Pergamon

Journal of Structural Geology, Vol. 18, No. 4, pp. 413 to 430, 1996

0191-8141/96 $15.00+0.00

0191-8141(95)00096-8

Emplacement of the Longmen Shan Thrust–Nappe Belt along the eastern margin of the Tibetan Plateau

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(*Received* 22 *February* 1995; *accepted in revised form* 26 *July* 1995)

Abstract—The topographic descent from the eastern margin of the Tibetan Plateau to the Sichuan Basin passes through the Longmen Shan Thrust–Nappe Belt, which is sub-divided by six NW-dipping, major listric thrusts, with accompanying duplexes and imbricate fans, into five large-scale nappes. Each nappe has its own stratigraphic and deformational features. In the inner Longmen Shan (Longmen Mountains), allochthonous nappe units have incorporated both Mesoproterozoic basement and Sinian (Neoproterozoic) to Triassic cover sequences as 'thick-skinned' horses; whereas in the frontal Longmen Shan, Sinian–Cretaceous cover sediments have been stripped from the basement as 'thin-skinned' fold and thrust sheets, including the extensively distributed klippen structures.

Pre-thrusting extension during Devonian to middle late Triassic times resulted in syn-depositional normal faults. Structural inversion of these faults initiated the 'Peng Xian-Guan Xian Basement Complex', Jiuding Shan and Tangwangzhai nappes during the early episode of the Indosinian orogeny (Norian to Rhaetian). This was followed by episodic thrusting during latest Triassic to Early Cretaceous times to develop the Guan Xian-An Xian and Southeastern Marginal nappes that have incorporated sediments from the neighbouring foreland basin into the frontal part of the Thrust–Nappe Belt. During a late Miocene reactivation of the pre-existing thrusts, differential thrusting occurred across the Thrust–Nappe Belt.

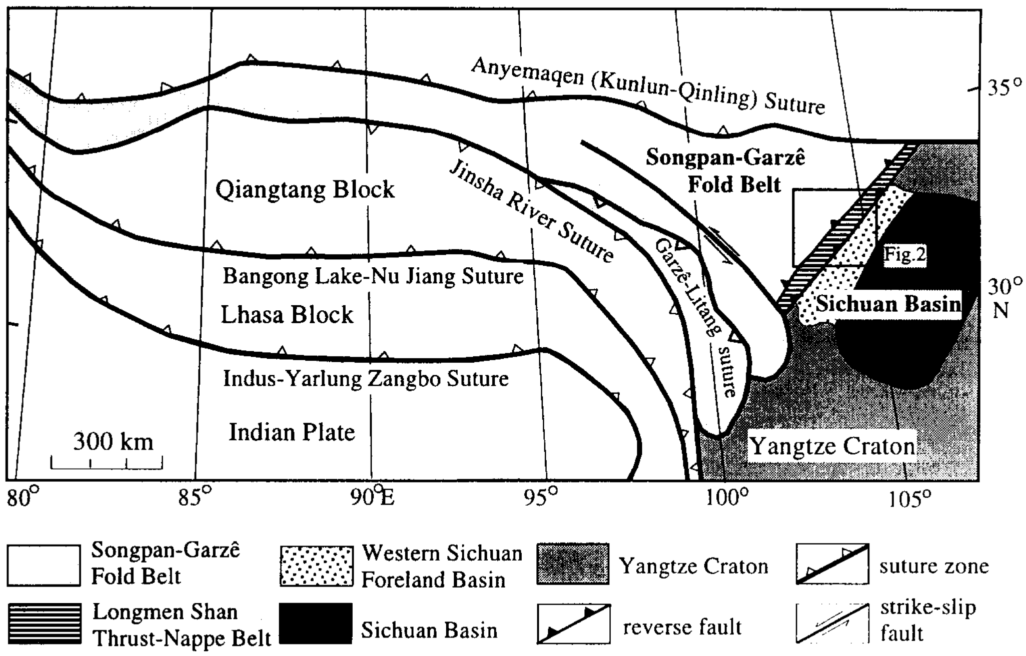

Fig. 1. Tectonic setting of the Longmen Shan Thrust–Nappe Belt along the eastern margin of the Tibetan Plateau and location of area described in this paper. Also shown are regionally important faults, sutures and blocks within the plateau and its relationship to the Indian Plate.

INTRODUCTION

The Longmen Shan Thrust–Nappe Belt, about 500 km long and 30–50 km wide, defines a major part of the highly dissected eastern margin of the Tibetan Plateau, where four tectonic units can be distinguished (Fig. 1). (1) The hinterland is dominated by the Songpan–Garzê Fold Belt, composed of Triassic turbidites and Palaeozoic greywacke–shale, that were folded and metamorphosed during the Late Triassic Indosinian orogeny. (2) The Longmen Shan Thrust–Nappe Belt, which is the subject of this paper, contains a number of large-scale nappes sub-divided by NW-dipping thrusts and is bounded to the E by (3) the Western Sichuan Foreland Basin, filled with Upper Triassic Xujiahe Formation–Quaternary terrestrial molasse and clastics, and (4) the

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unmetamorphosed and weakly deformed Yangtze Craton, composed of Sinian (Neoproterozoic) to middle Upper Triassic platform carbonates and younger terrestrial clastics, with its western part being occupied by the Sichuan Basin (Fig. 1).

Across the Longmen Shan (shan = mountains), topography rises rapidly from 500–600 m above sea level in the Sichuan Basin to elevations greater than 5000 m to form the eastern margin of the Tibetan Plateau. The current high elevation of the plateau is the manifestation of early Tertiary collision between India and the southern margin of Eurasia that is itself composed of previously accreted small continental blocks of Gondwana affinities (Mattauer 1986, Dewey *et al.* 1988, 1989, Chang *et al.* 1989). The absorption of India into Eurasia is accommodated by three major tectonic mechanisms: intracontinental shortening by folding and thrusting, A-subduction effecting a doubling of continental crust, and lateral expulsion of continental material (Howell 1989). An area equivalent to approximately 15% of the Tibetan Plateau may have been laterally extruded east of the Indian sub-continent indentor (Molnar & Tapponnier 1975, Dewey *et al.* 1989). In the Longmen Shan, the eastward extrusion of the Tibetan crust has been attributed in part or predominantly to thrusting (Mercier *et al.* 1987, Dewey *et al.* 1988, Burchfiel & Royden 1991). An assessment of these lateral extrusion models to date, however, has been hindered by uncertainties regarding the timing and nature of thrusting in the Longmen Shan Thrust–Nappe Belt.

The Longmen Shan Thrust–Nappe Belt, bounded by the Wenchuan–Maowen and Southeastern Marginal faults, contains several major thrust faults and nappes, and is divided by the Yingxiu–Beichuan Fault into inner and frontal belts (Fig. 2). Previous work has concentrated on oil and gas exploration in the frontal belt and little is known about the inner belt. As a result, several important aspects, such as the geometry, kinematics and evolutionary history of the Thrust–Nappe Belt remain unclear and controversial. For example, Luo (1984, 1991) suggests a 'thick-skinned' origin, where the thrust belt developed in response to northwestward subduction of the Yangtze Craton, but Xu *et al.* (1992) believe that it is a 'thin-skinned' thrust belt related to southeastward emplacement. The extensively distributed klippen structures are attributed to either gravity sliding (Zhao 1983, 1985, Lin & Wu 1991, Lu *et al.* 1993), or thrusting along the Yingxiu–Beichuan Fault (Liu & Dai 1986). In addition, it is suggested that the Thrust–Nappe Belt was initiated either between the Triassic and Jurassic (Tong 1992), or during the latest Triassic (Wang *et al.* 1989).

In this paper, we will describe the stratigraphy, structure and evolutionary history of the Thrust–Nappe Belt, based on over 10 months of our own fieldwork in the central sector of the Longmen Shan during 1991–1993, interpretation of seismic data obtained from the 1985–1987 China–America co-operation programme (Song 1989, Zeng *et al.* 1989), and drill-hole data that provide important sub-surface structural constraints. Our results show that both 'thick-skinned' and 'thin-skinned' thrust belts exist in the Longmen Shan, and the klippen structures are part of the Tangwangzhai Nappe, related to thrusting along the Xiangshui Fault. It will also be shown that the Longmen Shan Thrust–Nappe Belt was initiated during the early episode of the Indosinian orogeny, with a possible inversion of pre-existing syn-depositional normal faults. These subsequently underwent episodic thrusting from the latest Triassic to the Early Cretaceous and were reactivated again during the late Miocene.

STRATIGRAPHY

Three major tectono-stratigraphic units can be distinguished in the Longmen Shan and adjacent regions (Fig. 2): Mesoproterozoic basement, pre-Indosinian marine sediments from Sinian (Neoproterozoic) to middle Upper Triassic, and syn- to post-Indosinian terrestrial sediments (Upper Triassic Xujiahe Formation–Quaternary). The Mesoproterozoic basement, composed of granite, granodiorite, acidic to intermediate volcanics and various schists, was deformed and metamorphosed during the Jinning and Chengjiang movements (Wang *et al.* 1989, Tong 1992). Granite and granodiorite within the basement have been dated from 1017–1043 Ma (U–Pb technique) to 647–776 Ma (K–Ar whole rock) (Luo & Long 1992).

Sinian (Neoproterozoic) volcanics and dolomite unconformably overlie the Mesoproterozoic basement. Along the southeastern margin of the Songpan–Garzê Fold Belt, Cambrian–Silurian greywacke and shale are disconformably overlain by Devonian to Permian sandstone and shale, intercalated with minor limestone and basalt (Fig. 2). Triassic (T_1–T_3^2) turbidites, at least 6 km thick, are extensively distributed in the central part of the fold belt. These Sinian to Triassic sediments were folded and metamorphosed during the Indosinian orogeny, and locally are unconformably overlain by the uppermost Triassic Babao Shan Formation which is composed of acidic volcanics and clastics (Huang & Chen 1987, Liu *et al.* 1992). In the Yangtze Craton however, Devonian to middle Upper Triassic (D–T_3^2) sediments are dominated by relatively undeformed and unmetamorphosed carbonates.

Syn- to post-Indosinian terrestrial sediments were predominantly deposited in the Western Sichuan Foreland Basin (Fig. 3), whilst the Songpan–Garzê Fold Belt and evolving Thrust–Nappe Belt were uplifted and eroded. The composition and thickness of the sediments in the foreland basin are determined by their position relative to the evolving Thrust–Nappe Belt. Near the front of the Thrust–Nappe Belt, the Upper Triassic Xujiahe Formation, composed of alternating mudstone and sandstone (T_{3x}^{1-2} in Fig. 3) and thick conglomerate (T_{3x}^3), resting disconformably on middle Upper Triassic carbonates, can be related to early and middle episodes of the Indosinian orogeny. Jurassic to Lower Cretaceous deposits, composed of thickly layered to massive conglomerate (J_{1b}, J_{3l} and K_{1j} in Fig. 3) and alternating beds of sandstone and mudstone (J_{2q}, J_{2s} and J_{2sn}), can be

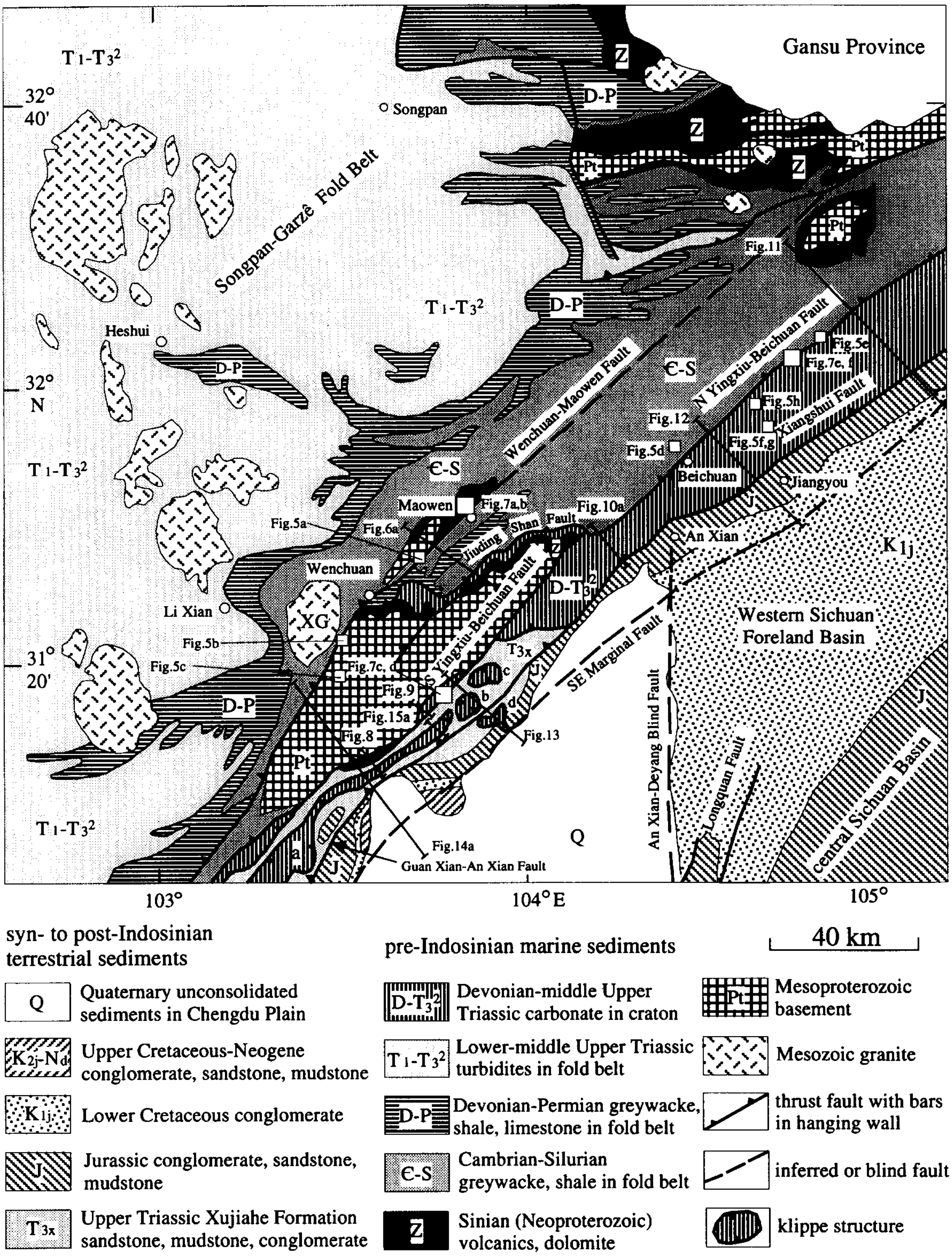

Fig. 2. Simplified geological map of the central Longmen Shan and adjacent regions. The Songpan–Garzê Fold Belt is located to the northwest of the northern Yingxiu–Beichuan, Jiuding Shan and southern Wenchuan–Maowen Faults, while the Yangtze Craton is located to the southeast of these faults. The Longmen Shan Thrust–Nappe Belt is bounded by the Wenchuan–Maowen and southeastern Marginal Faults. Symbol: XG = Xuelongbao Granite. Klippen structures: (a) Baiyunding–Xiaoyudong Klippe, (b) Tiantai Shan Klippe, (c) Jianfengding Klippe, (d) Tangbazi Klippe.

related to late Indosinian and early to middle Yenshanian thrusting. Upper Cretaceous to Neogene sediments (K_{2j}, K_{2g}, E_m and N_d in Fig. 3), composed of conglomerate, sandstone and mudstone, interbedded with gypsum and anhydrite, can be related to late Yenshanian and early Himalayan movements. The foreland basin fill (T_{3x}^{1-2}–Q in Fig. 3) is separated by several disconformities, with major unconformities existing between Paleogene/Neogene and Neogene/Quaternary deposits that can be related to the Himalayan orogeny. Unconsolidated Quaternary (Q) sediments are widely distributed in the Chengdu Plain.

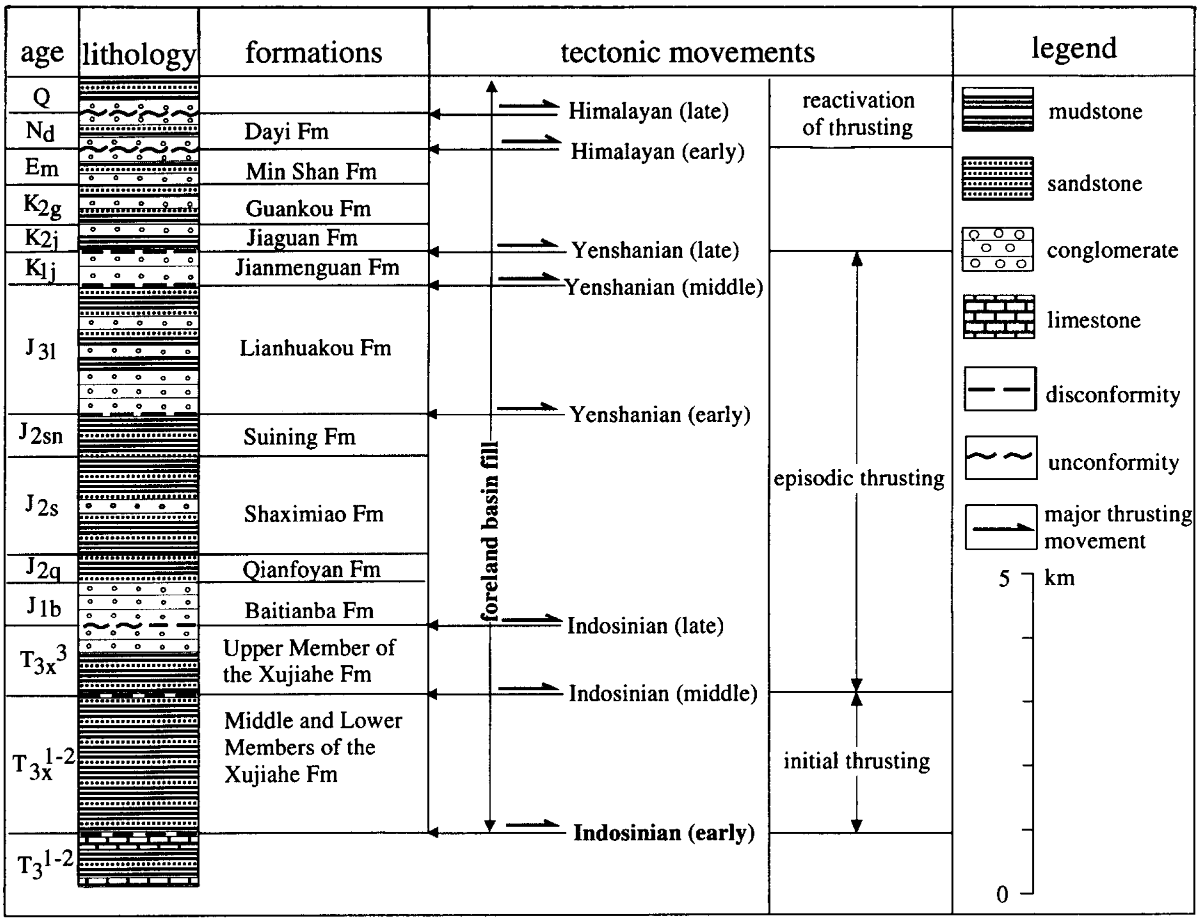

Fig. 3. Stratigraphy and tectonic movements related to the syn- and post-Indosinian sediments deposited in the Western Sichuan Foreland Basin.

NATURE OF MAIN THRUSTS

The stratigraphic pile in the Longmen Shan is bounded and sub-divided by six regionally significant, NW-dipping thrust faults into five large-scale nappes (Fig. 4), each of which has its own stratigraphic and deformational features. The major thrusts generally have a listric geometry and are accompanied by a splay of several second-order faults to form duplexes and imbricate fans.

Wenchuan–Maowen Fault

This defines the northwestern boundary of the Longmen Shan Thrust–Nappe Belt (Fig. 4), and is a composite set of sub-parallel, brittle structures superimposed on the 20–25 km wide, ductile Wenchuan–Maowen Shear Zone (Dirks *et al.* 1994, Worley & Wilson 1996). Between the towns of Wenchuan and Maowen, Mesoproterozoic basement tectonically overlies Sinian (Neoproterozoic) dolomite, and both are thrust onto Devonian or Silurian metasediments (Figs. 5a and 6a). Rocks adjacent to the main fault have been deformed into a zone, up to 100 m in width, composed of breccia, cataclasite and gouge, which are related to a series of northwestward-dipping, second-order faults (Fig. 6b), duplex structures and thin thrust sheets from several centimetres to tens of metres in thickness. Figure 5(a) shows one such thrust, the lower portion of which consists of gouge and breccia. Associated with the main fault is a series of smaller faults that occur predominantly, but not exclusively, in the footwall of the main thrust (Fig. 5a). Axial surfaces of folds adjacent to the fault generally dip to the northwest and the associated axial planar slaty cleavage sub-parallels the fault planes (Fig. 6c). Northwest of the 'Peng Xian-Guan Xian Basement Complex', Silurian schist is thrust onto Upper Sinian dolomite, which is in turn thrust southeastwards onto Mesoproterozoic basement with a gouge zone 20 cm wide (Fig. 5b). Numerous steep (60–80°) pitching slickenlines and accompanying steps and fractures on the fault surfaces that dip 60–85° to the northwest suggest that the Wenchuan–Maowen Fault is dominated by reverse faulting with transport to the southeast (Figs. 7a & b).

Jiuding Shan Fault

This is situated between the 'Peng Xian-Guan Xian Basement Complex' Nappe and the Jiuding Shan Nappe (Fig. 4), forming part of the tectonic boundary between the Songpan–Garzê Fold Belt and the Yangtze Craton (Fig. 2). The fault has a zigzag outcrop pattern (Fig. 2) and dips to both the northwest and northeast. Along the

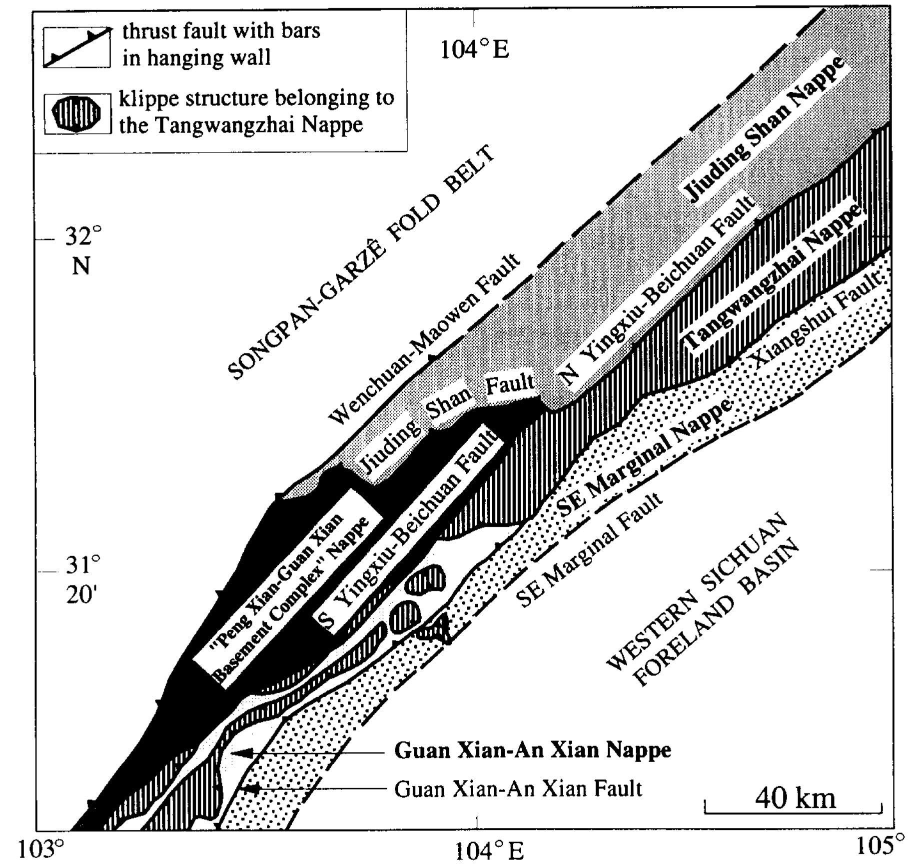

Fig. 4. Nappe sub-division and location of faults in the central Longmen Shan. Klippen structures are part of the Tangwangzhai Nappe, with the Xiangshui Fault at their base.

Jiuding Shan Fault, metamorphosed and intensely deformed Palaeozoic sediments in the fold belt, dominated by Silurian–Devonian shale and sandstone with minor limestone, are thrust onto Upper Palaeozoic unmetamorphosed carbonates in the craton, and both override Upper Sinian (Neoproterozoic) dolomite as thrusting propagated southeastwards (Fig. 6a).

Yingxiu–Beichuan Fault

This fault trends 035–045° and dips 50–70° to the northwest and is characterized by brittle fault rock products, such as breccia, cataclasite and gouge, although mylonitic carbonate has been locally observed. It is divided by the Jiuding Shan Fault into southern and northern segments which are related to the 'Peng Xian-Guan Xian Basement Complex' Nappe and the Jiuding Shan Nappe respectively (Fig. 4). Along the southern Yingxiu-Beichuan Fault, a single fault thrusts Mesoproterozoic basement onto Lower Sinian (Neoproterozoic) volcanics, which are composed of rhyolite, andesite, dacite and basalt and unconformably overlain by Devonian limestone and shale (Fig. 8). In other areas (Fig. 9), the major fault has transported Mesoproterozoic granite and metavolcanics onto Permian mylonitic limestone. In its footwall, there is a network of second-order faults that have thrust Mesoproterozoic basement and Lower Sinian volcanics onto Permian and Lower Triassic carbonates (Fig. 9), with gouge and breccia adjacent to the faults. These faults may coalesce downwards with the Xiangshui Fault to form an imbricate fan. Where Lower Sinian volcanics and Devonian to Triassic carbonates between the southern Yingxiu–Beichuan and Xiangshui faults are removed by erosion, Mesoproterozoic basement is in tectonic contact with Upper Triassic Xujiahe Formation (Fig. 2). Along the northern Yingxiu–Beichuan Fault, Lower Palaeozoic metamorphic greywacke and shale override unmetamorphosed Devonian limestone (Figs. 10 and 11). Steep (60–85°) pitching slickenside striations indicate that the Yingxiu–Beichuan Fault is dominated by southeastwards reverse movement (Figs. 7c & d). This is also complicated by many shallow (3–40°) pitching slickenlines which show dextral strike-slip on NWW- and E-W-striking slickensides, and sinistral strike-slip on NNE-striking slickensides (Figs. 7e & f), conforming to the general NW–SE-directed shortening.

The Yingxiu-Beichuan Fault separates metamorphic rocks in the inner Longmen Shan from unmetamorphosed rocks in the frontal Longmen Shan. In the inner Longmen Shan, Mesoproterozoic basement and Lower Palaeozoic metasediments are extensively exposed in the 'Peng Xian-Guan Xian Basement Complex' Nappe and the Jiuding Shan Nappe, respectively (Figs. 2 and 4). In the frontal Longmen Shan, Devonian to middle Upper Triassic, unmetamorphosed carbonates are predominantly exposed in the Tangwangzhai Nappe, while a sequence extending from Upper Triassic Xujiahe Formation to Cretaceous, unmetamorphosed terrestrial clastics is extensively exposed in the Guan Xian-An Xian and Southeastern Marginal nappes (Figs. 2 and 4).

Xiangshui Fault

This fault separates pre-Indosinian marine sediments within the Tangwangzhai Nappe and klippen structures, extensively distributed to the southeast of the 'Peng Xian-Guan Xian Basement Complex', from syn- to post-Indosinian terrestrial sediments that were deposited in the Western Sichuan Foreland Basin, thereby defining a major part of the northwestern margin of the foreland basin (Fig. 2). Very thick Devonian to Carboniferous carbonates are distributed in the hangingwall of the Xiangshui Fault, whereas these sediments are absent from the footwall of the fault (Figs. 11 and 12). Along the southeastern edge of the Tangwangzhai Nappe, the Xiangshui Fault has transported Devonian to middle Upper Triassic (T_3^2) carbonates onto the Xujiahe Formation (T_{3x})–Jurassic conglomerate, sandstone and mudstone (Figs. 10, 11 and 12). From seismic data (Song 1989, Zeng *et al.* 1989), the Xiangshui Fault has a listric geometry with a large displacement (Fig. 12) and coalesces with a basal detachment fault sitting between the Mesoproterozoic basement and Sinian (Neoproterozoic) cover sequence (Fig. 11).

The Xiangshui Fault is also located at the base of klippen structures composed of Devonian to middle Upper Triassic sediments which can be correlated to the same stratigraphic units in the Tangwangzhai Nappe. Following thrusting of Devonian to middle Upper Triassic carbonates onto the Upper Triassic Xujiahe Formation and Jurassic terrestrial deposits (Figs. 8 and 13), isolation by erosion of the allochthonous units has resulted in a series of klippen structures, such as the Baiyunding–Xiaoyudong, Tiantai Shan, Jianfengding and Tangbazi klippen (Fig. 2). Hence, in our interpretation, the Xiangshui Fault has an undulate cross-sectional geometry with thrusting along this fault and subsequent erosion responsible for the development of the klippen structures. Previous workers suggested that the klippen structures were developed by gravity sliding from the top of the 'Peng Xian-Guan Xian Basement Complex' or from the Songpan–Garzê Fold Belt (Zhao 1985, Lin & Wu 1991, Lu *et al.* 1993). The previous model, however, conflicts with the palaeogeographic data that the basement block was a tectonic high during most of the Palaeozoic, without deposition of sediments compared to those in the klippen structures (Tong 1992). Similarly, Devonian–middle Upper Triassic carbonates within the klippen structures are very different from the time equivalent stratigraphic units, dominated by greywacke and shale, in the adjacent Songpan–Garzê Fold Belt.

Guan Xian-An Xian Fault

This is a NW-dipping listric fault within the Western Sichuan Foreland Basin, and coalesces with a basal detachment fault between the Mesoproterozoic basement and Sinian (Neoproterozoic) sediments (Fig. 14a). The fault is located within the Upper Triassic Xujiahe Formation or between the Xujiahe Formation and Jurassic sediments, and intersects with the Xiangshui Fault to the northeast (Fig. 2). Rocks adjacent to the fault are commonly deformed into breccia and gouge, and deformation across the fault is accompanied by concentric folds (Fig. 13). The fault coincides, in extent, approximately with the distribution of klippen structures (Fig. 2), and disappears beneath the Tangwangzhai Nappe, as a result of differential thrusting along the Thrust–Nappe Belt. This suggests that thrusting along the Guan Xian-An Xian Fault is related, at least partly, to the development of klippen structures. Thrusting along this fault and the Southeastern Marginal Fault is responsible for the deformation and uplift of the northwestern part of the foreland basin.

Southeastern Marginal Fault

Situated along the southeastern margin of the Longmen Shan Thrust–Nappe Belt (Fig. 4), this is a blind fault in that it remains sub-surface beneath a cover of Jurassic to Cretaceous or Quaternary sediments in the foreland basin, and is recognized only in seismic sections (Lin & Wu 1991, Tong 1992). The fault is marked by an imbricate fan of NW-dipping blind faults or a single blind fault (Figs. 11, 12 and 14). Deformation across this fault is characterized by an abrupt change in bedding attitude which dips 40–50° to the southeast in the hangingwall, and remains sub-horizontal in the footwall (Fig. 13). Similar to the Xiangshui and Guan Xian-An Xian faults, the Southeastern Marginal Fault has a listric cross-sectional geometry and coalesces with a basal detachment fault along which cover sequences are stripped from the Mesoproterozoic basement (Fig. 14a).

DEFORMATION WITHIN THE NAPPES

'Peng Xian-Guan Xian Basement Complex' Nappe

This nappe, dominated by the 'Peng Xian-Guan Xian Basement Complex', is bounded by the Wenchuan–Maowen, Jiuding Shan and southern Yingxiu–Beichuan Faults (Figs. 2 and 14a). The Mesoproterozoic basement block is surrounded and unconformably overlain by Sinian (Neoproterozoic) volcanics and dolomite, which in turn are disconformably overlain by Devonian to middle Upper Triassic carbonates (Fig. 2). Lower Palaeozoic deposits are absent from this nappe, except on its southwestern margin (Fig. 2). Localized ductile shear zones with dominantly southeastward sense of transport (Fig. 5c), and mylonitic high-strain zones up to a kilometre in width have been identified in the northwestern part of the basement block, whereas numerous northeast-trending brittle fractures have been observed in the southeastern part of the basement block (Fig. 14b). Southeastward thrusting along the southern

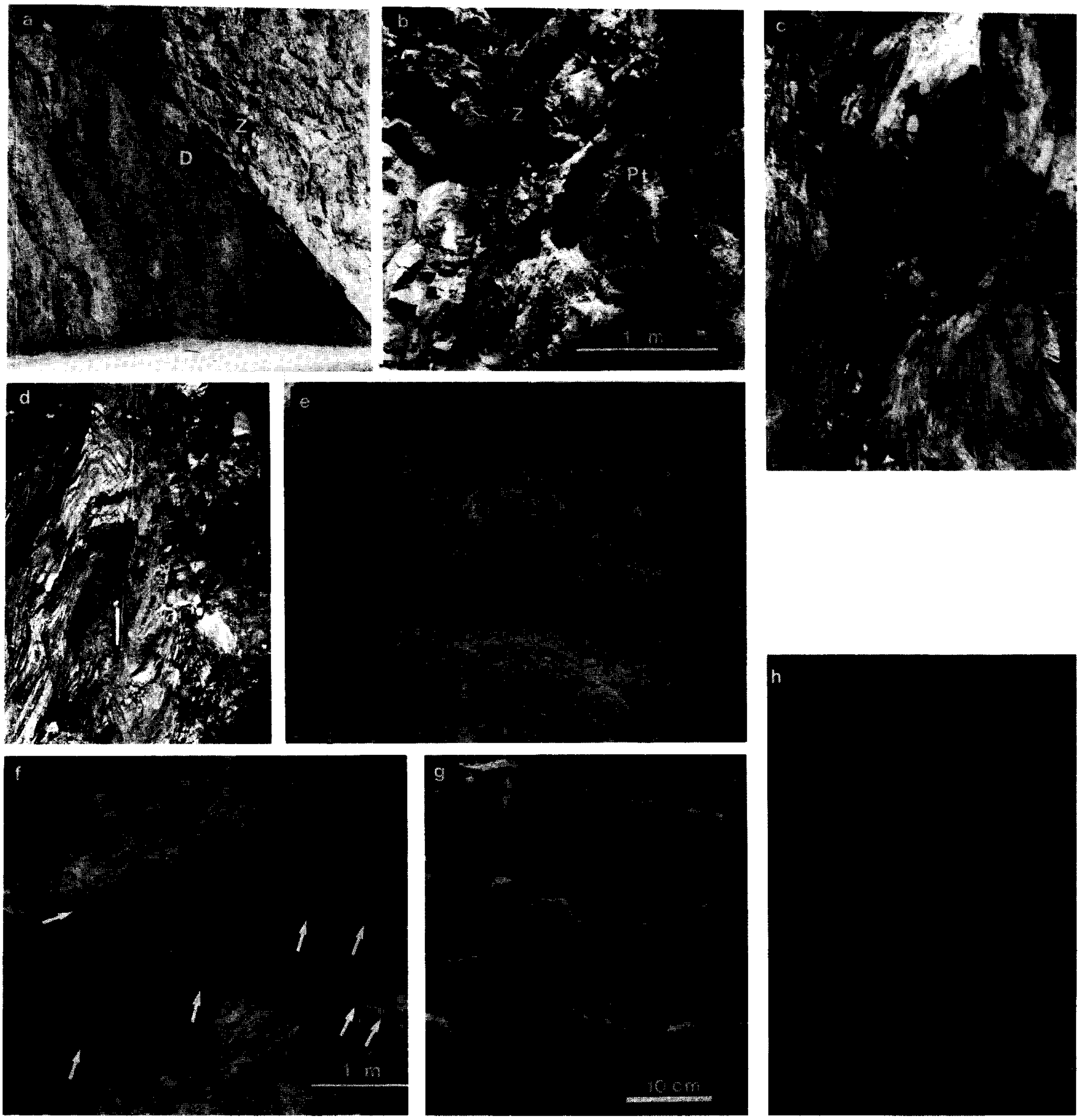

Fig. 5. Photographs showing deformation in the Longmen Shan Thrust–Nappe Belt. See Fig. 2 for location. (a) The Wenchuan–Maowen Fault at Yanmen. Sinian (Neoproterozoic) dolomite thrust southeastwards onto Devonian rocks which are deformed into gouge and breccia with second-order faults. Looking towards the southwest: note man for scale. (b) Sinian (Neoproterozoic) dolomite thrust onto Mesoproterozoic basement metavolcanics along the Wenchuan–Maowen Fault indicated by arrows, with a gouge zone of 20 cm in width. (c) A ductile shear zone in Mesoproterozoic metavolcanics of the 'Peng Xian-Guan Xian Basement Complex'. The curvature of foliation shows a reverse shear sense of northwest-over-southeast. Position and orientation of the ductile shear zone is indicated by the arrow. (d) Chevron folds with a limb thrust developed in Lower Cambrian siltstone and sandstone within the Jiuding Shan Nappe, west of Beichuan. Looking towards the northeast. (e) Localized duplex structures above a thrust ramp within the Yingxiu–Beichuan Fault, developed in interbedded Cambrian sandstone and graphite schist, 6 km southwest of Nanba. (f) Individual steep dipping slickensided fault surfaces (arrowed) that form portion of a complex array of duplex structures within the Devonian limestone in the centre of the Tangwangzhai Syncline. (g) Carbonate slickenfibres on reverse fault surface in the core of the Tangwangzhai Syncline. (h) Ridge and groove slickenline striations on steep dipping, bedding-parallel fault surface on northwestern limb of the Tangwangzhai Syncline, lens cap as scale.

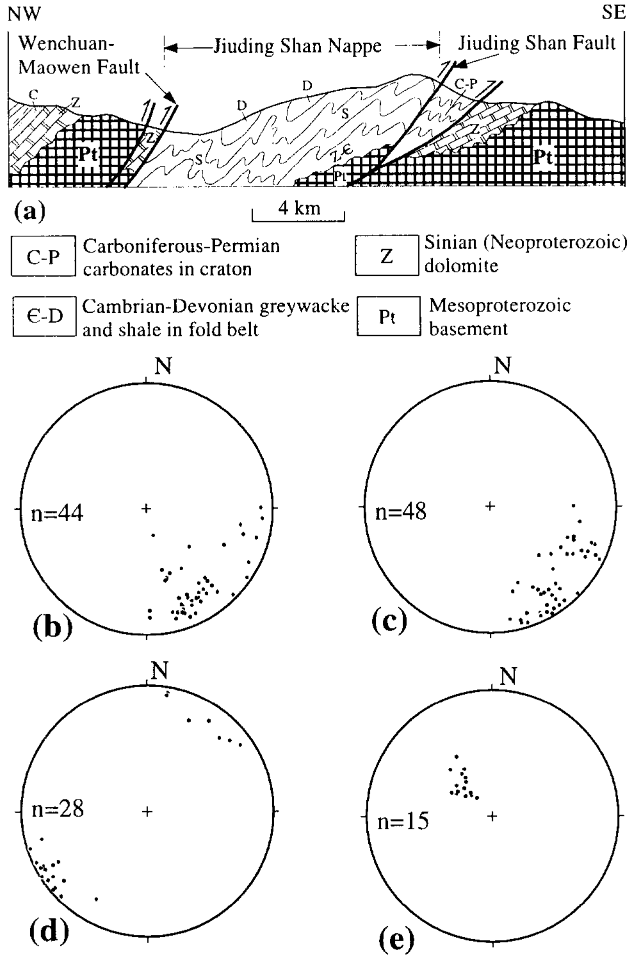

Fig. 6. (a) Structural cross-section through the Jiuding Shan Nappe (see Fig. 2 for location); lower-hemisphere, equal-area projections for (b) poles to fault planes within the Wenchuan–Maowen Fault zone, (c) fold axial surfaces and axial planar slaty cleavage, (d) fold axes and (e) stretching lineations, within the Jiuding Shan Nappe.

Yingxiu–Beichuan Fault has transported the Mesoproterozoic basement onto Lower Sinian (Neoproterozoic) volcanics (Figs. 8 and 14a), and onto Carboniferous to Lower Triassic carbonates (Figs. 9 and 13). Therefore, the 'Peng Xian-Guan Xian Basement Complex' Nappe is herein interpreted as a system of basement horses that were assembled in the early Indosinian orogeny. This basement complex nappe is 'thick-skinned' in nature, similar to the 'external massifs' of the Alps and the Blue Ridge anticlinorium in the Appalachians (Rodgers 1970, Hatcher 1981, Boyer & Elliott 1982).

Jiuding Shan Nappe

This is bounded by the Wenchuan–Maowen, Jiuding Shan and northern Yingxiu–Beichuan Faults (Fig. 4) and is mainly composed of Palaeozoic greywacke and shale which were metamorphosed to lower greenschist facies during the Late Triassic Indosinian orogeny (Chen *et al.* 1995). In the stratigraphically higher and more laminated Silurian to Devonian sediments, inclined to overturned folds, with gentle northwestern limbs and steep southeastern limbs, have been identified in the Jiuding Shan Nappe (Fig. 6a). Stretching lineations, defined by the alignment of muscovite, chlorite and elongate quartz on an axial planar slaty cleavage, plunge 50–75° to the northwest and indicate southeast-directed shortening (Fig. 6e). Within the Lower Cambrian siltstone and sandstone west of Beichuan, there are a series of mesoscopic chevron folds often with associated limb thrusts (Fig. 5d), whose axial surfaces dip 50–85° to the northwest and fold axes plunge 3–20° to both the northeast and southwest (Figs. 6c & d). The Jiuding Shan Nappe overrides Upper Palaeozoic carbonates along the Jiuding Shan Fault and the northern Yingxiu–Beichuan Fault (Figs. 6a and 10).

A seismic profile across Jiaoziding (Fig. 11) shows that the Jiuding Shan Nappe contains a number of sub-nappes defined by thrust faults with a flat and ramp geometry, and detachment faults between Mesoproterozoic basement and the Sinian (Neoproterozoic) cover sequence. At a higher structural level, Sinian to Silurian metasediments are deformed into southeast verging folds with an associated axial surface slaty cleavage above a basal fault. At deeper levels, however, the Mesoproterozoic basement has also been incorporated into allochthonous sheets (Fig. 11), similar to the 'Peng Xian-Guan Xian Basement Complex' Nappe.

Tangwangzhai Nappe

This is situated between the Yingxiu–Beichuan and Xiangshui Faults (Fig. 4). In contrast to the Jiuding Shan Nappe, the Tangwangzhai Nappe is dominated by Devonian–middle Upper Triassic unmetamorphosed carbonates that are deformed into large-scale open folds (Figs. 11 & 12). A series of NW-dipping listric thrusts sub-divide the Tangwangzhai Nappe into a number of sub-nappes, with the Xiangshui Fault at the base (Figs. 11 and 12), while seismic data (Song 1989, Zeng *et al.* 1989) also reveal the existence of several back-thrusts dipping to the southeast (Fig. 12). These sub-nappes are superimposed on each other, with exposed stratigraphic units becoming younger towards the southeast (Fig. 11). The major part of the Tangwangzhai Nappe, east of the N-trending fault located between Beichuan and An Xian (Fig. 2), is occupied by the highly dissected Tangwangzhai Syncline, with a wavelength up to 15 km (Figs. 11 and 12). Numerous minor thrusts and duplexes related to the Yingxiu–Beichuan Fault and within the core of the syncline (Figs. 5e and f) indicate NW–SE-directed shortening. These faults contain prominent steep pitching slickenlines that include fibrous growth (Fig. 5g) and ridge and groove striations (Fig. 5h) and lie normal to the syncline axis, indicating that the folding mechanism is dominantly one of flexural slip. West of the N-trending fault, however, deformation within the Tangwangzhai Nappe is characterized by a stack of meso- to macroscopic SE-verging folds and NW-dipping thrusts (Fig. 10). Along the Xiangshui Fault, the Tangwangzhai Nappe is transported onto the Upper Triassic Xujiahe Formation (T_{3x}) and Jurassic terrestrial sediments (Figs. 10, 11 and 12). The Xiangshui Fault has a flat-ramp geometry and becomes a bedding-plane thrust when

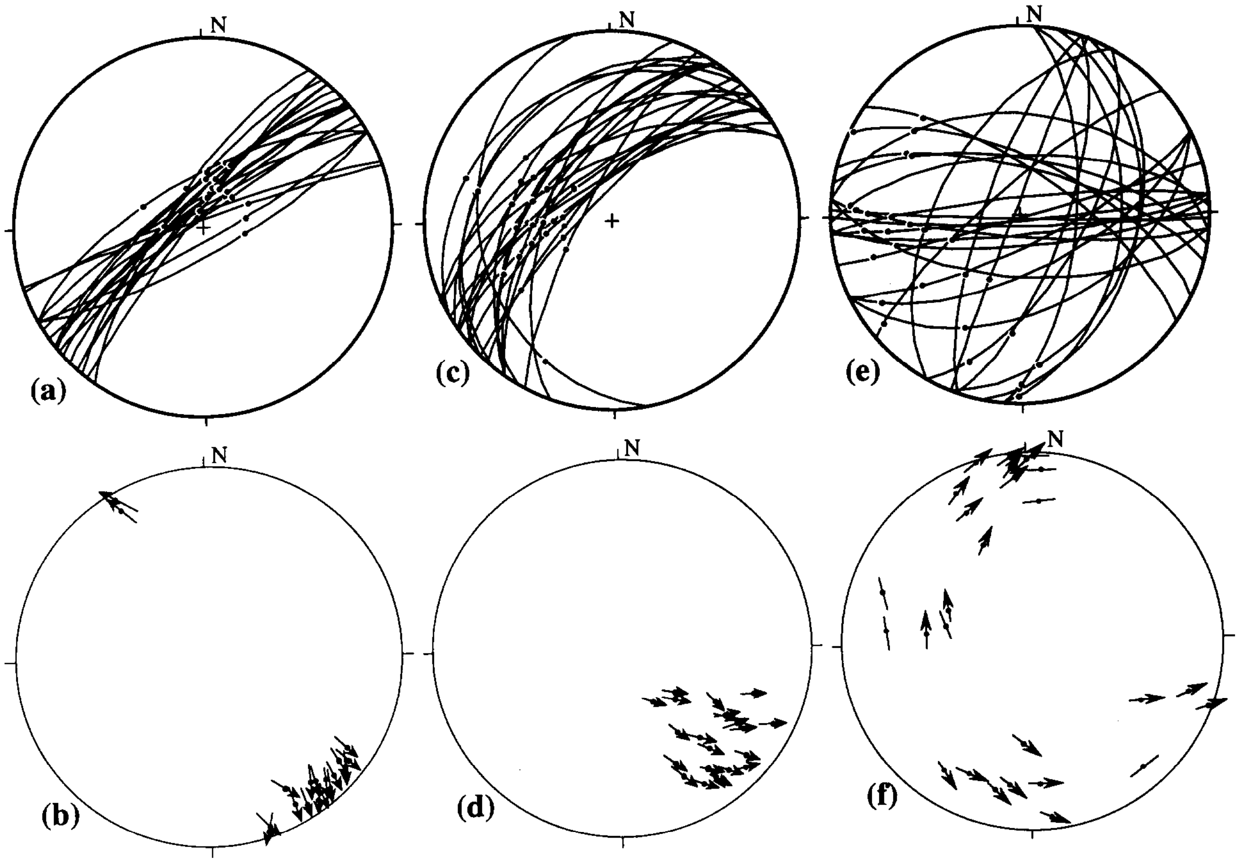

Fig. 7. Stereographic projections (lower-hemisphere, equal-area) of (a), (c) and (e) fault orientation (great circles) and slickenlines (dots), and (b), (d) and (f) poles to fault surfaces with the trace of the striae. Arrows indicate the movement direction of the hanging wall. See Fig. 2 for location: (a) & (b) within the Wenchuan–Maowen Fault zone at Shilipu, (c) & (d) within the southern Yingxiu–Beichuan Fault zone at Baishuihe, (e) & (f) within the northern Yingxiu–Beichuan fault zone at Guixi.

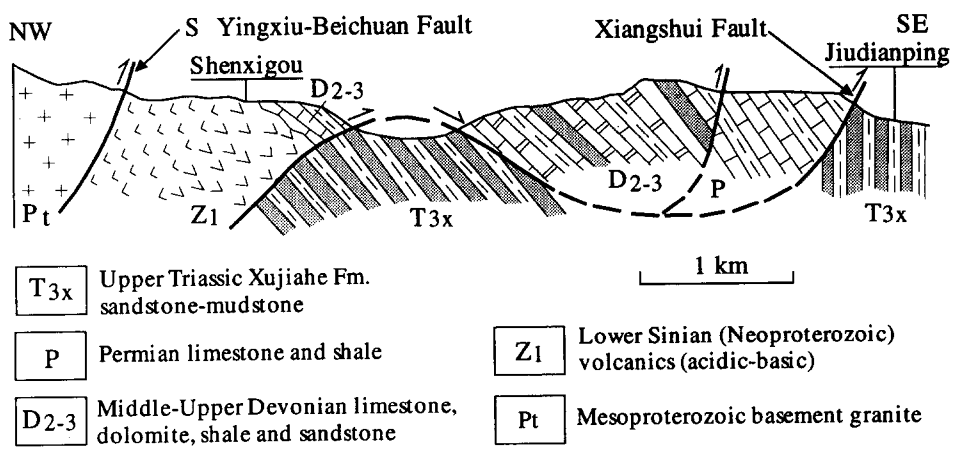

Fig. 8. A cross-section showing the southern Yingxiu–Beichuan Fault, and relationship of the Xiangshui Fault to klippen structure. See Fig. 2 for location.

situated either between Mesoproterozoic basement and Sinian (Neoproterozoic) rocks (Fig. 11) or at the base of Devonian sediments (Fig. 12). In contrast to the 'Peng Xian-Guan Xian Basement Complex' and Jiuding Shan nappes in the inner Longmen Shan, the thrust sheets of the Tangwangzhai Nappe have involved only cover sequences which are stripped from Mesoproterozoic basement (Fig. 11). Therefore the Tangwangzhai Nappe is interpreted in this paper as a 'thin-skinned' fold and thrust belt situated in the frontal Longmen Shan, and is comparable to the Helvetic and Subalpine zones in the western Alps and the Valley and Ridge province in the Appalachians (Rodgers 1970, Ramsay 1981, Boyer & Elliott 1982).

There is a stratigraphic continuity of Devonian to middle Upper Triassic carbonates between the klippen structures and the Tangwangzhai Nappe (Fig. 2) and both have a similar relationship to the Xiangshui Fault. Internal folds and thrusts within the klippen generally trend NE and parallel the strike of the major faults in the

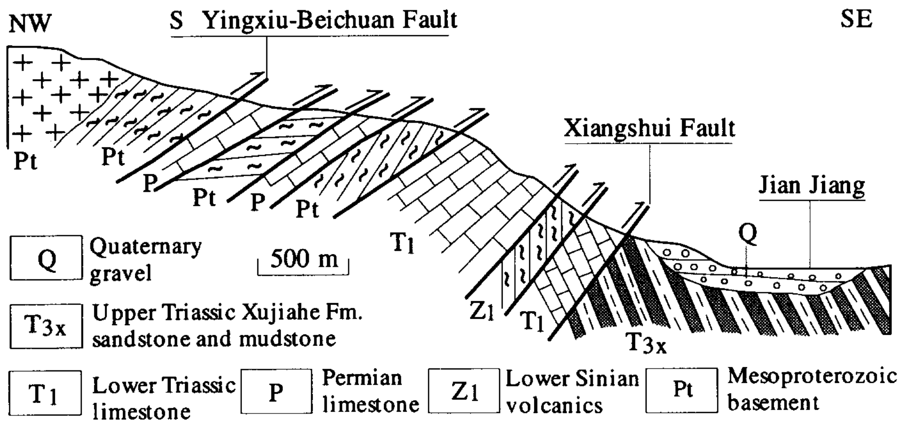

Fig. 9. Field sketch of second-order faults separating thin thrust sheets, between the southern Yingxiu–Beichuan Fault and Xiangshui Fault. See Fig. 2 for location.

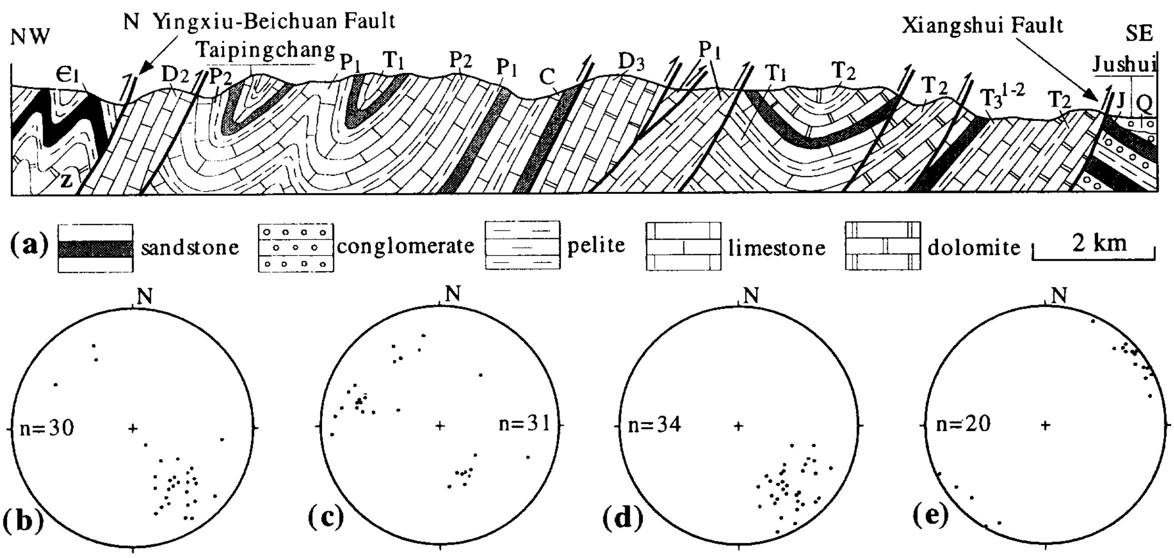

Fig. 10. (a) Structural cross-section through the Tangwangzhai Nappe (see Fig. 2 for location), west of the N-trending fault between Beichuan and An Xian, showing the southeastward vergence of folds and movement sense on thrust faults. (b)–(e) Lower-hemisphere, equal-area projections for (b) poles to major fault planes, (c) fractures (slickenside and joint), (d) fold axial surfaces, and (e) fold axes, within the nappe.

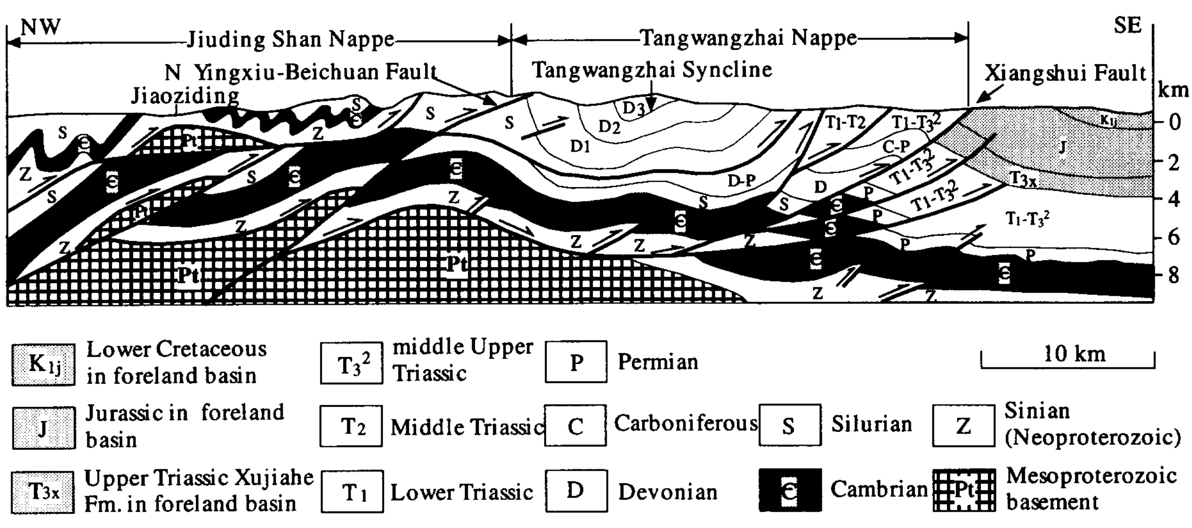

Fig. 11. Deformation within the Jiuding Shan and Tangwangzhai nappes, and relationship to the northern Yingxiu–Beichuan and Xiangshui Faults (deep structure interpreted from seismic profile L55 of Song 1989, Zeng *et al.* 1989). Note that the Jiuding Shan Nappe has incorporated Mesoproterozoic basement into thrust sheets, but the Tangwangzhai Nappe is composed of cover sediments from Sinian (Neoproterozoic) to middle Upper Triassic which are stripped from the Mesoproterozoic basement. Foreland basin sediments (T_{3x}–K_{1j}) were deposited to the southeast of the Xiangshui Fault that forms a major boundary of the foreland basin. See Fig. 2 for location.

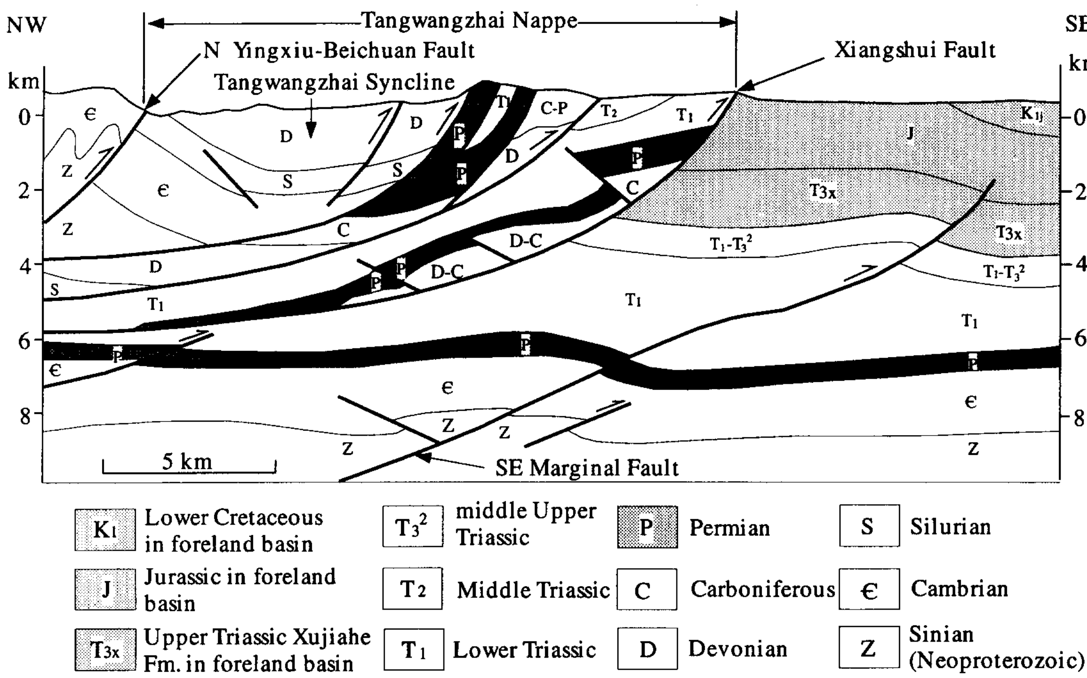

Fig. 12. Deformation within the Tangwangzhai Nappe and relationship of the Xiangshui Fault to the Western Sichuan Foreland Basin (deep structure based on seismic profile L14 of Song 1989, Zeng *et al.* 1989). Note that there are no Ordovician–Carboniferous sediments east of the listric Xiangshui Fault, but the Tangwangzhai Syncline is composed of very thick Devonian carbonates. Foreland basin sediments (T_{3x}–K_1) can be observed only to the southeast of the listric Xiangshui Fault with a large displacement. See Fig. 2 for location.

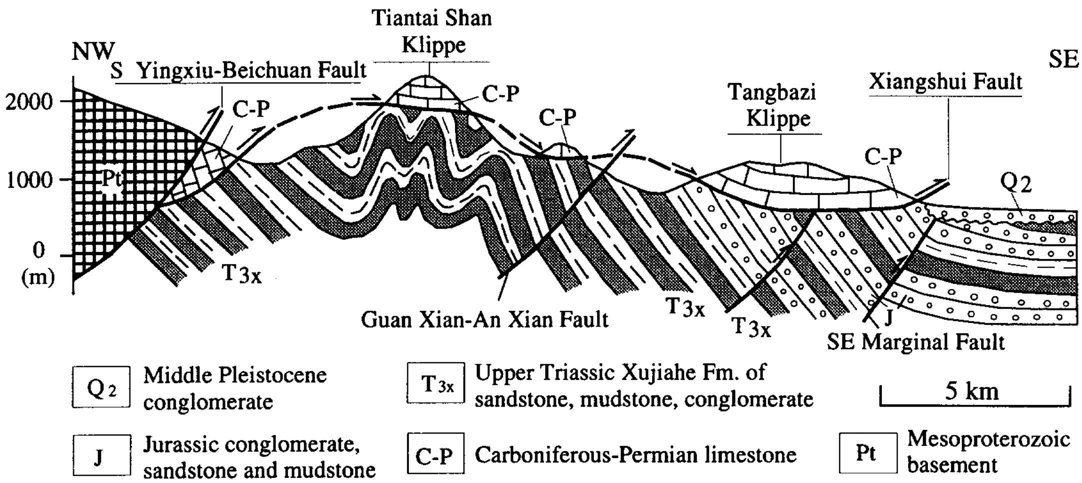

Fig. 13. The Xiangshui Fault with an undulate cross-sectional geometry at the base of the Tiantai Shan and Tangbazi klippen. Along the southern Yingxiu–Beichuan Fault, the Proterozoic basement is thrust onto Carboniferous–Permian limestone, which is in turn transported onto the Upper Triassic Xujiahe Formation–Jurassic sediments along the Xiangshui Fault. See Fig. 2 for location.

Thrust–Nappe Belt. For instance, the southeastern part of the Baiyunding–Xiaoyudong Klippe contains SE-verging, inclined to overturned folds, while its central part is deformed into inclined and recumbent folds and its northwestern part is deformed into upright folds (Figs. 15a–c). Hinterland dipping faults (Fig. 15d) and antiformal stacked faults are found within the klippe (Fig. 15a). Small-scale duplexes, imbricate fans and back thrusts develop within Permian massive limestone and Lower–Middle Triassic carbonate (Figs. 15e & f). Adjacent to the sole fault (i.e. the Xiangshui Fault), evidence of soft-sediment deformation, such as diapirs or flame structures, have been locally observed in the allochthonous sheet. The overall deformation pattern within the klippe is similar to that of the Tangwangzhai Nappe (Figs. 10 and 15). All these suggest that the klippen structures are part of the Tangwangzhai Nappe but have undergone more uplift and erosion.

Guan Xian-An Xian Nappe

This nappe, located to the southeast of the 'Peng Xian-Guan Xian Basement Complex' and between Xiangshui and Guan Xian-An Xian Faults, is composed of the Upper Triassic Xujiahe Formation underlain by pre-Indosinian marine sediments (Fig. 14a). Defor-

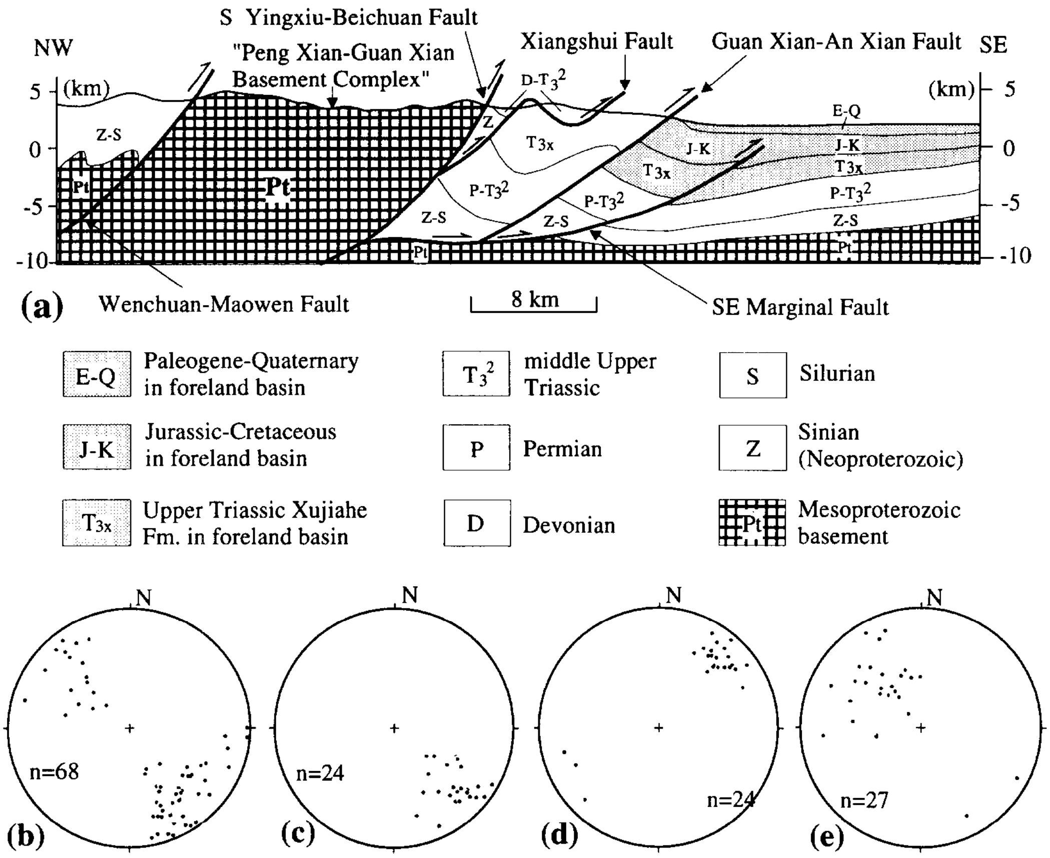

Fig. 14. (a) Generalized cross-section through the Longmen Shan Thrust–Nappe Belt (see Fig. 2 for location), and (b)–(e) lower-hemisphere, equal-area projections for (b) poles to fractures (joint and small fault) in the southeastern part of the 'Peng Xian-Guan Xian Basement Complex', (c) fold axial surfaces and (d) fold axes within the Guan Xian-An Xian Nappe and (e) bedding in the Southeastern Marginal Nappe. Note that the Guan Xian-An Xian and southeastern Marginal faults coalesce with a detachment fault between the Mesoproterozoic basement and Sinian (Neoproterozoic) sediments. See Fig. 2 for location.

mation within the nappe is characterized by SE-verging concentric folds, with axial surfaces dipping 40–80° to the northwest and fold axes plunging 5–35° to the northeast (Figs. 14c & d).

Southeastern Marginal Nappe

Situated between the Guan Xian-An Xian and Southeastern Marginal faults (Fig. 4), the nappe exposes rocks ranging from the Upper Triassic Xujiahe Formation (T_{3x}) up to Cretaceous terrestrial molasse and clastic deposits. Superficial deformation is dominated by SE-dipping monoclines in the hangingwall of the Southeastern Marginal Fault, while bedding in its footwall remains almost horizontal (Figs. 13 and 14e). Similar to the Tangwangzhai Nappe, the Southeastern Marginal and Guan Xian-An Xian nappes have also involved only cover sequences in their allochthons (Fig. 14a).

STRUCTURAL EVOLUTION OF THE THRUST–NAPPE BELT

Prior to the Indosinian orogeny, an extensional environment predominated along the western margin of the Yangtze Craton (Luo 1984, 1991). Superimposed on this were three principal episodes of Indosinian deformation which have been identified in the neighbouring Songpan–Garzê Fold Belt (Chen *et al.* 1995, Worley & Wilson 1995). Based on tectono-stratigraphic analysis, four evolutionary stages have been recognized within the Longmen Shan Thrust–Nappe Belt (Fig. 16).

Pre-thrusting extensional stage (D–T_3^2)

During the Late Palaeozoic, a number of extensional events attenuated the western passive margin of the Yangtze Craton (Han 1984, Luo 1984, 1991, Zhao 1985, Song 1989, Liu *et al.* 1990, Tong 1992), resulting in NE-trending syn-depositional normal faults (Fig. 16a). The exact nature of these faults and any basal detachment faults is unknown because of subsequent deformation and lack of exposure. However, an attempt to reconstruct the distribution of the Devonian carbonate sequences, from the stratigraphic data of Tong (1992) on the western margin of the Yangtze Craton, suggests that up to 6000 m of sediment was deposited during the Devonian between the existing location of the Yingxiu–Beichuan and Xiangshui Faults (Fig. 17). Across the Xiangshui Fault to the southeast, Devonian to Carboniferous sediments are absent, and Permian limestone disconformably overlies Cambrian sediments (Figs. 11

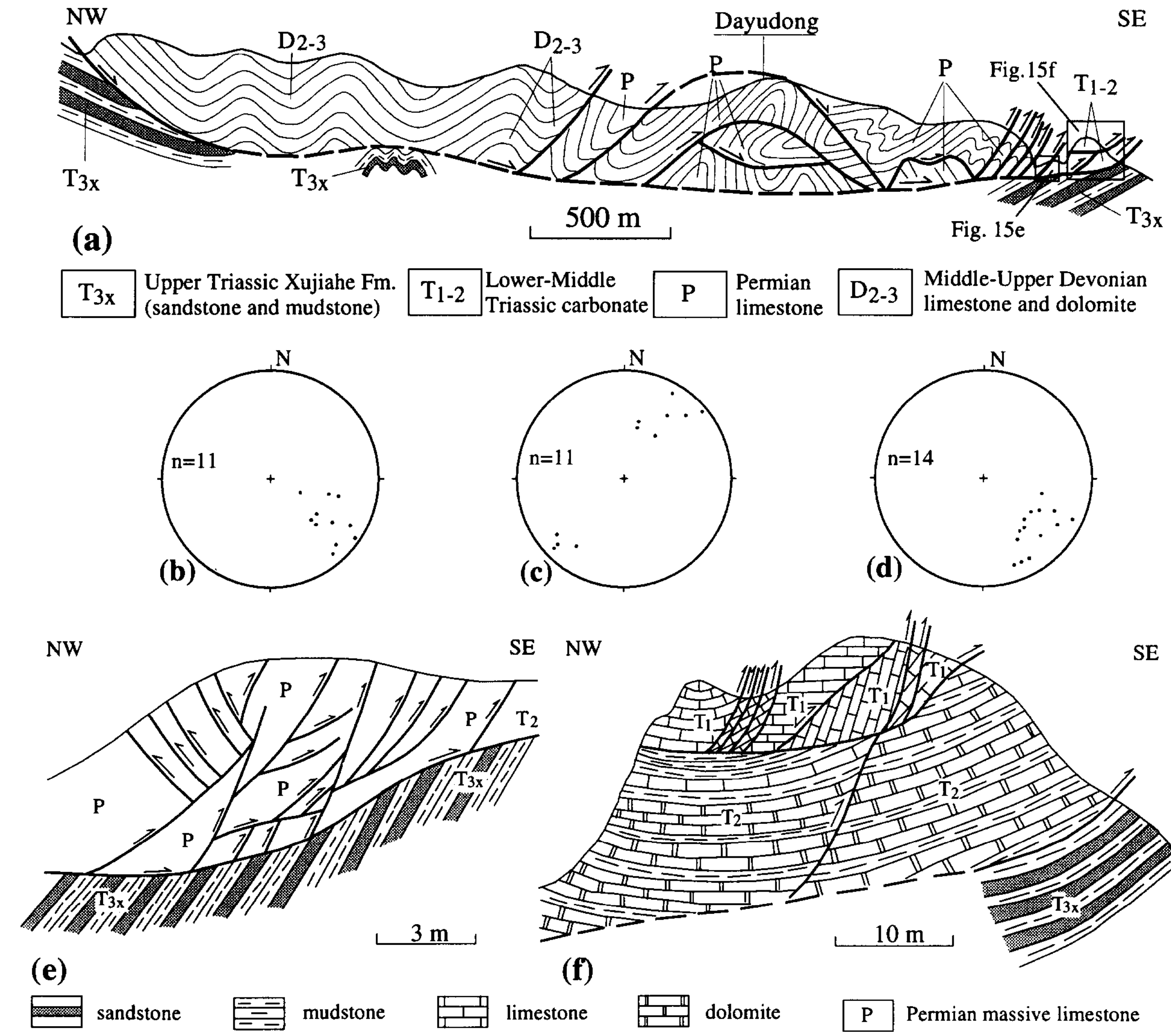

Fig. 15. (a) Internal deformation of the Baiyunding–Xiaoyudong Klippe between Xiaoyudong and Caoba, with the Xiangshui Fault at its base (see Fig. 2 for location), and (b)–(d) lower-hemisphere, equal-area projections for (b) poles to fold axial surfaces, (c) fold axes and (d) fault planes, within the klippe. (e) and (f) show detailed structural features in the southeastern part of the klippe where there are local splays all with a consistent sense of transport to the southeast. The relationship between the sole fault (Xiangshui Fault) and bedding attitude in both the allochthon and autochthon is only locally observed.

and 12). Similarly, across the Yingxiu–Beichuan Fault northwestwards, locally preserved Devonian sediments (less than 1000 m in thickness), in the inner Longmen Shan, are considerably thinner than between the Yingxiu–Beichuan and Xiangshui Faults (Fig. 17). This suggests that these faults were originally the sites of syn-depositional normal faults that controlled the deposition during this stage (Fig. 16a).

The climax to the extensional stage occurred during the Late Permian when the ‘Emei Shan Basalt’, up to 3000 m thick, was erupted along the western margin of the Yangtze Craton, especially in the Panxi Rift south of the Longmen Shan (Luo 1984, 1991, Tong 1992). Many Upper Permian basalts have been observed in the central–southwestern Longmen Shan and adjacent Songpan–Garzê Fold Belt as a result of this extension (Liu *et al.* 1991). Permian debris flow deposits associated with turbidites, which are indicative of an extensional environment, have been identified along the western passive margin of the Yangtze Craton (Chen 1985). Thick Triassic turbiditic sediments in the adjacent Songpan–Garzê Fold Belt are also related to the extensional stage (Liu *et al.* 1991).

Structural inversion and initial thrusting stage (T^1_{3x}–T^2_{3x})

It is suggested in this paper that structural inversion of pre-existing normal faults, corresponding to initial thrusting in the Longmen Shan Thrust–Nappe Belt, occurred during the early episode of the Indosinian orogeny, based on the following evidence. (1) The youngest pre-orogenic stratigraphic unit in the Songpan–Garzê Fold Belt is the Ya Jiang Formation of Norian age, which was folded and metamorphosed along with underlying sediments during the early Indosinian orogeny (Lu *et al.* 1988, Chen *et al.* 1995) and is locally overlain, unconformably, by the Babao Shan Formation of Rhaetian age (Huang & Chen 1987, Liu *et*

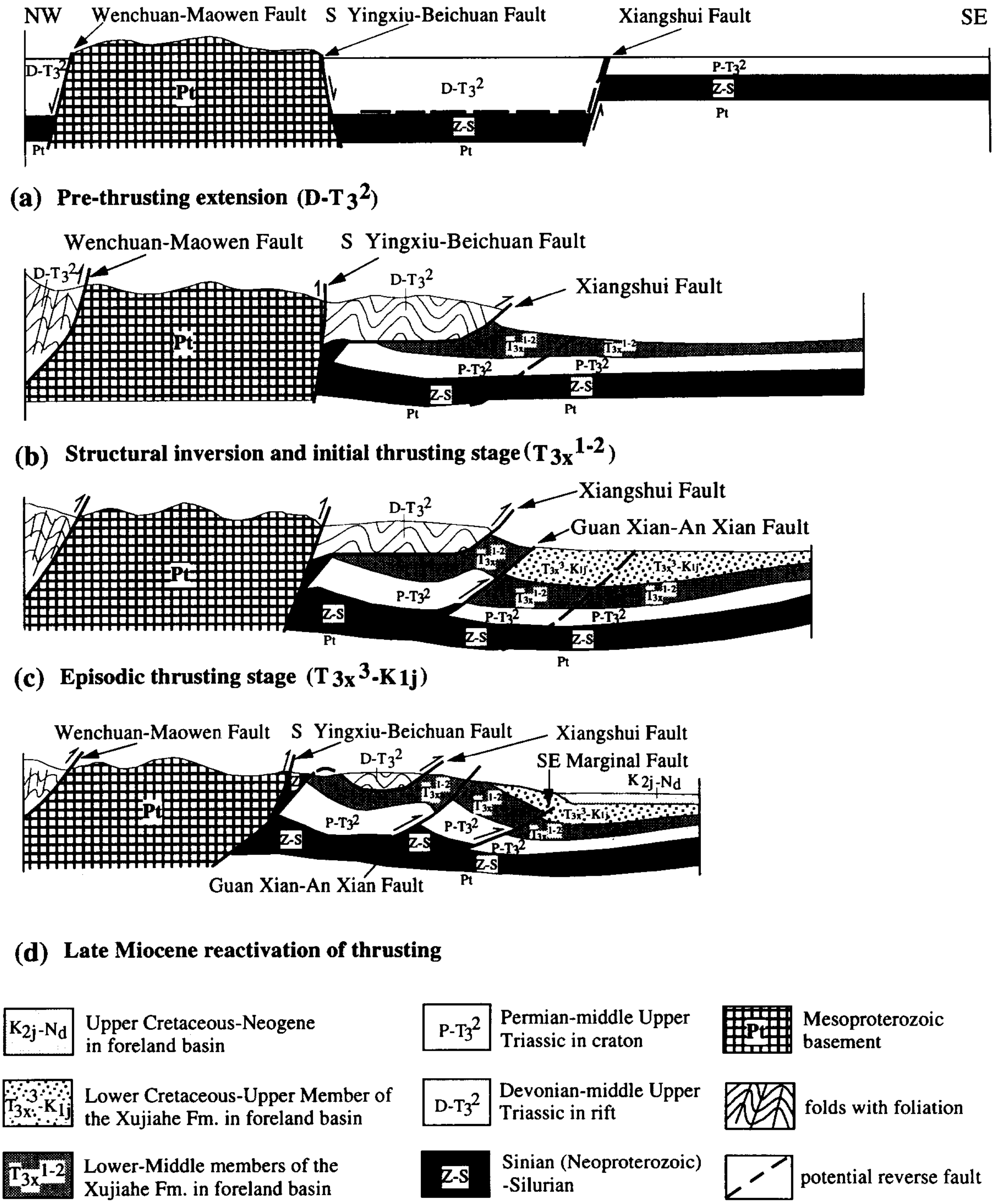

Fig. 16. A simplified geological model illustrating the evolution of the Longmen Shan Thrust–Nappe Belt and relationship to the development of the Western Sichuan Foreland Basin. The restored NW–SE geological cross-section is based on deformation across the central Longmen Shan, especially across the 'Peng Xian-Guan Xian Basement Complex' that is illustrated in Fig. 14a. (a) A schematic diagram that illustrates the relative thickness of Devonian–middle Upper Triassic sediments and relationship to possible syndepositional normal faults. The lower part of the Xiangshui Fault was not reactivated during later deformation. (b) Sediments in the Songpan–Garzê Fold Belt, west of the Wenchuan–Maowen Fault, were folded and metamorphosed; structural inversion occurred on pre-existing normal faults and initial thrusting resulted in emplacement of the 'Peng Xian-Guan Xian Basement Complex' Nappe and folds in the hangingwall of the Xiangshui Fault; thrusting and uplift in the evolving Thrust–Nappe Belt were accompanied by subsidence and deposition in the Western Sichuan Foreland Basin. (c) During the episodic thrusting stage, the foreland basin sequence was progressively incorporated into thrust sheets that contain the Upper Triassic Xujiahe Formation, and the depositional centre was shifted towards the southeast. (d) Reactivation occurred on pre-existing thrust, accompanied by isolation of klippen structures and deposition of Neogene conglomerate that contains pebbles from Mesoproterozoic basement and Mesozoic intrusive rocks.

al. 1992). The Babao Shan Formation can be correlated with the Upper Triassic Xujiahe Formation (T_{3x} in Fig. 3) in the Western Sichuan Foreland Basin. (2) The Lower–Middle members of the Xujiahe Formation (T_{3x}^{1-2} in Fig. 3) are composed of fine-grained, clastic sediments deposited in transitional marine–terrestrial conditions differing significantly from the shallow marine environment of the underlying carbonate. The thickness of the

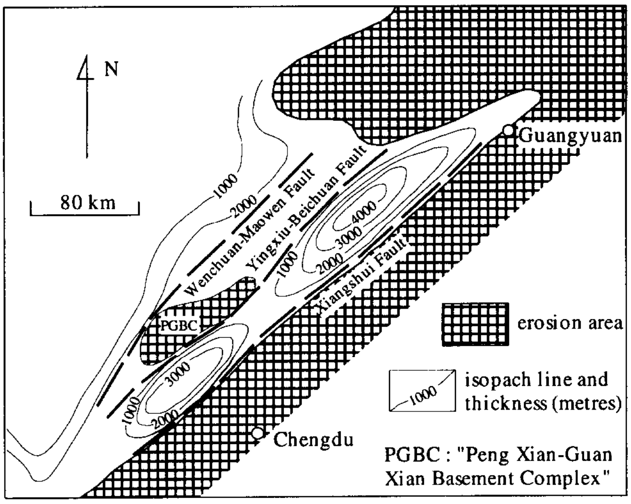

Fig. 17. Isopach map of Devonian sediments in the Longmen Shan and adjacent regions and possible relationship to the pre-existing, syndepositional normal faults. Thickness data according to Tong (1992).

fine-grained clastic (T_{3x}^{1-2}) sediments decreases dramatically or even pinches out towards the central Sichuan Basin to form a wedge that thickens towards the Longmen Shan (Chen *et al.* 1994a), suggesting an initiation of thrust activity (Beck *et al.* 1988); such an occurrence commonly typifies the oldest deposits of foreland basins (Allen *et al.* 1986).

At this stage, pre-existing syndepositional normal faults, located at the sites now occupied by the Wenchuan-Maowen and Yingxiu–Beichuan Faults, inverted their movements to become thrust faults (Fig. 16b). The originally SE-dipping, Yingxiu–Beichuan Fault was gradually rotated into a NW-dipping orientation, along which Proterozoic basement was thrust onto Sinian (Neoproterozoic) volcanics and Devonian to middle Upper Triassic carbonates. In addition, a new fault with a flat-ramp, cross-sectional geometry re-used part of the pre-existing Xiangshui Fault and transported Devonian to middle Upper Triassic carbonates southeastwards (Fig. 16b). Sediments within the Tangwangzhai Nappe were stripped from Mesoproterozoic basement (Fig. 11), or from Sinian (Neoproterozoic)–Silurian deposits (Fig. 12), along the Xiangshui Fault, and deformed into SE-verging folds accompanied by NW-dipping reverse faults.

Tectonic loading from the 'Peng Xian-Guan Xian Basement Complex' Nappe and Tangwangzhai Nappe resulted in substantial subsidence accompanied by deposition of the Xujiahe Formation (T_{3x}^{1-2}) in the Western Sichuan Foreland Basin (Fig. 16b). The process of thrusting and erosion in the Tangwangzhai Nappe was accompanied by subsidence and deposition in the foreland basin. Contemporaneous thrusting and deposition could explain the undulate cross-sectional geometry of the Xiangshui Fault (Figs. 8 and 13) and soft-sediment deformation adjacent to the fault. Large quantities of fluid existing in the newly deposited sediments may have led to fluid overpressures and decreased friction between the allochthon and autochthon, thus facilitating movement of the thrust sheet.

Episodic thrusting stage (T_{3x}^{3}–K_{1j})

From the Latest Triassic to the Early Cretaceous (T_{3x}^{3}–K_{1j}), four thick conglomerate units (T_{3x}^{3}, J_{1b}, J_{3l}, and K_{1j} in Fig. 3) were deposited in the Western Sichuan Foreland Basin and can be temporally related to four intense magmatic events at 210–195, 180–170, 160–150 and 140–110 Ma within the Songpan–Garzê Fold Belt (Luo & Long 1992). The sedimentary sequences in the foreland basin that relate to this stage are up to 6500 m in thickness and are separated by a number of disconformities (Fig. 3). These conglomerates and disconformities probably resulted from episodic thrusting and uplift occurring in the Longmen Shan Thrust–Nappe Belt during the Indosinian–Yenshanian movements. Pebble compositions of the conglomerates, dominated by limestone and dolomite, are comparable to the lithologies of the Tangwangzhai Nappe, suggesting that they were derived primarily from denudation of this nappe. In the meantime, the Guan Xian-An Xian Fault was activated, controlling the deposition of the T_{3x}^{3}–K_{1j} sediments (Fig. 16c).

By the end of Early Cretaceous, thrusting occurred along the Southeastern Marginal Fault, to deform and uplift the northwestern part of the Western Sichuan Foreland Basin. During Late Cretaceous–Palaeogene times, the northeastern part of the Western Sichuan Foreland Basin east of the An Xian–Deyang Blind Fault (Fig. 2) was uplifted, and deposition was restricted to the southwestern part of the foreland basin, with the extent of volume of foreland basin fill significantly decreased (Chen *et al.* 1994a). Thrusting may have occurred along part of the Southeastern Marginal fault during this period of time, but this fault has not penetrated to the surface.

Late Miocene reactivation of thrusting

Preliminary fission track data (Arne *et al.* 1994, Wilson *et al.* 1994) from the Longmen Shan and adjacent regions demonstrate that there is differential exhumation in response to episodic thrusting in the Thrust–Nappe Belt during the Tertiary. Zircon fission track data from Mesozoic granites intruding the Songpan–Garzê Fold Belt and from the 'Peng Xian-Guan Xian Basement Complex' show evidence for differential cooling during a mid-Tertiary brittle reactivation of the Wenchuan–Maowen Fault. Apatite fission track data from the same localities, as well as from Upper Triassic Xujiahe Formation to Upper Cretaceous sedimentary rocks of the Western Sichuan Foreland Basin display a prominent break in age across the Yingxiu–Beichuan and Xiangshui Faults that is attributed to Late Miocene reactivation of these structures. In both instances, the dramatic offset in fission track age across structure is independent of sample elevation, indicating that regional isostatically driven exhumation was punctuated by periods of tectonically induced cooling (Arne *et al.* 1994).

The pebble compositions of the Neogene Dayi Formation (N_d in Fig. 3), deposited in the southwestern part of the foreland basin, are dominated by granite and granodiorite that are comparable to the lithologies of the 'Peng Xian-Guan Xian Basement Complex' and Mesozoic intrusive rocks in the Songpan–Garzê Fold Belt. These pebbles are significantly different from those dominated by carbonates in the conglomerates of the Upper Triassic Xujiahe Formation to Palaeogene sediments. The first appearance of granite and granodiorite pebbles in the Neogene Dayi Formation also indicates reactivation of pre-existing thrust faults, which resulted in unroofing of Mesozoic intrusive rocks in the neighbouring Songpan–Garzê Fold Belt and separation of the Mesoproterozoic basement block from Devonian to middle Upper Triassic carbonates in the klippen structures (Fig. 16d).

As collision between the Indian and Eurasian plates occurred at 45 ± 5 Ma (Huang & Chen 1987, Dewey *et al.* 1988, 1989), the ongoing convergence between the plates has resulted in reactivation of thrusting along specific faults in the Longmen Shan and folding in the foreland basin deposits (Chen *et al.* 1994a,b). Major unconformities in the Longmen Shan exist between Palaeogene sediments and the Neogene Dayi Formation, and between the Dayi Formation and the Quaternary sediments, that can be related to Himalayan movements and the rapid uplift of the Tibetan Plateau (Tong 1992). Fault plane solutions of historical earthquakes indicate that the major faults such as the Wenchuan–Maowen and Yingxiu–Beichuan Faults are presently dominated by reverse movements (Chen *et al.* 1994b). It is the reactivation of these Late Triassic to Early Cretaceous thrusts, and not all the earlier thrusts, that is probably related to any eastward extrusion (Molnar & Tapponnier 1975, Dewey *et al.* 1989) of the Tibetan Plateau.

CONCLUSIONS

The Longmen Shan Thrust–Nappe Belt represents a tectonic transitional zone from the complexly deformed Songpan–Garzê Fold Belt to the relatively undeformed Sichuan Basin. The inner or hinterland parts of the Thrust–Nappe Belt, especially the 'Peng Xian-Guan Xian Basement Complex' Nappe which is comparable to the 'external massifs' of the Alps and the Blue Ridge anticlinorium in the Appalachians, show clear evidence for the predominance of Mesoproterozoic basement nappes, related to northwest-over-southeast, semi-ductile–brittle shear during the Late Triassic Indosinian orogeny. As thrusting propagated from hinterland to foreland in a 'piggy-back' fashion, cover sediments from Sinian (Neoproterozoic) to Cretaceous in the frontal Longmen Shan have been stripped from the underlying Mesoproterozoic basement and moved southeastwards as the Tangwangzhai, Guan Xian-An Xian and Southeastern Marginal nappes, which are comparable to the Helvetic and subalpine zones in the western Alps and the Valley and Ridge province in the Appalachians (Rodgers 1970). The extensively distributed klippen structures are part of the Tangwangzhai Nappe related to thrusting along the Xiangshui Fault.

In the frontal Longmen Shan, development of the nappes appears to follow the tectonic rules of brittle ramp and flat structures along one or more bedding-plane thrust faults, as in the subalpine zones in the western Alps (Pfiffner 1985). Major bedding-plane thrusts are situated along the boundaries between Mesoproterozoic basement/Sinian (Neoproterozoic) cover sequence, and at the base of Devonian carbonates.

This investigation has led to the recognition of at least four major evolutionary stages for the Longmen Shan Thrust–Nappe Belt. (1) Pre-thrusting extension from Devonian to middle Late Triassic times (D–T_3^2) developed NE-trending, syn-depositional normal faults. (2) Structural inversion of these faults during the early episode of the Indosinian orogeny initiated the Thrust–Nappe Belt, and was accompanied by deposition of fine-grained clastics (T_{3x}^{1-2}) in the Western Sichuan Foreland Basin. This was followed by (3) episodic thrusting during the Latest Triassic to Early Cretaceous (T_{3x}^3–K_{1j}) with deposition of several thick conglomerate units in the foreland basin, and by (4) reactivation of thrust faults during the Late Miocene. Shortening across the Longmen Shan has thus occurred episodically since the Late Triassic and cannot be attributed solely to the collision of India with Eurasia as implied by tectonic models invoking lateral extrusion.

Acknowledgements—Fieldwork for this project was financially supported by the Seismological Research Fund of the State Seismological Bureau of China, the National Natural Science Foundation of China, and from funding provided by the Australian Research Council. S.F.C. acknowledges the support of a University of Melbourne Postgraduate Scholarship during his Ph.D. candidature. Thanks go to Professors Qidong Deng and Zhili Luo, and to Paul Dirks, Shugen Liu and Xiaolin Zhao, as they have been involved in part of the fieldwork that formed a background to this paper. We would also like to acknowledge John Rodgers, Huafu Lu, Richard Norris, Dennis Arne and Brenton Worley for their valuable comments on earlier versions of this manuscript.

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