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Characteristics of Nappes and Segmentation of the Longmen Mountains Thrust Belt, Western Sichuan Basin, China

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Abstract

In order to reveal the nature of the segmentation of Longmen Mountains Thrust Belt caused by the three nappes (Jiaoziding, Jiudingshan, and Baoxing Nappe), several methods are applied in this paper, including field investigation, seismic explanation and balanced crossed section, etc. Results of research reveal that nappes in Longmen Mountains vary in geometry, kinematics, and dynamics. Jiaoziding Nappe has generally behaved in a ductile manner, whereas Jiudingshan Nappe has been rigid, and the rheology of Baoxing Nappe has been intermediate between that of the other two nappes. The development of nappes has resulted in tectonic segmentation of Longmen Mountains: the main structural style of the northern segment is thrust faulting, with Jiaoziding Nappe representing a giant syncline. Given its ductility, it absorbed lots of stress, with the least amount of tectonic shortening in the SE part of the nappe. In the middle segment, the deformation is controlled by the rigid Jiudingshan Nappe, whose frontal area records lots of tectonic shortening. Deformation in the southern segment is intermediate in character between that of the other two segments, characterized by horizontal zonation, as demonstrated by fault development, and vertical stratification, which indicates that fault development was controlled by lithology.

Keywords

Nappe, Tectonic Evolution, Segmentation, Decollement Layer, Longmen Mountains Thrust Belt

1. Introduction

Located on the western edge of the Western Sichuan Foreland Basin, the Longmen Mountains Thrust Belt records polyphase deformation and is characterized by complicated structures [1] [2] [3] [4] [5]. The belt shows clear tectonic segmentation, as described in previous publications. For example, Jia *et al.* (2006) divided the belt into northern and southern segments in the area of Anxian County [6], Li *et al.* (2005) recognized the Jiaoziding, Jiudingshan, and Baoxing nappes [7], and Liu (2006) identified three segments: a northern segment to the north of Deyang City, a southern segment to the south of Dujiangyan City (formerly known as Guanxian County, which is still used on occasion because of its important geological implications), and a third segment located between the them [8]. Jin *et al.* (2010) divided the Longmen Mountain Thrust Belt into three segments (northern, middle, and southern, separated by two transfer zones) based on seismic data and field surveys [9] [10]. Besides, some transverse faults (such as the Wolong-Huaiyuan fault and Huya fault) are studied and are taken for the boundaries between different fault zones by means of geophysical features [11] [12].

This paper focuses on the long standing nappes (the Jiaoziding, Jiudingshan, and Baoxing nappes) and their implication on the tectonic characteristics and evolution of Longmen Mountains Thrust Belt and even Western Sichuan Foreland Basin which has largely been neglected in previous studies, so the mechanism of segmentation of the Longmen Mountains Thrust Belt is further investigated in terms of three main nappes in this paper; these nappes are described and analyzed in terms of their geometry and kinematics, and the control by nappes on segmentation of the thrust belt and the tectonic evolution of the Western Sichuan Foreland Basin.

2. Method

2.1. Nappe Geometry

An analysis of structural styles at the surface and at depth indicates that the Jiaoziding, Jiudingshan, and Baoxing nappes differ in geometry (**Figure 1**; **Table 1**). The strike of beds within the three nappes is consistent (NE-SW), and the nappes are separated by the Anxian transfer zone (between the Jiaoziding and Jiudingshan nappes) and the Guanxian transfer zone (between the Jiudingshan and Baoxing nappes) [10]. The nappes are all large, from 1700 km^2 to 3000 km^2 (**Table 1**), with the Jiudingshan Nappe covering the widest area. The three nappes vary in terms of lithology: the Jiudingshan and Baoxing nappes consist of migmatite (formed mainly between Pre-Sinian and Triassic), whereas the Jiaoziding Nappe is a giant syncline composed of Devonian, Carboniferous, and Permian.

2.2. Kinematics

2.2.1. Jiaoziding Nappe

A typical section across the Jiaoziding Nappe was selected for the construction of

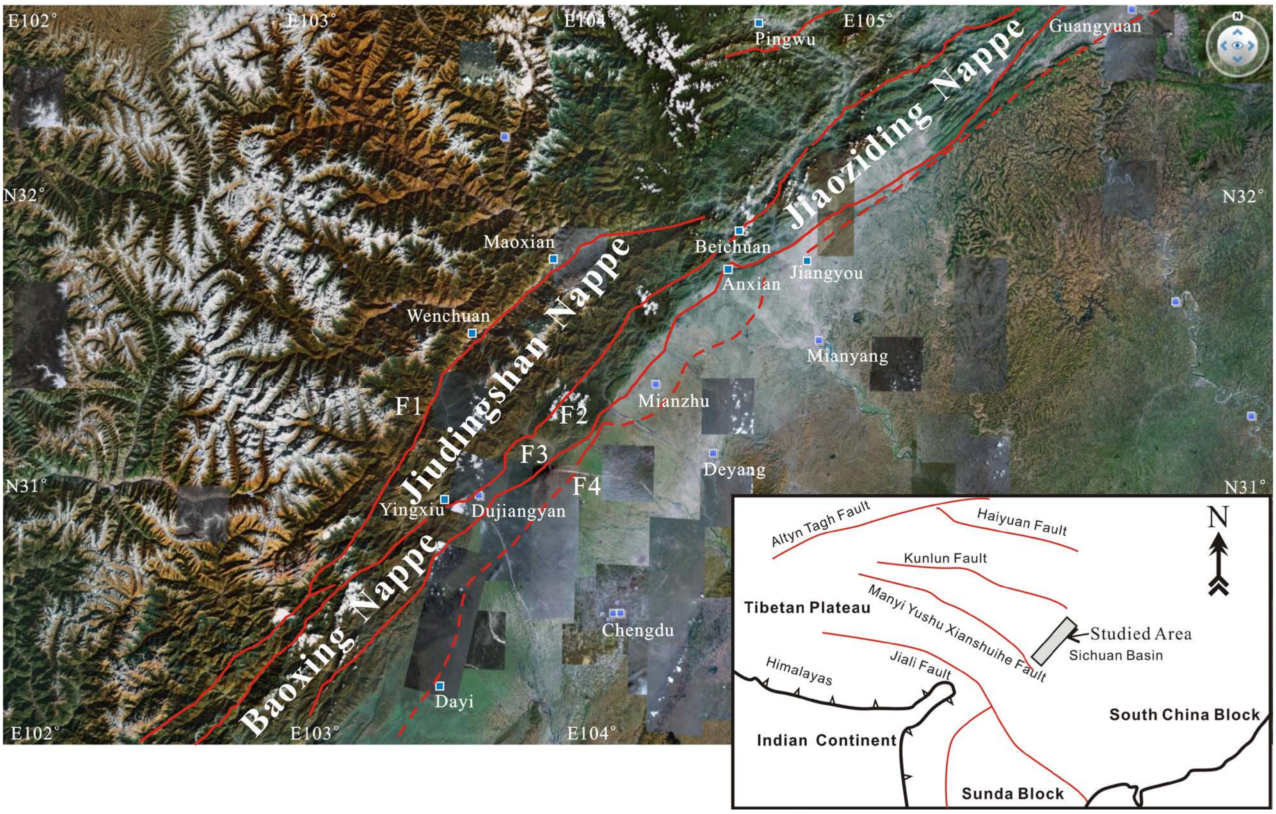

Figure 1. Three nappes in Longmen Mountains Thrust Belt (modified from Jin, *et al.* [9]). F1—Qingchuan-Maowen Fault; F2—Beichuan-Yingxiu Fault; F3—Majiaoba-Tongjichang-Shuangshi Fault; F4—Guangyuan-Guankou-Dayi Fault.

Table 1. Geometric features of nappes of Longmen Mountains Thrust Belt.

	Jiaoziding Nappe	Jiudingshan Nappe	Baoxing Nappe
Covered area/km^2	1700 - 1900	2500 - 3000	2400 - 2500
Depth/km	2 - 3	17	18
Direction of long axis	NE	NE	NE
Length of long axis/km	95	100	95
Length of short axis/km	10 - 20	35	30
Formation	D, C, P	Magmatite (PreZ-T)	Magmatite (PreZ-T)
Direction of main faults	NE, NNE	NE, NEE, NNE	NE, NEE, NNE
Character of fault	thrust fault	thrust fault	thrust fault
Length of faults/km	>20	>20	>20

The data above is obtained from the Regional Geological Map of Sichuan Province with scale of 1:200000.

a balanced cross-section (**Figure 2**). Analysis of the cross-section reveals a polyphase tectonic history comprising three important events: extension between Cambrian and Permian (total extension of 18.89 km), and contraction during the Late Triassic and during the Himalayan movement (1.81 - 65.5 Ma) (shortening of 10.6 and 28.75 km, respectively). The Himalayan movement (also referred to as the Sichuan Movement) involved the most intensive deformation, affecting large areas of the Sichuan Basin and producing the main phase of development of the Longmen Mountains Thrust Belt.

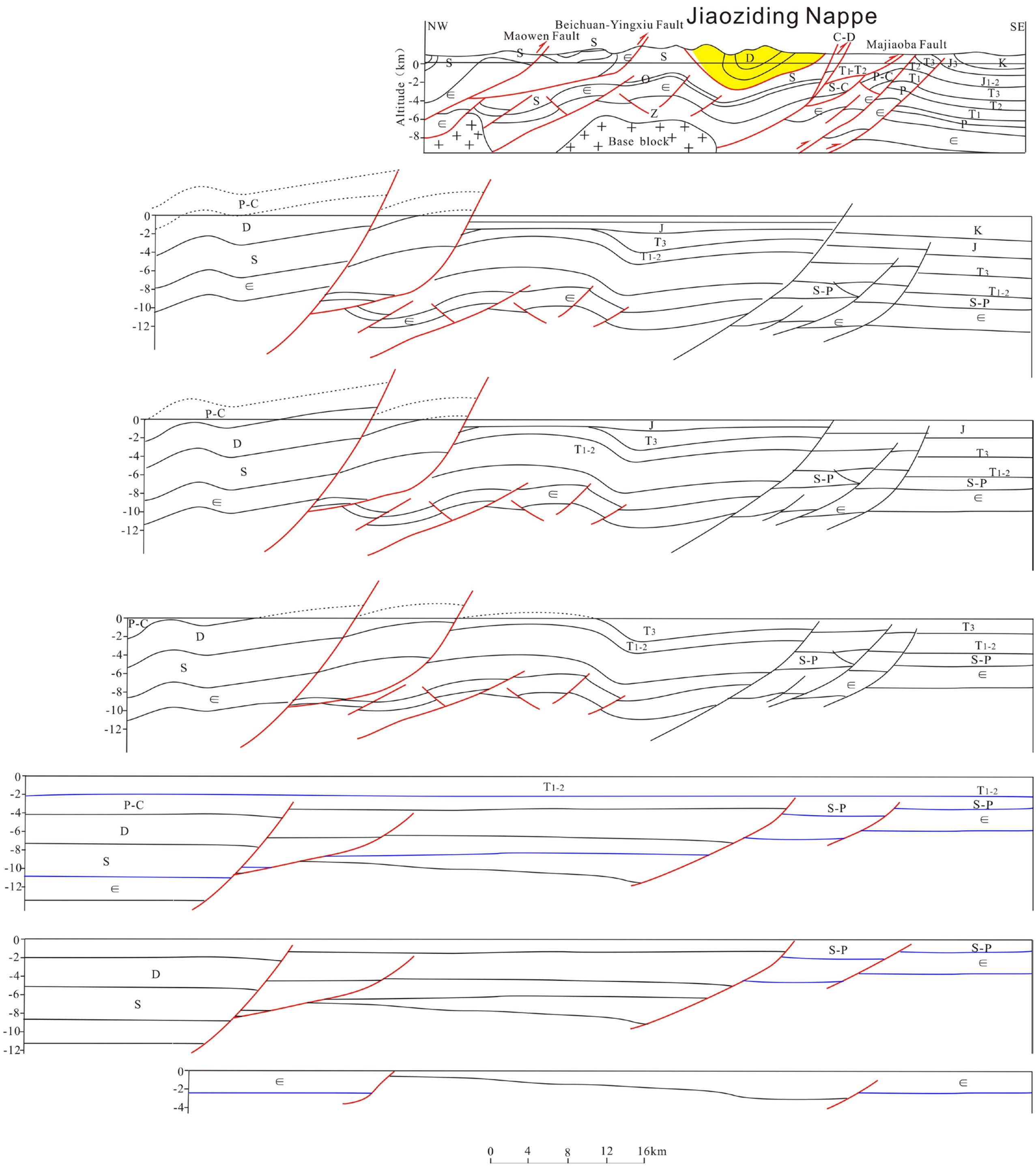

Figure 2. Balanced crossed section of Jiaoziding Nappe.

2.2.2. Jiudingshan Nappe

After the Jinning Movement, the Songpan-Aba Basin was connected to the Sichuan Basin, forming a single block known as the Yangtze unite basement. After Sinian, the palaeotopography undulating and the Jiudingshan Nappe was a palaeohigh [13], and this palaeohigh was the origin of subsequent tectonic palaeo-uplift and the formation and evolution of adjacent areas.

From the pre-Sinian to the Late Permian, the Songpan-Aba Basin experienced a widespread marine transgression and became a passive continental margin basin. Sediments were deposited under the control of the Qingling Ocean, producing an onlap unconformity between the basement and the overlying sedimentary cover. In the Early Silurian, the basin was separated from the Sichuan Basin and the Longmen Mountains Rift Trough was formed. Imbricate listric faults, striking NW-SE, formed at this time, merging at depth to form a large decoupling layer. A large volume of intrusive rocks was generated at this time, forming a palaeohigh under the control of large-scale deep-seated faults.

In the late Middle Triassic, the stress field affecting the Songpan-Aba Basin reversed from extension to compression, due to collision between the Yangtze and North China blocks. As a result, the imbricate listric faults that formed previously in an extensional field were transformed to shear or thrust faults, as was the deep-level decoupling fault. The process of deformation was piggy-back style, meaning that faults in the northwest formed earlier than those in the southeast [13].

A typical section across the Jiudingshan Nappe was selected for the construction of a balanced cross-section (**Figure 3**), revealing a similar polyphase tectonic evolution to that of the Jiaoziding Nappe, with three main events: a Late Ordovician event (tectonic shortening of 13.00%), a Late Triassic event (tectonic shortening of 8.13%), and a Himalayan Movement (tectonic shortening of 16.32%). The Himalayan Movement was the most intensive deformation event in the tectonic evolution of the Longmen Mountains Thrust Belt.

2.2.3. Baoxing Nappe

A balanced cross-section constructed through the Baoxing Nappe reveals that it also experienced a polyphase tectonic history (**Figure 4**), with the most intensive deformation in the late Middle Triassic. During this period, the stress field in the study area showed a gradual change from extension to compression, and the sedimentary environment changed gradually from marine to continental. Deformation of the Baoxing Nappe occurred much later than that of the Jiaoziding and Jiudingshan nappes, and plutonic rocks formed before Permian within an extensional stress field. There were two important periods in the evolution of Longmen Mountains Thrust Belt: the Late Triassic (tectonic shortening of 8.42%) and the Himalayan period (tectonic shortening of 36.53%). Deformation occurred earlier in the northern part of the Baoxing Nappe than in the southern part.

An analysis of balanced cross-sections of the three nappes reveals that the Universal Yangtze Platform was formed in South China from the Late Sinian to Middle Triassic [14], indicating sedimentary deposition at a continental margin or shallow marine environment, mainly carbonates and minor clastic sediments. Deformation during this period was mainly extensional, including decoupled faults that merged at depth with a large-scale décollement layer. Since the Triassic, the Longmen Mountains Thrust Belt has experienced intensive compressional

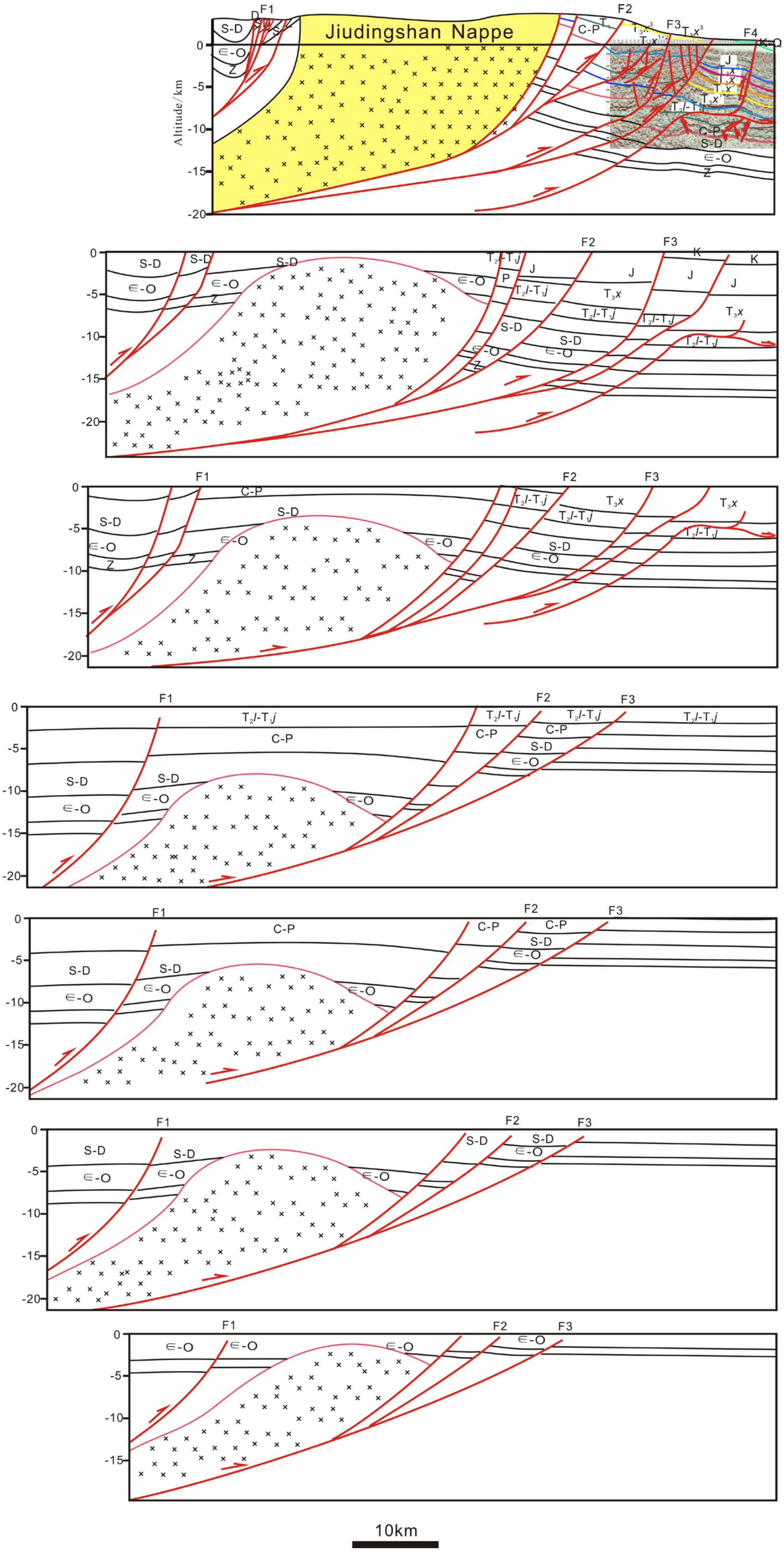

Figure 3. Balanced crossed section of Jiudingshan Nappe.

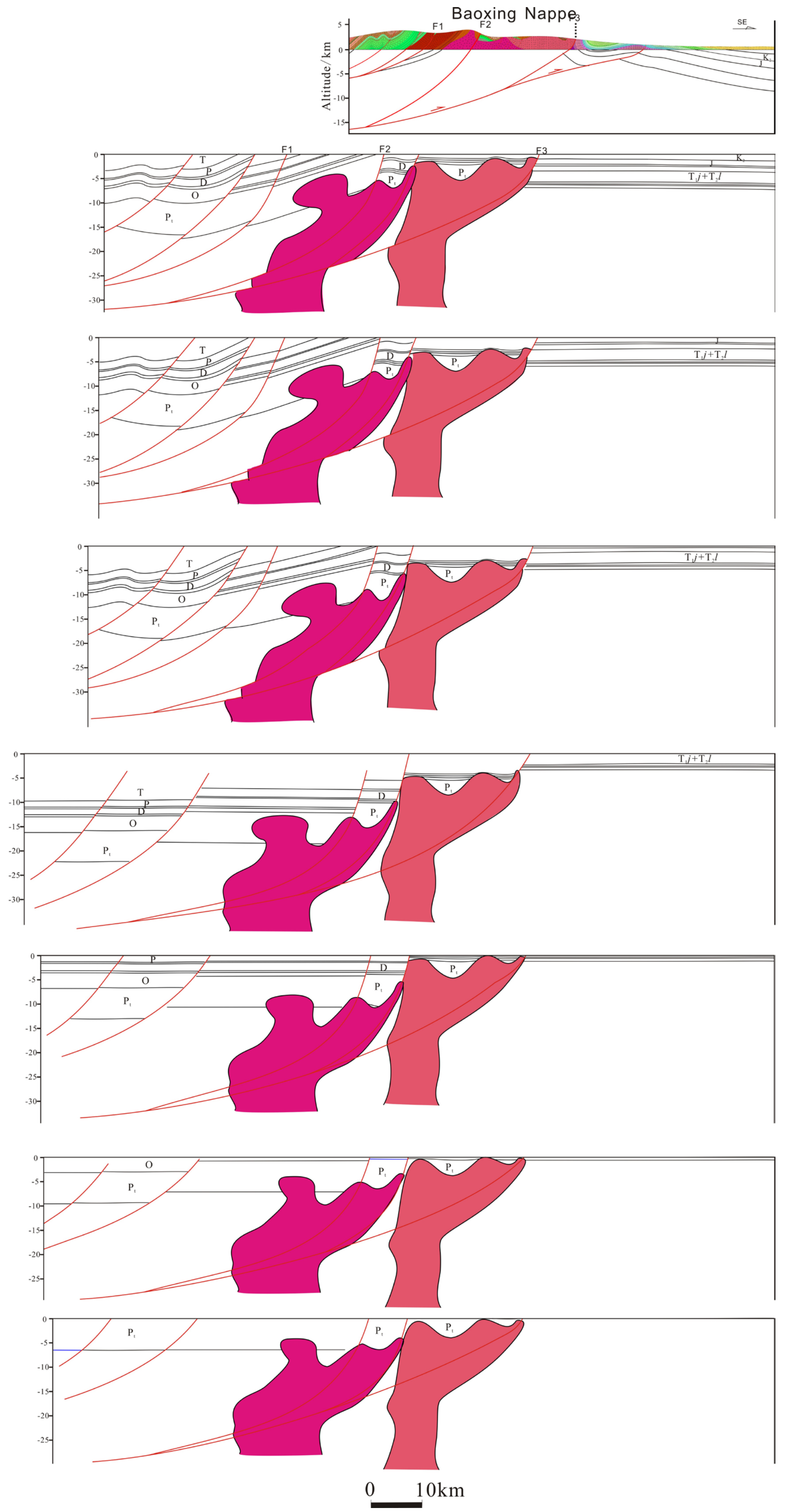

Figure 4. Balanced crossed section of Baoxing Nappe.

deformation (**Figure 5**), resulting in the deposition of continental sediments and the preservation of small areas of remnant oceanic basin. Liu (1993) reported that the thrust belt has been denuded by 5 - 10 km since the Miocene, with an uplift rate of 0.6 mm·a^{-1} [15].

The three nappes differ in terms of the timing of their formation and deformation, with the northern segment (Jiaoziding Nappe) pre-dating the southern segment (Baoxing Nappe). For example, the Jiaoziding Nappe has been deformed since the Middle Caledonian, which saw the formation of several large normal faults that were later reactivated as thrust faults. This tectonic activity continues to the present day, such as 5.12 big earthquake, which resulted from the combined influences of collision between the Yangtze and Tibet blocks, and multi-level detachment layers [10]. The Jiudingshan Nappe, located in the central section of the Longmen Mountains Thrust Belt, consists of a large-scale intrusion that formed during the Jinning Period. During subsequent tectonic events, the intrusion was uplifted, making the tectonic palaeohigh in adjacent areas disappeared.

The Baoxing Nappe, located in the southern part of the thrust belt, was deformed later than the other two nappes, recording deformation that began during the Indo-Chinese epoch. The northern segment was more intensively deformed during the early stages (such as Late Permian) whereas the southern segment was more intensively deformed during the late stages (such as Late Triassic) (**Figure 5**). Because of the contrasting rheology of the three nappes (*i.e.*, ductile versus brittle), the areas in front of the nappes experienced different amounts of tectonic shortening. Based on physical modeling, Yu *et al.* (2010) calculated shortening amounts for the northern, middle and southern segments of 32.72%, 39.63%, and 34.93%, respectively [16]. In summary, the timing of deformation of the Longmen Mountains Thrust Belt shows a younging trend from SE to NW, and a corresponding trend from ductile to brittle deformation.

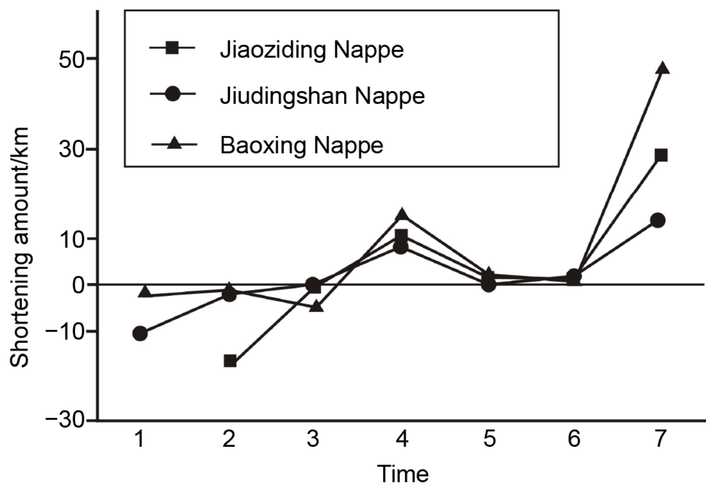

Figure 5. Tectonic shortage of three nappes in different periods. 1—Late Ordovician; 2—Late Permian; 3—Late period of Middle Triassic; 4—Late Triassic; 5—Late Jurassic; 6—Late Cretaceous; 7—Now.

3. Result

In terms of the tectonic framework, the Longmen Mountains Thrust Belt is located in a unique position, bound to the west by the Qinghai-Tibet Plateau and to the east by the Yangtze Plateau. The thrust belt is an important orogenic belt and foreland basin system with complicated structure and a long geological history. Large-scale orogenic processes began in the Late Indo-Chinese epoch. Two types of orogenic events (N-S and E-W compression) produced two corresponding tectonic systems (structures that strike E-W and N-S, respectively). During the Cenozoic, the northern part of the Qinghai-Tibet Plateau was extruded to the SE as a result of the northward indentation of the Indian Plate, producing intensive thrusting, strike-slip faulting, and uplift at the eastern edge of the Qinghai-Tibet Plateau.

As mentioned above, the three nappes differ in terms of their lithology, rheology, and tectonic evolution; consequently, it is considered that the nappes were subjected to different deformation mechanisms, which in turn affected the tectonic deformation of adjacent areas in the Longmen Mountains.

3.1. Jiaoziding Nappe

The Jiaoziding Nappe is a large-scale syncline that has experienced intensive tectonic shortening (shortening of 49.89%; **Table 2**). The NW part of the nappe was shortened by 39.93%, while the SE part was shortened by 10.25%, indicating that the nappe has absorbed a large amount of compressional stress during intensive tectonic deformation.

The NW, central, and SE parts of the nappe have been affected by ductile deformation, ductile-brittle deformation, and brittle deformation, respectively, resulting in the development of many thrust faults in the SE part. Yu *et al.* (2010) reported that deformation of the northern segment of the Guankou Fault is indicative of an imbricate basement-involved thrust for which its forward propagation has been restricted by an unconformity [16]. These observations indicate a progressive transition from ductile to brittle deformation from NW to SE.

The timing of deformation of the Jiaoziding Nappe is much earlier than that of the other two nappes, with the main deformation episodes being Middle Indosinian and Late Himalayan (also called the Sichuan Movement Episode). The NW part of the Jiaoziding Nappe records three main periods of deformation: Middle Caledonian, Middle Indosinian, and Late Himalayan. The SE part records two main periods of deformation: Late Indosinian (also called the Anxian Movement Episode) and Late Himalayan. These observations indicate that tectonic deformation of the Longmen Mountains Thrust Belt was piggy-back in style.

3.2. Jiudingshan Nappe

The Jiudingshan Nappe consists of a large-scale intrusive mass. Given its lithology, the nappe has experienced relatively little tectonic shortening (23.33%;

Table 2. Mechanism of deformation of nappes in Longmen Mountains Thrust Belt.

Mechanism of deformation		Jiaoziding Nappe	Jiudingshan Nappe	Baoxing Nappe
NW of Nappe	Mechanism	Ductile deformation	Ductile deformation	Ductile deformation
	Shortening (ratio)	17.88 km (39.93%)	6.67 km (29.20%)	18.68 km (29.31%)
	Deformation styles	Synclinorium, anticlinorium, cleavage, crumple, thrust belt, imbricated thrust fault, etc	Synclinorium, anticlinorium, cleavage, crumple, thrust belt, imbricated thrust fault, etc	Synclinorium, anticlinorium, cleavage, crumple, thrust belt, imbricated thrust fault, etc
	Deformation episodes	Middle Caledonian Movement, Middle Indosinian, Late Himalayan Movement (or Sichuan Movement)	Middle Caledonian Movement, Middle Indosinian, Late Himalayan Movement (or Sichuan Movement)	Late Indosinian movement (or Anxian Movement), Late Himalayan Movement (or Sichuan Movement)
Nappe	Mechanism	Ductile-brittle deformation	Brittle deformation	Brittle deformation
	Shortening (ratio)	22.34 km (49.89%)	5.33 km (23.33%)	34.90 km (54.76%)
	Deformation styles	Syncline	Thrust belt, X joint, etc	Thrust belt, X joint, etc
	Deformation episodes	Middle Indosinian, Late Himalayan (or Sichuan Movement)	Middle Indosinian, Late Himalayan (or Sichuan Movement)	Late Indosinian movement (or Anxian Movement), Late Himalayan Movement (or Sichuan Movement)
SE of Nappe	Mechanism	Brittle deformation	Brittle deformation	Brittle deformation
	Shortening (ratio)	4.59 km (10.25%)	10.84 km (47.46%)	10.15 km (15.93%)
	Deformation styles	Thrust fault, imbricated thrust fault, fault related fault, pop-up, etc.	Thrust fault, imbricated thrust fault, fault related fault, pop-up, etc.	Thrust fault, imbricated thrust fault, fault related fault, pop-up, anticline, syncline, etc
	Area affected	Within 15 km	Within 30 km	Within 25 km
	Deformation episodes	Late Indosinian movement (or Anxian Movement), Late Himalayan Movement (or Sichuan Movement)	Late Indosinian movement (or Anxian Movement), Late Himalayan Movement (or Sichuan Movement)	Late Indosinian movement (or Anxian Movement), Late Himalayan Movement (or Sichuan Movement)

Table 2). The NW part of the nappe was shortened by 29.20%, whereas the SE part was shortened by 47.46%. The lack of shortening of the Jiudingshan Nappe indicates that compressive stress was transmitted from NW to SE, with the SE part of the nappe experiencing the most intense deformation.

In terms of the nature of deformation, intensive brittle deformation is evident in the Jiudingshan Nappe, including thrust faults and conjugate joint sets. The NW part of the nappe has been affected by ductile deformation, whereas brittle deformation structures are evident in the SE part. Because of the existence of décollement layers, many thrust faults show features of vertical stratification. Similarly to the Jiaoziding Nappe, the overall deformation of the Jiudingshan Nappe shows a transition from ductile to brittle when moving from NW to SE.

In terms of the timing of deformation, the Jiudingshan Nappe records two main episodes: Middle Indosinian and Late Himalayan, with the latter event being important in terms of the development of the Longmen Mountains Thrust Belt and the adjacent foreland basin. Three deformation episodes are recorded in the NW part of the nappe: Middle Caledonian, Middle Indosinian, and Late Himalayan. The SE part of the nappe has experienced two deformation episodes: Late Indosinian and Late Himalayan. Similarly to the Jiaoziding Nappe, the Jiudingshan Nappe shows evidence of piggy-back deformation.

3.3. Baoxing Nappe

The Baoxing Nappe consists of multiple suites of volcanic rocks with a complicated pattern of surface outcrops. The amount of tectonic shortening of the nappe is 34.90 km, representing shortening of 54.76% (**Table 2**). The NW part of the nappe has been shortened by 29.31% and the NE part by 15.93%, indicating that the nappe absorbed a relatively large amount of tectonic stress during the deformation events.

In summary, the Jiudingshan Nappe, located in the middle of the Longmen Mountains Thrust Belt, consists of a large-scale intrusion and records less shortening than the other two nappes; the SE part of the nappe experienced the most intensive deformation. The Jiaoziding Nappe, in the northern part of the Longmen Mountains Thrust Belt, is a large-scale syncline that absorbed a large amount of tectonic stress, resulting in weak deformation in the SE part of Jiaoziding Nappe. The Baoxing Nappe is intermediate in deformation style between the Jiaoziding and Jiudingshan nappes.

4. Discussion

4.1. Effect of Nappe Development on Segmentation of the Sichuan Basin Basement

The Jiaoziding, Baoxing, and Jiudingshan nappes had an important influence on the evolution of the Longmen Mountains Thrust Belt. For example, the nappes controlled the character of basement beneath the belt. The segmentation of basement rocks is a primary feature of the Western Sichuan Foreland Basin (**Figure 6**); e.g., the basement can be divided into three main segments from Guangyuan City to the southern part of the Sichuan Basin, with the boundaries between the segments being consistent with the margins of the three nappes.

4.2. Influence of Nappe Development on Shallow Structures

In addition to affecting the basement of the Western Sichuan Basin, the three nappes controlled the nature of shallow deformation in the Longmen Mountains Thrust Belt and Western Sichuan Foreland Basin. The style of shallow deformation can generally be classified into three types: ductile, brittle, and intermediate, each of which is summarized below.

4.2.1. Jiaoziding Nappe (Typical Ductile Deformation)

Ductile deformation (such as cleavage development) is widespread west of the Qingchuan-Maowen Fault. Layers affected by ductile deformation are lower Palaeozoic in age. For example, the area west of the Jiudingshan Nappe (also

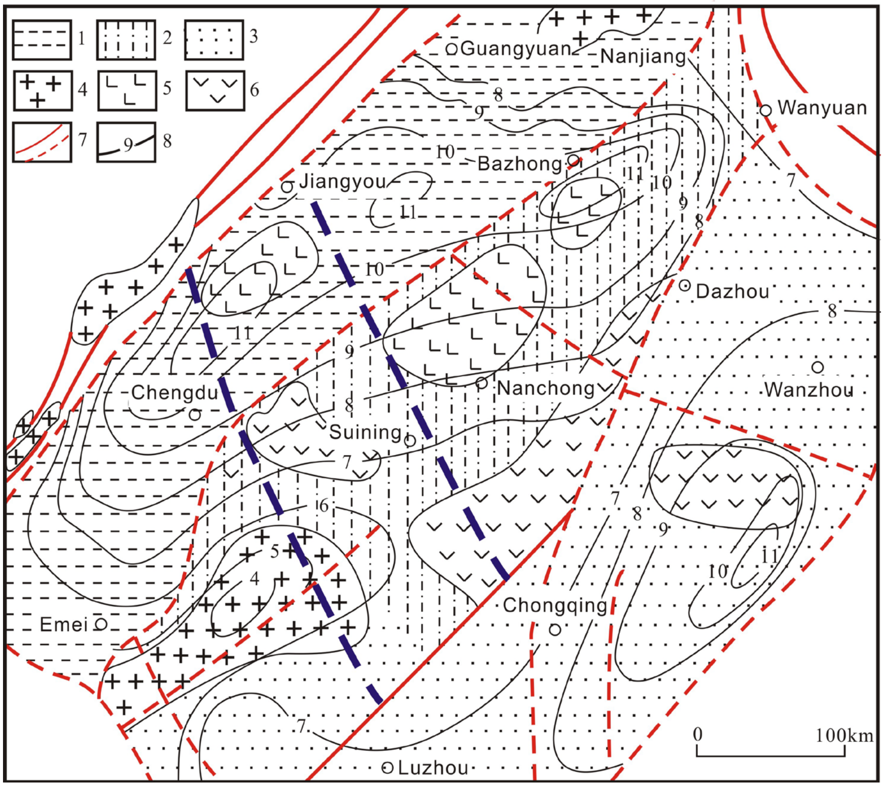

Figure 6. Basement of Sichuan Basin (Modified from Li, *et al.* [17]). 1—Middle Proterozoic Huangshuihe Group; 2—Paleoproterozoic-Archeozoic Kangding Group; 3—Neoproterozoic Banxi Group; 4—Intermediate acidity complex; 5—Basic complex; 6—Intermediate basic volcanic rock; 7—Assumed fault; 8-Contour line of basement's depth (km).

known as the Pengguan Nappe) (Figure 7) experienced ductile deformation as a result of tectonic compression since the Indo-Chinese epoch, when the rocks (including Silurian lithologies) west of the Jiudingshan Nappe were compressed and exhumed.

4.2.2. Jiudingshan Nappe (Typical Brittle Deformation)

Generally, brittle deformation is dominant east of the Majiaoba-Tongjichang-Shuangshi Fault (also known as the Guanxian Fault) (Figure 7). This observation may be explained by the following points: 1) this area is located far from the intensively deformed Longmen Mountains Thrust Belt and was subjected to relatively little tectonic stress; 2) this area did not experience intensive tectonic uplift, and sedimentation and deformation are restricted to shallow layers; 3) the deformed layers are mainly the Upper Triassic Xujiahe Formation, which is a continental facies or transitional facies comprising sandstone, conglomerate, and other lithologies susceptible to brittle deformation.

4.2.3. Baoxing Nappe (Intermediate Type)

Intermediate-type deformation is found between the areas dominated by ductile deformation and brittle deformation (at the surface, between the Qingchuan-Maowen Fault and Majiaoba-Tongjichang-Shuangshi Fault). Deformation

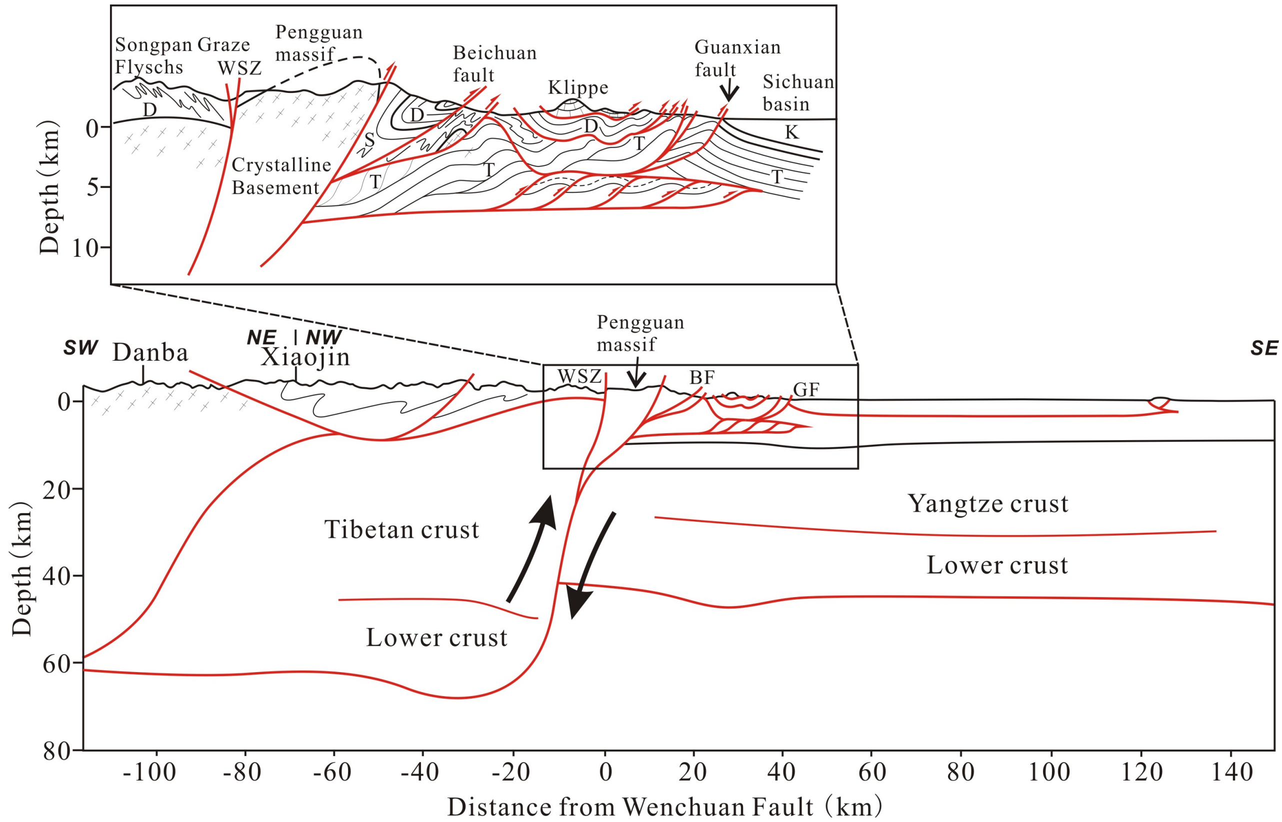

Figure 7. Relationship between Sichuan Basin and Songpan-Garze fold belt (Modified from Robert, *et al.* [18]).

structures in this region are dominated by fault-related folds, and thrust belts, and triangle belts.

5. Conclusions

Interpretations of field data and seismic data reveal that several tectonic segments within the Longmen Mountains Thrust Belt have contrasting deformation styles (**Figure 8**). In the northern segment, thrust nappes are the main deformation structure. Decollement layers have had a strong influence on the style of tectonic deformation, as shown by thrust faults that are developed from the Sinian to the Triassic. Several decollement layers can be found in this area and they are composed of some incompetent strata, such as salt, which can flow in the process of the tectonic deformation easily as a result of its characteristics of high mobility, so this behaviour can make the upper layer develop detachment deformation [19], such as fault-related folds and pop-up structures. The Jiaoziding Nappe, a large-scale syncline bounded by two large thrust faults, is the dominant structure of the northern segment.

In the middle segment, tectonic deformation was controlled by the Jiudingshan Nappe. Most of the thrust faults in this segment are basement-involved faults that extend from a regional decollement to the surface. Deformation in areas beneath the decollement layers is weaker than that above the layers. Deformation structures above the decollement layers include pop-up structures

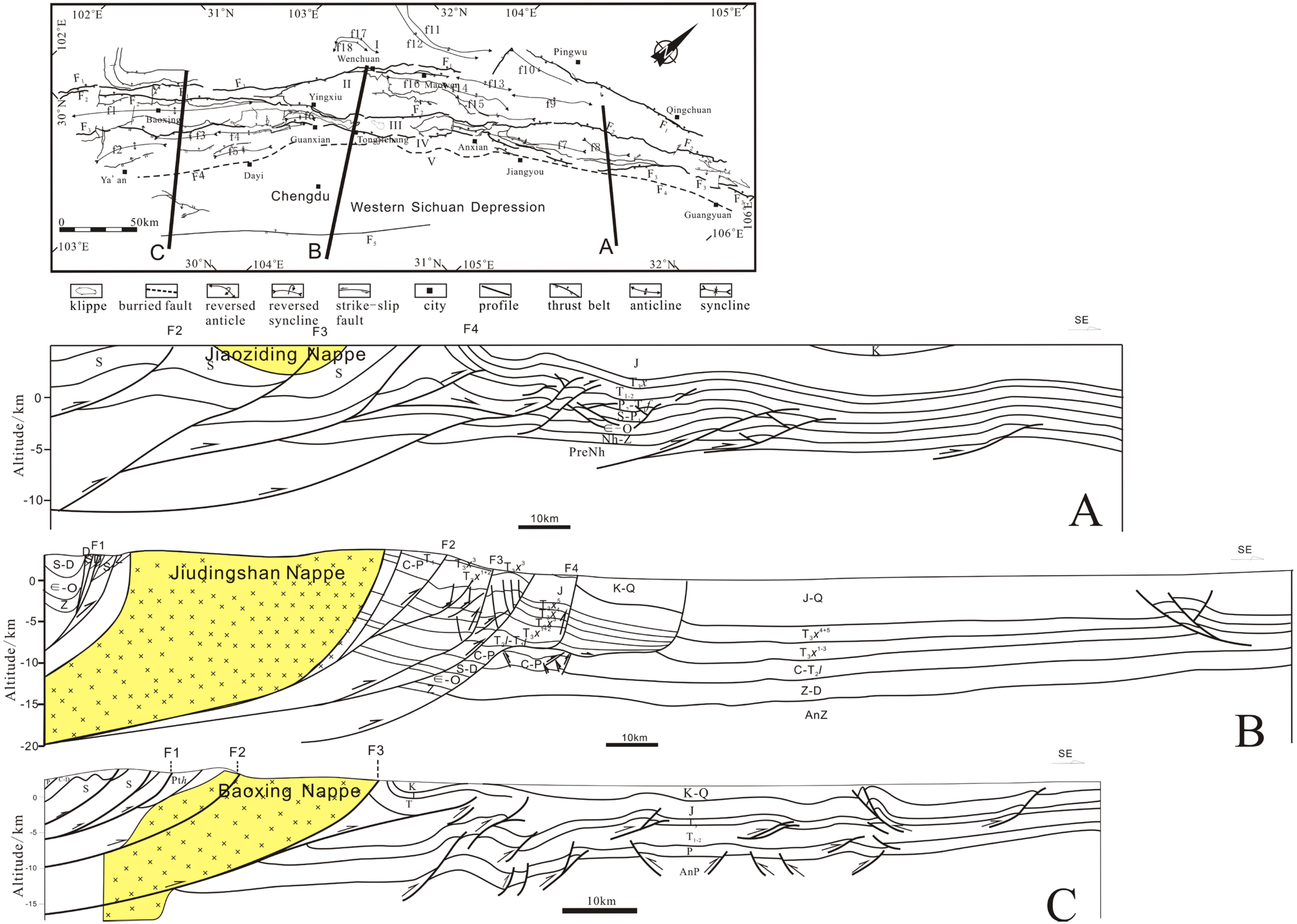

Figure 8. Model of segmentation of Longmen Mountains Thrust Belt. I—Songpan-Garze Tectonic Belt; II—Ductile Deformation Belt; III—Base-Involved Thrust Belt; IV—Frontal Fold-Thrust Belt; V—Foreland Depression; F1—Qingchuan-Maowen Fault; F2—Beichuan-Yingxiu Fault; F3—Majiaoba-Tongjichang-Shuangshi Fault; F4—Guangyuan-Guankou- Dayi Fault; f1—Baoxing Anticlinorium, f2—Lushan Syncline, f3—Nanbaoshan Syncline.

and fault-related folds, showing vertical stratification in cross-sections.

In the southern segment, tectonic deformation also shows zonation and stratification. The zonation reflects the fact that the thrust faults located east of the Majiaoba-Tongjichang-Shuangshi Fault are nearly small scaled, whereas the thrust faults located west of the fault are largely basement-involved structures. The Baoxing Nappe is a large-scale intrusion located between large thrust faults. The stratification arose because the faults are influenced by multiple factors (e.g., lithology), meaning that different layers are characterized by contrasting deformation styles.

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