

Research Article

Controls of Deep-Seated Faults and Folds on Hydrocarbon Fluid Migration and Accumulation in Sedimentary Basins: A Case Study from the Northwestern Sichuan Basin, China

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Deep-seated faults and folds of foreland basin systems have become important exploration targets in the recent years because they are crucial in controlling fluid migration and hydrocarbon accumulation. In this study, we analyzed the characteristics and formation history of these structures in the northwestern Sichuan Basin using recently acquired two-dimensional (2D) and three-dimensional (3D) seismic data. The seismic interpretation revealed that the thrust sheets, tectonic wedges, and foredeep were well developed in the northwestern Sichuan Basin from the mountain to the basin. Forward thrusts, fault-bend folds, and wedges are the main types of structures in the thrust sheets and tectonic wedges. The deep-seated faults and folds were easily recognized in the high-resolution 3D seismic data. The imbricate thrust faults that merged into detachment layers of the Lower Cambrian are the main types of structures in the foredeep, and they show a prominent strike-slip influence in the horizontal direction. The formation of these structures in the foredeep in the northwestern Sichuan Basin mainly endured two stages of thrusting, including those during the Middle-to-Late Triassic and Cenozoic. Based on the tectonic evolution and seismic data, we infer that these deep-seated faults and folds in the foredeep may have formed earlier than the northern Longmen Shan fold-and-thrust belts and they may have been initially active in the late of Early Triassic and reactive during the Cenozoic. Furthermore, evaporites in the Lower and Middle Triassic were crucial in forming these structures. The petroleum exploration data suggested that the deep-seated faults can facilitate hydrocarbon accumulation. The thrust faults in the foredeep were more likely to act as migration pathways for fluids instead of sealing barriers along the horizontal direction. The interconnected reservoirs of deep-seated folds possess a great potential to allow large-scale hydrocarbon accumulation. Our study provides a good example for evaluating the hydrocarbon exploration potential in the deeply buried area in the sedimentary basin.

1. Introduction

Fold-and-thrust belts are widely distributed in continental collision zones [1–3] and subduction belts [4–7] around the world, and they form the most important units of a fore-

land basin system. Several studies on the geometry [4–7], kinematics [2, 8], and formation mechanism [9–12] of fold-and-thrust belts have been conducted via different methods, such as seismic interpretation [13], numerical as well as physical modeling [14–18], and tectonic thermochronology [19,

20]. The broad fold-and-thrust systems exhibit various geometries and a combination of structural styles, including thick- and thin-skinned structures within and in front of orogenic belts [14]. From a mountain to a basin, tectonic wedges containing fault-bend folds as well as duplex structures, imbricated faults, back thrust structures, and fault propagation folds appear regularly, forming a complex structural system [9, 21–23]. Additionally, fold-and-thrust belts have become the most prolific hydrocarbon provinces of the world owing to the presence of these diverse structures along with a combination of other petroleum conditions [24]. However, owing to the restrictions in petroleum exploration, most hydrocarbons have been found in the thrust wedges or hanging walls of thrust faults, such as in the Zagros and North American fold-and-thrust belts [25, 26]. The characteristics of the deep-seated buried faults and folds in the foredeep, as well as their relationship with hydrocarbon fluid accumulation, are still poorly understood and also limit our understanding of the formation of deep-seated reservoirs.

With an area of approximately $1.8 \times 10^5 \text{ km}^2$, the Sichuan Basin is the most important gas-production field in China, with a total amount of produced natural gas resources reaching $14.33 \times 10^{12} \text{ m}^3$ [27]. The Longmen Shan fold-and-thrust belt (LSB) along the eastern margin of the Tibetan Plateau defines the west boundary of the Sichuan Basin, which is one of the largest active fold-and-thrust belts in western China with intricate structures and sedimentary sequences as well as a complex petroleum system. The peaks of the LSB are composed of Proterozoic granites and metamorphic rocks of the Yangtze Craton, which is similar to the basement of the Sichuan Basin. Nevertheless, within 50 km of distance across the LSB, the elevation drops from $\sim 4000 \text{ m}$ in the Tibetan Plateau to $\sim 500 \text{ m}$ in the Sichuan Basin. Therefore, the LSB can be defined as an area developing series of parallel NW-dipping thrust faults and forming extremely steep topographic gradient between the Tibetan Plateau and the Sichuan Basin. Previous studies and explorations focused on the thrust wedges in the Longmen Shan area but pay little attention to the footwall of the LSB. Since 2014, wells with depths over 7000 m, which is generally considered as the extremely deep buried strata, drilled through the wedges and adjacent foredeep in the northwestern Sichuan Basin, have suggested that the deeply buried areas of the basin possess great potential to allow hydrocarbon accumulation [28, 29]. However, the characteristics of deep-seated structures, the formation relationships among these structures, the evolution of fold-and-thrust belts, and the accumulation of hydrocarbon accumulation remain unknown and are currently under investigation. In this study, combined with the oil production data, we used recently acquired high-resolution seismic and well data to characterize deep-seated thrust faults and related folds and discuss the influence of the formation and activities of these structures on the accumulation and migration of hydrocarbon fluids.

2. Geological Setting

The Sichuan Basin is a rhombus-shaped, superimposed basin in western China (Figures 1(a) and 1(b)). Geotectonically, the most impressive characteristic of the Sichuan Basin

is that it is bound by several large fold-and-thrust belts, including the Longmen Shan to the northwest, Micang Shan and Daba Shan to the northeast, Huanan–Hubei–Guizhou to the southeast, and Kangdian to the southwest (Figure 1(b)). The basin can be divided into six units based on their tectonic characteristics (Figure 1(b)). The LSB contains three segments (northern, middle, and southern segments), which are divided by the cities of Anxian and Dujiangyan according to geological characteristics, topography, and seismic activities [30–32]. The northern LSB is located between the cities of Anxian and Guanyuan with a total length of over 200 km and a width of roughly over 30 km (Figure 1(c)). It comprises three major NW-dipping parallel thrust fault systems from NW to SE—the Qingchuan, Beichuan, and Majiaoba Faults (Figure 1(c)). Major structures are developed in front of the northern LSB, including the Zhongba, Haitangpu, Shuangyushi, Tianjingshan, Kuangshanliang, Shejianhe, Hewanchang, and Tongziguang [28]. In the case of Longmen Shan Mountain, the Tangwangzhai Nappe comprises a Silurian to Devonian and Jiaoziding domal complex that comprises rock massif, Sinian, and Paleozoic strata that were exhumated to the ground surface (Figure 1(c)). In front of the thrust wedges, it developed the large buried thrust fault F1 and several small-scale thrust faults, which are predominately NE-trending (Figure 1(d)). This foredeep area, which is our main concern, developed adjacent to the thrusts of the northern LSB.

The northwestern Sichuan Basin developed on the rigid Presinian basement of the Yangtze Craton [33–35]. The sedimentary cover comprises well-documented strata with a total thickness of over 10 km (Figure 2). The cratonic evolutionary stage deposited thick oceanic sediments from the Neoproterozoic to the Middle Triassic, including the sediments of the carbonate platform and passive continental margin [28, 36]. After intensive orogenic activities during the Late Triassic, the front of the northern LSB mainly deposited clastic sediments of continental foreland basin and depression from the Late Triassic to the Early Cretaceous (Figure 2). Strata from the Middle Cretaceous to the Neogene are not recorded in this area, and the Quaternary is sporadically distributed. Three regional detachments in the northwestern Sichuan Basin have developed in the Triassic evaporites from the Jialingjiang and Leikoupo Formations, Paleozoic shales from the Longmaxi Formation and the Upper Ordovician, and Cambrian shales and evaporites [37].

3. Data and Methods

Twenty-eight seismic cross-sections from the three-dimensional (3D) volume of the northwestern Sichuan Basin were collected from Southwest Oil and Gas Field Company, PetroChina and used for the seismic interpretation and building a 3D model (Figure 1(d)). Most of the seismic data possess a vertical axis in milliseconds and have not been depth-converted except for Line AA', which comes across the thrust sheets to the mountainside (Figure 1(d)). The earthquake data were collected from the database of the USGS (<https://earthquake.usgs.gov/>). The drilling-well and oil-production data were collected from Southwest Oil and Gas Field Company, PetroChina,

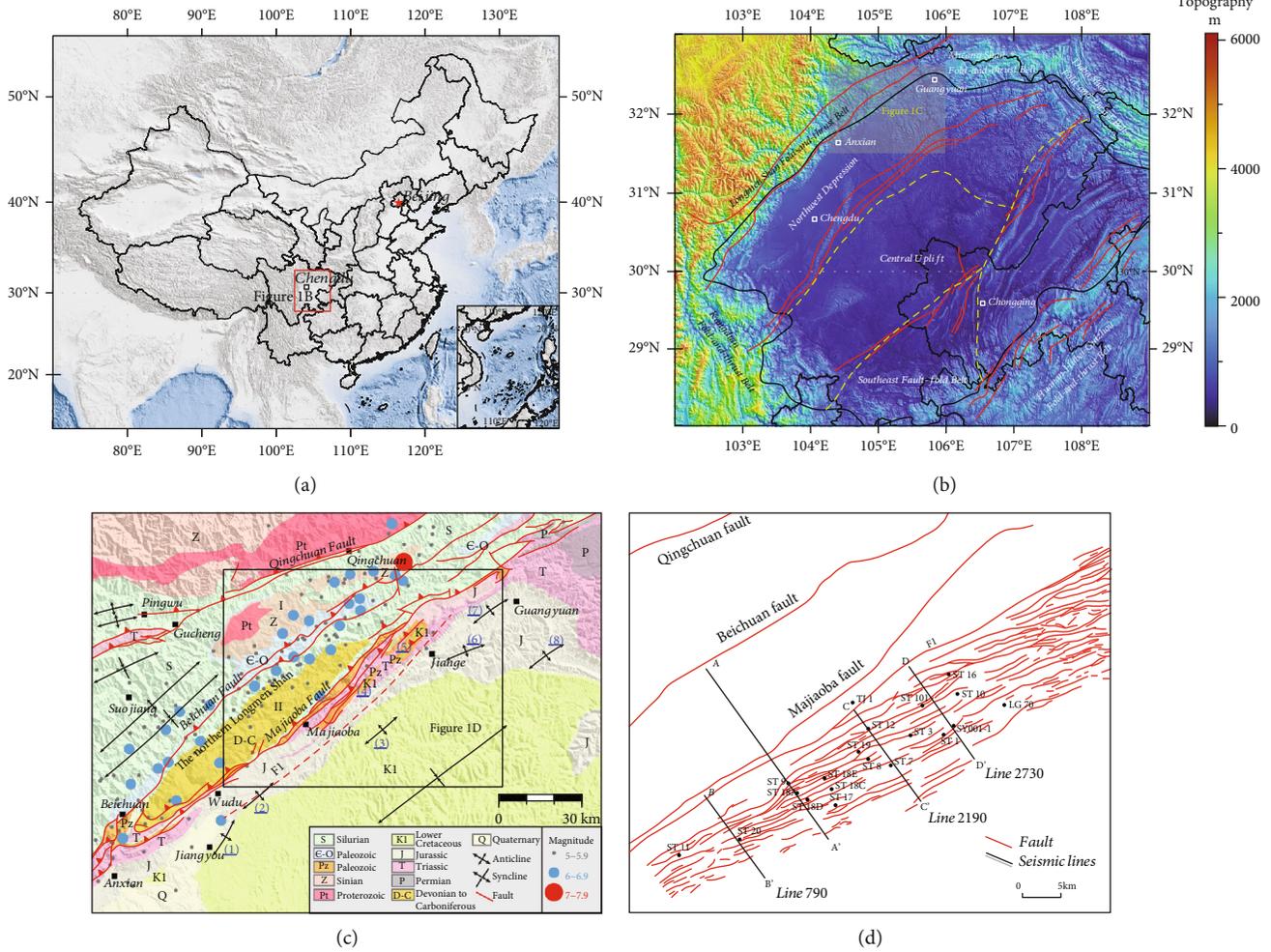


FIGURE 1: Maps showing the location of Sichuan Basin, tectonic units (modified after the Southwest Oil and Gas Field Company, PetroChina) in and surrounding the Sichuan Basin (the SRTM data are from the CGIAR). The geological map showing the basic geology around the northern Longmen Shan area [36]. The structural map of the Permian showing the seismic lines and fault distribution of the study area (modified after the Southwest Oil and Gas Field Company, PetroChina). The structures of Figure 2(c): I: Jiaoziding thrust nappe; II: Tangwangzhai thrust nappe; (1) Zhongba anticline; (2) Haitangpu anticline; (3) Shuangyushi anticline; (4) Tianjingshan anticline; (5) Kuangshanliang anticline; (6) Shejianhe anticline; (7) Hwanchang anticline; (8) Tongziguan anticline.

for analyzing the relationship between the deep-seated structures and hydrocarbon accumulation.

We adopted the following methods and workflows for conducting the seismic interpretation. Well-recognized signs were used in interpreting the faults and folds, such as fault cutoffs, discontinuity of reflectors, fault surface reflectors, bent strata, and fold axis. Classical models of thrust faults and fault-related folds were used for poorly imaged areas to identify the characteristics of structural combination, particularly for the deeply buried structures [21, 22, 38, 39]. For the long profiles that cut into the thrust sheets, we used the earthquake data to confine the position of faults. Based on seismic layers, which were calibrated by the Southwest Oil and Gas Field Company, PetroChina, the final relationship between the strata and faults was determined.

4. Deformation Characteristics of Deep-Seated Faults and Folds in Northwestern Sichuan Basin

4.1. Characteristics of Thrust Sheets. High-resolution section AA' reflects the thrust sheets of the northern Longmen Shan from the Majiaoba Fault to the mountainside (Figure 3). This depth-converted section shows the thickness of sedimentary cover and development of deep structures at approximately 10 km in depth. In the seismic profile, the reflectors of the thrust sheets exhibit a strongly bent shape as well as the fault cutoffs, fault surface reflectors, and rapid changes in the occurrence of strata can be easily recognized as the development of faults. The thrust sheets were interpreted as an NW-dipping imbricated fault system with the development of an apparently bent fault surface and fault-

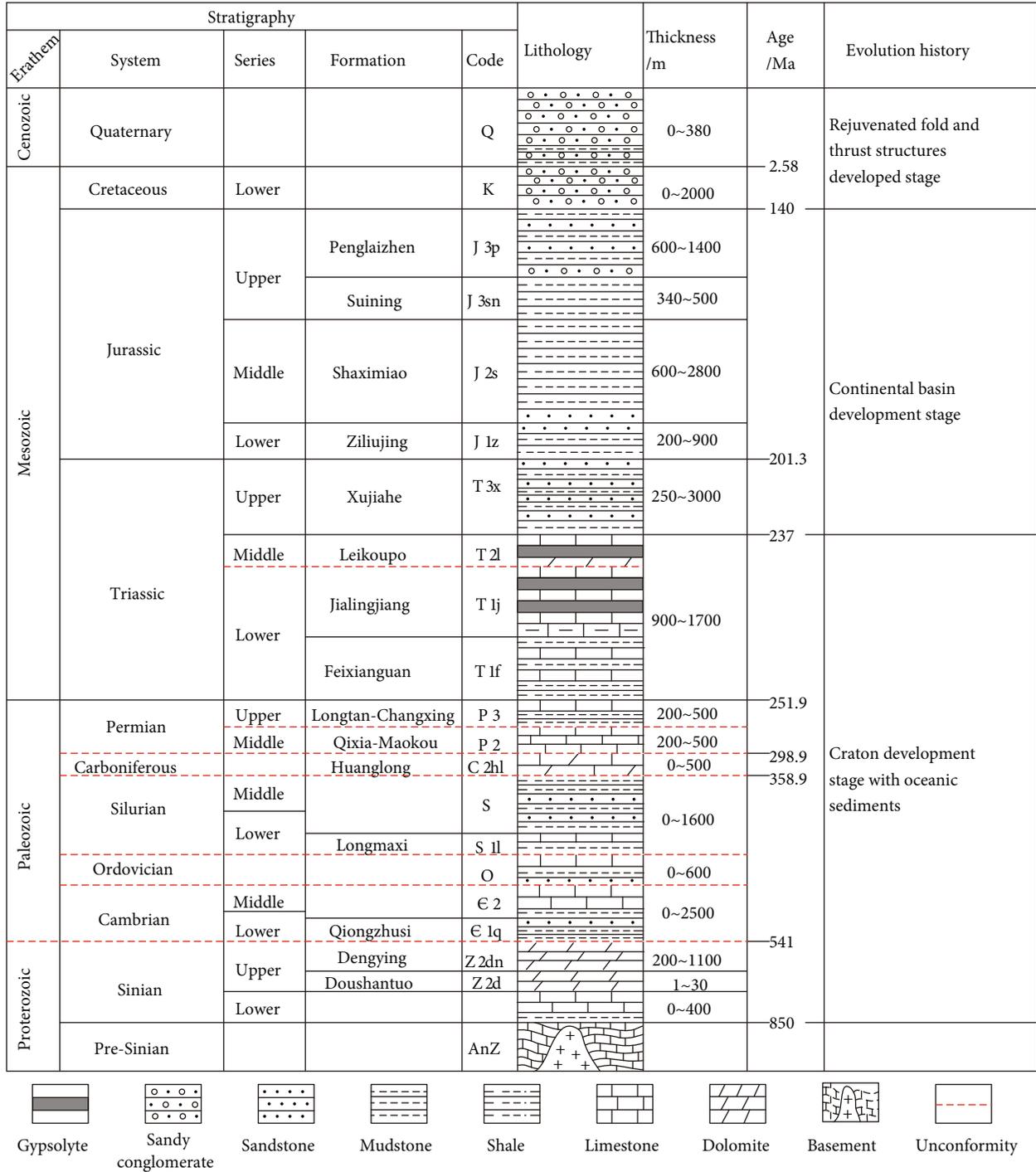


FIGURE 2: A diagram showing the stratigraphic sequence of the northern Longmen Shan area (modified after the Southwest Oil and Gas Field Company, PetroChina).

bend folds (Figure 3). The hanging wall of the Majiaoba Fault is mainly composed of Paleozoic strata, which are the core of the Tangwangzhai Nappe. The thrust sheets burying in the basin mainly involved the Paleozoic and Triassic strata. Near the surface, the Jurassic strata were deformed, forming a small anticline, which is well constrained by surface geology data (Figure 3). For the deeply buried area,

these thrust faults lie nearly parallel to each other and the dip angles become gentler moving from the upper to the lower parts. Earthquake records (Ms 4.9, 11-07-2014) may testify to the possible position and activity of the faults (Figure 3). The time-migrated section BB' reveals a part of the thrust sheets but does not reach the Majiaoba Fault (Figure 4). Moreover, it shows a bent fault surface and strata.

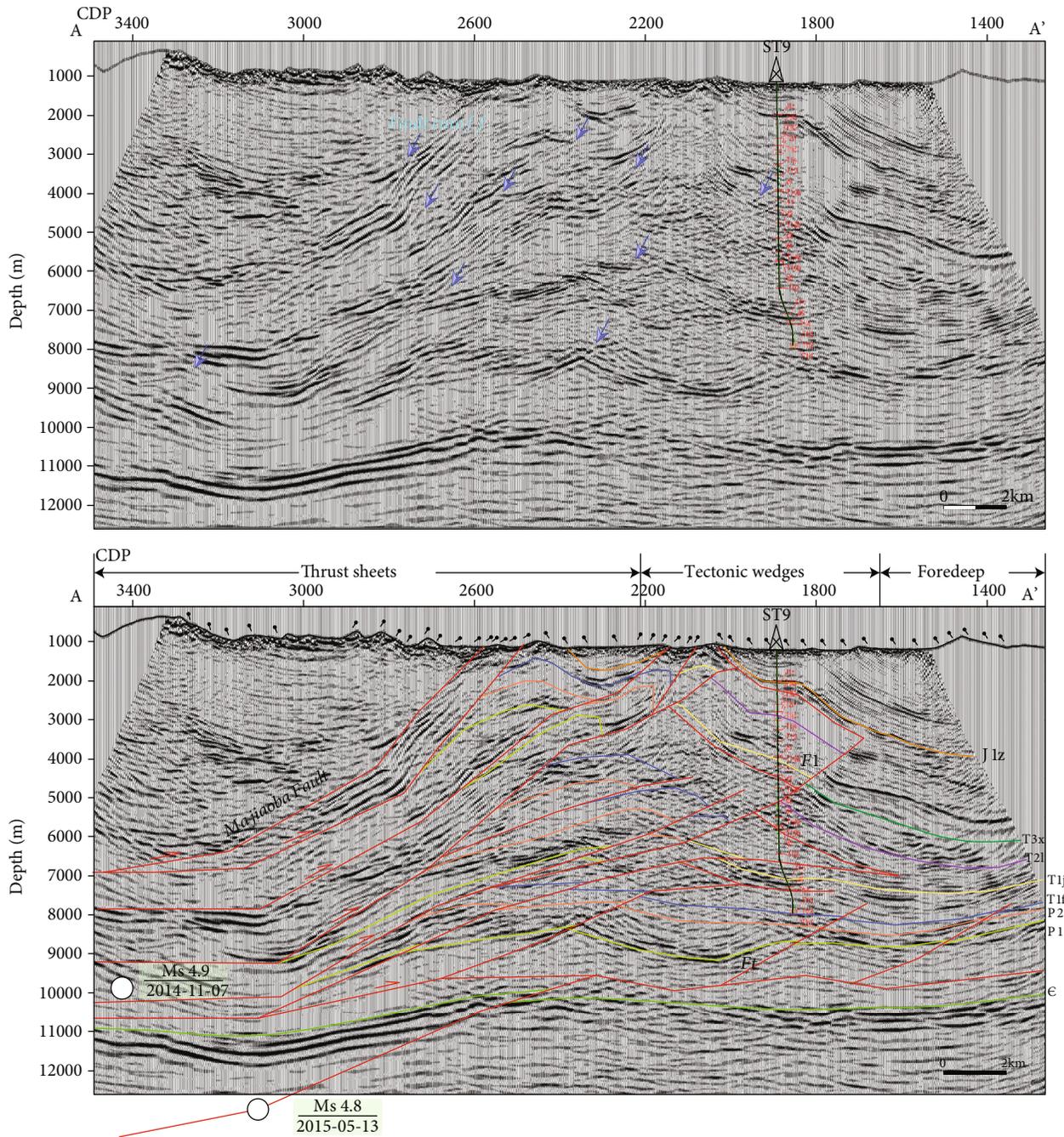


FIGURE 3: Uninterpreted (top) and interpreted (bottom) seismic profiles (2D data) across ST9 well in the northern Longmen Shan area, showing the characteristics of thrust sheets, tectonic wedges, and foredeep. The vertical axis is in meters. The earthquake data are from the database of USGS (<https://earthquake.usgs.gov/>). The location of this seismic line can be found in Figure 1(d). The full names of abbreviations of the strata can be found in Figure 2. Courtesy of the Southwest Oil and Gas Field Company, PetroChina for the seismic and surface geological data.

The hanging wall of the thrust faults in this section may deform part of the Triassic strata. Here, the unconformity between the Triassic and the Jurassic is more prominent, which manifests as different strata occurrences (Figure 4).

4.2. *Characteristics of Tectonic Wedges.* Tectonic wedges are clearly shown in seismic sections AA' and BB' (Figures 3

and 4). Intensive structural deformation made the seismic reflectors indistinguishable, affording inconclusive interpretation results. In section AA' (Figure 3), the limited recognizable reflectors exhibit a dip along the direction opposite to that of strata approximately between 1000 and 7000 m, whereas those approximately from 6000 to 7000 m of well ST9 roughly exhibit a wedge shape (Figure 3). We

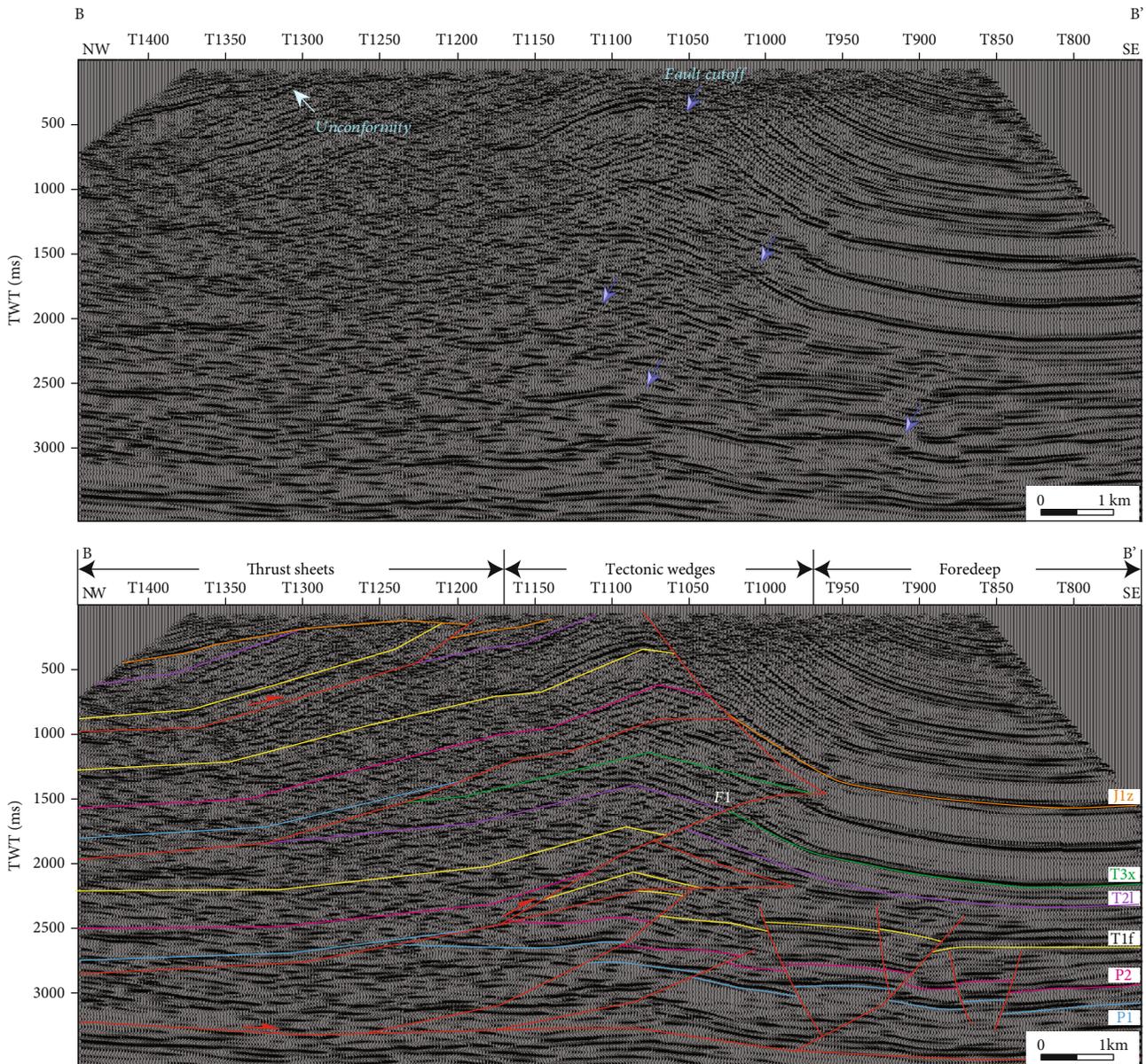


FIGURE 4: Uninterpreted (top) and interpreted (bottom) seismic profiles (3D data) in the northern Longmen Shan area (BB', Line 790), showing the characteristics of thrust sheets, tectonic wedges, and foredeep. The location of this seismic line can be found in Figure 1(d). The vertical axis is in milliseconds and not converted to depth. The full names of abbreviations of the strata can be found in Figure 2. Courtesy of the Southwest Oil and Gas Field Company, PetroChina.

interpreted these structures as tectonic wedges in front of the thrust sheets based on common wedge models [1, 7].

The F1 Fault is the main buried-blind fault of the tectonic wedges (Figures 3 and 4), which cuts off the sedimentary cover from the Cambrian to the Triassic and is truncated by the latter. The fault surface of the F1 Fault presents alternating fault flats and slopes, and the lower part of the fault surface is nearly parallel to the faults of the thrust sheets. For the upper part, the F1 Fault developed a small branch that cut into the Feixianguan Formation of the Triassic. Two conjugate faults may have developed in the tectonic wedges of the F1 Fault, and they separately exist in the Feixi-

anguan and Leikoupo Formations of the Triassic. These conjugate faults are supported by the seismic reflectors and cutoffs of the drill well (Figure 3). The lower conjugate fault in the Feixianguan Formation acts as an apparent boundary between SE-dipping strata above and chaotic seismic reflectors below. Furthermore, the upper conjugate fault acts as a boundary for different types of reflectors and it can be constrained by the surface geology data (Figure 3). The deformation of the Jurassic strata was possibly controlled by the upper conjugate fault. Below the two conjugate faults of the wedge, the hanging wall of the F1 Fault most likely shows breakthrough fault propagation folds, with the top

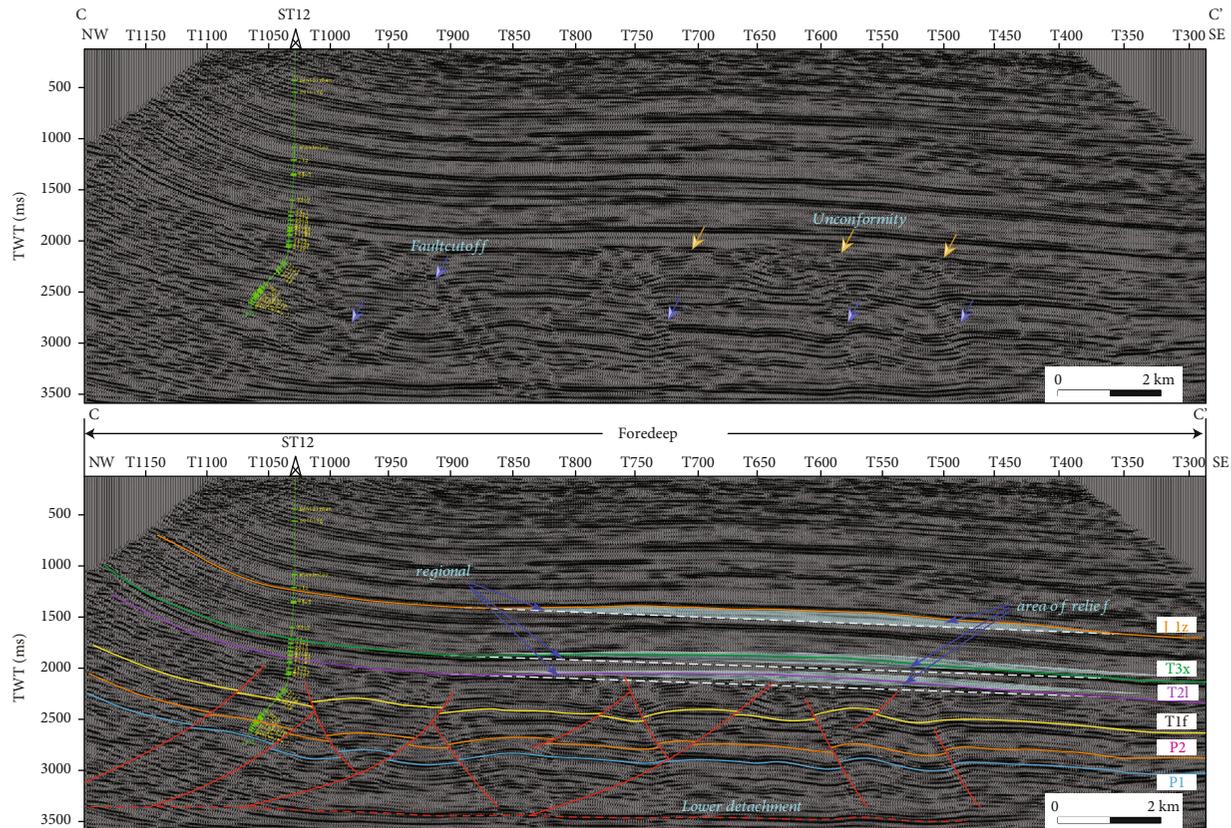


FIGURE 5: Uninterpreted (top) and interpreted (bottom) seismic profiles in the northern Longmen Shan area (CC', Line 2190), showing the characteristics of foredeep. The location of this seismic line can be found in Figure 1(d). The vertical axis is in milliseconds and not converted to depth. The full names of abbreviations of the strata can be found in Figure 2. Courtesy of the Southwest Oil and Gas Field Company, PetroChina.

strata truncated by the conjugate faults of the tectonic wedges [39]. The footwall of the F1 Fault may have developed two small wedges in the Lower and Middle Triassic, according to ideal models [39]. Because of the influence of the evaporite layers of the Jialingjiang and Leikoupo Formations of the Triassic, the strata became thicker than the normal layers. Buried below the wedges, the imbricate thrust faults that cut off the Paleozoic and Lower Triassic strata developed and they possibly merged into a detachment of the Lower Cambrian. Under these imbricate thrust faults, another thrust fault cut into the basement and formed a fault-bend fold, as may be inferred from earthquakes (Ms 4.8, 2015-05-13) and fault cutoffs.

The tectonic wedges can be recognized from 1000 to 2000 ms in section BB' from the 3D seismic volume (Figure 4). The blind F1 Fault acted as the dominant fault in the wedge with the development of a conjugate fault, which dipped the strata in opposite directions (Figure 4). The fault surface of the F1 Fault is much deeper in the upper part and then becomes nearly horizontal in the lower part. The hanging wall of the F1 Fault is interpreted as fault-bend folds. The footwall of the F1 Fault developed another small wedge within the Feixianguan Formation. The faults in the wedge connect with the F1 Fault, manifesting as

branches of it (Figure 4). The Jurassic and Middle-to-Upper Triassic show a similar deformation. Like section AA', an imbricate fault system developed below the wedges, which may merge into the nearly horizontal detachment fault at the Lower Cambrian.

Overall, the development of tectonic wedges in the northwestern Sichuan Basin shows apparent vertical stratification, including the wedges in the upper part and the buried imbricate thrust faults as well as nearly horizontal detachment in the lower part. The development of wedges and deformation of strata were highly influenced by the fault geometry.

4.3. Characteristics of the Buried Foredeep. The high-resolution 3D seismic data allows us to easily recognize the deep-seated faults and folds in the buried foredeep. Sections CC' and DD' were used for revealing the characteristics of the deformation of the foredeep (Figures 5 and 6).

Similar to the vertical stratification of tectonic wedges, the buried foredeep can be divided into two tectonic layers, which are separated by the evaporites of the Lower Triassic and unconformities between the Lower and Middle Triassic. The upper tectonic layers, which comprise the Middle-to-Upper Triassic, Jurassic, and Cretaceous, generally have

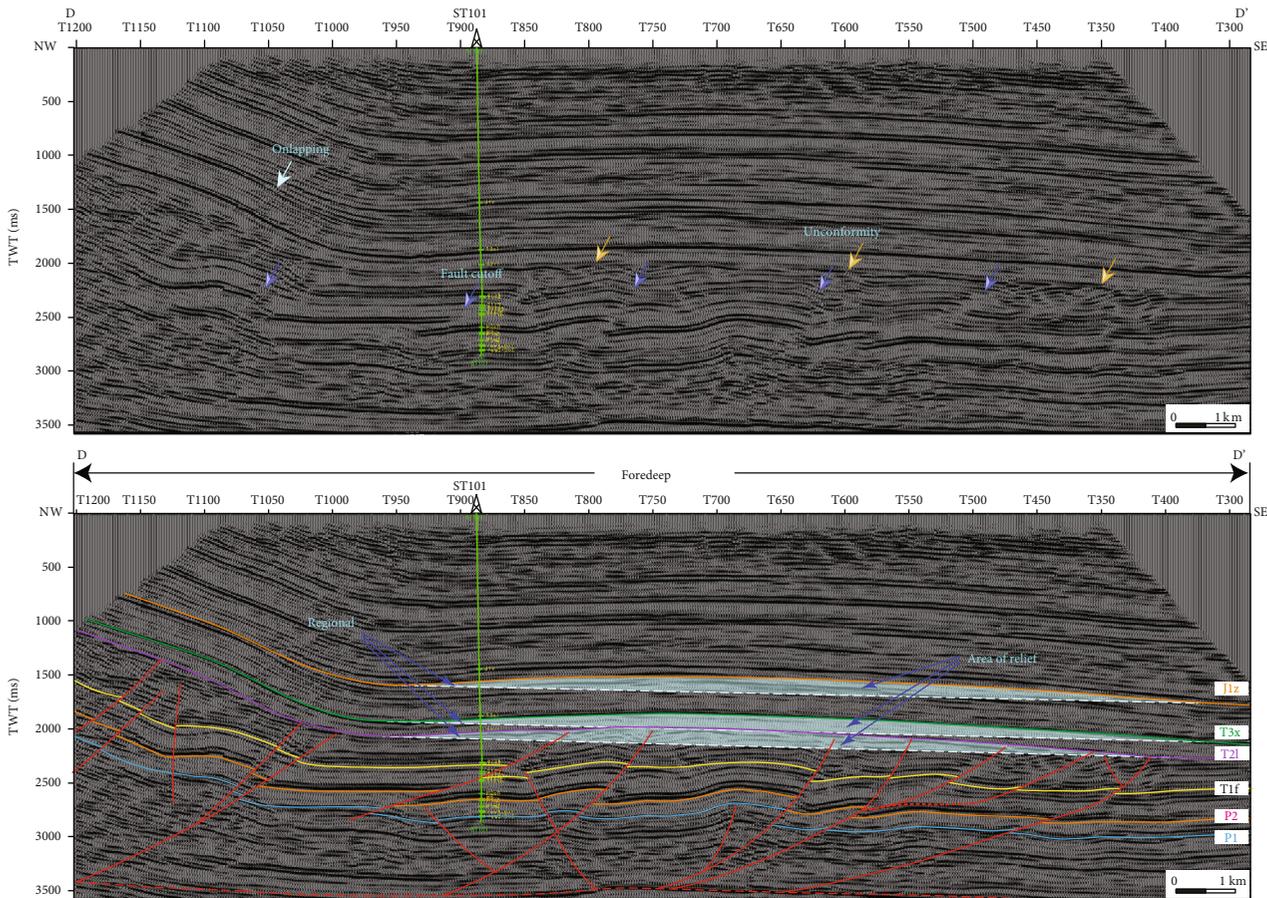


FIGURE 6: Uninterpreted (top) and interpreted (bottom) seismic profiles in the northern Longmen Shan area (DD', Line 2730), showing the characteristics of foredeep. The location of this seismic line can be found in Figure 1(d). The vertical axis is in milliseconds and not converted to depth. The full names of abbreviations of the strata can be found in Figure 2. Courtesy of the Southwest Oil and Gas Field Company, PetroChina.

similar occurrences of bent strata near the mountain. Based on the regional lines of these profiles, it was determined that a wide, open detachment fold was developed from the Late Early Triassic to Jurassic, showing an apparent area of relief (Figures 5 and 6). There are no apparent faults developed in the upper tectonic layers. Between the detachment layers of the evaporites of the Jialingjiang and Leikoupo Formations of the Triassic and shales as well as evaporites of the Middle-to-Lower and Middle Cambrian, the strata were deformed by forming imbricate fault systems, as described by the models. Additionally, some thrust faults developed antithetic faults, forming pop-up structures (Figures 5 and 6). For the bottom of these structures, the imbricate thrust faults may merge into the detachment fault of the Lower Cambrian (Figure 4), though some seismic data are not well exposed to the reflectors in the deep area. Near the mountainside, the Paleozoic and Middle as well as Lower Triassic strata are bent together because of the possible influence of the detachment fault in the deep of the section (Figures 5 and 6). To the basinward, the thickness of all groups of strata is nearly consistent, except for the Feixianguan Formation, which shows deformed reflectors under the influence of evaporites (Figures 5 and 6).

In the map view, the distribution of these imbricate thrust faults in the foredeep is predominantly NE-trending along the F1 and Majiaoba Faults (Figure 1(d)). Only a few small-scale faults are NW-trending. Most of the thrust faults distribute nearly parallel to each other, and some of these faults show inconspicuous *en échelon* patterns, such as in the area surrounding ST 20 well. Another noticeable feature of these thrust faults is that they usually have limited length and continuity, and they seldom connect with each other.

5. Discussions

5.1. Formation of Deep-Seated Faults and Folds in Foredeep and Their Relationship with the Longmen Shan Fold-and-Thrust Belts

5.1.1. Evolution of the Northern Longmen Shan Fold-and-Thrust Belts. Despite current observations of compressional structures being dominant in the entire Longmen Shan area, the structural deformation may still have endured a complex evolutionary history. Particularly, it may contain an extensional stage from the Neoproterozoic to the

Middle Triassic and a compressional stage since the Late Triassic [34, 37, 40–42].

The sedimentary sequences reflect that the western Sichuan Basin and the Longmen Shan area were mainly passive-continental deposited with the development of a carbonate platform under the extensional environment from the Neoproterozoic to the Middle Triassic, which formed several synsedimentary normal faults [42]. Owing to the influence of the breakup of the Rodinia Supercontinent, the Sichuan Basin was in an extensional environment during the Neoproterozoic [34, 43, 44], developing the carbonate sedimentation of the continental shelf [42]. From the Cambrian to the Ordovician, the western Sichuan Basin and Longmen Shan area deposited a limited number of clastic rocks to the west of the basin and carbonate deposition to the east [45]. From the Silurian to the Carboniferous, these areas deposited thick clastic and carbonate sediments to the west and the strata thin to the east [42, 46]. The deposition of the Permian was controlled by the regional extensional environments, with the deposition of a carbonate slope and rimmed platform [47]. The Early–Middle Triassic deposition of these areas mainly contains a carbonate platform with the development of multiple layers of evaporites [48], and the extensional setting generally stopped and changed into a compressional environment at the Late Triassic [37, 40, 42]. This transition of the stress field may have been recorded by the deformed structures, such as the Kuangshanliang and Jiulongshan anticlines and Majiaoba and Beichuan–Yingxiu Faults in the northern Longmen Shan area [29, 40, 42].

Along with the transition of the stress field in the Late Triassic, the previously normal faults were inverted into thrust faults. Two main compressional stages can be recognized in the northern Longmen Shan area. The main shortening was recorded by the formation of NE-trending thrust faults and the folds associated with them because of the closure of the Songpan–Ganzi Oceanic Basin in the Late Triassic, forming the foreland basin system [3, 35]. The foreland basin commonly developed the orogenic wedge, foredeep, forebulge, and back-bulge from the orogeny belts to the cratons [49, 50]. The development of foreland basin usually endures intensive plate subduction or collision, forming highly deformed fold-and-thrust belts in the orogenic wedges. The thrust sheets and tectonic wedges of the northern Longmen Shan act as part of the orogenic wedge of the western Sichuan foreland basin system (Figures 3 and 4). Our seismic interpretation reflects that the foredeep is well developed in this area (Figures 5 and 6). The highly deformed Triassic and Paleozoic strata that are cut off by the thrust fault system and the unconformities between the Triassic and the Jurassic (Figures 3–6) suggest the massive uplift and deformation of the northern LSB, which initially occurred during the Indosinian tectonic movement. This is supported by the field structural deformation, chronology data, and sedimentary records [51–54]. The mountain-source molasse deposition and close relationship between the uplift of the Longmen Shan and the subsidence history of the Sichuan Basin reflect the coupling of two tectonic units [32, 51]. Another shortened event occurred since the Cenozoic, which is recorded by huge differences in topogra-

phy between Tibet and Sichuan Basin, deformed and growth strata of the Late Mesozoic, and intensive earthquake events [3, 19, 55–58]. Different ideas proposed to explain the huge topography differences between Tibet and Sichuan Basin and the deformation of LSB in the Cenozoic, including the right-lateral strike-slip of LSBs [56, 59], lower-crust channel flow [35], and brittle crustal shortening [60].

5.1.2. Formation of Deep-Seated Faults and Folds and Their Relationship with the Fold-and-Thrust Belts. The formation periods of these deep-seated faults and folds are hotly debated, and two theories have been advanced: early formation during the Indosinian and late formation during the Cenozoic. Our seismic interpretation reflects that the strata in the foredeep are deformed, forming prominent imbricate and conjugate faults between the Lower Triassic and Paleozoic (Figures 3–6). All these faults merged into the deep detachment in the Lower Paleozoic and extended to the orogenic wedges, and the deep-seated faults and folds are more developed in the northeastern part of the study area (Figure 7). The seismic data suggested that the imbricate thrust faults were developed in the Paleozoic and Lower Triassic strata but did not cut through the Lower Triassic. The relatively regular seismic reflectors in the Lower Triassic are truncated at the top of their imbricate fans, reflecting the existence of unconformity between the Lower and Middle Triassic (Figures 5 and 6). The thickness of strata from the Paleozoic to Lower Triassic is quite stable with no apparent development of growth strata at the top of the fault-related fold, implying the formation of these faults may have endured a short period. The Late Triassic presents integrated contact with the upper and lower strata, and there are no prominent unconformities between the Triassic and the Jurassic. Influenced by the ductile evaporites in the Feixianguan Formation of the Lower Triassic, an upright, open detachment fold was developed from the upper part of the Lower Triassic to the Jurassic; a stable area of relief can be observed by recognizing the regional lines, suggesting this open detachment fold may have formed during the Cenozoic (Figures 5 and 6). The strata from the Paleozoic to the Jurassic and Cretaceous were bent together, showing that they deformed under the same tectonic movements in the Cenozoic. Based on these pieces of evidence, we infer that the deep-seated structures in the foredeep may have initially formed during the late of Early Triassic and were reactive at the Cenozoic. Furthermore, the detachment layers in the Lower Triassic and Lower Paleozoic played an important role in the formation of these structures (Figures 3–6). Therefore, along with the structural characteristics of the northern Longmen Shan area and the deep-seated faults and folds in the foredeep, we think the formation of the deep-seated thrust faults occurred slightly earlier than the uplift of the northern Longmen Shan fold-and-thrust belt, which may have mainly uplifted in the Late Triassic. During the Cenozoic, both the structures in the northern Longmen Shan and foredeep were deformed again, forming the open folds in the foredeep.

Limited seismic data revealed that the deep-seated faults and folds at the footwall of the thrust faults of tectonic

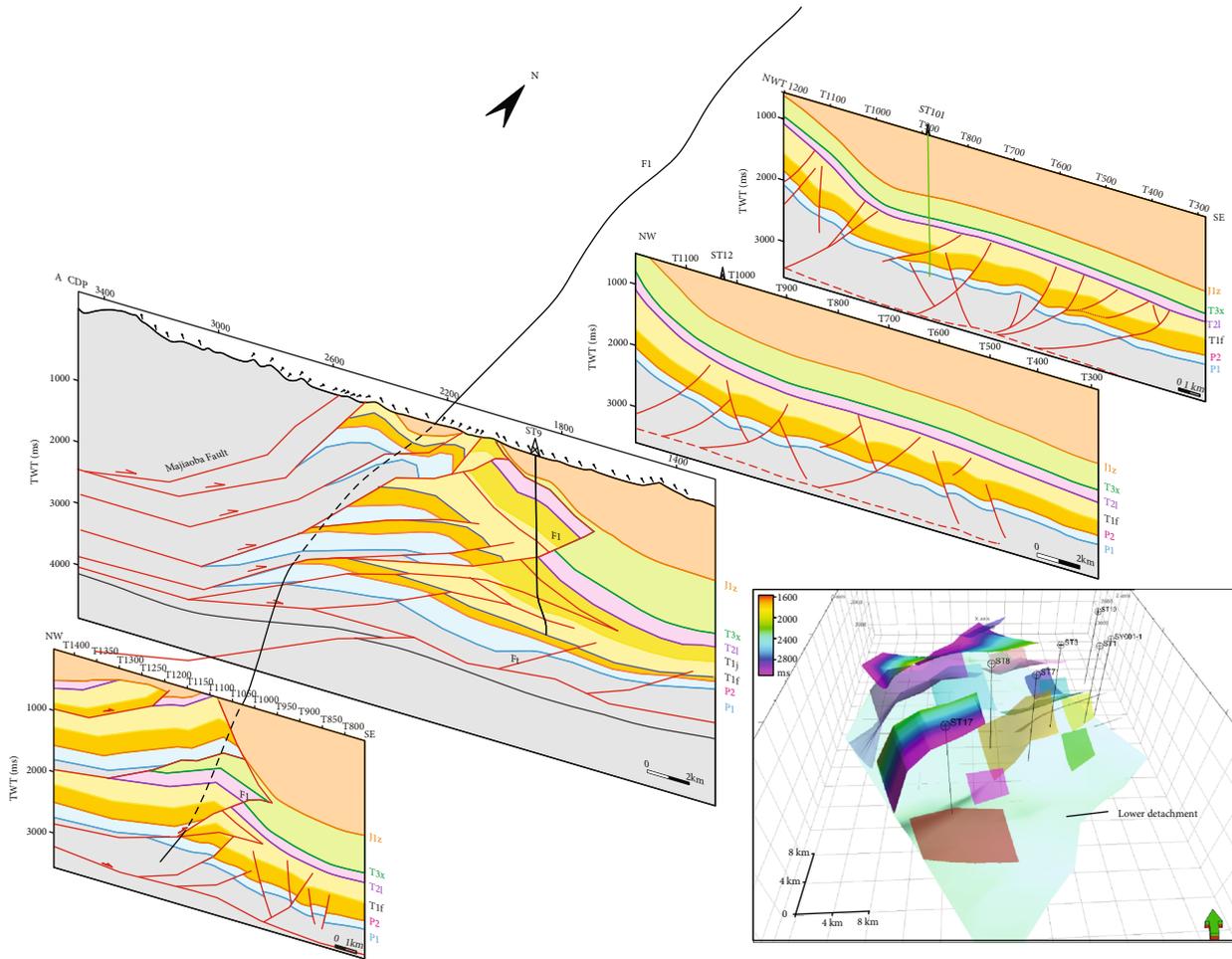


FIGURE 7: The 3D model showing the relationship between deep-seated structures in the foredeep and fold-and-thrust belts of northern Longmen Shan. The fault surface models were constructed by using the Petrel software. The right-left model shows the fault surfaces in the foredeep of Figures 5 and 6.

wedges may invert from the small-scale normal fault at the Late Triassic, such as the Ft fault below the ST9 well (Figure 3). The thickness of the Permian at either side of the Ft Fault is considerably different and gets thicker below the wedges, implying that it may have acted like a normal fault at the initial stage. Furthermore, the displacement of the imbricate thrust faults becomes increasingly smaller from the mountain to the basin. Therefore, we infer that the formation of the deep-seated faults and folds in the foredeep may have a forward development sequence from the mountain to the basin at the initial stage. Then, the strong activities of the northern Longmen Shan further accelerated the deformation of these deep-seated structures.

Except for the typical compressional imbricated thrust faults in the foredeep, the horizontal structural map (Figure 1(d)) reflects that these faults are arranged as roughly *en echelon* patterns, which are usually associated with the strike-slip stress field. This means that the formation of the northwestern Sichuan Basin endured a strike-slip component in the Cenozoic. It agrees with previous studies on the right-lateral strike-slip observation of this area [30, 55, 61].

5.2. Relationship between Deep-Seated Faults and Folds and Their Controlling Effects on the Hydrocarbon Fluid Accumulation. Years of petroleum exploration suggested that the LSB have excellent geological conditions for hydrocarbon accumulation [3, 62–64]. Some gas fields were discovered in the fold-and-thrust belts during past decades in the northern Longmen Shan area, such as the Kuangshanliang, Shejianhe, and Hewanchang [65–67]. Recently, exploration data revealed that the Permian strata of the deep-seated faults and folds of the foredeep contained an industrial gas field [68, 69]. The source rocks of the northwestern Sichuan Basin may contain shales of the Upper Neoproterozoic to the Lower Cambrian and carbonate rocks of the Permian, which can provide sufficient sources of hydrocarbon [70]. The intermediate-to-coarse-grained dolomites of the Permian were modified by multiple stages of hydrothermal fluids, which caused the dissolution of the dolomite with the combination of well-developed fractures, forming high-quality dolomite reservoirs in these deep-seated faults and folds [68].

The formation of all these geological conditions is highly related to the evolution of these structures, including the following:

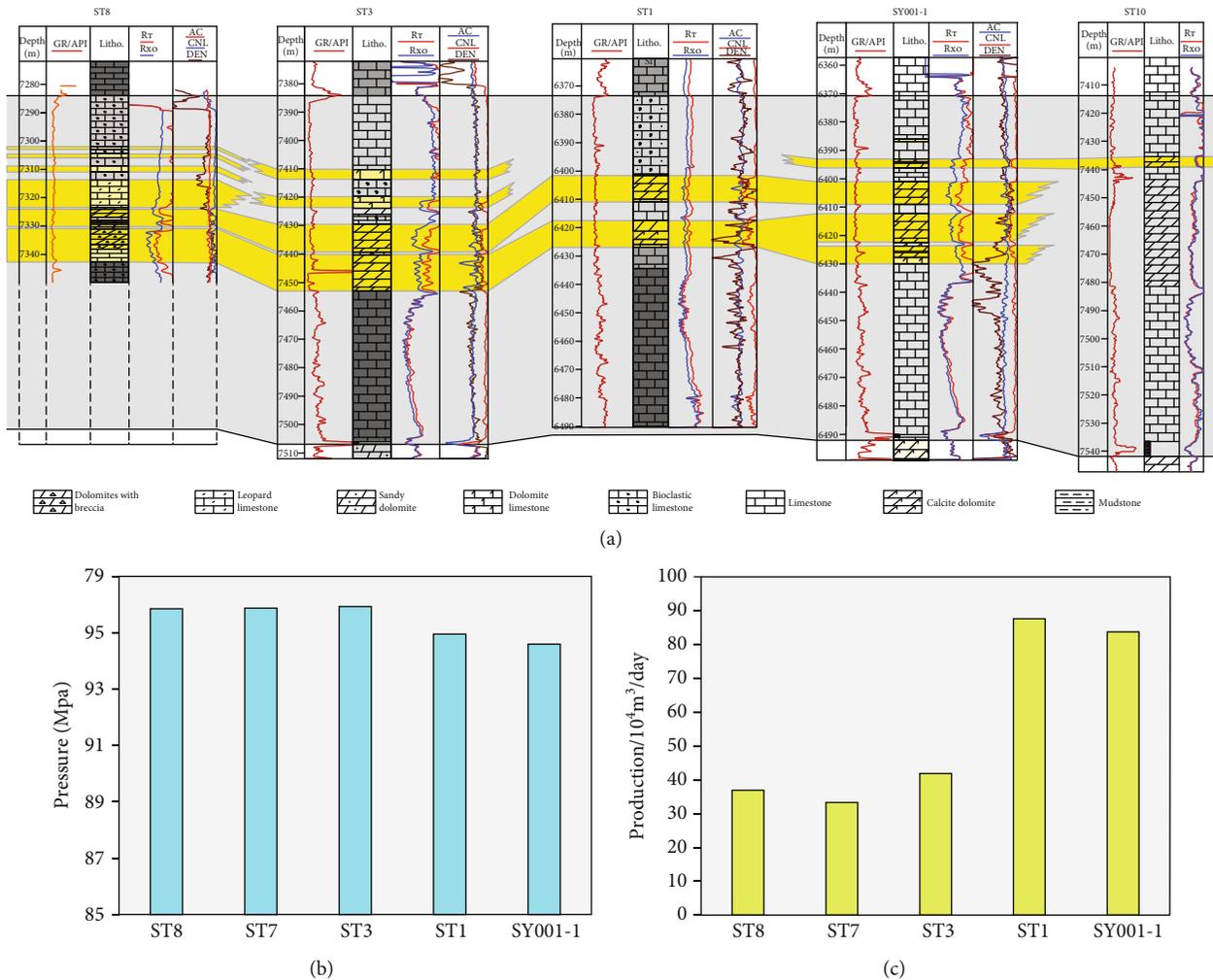


FIGURE 8: Well-correlation profile showing the characteristics of the main reservoir of Qixia Formation of Permian and gas layers (yellow layer) of deep-seated structures in the foredeep. The well data were based on Yang et al. and Bai et al. [28, 68]. The pressure data of gas layers and production data are based on the Southwest Oil and Gas Field Company, PetroChina. Well logs: GR is the gamma ray, RT is the resistivity log, Rxo is the flushed zone resistivity, AC is the acoustic log, CNL is the compensated neutron log, and DEN is the density log.

- (1) The deep-seated folds are great traps for hydrocarbon accumulation. The mudstones and evaporites of the Lower-to-Middle Triassic can act as efficient cover rocks for these traps [71]
- (2) The buried-history data indicated that the main oil and gas generation period of the source rocks in the Precambrian to Cambrian was from the Early Triassic to the Middle Jurassic, and oil and gas endured continuous charging from the Early Triassic to the Middle Jurassic and Late Cenozoic [62]. This means the two stages of compressional tectonic movement influenced the generation and charging of gas in this area. The activities of deep-seated structures of the foredeep during the Early Triassic provided a better match with the oil-and-gas-charging history
- (3) The well-developed fault system in the foredeep provided more pathways for hydrocarbon migration. These faults connected the deeper source rocks with

the dolomite reservoirs of the Permian and allowed the hydrocarbon fluids to migrate into traps. The well-correlation profile in the northwestern Sichuan Basin reflects that the gas mainly accumulated in the dolomites of the Permian, and the similarity of well logging data and lithology reflect the relative stability of the Permian strata (Figures 8(a)). These wells were distributed in different high points and were separated by different thrust faults. The gas production strata reflect that the pressure of gas-bearing layers is very constant, though these wells distribute in different locations and exhibit varied production (Figures 8(b) and 8(c)), implying that these reservoirs are interconnected with each other. The 3D model of these deep-seated thrust faults supports the possible connection of the reservoirs (Figure 7). These data suggest that the gas reservoir may extend over a large area, and the faults distributed between the wells may act more as the pathways

for hydrocarbon migration than as sealing barriers. This suggests that the limited horizontal stretching of the imbricated faults may form large-scale hydrocarbon accumulation without being blocked by the sealed faults

- (4) The deep-seated fault system can improve the quality of the reservoir. Exploration reflected that the dolomite is the main reservoir of the deep-seated structures, and the key points for the formation of these reservoirs include the deep burial dissolution effect and structural fractures [68, 72]. The development of faults will generate numerous fractures along the fault and form a damage zone [73–76]. The well-distributed fault system and its related fractures can accelerate the migration of hydrothermal fluids and dolomitization. Multiple stages of tectonic movements will bring different stages of hydrothermal activities, which can promote the dissolution of dolomites within the rocks and, along with the fractures, form a high-quality reservoir

6. Conclusions

Along with newly acquired high-resolution 2D and 3D seismic and gas production data, we analyzed the characteristics and evolution of deep-seated faults and folds of the northwestern Sichuan Basin. Our results and analysis afforded the following conclusions:

- (1) The thrust sheets, tectonic wedges, and foredeep can be recognized using the seismic data. The thrust sheets and tectonic wedges are characterized by forward thrusts, fault-bend folds, and structural wedges. The deep-seated faults and folds were discovered using 3D seismic data between the Paleozoic and the Lower Triassic in the foredeep, which showed obvious imbricated thrust faults and pop-up structures. These faults merged into the detachment layer in the Lower Cambrian
- (2) The deep-seated faults and folds in the foredeep were mainly formed in the Early Triassic and were reactive in the Cenozoic, presenting a forward developed sequence from the mountain to the basin. These thrust faults show an *en echelon* pattern in their horizontal mapping, implying the influence of the strike-slip stress field of the northwestern Sichuan Basin
- (3) The deep-seated faults and folds have great petroleum conditions for hydrocarbon accumulation. The thrust faults in the foredeep acted more as the pathways for hydrocarbon migration than as sealing barriers, suggesting that these deep-seated structures may form large-scale hydrocarbon accumulation

Data Availability

The (seismic and well) data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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