DEFORMATIONAL AND METAMORPHIC HISTORY OF THE CENTRAL LONGMEN MOUNTAINS, SICHUAN PROVINCE, CHINA

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Abstract In the central part of the Longmen Mountains, thrusts along the western edge of the Sichuan Basin originated from a metamorphic "root zone" directly northwest of the Wenchuan-Mouwen Fault. This fault represents the last, brittle deformational stages of a 20～25 km wide shear zone. The Wenchuan-Mouwen Shear Zone, that was active during the Indosinian, about 200 Ma ago.

In the Songpan-Ganzi Fold Belt NW of the Wenchuan-Mouwen Shear Zone, Indosinian, NE-SW compression resulted in D_1 thrusts overprinted by NW-trending, F_2, upright folds. While the Songpan-Ganzi Fold Belt was subjected to D_1-D_2 shortening, the adjacent Sichuan Basin remained undeformed. Differential strain between both terrains was accommodated across the Wenchuan-Mouwen Shear Zone, which developed during D_3 as a sinistral strike-slip zone. Continued NE-SW shortening of the Songpan-Ganzi Fold Belt led to SE-directed compression along the Longmen Mountains. This resulted in local crustal thickening and Barrovian-type metamorphism along the Wenchuan-Mouwen Shear Zone which gradually changed its kinematic character from sinistral, strike-slip to D_4, SE-directed thrusting. This thrusting led to the initial uplift of the metamorphic terrains and the emplacement of a first generation of nappes in the Longmen Mountains. The rocks were subsequently folded and intruded by granite plutons during a late stage of Indosinian deformation, D_5.

The current position of the Wenchuan-Mouwen Fault was established during a later stage of deformation which probably led to the rise of the Pengxian-Guanxian Basement Complex along the Yingxiu-Beichuan Fault. During this event, the Wenchuan-Mouwen Fault behaved as a brittle normal fault with a considerable sinistral component. This event probably corresponds to the second stage of nappe movement in the Longmen Mountains and may have occurred at the Jurassic-Tertiary boundary or during the Himalayan movement.

Key words Longmen Mountains; Songpan-Ganzi Fold Belt; Wenchuan-Mouwen Shear Zone;

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Wenchuan-Mouwen Fault; metamorphic belt; strike-slip zone

1 Introduction

The Longmen Mountains occur along the northeastern boundary of the Tibetan Plateau. They separate strongly deformed and metamorphosed rocks of the Songpan-Ganzi Fold Belt to the NE from relatively undeformed sediments in the Sichuan Basin to the SW (Fig. 1; eg. Li et al., 1975). Most of the deformation and metamorphism can be related to Indosinian movements at the end of the Triassic. During the later stages of this tectonic event, the Songpan-Ganzi Fold Belt was intruded by a suite of I-type granites that have been dated at 195～205 Ma using Rb/Sr whole rock analyses (Fig. 1; Yuan et al, 1991; Zhang et al., 1991).

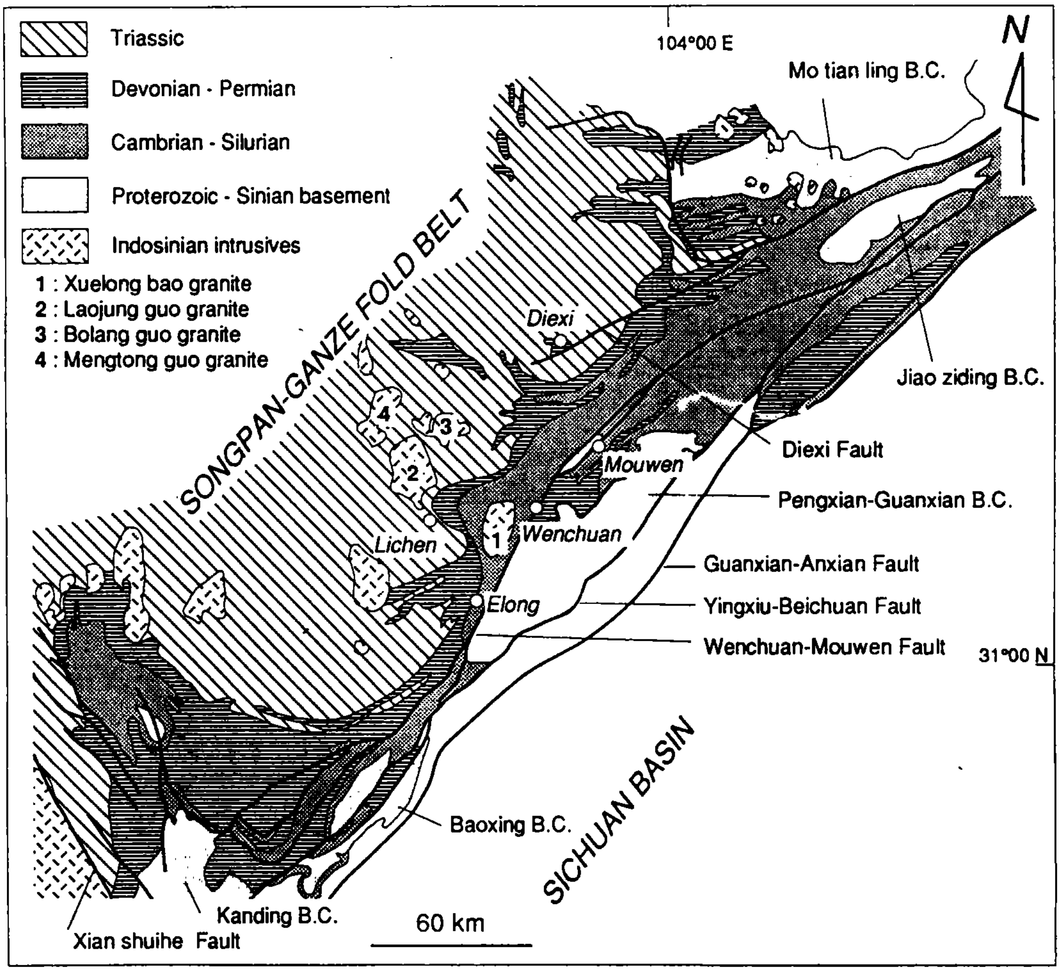

Fig. 1 Regional geological map of the Longmen Mountains. This study concentrates on the central section between Diexi, Mouwen, Elong and Lichen

Not only the structrual-metamorphic history of the Songpan-Ganzi Fold Belt differs markedly from the Sichuan Basin, but also its stratigraphic development (eg. Li et al. , 1975). All during the Palaeozoic the Longmen Mountains were situated along the eastern, passive margin of the Tethys ocean (Luo, 1991; Long, 1991). Consequently, Palaeozoic stratigraphic sequences in the Songhuan Basin are dominated by shallow marine, intra-continental clastic and carbonate deposits (Wang et al, 1989), whereas the Songpan-Ganzi Fold Belt is characterized by deeper marine turbidites (eg. Li et al. , 1975; Long, 1991). The edge of the continental margin was defined by several large, syn-depositional faults of which the Wenchuan-Mouwen Fault (WMF) and the Yingxiu-Beichuan Fault (YBF) were the most important (Fig. 1; Long, 1991). These faults represent major crustal discontinuities and were reactivated during all subsequent compressional events (Luo, 1991).

During the Indosinian, intense shortening of the Songpan-Ganzi Fold Belt was coeval with limited deformation in the Sichuan Basin. The differential strain between both terrains was accommodated across a 20～25 km wide zone of non-coaxial strain centred on what is currently the WMF. This essentially brittle fault represents the last stages of deformation along the noncoaxial zone. Throughout this paper, the non-coaxial zone will be referred to as the Wenchuan-Mouwen Shear Zone (WMSZ). From NW to SE, across the WMSZ, the number of deformational events, their complexity and intensity, as well as the metamorphic grade increase dramatically.

This paper discusses the preliminary results of field investigations along the metamorphic complex in the WMSZ, and presents an outline of the structural-metamorphic evolution of the area. In describing the structural-metamorphic history of this part of the Songpan-Ganzi Fold Belt, it is convenient to distinguish three structural metamorphic terrains or zones (Fig. 2):

Zone 1 occurs to the NW of the WMSZ in the Songpan-Ganzi Fold Belt proper. It is dominated by Triassic, pelitic sediments and structural trends are NW-SE. Regional metamorphic grade reached lower greenschist facies, although locally metamorphic conditions may have been higher in contact metamorphic aureoles around 200 Ma and 140 Ma granites.

Zone 2 includes the Wenchuan-Mouwen Shear Zone, which comprises the entire zone in which the NW-trending structures of zone 1 are rotated towards a NE trend. Regional metamorphism along the central axis of this zone reached barrovian-type, amphibolite facies grade (Hu, 1987), as contact metamorphic aureoles become harder to recognise.

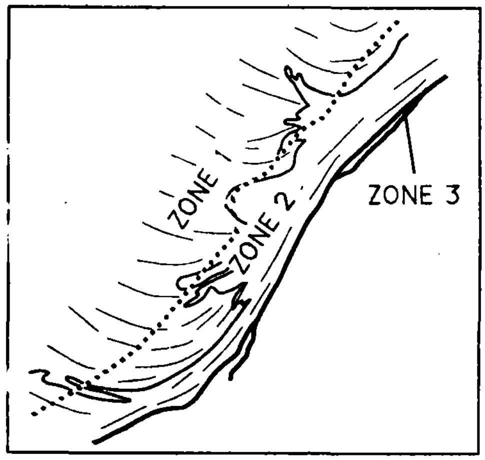

Fig. 2 Map showing the general structural trends in the central part of the western Longmen Mountains. Three structural zones can be distinguished; Zone 1, the Songpan-Ganzi Fold Belt; Zone 2, the Wenchuan-Mouwen Shear Zone; Zone 3, the Wenchuan-Mouwen Fault

Zone 3 represents the brittle-ductile Wenchuan-Mouwen Fault which mainly records post-Indosinian movements. The fault truncates regional and contact metamorphic isograds.

2 Structural history of the central Longmen Mountains NW of the Wenchuan-Mouwen Fault

2.1 Zone 1: the Songpan-Ganzi Fold Belt

This area is dominated by Triassic biotite-muscovite-schist and micaceous, metasandstone that are folded in tight to isoclinal, upright, similar folds, (F_2) which form the dominant structures. The limbs of many of the larger scale, F_2 folds are commony sheared and characterised by 5~50 m-scale duplex structures, asymmetric boudin trains, down-dip quartz fibre lineations on quartzite beds, and small shear zones associated with quartz veining. Although both limbs of either antiform or synform are commonly sheared in opposite directions, a NE over SW sense of shear was more frequently observed.

L_2 fold axes have a NW azimuth and are generally near-horizontal. The folds are associated with a penetrative NW-trending (typically 215/80) slaty cleavage, which locally contains a down-dip plunging mineral elongation lineation variably defined by oxidation spots around pyrite cubes, pressure shadows of quartz fibre 'beards' around pyrite cubes and aligned, fine-grained (<1mm) biotite crystals.

Locally, evidence of an earlier, D_1 event can be seen around the hinges of F_2-folds, especially near folded competent beds (quartzites or D_2-quartz veins). Here, S_2 crenulates an earlier slaty cleavage (S_1) which makes a very small angle with S_0. Other evidence for D_1 includes the zonal occurrence of abundant pre-D_2 quartz veins, which are now isoclinally folded in F_2.

The exact nature of D_1 is unclear, but two lines of evidence suggest that D_1 may have been associated with thin-skinned thrusting and crustal thickening.

1. S_1 is well developed around F_2 fold hinges near GR 183.62-35.31 (see Li, 1975 for grid references). In this area the thickness of the Permian-Carboniferous abruptly changes by a factor 10, as the Permian-Carboniferous repeats itself 3 times. Although this doubling was interpreted to result from D_2 folding (Li, 1975) it is much better explained with D_1 thrusts. Similar stratigraphic doublings can be observed elsewhere; eg. near GR 183.15-34.85 and GR 183.20-35.25.

2. The regionally penetrative S_2-slaty cleavage is partly defined by biotite. Assuming normal geotherms in the order of 20℃/km, burial to these depths suggests considerable pre-D_2 crustal thickening.

S_2 is refolded by only 1 regionally significant folding event, which is associated with a locally penetrative, crenulation cleavage. Although these folds only constitute the 2nd set of folds in zone 1, they can be correlated with F_5 folds in zone 2 (see below).

D_5 deformation is localised along a 40 km wide, NW-trending belt to the NW of Wenchuan, and is outlined by a series of granite intrusions which were emplaced late during D_5 (see below). Away from this belt F_5 folds and S_5 crenulation cleavages are uncommon.

F_5 folds are generally open to closed, reclined, parallel folds with steeply NW-plunging fold axes. S_5 crenulation cleavages are typically upright, trend NW-SE (typically 230/90), and consist of discrete solution surfaces enhanced by new-growth of white mica and, locally, biotite.

Granite intrusions are common in zone 1, and are located along the principal D_5 structure (Fig. 1, granites 1～4). The granite intrusions were emplaced late during D_5 because: 1) D_5 crenulations are truncated at the granite boundaries, whilst the axial planar S_5 foliation passes continuously into the granite. 2) Although S_5 occurs in the granite as an E-trending upright fabric defined by oriented biotite grains, it is only weakly developed relative to S_5 outside the granite. 3) Contact metamorphic biotite, cordierite and andalusite grains are weakly oriented in S_5 and locally define a mineral elongation lineation which typically plunges at 260/40. 4) The granites intrude major D_5 folds (eg. Li, 1975), but simultaneously occur along an S_5 trend (Li, 1975; Zhang, 1991).

A series of kink bands and late fracture (joint) surfaces crosscut all previous structures. The fractures contain slickensides which occur along bedding planes or joints, that generally dip steeply towards SE or SSE and contain low-angle, E-pitching quartz fibre lineations indicative of a sinistral sense of shear.

2.2 Zone 2: the Wenchuan-Mouwen ductile shear zone

Zone 2 is about 20～25 km wide and runs NE-SW, parallel to, and to the NW of the WMF. The northwest boundary of this zone is gradational and occurs in the area where S_0 and S_2 begin to rotate from the general NW-trend of zone 1 to a NE-trend which is typical for zone 2. This boundary area coincides with the first occurrence of an S_3 crenulation cleavage and associated F_3 mesoscopic folds.

On crossing zone 2 from NW to SE, the rocks increase in age from Upper Triassic to Silurian and locally even to Cambrian and Sinian (e. g. NW of Mouwen). Over the first 5 to 10 km, the 2 dominant foliations S_0 and S_2, change position from a NW to a NE trend. For the following 10～15 km, the foliations remain NE trending, parallel to the WMF. As S_0 and S_2 change orientation, they remain close to vertical suggesting that rotation occurred around a near vertical axis in response to strike-slip motion. An S_3 fabric initially develops as an upright, discrete, solution enhanced crenulation cleavage which is E-W-trending and associated with open to closed crenulation folds. From NW to SE across the first 5～10 km of zone 2, S_3 changes orientation from an E-W trend to a NE-SW trend (typically between 130/70 and 310/70) and then remains NE-trending and close to upright. Where this latter stage is reached, which generally coincides with first appearance of the ductile Silurian mica schists (see Li, 1975), S_3 has become the most dominant foliation, in which the earlier S_0, S_1 and S_2 foliations are transposed. Here F_3 folds are invariably isoclinal and commonly intrafolial or rootless. In the low-intensity D_3 areas, F_3 foldaxes (L_3) are highly variable and parallel the local S_0/S_3 intersection lineations. In spite of this variability, L_3 generally plunges steeply to SW (typically 220/80). In the same low-intensity D_3 areas, F_3 fold vergences vary depending on the pre-D_3 orientation of S_0 and S_2. However, as S_0 and S_2 trend towards parallelism with S_3, fold vergences are invariably sinistral within the horizontal plane.

Parallel to and directly NW of the WMF, S_3 transposition fabrics are transposed within an S_4 fabric, which is mylonitic in a 5 km wide zone, directly NW of the WMF (and in a 100～500 m wide zone SE of the WMF, eg. GR 183. 39-34. 42). D_4 effects become first visible, approximately 15 km

NW of the WMF, approximately in the same area where S_3 first constitutes the dominant foliation. In this low-intensity D_4 area, S_4 is an upright NE trending, discrete, solution-enhanced crenulation cleavage which, if viewed in isolation, is indistinguishable in orientation, style and metamorphic grade from S_3. The sole difference is the vergence of associated, mesoscopic, F_4 folds, which are generally SE verging around subhorizontal fold axes with azimuths to the NW or SE.

D_3 and D_4 effects can be distinguished if direct overprinting relationships are visible (eg. NW of Mouwen, between GR 183. 78-35. 24 and GR 183. 65-35. 26). D_3 and D_4 can also be separated using 1～5 mm long, euhedral, biotite flakes that overgrow S_3 but are wrapped in S_4. Locally, the biotite grains are aligned in a foliation, S_b, that generally dips 210/80. No structures associated with this fabric have been recognised. The biotite growth probably represents a stage of passive mineral growth within an uniaxial stress field, during the transition from D_3 to D_4.

In a 5 km wide zone NW of the WMF, S_4 is mylonic in nature and displays S-C fabrics, shearband fabrics and a generally weakly developed down-dip mineral elongation lineation that is generally defined by quartz-rodding in quartzitic units (micaceous units appear unsuitable for lineation development). The S_4 foliation gradually changes in dip from 130/90 to 130/70, as the zone records SE-directed thrusting resulting in uplift of the NW-block.

D_5 effects within zone 2 are similar to those described for zone 1 (see above), and are likewise restricted to one, 30 km-scale, box fold-like structure NW of Wenchuan (see Li, 1975).

Late structures overprinting D_5 include, in order of progressive development, kink bands (D_6), a series of shallowly SSW-dipping, en echelon quartz veins and later fractures and slickensides, commonly with a SW-trend and a sinistral strike-slip component (D_7～D_8).

2.3 Zone 3: the Wenchuan Mouwen Fault

The WMF, as mapped on the Guanxian and Mouwen map sheets (Li, 1975), is a relatively narrow brittle fault zone associated with an abrupt change in metamorphic grade, with highest grades to the NW of the WMF (Fig. 3). This change in grade is most obvious between Mouwen and Elong (Figs 1, 3) and becomes less pronounced towards the SW.

Direct outcrops in the WMF are rare. Along the road from Mouwen to Diexi, at GR 183. 92-35. 11, a section of the fault is outcropping which separates Silurian-chlorite-muscovite-schist to the SE from Cambrian quartzite and biotite-muscovite-schist to the NW. The fault zone is approximately 50 m wide, dips to 345/80 and consists of a 40～50 m wide breccia zone with fragments of mica schist and sandstone embedded in a dark (graphite-rich), cataclastic matrix. Downdip striaetions can be observed along some fracture surfaces which parallel the main fault, but the sense of shear is unclear. The Cambrian quartzite beds in the hanging wall of this fault are transected by numerous fracture surfaces and slickensided joints. Most slickensides are near vertical, trend parallel to the main fault and contain at least 3 quartz fiber lineations. In general, late, sinistral, strike-slip movement overprints earlier dip-slip movement of mainly reverse (NW-up) sense of shear.

Between Wenchuan and Mouwen, the WMF was observed at GR 183. 83-35. 00 where it separates Silurian chlorite-muscovite-schist to SW from Sinian limestone to the NE. Although the actual

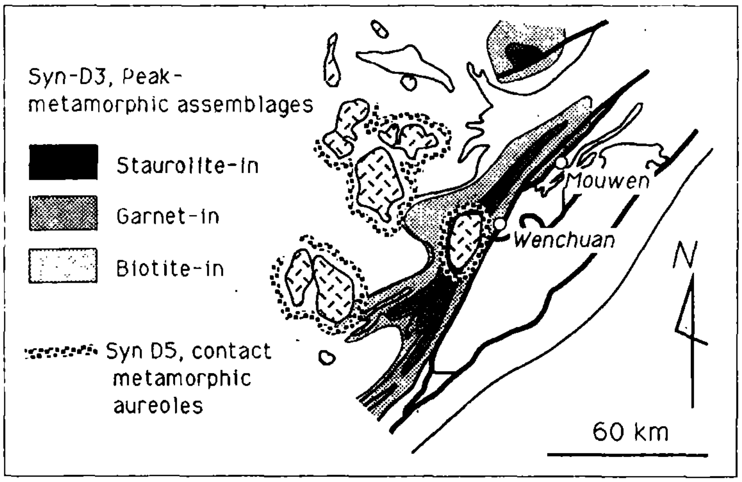

Fig. 3 Map showing the distribution of peak-metamorphic (post-D_3, pre-D_4) minerals and contact metamorphic aureoles in the central part of the western Longmen Mountains. Peak-metamorphic grades were highest in the central part of the Wenchuan-Mouwen Shear Zone (Zone 2)

fault is not exposed, the Sinian limestone directly north of the fault is strongly fractured and brecciated, and crosscut by numerous slickensided fracture surfaces that parallel the fault (310/78). Quartz fibres on the slickensides plunge down-dip and record a NW-up sense of shear.

Directly SW of Wenchuan, at GR 183.63-34.83, the main strand of the WMF is exposed in Sinian limestone. It occurs as two, closely spaced, 15～30 m wide breccia/cataclasite zones, which dip 300/65. Slickensided surfaces and drag folds on secondary fractures indicate a complicated movement history. Earliest lineations pitch steeply to moderately NE and record a dextral-SE-up, normal sense of movement. These are overprinted by subhorizontal lineations that record both sinistral and dextral senses of shear, although sinistral appears to be most common. The latest, most clearly developed striaetions generally display down-dip orientations with a reverse sense of movement. Therefore, in this section of the fault, early normal-dextral movement is overprinted by sinistral strike slip, whih in turn is overprinted by reverse dip-slip movement.

The SW-section of the WMF, near GR 183.39-34.42, separates Devonian and Silurian schist to the NW from Silurian and Sinian rocks to the SE (Li, 1975). Although the main section of the fault does not outcrop, rocks on either side of the fault are transected by numerous, 0.5～5m wide breccia zones and slickensides, especially in the basement rocks to the SE. The slickensides generally dip 285/70, parallel to the S_4, mylonitic foliation, and contain a quartz fiber lineation that pitches about 30°S, which is indicative for a sinistral, SE-up, normal sense of shear.

Near GR 183.36-34.46, a fault is exposed that runs parallel to, and 3 km to the NW of, the WMF. This fault separates Devonian to the NW from Silurian to the SE. The main fracture/breccia zones dip 304/87 and preserve little evidence for the sense of shear. However, secondary fractures (090/70, 070/20) commonly display drag folds with horizontal fold axes indicative of a SE-up, normal movement sense.

3 Metamorphic history of the central LongmenMountains NW of the Wenchuan-Mouwen Fault

3.1 Zone 1: the Songpan-Ganzi Fold Belt

3.1.1 Regional metamorphic conditions

In zone 1, the dominant S_2 foliation is generally defined by muscovite, chlorite, quartz and minor biotite. Regional metamorphic, garnet, cordierite, alumino-silicates or chloritoid have not been observed, placing rocks in the lower greenschist facies (380～420; Turner, 1981; Yardley, 1989). Reliable pressure estimates could not be made since pressure dependent assemblages have not been observed in this domain.

3.1.2 Contact metamorphism

Around the Indosinian granitoid intrusions, clear contact metamorphic aureoles developed (Fig. 3). The aureoles around the Bolangguo and Laojunguo granites, for example, are typically 2.5～4 km wide. On approaching the granites, biotite and muscovite blasts are generally the first contact metamorphism minerals to occur in hand specimen; these blasts increase in size from less than 1 mm to 3～5 mm, which appears to be their maximum size. Between 0.5～2 km from the granites, andalusite and cordierite are common additional phases with andalusites growing up to 10 cm in length and 1 cm in cross section. Close to the granites (0～500m), rare garnet may occur in rocks with Fe-rich bulk-compositions. Mafic rocks contain abundant green amphibole (hornblende close to the granites, actinolite further away from the granites). Kyanite, sillimanite and migmatite zones are absent within pelitic rocks close to the granite contact. The granites themselves contain rare, primary muscovite blasts, probably of magmatic origin.

The presence of primary muscovite in the granites in combination with contact metamorphic andalusite suggests an emplacement depth in the order of 300～400MPa (Zen, 1988) if the aluminium silicate triple point of Powell & Holland (1988) is considered. Given the lack of migmatites in the contact metamorphic auteoles, maximum temperatures did not exceed 650℃.

3.2 Zone 2: the Wenchuan-Mouwen ductile shear zone.

3.2.1 Regional metamorphic conditions

During the Indosinian events, peak-metamorphic conditions were reached within zone 2, along a narrow belt directly NW of the D_4-mylonite zone (Fig. 3). Across the D_4 mylonite zone grades gradually decrease to the SE until the WMF is reached, however, all rocks in this zone remain above biotite-grade. Across the WMF an abrupt change of grade can be observed as biotite becomes unstable (Fig. 3).

In the central Longmen Mountains regional metamorphic biotite, garnet, staurolite and kyanite isograds can be distinguished (Fig. 3; Hu, 1987). Common assemblages for each of these four metamorphic zones include, a) biotite-muscovite-chlorite-quartz, b) biotite-muscovite-garnet-quartz ± chloritoid, c) biotite-muscovite-garnet (cordierite)-staurolite-quartz, d) kyanite-staurolite-biotite-muscovite-quartz (Hu, 1987). These metamorphic facies zones for pelitic rocks are typical for medium-pressure

Barrovian-type metamorphism (eg. Harte & Hudson, 1979).

Highest metamorphic grades were reached in the kyanite zone, in the NE of Wolong National Park (GR 183. 35-34. 65). Kyanite-staurolite-biotite-muscovite-quartz assemblages suggest peak-metamorphic conditions of around 530～580℃ and 500～700MPa (Harte & Hudson, 1979). Maximum pressures were probably not much higher than 500MPa because staurolite-cordierite-chlorite-muscovite assemblages occur close to the kyanite-bearing assemblages.

Relationships between the various tectonic foliations and the coarse-grained, inclusion-rich, peak-metamorphic biotite ($\varnothing < 7$mm), garnet ($\varnothing < 1$ cm) and staurolite ($\varnothing < 3$cm) blasts are genrally visible in hand specimen.

In general, regional metamorphic biotite blasts, can be divided in fine grained biotite flakes which occur along S_2, coarser grained biotite grains which parallel S_3 and coarsest grained ($\varnothing < 7$mm) biotite flakes which overgrow S_3 and are wrapped in S_4.

Garnets are generally reddish pink (almandine-rich), and appear to partly overgrow S_3, although locally, they simultaneously appear to be wrapped in S_3 as well. Occasionally, straight to slightly bent inclusion trails can be observed in 0. 5 cm large garnets in the hinge regions of F_3 folds, where they are wrapped in S_3 (e. g. GR 183. 33-34. 47). These observations suggest syn-D_3 garnet growth.

Coarse-grained (<5cm) staurolite is generally unoriented and overgrows the syn-D_3 garnets, S_3-crenulation cleavage and post-D_3 biotite blasts. However, they are wrapped in the F_4 crenulation cleavage, suggesting post-D_3, pre-D_4 growth. Kyanite, although not observed in outcrop by the authors, probably grew during this stage as well.

A pre-D_4 peak of metamorphism is confirmed by the regional distribution of isograds, which are clearly folded/sheared in the D_4 mylonite zone, across which the metamorphic grade decreases gradually (Fig. 3; Li, 1975).

3. 2. 2 *Contact metamorphism*

Along the road section NW of Wenchuan, abundant, coarse-grained (0. 5～1 cm), undeformed (not fractured) garnet crystals occur that largely overgrow the S_5 crenulation cleavage and F_5 crenulations. These late, syn-D_5 garnet crystals are deep red and generally contain a core of pale-pink garnet (possibly more Mg-rich, higher pressure garnet (?) grown during $D_3 \sim D_4$), which locally contains nearly straight inclusion trails of fine-grained biotite. The same zone is characterized by numerous large (<7 mm) euhedral biotite crystals, which are generally unoriented and overgrow S_5.

Regionally, the euhedral late-S_5 garnet and biotite is restricted to an area close to the Xuelongbao basement complex. In fact, their size along the road section appears largest closest to this granite body (eg. at GR 183. 59-34. 91). Since the outcrop pattern of the Xuelongbao granite as well as its geochemistry (Li, 1975) are more akin to the Indosinian intrusives to the NW than to the Penxian-Guanxian Basement Complx to the SE (Fig 1), it is concluded that this body is in fact an Indosinian granite intruded late during D_5, and that 2nd stage of garnet-biotite growth restricted to its proximity, is contact metamorphic in origin.

4 Discussion

During D_1 and D_2, NE-SW compression led to thickening and folding of the Songpan-Ganzi Fold Belt. Although the exact nature of the D_1 deformation is unclear, the fact that (a) S_1 foliations appear to be layer-parallel, (b) doubling of the stratigraphy occurs in zones where S_1 is well developed and (c) biotite grades were reached at the onset of D_2, suggests that D_1 may have been associated with thrusting and substantial crustal thickening. Regional peak-metamorphic conditions in this region were reached during D_2 upright folding. Since the Sichuan Basin to the SW remained essentially undeformed during most Indosinian deformation, a zone characterised by noncoaxial deformation had to developed at the boundary of both terrains. This strike-slip zone focussed on an earlier, syn-sedimentary fault (Long, 1991) which developed at the boundary of a Palaeozoic, passive, continental margin (Luo, 1991), and was restricted to a 20～25km wide zone directly NW of the current position of the Wenchuan-Mouwen Fault. In this ductile shear zone, which we call the Wenchuan-Mouwen Shear Zone (WMSZ), sinistral strike-slip took place during D_3, progressively rotating and transposing S_0, S_1 and S_2 from a NW trend into a NE trending S_3 foliation. Due to the continued convergence of the Songpan-Ganzi Fold Belt, D_3 strike-slip on the WMSZ was compressional and led to crustal thickening and Barrovian-type metamorphism in a narrow belt along the shear zone. Peak-metamorphic conditions of around 500～700MPa and 530-kbar and 530～580℃ were reached syn-to post-D_3 as peak metamorphic minerals largely overgrow S_3 but are wrapped in S_4.

Subsequently, uplift of the thickened strike-slip zone occurred during D_4 along S_4 mylonites. S_4 parallels, and probably, progressively developed from the S_3 foliation, as compressional movement on the shear zone began to dominate over strike-slip movement. This trend may reflect the effects of continued NE-SW compression of the Songpan-Ganzi Fold Belt which would cause progressively increasing, SE-directed compression along its SE margin (which are the Longmen Mountains).

Continued NE-SW compression during D_5 caused some folding along a NW-trending belt, NW of Wenchuan. Although D_5 structures affect the D_4 mylonite, they do not extend beyond the brittle WMF. This suggests that D_5 structures formed in a similar compressional set-up as the D_1～D_4 structures, and that during D_5 the WMSZ had already narrowed down to the WMF.

A series of granites and granodiorites intruded late during D_5. Dates for these granites vary between 195～205 Ma (Yuan et al., 1991; Zhang et al., 1991), putting a minimum age on D_5. A maximum age for D_1 can be obtained from the deformed stratigraphy of the Songpan-Ganzi Fold Belt, the youngest units of which are Upper-Triassic, about 200～205 Ma old (T_3x; Li, 1975). This constrains the D_1 ～ D_5 structural-metamorphic history of the western Longmen Mountains to the Indosinian episode at the end of the Triassic and beginning of the Jurassic.

The uplift associated with D_4 caused a progressive narrowing of the WMSZ as metamorphic grades decreased. If it is assumed that pre-D_4 regional peak metamorphism occurred at around 500～700MPa and D_5-granite emplacement occurred at 300～400MPa, D_4 uplift of the area along the WMSZ may have been as much as 7～10 km. Such a displacement explains the occurrence of Silurian to Cambrian along the WMSZ as opposed to Triassic to the NW. This uplift was probably responsible for the first episode of nappe emplacement into the Sichuan Basin to the SW (compare to Lin & Wu, 1991).

Post-D_6 deformation is mainly concentrated in discrete, brittle fault zones, the most important of which is the Wenchuan-Mouwen Fault. In general, the WMF separates younger rocks to the NW from older rocks to the SE (Li 1975). The WMF is generally interpreted as a thrust fault and the stratigraphic relationships are explained to result from large differences in stratigraphic thickness of the Palaeozoic sediments on either side of the fault (Luo, 1991). Although this explanation may be applicable to the juxaposition of Silurian and basement rocks along the central section of the fault, it is hard to maintain further to the SW, where the fault separates Devonian from Silurian, and the Silurian on either side of the fault is indistinguishable. Therefore, there must have been an episode of normal faulting along the WMF. Evidence for this normal movement is locally preserved along early slickensides. The normal movement along the WMF was possibly related to the uplift of the Pengxian-Guanxian basement complex to the SE of the fault, and to a second stage of SE-ward emplacement of nappes onto the western margin of the Sichuan Basin (Cui et al., 1991; Lin & Wu, 1991). Later displacements of minor importance include sinistral strike-slip and reverse movement.

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四川龙门山中段变形和变质历史

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【摘要】在龙门山的中段，四川盆地西缘的逆冲断层起源于紧靠汶川-茂汶断裂西侧的变质"根带"。汶川-茂汶断裂代表一条20～25km宽的剪切带的晚期脆性变形阶段。该剪切带活动于大约200Ma前的印支期。

在汶川-茂汶剪切带北西侧的松潘-甘孜褶皱带中，印支期的NE-SW向挤压形成D_1逆冲断层，并被NW向F_2直立褶皱所叠加。当松潘-甘孜褶皱带受到D_1-D_2期缩短时，相邻的四川盆地并没有发生变形。两个地区的差异应变被发育于D_3的汶川-茂汶左行剪切带所容纳。松潘-甘孜褶皱带中持续的NE-SW向缩短导致了龙门山地区的SE向挤压。这种SE向挤压引起沿汶川-茂汶剪切带发生局部地壳加厚和巴罗型(Barrovian-type)变质作用。汶川-茂汶剪切带的运动学特点由D_3的左行剪切逐渐转变为D_4的SE向逆冲。这种逆冲作用引起了变质地区的初步隆起，以及龙门山地区第一期推覆体的就位。在印支期变形的后期(D_5)，岩石发生褶皱并被花岗岩体侵入。

现在的汶川-茂汶断裂位置是在更晚的变形阶段确立的。这个阶段的变形可能导致了彭灌基底杂岩沿着映秀-北川断裂发生隆起。在这一事件中，汶川-茂汶断裂是作为一条具有显著左行走滑分量的脆性正断层活动的。这一事件可能对应于龙门山地区的第二期推覆体运动，并且可能发生于侏罗纪—第三纪之间，或者是在喜马拉雅期。

关键词　龙门山；松潘-甘孜褶皱带；汶川-茂汶剪切带；汶川-茂汶断裂；变质带；走滑带