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Structural and thermal characters of the Longmen Shan (Sichuan, China)

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ABSTRACT

The Longmen Shan (Sichuan, China) is characterised by an unusual morphology which results from a Triassic prism tectonics and a more recent Neogene thick-skin thrusting. Among its specific features is the high elevation of the internal zones in continuity with the Songpan Garze fold-and-thrust belt (SG), which is associated with an abrupt 20 km Moho offset between the Sichuan Basin and the Tibetan plateau as revealed by the analysis of teleseismic data acquired by a dense seismic network. The jump in crustal thickness is located at the apex of the Wenchuan shear zone (WSZ) and marks the western boundary of the metamorphosed units of SG characterized by temperatures varying from 590 °C down to 300 °C as commonly observed in mature accretionary wedges. Both the structural style marked by intense shortening in tight kink folds and geophysical data suggest the presence of an horizontal discontinuity at ~15 km depth over a thick crust (~63 km).

The Longmen Shan east of the WSZ is characterized by thick-skin detachment which thrusts the internal sedimentary units and the Proterozoic basement over the series of the Sichuan Basin deposited on a thinner crust of ~44 km thick. The major front is the Beichuan Fault Zone (BFZ) which brought the internal zones onto Triassic and Jurassic series with lower temperatures (less than 400 °C). Locally, temperatures of ~425 °C are found just below the klippes.

These results are in agreement with an original contact of the SG zone represented by an accretionary wedge of sediments thrusted over the margin of the continental crust of the Yangtze craton in the early stage (Indosinian) of the evolution. The present-day slow E–W component of the convergence, added to the difference in crustal thickness caused the Yangtze crust to indent the Songpan Tibetan crust which was softened by a high thermal regime. As a response the edge of the Tibet crust was inflated to the bottom (up to 70 km), whereas to the top, the crystalline massif were exhumed and pushed the deformation eastward as emerging and blind thrusts. This configuration reflects a moderate shortening of the crust which behaves as a soft thick material abutting the resistant and cold Yangtze crust.

1. Introduction

The Longmen Shan is a range of about 350 km long and 50 km wide, striking NE–SW. The tectonic history of this belt began during the Triassic with the Indosinian orogeny, which was synchronous with the collision of the North China block with the South China block (Yangtze craton), and ended the closure of the Paleotethys. Magmatic events were recorded later during most of the Mesozoic (Roger et al., 2008), but the kinematic setting remains unclear. During the Cenozoic, old structures were reactivated and new ones formed, as a consequence of the distant India–Eurasia collision and the uplift of the Tibetan plateau (Yong et al., 2006).

In terms of morphology, the Longmen Shan differs significantly from most classical orogens of the world. It marks the steepest margin of the Tibetan Plateau. It is sharper than the Himalaya front due to the poor development of frontal foothills. However, unlike other regions with steep step gradient, the convergent rate <3 mm/year (Chen et al., 2000; Gan et al., 2007; Shen et al., 2009) across the range is strikingly low. In addition, the topographic front of the range rises gently from the basin toward the east, instead of being sharp and located on the main thrust, suggesting a complex geometry in the foothills.

To investigate the crustal structure Robert et al. (2010-this issue) performed a dense seismological profile across the Longmen Shan and Tibetan Margin. Robert et al. (2010-this issue) show a sharp vertical offset of the Moho of 20 km over 30 km wide, approximately above the Wenchuan shear Zone (WSZ).

Due to these peculiar features and to its location, the Longmen Shan is a key area to test different geodynamical models proposed for the building and the evolution of the Tibetan plateau. Several decades of studies performed by various teams document this area in terms of

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stratigraphy (Chen and Wilson, 1995; Yong et al., 2003; Yong et al., 2006; Burchfiel et al., 1995; Meng et al., 2006), structures (Chen and Wilson, 1995; Burchfiel et al., 1995; Harrowfield and Wilson, 2005; Roger et al., 2008; Burchfiel et al., 2008; Hubbard and Shaw, 2009), petrology (Worley and Wilson, 1996; Huang et al., 2003b; Harrowfield, 2001) and geophysics (Lev et al., 2006; Sol et al., 2007; Xu et al., 2007; Burchfiel et al., 2008; Lou et al., 2009; Robert et al., 2010-this issue). However the metamorphic conditions are still poorly known except locally in the Danba area where crustal exhumation involving migmatitic rocks has been well described (Huang et al., 2003a,b; Wallis et al., 2003).

The main goal of this paper is to combine available datasets with our new constraints on the geometry of the crust and thermal data to draw a cross-section which reconciles the deformation resulting from Triassic sedimentary accretion to Cenozoic and Quaternary thick-skin deformation.

2. Two crustal provinces separated by an intermediate zone: The Longmen Shan

The Longmen Shan marks sharp topography which is close but not exactly above the projected Moho step separating a 63 km thick crust under the Songpan Garze fold belt in this area to 44 km thick crust below the Sichuan basin (Robert et al., 2010-this issue). Actually, seismological data indicate that the Moho step is under the Wenchuan shear zone, while the topographic step is located eastward in the fold-and-thrust belt of the Yangtze platform.

We therefore identify two large crustal provinces in the Longmen Shan region: (1) The Songpan Garze unit and (2), the Yangtze affinities unit (Fig. 1).

(1) The Songpan Garze unit is major component of the Tibetan plateau. It is composed of a thick (5 to 10 km) sequence of lower and middle Triassic flysch-type sediments disconformably deposited on a thick (5–7 km) Palaeozoic cover of marging sediments (Mattaeur et al., 1992). In the Longmen Shan the Triassic flysch and the Palaeozoic cover are generally in thrust contact with Palaeozoic platform sediments that formed the cover of the Yangtze passive margin and its Proterozoic basement (Chen and Wilson, 1995; Harrowfield and Wilson, 2005).

(2) The Yangtze affinities unit which form the South-East province consists in Neoproterozoic crystalline massifs present along a narrow belt oriented NE–SW. It is composed of 4 large basement massifs (Pengguan, Xuelongbao, Baoxing and Tonghua massifs, see location in Fig. 1) over which most of the Neoproterozoic sedimentary cover has been eroded, together with the former thrust units. The Pengguan crystalline massif represents the core of the south Longmen Shan. It is bounded by the Wenchuan–Maowen shear zone to the west and the Beichuan thrust to the east (Fig. 1). The basement still supports part of its original marine Proterozoic sedimentary cover of Sinian carbonates. On the schematic map of Fig. 1, we therefore integrated the Proterozoic sediments north-east of the Pengguan massif to the basement unit. The sedimentary facies of Permian and Triassic rocks vary from the eastern to western sides of the Pengguan massif. To the east Permian and Triassic are dominated by limestone whereas thick monotonous clastic sediments are recorded during the same time span in the Songpan Garze unit. A Proterozoic basement, similar to that of the Longmen Shan, is exposed in Danba area, and is characterised by more distal Palaeozoic metagraywackes and metapelites metamorphosed under amphibolite to migmatite facies (Worley and Wilson, 1996; Harrowfield and Wilson, 2005; Yong et al., 2006) but is likely to be different in the central part of the Songpan Garze terrane.

As observed by previous authors, the definition of these tectonic zones intersects the former and paleogeographic zones which refer to original depositional environments (Harrowfield and Wilson, 2005; Yong et al., 2006)

3. Construction of a crustal section

In order to propose a synthetic crustal cross-section through the Longmen Shan we use both geophysical and geological data (Fig. 2). First, topographic radar based SRTM data, Landsat TM, Spot and Aster imagery, and geological maps at various scales are used to study the main tectonic structures (the 1:2.5M Geological Map of the People's Republic of China from Sinomaps Press, the new 1:5M Geological Map of Asia from CGMW, and 1/200.000 Geological Maps of Sichuan). The surface structures were also compared to existing sections (Worley and Wilson, 1996; Harrowfield and Wilson, 2005; Yong et al., 2006; Jia et al., 2006; Hubbard and Shaw, 2009; Wenzheng et al., 2009). The structures at depth were extracted from seismic profiles presented in Jia et al.

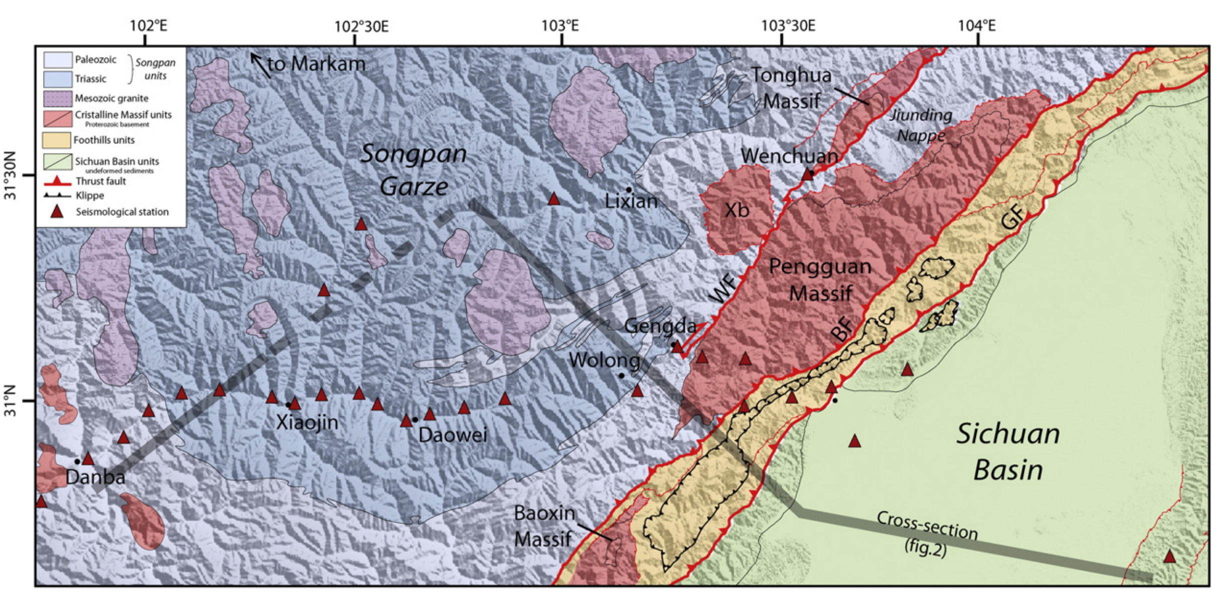

Fig. 1. Structural sketch of the Longmen Shan mountains area showing the relationships between the eastern Songpan Garze fold belt and the western Sichuan basin. The gray line correspond to the cross-section which is represented in Fig. 2. Xb: Xuelongbao massif, GF: Guanxian Fault, BF: Beichuan Fault, and WF: Wenchuan Fault.

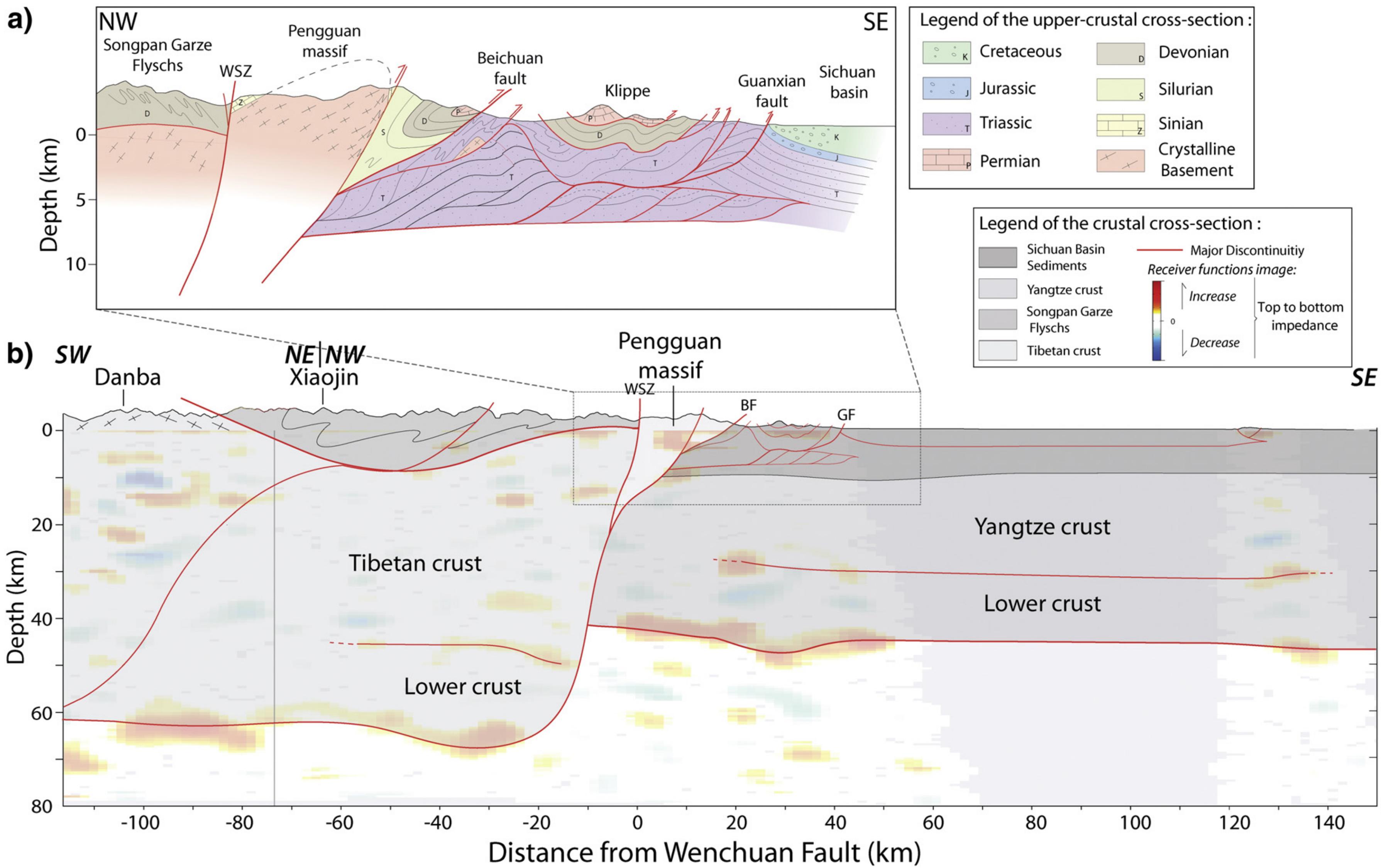

Fig. 2. a) Simplified cross-section of the frontal part of the Longmen Shan along the trend of the main section. Mostly Mesozoic sediments from Yangtze block (Sichuan basin) are involved except some of the internal Palaeozoic to Triassic sediments of the Jiunding nappe. b) Schematic section based on the receiver functions profile and seismic lines showing the thick Songpan crust impinged against the older and thinner Yangtze crust.

(2010-this issue) and Wenzheng et al. (2009) and on a profile based on receiver function and gravity data from Robert et al. (2010-this issue).

Part of the structure of the Longmen Shan is hereafter illustrated by a composite section between Gengda and Wolong (Fig. 2). This section runs approximately along strike the seismological profile described by Robert et al. (2010-this issue), and is supported by one available seismic lines (Wenzheng et al., 2009).

To the western part of the cross-section, the Songpan affinity mostly Devonian and Triassic deformed and metamorphosed sediments crop out.

Field observations indicate that in the Songpan unit, the structural style is dominated by at least two fabrics of schistosities S1 and S2 beared by two metamorphic paragenesis, related to the D1 and D2 events (Chen and Wilson, 1995; Worley and Wilson, 1996; Harrowfield and Wilson, 2005) (Fig. 3). The S1 fabric is co-axial with the tight folds F1 which characterize the Songpan tectonic province and the S2 is a well-defined although not always present crenulation. In the Danba area, the S2 is oblique to the S1 and indicates two discrete deformation events, whereas in the Wenchuan region the two events are at close angle and are more difficult to unravel. S1 is often attributed to the early event during the Triassic, which is associated with a thin-skin basal decollement of the sedimentary cover (Fig. 4) (Calassou, 1994; Harrowfield, 2001; Harrowfield and Wilson, 2005). Wilson et al. (1994) estimate that the thrusting and folding during D1 have resulted in greater than 50% shortening of the fold belt. The deformation is reoriented parallel to the plate boundary (Calassou, 1994; Worley and Wilson, 1996) due to the effect of simple shear along strike the Longmen Shan. D1 structures in the WSZ are transposed into S2 fabric (Worley and Wilson, 1996). The D2 deformation is spatially and temporally associated with the development of the WSZ (Worley and Wilson, 1996). This ductile deformation zone of several kilometres in width is underlined by a sub-vertical S2 schistosity, associated with C/S structures that mainly show top to the south-east movements and F2 folds (Fig. 4). D1 and D2 deformation phases are considered to be progressive subdivisions of the continuous south-directed Indosinian shortening (Harrowfield and Wilson, 2005; Harrowfield, 2001). In fact, these deformation phases occurred prior to emplacement of the Rilonguan granite (185 Ma) and the Northern Ma Nai granite (197 Ma) (Calassou, 1994). The exhumation of the Danba antiform has occurred during the early D2 phase which corresponds to active shortening of the overlying sedimentary pile (Harrowfield and Wilson, 2005).

S1 and S2 have different orientations on each side of the WSZ (Fig. 3), suggesting that the last reactivation of Wenchuan fault is younger than the acquisition of S1 and S2 in the Songpan Garze and Pengguan units. The WSZ is cross-cut by some brittle faults whose striations mainly indicate dextral movements.

The Pengguan massif consists of Proterozoic granodiorite associated with diorite. The basement still supports part of its original marine Proterozoic sedimentary cover of Sinian carbonates and quartzite. The sedimentary cover draws a fold along the Pengguan massif suggesting that the basement and the cover were fold as an anticline (Figs. 1 and 2). In the Pengguan massif, a schistosity S1 is locally developed. The orientation of the S1 is oblique to the strike of Beichuan fault suggesting that it has been developed before the activation of the Beichuan fault (Fig. 3).

The Beichuan fault marks the contact between the Pengguan massif and the overlying Palaeozoic sediments that constitute the deformed foothills. The Beichuan fault is a narrow zone of deformation running over 300 km, striking NE, dipping at 60° to the NW. It shows mostly thrust and dextral structures and allowed the exhumation of the Pengguan crystalline massif upon the sedimentary foreland (Fig. 2).

Field observations indicate that mostly folds and thrusts with limited schistosity develop in the foothills of the range South-East of the Beichuan fault. S0 strike is parallel to the Beichuan and Guanxian faults, suggesting that the deformation of stratification and the faults may be contemporaneous. Sediments of Devonian to Triassic age with a Yangtze affinity crop out as a succession slices and an elongated segmented klippe (Worley and Wilson, 1996) resting tectonically on gently folded Triassic sediments (Fig. 2, Fig. 5a). Further east, the Sichuan basin units are dipping toward the basin and are overthrusted by the gently folded Triassic and Jurassic sediments. The poor development of the foreland belt in the Longmen Shan range is due to a duplex system which is well imaged by seismic profiles (Jia et al., 2006, 2010-this issue; Wenzheng et al., 2009). Seismic lines in the

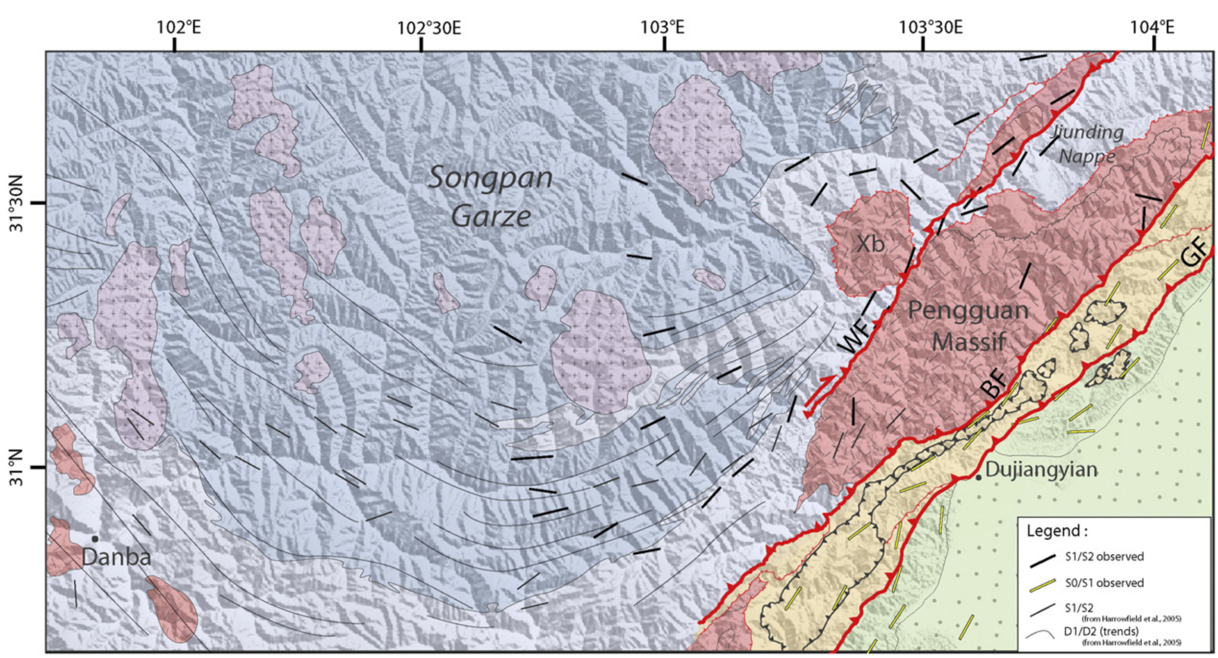

Fig. 3. Trends of selected structural elements (bedding as short segments in blue, major cleavage observed in black, cleavage from Harrowfield and Wilson, 2005 in gray). Continuous lines from Harrowfield and Wilson (2005), have been added to show the extension of the structures.

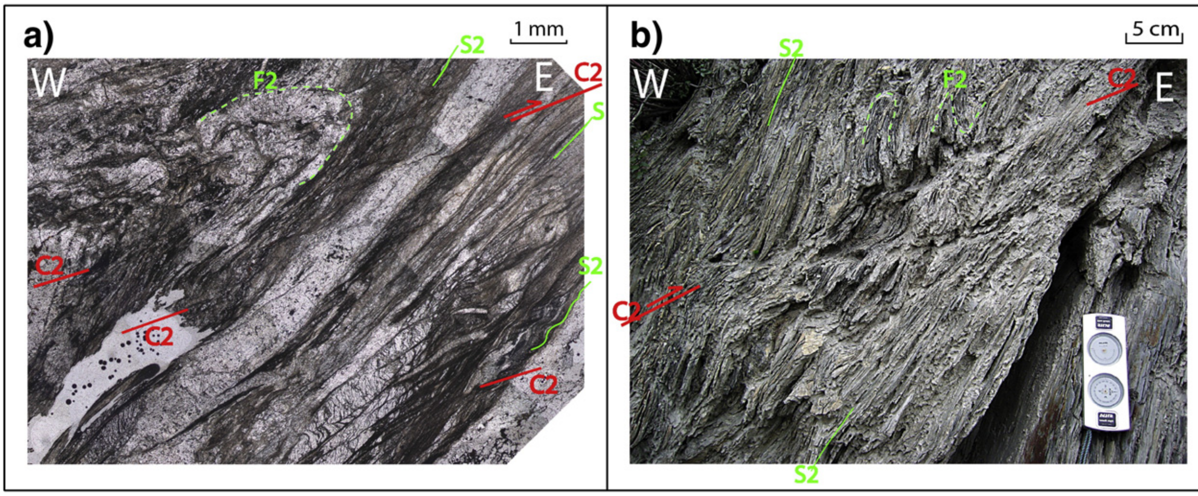

Fig. 4. Microscopic and macroscopic structures in Palaeozoic rocks sampled in the Wenchuan shear zone. a) Microscopic uncrossed polarized view of a thin section of an oriented Devonian black schist in the southern Wenchuan shear zone b) Macroscopic photograph of the outcrop showing thrusting with top to the East movement. The deformation at microscopic scale looks like the macroscopic deformation with top to the East sense of shear.

western part of the Sichuan basin generally indicate a decollement level within the Triassic shaly lithologies. Although no detailed geometry is imaged below the klippes and the frontal thrusts, an uplift of the decollement is required, resulting from the stacking of several sedimentary slices (Fig. 5). In the vicinity of the Beichuan fault, the deformation is more pronounced and tight duplexes are found. Near

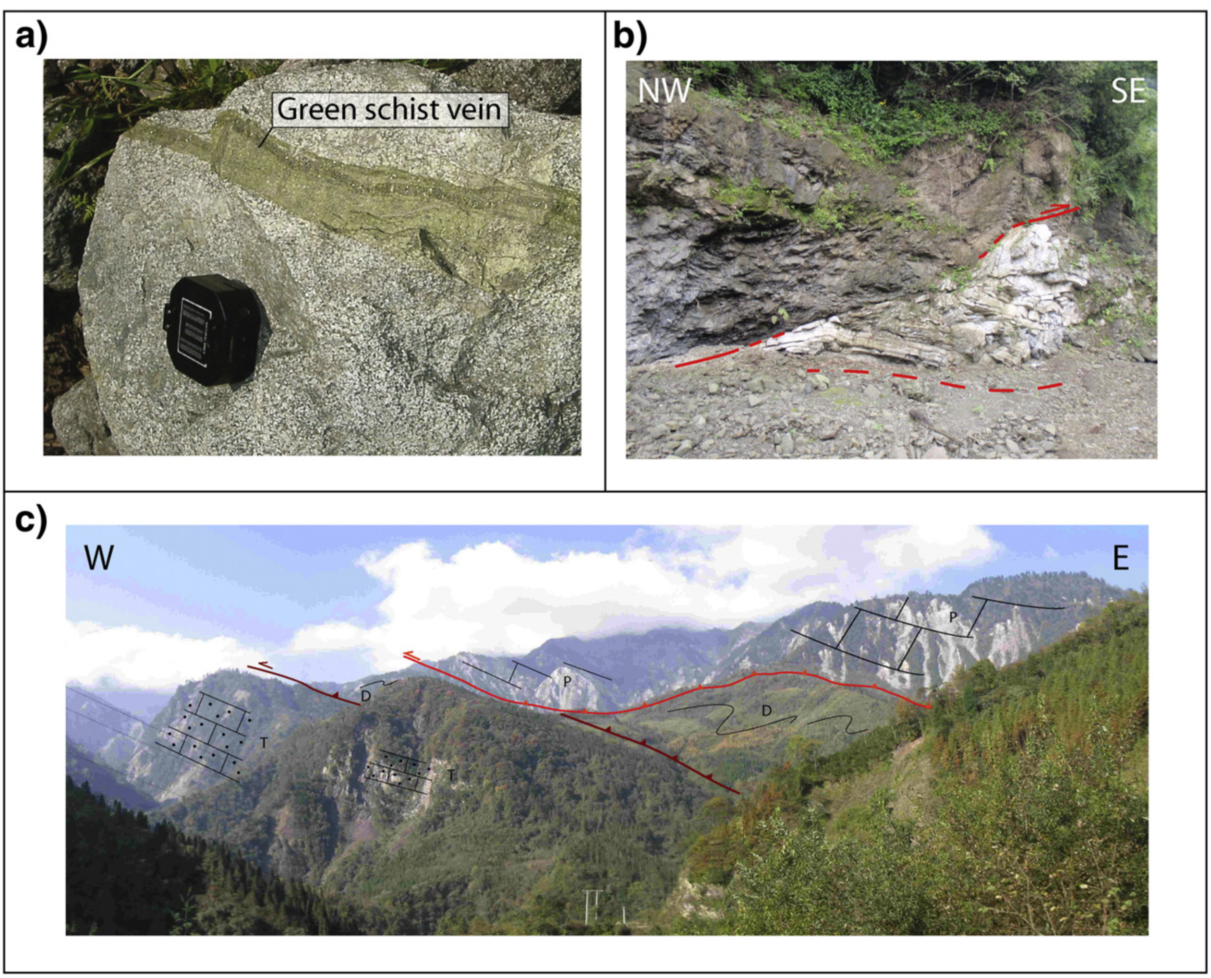

Fig. 5. a) Photograph of Pengguan crystalline rocks in the hangingwall of the Beichuan fault. The mostly underformed Proterozoic granite is crossed cut by veins full of greenschists minerals, chlorite, phengite, epidote, feldspars and calcite. b) Decametric boudin of Sinian limestones included in large shear with top to the SE movement. c) Panoramic view of a klippe (Permian and Devonian sediments) thrusted over Triassic sediments.

the contact with the Baoxing Massif, decametric boudins of Sinian limestone are included in large shears with top to the SE motion (Fig. 5).

4. Thermal structure

The main tectonic contacts are often associated with significant jumps of metamorphic *PT* conditions (Goffe and Chopin, 1986). We thus expect that the two contrasted crustal provinces recorded contrasted metamorphic conditions. Most of the published metamorphic studies were focused on the Danba area, were amphibolitic to migmatization facies conditions were described (Harrowfield and Wilson, 2005; Yong et al., 2006), with peak pressure of 8 kbar at 700 °C were reported (Huang et al., 2003a,b). Controversial Triassic, Cretaceous and Cenozoic ages were proposed for this barrovian metamorphism (Huang et al., 2003a,b; Wallis et al., 2003; Zhou et al., 2008; Itaya et al., 2009). Data are also available around the Xuelongbao massif close to the WSZ, where metamorphic conditions under amphobilitic facies are inferred (600 °C, 10 kbar) (Worley and Wilson, 1996).

To our knowledge, no detailed petrological study has been performed in the other parts of the belt. White micas and chlorite were recognized in the Palaeozoic cover of Pengguan massif in the Wenchuan shear zone along the Gengda cross-section (Chen and Wilson, 1995) then greenschist facies conditions where proposed for these rocks, contrasting with amphibolitic conditions recorded further north. However the lack of metamorphic mineral of higher grade is probably due to the bulk composition of the rocks, that are magnesian and calcic rich and aluminous poor, rather than to the pressure and temperature conditions of metamorphism. The petrological study is presently being carried out and we present hereafter preliminary results on Beichuan fault as well as thermal results.

Near Beichuan fault zone, the deformation in the footwall is marked by cataclastic Sinian limestones, while metamorphic veins filled with greenschists facies minerals (chlorites, white micas, epidotes, plagioclases and calcite) are observed in the hangingwall of Beichuan fault (Fig. 5). The pressure and temperature (*PT*) conditions of veins formation were estimated by de Sigoyer et al. (2008) using a multi-equilibrium calculations on white micas and chlorites in the vein. Pressures of about 9 to 10 kbar were estimated in the hangingwall of the Pengguan massif, associated with a low temperature of 350 °C. This first estimation has to be confirmed by further analyses along the Beichuan fault. Such metamorphic conditions suggest that the basement rocks uplifted from 25 km depth in cold context or associated with cold fluids. This *PT* estimation is compatible with a thrust movement along the Beichuan fault that allowed the exhumation of the Pengguan crystalline massif by thick-skin deformation onto the foothills.

4.1. Thermal data on the Longmen Shan and Songpan Garze from RSCM

As carbonaceous material is ubiquitous in most of the Longmen Shan and Songpan Garze we use in this study the geothermometer RSCM (Raman Spectroscopy of Carbonaceous Material) based on the evolution of the carbonaceous material structure. Because of irreversible character of graphitisation, the organic material is not sensitive to the retrograde conditions. This geothermometer provides estimates of peak temperature (±50 °C) in the range 250–650 °C (Beyssac et al., 2002; Lahfid, 2008).Following the commonly used analytical procedures, Raman spectra were obtained using a Renishaw InVia Reflex microspectrometer (Paris, ENS). We used a 514-nm Spectra Physics argon laser in circular polarization. 10 to 15 spectra were recorded for each sample and were then processed using the software Peakfit (Beyssac et al., 2003).

Finally, temperature peaks were determined on a large scale across the both provinces to reveal their thermal structure. 41 collected samples were analysed (Fig. 4 and Table 1).

Table 1
RSCM results with localization of the samples, age and short description of rocks (from the geological map) and obtained peaks of temperature.

Longitude	Latitude	Temp. (°C)	Description of the sample
101.985	31.348	599	Triassic flyschs
102.120	31.011	562	Triassic flyschs
102.300	31.850	515	Triassic flyschs
102.531	31.023	283	Triassic flyschs
102.556	31.013	291	Triassic flyschs
102.686	30.973	281	Triassic flyschs
102.706	31.860	504	Triassic flyschs
102.768	30.981	330	Triassic flyschs
102.894	30.911	312	Triassic flyschs
102.950	31.515	547	Triassic flyschs
102.966	30.881	349	Triassic flyschs
102.976	30.875	365	Triassic flyschs
103.000	30.900	413	Triassic flyschs
103.074	31.405	589	Triassic flyschs
103.164	31.016	490	Triassic flyschs
103.192	31.052	537	Silurian schists
103.209	31.058	550	Silurian schists
103.242	31.091	558	Triassic flyschs
103.259	31.123	582	Devonian black schists
103.267	31.123	564	Devonian black schists
103.291	30.768	368	Triassic sandstone
103.293	31.108	546	Silurian schists (not on the map)
103.293	31.108	560	Silurian schists (not on the map)
103.308	31.088	527	Silurian schists
103.323	31.561	534	Devonian black schists
103.388	30.799	424	Triassic sediments in the klippe
103.412	30.765	<250	Upper Triassic sediments
103.497	31.394	577	Silurian schists
103.469	31.032	354	Triassic sandstone
103.518	31.379	532	Silurian schists
103.530	31.024	331	Triassic mudstone
103.567	31.024	<250	Triassic sandstone with coal
103.581	31.488	552	Sedimentary cover of the Pgg massif
103.749	31.333	590	Calcareous interbedded in granodiorite
103.771	31.185	320	Jurassic sandstone
103.783	31.263	528	Sinian calcareous
103.818	31.764	572	Cambrian schist
103.850	31.131	370	Jurassic sandstone
103.852	31.719	574	Cambrian schist
103.963	31.429	396	Triassic sandstone
103.983	31.436	371	Triassic sandstone

The temperature map (Fig. 6) deduced from the RSCM analyses shows that the temperature peaks are not randomly distributed. The highest temperature zones are located on the margin of the Songpan Garze unit, close to Wenchuan and Danba area. In the absence of magmatic rocks associated with this high temperature conditions we propose that they reflect zones of major exhumation. These high temperatures are recorded in metasediments of Proterozoic to lower Triassic age, and may either be related to the Indosinian orogeny, or may be younger. Between Gengda and Danba across the Songpan Garze, weaker temperatures are probably associated with a shallower thrusted unit above the decollement. Further north in the middle part of the Songpan Garze flysch (Fig. 6), unexpected high temperatures were recorded within rocks devoid of any metamorphic minerals, temperature peaks reach 500 °C close to Markam and 590 °C close to Lixian (see location on Fig. 1).

The Pengguan unit (from the Beichuan fault to the Wenchuan fault zone) yield temperature peaks ranging between 530 and 590 °C suggesting important exhumation since the Triassic, whereas low temperatures <370 °C are recorded in the foothills of the Longmen Shan, in Paleozoic and Mesozoic sedimentary cover. The lower temperature peaks recorded in the foothills reflect a different metamorphic evolution for the foothills, as compared with those from the Songpan Garze unit.

The foothills sediments clearly belong to the para-autochtonous series of the Yangtze plate. Locally at the base of the klippes, higher temperatures of 400–425 °C were recorded (Fig. 5), suggesting that the klippes have tectonic origin (Meng et al., 2006) instead of gravity slide.

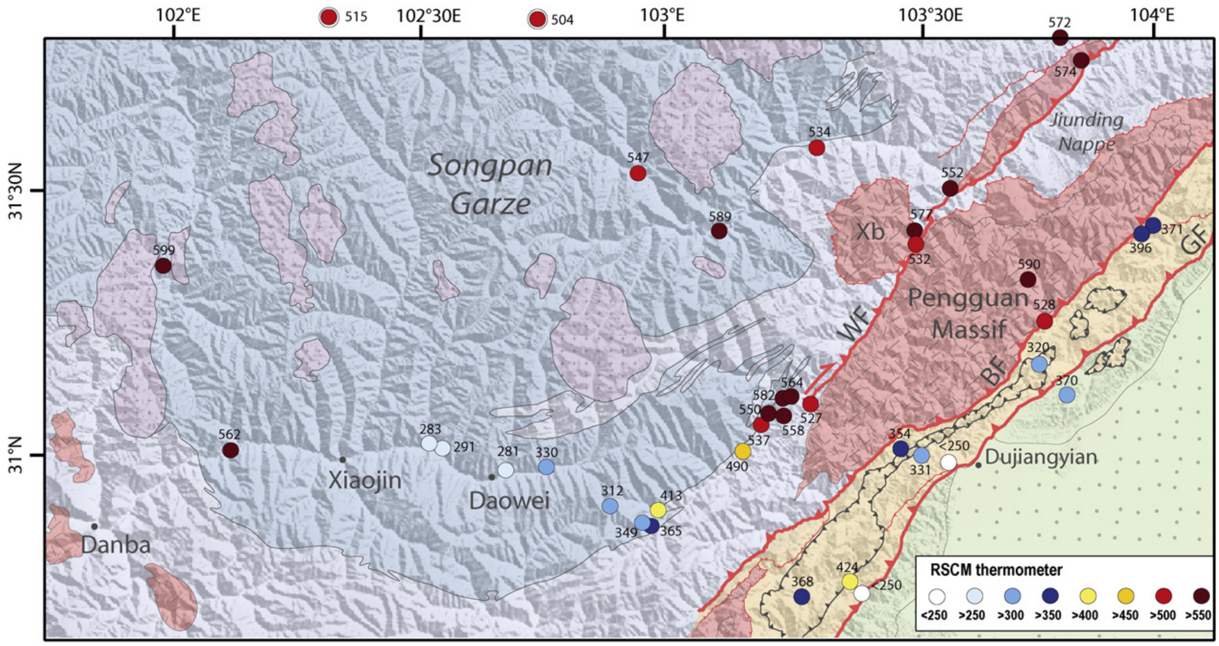

Fig. 6. SRTM and structural map of the Longmen Shan showing the peak temperatures recorded in the metasedimentary rocks by the graphitisation of carbonaceous materiel. Maximum temperature estimates are based on the RSCM thermometer (Raman Spectroscopy of Carbonaceous Material, Beyssac et al., 2002; Lahfid, 2008) between 250 and 650 °C. See Table 1 for precise locations of these data.

5. Discussion

The structure of this southern segment of the Longmen Shan results from a polyphase evolution which dates back from Triassic times and was built during two major stages of deformation with contrasting styles. One is marked by a prism tectonics and the other is thick-skin and therefore linked to the activity of deeply rooted faults that allowed the exhumation of metamorphic terranes and crystalline units. The timing of the events has been already attempted by Harrowfield and Wilson (2005), and is crucial since the variation of plate thicknesses probably condition the location and the style of deformation.

Early thickening of the sedimentary pile must have been associated with the constructing wedge during the Triassic, but cannot account for the thickening of the crust which is widespread over the Tibet Plateau during the Himalayan orogeny (Fielding et al., 1994; Arne et al., 1997; Kirby et al., 2002).

On the other hand, the Neogene reactivation under brittle conditions is evident in the foothills of the Longmen Shan and indicates shortening perpendicular to the range. Despite of this, the fold-and-thrust belt does not develop topography far into the foreland due to the existence of a blind decollement which uplifts the basin passively (Wenzheng et al., 2009; Jia et al., 2006, 2010-this issue). Indeed, reactivation as strike-slip occurs at places along the Beichuan Fault and is also well marked as flower structure post-dating the schistosity along the Wenchuan Fault south of Wolong. However, the large faults of Beichuan and Wenchuan appear to be deeply rooted (Hubbard and Shaw, 2009; Robert et al., 2010-this issue).

5.1. Geological record of the vertical motion

During the Triassic, the western Sichuan basin went from carbonate platform environment to a more unstable parallic and continental environment and, became a flexure loaded foredeep filled with several kilometres of nonmarine clastic rocks. These deposits demonstrate the existence of eroded emerged land at the margin of the Yangtze continent whereas to the north-west, continuous convergence was closing the limbs of the Paleotethys (Chen et al., 1994; Burchfiel et al., 1995; Yong et al., 2003).

The age of the exhumation of crystalline massif, or thick-skin is unclear. Chen and Wilson (1995) proposed that the Pengguan massif constituted a horst from the Late Palaeozoic which was slightly thrusted during the early Indosinian orogeny, therefore combining both thick and thin-skin tectonics at the same time. Later work emphasized the important exhumation of the Pengguan during Miocene time (Godard et al., 2009; Robert et al., 2010-this issue) and cross-cutting relationships suggest that the structure was rather acquired in at least two main stages; an Indosinian and an Himalayan stages. Results from fission tracks on zircons and apatites in the central part of the Longmen Shan suggest a strong exhumation of crystalline massif during the Miocene (11 Ma) (Arne et al., 1997; Kirby et al., 2002; Densmore et al., 2007; Godard et al., 2009). This Miocene re activation of older structures is crucial for the construction of the high relief of the Longmen Shan. It may be responsible for both the thickening of the Tibetan crust and allows thick-skinned deformation which propagated slowly south-eastward until now.

Sedimentary record also supports the two-phase evolution (Yong et al., 2003; Richardson et al., 2008).

Marines and then continental molasses have been deposited since the end of the Triassic in the foreland of the Longmen Shan. Relief did exist along this belt since the upper Triassic. However no metamorphic nor crystalline pebbles were observed in the molasses before the Eocene conglomerates, suggesting that the crystalline basement and metamorphic unit reached the surface only by Eocene times. This indirect information suggests that the Beichuan fault was already functioning as a thrust by Eocene time.

The subsidence history recorded in the Sichuan basin results directly from flexural loading, and suggests that two major tectonic events thickened the crust of the Longmen Shan (Jia et al., 2006). The first event during the Triassic is associated rapid thickening of the upper Triassic sediments in the foredeep (Wilson et al., 1994; Burchfiel et al., 1995; Yong et al., 2003; Jia et al., 2006). The second event has been attributed to uppermost Cretaceous–Paleogene (Jia et al., 2006) but its importance is difficult to estimate. Certainly, clastic sedimentation continued throughout the Mesozoic. Chen et al. (1994) propose that the ongoing convergence between the Indian and the Eurasian plates has resulted in reactivation of thrusting along specific faults in the Longmen Shan and folding in the foreland basin sediments. The major unconformities are within Paleogene and Neogene sediments and between Neogene formation and Quaternary (Tong, 1992).

5.2. Record of thermal history

The region covered by this study includes part of the Songpan tectonic zone, whose basement is not known in most areas, but is composed near Danba of migmatitic rocks with crust and relicts of ophiolite. It has been affected by metamorphic conditions during the Indosinian orogeny prior to suffer thickening in the Tertiary. This region which extends until the Wenchuan fault zone has a penetrative shistosity above a decollement level and reached relatively high temperatures. Long-term cooling histories have been obtained by various authors (Roger et al., 1995; Kirby et al., 2002; Huang et al., 2003b; Xiao et al., 2007; Itaya et al., 2009) on Mesozoic granites and on the metamorphic series near Danba. Data are still controversial, but show an early (Indosinian) metamorphic event, and a Cenozoic recrystallisation could be a possible interpretation of Cenozoic ages.

Early thickening of the sedimentary pile must have taken place as everywhere in the Songpan terrane during Triassic times and is recorded in the temperatures but cannot account for the thickening of the crust which is widespread over the Tibet Plateau during the Himalayan orogeny.

Above the edge of the Yangtze plate, in the Longmen Shan sensu stricto, structural and metamorphic data show that the Beichuan fault is related to thick-skinned deformation, as demonstrated by the recent May 2008 earthquake. The fold-and-thrust deformation is also observed on the frontal part of the belt, east of the Beichuan fault in the foothills (Hubbard and Shaw, 2009). The metamorphic *PT* path obtained on the hangingwall of Beichuan fault is compatible with thrust movement of the Beichuan fault that allows the exhumation of Pengguan massif from 25 km depth up to the surface. However, the large faults of Beichuan and Wenchuan appear to be deeply rooted (Hubbard and Shaw, 2009; Robert et al., 2010-this issue).

6. Conclusion

The thickness of the Songpan plate has therefore varied through times, relative to that of the Yangtze craton which, as a stable cratonic unit did not change. It was primarily a margin of the Paleotethys underlain by oceanic crust and thinned continental crust. Subduction of the Paleotethys led to a tremendous accumulation of sediments coming from the emerged margins and tectonic thickening in opposite verging accretionary wedges (Fig. 7). A present analog of this tectonic environment may be the present-day Molucca sea (Moore and Silver, 1987). The boundary between the plates was controlled mostly by wrenching (Harrowfield and Wilson, 2005) and topography already existed in the area since it shed clastics into the Sichuan Basin. However, it is principally during the Tertiary that crustal thickening occurred in the Tibet independently to the situation of the Longmen Shan. Thickening is illustrated by a steep Moho jump between a 45 km thick Yangtze continental crust and a 63 km thick Tibet-like crust (Robert et al., 2010-this issue). Together, the slow E–W component of the convergence and the difference in crustal thickness caused the Yangtze crust to indent the Tibetan crust which was softened by the high thermal regime. As a response the edge of the Tibet crust was inflated to the bottom (up to 70 km), whereas to the top, the crystalline massif were exhumed. This configuration reflects a moderate shortening of the crust which behaves as a soft thick material abutting the resistant and cold Yangtze crust (Fig. 7).

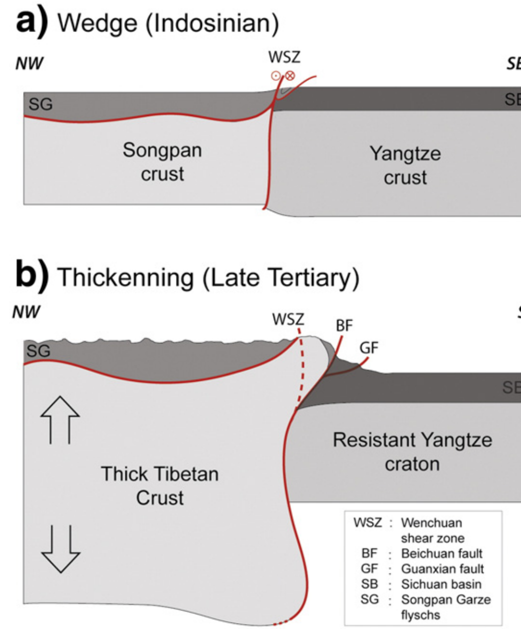

Fig. 7. Schematic scenario envisaged for the Longmen Shan along the geophysical profile. *Top*: During the early Indosinian event, the crust located west of the present Longmen Shan belonged to the margin of the Paleotethys and composed of a poorly known oceanic or thinned continental crust, and was adjacent to the continental crust of the Yangze block. A detachment that separated the sedimentary units involved in a subduction wedge created sedimentary thickening and shortening (very oblique to the section). *Bottom*: Crustal thickening during the Neogene as a result from the India/Eurasia convergence overthrew material from the soft Tibetan crust and its upper part composed of the crystalline massifs onto the Yangtze block.

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