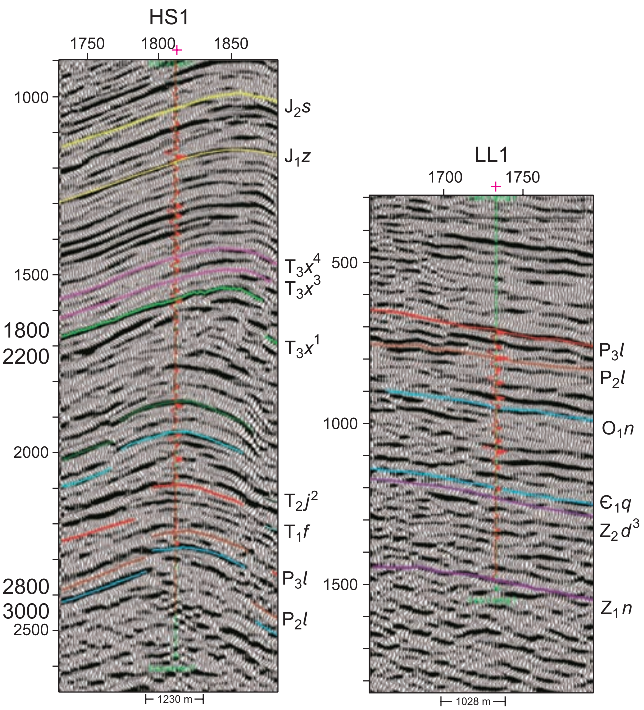

Fig. 3. Synthetic records of the HS1 and LL1 wells.

Classification of unconformities 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 is the unconformity between Sinian and Pre-Sinian systems. It is a basement unconformity formed between the basement of the Archean greenstone belt and gray gneiss and the Sinian System which overlay the basement (Li et al., 2010). The drilling data of the LL1 well also reveal this feature that the Sinian System directly covers the epimetamorphic rocks of the Pre-Sinian System;

(2) P/AnP is the angular unconformity between the Permian and pre-Permian systems. In the seismic profiles, the Cambrian, Ordovician, and Silurian systems are truncated by the Permian System

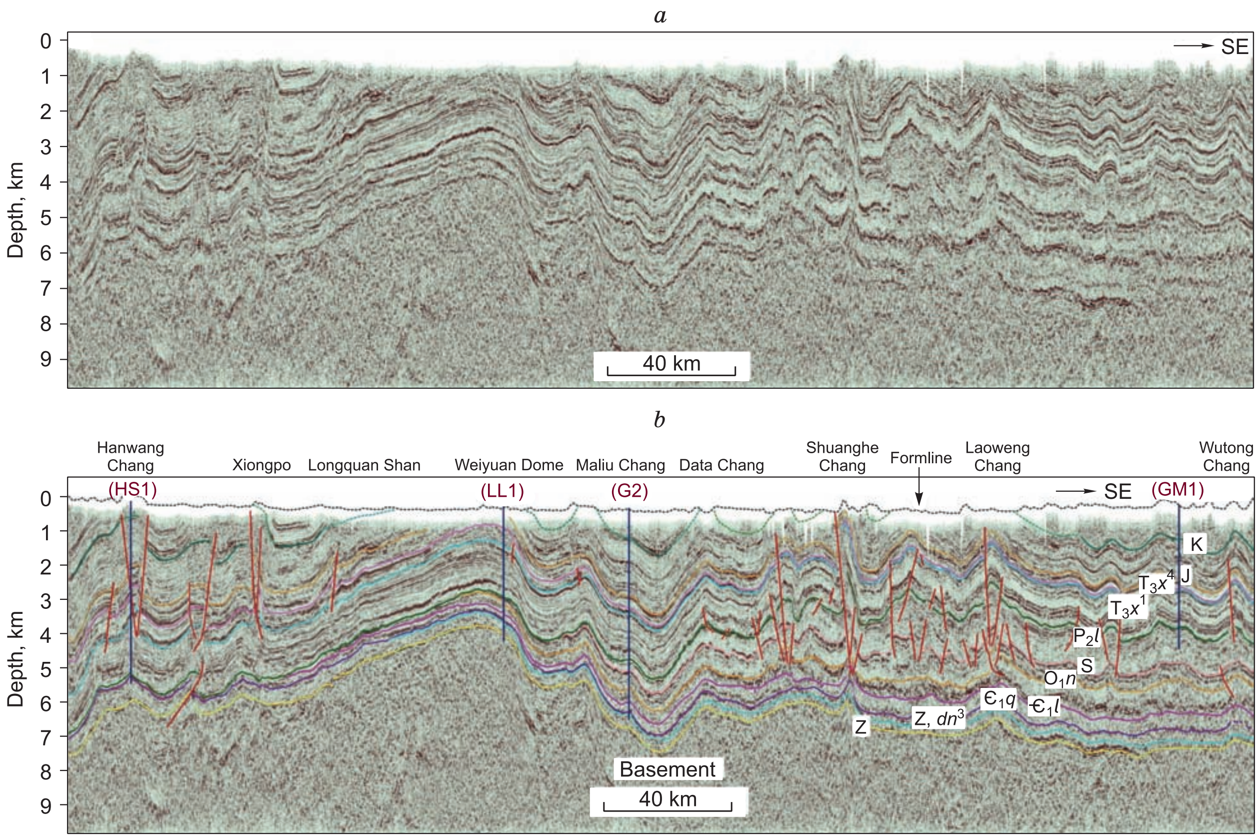

Fig. 4. Geological interpretation of seismic reflection profiles in the southern Sichuan Basin.

(Fig. 6). Even in the west of the Weiyuan dome, the middle Permian Liangshan Formation directly overlaps the weakly deformed Silurian, Ordovician, or Cambrian Systems. For example, the LL1 well shows that the underlying stratum of the Liangshan Formation (P_2l) is the Middle Ordovician Nanjinguan Formation (O_1n) (Fig. 3);

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

(4) T_3x^4/T_3x^3 is the onlap sedimentary unconformity between the third and fourth members of the Xujiahe Formation, which is distributed only in western Sichuan. In the seismic profiles, some microangle cuts are found at the top of the third member of the Xujiahe Formation in the west of the Weiyuan uplift (Fig. 10). Members 1–3 of the Xujiahe Formation are thick in the west and thin in the east (wedge-shaped). Eastward, the thickness of the sediments is rapidly decreasing, only tens of meters;

(5) K/J is the parallel unconformity between the Cretaceous and the Jurassic. Although the Cretaceous appears less in the seismic profiles and the shallow seismic reflection characteristics are not ideal, the field geological survey in Longmen Mountain and drilling data on the 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. The great difference between these two sedimentary facies reflects a contact of parallel unconformity.

According to the regional geologic setting and these five unconformities stages, the southern Sichuan Basin is divided into six tectonic layers vertically (Fig. 5): the pre-Sinian crystalline–folded 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.

CHARACTERISTICS OF PROTOTYPE BASINS IN DIFFERENT GEOLOGIC 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 the Sinian. Because of different tec-

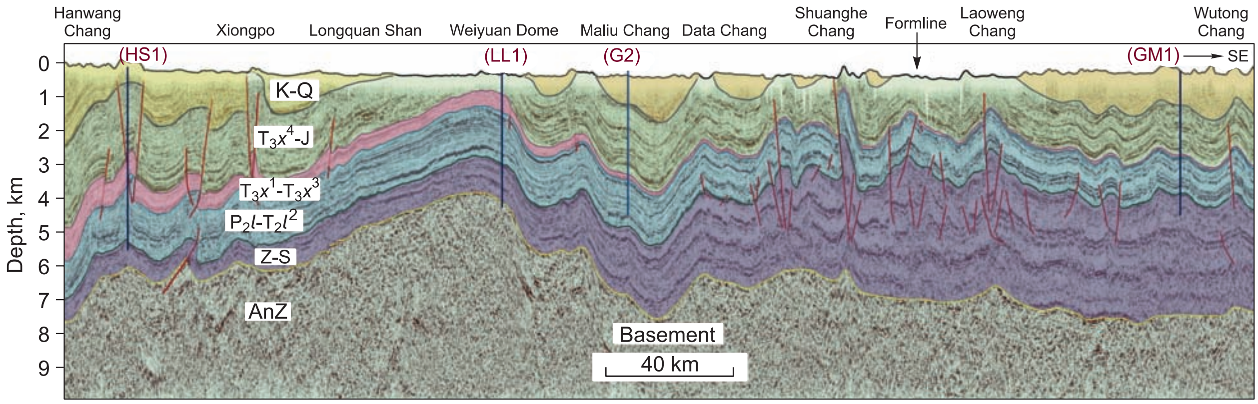

Fig. 5. Classification of tectonic layers in the southern Sichuan Basin.

tonic dynamics, prototype basins formed at each evolution stage and then were superimposed orderly in the longitudinal direction, influenced by the post-tectonic reconstruction. The characteristics of prototype basins in different geologic periods are discussed below.

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

After the formation of the pre-Sinian basement, the tectonic dynamic background changed from a compressive orogeny period to an extensional basin-forming period. During the Sinian–Silurian, the entire Sichuan Basin gradually exhibited a process of expansion and subsidence (Wang et al., 2002b; He et al., 2011; Li et al., 2011, 2014). Influenced by the Caledonian movement at the end of the Silurian, the structural framework of the Sichuan Basin underwent significant changes. The differential uplift activities of a large-scale uplift, depression, and fault block are particularly prominent (Wu et al., 2015). Especially, the strong uplift of the Leshan–Longnvsi paleouplift made the lower Paleozoic stratum exposed to denudation for a long time, and the Devonian–Carboniferous systems were largely absent, forming an angular unconformity between Permian and pre-Permian systems (Fig. 7). Based on this geologic understanding, we flatten the bottom of the Permian stratum using the Landmark software. The results show that the southern Sichuan Basin is characterized by a high in the center and west and a low in the east (Fig. 6*a*). The bottom boundary of the Ordovician and Silurian strata is truncated with a high angle by the Permian System (Fig. 6*b*). On the southeastern slope of the Leshan–Longnvsi paleouplift, not only is the Ordovician System superior to the Cambrian System, but also the Silurian System overlaps the Ordovician System (Fig. 6*c*). These geologic characteristics indicate that the Leshan–Longnvsi paleouplift is a synsedimentary anticline during the Caledonian, and its wide and gentle structural form is the result of vertical uplift of the crust (Li et al., 2011), which is also supported by the normal faults developed in the Sinian and Cambrian (Fig. 6*c*–*e*). These characteristics of the seismic profiles show that the southern Sichuan Basin represented an extensional environment in the Sinian–Silurian as a whole, and the uplift pattern in the basin should be a tectonic reflection for this environment.

In terms of sedimentary formation, the basement is composed of a set of granite in the southern Sichuan Basin. The first sedimentary Doushantuo Formation of the Sinian System (Ediacaran) deposited with a rhythmic neritic–lagoon carbonate, which resulted from the glacier melting in the Nanhua System in the Nantuo Ice Age and is widely distributed in the Yangtze Craton. As for drilling data, the data on the 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, and an interbedded set of fine sandstone and siltstone shale, limestone, and shale of the Ordovician stratum. These sediments demonstrate how the Sichuan Basin gradually transformed from continent to marine sedimentation at an early stage. Since then, the Cambrian–Silurian has shown the gradual expansion and subsidence of the sea basin. Based on the characteristics of seismic profiles and regional sedimentary records, it is believed that the prototype basin in the Sinian–Silurian was in an extensional environment, belonging to cratonic rift basins.

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 the 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. Also, the east–west “seesaw” transition took place (Li et al., 2012), which caused the

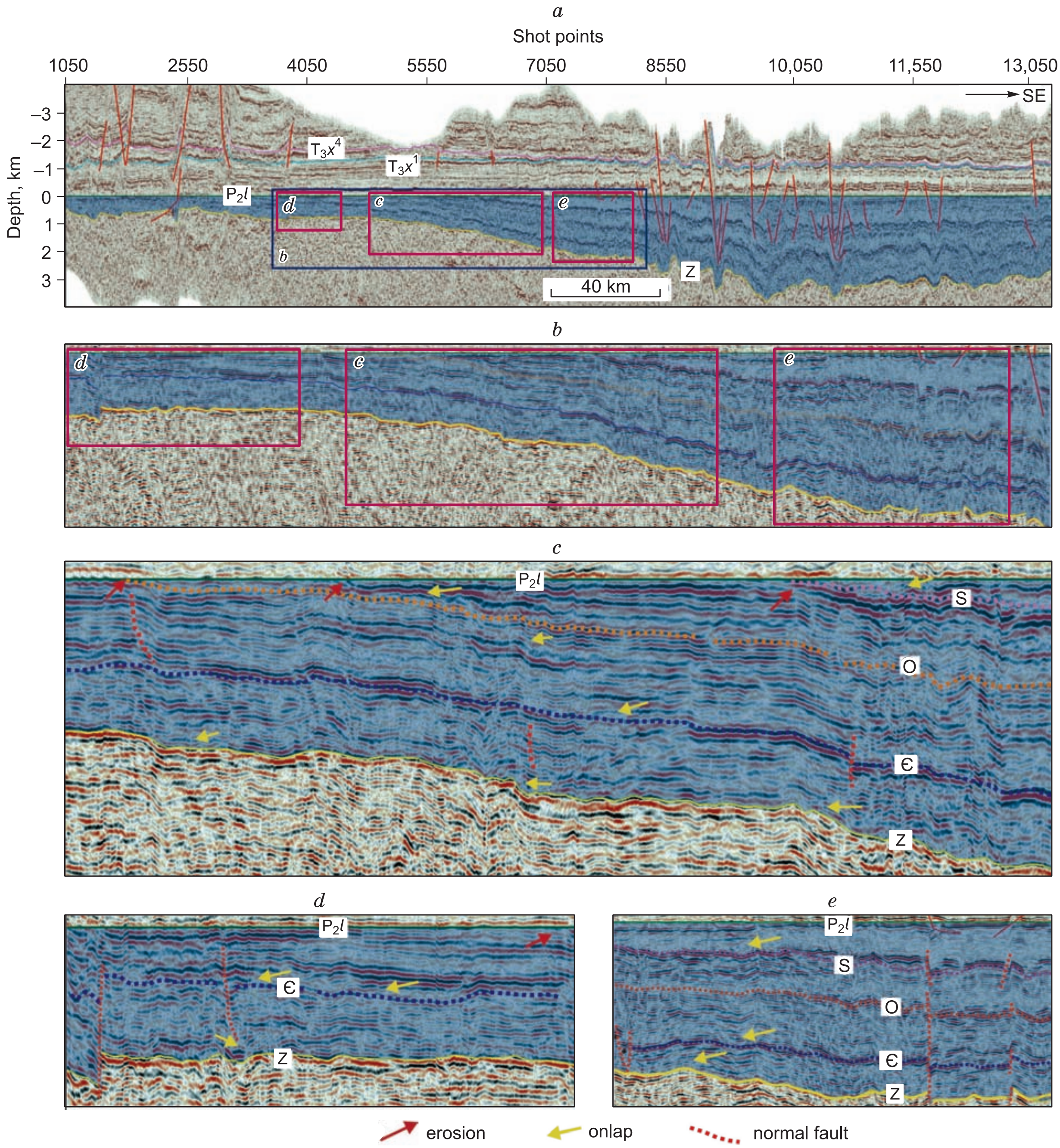

Fig. 6. Prototype basin and key geologic phenomena of the southern Sichuan Basin in the Sinian–Silurian.

Luzhou–Kaijiang uplift to result in the denudation of the Leikoupo Formation in the Luzhou area, forming a regional unconformity denudation surface (T_3x^1/T_2l) (Li et al., 2014; Wang et al., 2015). The bottom boundary of the Upper Triassic Xujiahe Formation (T_3x^1) is flattened (Figs. 8, 9), showing that the stratum represents planar sediments in the basin during the middle Permian–Middle Triassic (Figs. 8*a* and 9). There are almost no folds or thrust faults formed by large-scale horizontal compression, whereas the small–normal faults are relatively growing (Fig. 8*b*). The onlap phenomenon at the bottom of the Leikoupo Formation (Fig. 8*c*) indicates that the Luzhou uplift had an embryonic form during the Jialingjiang sedimentary period in the southeastern part of the basin. Meanwhile, the thinning and pinching-out of the Leikoupo Formation toward the core of the Luzhou paleouplift and the truncation of the top of the Leikoupo Formation indicate that the Luzhou paleouplift was in a process of continuous development and broadening, existing underwater in that stage.

From a standpoint of deposition, the basin began to subside and then experienced transgression in the early middle Permian, making the Liangshan Formation, which is a set of shallow gray mudstone and carbona-

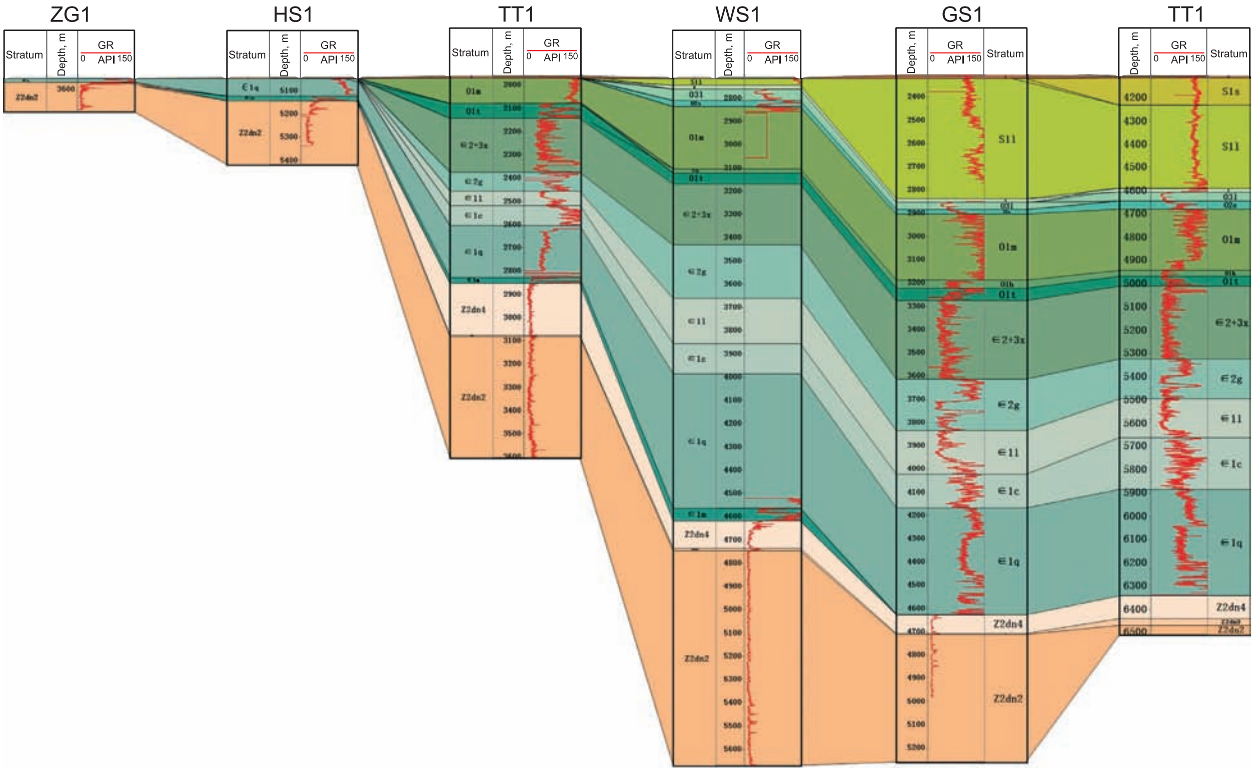

Fig. 7. Sedimentary stratigraphic correlation in the southern Sichuan Basin from the Sinian to the Silurian before the Permian (well-tie line shown in Fig. 2*b*).

ceous shale with a coal line directly overlying the Lower Paleozoic stratum (He et al., 2010; Huang et al., 2017). Subsequently, the extensive transgression made the Yangtze area become the normal shallow-sea carbonate platform facies. Longitudinally, the Qixia Formation and the Maokou Formation with the platform facies and gentle slope facies were deposited in the basin. In the late Permian, affected by the Emei taphrogenesis of the Dongwu movement, the basin was uplifted again, accompanied by the eruption of a large area of basalt, causing the formation of Emei basalt. Since then, the basin has subsided as a whole, depositing the upper Permian Changxing Formation composed of limestone, the Lower Triassic Feixianguan Formation 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 sea to land. Influenced by the Indosinian movement, the Sichuan Basin was relative to Longmen Mountain and the Songpan–Ganzi region overall uplift, causing the successive erosion of the eastern Sichuan Basin and resulting in a parallel unconformity contact between Leikoupo and Xujiahe Formations (Huang et al., 2011).

Both the sequences of sedimentary–tectonic evolution and features of the seismic profiles indicate the transgression and regression which the Southern Sichuan Basin experienced and further show that the basin was in the extensional tectonic dynamic environment. It is suggested that the regional basin was an intracraton sag basin under an environment of crustal oscillation during the middle Permian–Middle Triassic.

Basin prototype in the early 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 of carbonate rocks over the Yangtze Plate. In the early Late Triassic, owing to the differential uplift rates between the blocks, the Sichuan Basin was 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 et al., 2014), which controlled the development of a residual sea in the small area on the west side of the 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 part of the basin was asymmetrically wedge-shaped in a transverse cross section (Fig. 10*a*). On the other hand, Members 1–3 of the Xujiahe Formation onlapped onto the Leikoupo Formation, which was cut at a low angle by the bottom of the Xujiahe Formation. Further-

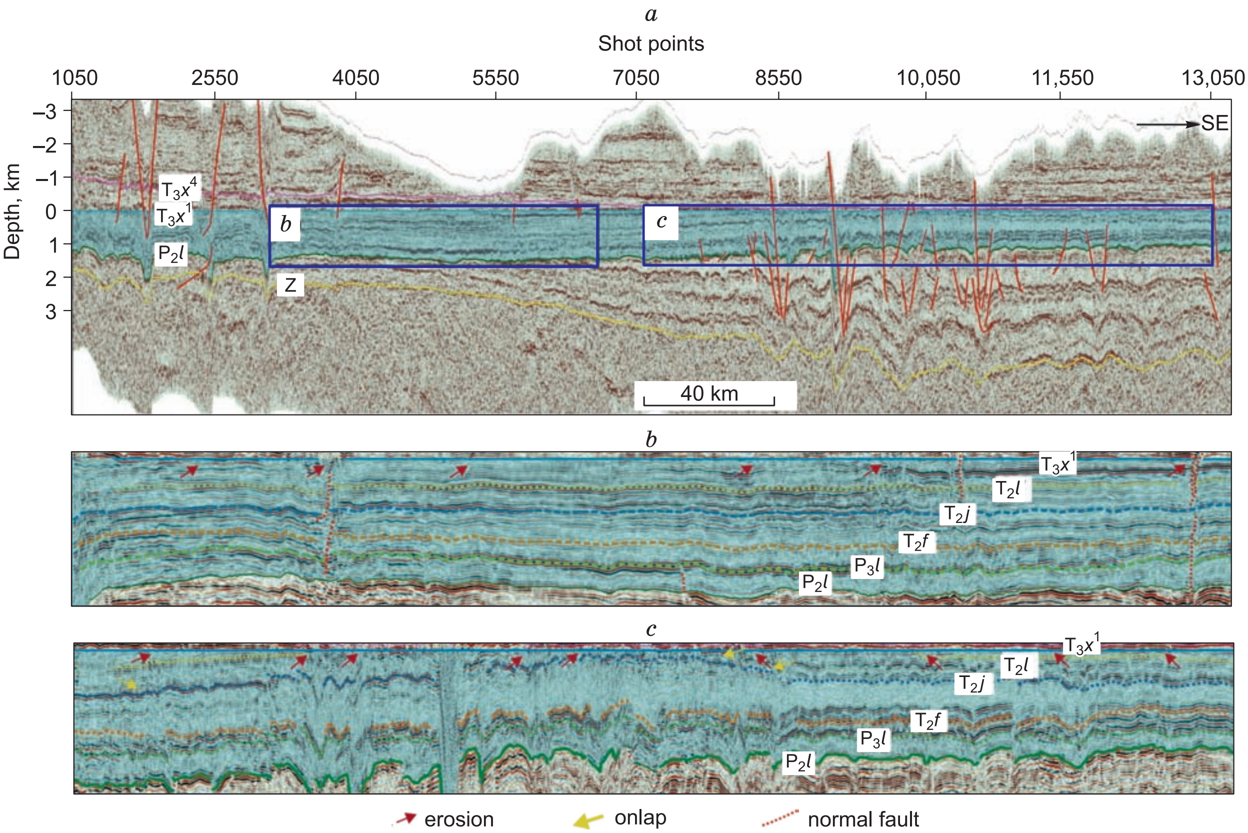

Fig. 8. Prototype basin and key geologic phenomena of the southern Sichuan Basin in the middle Permian–Middle Triassic.

more, small normal faults can be found in the residual sea of the southern Sichuan Basin (Fig. 10*b*, *c*). These seismic profiles suggest that the basin was still in an extensional tectonic dynamic setting.

From the point of sedimentation, coastal–shallow marine sediments deposited on the western side of the southern Sichuan Basin during the Carnian–Norian (T_3x^1–T_3x^3). For example, the lower part of Member 1 of the Xujiahe Formation is a platform facies (Zhu et al., 2017); the upper part is a bay facies; and Members 2–3 of the Xujiahe Formation are continental delta facies with a set of sandstone, mudstone-interbedded siltstone, and coal measure interbeds (Cui et al., 1991; Zheng et al., 2011). Owing to the high topography of the Luzhou paleouplift, the sedimentary succession is only 50–100 m thick on the east side of the basin. According to the characteristics of seismic profiles and the sedimentary succession records, the southern Sichuan Basin might be a downfaulted basin in the transitional environment between sea and land in the Carnian–Norian.

Basin prototype in the late Late Triassic–Jurassic (T_3x^4–J)

In the late Late Triassic (Rhaetian), 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 confined to the interior of the craton. The sediments were mainly continental fluvial and lake deposits (Fig. 11). In the late Middle Jurassic, subsequently, the tectonic dynamic environment of the basin experienced alternating changes of strong and weak extensions, which made the basin undergo from rapid to slow to stable subsidence changes in the Jurassic. Thus, the basin gradually enlarged the sedimentary range, even was deposited to the Yichang–Guiyang area in the east of the Qiyao Mountains (Li et al., 2011). The subsidence rate of the Sichuan Basin was much higher than the sedimentation rate of terrigenous clastic rocks, forming the largest lake basin in the Sichuan Basin in the Jurassic with coal-bearing clastic rock of the lacustrine marsh facies (Meng et al., 2005). Figures 8*a* and 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 platelike deposit. Combined with the seismic characteristics and sedimentary responses, this indicates that the basin underwent an overall subsidence and still was in a relatively quiet extensional dynamic background during the late Late Triassic–Jurassic; thus, the southern Sichuan Basin was a lake facies depression at that time.

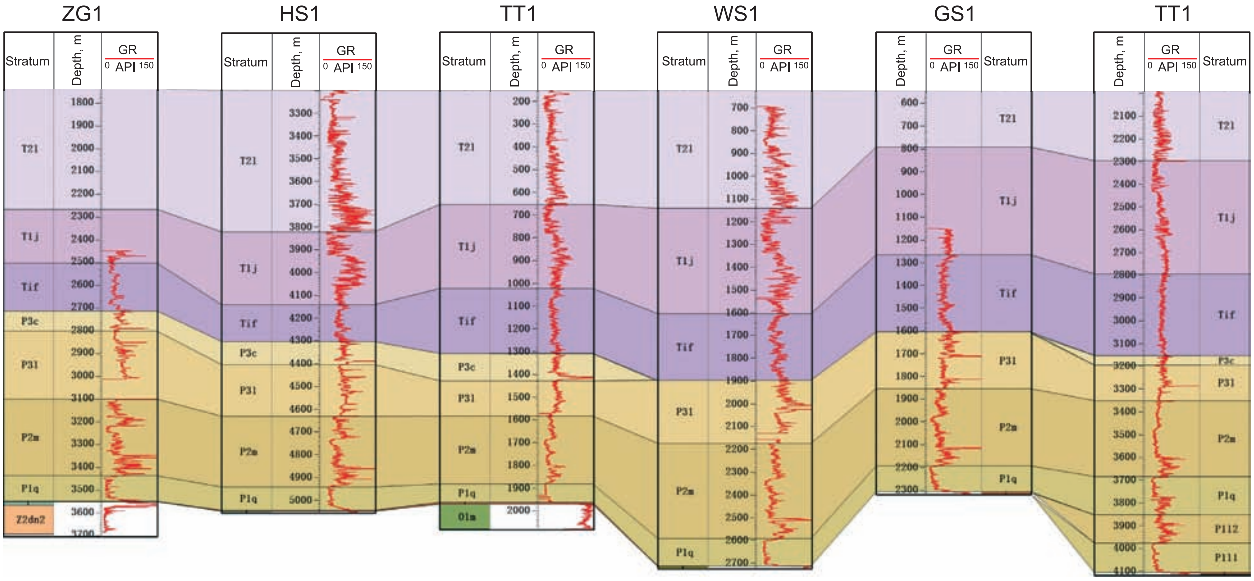

Fig. 9. Sedimentary stratigraphic correlation in the southern Sichuan Basin from the Permian to the Middle Triassic before the Late Triassic (well-tie line shown in Fig. 2*b*).

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

According to the geological survey, there is a parallel unconformity between the Jurassic and Cretaceous systems in the western Sichuan Basin (Wang and Xu, 2001; Long et al., 2011; Li et al., 2016). Because of the clutter of shallow seismic in-phase axes and only a small amount of the 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 on the HS1 well show that the Lower Cretaceous was eroded. The Cretaceous formation was deposited with a wedge shape, thick in the west and thin in the middle, and obviously thicker on the side of Longmen Mountain 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, thick at the bottom and thin at the top, indicates 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 the Yangtze Plate, the basin was gradually shrinking, so that the Paleogene–Quaternary strata were distributed only in the southwest of the basin (Chen et al., 2008; Zhu et al., 2009; Chen et al., 2011) (Fig. 2*b*). The thickness was only 100–500 m^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 using the equilibrium profiles technique.

(1) Z–S geologic periods

Before deposition of Z_1dn^3 (Fig. 13*a*). During the Sinian–Silurian, the entire Sichuan Basin gradually exhibited a process of expansion and subsidence (Wang et al., 2002a, b; He et al., 2011; Li et al., 2011, 2012, 2013, 2014). Members 1–2 of the Dengying Formation were widely deposited in the basin, with the thickness decreasing slightly from the northwest side to the southeast.

Before deposition of $Є_1q$ (Fig. 13*b*–*d*). Owing to the Tongwan I movement, the Sichuan Basin was uplifted, making the second member of the Dengying Formation subjected to denudation at a large scale. Subsequently, Members 3–4 of the Dengying Formation directly covered the residual stratum of Members 1–2 of the Dengying Formation, with the thickness increasing slightly from the northwest side to the southeast (Fig. 13*b*).

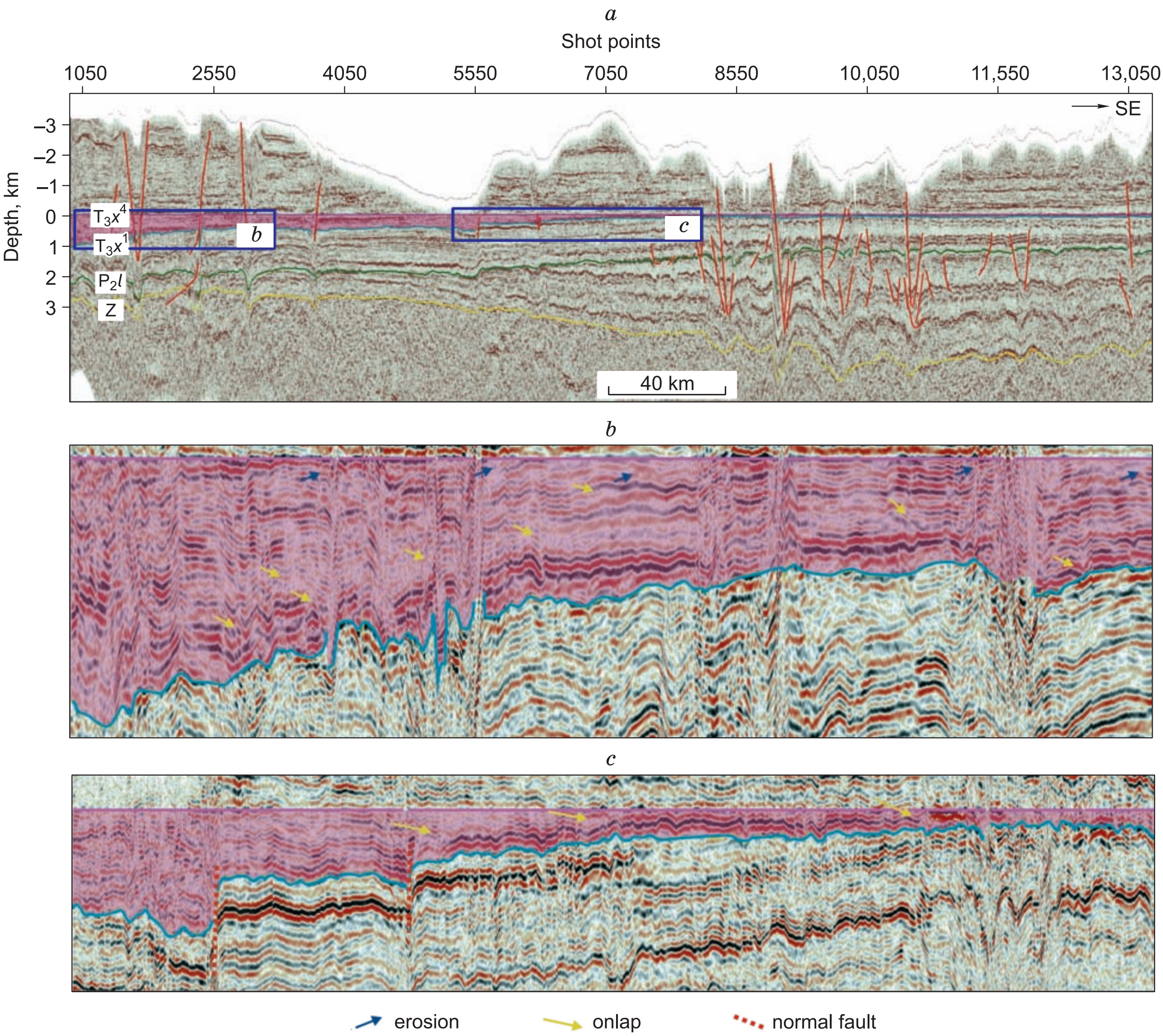

Fig. 10. Prototype basin and key geologic phenomena of the southern Sichuan Basin in the early Late Triassic (T_3x^1–T_3x^3).

Affected by the Tongwan II movement, the Sichuan Basin mainly experiences differential uplifting after the sedimentation of the Dengying Formation (Fig. 13*c*), having the stratum of the 3rd and 4th Members of the Dengying Formation denuded and flattened in the west of Longquan Mountain, only remaining a thin unit in the east.

Before deposition of $Є_1$l (Fig. 13*e*). After the Tongwan II movement, the Sichuan Basin overall subsided and accepted deposits, making an unconformity between the Qiongzhusi Formation and the residual stratum of the Dengying Formation, with the thickness increasing gradually from the west to the east of the basin. In this period, the Leshan–Longnvsi paleouplift became a miniature in the west of the Weiyuan area.

Before deposition of O_1n (Fig. 13*f*). In this tectonic background, the Leshan–Longnvsi paleouplift (Fig. 13*d*) 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 Laolongchang–Wutongchang field in the east, with the generally small thickness of the stratum from the west side to the east.

Before deposition of the Silurian (Fig. 13*g*). During the Ordovician, the tectonic setting of the basin was relatively quiet. It is characterized by extensive and stable deposition with a small and uniform thickness.

Before deposition of the Permian (Fig. 13*h*–*j*). In the Silurian, the Leshan–Longnvsi paleouplift (Fig. 13*d*) continually upheaved on the west side of the Sichuan Basin. As a result, it deposited huge sediments in the eastern part of the basin, whereas the sediments are quite thin at the core of the paleouplift (Fig. 13*h*). At the end of the Silurian, the Caledonian movement entered its peak period, making the Leshan–Longnvsi pale-

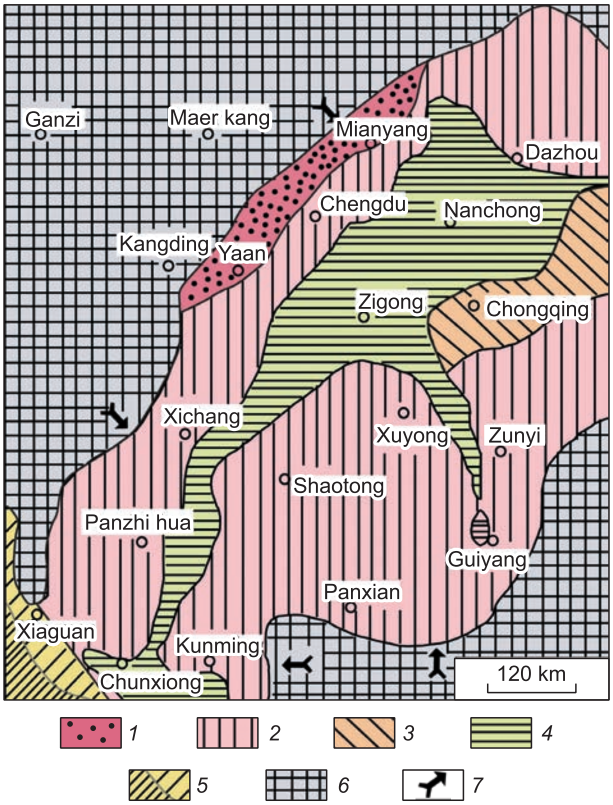

Fig. 11. Paleogeographic map of the Jurassic sedimentary facies in southwest China, modified from Li et al. (2011).

1, alluvial fan facies or alluvial plain facies; *2*, fluvial facies or lacustrine facies; *3*, lacustrine delta facies or lacustrine facies; *4*, fluvial alpine facies–lacustrine facies–swamp facies; *5*, alternate marine-terrestrial facies; *6*, mountain or hill areas; *7*, material transportation direction.

ouplift strongly upheaved vertically (Fig. 13*i*). Subsequently, the continuous differential uplift caused the Middle Sichuan and most of the Sichuan Basin to be exposed at the surface, which experienced long-term erosion and planation, leading to the extensive deletion of the Silurian, Ordovician, and Cambrian stratum in the field of the Leshan–Longnvsi paleouplift. The Leshan–Longnvsi paleouplift basically took shape during the period (Fig. 13*j*).

(2) P_2l–T_2l geologic periods

Before deposition of T_3x^1 (Fig. 13*j*). During the late Paleozoic–Middle Triassic, the tectonic dynamics was mainly manifested as the differential uplift of crust and epeirogenic movement in an extensional environment, a process in which the sea basin gradually shrank and the land gradually expanded (Li et al., 2011). At the beginning of the middle Permian, the crust entirely began to shake and sink, making the basin undergo a transgression once again. This resulted in a regional angular unconformity between the middle Permian and the lower Paleozoic stratum (Fig. 8*c*). In this period, the tectonic pattern of the Leshan–Longnvsi paleouplift changed little, whereas the Luzhou paleouplift (Fig. 13*k*) formed in this period, causing the sedimentary thickness of the middle Permian to Middle Triassic to gradually decrease from the northwest side to the southeast (Fig. 13*k*). Taking into account the regional geologic background, the evolution history, and characteristics of seismic profiles, we classify the prototype basin of the middle Permian and Middle Triassic as a marine intracratonic sag basin.

(3) T_3x^1–T_3x^3 geologic periods

Before deposition of T_3x^4 (Fig. 13*l*). Regionally, in the Carnian and Norian, there was no large-scale collision between the Qiangtang Block and Yangtze craton which could cause a horizontal compression geologic background, and most of the Songpan–Ganzi area in western Sichuan was still a passive continental margin (Meng Qingren et al., 2007). There was a faulted basin in front of Longmen Mountain, with Members 1–3 of the Xujiahe Formation successively depositing

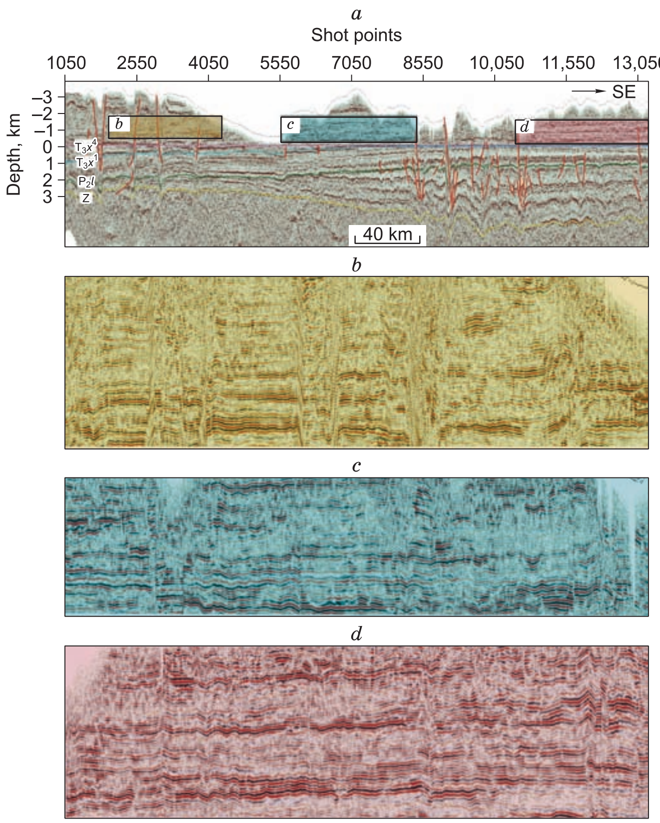

Fig. 12. Prototype basin and key geologic phenomena of the southern Sichuan Basin in the late Late Triassic–Jurassic (T_3x^4–J).

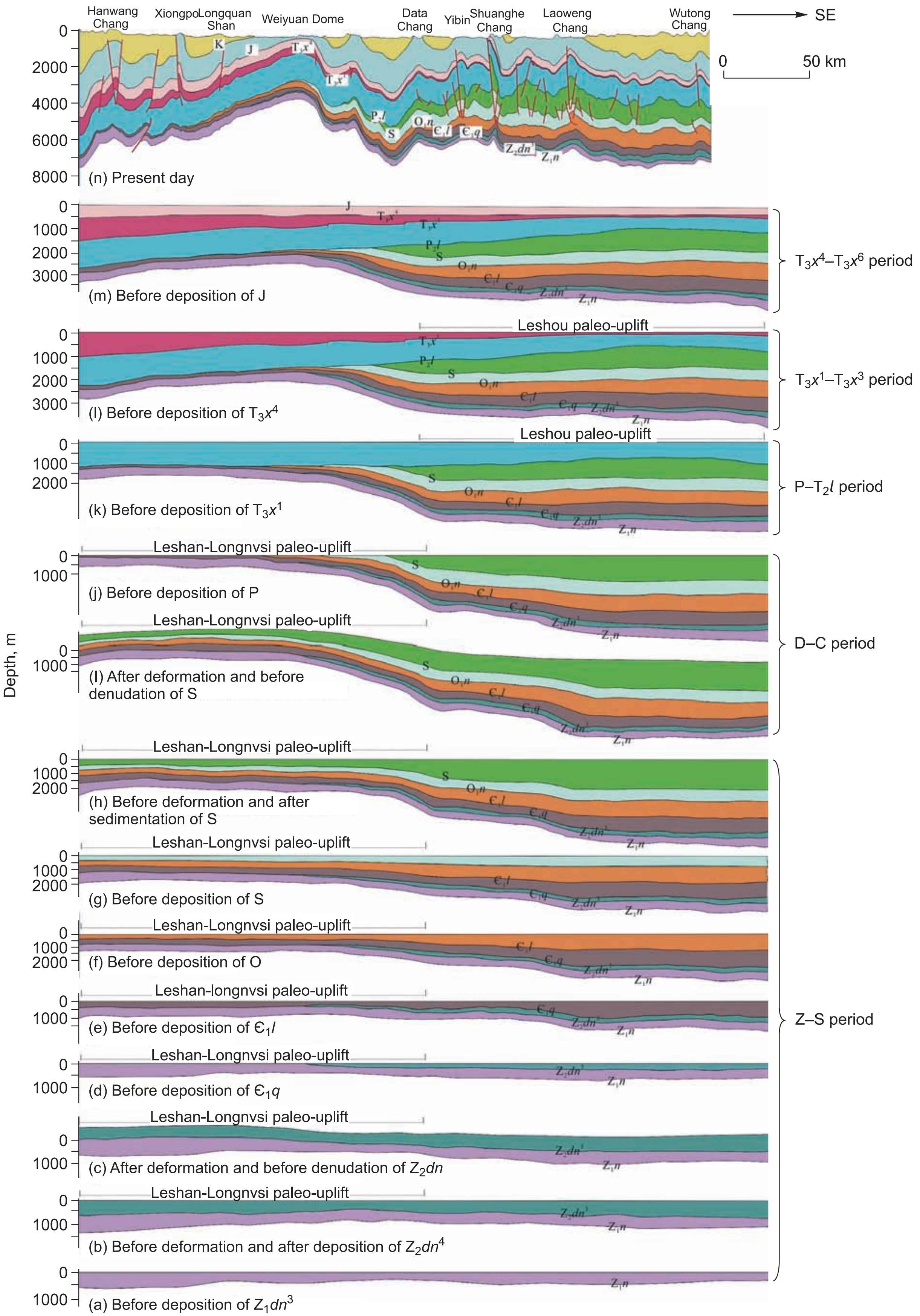

Fig. 13. Geologic evolution sections of the southern Sichuan Basin.

on the Middle Triassic stratum. The stratum gradually became thinner from the west side to the east, with some small normal faults developing inside. Taking into account the evolution history, sedimentary filling, and deformation characteristics, we believe that the basin is a marine and continental faulted basin in the deposition period of Members 1–3 of the Late Triassic.

(4) T_3x^4–J geologic periods

Before deposition of the Cretaceous (Fig. 13*m*). At the beginning of the Rhaetian (T_3x^4–T_3x^6), the Longmenshan and Songpan–Ganzi blocks continued to rise (Liu et al., 1996), whereas the basin still subsided extensively (Li et al., 2011, 2014). Before the deposition of the Jurassic System, Members 4–6 of the Xujiahe Formation began to deposit continuously throughout the basin. In the Jurassic, the tectonic movement was relatively weak. Widely deposited lacustrine red sand mudstone intercalated with shell limestone in the basin (Wang and Xu, 2001; He et al., 2011), mainly forming a large depression in a weak intracontinental extensional environment (Li and He, 2014). Moreover, the sedimentary characteristics of Member 4 of the Xujiahe Formation to the Jurassic stratum (tabular shape) indicate that no flexural subsidence occurred during the sedimentary period (Wang and Meng, 2008). That is, the foreland basin would not have formed at the front of Longmen Mountain in the Jurassic. Therefore, we classify the prototype of the regional basin as a continental depression in the late Late Triassic–Jurassic.

(5) K–Q geologic periods

Present day (Fig. 13*n*). In the Early Cretaceous, due to the subduction of the Indian Plate beneath the Eurasian Plate, the tectonic dynamic background of the regional basin changed from extension to compression with a shortening from northwest to southeast (Ren, 1987; Li 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 the Sichuan Basin undergo flexural subsidence, which deposited a thick Cretaceous stratum (Long et al., 2011). Under the influence of the Xishan movement, the Weiyuan dome gradually formed and became the highest structure at present, while the Leshan–Longnvsi paleouplift changed into a lower structure located on the slope of the Weiyuan dome. At the same time, the early prototype structures formed further, such as the Longquan Shan anticline on the west side of the Weiyuan dome and the Data Chang, Shuanghe Chang, Laoweng Chang, Wutong Chang, and other anticlines on 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 the Sichuan Basin, we think that the foreland basin evolution period (K–Q) was beginning from the Cretaceous.

Superimposed pattern of prototype basins

Since the Sinian, the Sichuan Basin has been involved in two evolution histories, including both the marine and terrestrial facies (Ma et al., 2009; Liu et al., 2017). At the end of the Middle Triassic, the Sichuan Basin ended off the evolution of marine sedimentation gradually transforming into the evolution of the terrestrial facies. The previous studies show that the transition from marine to terrestrial has a very close relationship with the structural coupling, which came from the Longmenshan orogenic belt, Songpan–Ganzi belt, and Sichuan Basin (the coupling of basin-range and basin-mountain). That is, the structural coupling of basin-range is changed to basin-mountain in which the tectonic dynamics changed from stretching to extrusion (Li et al., 2011). During the long geologic history, the sedimentary–tectonic evolution of the Sichuan Basin was comparatively complicated in that the changes of the properties and intensity of tectonic movement caused the crust quake of the 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. These stages form a superimposition of five types of prototype basins longitudinally as follows (bottom up order) (Fig. 14): marine rift craton basin (Z–S), marine intracraton 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" geologic structure of the multicycle basins.

The superimposition of multiple prototype basins is a combined effect of multiphase sea level fluctuation, multiphase tectonic activities and subsidence (He et al., 2008). Its essence is to form a set of reservoir and cap assemblages on the superimposition interface. Owing to the overlap of superposition interface, not only does it form the reservoir and cap assemblages, but also may lead to a superimposition of oil and gas reservoirs in different structural layers in space, forming the hydrocarbon accumulation area. The Proterozoic–Middle Triassic

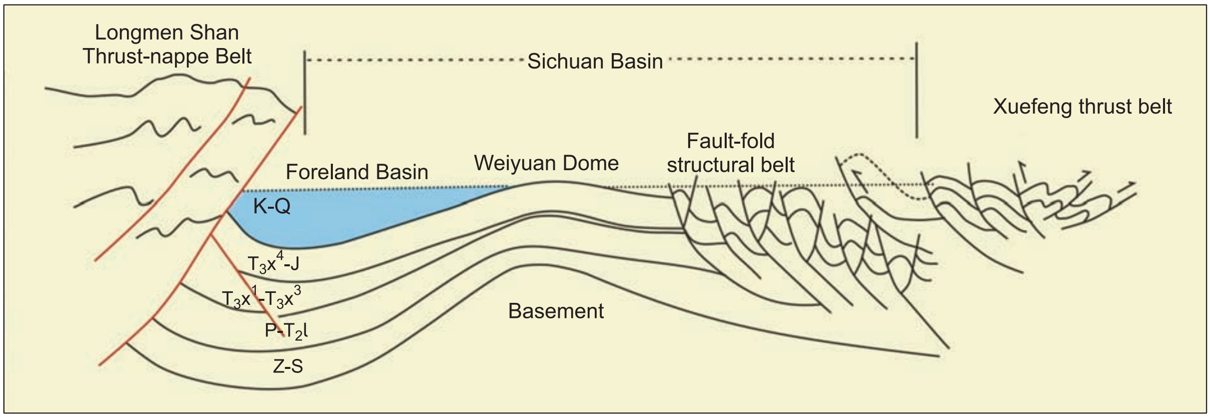

Fig. 14. Sketch of the superimposed pattern of the prototype basins in the southern Sichuan Basin.

sediments were mainly marine, with a thickness of 4000–7000 m in the southern Sichuan Basin (Li et al., 2011). In the marine strata, there are several sets of high-quality source rocks in different structural–sedimentary environments, such as a marine rift craton area, a marine intracraton sag area, and an alternate marine and terrestrial downfaulted area, which are superimposed with the reservoirs longitudinally, forming multiple oil–gas systems from the bottom up. Under the influence of the late stage tectonic transformation, the hydrocarbon accumulation in the southern Sichuan Basin has the characteristics of early accumulation and late adjustment. The previous research also shows that the gas resource occurrence is of "multiple strata, multiple types" in the area. All of them show the prospect of oil and gas in the southern Sichuan Basin has a huge potential for multilayer three-dimensional exploration.

CONCLUSIONS

By analyzing the sedimentary and structural characteristics of seismic reflection profiles, closely combined with tectonic evolution of the plates around the Upper Yangtze, we consider the geologic structure, development history of prototype basins, and their superimposed pattern of the southern Sichuan Basin. The conclusions of this study are as follows.

(1) Controlled by different vertical uplift of the crust and the activity of plates surrounding the Upper Yangtze, the southern Sichuan Basin underwent many tectonic movements with distinct deformations, resulting in five regional unconformities in the caprocks;

(2) The six tectonic layers distinguished based on the identified regional unconformities suggest that the study area was involved in the development of prototype basins in an oscillating crustal environment. From bottom to top, they are a marine rift craton basin (Z–S), a marine intracraton sag basin (P_2l–T_2l), an alternate marine and terrestrial downfaulted basin (T_3x^1–T_3x^3), a terrestrial depressed basin (T_3x^4–J), and a foreland basin (K–Q), respectively. These prototype basins are horizontally compounded and vertically superimposed, forming the "layered block" geologic structure of the multicycle basins;

(3) The essence of prototype basin superimposition is to form a set of reservoir and cap assemblages on the superimposition interface. This may lead to a superimposition of oil and gas reservoirs in different structural layers in space, forming the hydrocarbon accumulation area. Under the influence of the late-stage tectonic transformation, the hydrocarbon accumulation in the southern Sichuan Basin shows the characteristics of early accumulation and late adjustment and "multiple strata, multiple types" of gas resource occurrence.

This work was supported by the National Science and Technology Major Project of the Ministry of Science and Technology of China (Nos. 2016ZX05004-005, 2017ZX05008-001, and 2017ZX05008-005-003), the National Natural Science Foundation of China (No. 41672196), and the Sichuan Province Project (Nos. 2018TY0014, 2019YFS0076, KJ-2019-13).

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Рекомендована к печати
А.Э. Конторовичем

Поступила в редакцию 1 апреля 2019 г.,
принята в печать 27 ноября 2019 г.