Meso- and micro-structures and their tectonic implications in the middle segment of the Longmenshan Nappe Structure Zone, Sichuan Province, Southwest China

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Abstract

Various types of deformed meso- and micro-structures are well developed in the Longmenshan Nappe Structure Zone (LNSZ). These structures, most of which are believed to be related to thrusting since the Indosinian movement at the end of Triassic, show directly the deformation environment and development of the LNSZ. On the basis of the investigation in the field and under the optical microscope, six phases of deformation are recognized in the evolutionary history of the LNSZ, especially of the Wenchuan Nappe and the northwestern part of the Yingxiu Nappe. Analysis of deformation facies indicates that the deformation of the LNSZ shows a tendency, namely in temporal development ductile deformation of earlier phases is superposed by brittle one of later phases and in spatial distribution, ductilely deformed structures dominant in the northwest are changed into brittle ones dominant in the southeast. In other words, the mean ductility of rocks at deformation decreases with time and from the northwest to the southeast in space. And, the number of deformation phases which are distinguished in individual nappes decreases toward the southeast. Therefore, the development process of the LNSZ is considered as a continuous thrusting uplift from early to late and from the northwest to the southeast in a piggyback thrust propagation.

Key words: meso-structures, micro-structures, Longmenshan Nappe Structure Zone, mean ductility, deformation facies, ductile deformation, brittle deformation

Introduction

The Longmenshan Nappe Structure Zone (LNSZ) is located in the Longmenshan Mountains along the northwestern margin of Sichuan Basin, Southwest China (Fig. 1). The zone, which trends approximately NE–SW with length of about 500 km and width of 40–80 km, traditionally marks the boundary between the Songpan–Ganzi Fold System to the NW and the Sichuan Basin to the SE (Fig. 2). The Songpan–Ganzi Fold System is a triangle-shaped terrain that is bounded by deep fault zones and is dominated by strongly deformed and metamorphosed Triassic rocks. In the terrain, the rocks have suffered a regional metamorphism at the lower greenschist facies condition and have structural trends of NW–SE, sub-perpendicular to the LNSZ. The Songpan–Ganzi Fold System was intruded by a suite of I-type granites dated at 150–205 Ma during the later stages of the Indosinian movement and subsequent Yanshanian (Yenshanian) movement (Bureau of Geology and Mineral Resources of Sichuan Province, 1991; Yuan et al., 1991; Zhang et al., 1991). The exact boundary between the LNSZ and the Songpan–Ganzi Fold System is still unclear at present. The boundary seems to be structurally gradational. Dirks et al. (1992) thought of the strongly metamorphosed area to the northwest of the Wenchuan Fault Zone as the “root zone” of the LNSZ (Fig. 2). The Sichuan Basin is a terrain that is filled with the unmetamorphosed and relatively undeformed Mesozoic and Cenozoic sediments of continental facies and is markedly different from the Songpan–Ganzi Fold System in both tectono-metamorphic history and stratigraphic development (Luo,
thrusts and nappes. There are four major regional thrust zones in the LNSZ, that are Wenchuan Fault Zone (WFZ), Yingxiu Fault Zone (YFZ), Guanxian Fault Zone (GFZ) and Frontal Blind Fault Zone (FBBFZ) (Lin and Wu, 1991; Hou and Uemura, 1993) from the northwest to the southeast (Fig. 2). The WFZ and the YFZ are two of the most significant regional fault zones marking the edge of the continental margin (Long, 1991). These fault zones consist of several large, syn-depositional faults representing major crustal discontinuities during the Palaeozoic and were reactivated during subsequent compressional events (Luo, 1991; Long, 1991). All thrust zones, in general, dip to the NW at 50°–80° on the ground surface, showing high-angle faults. Downward, however, the dip angles flatten with depth into 5°–15° (Lin and Wu, 1991), finally joining into a sole detachment (Bureau of Geology and Mineral Resources of Sichuan Province, 1991).

The WFZ is developed along the northwestern margin of the LNSZ (Fig. 2). In the WFZ are dominate brittle deformation structures, which were formed by the movement of the WFZ with a sinistral component (Dirks et al., 1992), also with some striations of dextral strike-slip, mainly representing post-Indosinian movement. The brittle deformation zone is bordered with earlier mylonitic rocks. In the northeastern segment of the LNSZ, the WFZ occurs as a ductile shear zone (Lin and Wu, 1991; Zhang and Ding, 1991), indicating that the thrust was originated in ductile deformational conditions of deeper structural level (Sibson, 1977; Carter and Tsenn, 1987). On the northwest border of the WFZ there is a suit of the Palaeozoic deep marine turbidites (Long, 1991) and the Triassic pelitic sediments, which has been strongly metamorphosed and deformed. In the suit, the metamorphic grade increases toward the WFZ from lower green-schist facies in the northwest to higher green-schist facies, locally to amphibolite facies, in the southeast, and the complexity and intensity of deformation increase dramatically as well (Bureau of Geology and Mineral Resources of Sichuan Province, 1991; Dirks et al., 1992). Kyanite-bearing mica-quartz-schists that indicate the highest metamorphic grade in the area, the peak–metamorphic conditions being around 530–580°C and 500–700 MPa, occur to the immediately northwest of the WFZ (Dirks et al., 1992). Therefore the increasing in the metamorphic grade and deformation intensity toward the WFZ can be considered to be related to the development history of the WFZ. The YFZ, which is developed along the center of the LNSZ (Fig. 2), trends NE–SW. It separates the Palaeozoic rocks strongly deformed and metamorphosed and the pre–Sinian basement complex undergone migmatization on the northwest side from the Palaeozoic-Mesozoic shallow marine, intra-continental clastic and carbonate sedimentary
Fig. 2. Geological map of the Longmenshan Mountains (modified and simplified from Bureau of Geology and Mineral Resources of Sichuan Province, 1991). 1: Quaternary alluvial sediments. 2: Jurassic-Cretaceous. 3: upper Triassic (epimetamorphic phyllites to NW of the YFZ and sedimentary sandstones to SE of the YFZ). 4: Devonian-lower Triassic (metamorphic schists, marbles and phyllites, etc NW of the YFZ and unmetamorphosed marine facies carbonate rocks and clastic rocks to SE of the YFZ). 5: Silurian and small amounts of Cambrian and Ordovician (schists, phyllites, marbles and metatamstones, etc NW of the YFZ and unmetamorphosed or slightly metamorphosed marine facies clastic rocks to SE of the YFZ). 6: Sinian metadolomites and metatamstones. 7: Pre-Sinian basement complex. 8: Granites of Indosinian phase. 9: Gliding-spreading nappe (klippe). 10: Principal thrust and blind thrust. WFZ: Wenchuan Fault Zone. YFZ: Yingxiu Fault Zone. GFZ: Guanxian Fault Zone. QFZ: Qingchuan Fault Zone. JFZ: Jiudingshan Fault Zone. FBFZ: Front Blind Fault Zone.

rocks relatively weakly deformed and unmetamorphosed on the southeast side.

Nappes developed in the LNSZ have been divided into two types on the basis of formative mechanism (Lin and Wu, 1991; Hou and Uemura, 1993). One type is thrusting-spreading nappes of large areal extent in the LNSZ, which has a NW-inclined sole fault and internal faults with reverse sense and so were formed by lateral compression. The other is isolated klippen formed after the former type nappe formation and has a gently SE-inclined sole fault with normal sense. The klippen exhibit either very weak deformation except for the sole, or an extensional zone at the proximal end of the klippen and a compressional zone at the lower distal end. Some of them lie on molasse sediments supplied from the northwest. Therefore, the klippen is gliding-spreading nappes formed by gravity gliding from the northwestern uplift. Namely, the compression produced the former type nappes and an initial uplift of the Longmenshan Mountains, which was followed by gravitational gliding down the slopes of the uplift (Hou and Uemura, 1993). The thrusting-spreading nappes and their deformatinal structures are principal objects studied in this paper.

The thrusting-spreading nappes arrange in an imbricate pattern from the northwest to the southeast. They are named after their underlying thrusts, or Wenchuan Nappe (WN), Yingxiu Nappe (YN), Guanxian Nappe (GN) and Frontal Structure Zone (FSZ) (Fig. 3) (Lin and Wu, 1991; Hou and Uemura, 1993). The WN consists of metamorphosed Silurian and some Late-Palaeozoic, most of which are schists, phyllites and schistose marbles metamorphosed in a greenschist facies condition, locally intruded by I-type granitic bodies dated Indosinian periods. Some pre-Silurian rocks are contained as tectonic slices in the nappe and in the WFZ. The nappe thrusts over the pre-Sinian basement complex toward southeast by the WFZ in the middle segment of the LNSZ (Fig. 3) and its northeastern end is over lain by Qingchuan Nappe (Fig. 2). Regional deformed structures in the nappe are a series of large-scale tight to isoclinal folds with wavelengths of several kilometers, strike-lengths of dozens kilometers (Fig. 4) and an axial-plane $S_2$ foliation (Fig. 5a). The YN is a
Nappe structure map of the middle segment of the LNSZ

Fig. 3. Nappe structure map of the middle segment of the LNSZ. WN: Wenchuan Nappe. YN: Yingxiu Nappe. GN: Guanxian Nappe. FSZ: Frontal Structural Zone. JN: Jiudingshan Nappe. J-E: Jurassic-Cretaceous formation. Q: Quaternary formation. A-A', B-B': The line of cross-section in Fig. 3 and in Fig. 4, separately.

lozenge-shaped "rootless" allochthonous block (Song and Liu, 1991) that is mostly made up of the pre-Sinian basement complex, or Peng-Guan Complex, mostly migmatitized granitic rocks with remainders of amphibolite, biotite-leptite and metavolcanics, metasediments of pre-Sinian Huangshuihe Group (Bureau of Geology and Mineral Resources of Sichuan Province, 1991) and some Palaeozoic sedimentary covers remain on its top. The lozenge-shaped block is surrounded by faults and thrusts over the late-Triassic sediments toward southeast by the YFZ, but is overlain by the Jiudingshan Nappe (Zhao, 1985) at its northeastern end (Figs. 2 and 3). The GN consists mainly of Late-Triassic unmetamorphosed sedimentary rocks in the middle segment of the LNSZ and is covered partly by Jurassic sediments. The FSZ is a rather weakly strained area developed in the southeastern margin of the LNSZ. A few large gentle folds, joints and few faults are developed in the zone. Seismic data indicate clearly that there is a decollement zone in the Triassic strata in the FSZ (Lin and Wu, 1991). Therefore, the FSZ can be considered as a buried thrust front zone (Morley, 1986) of the LNSZ. Most part of the zone is covered by the Mesozoic and Cenozoic sediments. The shortening ratio of the LNSZ is 42%-63% calculated by the balanced cross-section (Lin and Wu, 1991).

The gliding-spread nappes, most of which are made up of Late-Palaeozoic carbonate sedimentary rocks and have become currently isolated klippen, are scattering in the southeastern margin of the LNSZ adjacent to the Sichuan Basin (Figs. 2 and 3). These klippen are considered to be a late stage product of the development of the LNSZ due to the gravitational instability of cover rocks, resulted from the topographic gradient following the piggyback thrusting of the LNSZ (Hou and Uemura, 1993).

**Deformation history**

Various types of deformed structures ranging from several tens of microns to some meters in scale have been observed on outcrops to in thin sections within individual nappes. Six phases of deformation (D₁-D₅) are recognized in the evolutional history of the LNSZ on the basis of the deformational nature, geometries, overprinting criteria and macro- to micro-structural development observable in the field and under the microscope. However, type of structures, degree of development and number of deformational events are variable in different nappes. They reflect the difference of deformational environment and history of individual nappes. We will describe the deformational features and distribution of various meso- and micro-structures in individual nappes.

As the result of structural analysis, it is clarified that most thin sections from the WN and the northwestern part of the YN preserve evidence for multi-phase deformation, whereas those from the southeastern part of the YN and the GN commonly exhibit rather slight and simple deformation. The results show the well correspondence with those of meso-structures.

1. **Wenchuan Nappe**

   Important meso- and micro-structures observed in the WN are various penetrative foliation, minor folds and mylonite zones, secondly kink bands, brittle faults and joints.

   **The first phase (D₁):** The foliation (S₁) is well-marked by lithological layering and quartzose bands with 1 mm–10 cm thick, being a bedding–parallel foliation, formed in the phase of deformation. Under the microscope, the foliation is defined by fine-grained quartz, muscovite and chlorite. The S₁ foliation has been folded intensely by open to isoclinal folds (F₁) (Figs. 5e–5h). The quartzose bands of long limbs of the folds are commonly elongated into a lenticular band, or forming a boudinage wrapped in S₁ (Figs. 5b and 5c). The S₁ can be considered as an incipient foliation formed during pre-thrusting metamorphic event.

   **The second phase (D₂):** The phase of deformation is characterized by the formation of mesoscopically–penetrative schistosity (S₂) (Fig. 5a), closed to isoclinal, rarely open, fold (F₂) with crenulation cleavage (S₂) at the fold limbs (Figs. 5e and 5f) and a shear zone 0.05–0.25 mm in widths (Fig. 5b) with strong schistosity (S₂). The penetrative schistosity is sub-parallel and parallel to the crenulation cleavage of the F₁ folds and to the shear zone schistosity. The spacing of S₂ cleavage is 0.5–5 mm or so. These three S₂ foliations cut S₁ and are the most dominant penetrative planar fabric in the WN (Fig. 5a), in which the earlier S₁ foliation are strongly transposed.

   The S₂ maintains nearly a constant attitude over all of the study area, vertical or steep dip to NW, N20°–50°E trending (Fig. 6a), rarely disrupted by later faults and is regarded as axial plane cleavage (S₀) of the large-scale tight to isoclinal, horizontal normal folds (F₁) in the WN (Fig. 4). The S₂ represents probably the regional compressive strain planes and indicates the considerable horizontal shortening in the WN.

   The F₂ is also one of the most significant, widespread deformed structures in the WN. The wavelengths of the folds range from 0.2 mm to several km, amplitudes from 0.2 mm to several km and interlimb angles from moderate to isoclinal (Figs. 4, 5b–5f). The geometry of the F₂ fold exhibits mostly asymmetrical but a variety of shapes depending on lithology (Figs. 5b–5d). Some of the F₂ folds are intrafolial or rootless. Some of them show pytymatic features. Few rounded reverse type kink bands (Uemura and Long, 1987) are also observed in the Silurian schists. In the Silurian mica-quartz-schists,
the $F_2$ is mostly asymmetrical upright and isoclinal fold (Figs. 5b and 5c) and its axial plane dips to NW steeply or vertically, parallel to the penetrative planar fabric $S_2$. The northwestern limbs of the folds are commonly longer than the southeastern ones in asymmetrical folds and the longer limbs are commonly elongated intensely forming pinch- and- swell structures and boudinages (e.g., Fig. 5b). The geometry of the folds generally indicates a SE-oriented movement. But in the Devonian schistose marbles and banded marbles the $F_2$ exhibits a nearly recumbent fold that axial planes are subhorizontal or gently dip to SW and hinges open to tight (Fig. 5d). These are mostly reclined folds (Naha, 1959; Sutton, 1960), namely, the dips of the axial planes are correlated with the plunge of these fold axes. However, all

Fig. 5. Various types of $D_2$ deformed structures in the WN. a. Penetrative schistosity ($S_2$) in Silurian schists. b. Intrafolial flowage fold ($F_2$) in Silurian schist and schistosity ($S_2$). The long limbs of the folds are elongated into boudinage. c. Rootless folds ($F_3$) in Silurian schist. d. Intrafolial folds ($F_3$) in Devonian foliated marble. e. and f. Crenulation cleavage ($S_3$), crenulation fold ($F_3$) and biotite porphyroblast. Inclusion trails in biotite porphyroblasts are continuous with matrix $S_1$ foliation. A sinistral shear sense is indicated along $S_2$. g. Garnet porphyroblast. Inclusion trails in the porphyroblast are compatible with the geometry of matrix $S_1$ foliation, but the folds in the porphyroblast are more open than those in matrix. h. The inclusion trails are straight in biotite porphyroblasts and oblique to matrix $S_1$ foliation at a low-angle.

meco- to micro- scopic $F_2$ fold axes nearly plunge to SW or NE (Fig. 6b), which are identical with the azimuths of axes of the large-scale folds and their trends are same to the trend of the WN. The formation of these folds, thus, can be attributed to SE-oriented compression during thrusting.

Biotite (0.3-3 mm in size) and garnet (1-3.5 mm in size) porphyroblasts are sometimes observed along $S_2$ and/or are wrapped within $S_2$ from schists (Figs. 5e- 5g). Mineral inclusions and inclusion trails are common in the biotite and garnet porphyroblasts. Most of the inclusions consist of fine-grained quartz. Individual quartz inclusions are commonly elliptical or elongate and are orientated, defining an internal foliation in the biotite and garnet crystals. The internal foliation is straight or curves smoothly into a
series of microfolds or shows a simple sigmoidal shape (Figs. 5e–5h). The inclusion trails align continuously across the porphyroblasts and maintain a continuation with S₁ (Figs. 5e–5f). The geometries of them are completely consistent with those of S₁ in matrix. The folds of trails within the garnet crystals, however, are more open than those in the matrix (Fig. 5g). The features suggest that the foliation defined by inclusion trails within the porphyroblasts is syntectonic with S₁. The inclusion trails tend to be nearly parallel from porphyroblast to porphyroblast. The parallelism of the inclusion trails themselves and the consistency with matrix fabric indicate that the biotite and garnet porphyroblasts have grown without rotation during the progressive deformation of D₁ (Bell and Rubenach, 1983; Vernon, 1988; Williams, 1994). The growth of the biotite and garnet porphyroblasts along S₁ also indicates a temperature rise during the formation of S₁ crenulation cleavage (Bell and Rubenach, 1983; Williams, 1994). The temperature rise during D₁ phase could be related to the regional thermal event and the emplacement of granite during Indosinian movement. Thus it is inferred that the peak–metamorphic condition of the Longmenshan region is reached during D₁ phase.

The third phase (D₂): The phase of deformation is represented by the formation of mylonite. Mylonitic rocks are mainly developed in the pre-Sinian granitic rocks along the either sides of the WFZ and in the Silurian schists to the northwest of the WFZ. The mylonite zones trend NE–SW or NNE–SSW, parallel to the strike of the WFZ. The mylonitic foliation (S₂), which develops in the mylonite zones, generally parallel to S₁, strikes N25°E–N35°E and dips vertically or at 70°–80° to NW. Stretching lineation on the mylonitic foliation plunges to S-SW at 60°–85° (Fig. 6c). Flxion banding defined by elongated ribbon minerals occurs in the mylonites, ranging 0.1–2 mm in thickness.

The WFZ is currently a fault zone that has about 100 m width and is dominated by brittle deformation such as faulting and fracturing. Near the WFZ, S₁ mylonitic foliation is cut by minor faults and fractures. Amounts of porphyroclasts decrease but recrystallized fine-grained minerals increase toward the WFZ, showing westward polarity of reduction of overall grain size. These facts indicate that the mylonite along either sides of the fault zone record the deformational history of earlier stage of the fault zone, and therefore, that there was a regional-scale ductile shear zone within a width up to several kilometers along the WFZ.

The S₀ foliation of mylonite derived from the pre-Sinian granitic rocks are defined by a dimensional preferred orientation of porphyroclasts of plagioclase, K-feldspar and epidote, and of the oriented alignment...
of quartz ribbons, quartzo-feldspathic ribbons, phyllosilicate layers rich in biotite, muscovite, and chlorite and fine-grained epidotes (Figs. 7a–7c). More than 90% of the ribboned felsic material consists of quartz and K-feldspar. Quartz ribbons are aggregates which elongated strongly with large aspect ratio (4:1–10:1). The undulatory extinction is ubiquitous in quartz crystals. Plagioclase is commonly present as large porphyroclasts but rarely as fine-grained crystals. Some feldspar crystals show evidence of kinking and lattice bending during the mylonitization (Fig. 7d). The porphyroclasts with the size ranging from 0.5 to 3 mm are elliptical with aspect ratio of about 2:1–3:1 and the long axes are generally subparallel to the matrix fabric (Fig. 7a).

Mylonites derived from pelitic schists commonly contain spindle-shaped large biotite porphyroclasts (mica fish) but rarely feldspar and quartz porphyroclasts, with 0.5–1 mm in size, within the fine-grained, strongly orientated quartz, muscovite and chlorite matrix (0.05–0.1 mm in size). The long axes of the porphyroclasts are nearly parallel to the mylonite foliation (Figs. 8a–8b). Biotite porphyroclasts rarely contain quartz inclusions and the quartz inclusion trails are oblique to the mylonite foliation (S3) at 30°–50° (Fig. 8c). The biotite porphyroclasts and inclusion trails inside the mylonite zones correspond to the biotite porphyroclasts grown at D3 phase and internal foliation (S2) in them, respectively, outside the zones. Namely, the D3 biotite porphyroblasts has been deformed into the D4 biotite porphyroclasts, although the distinction between S3 and S2 is difficult in many place because of the parallelism of these foliations. This indicates that the D4 mylonite was formed slightly later than S2 schistosity.

Some biotite porphyroclasts are sometimes elongated parallel to the S1 mylonitic foliations and L3 mineral lineations, forming microboudins (Fig. 8d). The separation of the microboudins are filled with chlorite and quartz. Fine-grained chlorites define the S3 foliation in the matrix of mylonites. These indicate the retrograde metamorphism during the mylonitization.

The mylonites show asymmetric structures such as S–C–C' structures (Figs. 7a and 7c), slightly asymmetric pressure shadows of finely recrystallized quartz and mica at the both wings of rotated porphyroclasts (Figs. 7a and 7c), and kinked porphyroclasts (Fig. 7d). These structures indicate that the mylonite-forming deformation took place due to shearing in a NW–SE sense.

**The fourth phase (D4)**: The D4 phase of deformation is characterized by S4 cleavage and F4 fold developed only locally. The S4, which is only found in the WFZ, is a closely-spaced (<1 cm) crenulation cleavage (Fig. 9c) or a wider-spaced (1–20 cm) shear cleavage (Fig. 9d). S4 trends NE–SW or ENE–WSW, dips to NW or NNW at 80° or vertically (Fig. 6e) and cuts S2 and S3 at 20°–40° clockwise to their strike (compared Figs. 6a and c with e), locally at high-angle. At some outcrops, minor chevron folds (Fv) of S4 are developed with vertically plunging fold axes (Fig. 9d) along S4 cleavage surface. S4 crenulation cleavage has rarely transformed into a shear cleavage with subhorizontal slicken line. The transformation and the obliquity of S4 against S2 and S3 suggest sinistral strike-slip shearing during the D4 phase.

F4 is a vertical fold of which axis plunges steeply to NE at 60°–90° (Fig. 6f), and folds S2 and S3. F4 occurs locally in the Silurian Maoxian Group schists close to the WFZ and in the Devonian Yuelizhai Group consisting of foliated thin-layered marble within the WFZ (Fig. 9d). The wavelengths of F4 folds range generally from 0.5 mm–10 cm up to 10 m. The F4 can be attributed to the strike-slip shearing along the
WFZ during D3 or later (Zhao, 1985; Lin and Wu, 1991; Dirks et al., 1992). The geometry of F3 indicates commonly a sense of sinistral shearing, but some evidences within the WFZ indicate dextral shearing.

The fifth phase (D4): Kink band (F3) with the geometries of angular type and/or discrete type (Figs. 9a–9b) (Uemura and Long, 1987), rarely rounded type, was formed during the phase of deformation. F3 is developed locally in calcite–schists and mica–quartz–schists of the study area in the middle segment of the LNSZ, but well developed in the south segment. Kink planes are NE or N in strike direction and dip to NW or W at 35°–60°, respectively (Fig. 6d). Few kink bands with kink plane dipping to SE at 30° or so are also observed. The kink planes cut S2 and S3 obliquely and a reverse sense of displacement along the kink planes is recognizable. Some kink bands of S2 are of asymmetric conjugate type (Fig. 9a) and normal type. The geometrical and deformational features suggest that the kink bands are formed in rather lower ductility condition (Uemura and Long, 1987), in other words, they are originated in a relatively shallower structural level and/or at the higher strain rate.

The sixth phase (D5): The phase of deformation is characterized by brittlely deformed structures such as fault and joint. The fault occurs commonly as either single, discrete fault slickenside or a fault zone with fault gouge, breccia and/or cataclasite ranging from several centimeters to several meters in width. D5 microcracks are often filled with calcite. The brittle structures cut all pre-existing structures (e.g., S3, Fig. 7b), representing clearly the latest deformation.

2. Yingxiu Nappe

Dominant deformed structures in the YN are characterized by foliation, various shear zones and shear joints. Few folds are found on outcrops in the investigating area because of lack of pre-existing planar structural element in the Peng–Guan Complex. Deformation structures in the northwestern part of the nappe are different from those in the southeastern part. Polyphase deformation is commonly recognized in the northwestern part, but only some brittle faults with cataclasites and joints occur in the southeastern part.

The first phase (D1): The phase of deformation, as same as in the WN, is characterized by S1 bedding foliation. S1 occurs mainly in the pre-Sinian
Huangshuihe Group metavolcanics and metasediments located in the northwestern part of the YN, adjacent to the WFZ. S_2 is obscured on most outcrops because being transposed intensely by S_3. At some outcrops and in thin-sections, the crenulation folds and pytymatic folds of S_3 with the wavelengths of 0.2–1 cm can be observed clearly (Figs. 10 b–10 c).

The second phase (D_2): Penetrative foliation S_2 and fold F_2 were formed in this phase. S_2 is crenulation cleavage and has a strike of N 30° E–N 40° E and dips to NW at 60°–85°, rarely vertical and cuts S_1 (Fig. 11 a). The oriented arrangement of fine-grained quartz, muscovite, chlorite and biotite define the cleavage S_2. Elongated mineral lineations plunging to SW at 60°–70° are rarely found on the cleavage surfaces. Although S_2 is one of the dominant planar fabric in the northwestern part of the YN, lithological control is obvious for S_2 because it is found only in the pelitic schists and foliated metavolcanics of the pre–Sinian Huangshuihe Group (Fig. 10 a), whereas S_3 can be hardly found in the pre–Sinian granitic rocks. F_2 fold is also present only in the pelitic schists of the Huangshuihe Group but observable in only some outcrops and in thin-section. F_3 has commonly the asymmetric geometry with the wavelengths of 0.2–1 cm (Figs. 10 b–10 c). Some tight chevron folds and pytymatic folds (F_3) of S_3 are also observed. The axial planes are subparallel and parallel to S_2 (Figs. 10 b–10 c).

The third phase (D_3): The phase of deformation is represented by mylonitization. The mylonitic rocks are only developed in the northwestern part of the YN adjacent to the WFZ, but are not found in the southeastern part of it. In the northwestern part of the YN, several mylonitic zones range from 2–10 m in widths, the widest about 30 m. The mylonites are derived from the surrounding coarse-grained and massive granitic rock. The mylonitic foliation (S_3) is defined by penetrative fluxion banding and/or preferred orientation of elongated porphyroclasts such as plagioclase, K-feldspar and quartz (Fig. 10 d), and recrystallized fine-grained minerals such as muscovite, chlorite, quartz, K-feldspar and a small amounts of plagioclase (Figs. 10 e–10 f). Although the S_3 is almost parallel to S_3 in many places (Fig. 11 b), the S_3 is characterized by grain-size reduction, unlike the S_5.
The deformational features of mylonite are the formation of alternate fluxion bandings rich in quartz or mica and ubiquitous undulatory extinction (Fig. 10c). Two texturally distinct types of quartz ribbons are recognized. One type is in which quartz forms elongate grains, and the other type is that in which it forms subequant to equigranular grains (Fig. 10f). Long axes of these quartz crystals are subparallel to the ribbon margins. The elongate quartz grains range in size from 10 to 30 μm, showing a well-developed grain-shape alignment. The subequant to equigranular quartz grains range from 50 μm to 0.1 mm in grain-size and show slight undulatory extinction, suggesting almost strain-free conditions. This might have been attributed to a thermal event or annealing after the mylonitization. The thermal event might be also supported by appearance of random-oriented myrmekitic intergrowths of plagioclase, quartz and K-feldspar in the granitic mylonites.

The constituent of the porphyroclasts exhibits a clear change in mylonites from the northwest to the southeast, and the mylonite is graded structurally southeastward into very weakly mylonitized or ductilely undeformed granites. In the northwest, plagioclase and K-feldspar are major components of the porphyroclasts, but quartz porphyroclasts are rarely found. Southeastward, quartz porphyroclasts in mylonites clearly increase and the ratio of the porphyroclast to the matrix also increases, indicating the D₃ mylonitization weakened. The porphyroclasts show undulatory extinction. Elongated ribbons of quartz is rare in the matrix (Fig. 10g). Adjacent deformed host quartz grains often have serrated grain boundaries between them due to growth of new grains and/or subgrains which are only found at the grain boundaries and along kink bands in host grains (Fig. 10g). Further southeastward, the minerals exhibit slightly strained or strain-free. The undeformed granitic rocks retain nearly their original igneous textures (Fig. 10h). These microstructural change shows that the deformation of rocks is degraded from mylonite through protomylonite to undeformed rock from the northwest to the southeast. Later brittle microcracks and cataclasite bands cut through the porphyroclasts, subgrains and new grains in the weakly mylonitized granites (Fig. 10g) and are also found in the undeformed granites. They occur along or associated with minor fault. In the YN the D₃ mylonitization was superposed by the later brittle deformation. These features of deformation in the YN clearly indicate that deformational depths of the rocks shallowen gradually toward the south-
Fig. 10. a. Crenulation cleavage (S_3) in the pre-Sinian Huangshuihe Group. b. Crenulation cleavage (S_3) and crenulation fold (F_3). c. Ptygmatic fold (F_3). d. Mylonite of D_3 in pre-Sinian granitic rock. e. Alternate fluxion bandings rich in quartz or mica in D_3 mylonite. f. S–C structure in D_3 mylonite of the YN. Two textural types of quartz ribbons, those in which quartz forms elongate grains (fine-grained) and those in which quartz forms subequal grains (coarse-grained). Asymmetrical pressure shadows occur as both wings of plagioclase porphyroclast, indicating a dextral shear sense. g. Quartz crystals are surrounded by fine new grains and subgrains. Coarse quartz and K-feldspar display undulatory extinction and are cut by later microcracks. h. The undeformed granitic rocks retain their original textures.
east.

The D9 mylonites of the YN show asymmetric structures such as S–C or S–C–C′ structures and asymmetric pressure shadows (Fig. 10f). Asymmetric pressure shadows of finely recrystallized quartz and mica commonly occur as both wings of a rigid feldspar porphyroclast in the D9 mylonites of the YN (Fig. 10f). The minerals in the pressure shadows consist of recrystallized fine-grained quartz, K-feldspar, plagioclase and mica. The shape of recrystallized quartz grains in pressure shadows shows an elongated fabric subparallel to mylonitic foliation (S9). Asymmetry of pressure shadows and S–C or S–C–C′ structures with respect to the mylonitic foliation suggests that southeastward thrusting occurred during the D9 mylonitization.

The fourth–fifth phases (D4–5) : S4–5 occurs locally as a slaty cleavage in pelitic schists or a fracture cleavage in granitic rocks (Fig. 12a) with clearly fractured surface. The S4–5 is nearly found in the northwestern part of the YN, cutting the pre-existing S3 and S9 and dips to NNW or SSE at 58°–90° (Fig. 11c). The geometries and the degree of development of the cleavage are controlled by lithology. The spacing of the cleavage is 0.1–10 cm. Tight chevron to open rounded minor folds, which folded S9, are rarely recognized.

The unmetamorphosed diabase dikes located in the northwestern part of the YN have been strongly cleaved by S4–5, whereas those located in the southeastern part only slightly fractured. In the dikes intruding into the granitic rocks, lenticular slices are formed by S1 fracture cleavage (Fig. 12b) dipping to NNW, partly to SE at 40°–80°, with the spacing 0.5–1 cm. A large amount of the dikes occur in the pre-Sinian Peng–Guan Complex. The dikes range from 50 cm to 10 m in widths and have the strike of NE or NNE, parallel or subparallel to the trend of the YN. Although the exact age data of the dikes in the YN have not been obtained so far, the simultaneous diabase dikes in the north segment of the LNSZ yielded a K–Ar age of 195 Ma (Liu et al., 1991). This indicates that the diabase dikes in the YN and WN are the products of Indosinian event. The diabase dikes in the WN cut commonly the kink band (F3) but those in the YN are cut by S4–5, thus it is inferred that the phase of deformation (D4–5) in the YN is slightly later than D4 in the WN.

The sixth phase (D6) : The phase of deformation is characterized by brittle fault and joint. Although the brittle faults can be observed over all the YN, the degree of development is stronger in the southeastern part of the nappe than in the northwestern part. Most faults have NW–dips at 30°–80° (Fig. 11d). Some of them indicate clearly a SE-oriented sense of dip-slip thrust, but the sense of displacement of most faults is unclear although striations can be observed along some fault surfaces. These faults are commonly associated with breccia, gouge, structural lenticular bodies or cataclasite and fracture cleavage zone (Fig. 12d).

In the YN, joint, mainly shear joint and extension joint, is also one of the dominant late deformed structures (Fig. 12c). Some joints are filled with calcite. Three dominant orientations of the joints are divided, but the temporal sequence of differently oriented joints is unclear.

3. Guanxian Nappe

In the GN, although some structural relations can be observed, it is hard to divide clear deformatonal phases and the rocks retain nearly the original sedimentary texture. Main meso-structures are dominated by parallel folds, brittle faults and joints, representing a deformation condition in relatively shallower structural level of the crust (Mattauer, 1980; Zhu and Song, 1990). No mylonitic rock is found in the nappe.

Fold : The folds developed in the GN are nearly upright to inclined parallel folds (Fig. 13) with the axes plunging to the NE or SW (Fig. 14a) and axial planes dipping steeply to the NW. Fold style and size vary with lithology. Broad, open folds with rounded hinges and wavelengths of 10–200 m occur in thickly or moderately bedded sandstones, whereas relatively tight folds with chevron hinges and wavelengths of 1–20 m occur in moderately to thinly bedded alternation of sandstone and mudstone. The geometry of folds is
Fig. 12. a. Slaty shear cleavage (S$_{a}$) in the metavolcanics of pre-Sinian Huangshuihe Group. b. Lenticular slices by cleavage (S$_{a}$) in the diabase dike. c. Shear joint (D$_{a}$) in granitic rock. d. Fracture zone and breccia (D$_{a}$) in granitic rock.

nearly either 1 B or 1 C (Ramsay, 1967) and the folds are commonly located adjacent to the front or to the basal glide-surfaces of gliding-spreading nappes (Hou and Uemura, 1993). A sense of SE-directing movement is given from the geometry of these folds.

**Brittle fault and joint**: In the GN, two groups of faults can be roughly classified by their attitude (Fig. 14 b) (Hou and Lin, 1993). One group has the strike of N 20°E–N 50°E, parallel or subparallel to regional thrusts and dips to NW at 35°–70°, rarely to SE. The group of faults commonly has a length of several to 10 kilometers and is associated with a fracture zone ranging from 10 cm to 5 m in thickness, with incohesive gouge, breccia and fracture cleavage. The sense of sinistral-thrusting or dextral-thrusting displacement is shown mostly in the group of faults. The group of the faults are considered as a secondary thrusting fault following the regional thrusting. The other group strikes in the direction of E–W or ESE–WNW, dipping N or S at the angles of 70°–90°, oblique to the trend of the regional thrusts. The lengths are commonly 2–3 km. A sense of dextral strike-slip is observed in the field. The group of faults could be a tear fault (Dahlstrom, 1970) formed during the emplacement of the GN. Besides of the faults, complicated crisscross joints are also a common structure in the GN.

Rare fracture cleavage and cataclasite is only observed in the nappe.

**Discussion**

Based on the above stated meso- and micro-structures developed in individual nappes, the deformation sequence, temporal and spatial change of the type of deformed structures and mean ductility (Uemura, 1981) at deformation are qualitatively summarized in Fig. 15. From the summarization, some understandings about the deformatonal nature and tectonic histories of the LNSZ can be obtained as follows:

1. The deformed structures of earlier phases are dominated by ductile deformation, whereas those of later phases are characterized by brittle deformation, especially in the WN and the northwestern part of the YN. The mean ductility at deformation decreases clearly with time. Its decrease with time is caused by the decrease of temperature and/or of effective confining pressure and/or increase of strain rate (Uemura, 1981). Generally speaking, as the effective confining pressure and temperature are related to the
buried depth, their decrease means that the temporal development of the deformation in the LNSZ can be explained by the continuous thrusting upward of the nappes from deeper to shallower structural levels of the earth's crust.

Because the metamorphic peak conditions of the WN rocks were around 300–450°C and 350–700 MPa (Bureau of Geology and Mineral Resources of Sichuan Province, 1991) which correspond to depths of 12–23 km, the currently exposed part of the WN has been uplifted at least 12 km since Indosinian movement. Whereas, the YN was only uplifted about 5 km by the YFZ (Lin and Wu, 1991). This indicates that the earlier was nappe formed, the farther was it uplifted.

2. The same tendency of change in mean ductility is suggested in spatial distribution of deformed structures. The WN are characterized by the dominance of ductilely deformed structures such as disharmonic, pytynmatic and intrafolial folds, penetrative foliation and mylonite, which represent the deformation at a high mean ductility condition in deeper level (Sibson, 1977; Uemura, 1981; Tullis et al., 1982; Carter and Tse, 1987). In the YN, deformatinal nature changes from NW to SE across the nappe. The ductile deformation structures such as mylonite and penetrative foliation are dominant in the NW part of the YN but the brittle one such as brittle faults and joints in the SE part. No mylonite is observable and ductilely deformed structures are rarely found in the SE part of the nappe. These indicate that there was difference in internal structural development of the nappe. The difference may has resulted from the development of secondary thrusting slices of the lozenge-shaped "rootless" allochthonous block, or Peng-Guan Complex, by the internal shear zones or faults in piggyback fashion from NW to SE, as same as whole the LNSZ. The deformed structures in the GN and in the FSZ are characterized by parallel, upright and inclined folds, brittle faults and various joints. Incohesive breccia, gouge and fracture cleavage are common in the fault zones, but cataclasites are rarely found. No obvious evidence of metamorphism and mylonitization is found in the nappes.

From the facts stated above, the deformation grade (Uemura, 1981) decreases from the northwest to the southeast. This means that the depths of the nappe formation shallow toward the southeast.

3. The number of deformation events and their complexity decrease from the WN to the FSZ. Both meso-structures and micro-structures in the WN and in the northwestern part of the YN preserve the evidence of polyphase deformation, but only one or two phases of deformation can be recognized for those in the southeastern part of the YN and in the GN. The evidence indicates that the northwestern flank of the LNSZ have undergone longer deformation history and more phases of deformation than the southeastern one.

4. On the basis of above described facts on meso- and micro-structures and their deformation sequence, the tectonic development of the LNSZ can be interpreted from the piggyback fashion of nappe formation (Dahlstrom, 1970; Butler, 1982; Lin and Wu, 1991; Hou and Uemura, 1993).

During D1 phase, medium-pressure type of regional dynamothermal metamorphism (Bureau of Geology and Mineral Resources of Sichuan Province, 1991) led to the formation of bedding-parallel foliation S1. From the Indosinian movement at the end of the Triassic and beginning of the Jurassic, D1 thrusting subsequently began in the northwestern flank of the Longmenshan Mountains and the WN was first formed. In the D2 phase, the LNSZ rocks attained the thermal peak metamorphic conditions represented by the appearance of biotite and garnet porphyroblasts. This thermal event might be related to granite emplacement and crustal thickening due to the Fz folding (see Fig. 4). The D2 phase can be considered as the principal phase of the formation and emplacement of the WN as the D3 deformation structures are most penetrative in the nappe. Also in the northwestern part of the YN the D3 deformations occurred to
<table>
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<tr>
<th>Deformation Phase</th>
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<td>Micro-structure</td>
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<td>microcrack</td>
<td>brittle fault and joint</td>
<td>microcrack</td>
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Fig. 15. Summarization of the deformed meso- and micro-structures in individual nappes. Dm: mean ductility. H, M and L: high, moderate and low, respectively.

form foliated zones and mylonitic zones.

After the D2 phase, the D3 mylonitization occurred associated to the retrograde metamorphism and up-lifting of the WN and YN. During the same phases, however, the southeastern flank of the Longmenshan Mountains remained still in the comparatively undeformed conditions but receiving a series of molasse sediments (Long, 1991; Cui et al., 1991; Lin, 1993). This can also be indicated by the facts that the rocks to the southeast of the YFZ are less metamorphosed and the Late–Triassic sediments to the southeast of the YFZ are covered partly by the Jurassic sediments (Fig. 2). Subsequently, thrusting propagated gradually toward the SE direction under the action of the continuous SE-directing compression and load derived from the preceding nappes. The WN, the YN, the GN and the FSZ were formed sequentially from NW to SE. The nappes formed in preceding stages were also uplifted and underwent polyphase deformation due to later thrusting, resulting in the superposition of structures originated in different phases and different structural levels. The differential uplift of the individual nappes results in present–day exposure of different structural levels. This evolving fashion also produced the topographic gradient declining to the SE, resulting in the gravitationally instable south-eastward gliding of thrust sheets to form the gliding-spreading nappes which now occur as klippes.

According to Luo (1986, 1991), the dynamic origin of the LNSZ is attributed to the subduction of the Yangzi (Yangtze) Plate locating to the east of the Longmen Mountains toward the hinterland of the Longmen Mountains, having been pushed by the Palaeo-Pacific Plate and affected by the static pressure derived from enormous thick sediments in the marginal depression of the western Sichuan.

The preceding discussion does not comment on the effect of strain rate. There is not any positive evidence to evaluate the change of strain rate through the whole process of deformation in the LNSZ. Even if the strain rate of the later deformation phases during the Himalayan movement in the LNSZ was considerably lower than that of the earlier phases during the Indoasian movement, the mean ductility at deformation might have decreased effectively due to the decrease of temperature and/or of effective confining pressure. If the strain rate was accelerated with time, the mean ductility might have decreased with time and the ductile deformation at the earlier phases changed into the brittle one. This shows well correspondence with the preceding discussion.

Conclusion

The six phases of deformations are discriminated in the nappes of the middle segment of the LNSZ, especially in the WN and the YN. Various types of meso-
and micro-structures with different deformatonal nature are formed respectively during these phases of deformations. A tendency for temporal development of the deformed structures is distinctly indicated, that is earlier dominant ductile deformation turns gradually to later dominant brittle one. The decrease of mean ductility with time results in that the deformatonal facies successively degraded with time. This suggests that the nappes were uplifted continuously from the deeper structural level to the shallower one.

Same tendency as temporal development is suggested in the spatial distribution of deformed structures. The structures undergone clearly ductile deformation occur almost in the nappes located in the northwestern flank of the LNSZ, whereas the deformed structures by brittle deformation are more common in the nappes located in the southeastern flank. The feature indicates that the ductile deformation weakens but the brittle deformation strengthens from NW to SE across the LNSZ, and the depths of the nappe formation shallowed toward the same direction.

Polyphase deformations and strong metamorphism have been developed in the northwestern flank of the LNSZ, whereas relatively simple deformation and no obvious metamorphism have occurred in the southeastern flank. Thus, the nappes located in the northwestern flank have undergone longer and more complex deformatonal histories than those located in the southeastern flank.

The development and distribution of meso- and micro-structures are well correspondence with the interpretation that the nappe structures in the Longmenshan Mountains have been propagated in a piggyback fashion from the northwest to the southeast.

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* in Chinese  ** in Chinese with English abstract  *** in Japanese with English abstract

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龍門山ナップ構造帯中部地域における小構造および微構造の形成過程は、6 回の変形時効に区分される、変形相解析の結果、本地域のナップにはひとつの明瞭な変形傾向が認識される。変形構造の時間的変化をみると、前期に形成された延性的な変形構造に、後期に形成された脆性的な変形構造が重複し、また空間的分布を見ると、北西から南東に向かって、延性的な変形構造が脆性的な変形構造に移り変わっていく。すなわち、変形時の岩体の平均延性度は時間とともに低下しているが、それと同時に北西から南東に向かっても低下している。各ナップの中には発達する各変形要素の平均延性度も同じ方向に向かって低下している。このような状況は、龍門山ナップ構造帯が "piggy-back thrust propagation" によって北西から南東に向かって順次形成され、全体としては時代とともに、変形の場所が深い所から浅い所へと移動し、同時に変形の速さも加速されていったものと解釈される。