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The Mesozoic along-strike tectono-metamorphic segmentation of Longmen Shan (eastern Tibetan plateau)

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Key Points:
- Metamorphic jumps of ~150°C, 5 kbar and ~50°C, 3 kbar are observed across the Wenchuan and Beichuan faults respectively.
- P-T-t conditions for the southern Longmen Shan –lower than for central Longmen Shan- do not exceed 395°C and 6 ± 2 kbar (at 80-33 Ma).
- Different segments of the Longmen Shan underwent different tectono-metamorphic evolution since the Mesozoic.
Abstract

The Longmen Shan belt (eastern border of the Tibetan plateau) constitutes a tectonically active region as demonstrated by the occurrence of the unexpected 2008 Mw 7.9 Wenchuan and 2013 Mw 6.6 Lushan earthquakes in the central and southern parts of the belt respectively. These events revealed the necessity of a better understanding of the long-term geological evolution of the belt and its effect on the present dynamics and crustal structure. New structural and thermobarometric data offer a comprehensive dataset of the paleo-temperatures across the belt and P-T estimates for low-grade metamorphic domains. In the central Longmen Shan, two metamorphic jumps of 150-200°C, 5-6 kbar and ~50°C, 3-5 kbar acquired during the Early Mesozoic are observed across the Wenchuan and Beichuan faults respectively, attesting to their thrusting movement and unrevealing a major decollement between the allochtonous Songpan-Garze metasedimentary cover (at T > 500°C) and the autochtonous units and the basement (T < 400°C). In the southern Longmen Shan, the only greenschist-facies metamorphism is observed both in the basement (360 ± 30°C, 6 ± 2 kbar) and in the metasedimentary cover (350 ± 30°C, 3 ± 1 kbar). Peak conditions were reached at c. 80-60 Ma in the basement and c. 55-33 Ma in the cover, c. 50 Ma after the greenschist-facies metamorphic overprint observed in the central Longmen Shan (c. 150-120 Ma). This along-strike metamorphic segmentation coincides well with the present fault segmentation and reveals that the central and southern Longmen Shan experienced different tectono-metamorphic histories since the Mesozoic.
1 Introduction

The Longmen Shan (LMS) thrust belt constitutes the eastern border of the Tibetan plateau (Fig. 1a,b), a tectonically active region as demonstrated by the occurrence of the Mw 7.9 Wenchuan (2008) and Mw 6.6 Lushan (2013) earthquakes in the central and southern parts of the belt respectively. The belt sits between the Sichuan basin to the east, which lies on the South China craton (e.g. Jiang et al., 2005; Huang et al., 2014) and the Songpan-Garze (SPG) block to the west and is structured along different NE-SW oriented, northwest dipping fault zones. In the central Longmen Shan, the three major faults classically identified are (from the west to the east): the Wenchuan fault (WF) that lies in the Wenchuan Shear zone (WSZ), the Beichuan and the Guanxian faults (BF and GF; Fig. 1 and 2). The Wenchuan and Beichuan faults are thought to be inherited from the Paleozoic, when the South China block represented a passive margin (Burchfiel et al., 1995; Chen et al., 1995; Roger et al., 2010) structured in tilted blocks (Jia et al., 2006). In the southern Longmen Shan, the Wulong and the Xiaoguanzi faults are often considered as the southern prolongation of the Wenchuan and Beichuan faults respectively (e.g. Cook et al., 2013; Tian et al., 2016), while the Shuangshi fault has been proposed to be the continuity of the Guanxian fault (Lichun et al., 2014; Fig. 1b-d).

The Wenchuan fault separates the Songpan Garze units from the Longmen Shan sensu stricto. Seismic investigations show that the SPG crust west of the WF is over thickened (> 60 km, Fig. 1d) compared to the South China crust (~40 km, Zhang et al., 2009; Robert et al., 2010a; Zhang et al., 2010). The timing and modality of the crustal thickening however still remain debated. Low-temperature thermochronology data obtained on the Pengguan, Baoxing, Xuelongbao and Tonghua crystalline massifs (slices of the South China basement) document a phase of exhumation of the belt since c. 30 Ma (Kirby et al., 2002; Godard et al., 2009; Wang et al., 2012; Tan et al., 2017). The shortening accommodated since the Oligocene has been estimated at ~35 km at the front of the Longmen Shan (Hubbard et al., 2009: Hubbard et al., 2010). Although this value is likely to be a minimal estimate due to the propagation of blind thrusts into the Sichuan basin and to the oblique component of the Beichuan fault imaged after the Wenchuan earthquake (e.g. de Michele et al., 2010b), it cannot explain the total crustal thickness observed in the SPG (e.g. Robert et al., 2010b).
An increasing number of studies propose that part of the crustal thickness of the Songpan-Garze terrane and of the central and southern Tibetan plateau is acquired during the Mesozoic (e.g. Kapp et al., 2003; Kapp et al., 2007; de Sigoyer et al., 2014; Xue et al., 2017; Airaghi et al., 2017a; Airaghi et al., 2017b; Billerot et al., 2017). Metamorphic and structural studies carried out in the Danba area (~ 200 km west of the LMS) and in the central Longmen Shan (Dirks et al., 1994; Worley & Wilson, 1996; Harrowfield & Wilson, 2005; Weller et al., 2013, Billerot et al., 2017; Airaghi et al., 2017a) as well as 40Ar/39Ar ages on clay mineral in pseudotachylites of the Beichuan fault (Zheng et al., 2016) suggest a compressive phase of deformation during the Late Triassic-Early Jurassic, driven by the closure of the Paleotethys. Recent petro-chronological studies have also documented a metamorphic and deformation event in the central Longmen Shan at the Early Cretaceous (Airaghi et al., 2017b; Airaghi et al., 2018). These studies are however still sparse and often restricted to the higher metamorphic units of the belt, limiting our understanding of the Mesozoic thermal and structural evolution of the Longmen Shan. Furthermore, substantial differences exist between the central and southern part of the belt. Structural and geochronological data show that the southern Longmen Shan experienced thickening and deformation during the Late Cretaceous-Early Paleogene (Tian et al., 2016). The southern area exhibits higher mean elevation, lower relief and lower channel steepness than the central LMS (Zhang et al., 2011). In the southern LMS the deformation propagated into the Sichuan basin and the southern Sichuan basin was the only locus of deposition along the belt during the Cenozoic (Burchfiel et al., 1995; Densmore et al., 2007). Differences between the southern and central LMS are also observed in the present tectonics. The 2008 Mw 7.9 Wenchuan earthquake epicenter was located on the Beichuan fault, which was re-activated with a thrusting and dextral strike-slip movements (e.g. Xu et al., 2009; de Michele et al., 2010b). The 2013 Mw 6.6 Lushan earthquake ruptured instead the Range Front Blind Thrust (RFBT), below the Shuangshi fault, with a pure thrusting movement (e.g. Liu et al., 2013), leaving in the middle an unbroken segment 50 km wide and put into question the connection between faults of the central and southern Longmen Shan.

Major questions therefore remain unresolved: (1) Did the southern and central Longmen Shan experience the same long-term geological evolution? (2) What does this imply in terms of long-term functioning of the major inherited faults?
This study uses a tectono-petrochronological approach to investigate if the long-term structuration of the Longmen Shan may help to understand the present tectonics. We present new field observations and structural data for both the central and southern Longmen Shan, a comprehensive dataset of the paleo-temperatures across the belt and the first barometric estimates for the low-grade metasedimentary rocks in the external domain of the central Longmen Shan (east of the Wenchuan fault) and in the southern Longmen Shan. This will allow us to (1) estimate the total exhumation cumulated during multiple deformation phases across the major faults, (2) discuss the link between the fault systems of the central and southern Longmen Shan at the long-term scale and (3) unravel an asymmetry in the geological evolution of the belt since the Mesozoic. The features recognized for the Longmen Shan may be characteristic of the evolution of other intracontinental thrust belts.

2 Geological setting and studied areas

In the central and southern Longmen Shan, the Neoproterozoic South China basement crops out through the sedimentary cover in the Xuelongbao, Tonghua, Pengguan and Baoxing massifs (Zhou et al., 2006; Yan et al., 2008; Meng et al., 2015; Fig. 1a-c and Fig. 2). Close to the Beichuan fault and within the Wenchuan shear zone, the crystalline massifs are affected by a brittle-ductile deformation underlined by multiples cm to m-scale greenschist-facies metamorphic shear zones and veins of few mm to few cm. Metamorphic overprint occurred at 280 ± 30 °C, 7 ±1 kbar (Pengguan massif) and 370 ± 35°C, 7 ±1 kbar (Tonghua massif) at c. 140-137 Ma (Airaghi et al., 2017b; Airaghi et al., 2018). Close to the Wulong fault the northern slice of the Baoxing massif (Fig. 2b) is also strongly deformed (up to mylonitisation; this study and Tian et al., 2016).

Stratigraphic and structural relations within the Paleozoic-Mesozoic metasedimentary cover allow three distinct sedimentary provinces to be recognized. They include:

1. **Allochthonous** units constituted by a thick (up 15 km prior to deformation; Calassou, 1994) series of strongly deformed and metamorphosed Paleozoic-Lower Triassic pelitic-dominated sediments deposited in the Songpan-Garze domain (Chen et al., 1995; Burchfiel et al., 1995;
Yan et al., 2011; Robert et al., 2010b). About 40 km northwest of the WF the sediments are intruded by different generations of syn to post deformation granites emplaced between 224 and 188 Ma (Roger et al., 2010; de Sigoyer et al., 2014), at a depth of 7-11 km (Dirks et al., 1994; Deschamps et al., 2018). The metasedimentary cover of the Tonghua and Xuelongbao massifs underwent an amphibolite-facies metamorphism at 9-12 kbar, 530-580°C (c. 220-180 Ma) underlined by Grt + Bt + Wm ± St (abbreviations are from Whitney & Evans, 2010 except Wm = white mica) and followed by a greenschist-facies overprint at 2-5 kbar, 350-400°C at c. 140 (Dirks et al. 1994; Worley & Wilson, 1996, Airaghi et al., 2017a, Airaghi et al. 2018);

2. para-autochthonous units of SPG origin mainly cropping out southeast of the Wenchuan fault and northwest of the NW dipping West Slope Fault (WSF in Fig. 1b and c), in the Jiuding Shan Nappe (Chen et al., 1995, Wang et al., 2014). These units are also highly deformed and include a series of marbles, carbonates and metapelites deposed on the South China margin in a more proximal environment compared to the allochthonous units (Burchfiel et al., 1995; Li et al., 2014). At the southern end of the Pengguan massif and in the foreland system para-autochthonous Devonian to Triassic units crop out as a system of klippen (Chen et al., 1995; Robert et al., 2010b; Zheng et al., 2014);

3. autochthonous units (~ 5 km thick prior to deformation) are characterized by a carbonated-dominated stratigraphy suggestive of a platform depositional environment (e.g. Li et al., 2003). They crop out at the front of the belt with a typical structure of a fold and thrust belt and triangle zones (Jia et al., 2006; Robert, 2011). In the footwall of the Beichuan fault no metamorphism is observed.

For the sake of clarity, three domains will be distinguished in the following: (1) the internal units including the terrains west of the Wenchuan fault in the central LMS, (2) the external units including the terrains east of the Wenchuan fault (the Pengguan massifs and its sedimentary cover) and (3) the units of the southern Longmen Shan (Baoxing massif and its metasedimentary cover). In the central Longmen Shan, a series of structural measurements, observations and samples were collected along
four transects perpendicular to the major structures (*North Tonghua transect*, samples labeled NT in Fig. 2a; *Shapai transect*, samples labeled XB or CH in Fig. 2c; *South Tonghua transect*, samples labeled W in Fig. 2c; *Sanjiang transect*, samples labeled SA Fig. 2d). A fifth transect in the *southern Longmen Shan* (samples labeled BA in Fig. 2b) that includes both the basement (northern slice of the Baoxing massif) and its metasedimentary cover were also studied. Samples collected along transects were supplemented by isolated samples collected in the Jiuding Nappe, in the Sinian sediments roofing the northern Pengguan crystalline massif, in the immediate footwall of the Wenchuan fault and in the foreland belt (samples labeled LM, Fig. 1b and 2a).

3 Field structures

3.1 The central Longmen Shan

3.1.1 Internal Units

In a regional framework the intensity of the deformation of the Paleozoic metasedimentary series in the internal units increases from the SPG terrain eastward, approaching the WSZ, where the base of the SPG sedimentary pile is exhumed, and is particularly relevant close to the contact with the crystalline massifs around which structures are deflected (Fig. 3). In all metasedimentary units, macrostructures related to three phases of ductile deformation (D1, D2, D3) and a late brittle-ductile deformation phase (D4) were observed, with different degrees of preservation that varies locally. In the crystalline basement, the D3 and D4 were mainly observed.

The first (D1) is particularly preserved in the North Tonghua transect. It is characterized by a pervasive sub-vertical slate cleavage (S1) striking from N30-N55 in the northernmost areas to N10-N40 north of the Sanjiang area (Fig. 3 and 4a,c).

S1 is mildly crenulated during a second deformation phase D2 according to steeply plunging upright to inclined F2 fold axes striking N60-N75 (Fig. 3). F2 folds are similar, tight to isoclinal and show in general symmetrical limbs (Fig. 4d, e). The main S2 cleavage develops parallel to the F2 axial planes (Fig. 3 and 4a, b and c). The S2 is deflected around the Xuelongbao massif (Fig. 3). At a large scale, D2 is responsible for the folding of the internal meta-sedimentary units along the Tonghua transect in a NE-SW oriented and SE-verging anticline and of the Silurian metasedimentary
rocks along the Shapai transect in a system of tight double verging anticlines and synclines due to the deflection of the structures around the Xuelongbao massif (Fig. 2c and 3). Here subparallel E-verging thrusts (N20-30 W40-80, top-to-E shearing) slice the Devonian-Carboniferous units (Fig. 3 and 4g).

The third ductile deformation phase D3 is responsible for the folding of the S2 and F2, according to F3 folds axes (F3 in Fig. 3 and 4a, c and d). This results in undulated F2 fold hinges or in twisted F2 folds. Folds tighten approaching the crystalline massifs. F3 are generally asymmetric, opened folds and develop with sub-horizontal axes striking at low angle with the north (Fig. 3 and 4f). D3 led to a co-planar and oblique reactivation of the S2 cleavage resulting in C3/S2-S3 composite structures (Fig. 4h). C/S structures indicate a top-to-SE sense of shear. Quartz veins associated with D2 are deformed by F3 resulting in quartz boudins (yellow in Fig. 4d). D3 is particularly well expressed in the Xuelongbao transect and north of the Sanjiang area. The contact between the Xuelongbao massif and the Silurian sediments is tectonic as attested by the pervasive deformation affecting the limit between the two lithologies (with C/S structures showing a top-to-E movement).

The different populations of striae recorded at the surfaces of single fault planes in the metasedimentary rocks indicate that the majority of the faults experienced an early thrusting movement followed by one or more re-activations as normal or strike slip faults related to the brittle deformation D4. The preserved thrust faults are generally N50-N70 (except along the Shapai transect where they are N20-N28), dipping 40-75W and show a top to southeast sense of shear (line 80-84NE). In the Devonian units east of the WF (outcrop lm142, Fig. 2a) thrust faults were re-activated firstly as normal faults (line 56SW) and then with a dextral strike-slip movement as indicated by sub-horizontal striae (9SW). In the Silurian metasedimentary rocks along the Tonghua transect (outcrop to13-4, Fig. 2a), thrust faults were instead firstly re-activated with a dextral strike-slip movement then with a normal movement. Dextral strike-slip faults are subvertical and oriented N50-62 (line 4E). Normal faults oriented N70, dipping 70-80W are locally observed north of the Pengguan massif and no large normal detachments were identified.
3.1.2 External Units

Three phases of ductile deformation were also observed in the external sedimentary units of the Longmen Shan. They are confined to the Silurian to Devonian para-autochthonous sediments of the Jiuding Shan Nappe. In this area the main cleavage is the S2 oriented N35, NW dipping and associated with F2 folds. F2 are folded by later F3 folds (Fig. 3). In the para-autochtonous units of the Sanjiang sector, Silurian sediments are folded by F2 and F3 faults and exhibit C3-S3 structures. C planes are flatter than S, strike in average at N161 27SE and are associated with NNW SSE trending folds (Fig. 3).

In the autochthonous units east of the West Slope Fault, the deformation is less intense and only one cleavage oriented N30 to N95 affects the original stratigraphy (S0) and is related to large folds. In the autochthonous units of the Sanjiang sector, east of the Beichuan fault, only one ductile deformation phase is superimposed to the stratigraphy S0.

3.2 The southern Longmen Shan

In the southern Longmen Shan, the Neoproterozoic crystalline basement crops out in two slices in the hanging walls of the Wulong and Xiaoguanzi faults (as in the internal and external domains of the central Longmen Shan). In the hanging wall of the Xiaoguanzi fault, the basement is weakly deformed. Metamorphic veins, a few mm to cm thick (filled with greenschist-facies mineral assemblages) locally cross cut the magmatic foliation. The strongest deformation is observed in the immediate hanging wall of the Wulong fault, where the basement is folded in a large-scale antiform and exhibits mylonitic and schistose zones (Fig. 2b and 5a) alternating with undeformed zones. Within the most deformed rocks, C-S structures showing a top-to-E sense of shear are observed (C N22 W30, S N25 W66, stretching lineation of N98; Fig. 2b and Fig. 5a). Late W-dipping semi-brittle normal faults (oriented N10 SW65) showing a top-to-the-W movement cross cut the earlier deformation (Fig. 5a). The ductile deformation within the basement underlined by pervasive schistosity is associated with metamorphic minerals typical of the greenschist-facies conditions, including white mica, chlorite and epidote.
The metasedimentary cover of Paleozoic marbles, limestone, calc-schists, sandstones and Triassic flysch is very deformed west of the Wulong fault (in a structural position equivalent to the internal domain of the central Longmen Shan), forming a system of NE-SW oriented and SE-verging folds (axes N18 to N56, S1-S2 N69-N41; Fig. 2b). The main cleavage particularly tight in the Silurian units is west dipping, subparallel to the bedding (Fig. 5b). Along the SE-NW directed transect crossing the Ordovician to Triassic sedimentary series (Fig. 2b), C-S structures indicate a top-to-E sense of shear (Fig. 5e) and are defined by greenschist-facies metamorphic minerals including white mica and chlorite developing in metamorphic veins or pervasively in larger volumes of rock. Three kilometers west of the Wulong fault (hanging wall), gauge zones made by metric blocs within a thin matrix are observed in the Proterozoic metasedimentary rocks (ba14-14 in Fig.2b). Here rocks are deformed (ba14-17) with the stretching lineation strongly dominant over the schistosity (S N65 66NW, pitch of L 78NW, Fig. 5c).

In the immediate footwall of the Wulong fault (ba14-13 in Fig. 2b), Silurian rocks are folded to form kink bands, (Fig. 5d), suggesting a brittle-ductile deformation. Eastward-plunging structures were locally observed; they were interpreted as the result of the tilting of original structures during the Cenozoic re-activation of the belt. No medium-grade metamorphic minerals were observed in the southern Longmen Shan as it was the case in the central part of the belt.

4 Sampling and sample description

Fifty-seven samples were collected for this study. Their elevation ranges between 1585 and 1710 m (North Tonghua), between 1460 and 1545 m (South Tonghua), between 2047 and 1850 m (Shapai), between 1720 and 1810 m (Sanjiang) and between 1100 and 1300 in the southern Longmen Shan (Baoxing area).

Among collected samples, 49 were organic-rich schists and carbonates suitable for the Raman Spectroscopy on Carbonaceous Material (RSCM) thermometry (Table S1). The mineralogy of
4.1 Central Longmen Shan

4.1.1 Internal Units (Shapai transect)

Samples from the Shapai transect collected for thermometric purposes (see Fig. 2c) exhibit three types of ductile microstructures related to three ductile deformation phases (D1, D2, D3). An early cleavage S1 (D1) is preserved in the inclusion trails of Grt, Bt, and St porphyroblasts (Fig. 6a, b). S1 is folded by a white-mica bearing crenulation cleavage S2 (D2) (Fig. 6a, b, and c). Euhedral porphyroblasts of Bt (± Grt, ± St) 500 µm-3 mm in size are rotated and wrapped in the S2 cleavage (Fig. 6a and b) and exhibit crenulated surfaces (Fig. 6b). Staurolite is only observed in samples collected in a narrow zone along the Shapai transect as 500 µm up to 3 cm porphyroblasts with X-shaped twins (Fig. 6b). No kyanite was observed. Biotite and ilmenite developed in pressure shadows around staurolite. Samples close to the Xuelongbao massif (e.g. ch09-241 and ch09-244) exhibit a tight folded cleavage made of elongated crystals of white mica and quartz microlithons (Fig. 6c) and no high-grade metamorphic minerals. White mica is folded at both the micrometric and the cm-scale along with Qz veins, while in the less deformed domains relics of biotite are preserved. Chlorite appears as crenulated flakes 200-500 µm large (Fig. 6c).

Approaching the Wenchuan Shear Zone, only greenschist-facies metamorphic assemblages are observed. In the strongly deformed sample lm223 (Long. 103.6049, Lat. 31.3885), collected within the Wenchuan Shear zone, eye-shaped nodules composed of Qz, brown to yellow Ep 200-300 µm in length, and Chl replacing Grt are wrapped in the main cleavage. (Fig. 6d).

4.1.2 External Units

In rocks of the external domain of the Longmen Shan, the only metamorphic assemblage characteristic of the greenschist facies conditions was observed made of Qz + K-Wm + Chl + Ep + Fs
+ oxides. In the para-autochthonous units of the Jiuding Shan Nappe (e.g. organic-rich schist lm09-59, Long. 103.7448, Lat. 31.5734), the S1 cleavage is sub-parallel to S0 (white layer in Fig. 6e) and crosscut by discrete S2 crenulation cleavage domains, folded at its turn. Oxides constitute aggregates with irregular borders, oriented in the main foliation, while the organic-rich material is localized in the microfolds hinges or in lenticular layers (e.g. Fig. 6e).

In the Devonian para-autochtonous sedimentary units of the Sanjiang sector (e.g. sample sa14-2) only one crenulation cleavage is observed superimposed to the S0. The main cleavage is underlined by elongated grains of 50-100 µm of white mica, organic-rich material and quartz grains affected by bulging recrystallization. This cleavage wraps nodules of rounded quartz grains (of 50-100 µm) which define eye-shaped structures sheared with a top-to-ESE sense of shear (Fig. 6f). No chlorite was observed in this sample.

In the Sinian sediments roofing the Pengguan massif (samples lm230 and lm09-37), rocks are the less deformed, metamorphosed under greenschist-facies conditions with chlorite developing along the main cleavage and in fractures of few µm in size in association with epidote and white mica (Fig. 6g). In sample lm09-37 Chl + Wm intergrowths develop in large (500-800 µm) flakes among Qz, Fs (± Ap; Fig. 6h).

4.2 The southern Longmen Shan

Among samples collected in the southern Longmen Shan for thermos-barometric purposes, ba14-15 and ba15-12 belong to the crystalline basement. Sample ba14-15 is a deformed metagranite where the magmatic assemblage of Fs + Pl + Qz + Bt is overprinted by secondary white mica stretched in zones of high strain (Fig. 7a). Feldspar is partly sericitized and quartz recrystallizes by bulging. The metagranite ba15-12 is mylonitic, with assemblage of Wm + Fs (K-fs and Ab) + Qz ± Pl ± Bt ± Ap. Two samples were collected from this outcrop. One (ba15-12c) exhibits C-S structures; the foliation (S) is defined by elongated chlorite and tiny white mica-rich layers, while shear planes (C) are defined by epidote (Fig. 7b). Feldspar is sericitized and locally defines eyes wrapped in the foliation. Feldspar and plagioclase show intracrystalline deformation features, including deformation twins, patchy
ondulose extinction and subgrains with weakly defined boundaries. Large quartz grains exhibit an
ondulose extinction, subgrains parallel to microcracks and irregular grain boundaries due to grain
boundary migration (Fig. 7c). Around larger grains, small grains form by bulging. The other sample
of the same outcrop, ba15-12d, shows a pervasive foliation made of sub-mm quartz grains and white
mica layers wrapping the weakly sericitized and deformed feldspar eye-shaped grains and defining a
top-to-E shearing (Fig. 7d). Quartz re-crystallizes by sub-grain rotation in the matrix and by bulging
around feldspar.

Among samples collected in the metasedimentary cover, ba15-1f represents a typical
organic material-rich sample, with an early S0-S1 cleavage deformed by a later S2 (Fig. 7e). Sample
ba15-10 is a deformed black schist with pelitic layers hosting greenschist-facies mineral assemblages.
A pervasive foliation (S0-S1) is cross cut by quartz veins rimmed by Chl + Wm + Qz (Fig. 7f). Larger
quartz grains exhibit folded inclusions trails and subgrains. Quartz recrystallized into smaller grains
by bulging and subgrain rotation. Sample ba14-14 is a Ca-rich metagraywacke with allochtonous
gains of quartz and calcite wrapped in the main foliation formed by white mica layers and
polycrystalline aggregates of quartz developed by subgrain rotation recrystallization (Fig. 7g).
Microstructures show a to top-to-E shearing (Fig. 7g). The top-to-the-E shearing is therefore
associated with greenschist-facies conditions.

5 Analytical and computational methods

The chemical compositions of the metamorphic minerals (chlorite and white mica) was analyzed to
retrieve P-T conditions of the greenschist-facies metamorphism in the external units of the central
Longmen Shan and in the southern Longmen Shan. The chemical composition of metamorphic
minerals related to the amphibolite-facies metamorphism has been described in detail elsewhere
(Dirks et al., 1994; Worley & Wilson, 1996; Airaghi et al., 2017a) and is beyond the scope of this
study.

Analyses of chlorite and white mica in samples lm230, lm09-37, sa14-2 (central LMS) and
ba14-14, ba15-12 and ba15-10 (southern LMS) were acquired with a JEOL JXA-8230 electron probe
micro-analyzer (EPMA) at Institut des Science de la Terre (ISTerre, Grenoble). Accelerating voltage was fixed at 15 keV with beam current of 12 nA and beam size of 1 µm. X-ray maps in samples ba15-12d were acquired at 15 keV, 100 nA, with a dwell time of 200 ms. Maps were quantified using the program XMapTools 2.3.1 (Lanari et al., 2014a).

Raman Spectroscopy on Carbonaceous Material (RSCM) thermometer (Beyssac et al., 2002) was used to estimate the maximum temperature ($T_{\text{max}}$) experienced by the organic material-rich samples in order to provide an image of the paleo-temperature at the scale of the belt. Ten to fifteen spectra were acquired per sample using a Renishaw InVia Reflex microspectrometer (Paris, ENS) with a 514-nm Spectra Physics diode laser in circular polarization and processed them with the software Peakfit.

RSCM was combined with the multi-equilibrium thermobarometry based on the thermodynamic properties and solid solutions models of Vidal et al. (2005, 2006) and Dubacq et al. (2010) to model the P-T conditions of the high variance assemblages involving Chl + Wm + Qz + H$_2$O in the samples lm230, lm09-37, sa14-14, ba15-12 and ba14-14, following the procedure described by Airaghi et al. (2017b) and Lanari et al. (2012). Metamorphic conditions were estimated from the intersection between the P-T equilibrium curves calculated for white mica and (1) the $T$ calculated for Chl in textural equilibrium (lm09-37 and lm230), or (2) the $T$ estimated for Chl with the thermometer of Massonne and Schreyer (1987) (sample ba15-10) or the (3) $T_{\text{max}}$ estimated with the RSCM (sa14-2) under the hypothesis that metamorphic white mica re-equilibrated at the temperature peak. The same approach was used to evaluate P conditions of white mica growth from published chemical compositions of white mica collected in the mylonitic basement of the southern Longmen Shan by Tian et al. (2016) (samples BX118 and BX127). When chlorite was not observed in the assemblage, reference temperature was fixed at 350-400°C, based on Qz and Fs deformation textures.

Two samples (ba14-14 and ba14-15) from the southern Longmen Shan were selected for in-situ $^{40}$Ar/$^{39}$Ar dating on white mica to constrain the timing of the greenschist-facies metamorphism. The age of metamorphism in the central Longmen Shan has already been constrained (Airaghi et al., 2017b, Airaghi et al., 2018). The in-situ $^{40}$Ar/$^{39}$Ar dating was done by UV laser ablation on polished 300 µm-thick sections cut mirror-like from the ones used for petrological observations. Samples were
dated at The Open University, UK, following the procedure described by Airaghi et al. (2018) and detailed in the Supporting Information. The fact that chemical heterogeneities in white mica may be smaller than the laser spot was taken into account and discussed below. Age uncertainties on the isotopic measurements are reported to 1σ. Only analyses showing no contamination by calcite or chlorine-bearing phases (checked with $^{38}\text{Ar}/^{39}\text{Ar}$ and $^{37}\text{Ar}/^{39}\text{Ar}$, see Table S1) were considered.

6 P-T-t results

6.1 Chemical composition of metamorphic minerals

Representative chemical analyses of metamorphic minerals are reported in Table 1 and Figure 8. In samples from the central Longmen Shan, the white mica in samples lm09-37, lm230 and sa14-2 exhibits an homogeneous chemical composition. Among them, white mica in sa14-2 is the one that exhibit the lowest $\text{Si}^{4+}$ content and $X_{\text{Mg}}$. In the crystalline basement of the southern Longmen Shan (sample ba15-12), compositional maps reveal the existence of two chemical groups of white mica (dominant muscovite composition of 50-70 %, Fig. 8a) occupying different microstructural sites. A Ti-rich, Fe-rich white mica is observed in the core of the white mica-bearing layers, along microcracks crossing the relics of ilmenite. This group (Wm1) shows the highest $\text{Si}^{4+}$, $\text{Ti}^{4+}$ contents and the lowest $X_{\text{Mg}}$ (Fig. 8a and Table 1). $\text{Si}^{4+}$ progressively decreases from the core to the rim of the white mica-bearing layer (Fig. 8a). The second compositional group of white mica (Wm2), with lower $\text{Si}^{4+}$, $\text{Ti}^{4+}$ contents wraps the Wm1 grains and forms the rims of the white-mica rich layers. In sample ba15-10 and ba14-14 (metasedimentary cover) white mica and chlorite exhibit a homogeneous chemical composition within each sample (Table 1), with white mica in sample ba14-14 exhibiting higher $\text{Si}^{4+}$ and lower $X_{\text{Mg}}$ than white mica in sample ba15-10 (Fig. 8a). Chlorite also exhibits a homogeneous composition within each sample (Fig. 8b). The lowest $\text{Si}^{4+}$ and highest $X_{\text{Mg}}$ is measured in chlorite of sample ba14-14 (Fig. 8b).
6.2 Thermobarometric and geochronological results

The 49 new maximum temperatures obtained by RSCM are summarized in Table S1 and integrated to existing temperatures in Figure 9a, b. Three NW-SE oriented profiles perpendicular to the Wenchuan and Beichuan faults were realized in the central Longmen Shan (where the density of samples was the highest) in order to track the temperature differences across the major structures. Samples collected in the Jiuding Nappe were projected along the profile of the North Tonghua transect (profile 2 in Fig. 9a) and integrated to data from Airaghi et al. (2017a). Samples of the Sanjiang sector were integrated to temperatures obtained by Robert et al. (2010b) in the Gengda area (Fig. 9a and profile 3 in Fig. 9a).

In the hanging wall of the WSZ $T_{\text{max}}$ range between 502°C and 619°C (± 30°C) with few localities showing $T_{\text{max}}$ between 470 and 481°C. Samples that experienced the highest $T_{\text{max}}$ of 594-619°C are located in the Devonian series along the Shapai transect. In all profiles of the hanging wall of the Wenchuan fault, isotherms wax and wane, with systematic temperature variations of 30-50°C (above the thermometer uncertainty), drawing a series of antiforms and synforms progressively tightened approaching the Wenchuan fault (e.g. profile 3 in Fig. 9a). Close to the Wenchuan fault, samples show $T_{\text{max}} > 500°C$ despite a mineral assemblage typical of the greenschist-facies conditions. Along all transects, $T_{\text{max}}$ sharply decrease of ~150°C across the WSZ: it does not exceed 380°C (± 30°C) in its footwall. The temperature jump is sharp and restrained to a band few meters to few kilometers wide. A thermal jump of ~50°C is also observed across the Beichuan fault, where $T_{\text{max}}$ decrease from 350-380°C (hanging wall) to < 330°C in the foreland belt (Fig. 9a). In the metasedimentary cover of the southern Longmen Shan $T_{\text{max}}$ do not exceed 394°C ± 30°C and no major temperature jumps are observed across the faults along the studied transect (Fig. 9b and Table S1).

P-T equilibrium conditions for sample lm09-37 and lm230 yield at 300 ± 30°C, 8 ± 1 kbar and 300 ± 30°C, 7 ± 1.5 kbar respectively (Fig. 10a) while sample sa14-2 shows a lower pressure of 4.5 ± 2 kbar for RSCM temperatures of 340 ± 30°C (Fig. 10b). In the Baoxing crystalline basement (sample ba15-12) P-T conditions yield at 360 ± 30°C, 6 ± 2 kbar. Wm1 plot at slightly higher pressure than Wm1 for the same temperature range (Fig. 10c). P-T estimates for white mica analyses from
Tian et al. (2016) provide consistent P-T results (Fig. 10d) at 6.5 ± 3 kbar, with the highest density of analyses at 6 ± 1 kbar, 350-400°C. The P-map obtained with the barometer of Massonne and Schreyer (1987) shows P conditions of 7-7.5 kbar for Wm1 and of 5.5 kbar for Wm2, with intermediate values for white mica located in the middle of the Wm-bearing layer (at T=400°C, Fig. 10e). In the sedimentary cover (samples ba15-10) T-conditions for chlorite yield at 350 ± 20°C. In this temperature range, P-conditions for the Wm-bearing assemblage in sample ba14-14 can be estimated at 3 ± 1 kbar, 350 ± 20°C (Fig. 10f).

Geochronological results for samples ba15-12 and ba14-14 are reported in the insets of Figures 10c and f and in table S2. White mica in sample ba14-15 (basement) yielded ages between 74.6 ± 6.1 and 58.8 ± 5.7 Ma. White mica in metasedimentary sample ba14-14 yielded younger ages ranging from 52 ± 2 to 33 ± 1.3 Ma.

6.3 Interpretation of P-T-t results

The range of the new RSCM T_{max} obtained for the internal units of the central Longmen Shan (> 500°C) is in line with the amphibolite-facies metamorphic minerals (St, Grt) observed in the peak mineral assemblage, with temperatures reported by Robert et al. (2010b) and Airaghi et al. (2017a) and with the peak metamorphic conditions estimated in Silurian and Devonian units along the South Tonghua, North Tonghua, Shapai and Gengda areas (north of the Sanjiang transects) with conventional barometry and thermodynamic modeling (Worley & Wilson, 1996; Robert, 2011; de Sigoyer et al., 2011; Airaghi et al., 2017a). No kyanite was observed in the metasedimentary cover around the Xuelongbao massif, in contrast to the observations of Worley & Wilson (1996). The P-T conditions obtained with the multi-equilibrium approach for the metasedimentary cover in the external units of the central Longmen Shan are consistent with the observed greenschist-facies peak mineral assemblage and are in line with temperatures obtained by RSCM.

In the southern Longmen Shan, P-T conditions are also consistent with RSCM T_{max} and the observed greenschist-facies mineral assemblage. Temperature estimates in the basement are compatible with the temperature range of ~300-400°C suggested by the ductile deformation of quartz
and quartz recrystallization mainly by bulging or subgrain rotation (Stipp et al., 2002; Passchier & Trouw, 2005). The chemistry of white mica in sample sample ba15-12 is very similar to the one measured by Tian et al. (2016). The Ti-enrichment of the Wm1 might be due to its grown from a Ti-rich biotite. Pressure conditions obtained for Wm1 with the Phg-Qz-H2O modeling approach are generally close to pressure conditions obtained for Wm2, although multiple analyses of Wm2 plot at lower pressure values. In contrast, the P-map obtained with the barometer of Massonne and Schreyer (1987) shows higher pressures for Wm1 (~7.5 kbar) than for Wm2 (~4 kbar). These observations may suggest decompression (exhumation) during the greenschist-facies overprint and the associated deformation in the crystalline basement.

The T estimates in both the basement and in the sedimentary cover of the southern Longmen Shan are lower than the nominal closure T for Ar in muscovite (425°C for a 100 µm radius grain, a cooling rate of 10°C and P=10 kbar; Harrison et al., 2009): ⁴⁰Ar/³⁹Ar dates are therefore interpreted as representing white mica crystallization ages. Since the chemical heterogeneities within white mica (10-20 µm) are smaller than the spatial resolution of the laser used for the in-situ dating (~65 µm), the calculated ⁴⁰Ar/³⁹Ar age might be affected by processes other than local in-situ K-Ar decay (e.g. Airaghi et al. 2018). In the Baoxing basement, the oldest ages (68-74.5 ± 6.1 Ma) could correspond to the relics of Wm1 and the youngest ages (58-60 ± 9 Ma) to the growth of Wm2, although the influence of the white mica grain size and deformation on the age dispersion cannot be discarded. These age intervals are consistent with the white ⁴⁰Ar/³⁹Ar white mica and biotite ages obtained by Tian et al. (2016) in the basement of the southern Longmen Shan.

In the metasedimentary rocks (ba14-14), the white mica ages are younger (<55 Ma) than in the basement. Although further investigations would be required to precisely assess the timing of the tectono-metamorphic evolution of the sedimentary cover, our results clearly show that the greenschist-facies metamorphism in the southern Longmen Shan is Late Cretaceous-Cenozoic in age.
7. DISCUSSION

7.1 Structural and P-T-t evolution of the central Longmen Shan

A very constant deformation scheme is observed in the internal metasedimentary series of the central Longmen Shan, at different spatial scales. It includes D1, D2, D3 ductile deformation phases and a D4 brittle-ductile phase of tilting, in line with the deformation phases observed by Harrowfield and Wilson (2005) in the Danba area and in the southern Longmen Shan. At a first order level, therefore, the internal metasedimentary units experienced a similar deformation history. Folds tighten approaching the crystalline massifs, suggesting that the Xuelongbao, Pengguan and Tonghua massif acted as rigid buttresses during the D2 deformation phase, although they were not yet exhumed. D2 is only observed in the metasedimentary cover and is coeval with, or postdated, the peak-T as suggested by the folded shape of the isotherms obtained by RSCM along the transects in the internal units and the fact that magmatic intrusion in the SPG are either deformed or crosscut earlier structures (Fig. 9a).

In all studied transects, similar peak metamorphic mineral assemblages are associated with similar microstructures, suggesting that the metamorphic peak (9-12 kbar, 530-580°C, Airaghi et al., 2017a, 2018) occurred coevally in the entire internal metasedimentary units, at c. 200-180 Ma (Huang et al., 2003a; Weller et al., 2013; Airaghi et al., 2018), lasting over 20 Ma. All the D3 structures observed both in the basement and in the metasedimentary cover are associated with NNE-SSW oriented structures such as F3 folds in the metasedimentary cover and top-to-SE shearing and greenschist-facies metamorphic minerals dated at Early Cretaceous (Fig., 11c; Airaghi et al., 2017b; Airaghi et al., 2018). These observations deviate from the top-to-NW ductile movement documented in the western part of the Pengguan massif along the WSZ by some previous study (Xu et al., 2008; Xue et al., 2017). Both tectonic dynamics can however co-exists and be consistent with a south-east thrusting during the Early Cretaceous, resulting in the formation of basement-slice-imbricated structures (this study, Xue et al., 2017, Airaghi et al., 2018). Furthermore, a Cretaceous re-activation is also recorded ~200 km NW of the Longmen Shan, in the Longriba fault zone and in the Aba block (Tian et al., 2014;
Ansberque et al., 2018), suggesting that a large portion of the eastern Tibet remained coupled during Cretaceous exhumation (Ansberque et al., 2018).

In the external metasedimentary units, two and three phases of ductile deformation are observed west and east of the WSF respectively. In the Devonian sediments (sample sa14-2) the P-T conditions of the greenschist-facies peak assemblage (4.5 ± 2 kbar, 340 ± 30°C) are close to the ones of the greenschist-facies overprint observed in the internal units, suggesting that in the external domain this late event might be the only re-crystallization event. The P-T conditions at 300 ± 30°C, 8 ±1 kbar obtained in the Sinian sediments roofing the Pengguan massif (samples lm230 and lm09-37) are instead in good agreement with the P-T estimates obtained for the Pengguan massif (Airaghi et al., 2017b). Assuming a density for the crust of 2700 kg m⁻³ and the lithostatic pressure hypothesis, these results imply that the Devonian sediments were exhumed from a depth of ~15 km and were partially thickened and detached over the basement (Pengguan massif) while the Sinian sediments experienced a coherent metamorphic history with the Pengguan massif and were exhumed from ~20 km depth. No ages are yet available for the metamorphic peak in the metasedimentary external units. Structural and sedimentary investigations in the foreland basin indicate however that the deformation phase related to thickening reached the front of the Longmen Shan by the Late Triassic (e.g. Chen et al., 1995; Li et al., 2003; Robert et al., 2011; Li et al., 2014b), in agreement with the ZFT at 180 Ma obtained by Arne et al. (1997) at the front of the belt and with the timing of the klippen emplacement (Zheng et al., 2014).

The metamorphic jump between the internal SPG metasedimentary units and the external units and the basement implies the existence of a major decollement between the two domains, at the time of the SPG nappe emplacement (Late Triassic-Early Jurassic, Fig. 11b and c). Field observations suggest the existence of sub-parallel thrusts within the SPG metasedimentary units contemporaneous with the medium-grade metamorphism, structurally rooted in a decollement (or ductile crustal layer) located in the Silurian schists (at the base of the post-rift sediments). The predominant structural style in the Longmen Shan during the Late Triassic-Early Jurassic was therefore thin-skinned (Fig. 11b). The record of the only D3 structures in the crystalline basement attest of the onset of the thick-skinned deformation at the Early Cretaceous and the re-activation of the Beichuan and Wenchuan faults (Fig.
The thick-skinned deformation became progressively dominant across the entire central Longmen Shan (Fig. 11d), as suggested by the recent 2008 Wenchuan earthquake nucleating in a basement fault that partly re-activated as a thrust.

7.2 Structural and P-T-t evolution of the southern Longmen Shan

In the southern Longmen Shan, only one major ductile deformation phase is observed and is defined by field structures indicating a top-to-east (top-to-the foreland) shearing associated with greenschist-facies metamorphism, in contrast with the Late Cretaceous to Paleogene, top-to-west (top-to-the hinterland) shearing previously proposed (Tian et al., 2016). However, these divergent observations can coexist as documented in the Pengguan massif during the Early Cretaceous (Xue et al., 2017). They are both compatible indeed with a phase of shortening and crustal thickening of the basement and the sedimentary cover. Shortening and crustal thickening stage is also in line with the presence of Late-Cretaceous-early Paleogene basins –interpreted as foreland basins– at the front of the southern part of the belt (Guo et al., 1996) and with the absence of an extensional basin filled with Paleogene sediments in the hanging wall of the major tectonic structures.

P-T conditions of the greenschist-facies assemblage in the crystalline rocks (360 ± 30°C, 6 ± 2 kbar) suggest that the basement in the hanging wall of the Wulong fault was exhumed from ~20 km depth (assuming the lithostatic pressure hypothesis with a crustal density of 2700 kg m⁻³), in agreement with the P-T-z conditions obtained in the Pengguan and Tonghua massifs (Airaghi et al., 2017b; Airaghi et al., 2018). The metasedimentary cover was instead exhumed from ~10 km depth (~3 kbar).

The age of the greenschist-facies overprint in the basement of c. 80-60 Ma is in very good agreement with the ⁴⁰Ar/³⁹Ar ages obtained by Tian et al. (2016) and with the ⁴⁰Ar/³⁹Ar biotite ages obtained by Zhou et al. (2008) in the basement of the Danba massif (Fig. 12). Hence, in the southern Longmen Shan –as in the southern margin of the eastern Tibetan plateau-, the basement was actively involved into metamorphism and deformation at the Late Cretaceous, while the sedimentary cover records a prolonged deformation event until the Eocene. At this time, the shortening and crustal
thickening was possibly triggered by the effects of the India-Asia convergence and the late subduction of the Tethys, firstly perceived from the southern LMS northwestwards to the Danba area, as also suggested by thermochronological data (e.g. Kirby et al., 2002; Cook et al., 2013).

7.3 Tectonic implications

7.3.2 The Long-term thrusting component of the major faults

The fact that the sharpest metamorphic jumps of ~5-6 kbar, 150-200°C and ~50°C observed across the Wenchuan and Beichuan faults respectively are Mesozoic in age suggests that these faults were already major active lithospheric boundaries during the Mesozoic. The record of Early Jurassic metamorphism in the internal Tonghua crystalline massif but not in the external Pengguan massif (Airaghi et al., 2017; 2018) also indicates that the Wenchuan fault constituted a major tectonic boundary already at that time. The distribution of metamorphic rocks in the central Longmen Shan therefore attests of a significant vertical component in the long-term functioning of the Beichuan and Wenchuan faults, with a minimum cumulated vertical offset for the two faults of ~20 km (Airaghi et al., 2017b). In the southern Longmen Shan the basement is also exhumed from ~20 km depth, attesting of the long-term thrusting movement also of the Wulong fault. Note that the amount of strike-slip component of the deformation during the Late Triassic-Early Jurassic is difficult to evaluate with the petrological approach used in this study and thus must remain, for the present, unquantified.

7.3.2 Continuity between the Wenchuan and Beichuan faults and faults of the southern Longmen Shan

Our petrological and structural approach reveals that the Beichuan fault separates low-grade metamorphic metasedimentary units to the west from non-metamorphic units to the east and favors the exhumation of the basement (Pengguan massif) in its hanging wall (Fig. 11d). A similar
configuration is observed for the Xiaoguanzi fault in the southern Longmen Shan (Fig. 9b). These faults might be therefore considered as structurally equivalent. By contrast, the Wenchuan fault corresponds (1) to a Late Triassic-Early Jurassic zone of decollement separating the medium-grade metasedimentary units from the base of SPG series to the west (internal units) and the low-grade metasedimentary units to the east (external units) where the basement is not exhumed or (2) to the tectonic boundary that limits the slices of the basement without any major metamorphic jump, where the basement is exhumed (e.g. Tonghua massif; Fig. 9a and 11d). Using a petrological approach, it is therefore possible to distinguish the SPG decollement level responsible for the metamorphic jump between internal and external units from the Wenchuan fault *sensu stricto* that favors for the exhumation of the basement in its hanging wall. In the southern Longmen Shan, the Wulong fault – often considered as the southern prolongation of the Wenchuan fault – also favors the exhumation of the basement in its hanging wall but it never corresponds to the limit between different metamorphic domains. Hence, if the Wulong fault cannot be considered as the southern prolongation of the SPG decollement level. This level may instead deviate from the central Longmen Shan westward, to join the Danba dome where medium-grade metamorphic rocks are exhumed (e.g. Weller et al., 2013; Billerot et al., 2017). The petrochronological approach thus allows to better define the Wenchuan fault zone and its petrological significance.

7.3.3 Different tectono-metamorphic evolutions for the central and southern Longmen Shan

Structural and petro-chronological data show that different tectono-metamorphic features are observed between the central and southern Longmen Shan. The metasedimentary cover of the southern area does not clearly record, for example, three stages of ductile deformation as observed in the central areas. Furthermore, the P-T conditions of the metasedimentary cover in the south are close to the ones observed in the external units of the central Longmen Shan but the amphibolite-facies metamorphism that characterizes the internal units of the central Longmen Shan is not observed in the south (Fig. 12). This suggests that the southern LMS never experienced the overthrusting of the
thickened Songpan-Garze units towards the external part of the belt. The different metamorphic
domains (blue and red in Fig. 12) are separated by a 30-40 km wide area where no metamorphic rocks
are observed (T <<330°C, white in Fig. 12). This non-metamorphic zone extends from the front of the
belt, westward within the Songpan-Garze terrain and corresponds to the area where zircon fission
track ages have not been re-set since the Triassic (Tan et al., 2014). Deep metamorphic units were
therefore never exhumed within this area.

Differences in the timing of metamorphism between the central and southern Longmen Shan are also observed. While in the south the greenschist-facies metamorphic event affecting the basement is younger than 80 Ma (yellow boxes in Fig. 12), in the central Longmen Shan it is dated at 140-120 Ma (white boxes in Fig. 12). This suggests that while the central Longmen Shan experienced a phase of thickening and exhumation during the Early Cretaceous, the southern Longmen Shan did not, or the Early Cretaceous event is there completely overprinted by the Cenozoic history. During the Cenozoic, the central Longmen Shan was therefore already at a higher structural level (below closure T of ZFTs) while the southern Longmen Shan experienced thickening and deformation. This is consistent with the stratigraphic record in the foreland Sichuan basin showing a migration of the depocenter northwards during the Early Cretaceous and southwards during the Cenozoic (e.g. Burchfiel et al., 1995; Meng et al., 2005). Hence, the central and southern Longmen Shan underwent different tectono-metamorphic histories since the Early Mesozoic, that results in an along-strike metamorphic segmentation of the belt. Different portions of the belt were therefore re-activated at different times, maybe due to a difference in the maturation of the associated fault systems.

7.3.4 Implications for the present tectonics

The relocation of the recent earthquake epicenters shows that the 2008 Mw 7.9 Wenchuan and 2013 Mw 6.6 Lushan earthquakes (green stars in Fig. 12) nucleated in areas where the crystalline basement crops out (filled black lines in Fig. 12). The epicenters are separated by an as-yet unbroken segment where recent earthquakes did not propagate, whose size broadly corresponds to the size of the area where no metamorphic rocks are observed (dashed black line and white area in Fig. 12). This
metamorphic segmentation might be controlled by tectonic structures (possibly inherited from the Paleozoic passive margin of the South China craton) that – on the base of the contours of metamorphic discontinuities – should be SE-NW oriented, subparallel to the Xianshui He fault. The lateral ramp of the RFBT (below the Shuangshi fault) that limited the propagation of the Lushan earthquake northeastward into the unbroken segment (Li et al., 2014c) might represent one of these structures. Inherited structures responsible for the along-strike metamorphic segmentation in the Longmen Shan might therefore still affect the present dynamics. They might also partially explain the present crustal structure of the belt imaged by seismic tomography at ~ 20 km depth (Wang et al., 2015). Our tectono-metamorphic approach thus offers new and complementary constraints to understand the importance of the Mesozoic geological inheritance in the present tectonics of the Longmen Shan.

8 Conclusions

- The equilibrium P-T conditions of the greenschist metamorphic assemblage in the external units of the central Longmen Shan yield at 300 ± 30°C, 7-8 ±1 kbar in the Sinian sediments remained attached to the Pengguan crystalline massif and at 340 ± 30°C, 4.5 ± 2 kbar in the para-autochthonous Devonian sediments.

- New petrological observations in the central Longmen Shan show a metamorphic jump of ~50°C (~3 kbar) across the Beichuan fault. A second metamorphic jump is observed across the SPG decollement zone (locally superposed to the Wenchuan fault) of ~150-200 °C, 5-6 kbar between the metasedimentary rocks of the internal units of the central Longmen Shan (T> 500°C) and metasedimentary rocks in the external units of the belt (T < 400°C). The SPG decollement limiting the different metamorphic provinces can therefore be distinguishing from the Wenchuan fault sensu stricto that favors the exhumation of the Xuelongbao and Tonghua crystalline massifs in its hanging wall and across which no major metamorphic jumps are observed.
• The metamorphic jumps across the Beichuan, Wenchuan and the SPG decollement zone attest to their long-term thrusting components and show that they already constituted major crustal boundaries from the Late Triassic-Early Jurassic.

• In the internal metasedimentary units of the central Longmen Shan three phases of ductile deformation are observed: D1, D2 related to top-to-SE shearing, D3 related to top-to-E shearing. In the southern Longmen Shan only one major ductile deformation phase related to top-to-ESE shearing is observed.

• No higher than greenschist-facies metamorphic conditions were reached in the basement and in the metasedimentary cover of the southern Longmen Shan. Peak conditions of 360 ± 30°C and 6 ± 2 kbar were reached at c. 80-58 Ma in the basement and 350 ± 30°C, 3 ± 1 kbar at c. 55-33 Ma in the metasedimentary cover.

• In the long term, the Wulong fault cannot be considered in continuity with the SPG decollement zone separating the internal and external units in the central Longmen Shan.

• The first comprehensive maps of paleo-temperatures for the entire Longmen Shan shows an along-stripe metamorphic segmentation between the central and southern Longmen Shan. The amphibolite-facies metamorphism related to the thickening and thrusting of the Songpan-Garze metasedimentary rocks is only observed in the central Longmen Shan while the greenschist-facies overprint observed in the basement is dated at c. 140-120 Ma in the central Longmen Shan and < 80 Ma in the southern Longmen Shan. The central and southern Longmen Shan therefore underwent different tectono-metamorphic histories since the Mesozoic maybe due to differences in the maturation of the associated fault systems.

• The metamorphic segmentation and the geographic distribution of the outcropping basement seem to mime the locations of the recent earthquake epicenters while the area where no long-term exhumation is observed well corresponds to the width of the unbroken segment where the rupture did not propagate. The inherited structures responsible for the long-term along-strike metamorphic segmentation might therefore still affect the present tectonics of the belt. Farther investigations on the reasons of the metamorphic segmentation are now required.
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Figure 1 Structural and geological map of the Longmen Shan area. (a) Simplified geological map of the eastern border of the Tibetan plateau, modified from Billerot et al. (2017). WF: Wenchuan fault, WSF: Western Slope fault, BF: Beichuan fault, GF: Guanxian fault, WuF: Wulong fault, XF: Xiaoguanzi fault, SF: Shuangshi fault. White frame: zoom of panel b. (b) Geological map of the central Longmen Shan modified from Cook et al. (2013) and adapted from 1:200,000 geologic map (Ministry of Geology and Mineral Resources, 1991). White frames: enlarged views in Figure 2. White dots: samples collected to complete transects of Figure 2 (see text for details). (c) Geological cross section along the profile AA' for the southern Longmen Shan, modified from Cook et al. (2013). (d)
Geological cross section along the profile BB’ for the central Longmen Shan. P-T-t conditions in frames are from Airaghi et al. (2017a; 2017b; 2018). The crustal structure is from receiver function data of Robert et al. (2010a).
Figure 2 Enlarged views of the geological map of the studied transects. (a) Area of the Tonghua transect (samples NT) and Jiuding Shan Nappe (samples Im). Symbols in yellow indicate the mineral assemblage observed by Airaghi et al. (2017a). Black: field stops (no sample collected). (b) Studied area in the southern Longmen Shan. The Baoxing crystalline massif (basement) crops out into two slices. The inset shows the direction and dip of S2 along the transect from samples ba14-8 to sample ba15-6. Black dots: field stops (no sample collected). (c) Location of the South Tonghua and Shapai transects in the Xuelongbao area. (d) Sanjiang transect area.
Figure 3 Structural map of the central Longmen Shan, based on our field investigations, superimposed on the geological map of the Longmen Shan and Songpan-Garze area adapted from 1:200,000 geologic map (Ministry of Geology and Mineral Resources, 1991). Black and grey stereograms indicate the orientations and dips of the S1 and S2 cleavages respectively. Rose diagrams represent the distribution of the main direction of the F2 and F3 folds measured in the field. Major tectonic discontinuities are indicated by continuous black lines. WF: Wenchuan fault, WSF: West Slope fault, BF: Beichuan fault, GF: Guanxian fault.
Figure 4 Photographs of the meso-scale structures observed in the field (internal units of central LMS). (a) Pervasive S2 crenulation cleavage (parallel to F2 folds) in the Silurian sediments of the
North Tonghua transect. F2 axes are folded (modified from Robert A., 2011). (b) Top-to-SE C/S structures in the garnet-biotite bearing metapelites of the North Tonghua section (close to locality to13-5 in Fig. 2a). (c) S1 and S2 cleavage preserved in the Silurian sediments north of the Tonghua massif. F2 are twisted (modified from Robert A., 2011). (d) F2 and F3 folds in the Devonian sediments of the Shapai transect. Quartz veins form bundins (yellow). (e) F2 folds in the Devonian sediments of the Shapai transect. (f) F3 folds observed close to the figure of panel e. (g) top-to-ESE thrust slicing the Devonian metasedimentary cover in the Shapai transect. (h) C3-S3 structures showing a top-to-SE shearing in the Devonian sediments of the Shapai transect.
Figure 5 Photographs of the meso-scale structures in the southern LMS. (a) Top-to-E shearing structures in mylonitic zones of the basement lately cross cut by top-to-W normal faults. (b) Pervasive schistosity parallel to the bedding in the Ordovician units close to the outcrop ba14-22 (Fig. 2b). (c) Constriction features in the Proterozoic units close to the outcrop ba14-17. (d) Kink bands close to the outcrop ba14-13. (e) Top-to-E shearing structures in the Silurian sediments close to the outcrop ba14-19.
Figure 6 Photomicrographs of representative samples collected in the internal and external metasedimentary units. Abbreviation are from Whitney and Evans (2010), except Wm = white mica. (a) Biotite-bearing shistosity along the Shapai transect. (b) Deformed staurolite porphyroblast in the Shapai area. (c) Chl-Wm microfolds close to the contact between the metasedimentary cover and the Xuelongbao massif. (d) Ep + Qz + Chl pseudomorph of garnet close to the WSZ. (e) Greenschist-facies bearing assemblage in sample lm230. (f) Deformed organic-rich schist lm09-59. (g) Backscatter image (BSE) of the Chl + Wm intergrowths in sample lm09-37. (h) Plain Polarized Light (PPL) image of the Wm-bearing metagreywacke sa14-2.
Figure 7 Photomicrographs of samples collected in the southern LMS. (a) Plain Polarized Light (PPL) image of white mica layers in metagranite ba14-15. (b) C-S structures in sample ba15-12 from the crystalline basement. (c) PPL image of quartz subgrains and recrystallization by bulging in sample ba15-12c. (d) PPL image of feldspar grains wrapped in the white mica-bearing S2 cleavage defining the main foliation. (e) Organic material-rich sample showing a S1 and S2 cleavage. (f) Chlorite and white mica assemblage in the black schist ba15-10. (g) White mica-bearing cleavage wrapping an allochthonous feldspar grain in sample ba14-14.
**Figure 8** $\text{Si}^{4+}$ vs $X_{\text{Mg}}$ diagram of white mica (a) and chlorite (b) chemical compositions analyzed in samples collected for thermo-barometric proposes (see text for details). The $\text{Si}^{4+}$ of white mica 1 (Wm1) in sample ba15-12c progressively decreases from the core to the rim of the white mica-bearing layers to reach the composition of Wm2 (black arrow).
Figure 9: Maximum temperatures ($T_{\text{max}}$) obtained with the RSCM thermometry. (a) Distribution of $T_{\text{max}}$ in the geological map of central (a) and southern (b) Longmen Shan. Black lines 1, 2, 3, 4 indicate profiles on the right hand. WF: Wenchuan fault, BF: Beichuan fault, WuF: Wulong fault. In profiles, the $T_{\text{max}}$ plotted in a temperature vs distance to the WF (1, 2, 3) or WuF (4). The error reported on $T_{\text{max}}$ is the standard deviation. Results from the Gengda area (black frame along profile 3) are from Robert et al. (2010b). The profile between samples in the hanging and footwall of the Beichuan fault is extrapolated (dashed black line). Dashed red lines in profile 3 represent the location of the different branches of the WF and BF.
Figure 10 P-T-t results. (a) P-T white mica lines for samples lm09-37 and lm230 (sediments roofing the Pengguan massif). Colored frames are temperatures obtained from chlorite. Crosses indicate the estimated P-T conditions for the greenschist-facies assemblage. (b) P-T conditions for sample sa14-2. (c) White mica P-T lines for samples from the basement ba15-12 in the southern Longmen Shan. Wm1 plot at slightly higher P (or lower T) than Wm2. The inset shows the $^{40}$Ar/$^{39}$Ar white mica ages
for sample ba14-15 sorted by increasing age. (c) P-T lines obtained from the chemical compositions of white mica analyzed by Tian et al. (2016) for samples similar to ba15-12. (e) P-map obtained with the barometer of Massonne and Schreyer (1987) for a white mica-bearing layer in sample ba15-12. (f) White mica P-lines for sample ba14-14 (sedimentary cover). Temperatures are estimated from chlorite in sample ba15-10 (bottom right inset). The top-left inset shows $^{40}\text{Ar}/^{39}\text{Ar}$ white mica ages of sample ba14-14 sorted by increasing age.
Figure 11 Interpretative cross sections of the tectonic evolution of the Longmen Shan from the Paleozoic to the present. The left insets show a regional view of the geodynamics at each step, evinced from structural observations and from the reconstructions of Roger et al. (2008). The shortening during the Triassic-Jurassic is only qualitative. Yellow dots: position of the highest metamorphic rocks at each stage. White arrows: shortening direction. WF: Wenchuan fault, BF: Beichuan fault, GF: Guanxian fault, SPG: Songpan-Garze, YI: Yidun terrane. (a) Passive margin at the Paleozoic. (b) Late Triassic-Early Jurassic compression and exhumation. The orientation of the D2 structures are regionally compatible with top-to-south thrusting orientation related to the N-S directed closure of the northern branch of the Paleotethys and with the contemporary clockwise rotation of the South China block (inset; e.g. Harrowfield & Wilson, 2005; Meng et al., 2005; Deng et al., 2007). (c) Early Cretaceous re-activation. The orientation of the structure is regionally compatible with the E-W compression (inset). (d) Schematic cross section of the present structure of the belt.
Figure 12 Map of the maximum temperatures experienced by the metasedimentary units along the entire Longmen Shan, from a compilation of newly acquired and previously published (Robert et al., 2010b; Airaghi et al., 2017a) RSCM $T_{\text{max}}$. WF: Wenchuan fault, BF: Beichuan fault, GF: Guanxian fault, WuF: Wulong fault, XF: Xiaoguanzi fault, SF: Shuangshi fault, Ka: Kanding. High temperatures in the central Songpan-Garze (SPG). Filled black contours: crystalline massifs (basement). Dashed black circle: unbroken segments between the 2008 Mw 7.9 Wenchuan and 2013 Mw 6.6 Lushan seismic ruptures (e.g. Wang et al., 2015). GS: Greenschist-facies metamorphism.

Numbers in boxes are ages from this study (yellow) and from literature (white). Ages linked to the crystallization of metamorphic minerals along S2 cleavage during the regional amphibolite-facies metamorphism are: 1: U-Pb monazite and Sm-Nd garnet ages of Huang et al. (2003a), 2: $^{40}$Ar/$^{39}$Ar amphibole and biotite ages of Zhou et al. (2008), 3: U-Pb monazite ages of Weller et al. (2013), 6: $^{40}$Ar/$^{39}$Ar biotite and U-Pb allanite ages (metasediments) of Airaghi et al. (2018). Ages dating the greenschist-facies metamorphism are: 4: $^{40}$Ar/$^{39}$Ar muscovite and biotite ages of Tian et al. (2016), 5: $^{40}$Ar/$^{39}$Ar muscovite ages of Airaghi et al. (2017b), 6: $^{40}$Ar/$^{39}$Ar muscovite (basement).
Table 1: Representative chemical compositions of analyzed metamorphic minerals (chlorite and white mica).

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