Late Cretaceous – earliest Paleogene deformation in the Longmen Shan fold-and-thrust belt,
eastern Tibetan Plateau margin: Pre-Cenozoic thickened crust?

Yuntao Tian^{1,2,3}, Barry P. Kohn¹, David Phillips¹, Shengbiao Hu⁴, Andrew J. W. Gleadow¹,
Andrew Carter⁵

¹ *School of Earth Sciences, The University of Melbourne, Victoria 3010, Australia*

² *Department of Earth Sciences, University College London, London, WC1E 6BT, UK*

³ *Department of Earth Sciences and Geological Engineering, Sun Yat-sen University,
Guangzhou, 510275, PR China*

⁴ *State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics,
Chinese Academy of Sciences, Beijing 100029, China*

⁵ *Department of Earth and Planetary Sciences, Birkbeck, University of London, Malet Street,
London WC1E 7HX, UK*

Corresponding author:

Yuntao Tian

Department of Earth Sciences

University College London

Gower Street

London WC1E 6BT

United Kingdom

Email: y.t.tian@ucl.ac.uk

This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: [10.1002/2016TC004182](https://doi.org/10.1002/2016TC004182)

Author Manuscript

Key Points:

Late Cretaceous – earliest Paleogene hinterland deformation

Contemporaneous shortening in the foreland side

Pre-Cenozoic thickened crust at the eastern Tibetan Plateau margin

Abstract

This study presents structural and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological data from the southern part of the Longmen Shan fold-and-thrust belt that forms the eastern margin of the Tibetan Plateau. Investigations focused on hinterland ductile top-to-the-WNW shear deformation, which has been linked previously to late Cenozoic lower crustal flow. Consistent with previous studies, the sense of deformation is mapped as top-to-the-WNW in the Longmen Shan hinterland. The timing of the deformation is constrained by $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological data of recrystallised minerals aligned along the shear foliation as late Cretaceous – earliest Paleogene, thus predating the inferred late Cenozoic crustal flow. This deformation is contemporaneous with SE-verging thrusting and loading along the Longmen Shan front, which formed a coeval ~2-3 km thick foredeep sequence along the southwestern margin of the Sichuan Basin. In the context of the regional geology, this tectonic configuration could result from either extrusion of a crustal wedge or back-thrust in a duplex. Compared to other orogens, where similar crustal configurations have been reported, it is speculated that the eastern Tibetan Plateau margin acquired thickened crust and highly elevated topography in late Cretaceous – earliest Paleogene time.

Index Terms and Keywords:

Tectonophysics: Continental tectonics-general (8110); Geographic Location: Asia (9320); Microstructures (8030); Radioisotope geochronology (1115); Continental contractional orogenic belts and inversion tectonics (8102)

1. Introduction

Manuscript
Numerous studies have sought to explain the formation of the thickened crust and elevated topography of the Tibetan Plateau [see reviews by *Molnar*, 1988; *Harrison et al.*, 1992; *Yin and Harrison*, 2000], with a focus on the role of crustal and/or mantle processes following the onset of early Cenozoic Indo-Asia collision [e.g., *England and Houseman*, 1986; *Tappin et al.*, 2001; *Royden et al.*, 2008]. By contrast, a growing number of studies in the central and southern Tibetan Plateau, have pointed out that by the end of the Cretaceous, some parts of the central Tibetan Plateau already had thickened crust and elevated topography in response to Mesozoic orogenesis associated with terrane and arc collisions [e.g., *England and Searle*, 1986; *Murphy et al.*, 1997; *Kapp et al.*, 2003; *Robinson et al.*, 2004; *Kapp et al.*, 2007].

The eastern Tibetan Plateau margin, which is defined by the NE-striking Longmen Shan fold-and-thrust belt, has a thick crust (~60 km) and high topographic relief, and has experienced multiple phases of deformation. These include early Mesozoic and late Cenozoic phases of intra-continental orogenesis [*SBGMR*, 1991; *Burchfiel et al.*, 1995; *Chen et al.*, 1995; *Tian et al.*, 2013; *Wang et al.*, 2014], and a period of top-to-the-WNW sense of shear, whose timing is a matter of debate [e.g., *Burchfiel et al.*, 1995; *Xu et al.*, 2008; *Zhou et al.*, 2008]. Despite a long history of deformation, the various models that have been proposed to explain the formation of the thickened crust in the Longmen Shan, such as lower crustal flow [e.g., *Clark et al.*, 2005; *Royden et al.*, 2008] or crustal shortening and extrusion [e.g., *Hubbard and Shaw*, 2009; *Tian et al.*, 2013], have not considered possible contributions from pre-Cenozoic deformation, in part because the timing of these deformation events is poorly constrained.

Given that an explanation for the top-to-the-WNW shear zone has been a key element of previous tectonic models, it is crucial to determine the timing of shearing. Unfortunately, current constraints on the timing are poor. Shearing has been identified on the hinterland side

of the Longmen Shan and the Danba Antiform immediately south of the Longmen Shan [SBGMR, 1991; Burchfiel *et al.*, 1995; Xu *et al.*, 2008; Zhou *et al.*, 2008]. Studies of the Danba Antiform interpreted the top-to-the-WNW shearing as resulting from mid Jurassic - early Paleogene (173-160 Ma and 81-47 Ma) post-orogenic progressive extension of the late Triassic orogen [Zhou *et al.*, 2008], or early Cretaceous (~120 Ma) deep crustal extrusion [Xu *et al.*, 2008]. Other studies inferred that shearing in the Longmen Shan hinterland as a phase of late Cenozoic extension [Burchfiel *et al.*, 1995; Meng *et al.*, 2006; Cook *et al.*, 2013], driven by outward extrusion of the lower crust [Burchfiel *et al.*, 1995, 2008; Clark *et al.*, 2005; Royden *et al.*, 2008]. To address this question, we conducted a detailed structural and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological study on shear structures preserved in the southern Longmen Shan (Figs. 1 and 2). The results are interpreted in the context of previous low-temperature thermochronology data in the Longmen Shan, as well as sedimentary and seismic survey data from the foreland Sichuan Basin immediately east of the Longmen Shan.

2. Geological setting

The regional structural geometry of the Longmen Shan fold-thrust belt is defined by three parallel NW-dipping fault zones (Fig. 1); from the hinterland (northwest) to the foreland (southeast), these include the Wenchuan-Maowen Fault (WMF), the Yingxiu-Beichuan Fault (YBF) and the Guanxian-Anxian Fault (GAF). Neoproterozoic basement rocks, surrounded by Paleozoic sedimentary strata, outcrop in the core part of the Longmen Shan. To the west of the Longmen Shan, lies the Songpan Gaze terrane, which is covered by a thick (>8-10 km) sequence of strongly folded Triassic flysch deposits [Chang, 2000; Roger *et al.*, 2008; Ding *et al.*, 2012]. The Songpan-Ganze terrane was intruded by late Triassic - Jurassic granitoids and a few Miocene plutons developed along the deep seated Xianshuihe fault, probably in relation to left-lateral slip of the fault [Fig. 1 and Roger *et al.*, 1995]. Except for Pliocene-Quaternary glacial and fluvial sediments, late Jurassic – Cenozoic strata are absent from this terrane. To the east, the terrestrial Sichuan Basin accommodated >6 km of late Triassic – Quaternary deposits [SBGMR, 1991; Guo *et al.*, 1996; Li *et al.*, 2003].

In the study area (the southern Longmen Shan), lithological units with different deformation characteristics are separated by several faults (Fig. 2a). West of the Longdong

fault zone, upper Paleozoic marine limestone-sandstone-mudstone and Triassic Songpan-Ganze flysch are strongly folded (Fig. 2b). The fault zone juxtaposed Ordovician strata over Devonian sequences. Ordovician - Devonian strata within the fault zone are strongly attenuated, forming a tectonic window where the underlying schistose Neoproterozoic rocks crop out (Fig. 2a). To the east, in the footwall of the fault zone, Neoproterozoic basement and Paleozoic rocks are strongly mylonitised, schistosed and faulted. Detailed mapping within this domain suggests a phase of top-to-the-WNW shearing (see section 3 for details). Farther east, Neoproterozoic basement rocks exposed between the Wulong and Xiaoguanzi faults, which are southern extensions of the WMF and YBF, respectively [Burchfiel *et al.*, 1995; Tao, 1999], are less deformed, or undeformed (Fig. 2). Note that the Xiaoguanzi fault is also locally named as the Erwangmiao fault [e.g., Cook *et al.*, 2013]. East of the Xiaoguanzi fault, terrestrial Triassic to Quaternary sediments are folded and faulted. In following sections, local fault nomenclature (Wulong and Xiaoguanzi faults) in the southern LMS will be replaced by the YBF and WMF, which have been more widely used in previous literature.

The Longmen Shan fold-thrust belt experienced two phases of orogenic shortening in the early Mesozoic and later Cenozoic, respectively [e.g., Burchfiel *et al.*, 1995; Yan *et al.*, 2011]. The first shortening phase is SE-SSE-verging, as expressed by structures at different scales. Kilometer-scale klippe structures developed in both the Longmen Shan front and hinterland (Fig. 2a). Along the Longmen Shan front, Neoproterozoic basement and Paleozoic rocks tectonically overlie late Triassic – Cretaceous sedimentary rocks; and on the western, hinterland side of the Longmen Shan, strongly folded Triassic flysch sediments tectonically overlie Permian rocks. These allochthonous blocks were formed by SSE-verging thrusting of the Longmen Shan fold-thrust belt and the Songpan-Ganze terrane. At a meter-scale, tight folds (F1) in the Triassic flysch and Paleozoic rocks indicate NNW-SSE shortening of the Longmen Shan hinterland (Fig. 2b). Within the early Paleozoic and Precambrian rocks on the hinterland side, structures such as boudinaged sandstone and/or quartz vein and S-C fabrics indicate SE directed thrusting.

The timing of the first phase of shortening is well constrained. Firstly, the presence of klippen of Paleozoic and Precambrian rocks over Triassic sediments in the Longmen Shan front indicate that these structures were formed during the late Triassic or later (Figs. 2a, 2d).

Secondly, geochronological data suggest that deformation had initiated before or at 237-190 Ma [Huang *et al.*, 2003; Weller *et al.*, 2013]: (i) the oldest U–Th–Pb monazite and Sm–Nd garnet ages (204-190 Ma), derived from metamorphosed rocks in the Danba Antiform, immediately south of the Longmen Shan, were interpreted as dating the timing of Barrovian metamorphism associated with the deformation [Huang *et al.*, 2003; Weller *et al.*, 2013]. (ii) $^{40}\text{Ar}/^{39}\text{Ar}$ dating of early Paleozoic schistose rocks from the northern Longmen Shan yielded ages between 237-208 Ma, which were interpreted as minimum age constraints for Mesozoic shortening [Yan *et al.*, 2011]. Thirdly, late Triassic flexural subsidence of the western Sichuan Basin, which accommodated > 4 km thick sediments in the foredeep, achieved the eastward loading and shortening along the Longmen Shan.

In late Cenozoic time, the Longmen Shan fold-thrust belt was reactivated [e.g., Burchfiel *et al.*, 1995; Wang *et al.*, 2012; Tian *et al.*, 2013]. This latest shortening is brittle and SE-SSE-verging, forming numbers of brittle faults, slickenlines, and widely developed fractures in the basement and Paleozoic rocks in the Longmen Shan. In the Longmen Shan front and southwestern Sichuan Basin, Eocene, Oligocene and Quaternary strata were folded and faulted [e.g., SBGMR, 1991; Burchfiel *et al.*, 1995; Jia *et al.*, 2006]. These structures and the evidence for active faulting [e.g., Densmore *et al.*, 2007; Zhang *et al.*, 2010] have been interpreted as a response to Cenozoic intra-continental shortening [e.g., Tian *et al.*, 2013]. Further, several low-temperature thermochronology studies suggest that the Longmen Shan experienced a phase of enhanced exhumation in the late Cenozoic [Kirby *et al.*, 2002; Godard *et al.*, 2009; Wang *et al.*, 2012; Cook *et al.*, 2013; Guenther *et al.*, 2014], and that the pattern of exhumation is controlled by the main faults [Tian *et al.*, 2013]. Worth noting is that Late Cenozoic sediments are absent along the Longmen Shan front. This may indicate that the shortening is not significant [Burchfiel *et al.*, 1995]. It is also possible that the sediments were once deposited and later removed by regional denudation in the Sichuan Basin, which experienced ~1-5 km unroofing since Oligocene time, as indicated by thermal history modelling of low-temperature thermochronological data [Richardson *et al.*, 2008; Tian *et al.*, 2012a,b].

3. Top-to-the-hinterland shear and coeval top-to-the-foreland shortening

Except for early Mesozoic and late Cenozoic phases of foreland-verging shortening, summarised above, a further set of deformation features characterised by top-to-the-hinterland shear, has been briefly reported in the southern Longmen Shan by previous studies [Burchfiel *et al.*, 1995; Xu *et al.*, 2008]. We expand on this observation through detailed structural mapping along two fluvial valleys (Fig. 2a), are presented below.

3.1. Top-to-the-hinterland shear

A belt of top-to-the-WNW shear deformation is mapped within Precambrian and Paleozoic rocks exposed east of the Paleozoic cover sediments (Figs. 1-3), as shown by various features at different scales in different rocks. On a regional scale, the deformation may have extended more than 200 kilometers from the southern Longmen Shan to the Danba Antiform, forming a continuous ductile top-to-the-WNW detachment fault (Fig. 1). At a local scale, top-to-the-WNW shear foliations, mineral stretching lineations, quartz boudinage features and a variety of deformation fabrics (e.g. S-C-C' fabrics, asymmetric folds) are observed in mylonised and/or schistose Neoproterozoic basement and early Paleozoic rocks east of the Longdong fault zone (Fig. 4).

The strongest deformation related to the shear was developed in the mylonitised and schistose Neoproterozoic basement rocks exposed immediately west of the WMF (Figs. 2-4). Within these rocks, mylonites with different matrix-to-porphyroblast ratios were developed (Figs. 4a, d). Aspect ratios of elongated minerals range between 2 and 10. Kinematic indicators (e.g. asymmetric fold, S-C-C' fabrics and sigmoidal objects) suggest a top-to-the-WNW sense of deformation (Figs. 4a-b). These observations, on an outcrop-scale, are consistent with those microstructures at both millimeter- (Fig. 4c) and micrometer-scales (lattice preferred orientation of quartz) [Xu *et al.*, 2008]. Furthermore, within the mylonite zone, undeformed Neoproterozoic basement rocks are also observed (Fig. 3a).

West of the mylonite zone, in the interbedded limestone-sandstone-mudstone Paleozoic cover rocks, the top-to-the-WNW shear foliation is parallel with the bedding (Fig. 2). In these layers brittle-ductile deformation features, such as boudinaged sandstone layers and S-C-C' fabrics, showing top-to-the-WNW directed shear, were developed (Fig. 2c). Early Paleozoic strata immediately west of the mylonitised pre-Cambrian rocks are considerably thinner than

those exposed in areas to the south and north (Figs. 2a, e). This attenuation zone has been named as the Longdong fault [e.g., *Tao et al.*, 1999].

Within the Paleozoic cover rocks, exposed immediately east of the WMF, boudinaged sandstone layers showing top-to-the-NW shear features are also observed (Figs. 4e1, e2). These deformed Paleozoic rocks are thought to be allochthonous in nature, and were juxtaposed above the eastern sheet of the basement rocks during late Cenozoic SE-verging thrusting (see section 5.2 for details).

The shear foliation and mineral stretching lineations dip and plunge mostly W-NW (Figs. 3, 4a), but occasionally towards the E-SE, and probably formed by tilting of the original foliation during late Cenozoic faulting (Fig. 3).

Mylonitisation associated with shearing occurred under greenschist-facies conditions. The mineral assemblages defining the foliation and/or lineation fabrics within the mylonitised basement rocks include quartz + feldspar + biotite + white mica + chlorite (Table 1), i.e. no high-grade metamorphic minerals were observed. Further, brittle-ductile deformation is common in most minerals (Fig. 5). For example, feldspar deformation is dominantly brittle, forming structures such as tapering deformation twins, kink bends and grain breakage (Figs. 5a, c). However, quartz in the mylonite was deformed ductily, as indicated by sigmoidal structures, undulose extinction in remnant quartz, and recrystallized quartz produced by subgrain rotation (SGR) (Figs. 5 b-e).

Previous temperature calibrations on quartz and feldspar deformation suggest that recrystallized quartz is formed by subgrain rotation (SGR) under low-medium grade conditions with deformation temperatures between 400-500°C, whereas undulose extinction in remnant quartz forms at lower temperatures (<300-400°C) [e.g., *Stipp et al.*, 2002; *Passchier and Trouw*, 2005]. Tapering deformation twins and kink bends in feldspar occur at similar deformation temperatures (400-500°C) [e.g., *Ji et al.*, 1998; *Passchier and Trouw*, 2005]. Therefore, the mineral assemblages and micro-deformation features described above suggest that deformation temperatures of the top-to-the- WNW shear may have reached a maximum temperature of 400-500°C, and most likely occurred at 300-450°C. This suggests that shear deformation occurred at a crustal depth of ~15-20 km, assuming a typical

geothermal gradient of 20-30°C/km for an orogenic belt [Pollack *et al.*, 1993; Hu *et al.*, 2000; Xu *et al.*, 2011].

The timing of top-to-the-WNW shear is late Cretaceous – early Paleogene, as constrained by new $^{40}\text{Ar}/^{39}\text{Ar}$ data is presented in section 4 below.

3.2. Coeval top-to-the-foreland shortening

On the foreland side, a phase of SE-directed late Cretaceous – early Paleogene shortening can be inferred from previously reported seismic profiles and the depositional history of the southwestern Sichuan Basin [Guo *et al.*, 1996; Jia *et al.*, 2006]. In the southwestern Sichuan Basin and areas farther south, a belt of late Cretaceous – early Paleogene depocenters, running parallel to the Longmen Shan strike, developed (Fig. 6). The coeval paleocurrent direction was eastward, indicating that the Longmen Shan and Songpan-Ganze terrane were the main sediment sources. The late Cretaceous – early Paleogene basins are interpreted as foreland basins, formed by crustal overloading along frontal thrusts of the Longmen Shan fold-thrust belt [SBGMR, 1991; Guo *et al.*, 1996].

Evidence for this phase of shortening along the Longmen Shan front is strongly supported by coeval growth strata revealed by seismic studies [Jia *et al.*, 2006] (Fig. 7). The late Cretaceous – early Paleogene age of sediments in the southwestern Sichuan Basin is well constrained by both paleomagnetic [Zhuang *et al.*, 1988; Enkin *et al.*, 1991; Huang and Opdyke, 1992] and paleontological data [SBGMR, 1991; Guo *et al.*, 1996]. This evidence suggests that the late Cretaceous – early Paleogene shortening is contemporaneous with the top-to-the-WNW shear the Longmen Shan hinterland side.

4. Sampling and analytical strategies

$^{40}\text{Ar}/^{39}\text{Ar}$ geochronology has been used to constrain the timing of the deformation. The dated samples cover the two main kinds of deformed rocks in the shear zone, namely mylonite and schist. One undeformed granite sample from the zone was also dated for comparison. All samples were collected from two transects in the southern and northern portions of the shear zone (Figs. 2, 3), where outcrops are fresh and deformation indicators

are clear. Detailed location information and petrographic features for the samples are listed in Table 1.

Biotite and white mica in the sheared samples are elongated and aligned along the foliation. Their dimensions are about 100-300 μm wide by $> 300 \mu\text{m}$ long (Fig. 5c-e). No inherited euhedral grains were observed. Biotite in the undeformed sample (BX100) is subhedral and coarse-grained, $\sim 400 \mu\text{m}$ in both width and length. Biotite in both deformed and undeformed samples is brown to green in colour and has been partly chloritised.

White mica and biotite separates as well as a fine-grained mineral aggregate (sample BX102 only) were prepared for $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology using standard crushing, sieving, electromagnetic, and heavy liquid mineral separation techniques. Each separate was then handpicked to the highest level of purity possible. Electron microprobe analyses (EMPA) were carried out on representative grains to quantify the composition of minerals used for $^{40}\text{Ar}/^{39}\text{Ar}$ analysis. Analyses were made on both grain margin and interior; and because no chemical zoning was observed, data from different grain areas are not distinguished.

Analytical methods for EMPA and $^{40}\text{Ar}/^{39}\text{Ar}$ analyses are detailed in Supplementary material S1 and S2, respectively and the resulting data are listed in Supplementary material Tables S1 and S2, respectively.

5. Results and interpretation

5.1. EMPA results

The K_2O versus SiO_2 plot differentiates the mineral aggregate, white mica and biotite samples (Fig. 8, Table S1). The mineral aggregate of sample BX102 shows significant variation in SiO_2 and K_2O , ranging from 25 to 98 wt% and from 0 to 11 wt%, respectively (Fig. 8a). These results are consistent with petrographic observations that the aggregate consists of a mixture of mica, feldspar and quartz. White mica in samples BX118 and BX127 has SiO_2 and K_2O content of 46-58 wt% and 10-12 wt%, respectively; whereas biotite shows relatively lower SiO_2 and K_2O content of 32-42 wt% and 7-10.3 wt%, respectively (Fig. 8b, Table S1).

Biotite microprobe results show evident compositional differences between deformed and undeformed samples (Fig. 9). Biotite from the undeformed sample BX100 has higher

FeO (27-35 wt%) and TiO₂ (2.1-3.2 wt%) contents, and lower MgO content (1-3 wt%) compared to mylonitised samples (BX118, BX120, BX127), whose FeO, TiO₂ and MgO content is 10-29 wt%, 0.9-2.0 wt% and 5-17 wt%, respectively (Fig. 9b, c). In the Al – Mg – Fe ternary plot, the undeformed biotite of BX100 falls on the boundary between the peraluminous (P) and alkaline (A) fields; whereas all deformed biotite fall into the calc-alkaline (C) field, or onto the calc-alkaline (C) and peraluminous (P) boundary (Fig. 9d). These results indicate that biotite composition may have changed significantly during mylonitisation by recrystallization, consistent with the petrographic observations that these biotite grains are elongated and aligned along the shear foliation (Fig. 5c-e). Furthermore, the K₂O content (7-10.3 wt%) in all biotite samples is lower than that of pure biotite (11%); this may be related to partial chloritisation observed in all samples (Table 1).

White mica from samples BX118 and BX127 have similar chemistry, except for Ti (Fig. 10 and Table S1). These white mica occurrences show an evident deviation from the end-member muscovite. They are phengitic and Si⁴⁺ varies between 6.60 and 6.75, as calculated based on 22 oxygens (Fig. 10a). The white mica compositions also deviate from the ideal muscovite-phengite tie line; and this may result from the increase of Fe and Mg replacing Al and to partial alteration (chloritisation), as shown by the negative relationship between the Mg+Fe (amu) and Al (amu) (Fig. 10b). The compositional deviation from muscovite is consistent with petrographic observations that they are elongated and form the mylonite foliation (Fig. 5e). Therefore, similar to biotite in the mylonite, the phengitic white mica was formed by recrystallisation during mylonitisation.

5.2. ⁴⁰Ar/³⁹Ar geochronological results

In samples, except for sample BX102, The biotite and white mica separates yield reasonably concordant age spectra, although sufficient discordance exists in some samples (BX120 and BX127) to preclude the calculation of plateau ages. White mica and biotite from the mylonite samples (BX102, BX118, BX120 and BX127) yield plateau and/or weighted mean ages ranging between 58 and 75 Ma (Figs. 8a-f, Table 2). The biotite ⁴⁰Ar/³⁹Ar age [61.0 ± 0.2 (2σ, if not specified) Ma] from the mylonite sample BX127 is slightly older by ~2% than the white mica age (59.4 ± 0.5) from the same sample. The inverse isochron plot of the

biotite data indicates an initial $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 304 ± 24 (Fig. S1), close to the atmospheric ratio (295.5), suggesting the absence of excess ^{40}Ar in the biotite sample.

Staircase age spectra are observed for the mineral aggregate sample BX102 (Fig. 8e), white mica samples BX118 and BX127 (Figs. 8a, c) and biotite sample BX120 (Fig. 8f). This pattern is most evident for the fine-grained mineral aggregate, which exhibits ages increasing from ~40-20 Ma to ~69-65 Ma from low to high temperature steps (Fig. 7e). Other age spectra include relatively young ages (75-40 Ma) from initial low temperature steps, representing <20% of the total ^{39}Ar released, but older and more consistent ages (73-59 Ma) for intermediate and high temperature steps (Figs. 8a, c, f). Biotite age spectra of samples BX118 and BX127 are relatively flat, yielding plateau ages of 61-58 Ma (Fig. 8b, d).

Compared to ages from the mylonite sample, biotite from the undeformed granite sample BX100 yields an older age, with the age spectrum characterised by an initial age increase from ~119 Ma to ~124 Ma followed by a decrease to ~115 Ma from low- to high-temperature steps (Fig. 8, Table 2). The low to intermediate temperature steps of the age spectrum yield an age plateau at 119.8 ± 1.6 Ma.

To summarize, the $^{40}\text{Ar}/^{39}\text{Ar}$ analyses show that: (1) white mica and mineral aggregates have staircase age spectra, whereas the biotite age spectra are flat; (2) the mylonite samples have younger ages (~75-58 Ma) than the undeformed granite (~120 Ma).

5.3. $^{40}\text{Ar}/^{39}\text{Ar}$ data interpretation

The biotite age of sample BX100 is evidently older than white mica and biotite ages from other samples, even though they are geographically close to each other (within 1.5 km). This age is unlikely to have resulted from the presence of excess ^{40}Ar for the following reasons. (1) The age spectra of this sample is flat; whereas those with excess ^{40}Ar are often irregular [e.g., *McDougall and Harrison, 1999*]. (2) The inverse isochron plot of the sample indicates an initial $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 288 ± 30 (Fig. S1), close to the atmospheric ratio (295.5), suggesting the absence of excess ^{40}Ar in the biotite sample. The $^{40}\text{Ar}/^{39}\text{Ar}$ age is significantly younger than the Precambrian rock crystallization age, indicating significant loss of radiogenic ^{40}Ar after emplacement. Considering that the dated biotite grains are undeformed (Fig. 5c-e), the loss of ^{40}Ar is likely to have resulted from hydrothermal alteration or thermal diffusion. On

the basis of these results, the early Cretaceous age of the sample BX100 is interpreted as resulting from the partial resetting of Precambrian biotite $^{40}\text{Ar}/^{39}\text{Ar}$ system during the late Cretaceous.

There are several possibilities that might account for the presence of younger ages in the initial steps of the white mica age spectra (Fig. 8a, c). Firstly, chemical alteration of white mica has been suggested as a possible mechanism to cause loss of ^{40}Ar and younger ages [e.g., Hames and Cheney, 1997; Allaz *et al.*, 2011; Verdel *et al.*, 2012]. Petrographic observations and EMPA results indicate partial alteration of the white mica and biotite. Interestingly, in our samples the form of the mylonite biotite age spectra do not appear to have been adversely influenced by the effects of alteration (Figs. 8b, d, f), in contrast to studies from other areas [e.g., Di Vincenzo *et al.*, 2003; Allaz *et al.*, 2011]. Furthermore, it is also likely that the younger ages in the initial degassing steps were caused by thermally induced diffusive loss of ^{40}Ar during Cenozoic exhumation, given that, similar to K-feldspars, muscovite may contain a distribution of ^{40}Ar diffusion domains [e.g., McDougall and Harrison, 1999; Harrison *et al.*, 2009]. The above interpretations are supported by the presence of the Cenozoic deformation phase (see above) and Miocene zircon (U-Th)/He cooling ages that record significant late Cenozoic exhumation of the mylonite [Tian *et al.*, 2013].

The staircase age spectrum of the mineral aggregate in sample BX102 (consisting of a mixture of micas, feldspar and quartz; Fig. 8e) is commonly observed in fine-grained mineral mixes [e.g., Kirschner *et al.*, 1996; Fergusson and Phillips, 2001]. The obviously younger mid - early Cenozoic ages (30-60 Ma) observed in the first degassing steps suggest partial loss of ^{40}Ar during the Cenozoic. This loss most likely results from the complex composition of the aggregate, as shown by both petrographic and EMPA results (Table 1 and Fig. 8a). Other mechanisms, such as chemical alteration (see above) or diffusive loss during Cenozoic cooling may also be possible. Furthermore, recoil loss and redistribution (between high- and low-potassium phases) of ^{39}Ar during irradiation of fine-grained minerals in a nuclear reactor may result in apparently older ages and negatively stepped age spectra [e.g., McDougall and Harrison, 1999; Fergusson and Phillips, 2001]. The total gas age of sample BX102 (58.6 ± 1.4 Ma) is slightly younger than those of other mylonite samples (75-58 Ma),

consistent with predominant partial loss of ^{40}Ar , as discussed above, and more limited ^{39}Ar recoil effects.

Nonetheless, a process is required to explain the presence of the consistent late Cretaceous – earliest Paleogene plateau or weighted mean ages (for the intermediate and high temperature steps) in all deformed samples. Dynamic recrystallization, intra-grain deformation and thermal resetting are two mechanisms for resetting Ar isotopic systematics [e.g., *Kirschner et al.*, 1996; *McDougall and Harrison*, 1999; *Mulch and Cosca*, 2004; *Cosca et al.*, 2011]. Biotite and white mica in the mylonite samples are strongly deformed and aligned along the shear foliation (Figs. 4, 5), suggesting that dynamic recrystallisation during shearing probably reset the Ar isotopic systematics, as reported from other foliated rocks [e.g., *Kirschner et al.*, 1996; *Dunlap*, 1997; *Mulch and Cosca*, 2004], and experimentally sheared samples [*Cosca et al.*, 2011]. This interpretation is supported by the petrographic and EMPA results, showing significant differences in biotite texture and composition between deformed and undeformed samples. Recrystallization during mylonitisation appears to have completely reset the Ar systematics. From this perspective, these late Cretaceous – earliest Paleogene $^{40}\text{Ar}/^{39}\text{Ar}$ ages are interpreted as the time of recrystallization, and thus mylonitisation.

Alternatively, argon systematics can be reset at high temperatures, in which case the mineral $^{40}\text{Ar}/^{39}\text{Ar}$ ages could be interpreted as cooling ages [e.g., *McDougall and Harrison*, 1999]. In this scenario, we would expect that $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the narrow mylonite zone (~2 kms wide) to be comparable, considering that they were exhumed from a similar depth. However, this is inconsistent with the observation that the undeformed granite sample BX100 from the mylonite zone yields a significantly older biotite age (119.8 ± 1.6 Ma) than the nearby mylonite samples. Thus, we argue that thermal overprinting was not the main process for resetting the $^{40}\text{Ar}/^{39}\text{Ar}$ systematics of the current samples. Similar findings have been reported in low-grade mylonites from other deformation belts [e.g. *Dunlap*, 1997; *Mulch and Cosca*, 2004; *Kellett et al.*, 2016].

6. Discussion

6.1. Lateral comparison of top-to-the-WNW shear deformation

Similar late Cretaceous - earliest Paleogene top-to-the-WNW shear has been reported in the Danba Antiform, immediately south of the area (Fig. 1b) [Xu *et al.*, 2008; Zhou *et al.*, 2008]. In that area, shearing was found to be associated with lower greenschist facies metamorphism, as indicated by a chlorite – biotite – muscovite – quartz mineral assemblage. $^{40}\text{Ar}/^{39}\text{Ar}$ biotite and muscovite ages from the deformation domain are 81-47 Ma [Zhou *et al.*, 2008]. The characteristics of the top-to-the-WNW shear in the Danba Antiform are similar to those observed in the study area of this work. Considering the adjacent location of the two areas, it is likely that the late Cretaceous - earliest Paleogene top-to-the-WNW shear may have extended ~200 kilometers from the Longmen Shan to the Danba Antiform.

On the basis of a rapid phase of cooling between 65-50 Ma, Wallis *et al.* [2003] argued for an early Cenozoic phase of Barrovian metamorphism and N-S crustal shortening in the Danba Antiform. These geochronology results are similar to those reported from other studies [Huang *et al.*, 2003; Xu *et al.*, 2008; Zhou *et al.*, 2008]. However, the structural results and interpretations are at odds with other detailed structural, petrological and geochronological studies which support late Triassic – early Jurassic Barrovian metamorphism and shortening [Huang *et al.*, 2003; Weller *et al.*, 2013], followed by a phase of top-to-the-WNW shearing, which is interpreted as resulting from late Cretaceous - earliest Paleogene extension [Xu *et al.*, 2008; Zhou *et al.*, 2008].

In areas to the north of the study area, no evidence for late Cretaceous - earliest Paleogene top-to-the-WNW shearing has been reported. Detailed structural studies by Yan *et al.* [2011] identified a phase of top-to-the-SE normal faulting in the northern Longmen Shan based on several lines of evidence: (i) juxtaposition of Silurian strata over the Precambrian basement, (ii) ductile deformation zones containing a 10–50 cm thick phyllonite and mylonite, showing top-to-the-SE normal faulting, (iii) presence of a high angle normal fault between Jurassic sediments and older strata. Yan *et al.* [2011] also reported three early Jurassic $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite ages (193-159 Ma) from the ductile normal faulting domain that may constrain the timing of this deformation. The early Jurassic normal faulting in the northern Longmen Shan differs in both the timing and sense of shear from the late Cretaceous - earliest Paleogene deformation in the southern Longmen Shan and Danba Antiform. If the difference in sense of shear was caused by re-orientation during the late Cenozoic shortening,

a massive clockwise rotation by 90-120° would be required, predicting a significant rotation of the Sichuan Basin. However, such rotation is not observed from paleomagnetic studies [Enkin *et al.*, 1991; Huang and Opdyke, 1992].

6.2. Late Cenozoic tectonic imprint

Within the WMF fault zone, where unambiguous top-to-the-WNW shear features are preserved, structural indicators showing SE-verging reverse faulting is also observed. These structures are mostly brittle or brittle-ductile, and co-planar with top-to-the-WNW shear. These features are interpreted as resulting from the late Cenozoic crustal shortening, shown by late Cenozoic structures in the basin front and significant (~7-10 km) rock exhumation inferred from thermochronological data (see section 2 for details). Based on this interpretation, it is speculated that Paleozoic strata, exposed between the two sheets of Neoproterozoic basement rocks (Fig. 2a), that show evidence of top-to-the-WNW shear (Figs. 4e1, e2), are allochthonous, and were juxtaposed above the eastern sheet of the basement rocks during late Cenozoic SE-verging thrusting (Fig. 2e). This explanation differs from that given by Burchfiel *et al.* [1995] and Cook *et al.* [2013], which interpreted the shear in those Paleozoic strata as indicating a Cenozoic normal fault penetrating through the Paleozoic sequence down to basement rocks at depth.

6.3. Dynamics of late Cretaceous - earliest Paleogene shear

Several geological and geophysical studies suggest that the Longmen Shan fold-and-thrust belt is thin skinned, characterised by a set of listric reverse faults that merge into a detachment at depths of ~20-30 km [Tian *et al.*, 2013, and references therein]. Such a crustal geometry is considered to have been inherited from early Mesozoic intra-continental shortening between the Songpan-Ganze terrane and the Sichuan Basin (Fig. 9a) [e.g., SBGMR, 1991; Burchfiel *et al.*, 1995; Chen *et al.*, 1995; Tian *et al.*, 2013].

The late Cretaceous – earliest Paleogene structural architecture, including contemporaneous top-to-the-hinterland shearing and top-to-the-foreland shortening in the hinterland and foreland sides respectively, is also thin-skinned. No high pressure-temperature metamorphic minerals, and no late Cretaceous – earliest Paleogene magmatism have been

reported in the study area. The deformation is therefore considered to have occurred under low-pressure-temperature conditions (greenschist metamorphic grade).

Previous studies interpreted the top-to-the-WNW shear as resulting from crustal extension [e.g. *Burchfiel et al.* 1995; *Xu et al.*, 2008; *Zhou et al.*, 2008]. In this case, a normal fault would be expected in areas west of the mylonite zone. The significantly attenuated Ordovician – Devonian cover rocks, which are mechanically weak shale and salt, may have hosted the normal fault. If the above interpretation is correct, the late Cretaceous – earliest Paleogene crustal configuration would be characterised by extension in the hinterland and shortening in the foreland. Such a deformation pattern would indicate that the late Cretaceous – earliest Paleogene Longmen Shan tectonics was controlled by crustal wedge extrusion (Fig. 12a). This tectonic model has been used for explaining similar structural configurations in other regions [e.g. *Burchfiel et al.* 1992], and implies that under conditions of compression, extrusion of a hinterland-tapering crustal wedge forms an extruded crustal wedge, bounded by a thrust on the foreland side and a normal fault on the hinterland side. This interpretation would predict an extensional basin in the hanging wall side of the extensional zone. However, late Cretaceous – earliest Paleogene sediments have not been mapped in the hinterland areas (Fig. 2a). It is also possible that the extensional basin might have been removed by significant Cenozoic denudation [e.g., *Arne et al.*, 1997; *Kirby et al.*, 2002, *Tian et al.*, 2013].

Alternatively, top-to-the-hinterland shearing could also be formed by crustal duplexing (Fig. 9b). This model infers that a crustal wedge, bounded by a foreland-ward floor thrust and a hinterland-ward roof thrust, is formed by numerous imbricate thrust faults branching off from a floor thrust and curve upward to join a roof thrust. The roof thrust can have an opposite sense-of-shear to the floor thrust [*Price*, 1986; *Webb et al.*, 2007, 2011]. The top-to-the-hinterland shear observed in the hinterland areas of the Longmen Shan may correspond to the deformation along the roof thrust in the model. This model is consistent with the regional W-E contraction stress field, and the development of the coeval foreland basin east of the Longmen Shan.

A third model, channel flow of middle and/or lower crust, can also produce a crustal configuration characterised by contemporaneous hinterland-ward shear and foreland-ward shortening [e.g., *Beaumont et al.*, 2001 and references therein]. The model involves melt-

weakened middle and/or lower crust, driven by topographic loading in an orogen interior and surface erosion at the orogen front, that decouples from the upper crust and flows outward towards the orogen front. Decoupling between the flowing middle and/or lower crust and upper crust forms a ductile hinterland-ward shear zone on the backside of the flow channel, and a thrust fault on the frontal side (Fig. 10a). One of the many features of this model is the presence of molten material (e.g. leucogranitic magmatism). However, such magmatism is absent from the Cretaceous – Cenozoic Longmen Shan. The youngest granitic intrusion in the Longmen Shan is late Jurassic, whereas younger plutons occur in areas along and south of the Xianshuihe fault [e.g., *Roger et al.*, 2008].

6.4. Inherited topographic relief and crustal thickness

Contemporaneous intra-continental hinterland-ward shear and foreland shortening has been recognized in other orogenic belts, such as the Miocene Himalayas (introduced above), late Devonian Quebec Appalachians [e.g., *Pinet et al.*, 1996; *Castonguay et al.*, 2007], Scandinavian Caledonides [e.g., *Hartz and Andresen*, 1997; *Grimmer et al.*, 2015], central East Greenland Caledonides [e.g., *White and Hodges*, 2002; *Johnston et al.*, 2010], and the Alpine orogen [e.g., *Tavarnelli*, 1999; *Schmid et al.*, 2004; *Selverstone*, 2005]. This kind of intra-continental deformation has been recognized during both syn- and post-orogenic periods in these orogens. Although the detailed processes and mechanisms for forming the structural combination vary fundamentally from one case to another, a common feature is that it occurs in regions with thickened crust [e.g., *Hartz and Andresen*, 1997; *Yin and Harrison*, 2000; *Schmid et al.*, 2004; *Grimmer et al.*, 2015]. It is therefore reasonable to suggest that Longmen Shan crust had reached a considerable thickness by the late Cretaceous – earliest Paleogene. This inference is consistent with the development of (1) a late Triassic – early Jurassic thickened crust as indicated by the coeval Barrovian metamorphism and shortening [*Huang et al.*, 2003; *Weller et al.*, 2013], and (2) a late Cretaceous – early Paleogene ~2-3 km foredeep in the southwestern Sichuan Basin (Fig. 6), indicating a high topographic load above the western margin.

6.5. Implications for regional Cenozoic tectonics

If correct, the interpretation of a pre-Cenozoic thickened crust in the Longmen Shan region would have important implications for the Cenozoic paleo-altimetry and tectonics of the eastern Tibetan Plateau. This interpretation is consistent with paleo-altimetric studies using oxygen isotopes by *Hoke et al.* [2015], which suggested that the southeastern Tibetan Plateau had reached its present high elevation by as early as late Eocene time. Further, it is likely that some of the present crustal thickness (~60 km) is inherited from the Mesozoic, highlighting the role of late Mesozoic tectonics in forming the thickened crust in the present eastern Tibetan Plateau, as proposed for other areas of the Tibetan Plateau [e.g., *England and Searle*, 1986; *Murphy et al.*, 1997; *Kapp et al.*, 2003; *Robinson et al.*, 2004].

Furthermore, possible pre-Cenozoic thickened crust has implications for geodynamic models proposed for explaining the Cenozoic deformation and the formation of the present thickened crust in the eastern Tibetan Plateau. The models can be categorised into two end-member models – the upper crustal shortening model [e.g., *Tapponnier et al.*, 2001; *Hubbard and Shaw*, 2009; *Tian et al.*, 2013] and the lower crustal flow model [e.g., *Burchfiel et al.*, 1995, 2008; *Clark et al.*, 2005; *Royden et al.*, 2008]. The first model argues that shortening in the Longmen Shan was triggered by eastward movement of the upper crust of the Songpan-Ganze terrane along a detachment fault at a depth of ~20-30 km. The thrust rocks were back-thrust, piled up and thrust upwards by steeply NW-dipping, out-of-sequence reverse faults beneath the Longmen Shan, thus building up the thickened crust and high elevations in the eastern Tibetan Plateau [*Tian et al.*, 2013]. The other end-member model, the lower crustal flow model, infers that the flow of ductile lower crustal material away from the central Tibetan Plateau, impeded by the strong crust of the Yangtze Craton beneath the Sichuan Basin, would increase topographic relief in the Longmen Shan by inflating its lower crust [e.g., *Burchfiel et al.*, 1995, 2008; *Clark et al.*, 2005; *Royden et al.*, 2008]. In this model, the upper crust responds passively to the extrusion of deeper materials; thus late Cenozoic normal faulting is predicted along the backside of the ‘channel’, which is regarded as the WMF [e.g., *Burchfiel et al.*, 2008; *Royden et al.*, 2008].

As to the upper crustal shortening model, the pre-Cenozoic thickened crust explains the formation of the present eastern Tibetan Plateau margin under limited upper crustal convergence. Inter-seismic GPS observations indicate that upper crustal NW-SE shortening

along the Longmen Shan is no more than 2-3 mm/yr [e.g., *Zhang et al.*, 2004]. Further, on the foreland side, no apparent deep late Cenozoic flexural basins were developed, suggesting total crustal shortening across the Longmen Shan was perhaps limited [*Burchfiel et al.*, 1995]. Such restricted convergence would be difficult to reconcile with a scenario for the formation of the thickened crust of the Longmen Shan. However, since the Longmen Shan probably gained considerable crustal thickness in pre-Cenozoic time, significant convergence involving an upper crustal mechanism may not be required, even though it cannot be ruled out [*Tian et al.*, 2013, and references therein].

Concerning the lower crustal flow model, as pointed out by *Rey et al.* [2010], a weak lower crust develops to allow lateral flow when a critical crustal thickness (~50 km) is reached, indicating that lower crustal flow is a consequence of crustal thickening, rather than its cause. If lower crustal flow did exist in the eastern Tibetan Plateau, it should be considered as a response to crustal thickening in both Cenozoic and pre-Cenozoic time; and its role in forming the thickened crustal should be minor and cannot be invoked to account for all the crustal thickening in this region of the plateau. Further, the timing of ductile hinterland-ward shear in the Longmen Shan hinterland as reported here, precludes it from being a response to late Cenozoic lower crustal flow, as proposed by previous studies [e.g., *Burchfiel et al.*, 1995, 2008; *Clark et al.*, 2005; *Royden et al.*, 2008].

7. Conclusions

Structural, petrographic, mineral composition and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological results reported in this work identify a phase of late Cretaceous – earliest Paleogene (58-75 Ma) top-to-the-hinterland shearing on the hinterland (western) side of the Longmen Shan. This deformation is contemporaneous with SE-verging thrusting on the foreland side. In the context of the regional geology, such a tectonic configuration could result either from extrusion of a crustal wedge or back-thrust in a duplex.

The development of intensive intra-continental deformation and a deep foreland basin in the southwestern Sichuan Basin suggest that a thickened crust likely already existed in the Longmen Shan by late Cretaceous – earliest Paleogene time. We therefore conclude that it is

likely that the present over-thickened crust in the eastern Tibetan Plateau is partly inherited from Mesozoic deformation events.

Acknowledgements

YT is grateful to Z. Tian and Z. Yan for field assistance, to S. Szczepanski for assistance with the $^{40}\text{Ar}/^{39}\text{Ar}$ analyses, to C. Seiler for his expert advice on structural geology, and A. Beard of Birkbeck for his assistance in microprobe analyses. The University of Melbourne $^{40}\text{Ar}/^{39}\text{Ar}$ facility is supported by the National Collaborative Research Infrastructure Strategy AuScope program. This manuscript was improved substantially by constructive reviews of A. Webb, A. Robinson, D. Kellett, P. Kapp and an anonymous reviewer, and editorial work by N. Niemi. A more detailed discussion of the analytical methodology can be found in the supporting information [Steiger and Jäger, 1977; Renne et al., 1998; McDougall and Harrison 1999]. The data for this paper are included in the manuscript and the associated supplementary materials.

References:

- Abdel-Ramman, A.-F. M., 1994, Nature of Biotites from Alkaline, Calc-alkaline, and Peraluminous Magmas: *Journal of Petrology*, v. 35, no. 2, p. 525-541, doi: 10.1093/petrology/35.2.525.
- Allaz, J., M. Engi, A. Berger, and I. M. Villa (2011), The Effects of Retrograde Reactions and of Diffusion on ^{40}Ar – ^{39}Ar Ages of Micas, *J. Petrol.*, 52(4), 691-716, doi: 10.1093/petrology/egq100.
- Beaumont, C., R. A. Jamieson, M. H. Nguyen, and B. Lee (2001), Himalayan tectonics explained by extrusion of a low-viscosity crustal channel coupled to focused surface denudation, *Nature*, 414(6865), 738-742.
- Burchfiel, B. C., Z. Chen, Y. Liu, and L. H. Royden (1995), Tectonics of the Longmen Shan and adjacent regions, central China, *Int. Geol. Rev.*, 37(8), 661-735.
- Burchfiel, B. C., C. Zhiliang, K. V. Hodges, L. Yuping, L. H. Royden, D. Changrong, and X. Jiene (1992), The South Tibetan Detachment System, Himalayan Orogen: Extension Contemporaneous With and Parallel to Shortening in a Collisional Mountain Belt, *Spec. Pap. Geol. Soc. Am*, 269, 1-41, doi: 10.1130/SPE269-p1.
- Burchfiel, B. C., L. H. Royden, R. D. van der Hilst, B. H. Hager, Z. Chen, R. W. King, C. Li, J. Lü, H. Yao, and E. Kirby (2008), A geological and geophysical context for the Wenchuan earthquake of 12 May 2008, Sichuan, People's Republic of China, *GSA Today*, 18(7), 1-11.

- Burg, J. P., M. Brunel, D. Gapais, G. M. Chen, and G. H. Liu (1984), Deformation of leucogranites of the crystalline Main Central Sheet in southern Tibet (China), *J. Struct. Geol.*, 6(5), 535-542, doi: [http://dx.doi.org/10.1016/0191-8141\(84\)90063-4](http://dx.doi.org/10.1016/0191-8141(84)90063-4).
- Castonguay, S., G. Ruffet, and A. Tremblay (2007), Dating polyphase deformation across low-grade metamorphic belts: An example based on $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite age constraints from the southern Quebec Appalachians, Canada, *Geol. Soc. Am. Bull.*, 119(7-8), 978-992, doi: 10.1130/b26046.1.
- Chang, E. Z. (2000), Geology and tectonics of the Songpan-Ganzi fold belt, southwestern China, *Int. Geol. Rev.*, 42(9), 813-831.
- Chen, S. F., C. J. L. Wilson, and B. A. Worley (1995), Tectonic transition from the Songpan-Ganzi fold belt to the Sichuan Basin, south-western China, *Basin Res.*, 7(3), 235-253.
- Clark, M. K., J. W. M. Bush, and L. H. Royden (2005), Dynamic topography produced by lower crustal flow against rheological strength heterogeneities bordering the Tibetan Plateau, *Geophys. J. Int.*, 162(2), 575-590, doi: 10.1111/j.1365-246X.2005.02580.x.
- Cook, K. L., L. H. Royden, B. C. Burchfiel, Y.-H. Lee, and X. Tan (2013), Constraints on Cenozoic tectonics in the southwestern Longmen Shan from low-temperature thermochronology, *Lithosphere*, 5(4), 393-406, doi: 10.1130/1263.1.
- Cosca, M., H. Stuntz, A.-L. Bourgeix, and J. P. Lee (2011), ^{40}Ar loss in experimentally deformed muscovite and biotite with implications for $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of naturally deformed rocks, *Geochim. Cosmochim. Acta*, 75(24), 7759-7778, doi: 10.1016/j.gca.2011.10.012.
- Densmore, A. L., M. A. Ellis, Y. Li, R. J. Zhou, G. S. Hancock, and N. Richardson (2007), Active tectonics of the Beichuan and Pengguan faults at the eastern margin of the Tibetan Plateau, *Tectonics*, 26, TC4005, doi:10.1029/2006TC001987.
- Di Vincenzo, G., C. Viti, and S. Rocchi (2003), The effect of chlorite interlayering on $^{40}\text{Ar}/^{39}\text{Ar}$ biotite dating: an $^{40}\text{Ar}/^{39}\text{Ar}$ laser-probe and TEM investigations of variably chloritised biotites, *Contributions to Mineralogy and Petrology*, 145(6), 643-658, doi: 10.1007/s00410-003-0472-z.
- Ding, L., D. Yang, F. L. Cai, A. Pullen, P. Kapp, G. E. Gehrels, L. Y. Zhang, Q. H. Zhang, Q. Z. Lai, Y. H. Yue, and R. D. Shi (2013), Provenance analysis of the Mesozoic Hoh-Xil-Songpan-Ganzi turbidites in northern Tibet: Implications for the tectonic evolution of the eastern Paleo-Tethys Ocean, *Tectonics*, 32, 34-48, doi: 10.1002/tect.20013.
- Dunlap, W. (1997), Neocrystallization or cooling? $^{40}\text{Ar}/^{39}\text{Ar}$ ages of white micas from low-grade mylonites, *Chem. Geol.*, 143(3-4), 181-203.
- England, P., and G. Houseman (1986), Finite Strain Calculations of Continental Deformation 2. Comparison With the India-Asia Collision Zone, *J. Geophys. Res.*, 91(B3), 3664-3676, doi: 10.1029/JB091iB03p03664.
- England, P., and M. Searle (1986), The Cretaceous-tertiary deformation of the Lhasa Block and its implications for crustal thickening in Tibet, *Tectonics*, 5(1), 1-14.
- Enkin, P. J., Y. Chen, V. Courtillot, J. Besse, L. Xing, Z. Zhang, Z. Zhuang, and J. Zhang (1991), A Cretaceous pole from south China, and the Mesozoic hairpin turn of the Eurasian apparent polar wander path, *Journal of Geophysical Research: Solid Earth*, 96(B3), 4007-4027, doi: 10.1029/90jb01904.

- Fergusson, C. L., and D. Phillips (2001), $^{40}\text{Ar}/^{39}\text{Ar}$ and K–Ar age constraints on the timing of regional deformation, south coast of New South Wales, Lachlan Fold Belt: problems and implications, *Aust. J. Earth Sci.*, 48(3), 395–408, doi: 10.1046/j.1440-0952.2001.00866.x.
- Godard, V., R. Pik, J. Lavé, R. Cattin, B. Tibari, J. de Sigoyer, M. Pubellier, and J. Zhu (2009), Late Cenozoic evolution of the central Longmen Shan, eastern Tibet: Insight from (U–Th)/He thermochronometry, *Tectonics*, 28, TC5009, doi:10.1029/2008TC002407.
- Grimmer, J. C., J. Glodny, K. Druppel, R. O. Greiling, and A. Kontny (2015), Early- to mid-Silurian extrusion wedge tectonics in the central Scandinavian Caledonides, *Geology*, 43(4), 347–350, doi: 10.1130/g36433.1.
- Guenther, W. R., P. W. Reiners, and Y. Tian (2014), Interpreting date–eU correlations in zircon (U–Th)/He datasets: A case study from the Longmen Shan, China, *Earth Planet. Sci. Lett.*, 403(0), 328–339, doi: http://dx.doi.org/10.1016/j.epsl.2014.06.050.
- Guo, Z., K. Deng, and Y. Han (1996), *Formation and Evolution of the Sichuan Basin*, Geologic Publishing House, Beijing.
- Halim, N., J. P. Cogné, Y. Chen, R. Atasiei, J. Besse, V. Courtillot, S. Gilder, J. Marcoux, and R. L. Zhao (1998), New Cretaceous and Early Tertiary paleomagnetic results from Xinling-Lanzhou basin, Kunlun and Qiangtang blocks, China: Implications on the geodynamic evolution of Asia, *J. Geophys. Res.*, 103(B9), 21025–21045, doi: 10.1029/98jb01118.
- Hames, W. E., and J. Cheney (1997), On the loss of ^{40}Ar from muscovite during poly/metamorphism, *Geochim. Cosmochim. Acta*, 61(18), 3863–3872.
- Harrison, T. M., P. Copeland, W. S. F. Kidd, and A. Yin (1992), Raising Tibet, *Science*, 255(5052), 1663–1670, doi: 10.1126/science.255.5052.1663.
- Harrison, T. M., J. Célérier, A. B. Aikman, J. Hermann, and M. T. Heizler (2009), Diffusion of ^{40}Ar in muscovite, *Geochim. Cosmochim. Acta*, 73(4), 1039–1051, doi: 10.1016/j.gca.2008.09.038.
- Hartz, E. H., and A. Andresen (1997), From collision to collapse: Complex strain permutations in the hinterland of the Scandinavian Caledonides, *Journal of Geophysical Research: Solid Earth*, 102(B11), 24697–24711, doi: 10.1029/97JB02275.
- Hoke, G. D., J. Liu-Zeng, M. T. Hren, G. K. Wissink, and C. N. Garzione (2014), Stable isotopes reveal high southeast Tibetan Plateau margin since the Paleogene, *Earth Planet. Sci. Lett.*, 394(0), 270–278, doi: http://dx.doi.org/10.1016/j.epsl.2014.03.007.
- Hu, S. B., L. J. He, and J. Y. Wang (2000), Heat flow in the continental area of China: a new data set, *Earth Planet. Sci. Lett.*, 179(2), 407–419.
- Huang, K., and N. D. Opdyke (1992), Paleomagnetism of Cretaceous to lower Tertiary rocks from southwestern Sichuan: a revisit, *Earth Planet. Sci. Lett.*, 112(1–4), 29–40, doi: http://dx.doi.org/10.1016/0012-821X(92)90004-F.
- Huang, M. H., I. S. Buick, and L. W. Hou (2003), Tectonometamorphic Evolution of the Eastern Tibet Plateau: Evidence from the Central Songpan–Garzê Orogenic Belt, Western China, *J. Petrol.*, 44(2), 255–278, doi: 10.1093/petrology/44.2.255.
- Hubbard, J., and J. H. Shaw (2009), Uplift of the Longmen Shan and Tibetan plateau, and the 2008 Wenchuan ($M = 7.9$) earthquake, *Nature*, 458(7235), 194–197.

- Hubbard, J., J. H. Shaw, and Y. Klinger (2010), Structural Setting of the 2008 Mw 7.9 Wenchuan, China, Earthquake, *Bull. Seismol. Soc. Am.*, *100*(5B), 2713-2735, doi: 10.1785/0120090341.
- Ji, S., A. Snoke, J. Tullis, and V. Todd (1998), Kink bands and recrystallization in plagioclase, in *Fault related rocks—a photographic atlas*, edited by A. W. Snoke, J. Tullis and V. R. Todd, pp. 278-279, Princeton University Press.
- Jia, D., G. Q. Wei, Z. X. Chen, B. L. Li, Q. Zen, and G. Yang (2006), Longmen Shan fold-thrust belt and its relation to the western Sichuan Basin in central China: New insights from hydrocarbon exploration, *AAPG Bull.*, *90*(9), 1425-1447.
- Johnston, S. M., E. H. Hartz, H. K. Brueckner, and G. E. Gehrels (2010), U–Pb zircon geochronology and tectonostratigraphy of southern Liverpool Land, East Greenland: Implications for deformation in the overriding plates of continental collisions, *Earth Planet. Sci. Lett.*, *297*(3–4), 512-524, doi: <http://dx.doi.org/10.1016/j.epsl.2010.07.003>.
- Kapp, P., P. G. DeCelles, G. E. Gehrels, M. Heizler, and L. Ding (2007), Geological records of the Lhasa-Qiangtang and Indo-Asian collisions in the Nima area of central Tibet, *Geol. Soc. Am. Bull.*, *119*(7-8), 917-933, doi: 10.1130/b26033.1.
- Kapp, P., M. A. Murphy, A. Yin, T. M. Harrison, L. Ding, and J. Guo (2003), Mesozoic and Cenozoic tectonic evolution of the Shiquanhe area of western Tibet, *Tectonics*, *22*(4), 1029.
- Kellett, D. A., C. Warren, K. P. Larson, H. Zwingmann, C. R. van Staal, and N. Rogers (2016), Influence of deformation and fluids on Ar retention in white mica: Dating the Dover Fault, Newfoundland Appalachians, *Lithos*, *254–255*, 1-17, doi: <http://dx.doi.org/10.1016/j.lithos.2016.03.003>.
- Kirby, E., P. W. Reiners, M. A. Krol, K. X. Whipple, K. V. Hodges, K. A. Farley, W. Q. Tang, and Z. L. Chen (2002), Late Cenozoic evolution of the eastern margin of the Tibetan Plateau: Inferences from Ar-40/Ar-39 and (U-Th)/He thermochronology, *Tectonics*, *21*(1), 10.1029/2000TC001246.
- Kirschner, D. L., M. A. Cosca, H. Masson, and J. C. Hunziker (1996), Staircase 40/Ar39Ar spectra of fine-grained white mica: Timing and duration of deformation and empirical constraints on argon diffusion, *Geology*, *24*(8), 747-750, doi: 10.1130/0091-7613(1996)024<0747:saasof>2.3.co;2.
- Li, Y., P. A. Allen, A. L. Densmore, and X. Qiang (2003), Evolution of the Longmen Shan Foreland Basin (Western Sichuan, China) during the Late Triassic Indosinian orogeny, *Basin Res.*, *15*(1), 117-138.
- Ludwig, K. R. (1991), ISOPLOT: a plotting and regression program for radiogenic-isotope data: version 2.53Rep., Open File Report 91-445, U. S. Geological Survey.
- Matchan, E., and D. Phillips (2011), New 40Ar/39Ar ages for selected young (<1 Ma) basalt flows of the Newer Volcanic Province, southeastern Australia, *Quat. Geochronol.*, *6*(3–4), 356-368, doi: <http://dx.doi.org/10.1016/j.quageo.2011.03.002>.
- McDougall, I., and T. M. Harrison (1999), *Geochronology and Thermochronology by the 40Ar/39Ar Method*, Oxford University Press, New York.
- Meng, Q. R., J.-M. Hu, E. Wang, and H.-J. Qu (2006), Late Cenozoic denudation by large-magnitude landslides in the eastern edge of Tibetan Plateau, *Earth Planet. Sci. Lett.*, *243*(1-2), 252-267.

- Molnar, P. (1988), Continental tectonics in the aftermath of plate tectonics, *Nature*, 335, 131-137.
- Mulch, A., and M. A. Cosca (2004), Recrystallization or cooling ages: in situ UV-laser $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of muscovite in mylonitic rocks, *J. Geol. Soc.*, 161(4), 573-582.
- Murphy, M. A., A. Yin, T. M. Harrison, S. B. Durr, C. Z. F. J. Ryerson, W. S. F. Kidd, W. X. and Z. X (1997), Did the Indo-Asian collision alone create the Tibetan plateau?, *Geology*, 25(8), 719-722, doi: 10.1130/0091-7613(1997)025<0719:dtiaca>2.3.co;2.
- Passchier, C. W., and R. A. J. Trouw (2005), *Microtectonics*, Springer Verlag, Berlin Heidelberg.
- Pinet, N., M. Tremblay, and M. Sosson (1996), Extension versus shortening models for hinterland-directed motions in the southern Québec Appalachians, *Tectonophysics*, 267(1-4), 239-256, doi: [http://dx.doi.org/10.1016/S0040-1951\(96\)00096-0](http://dx.doi.org/10.1016/S0040-1951(96)00096-0).
- Pollack, H. N., S. J. Hurter, and J. R. Johnson (1993), Heat flow from the Earth's interior: Analysis of the global data set, *Rev. Geophys.*, 31(3), 267-280, doi: 10.1029/93RG01249.
- Price, R. A. (1986), The southeastern Canadian Cordillera: Thrust faulting, tectonic wedging, and exhumation of the lithosphere, *J. Struct. Geol.*, 8(3-4), 239-254, doi: [http://dx.doi.org/10.1016/0191-8141\(86\)90046-5](http://dx.doi.org/10.1016/0191-8141(86)90046-5).
- Renne, P. R., C. C. Swisher, A. L. Deino, D. B. Karner, T. L. Owens, and D. J. DePaolo (1998), Intercalibration of standards, absolute ages and uncertainties in $^{40}\text{Ar}/^{39}\text{Ar}$ dating, *Chem. Geol.*, 145(1-2), 117-152, doi: [http://dx.doi.org/10.1016/S0009-2541\(97\)00159-9](http://dx.doi.org/10.1016/S0009-2541(97)00159-9).
- Rey, P. F., C. Teyssier, and D. L. Whitney (2010), Limit of channel flow in orogenic plateaux, *Lithosphere*, 2(5), 328-332, doi: 10.1130/1114.1.
- Richardson, N. J., A. L. Densmore, D. Seward, A. Fowler, M. Wipf, M. A. Ellis, L. Yong, and Y. Zhang (2008), Extraordinary denudation in the Sichuan Basin: Insights from low-temperature thermochronology adjacent to the eastern margin of the Tibetan Plateau, *J. Geophys. Res.*, 113, B04409, doi:10.1029/2006JB004739., doi: 10.1029/2006jb004739.
- Robinson, A. C., A. Yin, C. E. Manning, T. M. Harrison, S. H. Zhang, and X. F. Wang (2004), Tectonic evolution of the northeastern Pamir: Constraints from the northern portion of the Cenozoic Kongur Shan extensional system, western China, *Geol. Soc. Am. Bull.*, 116(7-8), 953-973, doi: 10.1130/b25375.1.
- Roger, F., M. Jolivet, and J. Malavieille (2008), Tectonic evolution of the Triassic fold belts of Tibet, *Comptes Rendus Geosciences*, 340(2-3), 180-189.
- Roger, F., S. Calassou, J. Lancelot, J. Malavieille, M. Mattauer, X. Zhiqin, H. Ziwen, and H. Liwei (1995), Miocene emplacement and deformation of the Konga Shan granite (Xinshui He fault zone, west Sichuan, China): Geodynamic implications, *Earth Planet. Sci. Lett.*, 130(1-4), 201-216, doi: 10.1016/0012-821x(94)00252-t.
- Royden, L. H., B. C. Burchfiel, and R. D. van der Hilst (2008), The Geological Evolution of the Tibetan Plateau, *Science*, 321(5892), 1054-1058, doi: 10.1126/science.1155371.
- SBGMR (Sichuan Bureau of Geology and Mineral Resources) (1976), Geological map of the Baoxing area, scale 1:200,000, sheet G-48-XIII, Chengdu.
- SBGMR (Sichuan Bureau of Geology and Mineral Resources) (1991), *Regional Geology of Sichuan Province*, 728 pp., Geol. Publ. House, Beijing.

- Schmid, S., B. Fügenschuh, E. Kissling, and R. Schuster (2004), Tectonic map and overall architecture of the Alpine orogen, *Eclogae Geologicae Helvetiae*, 97(1), 93-117, doi: 10.1007/s00015-004-1113-x.
- Selverstone, J. (2005), Are the Alps Collapsing?, *Annu. Rev. Earth Planet. Sci.*, 33(1), 113-132, doi: 10.1146/annurev.earth.33.092203.122535.
- Steiger, R. H., and E. Jäger (1977), Subcommittee on geochronology: Convention on the use of decay constants in geo- and cosmochemistry, *Earth Planet. Sci. Lett.*, 36(3), 359-362, doi: [http://dx.doi.org/10.1016/0012-821X\(77\)90060](http://dx.doi.org/10.1016/0012-821X(77)90060)
- Stipp, M., H. Stünitz, R. Heilbronner, and S. M. Schmid (2002), The eastern Tonale fault zone: a natural laboratory for crystal plastic deformation of quartz over a temperature range from 250 to 700° C, *J. Struct. Geol.*, 24(12), 1861-1884.
- Tapponnier, P., Z. Xu, F. Roger, B. Meyer, N. Arnaud, G. Wittlinger, and J. Yang (2001), Oblique Stepwise Rise and Growth of the Tibet Plateau, *Science*, 294(5547), 1671-1677, doi: 10.1126/science.105978.
- Tavarnelli, E. (1999), Normal faults in thrust sheets: pre-orogenic extension, post-orogenic extension, or both?, *J. Struct. Geol.*, 21(8-9), 1011-1018, doi: [http://dx.doi.org/10.1016/S0191-8141\(99\)00034-6](http://dx.doi.org/10.1016/S0191-8141(99)00034-6).
- Tian, Y., B. P. Kohn, A. J. W. Gleadow, and S. Hu (2013), Constructing the Longmen Shan eastern Tibetan Plateau margin: insights from low-temperature thermochronology, *Tectonics*, 32, 576-592, doi: 10.1002/tect.20043.
- Tian, Y., B. P. Kohn, C. Zhu, M. Xu, S. Hu, and A. J. W. Gleadow (2012a), Post-orogenic evolution of the Mesozoic Micang Shan Foreland Basin system, central China, *Basin Res.*, 24(1), 70-90, doi: 10.1111/j.1365-2117.2011.00516.x.
- Tian, Y., N. Qiu, B. P. Kohn, C. Zhu, S. Hu, A. J. W. Gleadow, and B. I. A. McInnes (2012b), Detrital zircon (U-Th)/He thermochronometry of the Mesozoic Daba Shan Foreland Basin, central China: Evidence for timing of post-orogenic denudation, *Tectonophysics*, 570-571, 65-77, doi: 10.1016/j.tecto.2012.08.010.
- Verdel, C., B. A. van der Pluijm, and N. Niemi (2012), Variation of illite/muscovite ⁴⁰Ar/³⁹Ar age spectra during progressive low-grade metamorphism: an example from the US Cordillera, *Contributions to Mineralogy and Petrology*, 164(3), 521-536, doi: 10.1007/s00410-012-0751-7.
- Wallis, S., T. Tsujimori, M. Aoya, T. Kawakami, K. Terada, K. Suzuki, H. Hyodo, J. Qin, Z. Xia, and J. Tian (2003), Cenozoic and Mesozoic metamorphism in the Longmenshan orogen: Implications for geodynamic models of eastern Tibet, *Geology*, 31(9), 745-748, doi: 10.1130/g19562.1.
- Wang, E., E. Kirby, K. P. Furlong, M. van Soest, G. Xu, X. Shi, P. J. J. Kamp, and K. V. Hodges (2012), Two-phase growth of high topography in eastern Tibet during the Cenozoic, *Nat. Geosci.*, 5(9), 640-645, doi: 10.1038/ngeo1538.
- Wang, E., X. Meng, Z. Su, Q. Meng, J. J. Chu, Z. Chen, G. Wang, X. Shi, and X. Liang (2014), Block rotation: Tectonic response of the Sichuan basin to the southeastward growth of the Tibetan Plateau along the Xianshuihe-Xiaojiang fault, *Tectonics*, 2013TC003337, doi: 10.1002/2013TC003337.
- Webb, A. A. G., A. Yin, T. M. Harrison, J. Célérier, and W. P. Burgess (2007), The leading edge of the Greater Himalayan Crystalline complex revealed in the NW Indian Himalaya:

- Implications for the evolution of the Himalayan orogen, *Geology*, 35(10), 955-958, doi: 10.1130/g23931a.1.
- Webb, A. A. G., A. K. Schmitt, D. He, and E. L. Weigand (2011), Structural and geochronological evidence for the leading edge of the Greater Himalayan Crystalline complex in the central Nepal Himalaya, *Earth Planet. Sci. Lett.*, 304(3-4), 483-495, doi: 10.1016/j.epsl.2011.02.024.
- Weller, O. M., M. R. St-Onge, D. J. Waters, N. Rayner, M. P. Searle, S. L. Chung, R. M. Palin, Y. H. Lee, and X. Xu (2013), Quantifying Barrovian metamorphism in the Danba Structural Culmination of eastern Tibet, *J. Metamorph. Geol.*, 31(9), 909-935, doi: 10.1111/jmg.12050.
- White, H. R., and K. V. Hodges (2002), Multistage extensional evolution of the central East Greenland Caledonides, *Tectonics*, 21(5), 1048, doi: 10.1029/2001TC001308.
- Worley, B., R. Powell, and C. J. L. Wilson (1997), Crenulation cleavage formation: Evolving diffusion, deformation and equilibration mechanisms with increasing metamorphic grade, *J. Struct. Geol.*, 19(8), 1121-1135, doi: 10.1016/s0191-8141(97)00026-6.
- Wu, C., K. D. Nelson, G. Wortman, S. D. Samson, Y. Yue, J. Li, W. S. F. Kidd, and M. A. Edwards (1998), Yadong cross structure and South Tibetan Detachment in the east central Himalaya (89°–90°E), *Tectonics*, 17(1), 28-45, doi: 10.1029/97tc03386.
- Xu, M., C. Zhu, Y. Tian, S. Rao, and S. Hu (2011), Borehole temperature logging and characteristics of subsurface temperature in Sichuan Basin, *Chin. J. Geophys.*, 54(4), 1052-1060.
- Xu, Z. Q., L. W. Hou, Z. X. Wang, X. F. Hu, and M. H. Huang (1992), *Orogenic processes of the Songpan-Garzê orogenic belt of China*, 190 pp., Geological Publishing House, Beijing.
- Xu, Z. Q., S. C. Ji, H. B. Li, L. W. Hou, X. F. Fu, and Z. H. Cai (2008), Uplift of the Longmen Shan range and the Wenchuan earthquake, *Episodes*, 31(3), 291-301.
- Yan, D. P., M.-F. Zhou, S.-B. Li, and G.-Q. Wei (2011), Structural and geochronological constraints on the Mesozoic-Cenozoic tectonic evolution of the Longmen Shan thrust belt, eastern Tibetan Plateau, *Tectonics*, 30, TC6005, doi:10.1029/2011TC002867, doi: 10.1029/2011tc002867.
- Yin, A., and T. M. Harrison (2000), Geologic Evolution of the Himalayan-Tibetan Orogen, *Annu. Rev. Earth Planet. Sci.*, 28(1), 211-280, doi: 10.1146/annurev.earth.28.1.211.
- Zhang, P.-Z., X.-z. Wen, Z.-K. Shen, and J.-h. Chen (2010), Oblique, High-Angle, Listric-Reverse Faulting and Associated Development of Strain: The Wenchuan Earthquake of May 12, 2008, Sichuan, China, *Annu. Rev. Earth Planet. Sci.*, 38(1), 353-382, doi: 10.1146/annurev-earth-040809-152602.
- Zhang, P., Z. Shen, M. Wang, W. Gan, R. Burgmann, P. Molnar, Q. Wang, Z. Niu, J. Sun, J. Wu, S. Hanrong, and Y. Xinzhaoh (2004), Continuous deformation of the Tibetan Plateau from global positioning system data, *Geology*, 32(9), 809-812, doi: 10.1130/g20554.1.
- Zhou, M. F., D.-P. Yan, P. M. Vasconcelos, J.-W. Li, and R.-Z. Hu (2008), Structural and geochronological constraints on the tectono-thermal evolution of the Danba domal terrane, eastern margin of the Tibetan plateau, *J. Asian Earth Sci.*, 33(5-6), 414-427, doi: DOI: 10.1016/j.jseaes.2008.03.003.

Zhuang, Z. H., D. X. Tian, X. H. Ma, X. F. Ren, X. C. Jiang, and S. L. Xu (1988), A paleomagnetic study along the Ya'an-Tianquan Cretaceous–Eogene section in Sichuan Basin:, *Geophys. Geochem. Explor.*, 12, 224–228.

Author Manuscript

Tables:

Table 1. Locality, petrographic and microstructural data of dated samples.

Sample No.	Lithology	Location (°E/°N)	Mineral assemblage	Dated minerals	Grain size (µm)	Micro-deformation features in quartz (Q) and feldspar (Fds)
BX100	Undeformed granite	102.886/ 30.559	Q + Fds + Bt + Wm + Chl	Bt	>300	-
BX102	Granitic mylonite	102.762/ 30.414	Q + Fds + Agg + Hb + Chl	Agg	<5	Tapering deformation twins and kink bend for fds; Undulose extinction and recrystallized subgrain for Q
BX118	Granitic mylonite	102.880/ 30.574	Q + Fds + Bt + Wm + Chl	Bt, Wm	180- 250	Brittle fracture for Fds; Undulose extinction and recrystallized subgrain for Q
BX120	Biotite schist	102.878/ 30.579	Bt + Q + Wm + Chl	Bt	180- 250	Undulose extinction and recrystallized subgrain for Q
BX127	Granitic mylonite	102.883/ 30.566	Q + Fds + Bt + Wm + Chl	Bt, Wm	180- 250	Brittle fracture for Fds; Undulose extinction and recrystallized subgrain for Q

Mineral abbreviations: Agg = aggregate, a mixture of fine-grained white mica, quartz, and feldspar; Bt = Biotite; Chl = Chlorite; Fds = Feldspar; Hb = Hornblende; Wm = white mica; Q = Quartz.

Table 2. Summary of $^{40}\text{Ar}/^{39}\text{Ar}$ dating results.

Sample No.	Mineral	* Plateau age (Ma $\pm$ 2 σ)	* Weighted mean age (Ma $\pm$ 2 σ)	% ^{39}Ar in plateau or weighted mean age (Ma $\pm$ 2 σ)	Total gas age (Ma $\pm$ 2 σ)
BX100	Biotite	119.8 $\pm$ 0.8	119.8 $\pm$ 1.3	55%	120.5 $\pm$ 2.4
BX102	Aggregate	-	67.3 $\pm$ 2.6	38%	58.6 $\pm$ 1.4
BX118	Biotite	57.8 $\pm$ 0.5	57.8 $\pm$ 0.5	63%	59.2 $\pm$ 0.8
BX118	white mica	73.3 $\pm$ 0.4	73.3 $\pm$ 0.4	68%	72.7 $\pm$ 1.0
BX120	Biotite	-	75.1 $\pm$ 1.4	85%	73.9 $\pm$ 0.4
BX127	Biotite	61.0 $\pm$ 0.2	61.0 $\pm$ 0.2	100%	61.1 $\pm$ 0.6
BX127	White mica	-	59.4 $\pm$ 0.5	85%	58.8 $\pm$ 0.4

* Calculated using Isoplot [Ludwig, 1991].

Figure captions:

Figure 1. (a) Tectonic map showing the main structures of the Tibetan Plateau and location of the study area (shaded square). Abbreviations: ATF = Altyn Tagh Fault; DA = Danba Antiform; GXF = Ganzi-Xianshuihe Fault; HF = Haiyuan Fault; JF = Jiali Fault; KLF = Kunlun Fault; KF = Karakorum Fault; RRF = Red River Fault; SF = Sagaing fault, SGT = Songpan-Ganze terrane, TB = Tarim Basin, TP = Tibetan Plateau. (b) Generalized geological map of the Longmen Shan, modified after SBGMR [1991], Burchfiel et al. [1995], and Tian et al. [2015]. Also shown is the location of Fig. 2. F1 = Guanxian-Anxian Fault; F2 = Yingxin-Beichuan Fault; F3 = Wenchuan-Maowen Fault; BM = Baoxing massif; PM = Pengguan massif; XM = Xuelongbao massif.

Figure 2. (a) Detailed geological map of the southern Longmen Shan that combines our mapping results with the geological map of the Baoxing area (scale: 1:200,000) [SBGMR, 1976]. Labels for lithological units are explained in the legend. (b) View to the west of an overturned fold (F1) in Triassic flysch with stereographic projection of the F1 fold axial planes representative of the folding in Triassic flysch in the southern Longmen Shan hinterland. This indicates that D1 deformation results from NNW-SSE shortening. (c) Southwestward view of early Paleozoic sandstone that outcrops west of the WMF fault zone. (d) S-C-C' fabrics showing a top-to-the-NW sense of shear. (e) Geological section (X-X' in 2a) across the southern Longmen Shan.

Figure 3. Two cross-sections (a1, b1), showing detailed geology of the mylonite belt with locations of samples collected for $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology. Also shown are the (a2) and (b2) stereographic projections of the top-to-the-WNW shear foliation and lineation measured at sites along the (a1) and (b1) cross-sections respectively. The locations of these cross-sections are shown in Fig. 2. For clearer illustration of the profiles, the horizontal axes of panel a1 and b1 have been exaggerated by ~8 and ~40 times, respectively.

Figure 4. Characteristic kinematic indicators for top-to-the-WNW shearing. (a) Block view showing top-to-the-WNW shear foliation and stretching lineation on the foliation surface (sample BX118), and kinematic indicators on the facet parallel to the lineation and normal to the foliation. (b) Close-up view of the left-lateral sigmoidal granitic porphyroblast shown in panel (a). (c) Sigmoidal quartz porphyroblast showing top-to-the-WNW-ward sense of shear (sample BX118). (d) Polished surface showing contact between mylonite with different matrix-to-porphyroclast ratios. S(C)-C' fabric in the relatively coarser mylonite shows top-to-the-WNW sense of shear (sample BX104). (e1, e2) Southwestward view of boudinaged sandstone interbedded with mudstone (outcropping immediately east of the WMF fault zone), showing top-to-the-NW-ward shear. Panel e2 is schematic of e1. (f) left-lateral sigmoidal feldspar porphyroblast in mylonitised Neoproterozoic volcanic rock. See figure 3 and table 1 for sample locations.

Figure 5. Microscopic features of dated samples. (a) Brittle kink bands and tapering deformation twins in feldspar, surrounded by quartz subgrains and mineral aggregates formed by fine-grained mica, quartz and feldspar (sample BX102); (b) Undulose extinction in remnant quartz core, surrounded by elongated and recrystallized quartz subgrains in sample BX102. (c) Feldspar surrounded by elongated and recrystallized quartz subgrains (BX118). (d) Dynamically recrystallized quartz formed by subgrain rotation recrystallization (BX120). Biotite in this sample is elongated and aligned along the shear foliation. (e) Elongated white mica and biotite, distributed in the pressure shadow around a porphyroclast in sample BX127.

The sub-horizontally distributed mineral aggregate (a and b), biotite (panels c-e) and white mica (d) defines the shear foliation. See figure 3 and table 1 for sample locations. (f) Microscope photo of undeformed sample BX100. Biotite in the sample is subhedral.

Figure 6. Isopach map (m) for late Cretaceous - early Paleogene sedimentation in the southwestern Sichuan Basin, modified after Guo et al. [1996]. Development of the foredeep in front of the southern Longmen Shan required significant thrust loading along the southwestern margin of the Sichuan Basin. The approximate location of figure 2 is marked for comparison.

Figure 7. A seismic profile oriented across the Longmen Shan front, modified from Jia et al. [2006]. See figure 2 for location. Note the late Cretaceous – Paleogene growth strata in the forelimb of an anticline, indicating coeval crustal shortening at the Longmen Shan front, which is interpreted here as D_2^2 . Abbreviations (from young to old): OL = base of Oligocene (Lushan Formation); EM = base of Eocene and Paleocene (Mingshan Formation); KG = base of uppermost Cretaceous (Guankou Formation); KJ = base of Lower Cretaceous (Jiaguan Formation); J = base Jurassic; TX = base of Upper Triassic (Xujiahe Formation).

Fig. 8. (a) SiO_2 versus K_2O plots for all samples. The plot shows that the mineral aggregate of sample BX102 has significant variations in SiO_2 and K_2O content. (b) A close-up view of SiO_2 versus K_2O plot of white mica and biotite samples. White mica has higher SiO_2 and K_2O content than biotite.

Figure 9. (a) Al_2O_3 versus K_2O , (b) MgO versus FeO (total Fe as FeO), and (c) MgO versus TiO_2 scatter plots for all biotite samples. (d) Ternary plot of Al_2O_3 , MgO and FeO content of all biotite samples. Fields for alkaline (A), calc-alkaline (C) field and peraluminous (P) as defined by Abdel-Rahman (1994).

Figure 10. (a) Al (atu) versus Si (atu), (b) Al (atu) versus Mg+Fe (atu), (c) Ti (atu) versus Si (atu), and (d) Fe (atu) versus Mg (atu) plots for white mica samples. Most elements are similar in content in the two samples, except for Ti and Al.

Figure 11. $^{40}\text{Ar}/^{39}\text{Ar}$ spectra plots. Steps filled in black are those fulfilling requirements for calculating plateau ages. Results and statistics related to plateau age calculations are summarised in the lower panel of relevant plots. Arrows above the age spectra show the range of steps used for calculating weighted mean ages (above the arrows). Age calculation results are summarised in Table 2; and detailed step-heating results are presented in Supplementary material S2.

Figure 12. Possible models for explaining contemporaneous late Cretaceous – earliest Paleogene top-to-the-hinterland shear and foreland thrusting in the Longmen Shan. (a) Crustal wedge extrusion model. Extrusion of a crustal wedge forms a crustal configuration with extensional zone and a shortening zone in the hinterland and foreland, respectively. (b) Duplex model. This model infers that a crustal wedge, bounded by a foreland-ward floor thrust and a hinterland-ward roof thrust, is formed by numerous imbricate thrust faults branching off from a floor thrust, which curve upwards to join a roof thrust. The roof thrust can have a top-to-the-hinterland sense of shear, opposite sense-of-shear to the floor thrust. (c) Lower crustal flow model. Outward extrusion of melt-weakened lower crust forms a normal fault and a thrust at the back and front of the flow channel, respectively (modified from Beaumont et al. 2004).

Author

A

Auth

Minerva Access is the Institutional Repository of The University of Melbourne

Author/s:

Tian, Y;Kohn, BP;Phillips, D;Hu, S;Gleadow, AJW;Carter, A

Title:

Late Cretaceous-earliest Paleogene deformation in the Longmen Shan fold-and-thrust belt, eastern Tibetan Plateau margin: Pre-Cenozoic thickened crust?

Date:

2016-10-01

Citation:

Tian, Y., Kohn, B. P., Phillips, D., Hu, S., Gleadow, A. J. W. & Carter, A. (2016). Late Cretaceous-earliest Paleogene deformation in the Longmen Shan fold-and-thrust belt, eastern Tibetan Plateau margin: Pre-Cenozoic thickened crust?. *TECTONICS*, 35 (10), pp.2293-2312. <https://doi.org/10.1002/2016TC004182>.

Persistent Link:

<http://hdl.handle.net/11343/291803>