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Zhenhua Xue, Wei Lin, Yang Chu, Michel Faure, Yan Chen, Wenbin Ji,  
Huaning Qiu

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1 **An intracontinental orogen exhumed by basement-slice-imbrication in the**  
2 **Longmenshan Thrust Belt of the Eastern Tibetan Plateau**

3  
4 **Zhenhua Xue<sup>1,2,3</sup>, Wei Lin<sup>2,4</sup>, Yang Chu<sup>2,4</sup>, Michel Faure<sup>3</sup>, Yan Chen<sup>3</sup>, Wenbin Ji<sup>5</sup>,**  
5 **Huaning Qiu<sup>6</sup>**

6 <sup>1</sup>School of Earth Sciences, China University of Geosciences, Wuhan 430074, China

7 <sup>2</sup>State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics,  
8 Chinese Academy of Sciences, Beijing 100029, China

9 <sup>3</sup>Univ. Orléans, CNRS, BRGM, ISTO, UMR 7327, F-45071, Orléans, France

10 <sup>4</sup>University of Chinese Academy of Sciences, Beijing 100049, China

11 <sup>5</sup>Department of Geology, Northwest University, Xi'an 710069, China

12 <sup>6</sup>Key Laboratory of Tectonics and Petroleum Resources (China University of  
13 Geosciences), Ministry of Education, Wuhan 430074, China

14 Corresponding author: Wei Lin (linwei@mail.iggcas.ac.cn)

15  
16 **Key Points**

17 1. The double-vergent structure of the Longmenshan belt was established during the  
18 late Triassic intracontinental underthrusting

19 2. Boundary faults of the NW-normal faulting and SE-thrusting facilitated the SE-ward  
20 basement-slice imbrication

21 3. The episodic basement-slice imbrication exhumed the early Mesozoic metamorphic  
22 rocks

23  
24 **Abstract** The Longmenshan Thrust Belt (LMTB) in the Eastern Tibet resulted from a  
25 Mesozoic orogeny and Cenozoic reworking. It is generally believed that the Cenozoic  
26 tectonics along the LMTB are mostly inherited from the Mesozoic one. Reconstruct the  
27 Mesozoic tectonics of the LMTB is therefore important for understanding its  
28 evolutionary history. On the basis of detailed structural analysis, we recognized a Main  
29 Central Boundary that divides the LMTB into a Southeastern Zone and a Northwestern  
30 Zone. Both zones underwent a main D<sub>1</sub> event characterized by the D<sub>1E</sub> top-to-the-SE  
31 thrusting in the Southeastern Zone and the D<sub>1W</sub> top-to-the-NW/N thrusting in the  
32 Northwestern Zone. In the Southeastern Zone, a D<sub>2</sub> top-to-the-NW/N normal faulting

33 that cuts the D<sub>1E</sub> structures is developed along the NW boundary of the basement  
34 complexes. Newly obtained and previous geochronological data indicate that the D<sub>1E</sub>  
35 and D<sub>1W</sub> event occurred synchronously at *ca.* 224–219 Ma, and the D<sub>2</sub> top-to-the-NW/N  
36 normal faulting was episodically activated at *ca.* 166–160 Ma, 141–120 Ma, 81–47 Ma  
37 and 27–25 Ma. Episodically and synchronously activated top-to-the-NW normal  
38 faulting and top-to-the-SE thrusting along the northwest and southeast boundary of the  
39 basement complexes, respectively, let us propose that the basement-slices were  
40 episodically imbricated to the SE during the late Jurassic–early Cretaceous and late  
41 Cretaceous–earliest Paleocene. The D<sub>1</sub> amphibolite-facies metamorphic rocks above  
42 the basement complexes recorded fast exhumation during the late Jurassic–early  
43 Cretaceous. We propose that the early Mesozoic northwestward basement  
44 underthrusting along a crustal “weak zone” was responsible for the D<sub>1</sub> double-vergent  
45 thrusting and amphibolite-facies metamorphism. Subsequent basement-slice  
46 imbrications reworked the LMTB and exhumed the amphibolite-facies rocks. Our  
47 results highlight the importance of basement underthrusting and imbrication in the  
48 formation and reworking of the intracontinental Longmenshan Thrust Belt in the  
49 Eastern Tibet.

50

## 51 **1. Introduction**

52 The Longmenshan Thrust Belt (LMTB; Figure 1a), at the eastern margin of the  
53 Tibetan Plateau, has attracted attentions of geologists due to the paradox between low  
54 convergence rate (Zhang et al., 2004; Shen et al., 2009) and extremely high topographic  
55 gradient (Clark and Royden, 2000; Royden et al., 2008) as well as intense seismic  
56 activities (e.g., 2008 Wenchuan Mw 7.9 earthquake, 2013 Lushan Mw 7.0 earthquake,  
57 and 2017 Jiuzhaigou Mw 7.0 earthquake). This paradox has spawned a vigorous debate  
58 regarding the roles of upper crustal faulting (Hubbard and Shaw, 2009) and lower crust  
59 channel flow (Royden et al., 2008) in building and maintaining such a high Tibetan  
60 Plateau margin. However, both models attribute shortening and crustal thickening of  
61 the LMTB to the late Cenozoic evolution, and underestimate the importance of widely  
62 recognized Mesozoic tectonics along the LMTB (Xu et al., 1992; Burchfiel et al., 1995;  
63 Worley and Wilson, 1996). Furthermore, it has been reached a consensus that the  
64 LMTB is mainly inherited from the Mesozoic tectonic framework (Burchfiel et al.,

65 1995; Meng et al., 2005). Elucidating the Mesozoic tectonics of the LMTB and its  
66 adjacent areas is therefore crucial to understand the tectonic evolution of the LMTB.

67 The prominent deformation recorded in the LMTB and adjacent areas is indicated  
68 by observations including: 1) the peripheral foreland basin formed due to the  
69 southeastward thrusting and loading of the LMTB (Chen et al., 1994; Li et al., 2003);  
70 2) the early Jurassic rocks unconformably overlies extensively folded late Triassic rocks  
71 (BGMRSF, 1991; Xu et al., 1992; Burchfiel et al., 1995); 3) the pervasive orogen-  
72 parallel klippen and nappe belt sitting on the foot hills of the Longmen Mountains are  
73 believed related to the regional top-to-the-SE thrusting (Figure 2); 4) the consistent top-  
74 to-the-SE thrusting indicated by different indicators at various scales (Xu et al., 1992;  
75 Burchfiel et al., 1995; Chen et al., 1995; Chen and Wilson, 1996; Jia et al., 2006; Yan  
76 et al., 2011; Yan et al., 2018); 5) the pervasive upright folding in the adjacent Songpan–  
77 Ganzi Terrane was thought synchronous to the early Mesozoic deformation of the  
78 LMTB (Burchfiel et al., 1995; Chen et al., 1995; Harrowfield and Wilson, 2005). This  
79 prominent deformation event was constrained to *ca.* 234–200 Ma by basin tectonics,  
80 timing of the top-to-the-SE/SSE shearing and syntectonic metamorphism, which  
81 indicated an early Mesozoic orogeny of the LMTB (Chen et al., 1994; Li et al., 2003;  
82 Yan et al., 2011; Zheng et al., 2014; Xue et al., 2016; Zheng et al., 2016; Airaghi et al.,  
83 2018a; Airaghi et al., 2018b; Yan et al., 2018).

84 The early Mesozoic tectonic evolutionary mechanism accounting for the above  
85 observations, however, is still in dispute. Sengör (1984) and Luo (1991) suggested that  
86 the LMTB is an early Mesozoic intracontinental subduction zone accommodating  
87 multi-stage crustal shortening. Then, Xu et al. (1992) proposed a bivergent subduction  
88 model in which the Songpan–Ganzi Terrane sedimentary cover has been “pushed” to  
89 the southeast on top of the Yangtze Block due to the bivergent subduction along the  
90 Anyuqen and Jinshajiang Suture Zones. The current models suggested that the  
91 Songpan–Ganzi sedimentary cover were overthrust southwards on the Yangtze Block  
92 along a decollement in response to the closure of the Paleotethys (Mattaer et al., 1992;  
93 Calassou, 1994; Dirks et al., 1994; Chen and Wilson, 1996; Worley and Wilson, 1996;  
94 Roger et al., 2004; Harrowfield and Wilson, 2005; de Sigoyer et al., 2014; Yan et al.,  
95 2018).

96 Apart from the early Mesozoic top-to-the-SE/SSE thrusting along the LMTB, an  
97 increasing number of studies proposed a top-to-the-NW normal faulting that developed

98 along the NW boundary of the orogen-parallel and stripped Neoproterozoic complexes  
99 (Figure 1b)(Xu et al., 2008; Zhou et al., 2008; Tian et al., 2016; Billerot et al., 2017;  
100 Xue et al., 2017; Airaghi et al., 2018b). However, timing and significance of the top-  
101 to-the-NW normal faulting are in dispute that have resulted in several different models,  
102 such as: 1) mid-Jurassic to early Paleogene (173–160 Ma and 81–47 Ma) post orogenic  
103 extension (comparing to the early Mesozoic orogeny)(Zhou et al., 2008), 2) early  
104 Cretaceous (~120 Ma) crustal-scale wedge extrusion (Xu et al., 2008), 3) episodic  
105 eastward basement-slice-imbrication during the late Jurassic–early Cretaceous and late  
106 Cretaceous–Earliest Paleogene (Billerot et al., 2017; Xue et al., 2017), and, 4)  
107 formation of a late Cretaceous–earliest Paleogene crustal scale duplex (Tian et al.,  
108 2016). Based on the above compilation, most previous works have proposed that the  
109 top-to-the-NW normal faulting occurred in the late Mesozoic.

110 Major questions therefore remain unsolved: 1) Considering previous early Mesozoic  
111 tectonic models of the LMTB, whether did the significant shortening recorded in the  
112 LMTB correspond to the imbricated thrust system during the Paleotethys' closure, or  
113 to the intracontinental underthrusting along the Longmenshan belt? 2) What is the  
114 tectonic significance of the top-to-the-NW normal faulting (mostly late Mesozoic) and  
115 emplacement of the Neoproterozoic complexes? Therefore, an overall accurate  
116 reconstruction of the Mesozoic tectonics of the LMTB and its adjacent areas, especially  
117 its detailed structural analysis and timing, are of great importance.

118 This study presents detailed field investigations focusing on structural geometry and  
119 kinematic reconstruction, and geochronological constraints including zircon U–Pb  
120 dating of synkinematic plutonic rocks and  $^{40}\text{Ar}/^{39}\text{Ar}$  dating on the synmetamorphic  
121 micas of the LMTB. In conjunction with previous published geochronological and  
122 metamorphic data, a new geodynamic model was proposed to interpret the Mesozoic  
123 tectonic evolutionary history of the LMTB.

124

## 125 **2. Geological Setting**

126 At the eastern margin of the Tibetan Plateau, the LMTB separates the intensely  
127 folded and metamorphosed (Greenschist facies grade) Songpan–Ganzi Terrane to the  
128 NW, and the weakly/undeformed Sichuan Basin to the SE (Figure 1a). The triangle-  
129 shaped Songpan–Ganzi Terrane is separated from the western Qinling–Dabie Orogenic

130 Belt to the north by the East Kunlun–Anymaqen Suture Zone, from the Qiangtang  
131 Block to the southwest by the Jinshajiang Suture Zone (Figure 1a).

## 132 2.1 Songpan–Ganzi Terrane

133 The Songpan–Ganzi Terrane mainly comprises ~5–15 km-thick intensely folded late  
134 Triassic turbidites (Calassou, 1994; Harrowfield and Wilson, 2005; Zhang et al., 2006c;  
135 Zhang et al., 2008; Yin, 2015). The provenance of the turbidites includes the Kunlun  
136 Mountains, North China Block, South China Block and southwest Qinling Orogenic  
137 Belt (Yin and Nie, 1993; Enkelmann et al., 2007; Weislogel et al., 2010). Voluminous  
138 felsic plutons intruded the Songpan–Ganzi Terrane at *ca.* 226–205 Ma, dominantly  
139 derived from partial melting of the Neoproterozoic basement and sedimentary cover of  
140 the Songpan–Ganzi Terrane, with negligible amounts of mantle material (Figure  
141 1b)(Roger et al., 2004; Hu et al., 2005; Zhang et al., 2006b; Zhang et al., 2007; de  
142 Sigoyer et al., 2014). Both geophysical and geological data indicate a continental crust  
143 of Yangtze Block affinity underlying the eastern Songpan–Ganzi Terrane (Roger et al.,  
144 2004; Hu et al., 2005; Zhang et al., 2009; Weislogel et al., 2010; Zhang et al., 2010;  
145 Guo et al., 2013).

## 146 2.2 Sichuan Basin of the Yangtze Block

147 The Sichuan Basin, located in the Yangtze Block of northwest South China Block  
148 (Figure 1a), preserves a Paleoproterozoic to Neoproterozoic basement overlain by  
149 Neoproterozoic to Cenozoic sedimentary sequences. Silurian–Devonian abyssal  
150 deposits and radiolarian chert suggested a long period of rifting during the Silurian to  
151 Devonian ages along the western part of the Yangtze Block (Long, 1991; Luo, 1991;  
152 Chang, 2000; Li, 2009). This rift was revealed by high-resolution seismic reflection  
153 profile as well (Jia et al., 2006). During middle–late Triassic ages, coeval with the  
154 southeastward thrusting and loading of the LMTB, the western Sichuan Basin began  
155 subsiding flexurally and evolved into an epicontinental foreland basin (Figure 2).  
156 Thrust sheets were transported to the southeast synchronously and intensely folded at  
157 the end of the late Triassic (Chen et al., 1994; Chen and Wilson, 1996; Li et al., 2013c).  
158 The continuous sedimentation of the middle Jurassic–upper Cretaceous deposits  
159 implies a pronounced subsidence at the western Sichuan foreland basin during this  
160 period (Burchfiel et al., 1995; Chen et al., 1995). Episodic SE-ward thrusting and  
161 loading of the LMTB were indicated by the wedge-shaped megasequences of the  
162 western Sichuan foreland basin, namely, in late Triassic–early Jurassic, late Jurassic–

163 early Cretaceous and late Cretaceous–earliest Paleocene (Xu et al., 2008; Li et al.,  
164 2013c; Tian et al., 2016).

### 165 2.3 The LMTB

166 The NE-striking LMTB merges into the western Qinling Orogenic Belt to the  
167 northeast and is truncated by the Xianshuihe Fault to the southwest (Figure 1a).

#### 168 2.3.1 Major faults of the LMTB

169 The regional tectonic architecture of the LMTB is defined by four major NE–SW  
170 striking faults, namely from the southeast to the northwest, the Anxian–Guanxian Fault  
171 ( $T_1$  in Figure 1b), the Yingxiu–Beichuan Fault ( $T_2$  in Figure 1b), the Wenchuan–  
172 Maoxian Fault ( $T_3$  in Figure 1b), and the Qingchuan–Pingwu Fault ( $T_4$  in Figure 1b).

173 The Anxian–Guanxian Fault dips to the northwest by  $30\text{--}50^\circ$  and crosscuts the late  
174 Triassic–early Jurassic rocks. Approaching northwestwards, the Yingxiu–Beichuan  
175 Fault dipping  $40\text{--}60^\circ$  to the NW separates the Sichuan foreland basin to the southeast  
176 from the LMTB hinterland (BGMRSF, 1991; Xu et al., 1992; Burchfiel et al., 1995).

177 The Wenchuan–Maoxian Fault dipping  $30\text{--}50^\circ$  to the NW was episodically activated  
178 since *ca.* 220 Ma (Burchfiel et al., 1995; Yan et al., 2008; Zheng et al., 2016). Seismic  
179 reflection profile showed that the ENE-striking Qingchuan–Pingwu Fault dips to the  
180 NNW or SSE at variable angles (Wang et al., 2000; Jia et al., 2006; Lin et al., 2014).

181 The northern LMTB was dissected by the Qingchuan–Pingwu Fault and incorporated  
182 to northwestward- and southeastward-thrusting that resemble a positive flower  
183 structure (Jia et al., 2006). The Wenchuan–Maoxian Fault and Qingchuan–Pingwu  
184 Fault are characterized by mylonite overprinted by breccia and gouge (Chen and Wilson,  
185 1996; Li et al., 2013a; Li et al., 2015).

#### 186 2.3.2 Basement complexes in the LMTB

187 The basement complexes that distributes from the NE to the SW in the LMTB are  
188 composed of Neoproterozoic meta-granites overlain by a Neoproterozoic meta-  
189 sedimentary cover, such as the Danba (DB), Kanding (KD), Wulong (WL), Baoxing  
190 (BX), Pengguan (PG), Moutuo (MT), Xuelongbao (XLB) and Jiaoziding (JZD)  
191 complexes (Figure 1b). These basement complexes share similar lithology with the  
192 Yangtze Block basement (BGMRSF, 1991). Field observations, Anisotropy of  
193 Magnetic Susceptibility (AMS) and gravity modeling have suggested that these  
194 basement complexes were strongly deformed and imbricated southeastwards as

195 basement-slices (Ma et al., 1996; Xu et al., 2008; Tian et al., 2016; Airaghi et al., 2017b;  
196 Billerot et al., 2017; Xue et al., 2017).

### 197 2.3.3 Metamorphism in the LMTB

198 Two amphibolite facies metamorphic zones have been recognized in the meta-  
199 sedimentary cover in the Wenchuan–Xuelongbao area and the Danba area (Dirks et al.,  
200 1994; Huang et al., 2003a; Zhou et al., 2008; Airaghi et al., 2018a; Airaghi et al., 2018b).  
201 Petrological studies (garnet–amphibolite–biotite thermometer, pseudosection using  
202 Perplex modeling and chlorite–white mica–quartz thermal dynamic equilibrium)  
203 constrain the peak metamorphic conditions at  $\sim 11 \pm 2$  kbar,  $\sim 620$  °C in the Wenchuan–  
204 Xuelongbao area (Dirks et al., 1994; Airaghi et al., 2018a) and  $\sim 5.3$ –8 kbar, 570–680  
205 °C in the Danba area (Huang et al., 2003a; Weller et al., 2013). The Wenchuan–  
206 Xuelongbao metamorphic belt reached amphibolite facies conditions at *ca.* 210–180  
207 Ma (Airaghi et al., 2018a; Airaghi et al., 2018c) and recorded fast exhumation at *ca.*  
208 140–120 Ma (Arne et al., 1997; Airaghi et al., 2018c). The Danba amphibolite-facies  
209 metamorphic belt reached peak conditions at *ca.* 205–180 Ma (Huang et al., 2003a;  
210 Weller et al., 2013) and initiated enhanced rapid cooling at *ca.* 168–158 Ma (Huang et  
211 al., 2003a; Zhou et al., 2008).

212 Apart from these two amphibolite facies metamorphic zones, late Triassic  
213 blueschists occur as lenses along the Qingchuan–Pingwu Fault, with peak metamorphic  
214 pressure attained to 5.2–6.5 kbar (Wei, 1994; Xu et al., 2020). The blueschist then have  
215 been retrograded to greenschist in a nearly isothermal decompression way (Wei, 1994).

### 216 2.3.4 Tectonic events of the LMTB

217 The LMTB recorded at least three phases of deformation, including (1) D<sub>1</sub>, the late  
218 Triassic to early Jurassic regional top-to-the-SE thrusting, (2) D<sub>2</sub>, the top-to-the-NW/N  
219 normal faulting of poorly constrained timing and tectonic significance, and (3) D<sub>3</sub>, the  
220 Cenozoic shortening reactivation (Xu et al., 1992; Burchfiel et al., 2008; Richardson et  
221 al., 2008; Xu et al., 2008; Li et al., 2013a; Li et al., 2015; Tian et al., 2016; Xue et al.,  
222 2017). The D<sub>1</sub> deformation is well identified by penetrative cleavages (S<sub>1</sub>), mineral and  
223 stretching lineation (L<sub>1</sub>) in the Wenchuan area, and the top-to-the-SE thrust sheets and  
224 nappes over the intensely folded late Triassic sequences in the western Sichuan foreland  
225 basin (Xu et al., 1992; Burchfiel et al., 1995; Worley and Wilson, 1996; Li et al., 2003).  
226 Most parts of the Songpan–Ganzi Terrane show slow cooling rate at *ca.* 1°C/Ma since  
227 the early Mesozoic (Huang et al., 2003a; Huang et al., 2003b; Roger et al., 2011).



228 However, an enhanced cooling event (*ca.* 8°C/Ma) during the late Jurassic to Eocene  
229 was reported at the peripheries of the Songpan–Ganzi Terrane, especially in the  
230 Wenchuan and Danba areas (Yuan et al., 1991; Arne et al., 1997; Huang et al., 2003a).  
231 This rapid cooling event probably responded to the D<sub>2</sub> top-to-the-NW/N normal  
232 faulting. The belt characterized by the top-to-the-NW normal faulting developed along  
233 the northwest/north boundary of the basement complexes was entitled as the East Tibet  
234 Detachment (Wang et al., 2012b). The D<sub>3</sub> deformation was thought to have initiated  
235 since *ca.* 30–25 Ma that builds the present Longmen mountains of the eastern Tibetan  
236 Plateau (Clark and Royden, 2000; Kirby et al., 2002; Wang et al., 2012a).

237

### 238 **3. Structural analysis of the LMTB**

#### 239 3.1 Structural subdivisions of the LMTB

240 The LMTB was interpreted as an allochthonous sheet thrusting southeastward upon  
241 the autochthonous western Sichuan Foreland Basin (Xu et al., 1992; Burchfiel et al.,  
242 1995; Worley and Wilson, 1996; Robert et al., 2010a). Based on structural  
243 investigations, we present revised structural subdivisions of the LMTB. Firstly, the  
244 LMTB is divided into a Southeastern Zone and a Northwestern Zone by a Main Central  
245 Boundary (see Section 3.2; Figure 3a). According to the lithology, deformation  
246 intensity, and metamorphic grade, the Southeastern Zone can be further subdivided into  
247 four subdivisions (Figure 3). They are, from the southeast to the northwest: i) the  
248 undeformed Autochthon that comprises the western part of the Sichuan Foreland Basin,  
249 ii) the Para-autochthon, transported southeastwards along the Anxian–Guanxian Fault  
250 and rests over the Autochthon, iii) the Allochthon that traveled southeastwards much  
251 further on top of the Para-autochthon, and iv) the Inner Metamorphic Core that recorded  
252 the highest metamorphic conditions (*i.e.*, amphibolite facies) among the Southeastern  
253 Zone. The four subdivisions in the Southeastern Zone are separated by the three major  
254 listric faults of the LMTB (Figure 3; see in Section 2.3.1).

255 i) The Autochthon, located to the southeast of the Anxian–Guanxian Fault, is mainly  
256 composed of Jurassic–Cretaceous strata and overlying Cenozoic sediments (Figures 3  
257 and 4). The Jurassic–Cretaceous strata were deposited in circumstances of alluvial,  
258 fluvio-deltaic, and lacustrine fills, characterized by medium and coarse-grained  
259 sandstone with some conglomeratic layers at the base. Total thickness of the Jurassic–  
260 Cretaceous sequences is more than 5 km (BGMRSP, 1991). In the northern part of the

261 LMTB, close to Anxian and Jiangyou county, the early Jurassic and overlying  
262 Cretaceous to Cenozoic sequences are dipping to the southeast that unconformably rest  
263 on the intensively folded late Triassic rocks (Figures 2 and 4c–d)(BGMRSF, 1991).

264 ii) The Para-autochthon is sandwiched by the Anxian–Guanxian Fault and the  
265 Yingxiu–Beichuan Fault, with its half area covered by klippen and nappes from the  
266 Allochthon (Figure 3). The Late Triassic Xujiahe Formation dominated in this  
267 subdivision either passes up from the earliest late Triassic marine sandstone or  
268 unconformably overlies the middle Triassic limestone (Li et al., 2003; Meng et al.,  
269 2005). The Xujiahe Formation shows markable lateral variation in both thickness and  
270 sedimentary facies. Coarse-grained sediments, such as alluvial conglomerate bodies  
271 occur close to the Yingxiu–Beichuan Fault, but change into fine-grained lacustrine  
272 sediments toward to the basin interior.

273 iii) The Allochthon is mainly exposed between the Wenchuan–Maoxian Fault and  
274 the Yingxiu–Beichuan Fault, and also includes the klippen and nappes resting on top  
275 of the Para-autochthon (Figures 2 and 3a). Northwest to the Yingxiu–Beichuan Fault,  
276 this subdivision mainly consists of Silurian shale and greywacke with the bedding  
277 completely transposed into foliation. Greenschist-facies metamorphism is indicated by  
278 mineral assemblages of fine-grained muscovite + chlorite + quartz (Airaghi et al.,  
279 2017b; Xue et al., 2017). Metamorphic condition jumps of  $\sim 50$  °C, 3–5 kbar  
280 southeastwards across the Yingxiu–Beichuan Fault suggest that the Allochthon are  
281 more deformed and metamorphosed in a deeper structural level than the Para-  
282 autochthon (Robert et al., 2010a; Airaghi et al., 2018b). Neoproterozoic complexes  
283 including the Pengguan and Jiaoziding complexes are distributed in this subdivision.  
284 Southeast to the Yingxiu–Beichuan Fault, klippen and nappes are mainly composed of  
285 Devonian to early Triassic thick-bedded limestone and marine sandstone (Figures 2, 3  
286 and 4a–d).

287 iv) The Inner Metamorphic Core comprises phyllite and micaschist that are mostly  
288 metamorphosed Silurian sediments (Figures 2 and 3). Amphibolite-facies metamorphic  
289 zone that wraps the oval-shaped Xuelongbao (XLB in Figure 2) and stripped Moutuo  
290 (MT in Figure 2) complexes records the highest-grade metamorphism within the  
291 Southeastern Zone (Dirks et al., 1994; Airaghi et al., 2017a; Airaghi et al., 2018a). Peak  
292 P–T condition attained to  $\sim 11 \pm 2$  kbar and  $\sim 620$  °C at the southernmost margin of the  
293 Xuelongbao complex calculated from metamorphic assemblages of biotite + garnet +

294 staurolite + muscovite + kyanite (Dirks et al., 1994; Airaghi et al., 2018a). Based on  
295 the enhanced metamorphic grade and deformation intensity, the Inner Metamorphic  
296 Core are therefore more deformed and metamorphosed in a deeper structural level than  
297 the Allochthon.

298 The Northwestern Zone includes eastern Songpan–Ganzi Terrane with  
299 Neoproterozoic sequences outcropped in the north and Paleozoic sequences outcropped  
300 in the south (Figures 2 and 3). The northern Northwestern Zone mainly consists of two  
301 Neoproterozoic Groups, namely, 1) the volcanic Bikou Group defined by mafic lavas  
302 within its lower part and ranges from mafic to intermediate–felsic within its upper  
303 portion, and 2) the Hengdan Group tectonically resting on the Bikou Group is composed  
304 of black, thin-bedded pyrite-bearing shales and interbedded thinly volcanoclastic  
305 sandstone and siltstone (Yan et al., 2003; Druschke and Wang, 2006). The southern  
306 Northwestern Zone includes Devonian Weixian Formation and the Triassic sequences.  
307 The Devonian sequences consist mainly of quartziferous phyllite to schist and  
308 interbedded quartzite. The overlying Triassic Xikang Group is dominated by thick and  
309 highly repetitious flysch sediments. Although different rock units comprising the  
310 northern and southern Northwestern Zone, it was metamorphosed under similar  
311 greenschist facies conditions (Figures 1b and 2)(Xu et al., 1992; Liu et al., 2008)

312

### 313 3.2 The Main Central Boundary

314 The Main Central Boundary serves as a major tectonic boundary separating the  
315 Northwestern Zone and the Southeastern Zone. It corresponds to the southern branch  
316 of the Qingchuan Fault (T<sub>4</sub> in figure 2) in the north (BGMRSF, 1991), and to a vertical  
317 cleavage zone within the Paleozoic rocks in the south (Figure 2). To the SE of the Main  
318 Central Boundary, all structural planes in the Southeastern Zone, including foliations,  
319 cleavages, and fold axial planes, are exclusively dipping to the NW. Various kinematic  
320 indicators in the Southeastern Zone suggest a consistent top-to-the-SE/S thrusting. To  
321 the NW of the Main Central Boundary, the Northwestern Zone is characterized by the  
322 SSE-dipping planar structures and associated top-to-the-NW thrusting (Figure 3).

323 The Qingchuan–Pingwu Fault, as the northern segment of the Main Central  
324 Boundary, is a major tectonic boundary. Seismic profiles, drill data (Jia et al., 2006)  
325 and field observations indicate that the Qingchuan–Pingwu Fault is a positive flower  
326 structure developed in a transpressional system. Microfabric study (Wang et al., 2000)

327 indicated that the Qingchuan–Pingwu Fault was originated from a deep-seated ductile  
328 shear zone during late Triassic and overprinted by Cenozoic brittle deformation at very  
329 least. It is the late Triassic deep-seated ductilely sheared Qingchuan–Pingwu Fault  
330 rather than the Cenozoic brittle one that separates the LMTB into the Southeastern Zone  
331 and Northwestern Zone.

332 The southern segment of the Main Central Boundary roughly distributes along the  
333 geological boundary between the Silurian and Devonian–Permian sequences (Figure 2).  
334 Macroscopically, this segment of Main Central Boundary shows predominant vertical  
335 cleavage and foliation within intensely deformed argillaceous limestone, graphitic  
336 pelite and thin-bedded limestone–quartz ribbon interlayers (Figures 3a and 5). Their  
337 bedding ( $S_0$ ) can be distinguished by the compositional variations that is parallel to the  
338 cleavages (Figure 3a and 5b). Associated rootless folds imply significant shortening  
339 during the formation of the Main Central Boundary (Figures 3a and 5b–c). P-wave  
340 receive function and seismic reflection profiles revealed a Moho at ~36–40 km depth  
341 beneath the Sichuan Basin that gradually deepens northwestwards at ~63 km depth  
342 beneath the eastern Tibet (Guo et al., 2013). This transition occurs beneath the  
343 Wenchuan Shear Zone (corresponding to Inner Metamorphic Core) over a horizontal  
344 distance of fewer than 30 km (Robert et al., 2010b; Zhang et al., 2010; Guo et al., 2013).  
345 Geophysical profiles, therefore, support the statement that the southern Main Central  
346 Boundary, as the northwest boundary of the Inner Metamorphic Core, serves as a major  
347 tectonic boundary.

### 348 3.3 The main deformation ( $D_1$ )

349 The  $D_1$  main deformation is defined by a NW–SE striking stretching lineation  
350 recognized in both the Southeastern and Northwestern zones which is separated by the  
351 Main Central Boundary (Figure 2). Kinematic indicators indicate a top-to-the-SE  
352 thrusting and a top-to-the-N/NW thrusting in the Southeastern and the Northwestern  
353 zones, respectively. Since there is no evidence of superposition between these two  
354 senses of shear, it is difficult to precisely define the relative timing of these opposite  
355 shearing events. Nevertheless, to clarify the presentation of the deformation events, in  
356 the following, we distinguish  $D_{1E}$ , the top-to-the-SE thrusting in the Southeastern Zone,  
357 and  $D_{1W}$ , the top-to-the-NW/N thrusting in the Northwestern Zone, respectively.

#### 358 3.3.1 Top-to-the-SE thrusting in the Southeastern Zone ( $D_{1E}$ )

359 The top-to-the-SE shearing and thrusting are widespread in the Southeastern Zone  
360 at variable scales, except that the Autochthon merely recorded long-wavelength fold  
361 and monoclines toward the interior of the Sichuan Basin (Figure 4). The  $D_{1E}$  top-to-  
362 the-SE thrusting is most developed in the Inner Metamorphic Core and generally  
363 attenuated southeastwards.

364 The Inner Metamorphic Core was ductilely deformed showing predominant NW-  
365 dipping foliation ( $S_1$ ) at varied angles between 60–90°. Specifically, the foliation  
366 gradually steepens when approaching the Main Central Boundary, and eventually  
367 presents in a vertical attitude (Figures 2–4). This changing trend of foliation implies  
368 that the deformation intensified toward the Main Central Boundary. Foliations mostly  
369 consist of an alternation of biotite-white mica-rich and light-colored, pelitic interlayers  
370 (Figures 3a and 6a–b). Along the transect from Wenchuan county to Xuecheng town,  
371 an NW-plunging mineral and stretching lineation ( $L_1$ ) defined by aligned newly formed  
372 biotite, white mica, elongated quartz aggregates, or iron-oxide pods are well developed  
373 (Figures 3a and 6a). Kinematic indicators document a consistent top-to-the-SE  
374 thrusting in the Inner Metamorphic Core. Such as asymmetric pyrite pressure shadow  
375 in mica-schist (Figures 3a and 6b) and sigma-shaped feldspar porphyroclasts in  
376 paragneiss (Figures 3a and 6c) both show top-to-the-SE thrusting. Photomicrographs  
377 (perpendicular to the foliation and parallel to the lineation) show that newly formed  
378 white mica oriented as compaction plane (S) and shear plane (C), both of which  
379 composes an S-C fabric documenting a consistent top-to-the-SE thrusting (Figures 3a  
380 and 6d).

381 In the Allochthon, the Neoproterozoic complexes such as the Pengguan and  
382 Jiaoziding complexes, mostly show brittle deformation characterized by subhorizontal  
383 joints. Inside the Pengguan complex, several NE–SW trending ductile shear zones  
384 dissected and thrust the granitic rocks to the southeast (Airaghi et al., 2017b; Xue et al.,  
385 2017). Upon the granitic rocks, the Neoproterozoic Huangshuihe Group recorded  
386 extensive shearing and sigmoid pelitic lens incorporated to the top-to-the-SE thrusting  
387 (Figures 3a and 6e). Structural planes including axial planar cleavages and spaced  
388 cleavages dip to the northwest at angles of 30–65° (Figures 2–4). Fine-grained white  
389 mica and chlorite are developed on these structural planes demonstrating a greenschist  
390 facies grade of deformation. Sigma-shaped sandy lens in the Silurian pelitic schist  
391 indicate a top-to-the-SE thrusting as well (Figures 3a and 6f).

392 As part of the Allochthon, most of the klippen are synclines overturned to the SE,  
393 with SE-ward reverse fault which dissected the thick Devonian limestone at the rear of  
394 the klippe (Figures 2 and 6g), and show a consistent top-to-the-SE thrusting (BGMRSF,  
395 1991).

396 In the Para-autochthon, the late Triassic Xujiahe sandstone is intensively folded as  
397 indicated by the NE-SW trending  $\pi$ -circle-projected axis of bedding (Figures 3b-d). In  
398 the south part, multi  $\pi$  circle-Axis exist roughly trending NE-SW, implying multiphase  
399 of shearing and thrusting. Folds are mostly overturned to the SE indicating a top-to-  
400 the-SE thrusting (Figure 2). Axial planar cleavages are locally developed that gradually  
401 intensified and more penetrative approaching northwestward to the Yingxiu–Beichuan  
402 Fault. This cleavage-enhancing trend implies a northwestward increase in deformation  
403 intensity. In mudstone–sandstone interlayered rocks, competence contrast facilitates  
404 the formation of layer-parallel slip and shearing. Sigmoid lens as well as “cold” shear-  
405 band fabrics consistently indicate a top-to-the-SE thrusting (Figures 3a and 6h).

406 In the Autochthon, lower Jurassic strata and overlying continuous Cretaceous–  
407 Cenozoic sequences are mostly concordantly folded in a long-wavelength way. The  
408 fact that early Jurassic rocks locally overturned to the southeast (North to the Tangbazi  
409 town; Figure 2) therefore implies a post-Jurassic reactivation of the SE-directed  
410 thrusting (Figures 2 and 4d).

#### 411 3.3.2 Top-to-the-NW/N thrusting in the Northwestern Zone ( $D_{1W}$ )

412 The structures and kinematics within the Northwestern Zone are different from those  
413 within the Southeastern Zone. In the northern Northwestern Zone, S-dipping foliation  
414 and associated downdip lineation are well developed. Lineations are defined by aligned  
415 calcite, fine-grained white mica, and oxide pods (Figures 2, 3a and 7a). Along the  
416 lineation, a consistent top-to-the-N/NW shearing and thrusting is determined by various  
417 kinematic indicators, such as sigma-shaped pebbles in strongly sheared meta-  
418 conglomerate (Figures 3a and 7b) and asymmetric pressure shadow in sandy–pelitic  
419 schist. Photomicrographs show that quartz ribbon (Figures 3a and 7c) and sigma-shaped  
420 feldspar porphyroclasts (Figures 3a and 7d) both indicate a top-to-the-N thrusting. In  
421 the north of the Pingwu city, greywacke and siltstone were extensively folded verging  
422 to the north with associated meter-scale reverse fault cutting fold limbs (Figures 3a and  
423 7e). West to the Pingwu city, bedding (depicted by compositional banding) completely

424 transposed to SE-dipping foliations in response to the northward shearing and thrusting  
425 (Figures 3a and 7f).

426 In the southern Northwestern Zone, axial planar cleavage developed in the thin-  
427 bedded limestone mostly dips to the SE but strikes roughly along the margin of the  
428 Xuelongbao complex (Figure 2). On the foliation, lineation plunges to the SE at ~65–  
429 70° (Figures 2 and 3a). Along the lineation, asymmetric pressure shadow of calcite tail  
430 around garnet pseudomorph indicates a top-to-the-NW thrusting (Figures 3a and 7g).  
431 Asymmetric NW-verging folds are developed at different scales. The late Triassic  
432 turbidite was involved in a hundred-meter scale chevron fold verging to the NW that is  
433 consistent with the top-to-the-NW thrusting (Figures 3a and 7h). In the whole  
434 Northwestern Zone, the top-to-the-NW/N thrusting is indicated by the pervasive  
435 NW/N-overtaken bedding as well (Figure 2)(BGMRS, 1991).

#### 436 3.3.3 Syntectonic ( $D_{1W}$ ) Mupi pluton in the Northwestern Zone

437 In the Northwestern Zone, north of the Pingwu city, the Mupi pluton is a coarse-  
438 grained diorite and granodiorite pluton with prominent syntectonic features (Figure 2).  
439 At its southern margin, the contact between the pluton and the country rock is rather  
440 ambiguous. Strong mylonitisation with S-dipping foliation deformed both the country  
441 rocks and the south margin of the pluton (Figures 3a and 8c). On the S-dipping foliation  
442 ( $S_1$ ), aligned biotite and sheared feldspar define a mylonitic lineation plunging south at  
443 ~45–75°. Kinematic indicators including sigmoidal feldspar porphyroclasts and shear-  
444 bands both indicate a top-to-the-N shearing related to thrusting (Figures 3a and 8d).  
445 About 10–15 meters northwards from the south margin of the pluton, a set of quartz +  
446 feldspar veins parallel to the shear foliation (Figures 3a and 8b), in which the quartz  
447 and feldspar did not record ductile deformation. Further north ~30 meters from the  
448 south margin of the pluton, the pluton rocks show magmatic fabric with euhedral  
449 feldspar randomly distributed (Figures 3a and 8a). Cracks in feldspar grains are sub-  
450 parallel to the shear planes and infilled with quartz (Figures 8e and S1). These cracks  
451 in conjunction with the foliation-parallel quartz + feldspar veins indicate that a brittle  
452 deformation of the feldspar occurred in the presence of residual melt. Therefore, based  
453 on the textural criteria proposed by Paterson et al. (1989), we prefer to interpret the  
454 Mupi pluton as a syntectonic one relating to the  $D_{1W}$  deformation.

455

456 3.4 Top-to-the-NW normal faulting along the northwest boundary of the basement  
457 complexes (D<sub>2</sub>)

458 Most of the Neoproterozoic basement complexes in the Southeastern Zone are  
459 devoid of ductile deformation but characterized by widespread subhorizontal joints  
460 (Xue et al., 2017). Mylonite is localized along the northwest boundary of the  
461 Xuelongbao and Pengguan complexes. Along the western boundary of the Xuelongbao  
462 complex, foliation dips to the NW at 45–80° with lineation plunging to the west (Figure  
463 2). These structural foliations and lineations are difficult to distinguish from those of  
464 the D<sub>1E</sub> deformation structures. However, sigmoidal feldspar clasts and S/C fabric  
465 indicate different kinematics of top-to-the-NW normal faulting (Figures 3a and 9a). The  
466 Silurian rock directly overlies the Neoproterozoic Pengguan complex also supports  
467 NW-ward normal faulting (Figure 2).

468 Along the northwest boundary of the Pengguan complex, mylonitic foliation dips to  
469 the NW at high angles of ~80° (Figures 3a and 9b) with lineation steeply plunging to  
470 the NW, except for a few SE- or N-dipping foliations that probably resulted from tilting  
471 of the original foliations by the Cenozoic deformation (Figure 2). Photomicrographs  
472 including asymmetric mica fishes (Figures 3a and 9c), sigmoidal feldspar  
473 porphyroclasts (Figures 3a and 9d), and S/C fabric of white mica (Figures S2c and e)  
474 indicate a top-to-the-NW normal faulting. The deformed rocks experienced syntectonic  
475 greenschist-facies metamorphism with a mineral assemblage of quartz + feldspar +  
476 biotite + white mica + chlorite (Figures S2e–f).

477 Microscopic structures from the northwest Pengguan complex show sigma-shaped  
478 porphyroclast, quartz ribbon (Figures 3a and 9f), and white mica shear-band fabric  
479 (Figures 3a and 9g), indicating a top-to-the-SE shearing related to the D<sub>1E</sub> deformation.  
480 However, all these structures are cut by NW-dipping shear-bands (Figures 3a and 9e).  
481 In the western flank of the Wulong complex, about 60 km southwest to the Pengguan  
482 complex, a similar top-to-the-NW normal fault with greenschist-facies metamorphism  
483 that cuts D<sub>1E</sub>-related thrust sheet has been previously reported as well (Figure  
484 1b)(Burchfiel et al., 1995; Tian et al., 2016; Airaghi et al., 2018b). Thus, we interpret  
485 the top-to-the-NW normal faulting in the northwest Pengguan complex and the  
486 Xuelongbao complex as the D<sub>2</sub> event after the D<sub>1E</sub> top-to-the-SE thrusting in the  
487 Southeastern Zone.

488



#### 489 **4. Geochronological constraints**

490 In order to constrain the timing of the D<sub>1</sub> double-vergent thrusting and the D<sub>2</sub> top-  
491 to-the-NW normal faulting, SIMS U–Pb dating on zircons from the synkinematic Mupi  
492 pluton and <sup>40</sup>Ar–<sup>39</sup>Ar dating on metamorphic white mica, biotite and fine-grained white  
493 mica were carried out.

##### 494 4.1 Analytical methods

###### 495 4.1.1 Zircon SIMS U-Pb dating

496 Zircon concentrates were extracted using conventional crushing and separation  
497 techniques. After set in epoxy resin mounts, mineral grains were polished to their cores.  
498 Cathodoluminescence (CL) imaging was performed to observe their internal structure  
499 and find suitable positions for spot analyses. Geochronological data were acquired at  
500 the State Key Laboratory of Lithospheric Evolution, Institute of Geology and  
501 Geophysics, Chinese Academy of Sciences (IGGCAS).

502 U–Pb zircon dating was conducted on a Cameca IMS–1280HR SIMS following the  
503 analytical procedures described by Li et al. (2009). The primary O<sup>2-</sup> ion beam was  
504 focused to elliptical spots with the sizes of 20 μm×30 μm. Measured Pb/U ratios were  
505 calibrated relative to the zircon standard Plešovice (Sláma et al., 2008). Non-radiogenic  
506 Pb was subtracted from the measured Pb isotopic composition using the measured <sup>204</sup>Pb  
507 and the present-day average terrestrial Pb isotopic composition in the model of (Stacey  
508 and Kramers, 1975). U–Pb data were plotted and calculated using the program Isoplot  
509 3.00 (Ludwig, 2003), and age uncertainties are quoted at the 95% confidence level  
510 except for those noted otherwise. Measurements on a second zircon standard Qinghu  
511 were interspersed with unknowns to monitor the external uncertainties, and yielded  
512 concordia ages of 159.6 ± 1.6 Ma (MSWD = 0.28, N = 6), which are identical within  
513 errors to the recommended age (159.5 ± 0.2 Ma)(Li et al., 2013b).

###### 514 4.1.2 <sup>40</sup>Ar–<sup>39</sup>Ar dating

515 Micas were separated from eight micaschist, gneiss, and mylonite samples for  
516 <sup>40</sup>Ar/<sup>39</sup>Ar dating by step-heating technique. Minerals were irradiated and measured in  
517 the Ar-Ar Laboratory, School of Earth Sciences of the University of Melbourne. Hand-  
518 picked grains were cleaned in de-ionized water and acetone. Samples were weighted  
519 and loaded into aluminum packets for irradiation. The packets were placed in a silicate  
520 glass tube (Can UM#80), interleaved with packets containing the flux monitor Mount  
521 Dromedary Biotite (Age = 99.125 ± 0.076 Ma)(Phillips et al., 2017). The canister was

522 irradiated for 40 MWhr in the CLICIT facility of the Oregon State University TRIGA  
523 reactor, USA. The measured isotopic ratios were corrected for system blanks, mass  
524 discrimination, and irradiation-induced interference. Plateau and/or total gas ages with  
525  $2\sigma$  uncertainties were calculated and calibrated based on methods proposed by (Lee et  
526 al., 2006). Analytical data are presented in Table S2 (Xue et al., 2020), and the age  
527 spectra are presented in Figure 11. Argon age plateaus are defined by contiguous gas  
528 fractions that together represent more than 50% of the total  $^{39}\text{Ar}$  released from the  
529 sample and for which no difference in age can be detected between any two fractions  
530 at the 95% confidence level (Fleck et al., 1997). According to this definition, all argon  
531 age spectra in this work, except for sample CX33, do not yield plateau ages (Figure 11).  
532 We choose contiguous steps within 95% confidence close to 50% of the total  $^{39}\text{Ar}$   
533 released (CX6A white mica), or contiguous steps close to 95% confidence more than  
534 50% of the total  $^{39}\text{Ar}$  released (CX2, CX6B, CX25, CX44 white mica), to calculate  
535 weighted mean ages (Figure 11).

536

## 537 4.2 Results

### 538 4.2.1 U–Pb dating on synkinematic Mupi pluton

539 Zircons from the Mupi pluton are pink to colorless, 80 to 200  $\mu\text{m}$  long with  
540 length/width ratios from 2 to 3. They show well-developed crystal morphologies. CL  
541 images of zircons show that most of the zircons have well-developed oscillatory zoning  
542 of igneous origin and some grains have an inherited core (Figure 10a). Under guidance  
543 of the zircon CL images, analyzed spots were positioned on the oscillatory zircon  
544 mantle/margin when there are exist inherited zircon cores. SIMS U–Pb zircon results  
545 are listed in Table S1. The SIMS U–Pb dating of the Mupi pluton yields a concordant  
546 age of  $219.1 \pm 1.7$  Ma (MSWD = 0.99, N = 15; Figure 10b).

### 547 4.2.2 $^{40}\text{Ar}$ – $^{39}\text{Ar}$ dating

548 Sample CX44 collected from the northern Northwestern Zone (Figure 12) is  
549 micaschist with penetrative SSE-dipping foliation and associated S-plunging lineation  
550 related to the  $D_{1W}$  top-to-the-N thrusting. The CX44 micaschist contains domains rich  
551 in fine-grained white mica and quartz that define the shear foliation (Figures S2a–b).  
552 Multi-grain white mica (211–152  $\mu\text{m}$ ) separated from CX44 yields a weighted mean  
553 age of  $224.1 \pm 1.7$  Ma, accounting for 81% of released  $^{39}\text{Ar}$  (Figures 11a and Table 1).

554 Sample CX12 collected from the southern Northwestern Zone (Figure 12) is  
555 micaschist involved in the D<sub>1W</sub> top-to-the-NW thrusting. Shear foliation is defined by  
556 aligned fine-grained white mica (Figure 7g). Two aliquots of fine-grained white mica  
557 (104–66 μm) of CX12A & CX12B show discordant stair-shaped spectra increasing  
558 from ~65–70 Ma to ~150 Ma and ~120 Ma, respectively (Figures 11b–c and Table 1).

559 Samples CX6 and CX33 (Figure 12), collected from the Inner Metamorphic Core  
560 within the Southeastern Zone, are characterized by penetrative NW-dipping foliation  
561 and NW-plunging lineation that was involved in D<sub>1E</sub> top-to-the-SE thrusting. In these  
562 two samples, the foliations and associated lineations are defined by white mica (Figures  
563 6d and S2g). Two aliquots of white mica (152–211 μm) of CX6A and CX6B yield  
564 equivalent weighted mean ages of 124 ± 1.9 Ma and 126.3 ± 3.3 Ma, respectively  
565 (Figure 11d–e). Multi-grain white mica (152–211 μm) from CX33 yields a plateau age  
566 of 148.2 ± 1.2 Ma (>60% of the total <sup>39</sup>Ar; Figure 11f and Table 1).

567 Samples CX25 from micaschist of the Xuelongbao complex and CX18, CX19 from  
568 gneiss/mylonite of the Pengguan complex (Figures 12) show well-developed NW-  
569 dipping foliations related to the D<sub>2</sub> top-to-the-NW normal faulting (Figures S2c–f).  
570 White mica (211–152 μm) in CX25 that defines the shear planes (Figures S2e–f) was  
571 selected for <sup>40</sup>Ar/<sup>39</sup>Ar dating. Five steps of sample CX25 with ~80% released <sup>39</sup>Ar  
572 yields a weighted mean age of 79.7 ± 2.7 Ma (Figure 11h). Samples of CX18 and CX19  
573 have stair-shaped spectra, in which ages increase from ~50–60 Ma to ~110–135 Ma  
574 from low- to high-temperature steps (Figure 11i–k and Table 1).

575 Sample CX2 from the northwest boundary of the Pengguan complex (in a structural  
576 position equivalent to the samples CX18 and CX19; Figure 12) was involved in the D<sub>2</sub>  
577 top-to-the-NW normal faulting (Figures 3 and 9g–i). Multi-grain white mica (211–152  
578 μm) from CX2 yields a weighted mean age of 26.23 ± 0.99 Ma at low- to medium-  
579 temperature steps (>50% of the total <sup>39</sup>Ar released; Figure 11g and Table 1).

580

## 581 4.3 Interpretation of the geochronological results

### 582 4.3.1 Zircon U-Pb data interpretation

583 In the northern Northwestern Zone, the Mupi pluton shows a continuous transition  
584 from mylonitic fabrics along the pluton margin to magmatic fabrics in the pluton  
585 interior, arguing for its synkinematic emplacement. This deduction is supported by the  
586 fact that quartz + feldspar veins parallel to the mylonitic foliation, and feldspar records

587 brittle deformation occurred in the presence of residual melt (see details in Section  
588 3.3.3). Thus, the D<sub>1W</sub> top-to-the-N/NW thrusting is closely related to the emplacement  
589 of the Mupi pluton. Our zircon U–Pb ages reveal that the Mupi pluton emplaced at *ca.*  
590 219 Ma, therefore place age constraint on the D<sub>1W</sub> top-to-the-N/NW thrusting at *ca.*  
591 219 Ma (Figure 12).

#### 592 4.3.2 <sup>40</sup>Ar–<sup>39</sup>Ar data interpretation

593 All samples show high radiogenic <sup>39</sup>Ar and almost all steps are clustered at the  
594 horizontal <sup>39</sup>Ar/<sup>40</sup>Ar axis that does not define a real inverse isochron line (Table S2;  
595 Figure S3). Most of the step-ages calculated both by using initial <sup>40</sup>Ar/<sup>36</sup>Ar of 298.56  
596 (Lee et al., 2006) and from the so-called inverse isochron show nearly no difference  
597 (Table S2). Thus, the inverse isochron ages (though identical to their weighted mean  
598 ages or plateau ages) and the fake extraneous atmosphere argon are meaningless and  
599 will not be further discussed (Figure S3; Table S2).

600 Concordant white mica <sup>40</sup>Ar–<sup>39</sup>Ar spectra, such as those yielded by samples of CX44  
601 (81.6% released <sup>39</sup>Ar), CX6A (49.5% released <sup>39</sup>Ar), CX6B (52.4% released <sup>39</sup>Ar),  
602 CX33 (60.1% released <sup>39</sup>Ar), CX2 (53.6% released <sup>39</sup>Ar) and CX25 (79.7% released  
603 <sup>39</sup>Ar), are typical of samples that have remained a closed system since  
604 thermal/mylonitic resetting or crystallization (Figures 11a and d–h). Similar rocks to  
605 sample CX44 recorded greenschist facies metamorphism under temperatures of 260–  
606 310 °C (chlorite + white mica multi-equilibrium thermometer; Liu et al., 2008), which  
607 is lower than the white mica argon closure temperature of *ca.* 425 °C (100 μm  
608 grain)(Harrison et al., 2009). Considering that the dated mica grains are strongly  
609 deformed by the top-to-the-N/NW thrusting, we, therefore, interpret that the 224.1 ±  
610 1.7 Ma argon age of CX44 recorded the timing of the white mica recrystallization  
611 related to the D<sub>1W</sub> thrusting event.

612 Samples of CX6A & CX6B, and CX33 from the Inner Metamorphic Core, CX2 and  
613 CX25 from the mylonite zone along the northwest boundary of the Pengguan and  
614 Xuelongbao complexes have been deformed and metamorphosed at temperatures  
615 of >530°C (Raman Spectroscopy on Carbonaceous Material; Robert et al., 2010b).  
616 These temperatures are higher than the closure temperature (425 °C) of the *ca.* 100 μm  
617 radius muscovite grain (Harrison et al., 2009). There is no evidence of any post late  
618 Cretaceous to Cenozoic magmatism along the LMTB and its adjacent eastern Songpan–  
619 Ganzi Terrane. Thus, the flattened spectra of CX6A (124 ± 1.9 Ma), CX6B (126.3 ±

620 3.3), CX33 ( $148.2 \pm 1.2$  Ma), CX2 ( $26.2 \pm 0.9$  Ma), and CX25 ( $79.7 \pm 2.7$  Ma) are  
621 probably cooling ages when deformation rapidly exhumed those rocks through the ca.  
622  $425$  °C geothermal depth. These cooling ages, therefore, can represent the timing of  
623 deformations. In this scenario, considering samples of CX6A, CX6B and CX33 were  
624 involved in top-to-the-SE thrusting, we interpret the dates of 148 Ma and 124 Ma as  
625 ages to SE-ward thrusting and rapid exhumation. Samples of CX2 and CX25 collected  
626 from the northwest boundary of the Pengguan and Xuelongbao complexes were  
627 involved in top-to-the-NW normal faulting, which may imply that the top-to-the-NW  
628 normal faulting occurred at *ca.* 27 Ma along the northwest boundary of the Pengguan  
629 complex, and at *ca.* 80 Ma along the northwest boundary of the Xuelongbao complex,  
630 respectively.

631 Discordant stair-shaped spectra, such as those observed from the samples of CX12,  
632 CX18, and CX19 (Figures 11b–c, i–k), are commonly observed in fine-grained mineral  
633 mixes (Tian et al., 2016). Those staircase spectra indicate  $^{40}\text{Ar}$  diffusive loss that is  
634 possibly related to chemical alteration, a subsequent thermal event disturbance, or  
635 argon loss during the late stage mylonitisation (Costa and Maluski, 1988; Lovera et al.,  
636 1989; West and Lux, 1993). The oldest age of the stair-shaped spectra is a minimum  
637 one for the fine-grained white mica closure age (McDougall and Harrison, 1988).  
638 Samples of CX12, CX18, and CX19 have been deformed at temperatures  $>530$ °C as  
639 well (Raman Spectroscopy on Carbonaceous Material; Robert et al., 2010).  
640 Considering the size of white mica (104–66  $\mu\text{m}$ ), the argon-argon system of fine-  
641 grained mica should be completely reset (Harrison et al., 2009). According to the stair-  
642 shaped spectra, samples of CX12A, CX12B, CX18, CX19A, CX19B may have  
643 recrystallized or been reset before  $146.5 \pm 2.7$  Ma,  $119 \pm 1.3$  Ma,  $111.1 \pm 0.2$  Ma,  $133.7$   
644  $\pm 3.3$  Ma, and  $139.3 \pm 1.1$  Ma, respectively (Figures 11b–c, i–k). These oldest ages of  
645 the stair-shaped spectra possibly resulted from the 148–124 Ma mylonitisation as  
646 implied by  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  cooling ages of CX6A, CX6B, and CX33.

647 Chemical alteration should have led to a more profound influence on the fine-  
648 grained white mica of CX12, CX18, and CX19 that may result in  $^{40}\text{Ar}$  diffusive loss  
649 and flattened spectra (Harrison et al., 2009). In this way, considering samples of CX2,  
650 CX18, CX19, and CX25 located at the same structural position along the northwest  
651 boundary of the Neoproterozoic complexes, we may expect that CX2 and CX25,  
652 showing stair-shaped spectrum and CX18, CX19 and presenting flattened spectra, yield

653 younger ages, however, it is not the case (Figures 11g–k). Thus, chemical alteration  
654 and related  $^{40}\text{Ar}$  diffusive loss may not be the main factor to account for the stair-shaped  
655 spectra.

656 An alternative interpretation may suggest that the youngest age of the stair-shaped  
657 spectra gives a maximum age of the thermal overprint or late-stage mylonitisation  
658 (Costa and Maluski, 1988; Lovera et al., 1989; West and Lux, 1993). As stated above,  
659 no magmatism of late Mesozoic–Cenozoic ages has been reported along the LMTB.  
660 Thus, the post-cooling thermal event may not be responsible for the minimum ages of  
661 the stair-shaped spectra. The youngest ages in the stair-shaped spectra therefore most  
662 likely indicate late-stage mylonitisation after ~60–50 Ma (Figures 11i–k), which  
663 possibly related to the *ca.* 27 Ma top-to-the-NW faulting along the northwest boundary  
664 of the Pengguan complex. It is worth to note that the CX12A and CX12B fine-grained  
665 white mica from the Northwestern Zone (Figure 12), far away from the Pengguan  
666 complex, show older minimum ages of  $64.7 \pm 1.3$  Ma and  $72.2 \pm 1.4$  Ma comparing  
667 with the  $50 \pm 0.1$  Ma,  $59 \pm 0.3$  Ma, and  $58.4 \pm 0.4$  Ma of the CX18, CX19A and CX19B  
668 (Figures 11b–c, j–l), which may suggest that the CX12 has been less affected by the  
669 top-to-the-NW normal faulting comparing to the CX18 and CX19.

670

## 671 **5 Discussion**

### 672 **5.1 Summary of our newly obtained structural results**

673 On the basis of detailed structural analyses, a Main Central Boundary and a  $D_{1W}$  top-  
674 to-the-N/NW thrusting in the Northwestern Zone are argued for the first time in the  
675 LMTB. The Main Central Boundary corresponds to a major tectonic boundary  
676 supported both by field structures and geophysical profile (Jia et al., 2006; Robert et al.,  
677 2010b), which divides the LMTB into a Northwestern Zone (part of the Songpan–Ganzi  
678 Terrane) to the northwest and a Southeastern Zone to the southeast. The Southeastern  
679 Zone is characterized by exclusively NW-dipping foliations and associated  $D_{1E}$  top-to-  
680 the-SE thrusting, while the Northwestern Zone is characterized by exclusively SE-  
681 dipping foliations and associated  $D_{1W}$  top-to-the-NW thrusting.

682 This study subdivides the Southeastern Zone of the LMTB into four units based on  
683 increasing deformation intensities and metamorphic grades from southeast to northwest,  
684 namely the Autochthon, Para-autochthon, Allochthon, and Inner Metamorphic Core.  
685 This subdivision pattern is revised from the previous one that divided the LMTB into

686 an allochthonous sheet thrust southeastwards on top of the autochthonous Sichuan  
687 Foreland Basin (Xu et al., 1992; Burchfiel et al., 1995; Worley and Wilson, 1996).

688 In the Southeastern Zone, a D<sub>2</sub> top-to-the-NW normal faulting that cuts the D<sub>1E</sub> top-  
689 to-the-SE thrusting is recognized along the northwest boundary of the Pengguan and  
690 Xuelongbao complexes.

691

## 692 **5.2 Polyphase deformations along the LMTB**

693 According to the geometric and kinematic features and overprinting relationship,  
694 together with <sup>40</sup>Ar-<sup>39</sup>Ar and zircon U–Pb data, which allow us to draw a polyphase  
695 deformation sequence of the LMTB.

### 696 5.2.1 Timing of the D<sub>1</sub> main deformation event

697 Timing of the D<sub>1W</sub> top-to-the-N/NW thrusting is firstly constrained by the emplaced  
698 timing of the syntectonic Mupi pluton at *ca.* 219 Ma (Figure 12). Synkinematic  
699 recrystallized white mica of sample CX44 that is involved in the top-to-the-N/NW  
700 thrusting yields a weighted mean age of 224.1 ± 1.7 Ma, which places a second age  
701 constraint on the D<sub>1W</sub> top-to-the-N/NW thrusting. This newly obtained argon age is  
702 consistent with previously published white mica <sup>40</sup>Ar-<sup>39</sup>Ar ages at *ca.* 237–202 Ma from  
703 the northern Northwestern Zone (Figure 12)(Yan et al., 2011; Yan et al., 2018). The  
704 fact that the zircon U–Pb age of the Mupi pluton is *ca.* 5 Ma younger than the  
705 synkinematic white mica <sup>40</sup>Ar-<sup>39</sup>Ar age may suggest the Mupi pluton emplaced during  
706 the late phase of the D<sub>1W</sub> event. Based on the zircon U–Pb age of syntectonic Mupi  
707 pluton and synkinematic white mica <sup>40</sup>Ar-<sup>39</sup>Ar age, we, therefore, suggest that the D<sub>1W</sub>  
708 top-to-the-N/NW thrusting event occurred at *ca.* 224–219 Ma.

709 The D<sub>1E</sub> top-to-the-SE thrusting within the Southeastern Zone has been constrained  
710 in the late Triassic for the following arguments: 1) Field observations and seismic  
711 reflection profile revealed that late Jurassic–Cenozoic rocks unconformably overly on  
712 intensively folded rocks as young as late Triassic (Figures 2 and 4a–d)(BGMRSRSP, 1991;  
713 Jia et al., 2006); 2) Detailed petrological analyses and in-situ allanite U–Pb dating and  
714 biotite <sup>40</sup>Ar/<sup>39</sup>Ar dating revealed a *ca.* 204–190 Ma peak metamorphism in the Inner  
715 Metamorphic Core that postdates the D<sub>1E</sub> event (Airaghi et al., 2017a; 2018a; 2018c);  
716 3) The ages of the voluminous magmatism intruding the extensively folded Songpan–  
717 Ganzi Terrane range between 223 and 200 Ma, which postdates the folding in the  
718 Songpan–Ganzi Terrane and the top-to-the-SE thrusting of the LMTB (Figure 12)(Xu

719 et al., 1992; Roger et al., 2004; Harrowfield and Wilson, 2005; Hu et al., 2005; Zhang  
720 et al., 2007; de Sigoyer et al., 2014). Thus, the regional D<sub>1E</sub> top-to-the-SE thrusting was  
721 at least activated during the late Triassic, together with the contemporary D<sub>1W</sub> top-to-  
722 the-N/NW thrusting recorded within the Northwestern Zone, both of which compose  
723 the *ca.* 224–219 Ma main D<sub>1</sub> double-vergent event.

#### 724 5.2.2 Timing of the D<sub>2</sub> top-to-the-NW normal faulting

725 According to the newly obtained <sup>40</sup>Ar-<sup>39</sup>Ar ages, the timing of the D<sub>2</sub> top-to-the-NW  
726 normal faulting occurred along the northwest boundary of the Pengguan (*ca.* 27 Ma)  
727 and Xuelongbao (*ca.* 80 Ma) complexes are quite different. The top-to-the-NW/N  
728 normal faulting is widespread in an over 300 km long zone along the northern margins  
729 of the Danba and Kangding complexes, and the northwest margins of the Baoxing,  
730 Wulong, Xuelongbao, Moutuo, Pengguan, and Jiaoziding complexes (Figure  
731 12)(Burchfiel et al., 1995; Xu et al., 2008; Tian et al., 2016; Xue et al., 2017). This belt  
732 of top-to-the-NW normal faulting has previously been entitled East Tibet Detachment  
733 (Figure 12)(Wang et al., 2012b). Timing of the East Tibet Detachment top-to-the-NW  
734 normal faulting is different at different localities. Hames and Burchfiel (1993) reported  
735 a top-to-the-NW normal faulting and syntectonic metamorphism at *ca.* 25 Ma along the  
736 northwest Pengguan complex that is in accordance with the *ca.* 27 Ma top-to-the-NW  
737 normal faulting as indicated by sample CX2 (Figure 12).

738 Along the northwest boundary of the Wulong complex and north boundary of the  
739 Danba complex, the top-to-the-NW/N normal faulting was constrained to *ca.* 81–47 Ma  
740 (<sup>40</sup>Ar/<sup>39</sup>Ar dating on metamorphic biotite and white mica; Figure 12)(Zhou et al., 2008;  
741 Tian et al., 2016). This phase of the top-to-the-NW normal faulting is recorded along  
742 the northwest boundary of the Xuelongbao complex (*ca.* 80 Ma <sup>40</sup>Ar-<sup>39</sup>Ar age of sample  
743 CX25) as well.

744 A period of the top-to-the-NW/N normal faulting at *ca.* 166–159 Ma was reported  
745 at the northwest boundary of the Jiaoziding and Pengguan complexes, and the north  
746 boundary of the Danba complex (Figure 12)(Dirks et al., 1994; Zhou et al., 2008; Li,  
747 2009). Whereas, younger ages of *ca.* 122–120 Ma related to the top-to-the-N normal  
748 faulting at the north boundary of the Danba complex were reported as well (Figure  
749 12)(Xu et al., 2008).

750 In summary, the timing of the top-to-the-NW normal faulting of the East Tibet  
751 Detachment are scattered at *ca.* 166–159 Ma (north Danba, northwest Pengguan,



752 northwest Jiaoziding), *ca.* 122–120 Ma (north Danba), *ca.* 81–47 Ma (north Danba,  
753 northwest Wulong) and *ca.* 27–25 Ma (northwest Pengguan; Figure 12). Nonetheless,  
754 a process is required to explain these four groups of well-defined argon plateau ages  
755 that do not show an age-changing trend in map view (Figure 12). We, therefore, prefer  
756 to interpret that the top-to-the-NW/N normal faulting of the East Tibet Detachment was  
757 episodically and co-planarly activated at *ca.* 166–159 Ma, *ca.* 122–120 Ma, *ca.* 81–47  
758 Ma, and *ca.* 27–25 Ma (Figure 12). The late-stage activations could partially reset the  
759 fine-grained white mica argon system that resulted in stair-shaped spectra yielded by  
760 samples of CX18 and CX19 (Figures 11 and 12).

761

### 762 **5.3 Episodic basement-slice-imbrication and amphibolite facies metamorphic rock** 763 **exhumation**

764 The Western Sichuan Foreland Basin (WSFB) was formed by loading and  
765 subsidence due to the southeastward thrusting of the LMTB along the Yingxiu–  
766 Beichuan Fault and Xiaoguanzi Fault ( $T_2$  in Figure 12)(Chen and Wilson, 1996; Li et  
767 al., 2003). Episodic terrestrial deposition in the WSFB from the late Triassic to the  
768 present day indicates that the LMTB continued to be tectonically active episodically  
769 during the late Triassic to early Jurassic, late Jurassic to early Cretaceous, and late  
770 Cretaceous to earliest Paleocene (Figure 12)(Xu et al., 2008; Li et al., 2013c; Tian et  
771 al., 2016).

772 The late Jurassic to early Cretaceous southeastward thrusting of the Yingxiu–  
773 Beichuan Fault and Xiaoguanzi Fault ( $T_2$  in Figure 12), as the southeast boundary Fault  
774 of the Pengguan and Baoxing complexes, overlaps the *ca.* 166–159 Ma and *ca.* 122–  
775 120 Ma top-to-the-NW/N normal faulting along the NW boundary of the Jiaoziding  
776 complex and the north boundary of the Danba complex (Figure 12)(Xu et al., 2008;  
777 Zhou et al., 2008; Li, 2009). The late Cretaceous–earliest Paleocene southeastward  
778 thrusting of the Yingxiu–Beichuan Fault and Xiaoguanzi Fault is also coeval with the  
779 top-to-the-NW/N normal faulting along the NW boundary of the Xuelongbao (CX25  
780 in this study) and Wulong (Tian et al., 2016) complexes (Figure 12). Furthermore, both  
781 the top-to-the-SE thrusting and top-to-the-NW normal faulting along the southeast and  
782 northwest boundaries of the complexes occurred under similar greenschist-facies  
783 metamorphic conditions (Airaghi et al., 2017b; Xue et al., 2017). Conjugated  
784 kinematics of boundary SE-thrusting and NW-normal faulting characterized by similar

785 metamorphic conditions and synchronous timing let us propose that the Xuelongbao,  
786 Pengguan, Baoxing and Wulong complexes were episodically imbricated to the  
787 southeast as basement-slices during late Jurassic–early Cretaceous and late Cretaceous–  
788 earliest Paleocene.

789 Numerical modeling of co-seismic slip vectors vs. fault angles indicates that the  
790 latest high-angle listric Yingxiu–Beichuan Fault might have facilitated the vertical  
791 imbrication of the Pengguan complex with no need of the SE-ward thrusting and  
792 loading (Feng et al., 2015). This feature explains the absence of a rejuvenated foreland  
793 basin contemporary to the 27–25 Ma basement imbrication. Nevertheless, the 27–25  
794 Ma basement slice imbrication of the Pengguan complex is compatible with its 30–25  
795 Ma fast cooling (Figure 12)(Wang et al., 2012a).

796 In the map view, two amphibolite facies metamorphic zones wrap the Xuelongbao  
797 and Danba complexes (Figure 13a). Both amphibolite facies metamorphic zones  
798 reached peak conditions at *ca.* 210–180 Ma post to the late Triassic orogeny (Figure  
799 12)(Dirks et al., 1994; Huang et al., 2003a; Weller et al., 2013; Airaghi et al., 2018a).  
800 Gravity anomaly indicated that the Xuelongbao complex probably extends  
801 northeastwards beneath and parallel to the amphibolite facies metamorphic rocks (Xue  
802 et al., 2017). Coincidentally, the Wenchuan–Xuelongbao and Danba amphibolite facies  
803 metamorphic zones experienced rapid exhumation and cooling during the late Jurassic  
804 to early Cretaceous (CX12 and CX33 in this work) that is coeval with the  
805 aforementioned late Jurassic–early Cretaceous basement-slice-imbrication (Figure  
806 13b)(Arne et al., 1997; Huang et al., 2003a; Tian et al., 2016; Airaghi et al., 2018a).  
807 Both gravity inversion (Xue et al., 2017) and seismic reflection profiles (Guo et al.,  
808 2013) revealed a belt of basement-slice hidden right beneath a Mesozoic Laojungou  
809 granite ( $224 \pm 5$  Ma; Zhao et al., 2007) within the east Songpan–Ganzi Terrane (Figure  
810 13a). The Laojungou granite recorded rapid exhumation and cooling during the late  
811 Jurassic to early Cretaceous as well (Figure 13b)(Yuan et al., 1991).

812 Considering the spatial–cooling–imbricating relationships between the Laojungou  
813 granite, amphibolite facies metamorphic zones and basement-slices, we interpret that  
814 the Laojungou granite and amphibolite facies metamorphic rocks were popped up by a  
815 basement-slice-imbrication during the late Jurassic–early Cretaceous. The basement-  
816 slice-imbrication was responsible for localized fast cooling and exhumation of the  
817 amphibolite-facies metamorphic rocks. However, the Wenchuan–Xuelongbao

818 metamorphic sedimentary cover does not show fast cooling during the late Cretaceous–  
819 earliest Paleocene and at *ca.* 27–25 Ma comparing to the basement-slice-imbrication  
820 (Figure 13b), which needs further work.

821

#### 822 **5.4 Mesozoic tectonic evolution of the LMTB**

823 The Mesozoic tectonic evolution of the LMTB can be summarized as follows  
824 without consideration of the top-to-the-N/NW thrusting in the Northwestern Zone.  
825 Namely, the Songpan–Ganzi Terrane subducted to the north along the Anymaqen  
826 Suture Zone and/or to the southwest along the Jinshajiang Suture Zone, which resulted  
827 in the top-to-the-S shearing of the thick Triassic flysch cover along a basal decollement  
828 layer (Mattauer et al., 1992; Calassou, 1994) and associated sinistral strike-slip to the  
829 southeastward thrusting in the LMTB (Xu et al., 1992; Dirks et al., 1994; Burchfiel et  
830 al., 1995; Worley and Wilson, 1996; Roger et al., 2004; Harrowfield and Wilson, 2005).  
831 The amphibolite facies metamorphism in the Wenchuan–Xuelongbao area reached the  
832 peak pressure of  $> 11 \pm 2$  kbar at *ca.* 200 Ma (Airaghi et al., 2018b) required a  
833 sedimentary cover more than 30 km in thickness. However, high-resolution seismic  
834 reflection and gravity modeling profiles revealed a ~20 km thickness cover of the  
835 Songpan–Ganzi Terrane (Guo et al., 2013; Xue et al., 2017) that is far thinner than the  
836 required ~30 km thickness.

837 In contrast, Sengör (1984) and Luo (1991) regarded the LMTB as an early Mesozoic  
838 intracontinental subduction zone but lack details of structural observation. Considering  
839 the pervasive top-to-the-N/NW thrusting in the Northwestern Zone and top-to-the-SE  
840 thrusting in the Southeastern Zone, we thus prefer an early Mesozoic intracontinental  
841 subduction along the LMTB.

842 In this work, the Main Central Boundary, devoid of ophiolitic rocks separating the  
843 Southeastern Zone to the SE from the Northwestern Zone to the NW, does not represent  
844 an ophiolitic suture zone, but a tectonic “scar” corresponding to the place where the  
845 Yangtze basement was underthrust. Like the Chenzhou–Linwu Fault in the  
846 Xuefengshan Intracontinental Orogen (South China) where the South China Block  
847 underthrust (Chu et al., 2012a; Chu et al., 2012b). Along the LMTB, the  
848 underthrusting was coeval with important burial ( $> 11 \pm 2$  kbar) and the double-vergent  
849 thrusting in both sides of the Main Central Boundary. The basement underthrusting is  
850 also supported by the blueschist with intraplate affinity reported along the Qingchuan–

851 Pingwu Fault (Wei, 1994; Xu et al., 2020). A new tectonic scenario is proposed here  
852 (Figure 14). In the pre-middle Triassic times, the Longmenshan area along the western  
853 Yangtze margin was a failed rift evidenced by radiolarian chert, abyssal deposits, slump  
854 structures (Long, 1991; Luo, 1991; Chang, 2000; Li, 2009) and seismic profile (Jia et  
855 al., 2006). Accompany with the pre-middle Triassic rifting, a series of NW-dipping syn-  
856 depositional normal faults developed in the Longmenshan area that dissected the  
857 western Yangtze basement to slices, and the lower crust thinned significantly that  
858 resulted in a local “weak zone” in the lower crust (Figure 14a).

859 During the late Triassic, the Yangtze basement underthrusting along the “weak zone”  
860 accommodated by inversion of the normal faults, which can be linked to the far-field  
861 effect of the Paleotethys’ closure (Figure 14b)(Luo, 1991; Chen and Wilson, 1996;  
862 Meng et al., 2005; Yan et al., 2019). The sedimentary cover was simultaneously  
863 shortened by a top-to-the-SE thrusting and a top-to-the-NW thrusting associated with  
864 the main D<sub>1</sub> event (Figure 14b). The domain of the top-to-the-SE thrusting in the  
865 Southeastern Zone is larger and more extensive than the top-to-the-NW thrusting in the  
866 Northwestern Zone. Similar structures were developed in the north Himalaya where a  
867 large domain experienced a top-to-the-S thrusting, compared to a small domain with a  
868 top-to-the-N thrusting due to the northward subduction of the India plate (Dewey, 1988;  
869 Harrison, 1992). We thus favor an NW-ward basement underthrusting along the LMTB  
870 (Figure 14b). The large amount of rift rocks transported southeastwards and overlain  
871 the autochthonous foreland basin. In addition, a large volume of rocks was  
872 underthrust to crustal depth deeper than 30 km and metamorphosed, as documented  
873 by the *ca.* 210–180 Ma amphibolite-facies metamorphic zone that metamorphosed at a  
874 peak pressure of  $> 11\pm 2$  kbar (Figure 12)(Weller et al., 2013; Airaghi et al., 2018a;  
875 Airaghi et al., 2018b; Airaghi et al., 2018c).

876 During periods of the late Jurassic–early Cretaceous, late Cretaceous–earliest  
877 Paleogene, the accretion of Gondwana-derived Terranes to the southern Eurasia plate  
878 had resulted in episodic compression in the Longmenshan area (Dewey, 1988; Xu et  
879 al., 1992). We cannot rule out the possible contribution of the 150–140 Ma and 120–  
880 105 Ma compression resulted from the westward subduction of the Paleo-Pacific plate  
881 subduction (Chu et al., 2019). Under the regional episodic compression, basement-  
882 slices represented by the Neoproterozoic complexes along the weak zone of the  
883 Yangtze Block, including the Xuelongbao, Moutuo, and Danba complexes,

884 episodically imbricated southeastwards along the inherited faults. Basement-slice-  
885 imbrication then exhumed the basement complexes and the amphibolite facies  
886 metamorphic rocks as documented by the synchronously fast cooling of the meta-  
887 sediments and the basement complexes (Figures 12 and 14d)(Yuan et al., 1991; Arne  
888 et al., 1997; Huang et al., 2003b; Weller et al., 2013; Tian et al., 2016). Basement-slice-  
889 imbrication also reworked the late Triassic allochthonous–autochthonous LMTB into  
890 four subdivisions (Figure 14d).

891

## 892 **7 Conclusions**

893 Based on structural analysis and previous geophysical profile, we have delineated a  
894 Main Central Boundary that separates the Longmenshan Thrust Belt into a Southeastern  
895 Zone to the southeast and a Northwestern Zone to the northwest.

896 On the basis of different lithologies, increasing strain intensity and metamorphic  
897 grade, the Southeastern Zone is revised into four subdivisions, namely, the Autochthon,  
898 Para-autochthon, Allochthon, and Inner Metamorphic Core.

899 The detailed structural analysis allows us recognizing the multiphase deformation of  
900 the LMTB. A main  $D_1$  double-vergent thrusting event, characterized by the  $D_{1E}$  top-to-  
901 the-SE thrusting in the Southeastern Zone and the  $D_{1W}$  top-to-the-NW/N thrusting in  
902 the Northwestern Zone, has been recognized. The  $D_{1E}$  and  $D_{1W}$  events were  
903 synchronously occurred corresponding to a late Triassic intracontinental underthrusting  
904 along a “weak zone” of the LMTB. A  $D_2$  top-to-the-NW normal faulting that cuts the  
905  $D_{1E}$  top-to-the-SE thrusting has been recognized along the NW boundary of the  
906 basement complexes in the Southeastern Zone.

907 Geochronological constraints obtained from this study and the previously published  
908 ones indicate that the main  $D_1$  event occurred at *ca.* 224–219 Ma and the  $D_2$  was  
909 episodically activated at *ca.* 166–160 Ma, 141–120 Ma, 81–47 Ma, and 27–25 Ma. The  
910 episodically and synchronously activated top-to-the-NW normal faulting and top-to-  
911 the-SE thrusting along the northwest and SE boundaries of the basement complexes let  
912 us propose that the basement-slices episodically imbricated to the SE during the late  
913 Jurassic–early Cretaceous and late Cretaceous–earliest Paleocene. The basement-slice  
914 imbrication exhumed the  $D_1$ -related amphibolite facies rocks to the subaerial and  
915 reworked allochthonous–autochthonous LMTB into a four subdivision one.

916

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924 zircons (Table S1) and  $^{40}\text{Ar}/^{39}\text{Ar}$  dating on micas (Table S2) for this paper are available  
925 in the supplementary materials.

926

927 **Figure captions**

928 Figure 1. (a) Simplified tectonic sketch of China. QLDB: Qingling–Dabie Orogenic Belt; EKL–  
929 ANMQS: East Kunlun–Anymaqen Suture Zone; JSZ: Jinshajiang Suture Zone; SGT: Songpan–Ganzi  
930 Terrane; LMTB: Longmenshan Thrust Belt; ICB: Indochina Block; (b) Simplified geological map of the  
931 Longmenshan Thrust Belt, modified after BGMRS (1991), Burchfiel et al. (1995) and Xu et al. (2008).  
932 T<sub>1</sub>: Anxian–Guanxian Fault; T<sub>2</sub>: Yingxiu–Beichuan Fault; T<sub>3</sub>: Wenchuan–Maoxian Fault; T<sub>4</sub>:  
933 Qingchuan–Pingwu Fault; JZD: Jiaoziding complex; PG: Pengguan complex; XLB: Xuelongbao  
934 complex; BX: Baoxing complex; KD: Kangding complex; DB: Danba complex; MT: Moutuo complex;  
935 WL: Wulong complex; RLG: Rilonguan granite; LJG: Laojungou granite.

936

937 Figure 2. Geological map of the north and middle parts of the LMTB and its adjacent area, modified after  
938 BGMRS (1991) and Xu et al. (2008). MP: Mupi pluton. Symbols and acronyms are the same as in  
939 Figure 1.

940

941 Figure 3. (a) Structural division, field elements including foliation, lineation, and kinematics of the  
942 LMTB. (b–d)  $\pi$ -circle projection of the bedding ( $S_0$ ) in the Para-autochthon from south to north. All field  
943 elements are shown in a lower hemisphere equal-area projection. Symbols and acronyms are the same as  
944 in Figure 1.

945

946 Figure 4. (a–d) Geological cross-sections perpendicular to the LMTB. Purple solid lines represent the  
947 foliations attitude (Locations are marked in Figure 2). Subaerial structures of these cross-sections are  
948 based on our field mapping and the deep structures are based on seismic reflection data of Jia et al. (2006)  
949 and Guo et al. (2013). The black dashed lines represent speculated folds. (e) Flower structure revealed

950 by the seismic reflection profile processed by Jia et al. (2006)(Location is marked in Figure 4d). MCB:  
951 Main Central Boundary; AGF: Anxian–Guanxian Fault; YBF: Yingxiu–Beichuan Fault; WMF:  
952 Wenchuan–Maoxian Fault; QCF: Qingchuan–Pingwu Fault. Other symbols and acronyms are the same  
953 as in Figure 1

954

955 Figure 5. Rock characteristics and deformation style of the Main Central Boundary. (a) Intensely  
956 deformed argillaceous limestone characterized by a vertical foliation [31°34.833' N, 103°24.041' E]. (b)  
957 Graphite-bearing pelite was intensely foliated to shale with vertical attitude [31°35.916' N, 103°24.008'  
958 E]. (c) Foliated thin-bedded limestone and quartz ribbon interlayer and rootless intra-folial folds coexist  
959 with vertical foliation [31°48.403' N, 103°44.080' E]. Rootless folds in figures b–c implying significant  
960 shortening. Locations are presented in Figure 3a.

961

962 Figure 6. Structural features related to the Main Deformation ( $D_{IE}$ ) in the Southeastern Zone. **In the**  
963 **Inner Metamorphic Core:** (a) Lineation formed by aligned biotite plunging N335° by 30° on the S-  
964 dipping foliation [31°30.359' N, 103°34.123' E]. (b) Asymmetric pyrite pressure shadow indicating a  
965 top-to-the-SE thrusting [31°42.210' N, 103°51.067' E]. (c) Sigma-shaped feldspar porphyroclast in  
966 paragneiss indicating a top-to-the-SE thrusting [31°05.193' N, 103°18.730' E]. (d) S/C fabric observed  
967 under Cross Polarized Light (CPL) indicating a top-to-the-SE thrusting. **In the Allochthon:** (e) Sigmoid  
968 pelitic lens and “cold” S/C structures developed in the Neoproterozoic Huangshuihe Group suggesting a  
969 top-to-the-SE thrusting [31°16.195' N, 103°46.747' E]. (f) Sigma-shaped sandy lens in Silurian  
970 pelitic schist within the nappe indicating a top-to-the-SE thrusting [32°04.577' N, 104°40.599' E]. (g) At  
971 the rear of the klippe, thick-bedded limestone thrust to the SE along an NW-dipping reverse fault  
972 [31°11.530' N, 103°45.929' E]. **In the Para-autochthon:** (h) Sigmoid lens and “cold” S/C fabrics  
973 indicating a top-to-the-SE thrusting [30°55.403' N, 103°20.495' E]. Figure locations are marked in Figure  
974 3a. X and Z axes are marked on the figures. Mineral abbreviations are after Kretz (1983).

975

976 Figure 7. Structural features related to the Main Deformation ( $D_{IW}$ ) in the Northwestern Zone. **In the**  
977 **northern Northwestern Zone:** (a) Aligned calcite, fine-grained white mica, and oxide-pods define  
978 lineation plunging to the south on the S-dipping foliation [32°30.892' N, 104°08.178' E]. (b) Sigma-  
979 shaped pebbles in a meta-conglomerate indicating a top-to-the-N sense of shear [32°53.562' N,  
980 105°04.820' E]. (c) Deflected quartz ribbon observed under CPL indicating a top-to-the-N thrusting. (d)  
981 Asymmetric feldspar porphyroclast wrapped by deflected white mica suggesting a top-to-the-N thrusting.  
982 (e) Northward verging chevron fold associated with meter-scale reverse fault indicating a top-to-the-N

983 thrusting [32°25.219' N, 104°31.513' E]. (f) Bedding depicted by compositional banding showing an N-  
984 verging fold, and bedding to sub-parallel to the foliation in the limbs [32°228.591' N, 104°26.763' E]. **In**  
985 **the southern Northwestern Zone:** (g) Asymmetric garnet pseudomorph pressure shadow suggesting a  
986 top-to-the-NW thrusting. (h) Hundred-meter scale chevron fold verging to the NW indicating a top-to-  
987 the-NW thrusting [31°33.912' N, 103°16.680' E]. Figure locations are marked in Figure 3a. X and Z axes  
988 are marked on the figures. Mineral abbreviations are after Kretz (1983).

989

990 Figure 8. Features of the syn-tectonic Mupi pluton in the Northwestern Zone [32°31.445' N, 104°32.456'  
991 E]. (a) Magmatic fabric of the Mupi pluton with euhedral feldspar randomly distributed, about 30 meters  
992 north to the south margin of the Mupi pluton. (b) Quartz + feldspar veins parallel to the shear foliation,  
993 about 10-15 meters north to the pluton south margin. (c) Strong mylonitisation at the south margin of the  
994 pluton shares similar structural geometry and kinematics with the country rock. (d) Asymmetric feldspar  
995 porphyroclasts, synthetic offset of feldspar fragments along shear band in XZ plane indicating a top-to-  
996 the-N thrusting. (e) Panorama of thin section under CPL of the Mupi pluton, the feldspar brittle cracks  
997 (marked by red arrow) infilled by quartz subparallel to the shear foliation. X and Z axes are marked on  
998 the figures. Figure locations are marked in Figure 3a. Mineral abbreviations are after Kretz (1983).

999

1000 Figure 9. Structural features related to the top-to-the-NW normal faulting along the northwest boundary  
1001 of the Neoproterozoic complexes. (a) At the northwest boundary of the **Xuelongbao complex**, sigmoid  
1002 feldspar phenocrysts associated with S/C fabric indicating a top-to-the-NW normal faulting [31°19.683'  
1003 N, 103°23.874' E]. At the northwest boundary of the **Pengguan complex:** (b) Granitic mylonite having  
1004 foliation dips to the NW [31°22.931' N, 103°30.364' E]. (c–d) Mica fish in the quartz schist (PPL) and  
1005  $\sigma$ -type porphyroclast (CPL) wrapped by deflected micas indicating a top-to-the-NW normal faulting. (e)  
1006 Shear-band (white dashed line) distributes from the upper-right corner to the lower-left corner that cuts  
1007 the whole thin section indicate a top-to-the-NW normal faulting, CPL. Sigmoid porphyroclast (e),  
1008 incipient shear band inclining to the SE (f), and white mica shear-band fabric (g) indicate a top-to-the-  
1009 SE thrusting related to D<sub>1E</sub>. All of them are cut by the white shear band related to the D<sub>2</sub> top-to-the-NW  
1010 normal faulting, CPL. Locations are marked in Figure 3a. X and Z axes are marked on the figures.  
1011 Mineral abbreviations are after Kretz (1983).

1012

1013 Figure 10. (a) CL images of the representative zircons from the Mupi pluton. The scale bar represents  
1014 100  $\mu\text{m}$ . (b) SIMS U–Pb Concordia diagram of zircons of the syntectonic Mupi pluton.

1015



1016 Figure 11.  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  age spectra of the dated samples. We carried out a two-aliquot analysis of micas  
1017 from CX6, CX12, and CX19 to exclude the influence of occasional deviation on the stair-case age  
1018 spectrum, and the two-aliquot results are labeled with the suffix of A and B (eg., CX6A, CX6B, CX12A,  
1019 CX12B, CX19A, CX19B). Inverse isochron diagrams are presented in Figure S3.  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  calculation  
1020 results are  
1021 summarized in Table 1, and detailed step-heating results are presented in the supporting information  
1022 Table S2.

1023

1024 Figure 12. Geochronological constraints compiled from published and this study. Ages are shown by the  
1025 method used to determine the age (A = Ar/Ar; K = K/Ar; U = U/Pb; F = Fission track) and mineral used  
1026 (Am = Amphibole; B = biotite; M = Muscovite; Z = zircon; Mn = monazite; I= illite; S = Sericite; Wm  
1027 = white mica). 1. Li (2009); 2. Yan et al. (2018); 3. Yan et al. (2011); 4. Arne et al. (1997); 5. Airaghi et  
1028 al. (2017b); 6. Airaghi et al. (2018a); 7. Airaghi et al. (2018b); 8. Airaghi et al. (2018c); 9. Zheng et al.  
1029 (2016); 10. Yan et al. (2008); 11. Zheng et al. (2014); 12. Tian et al. (2016); 13. Huang et al. (2003a);  
1030 14. Weller et al. (2013); 15. Xu et al. (2008); 16. Zhou et al. (2008); 17. Wallis et al. (2003); 18. Zhou et  
1031 al. (2002); 19. Xia (1993); 20. Xu et al. (1992); 21. Yuan et al. (1991); 22. Hu et al. (2005); 23. Zhao  
1032 (2007); 24. Kirby et al. (2002); 25. Roger et al. (2004); 26. Zhang et al. (2006a); 27. Yuan et al. (2010);  
1033 28. BGMRS (1991); 29. Li et al. (2013c); 30. Wang et al. (2012a). 31. Hames and Burchfiel (1993).  
1034 Symbols and acronyms are the same as in Figure 2.

1035

1036 Figure 13. (a) Spatial relationship between the amphibolite facies metamorphic zones and the basement  
1037 complexes along the peripheries of the Songpan–Ganzi Terrane. Isograd lines are presented in color  
1038 dashed lines accompany relating mineral abbreviations. Mineral abbreviations are after Kretz (1983)  
1039 except Liq representing the magmatic zone. Symbols and acronyms are the same as in Figure 12. (b)  
1040 Compiled cooling histories for the Wenchuan–Xuelongbao amphibolite facies metamorphic belt  
1041 (WXAB, bold dashed line)(Airaghi et al., 2018a), the Danba amphibolite facies metamorphic belt  
1042 (DBAB), and migmatite zone (DBM, thin dashed line)(Huang et al., 2003a), and the Mesozoic  
1043 Laojungou granite (LJG, bold gray line)(Yuan et al., 1991). Gray frames show the three episodes of  
1044 basement-slice-imbrication at late Jurassic–early Cretaceous, late Cretaceous–Earliest Paleocene, *ca.*  
1045 27–25 Ma. The Wenchuan–Xuelongbao and the Danba amphibolite facies metamorphic belt and the  
1046 Laojungou granite experienced a rapid exhumation and cooling during the late Jurassic to the late  
1047 Cretaceous, and 27-25 Ma.

1048

1049 Figure 14. A possible Mesozoic tectonic evolutionary scenario of the LMTB and adjacent area. (a) Pre-  
1050 middle Triassic rifting of the Yangtze Block resulted in crustal thinning and a potential “weak zone” in  
1051 the future Longmenshan area. (b) During the late Triassic, NW-ward Yangtze basement underthrusting  
1052 along the “weak zone” resulted in extensive shortening, inversion of syn-depositional normal Fault. The  
1053 sedimentary rocks were buried to a crustal depth deeper than 30 km. NW- and SE-ward thrusting, and  
1054 associated nappe belt formed at this time. (c) During the late Triassic to early Jurassic, the underthrust  
1055 rocks were metamorphosed. Gradient color from green to dark blue in the Inner Metamorphic Core  
1056 represents show the low- to high-metamorphic grade. (d) late Jurassic–Miocene, basement-slice  
1057 episodically imbricated to the SE that exhumed the amphibolite facies metamorphic rocks to the subaerial  
1058 and reworked the LMTB. Symbols and acronyms are the same as in Figure 2.

1059

1060 Table 1. Summary of  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  dating results

1061

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Figure 1

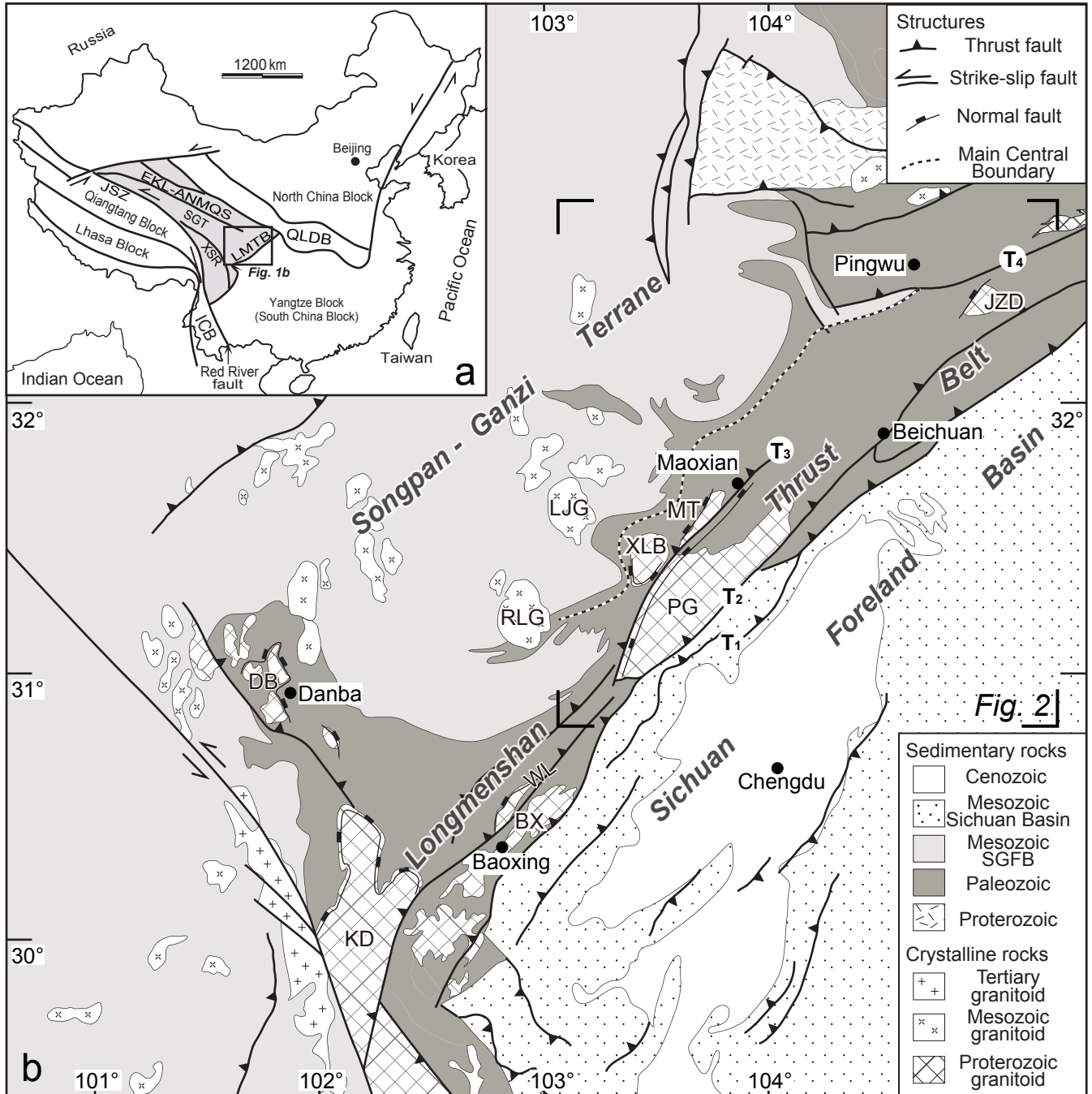




Figure 2

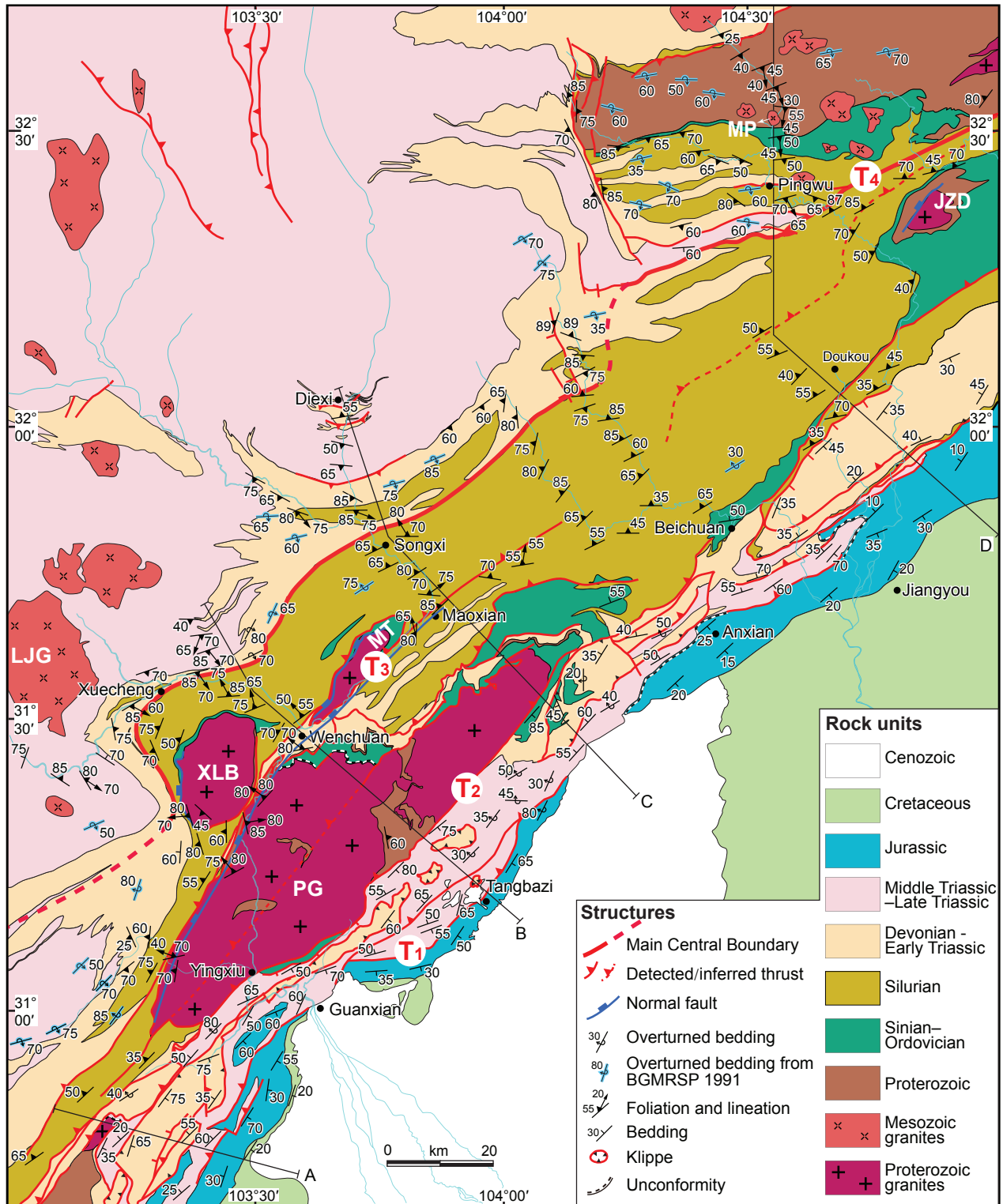
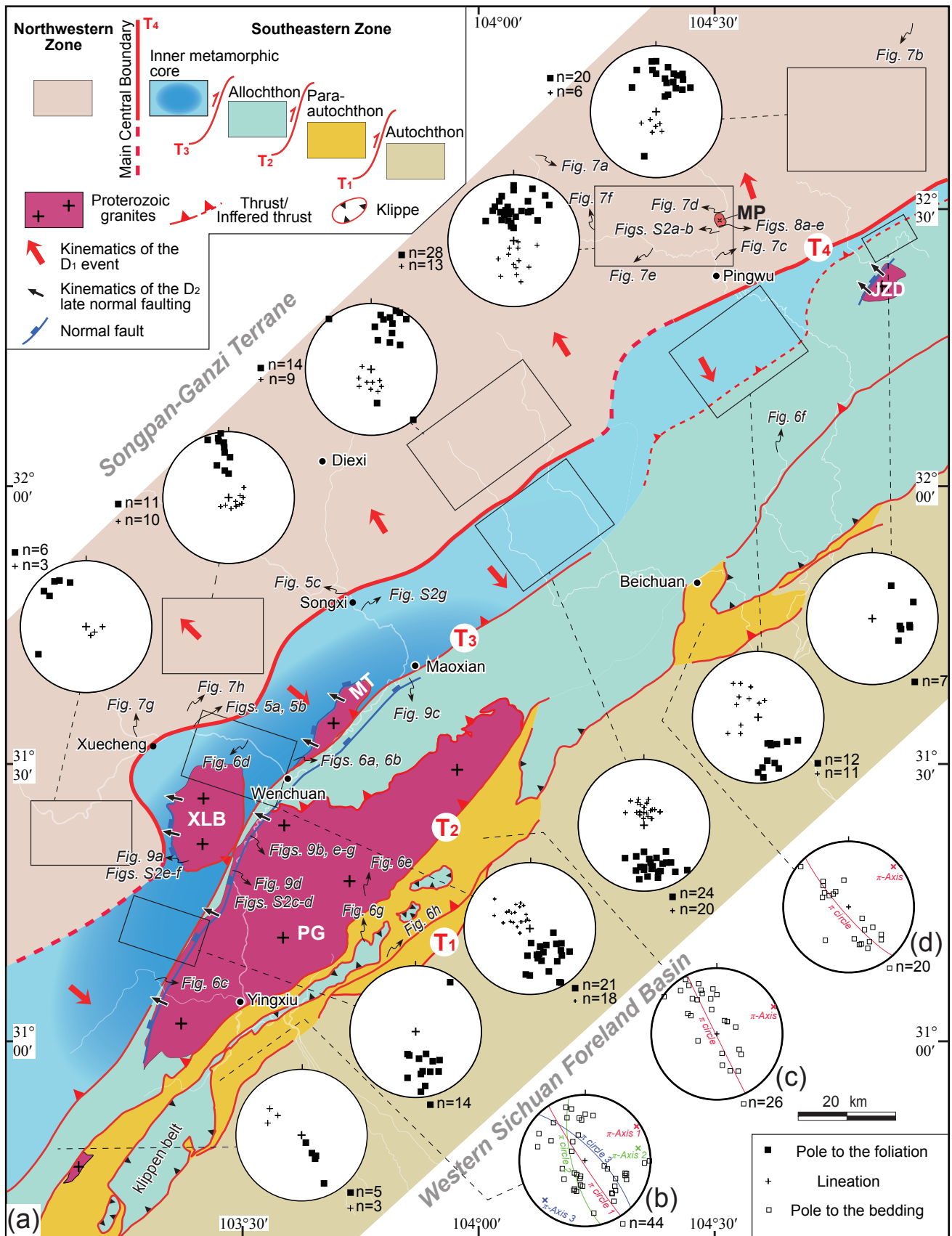


Figure 3



**Figure 4**

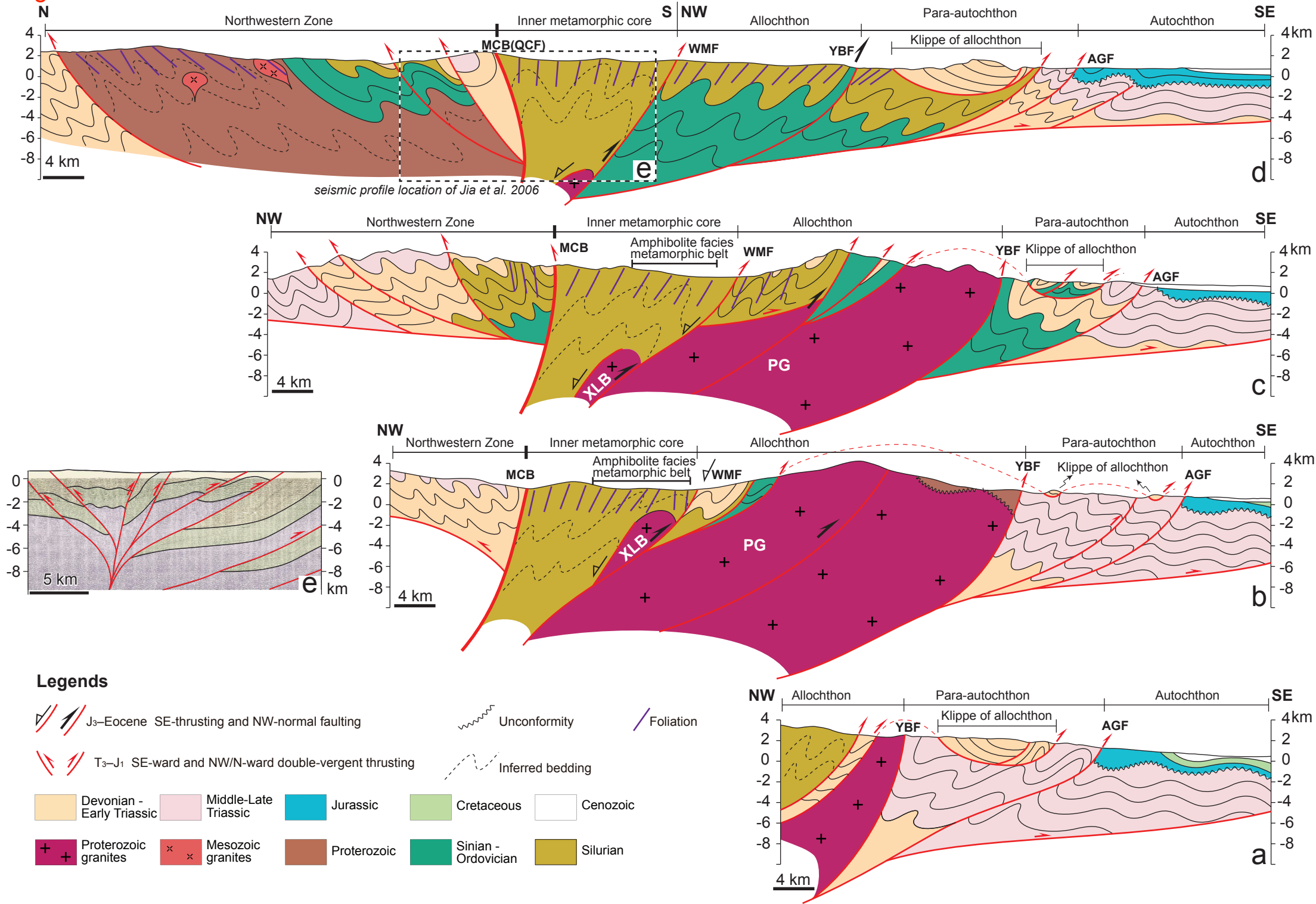


Figure 5

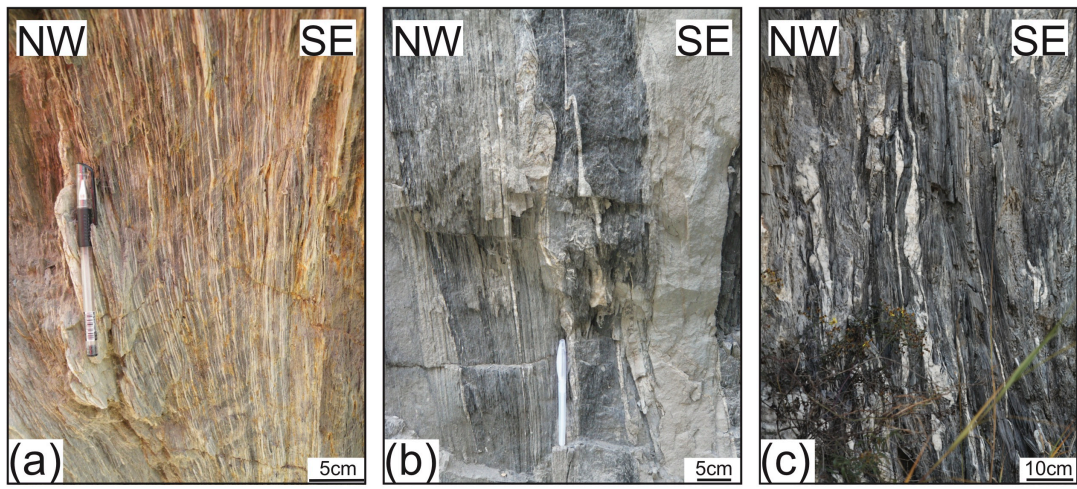


Figure 6

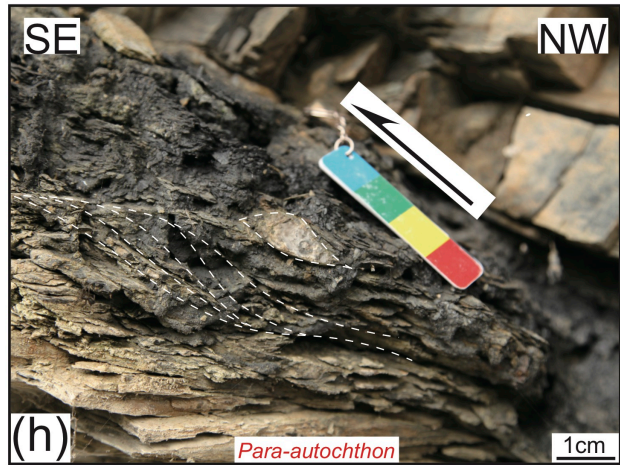
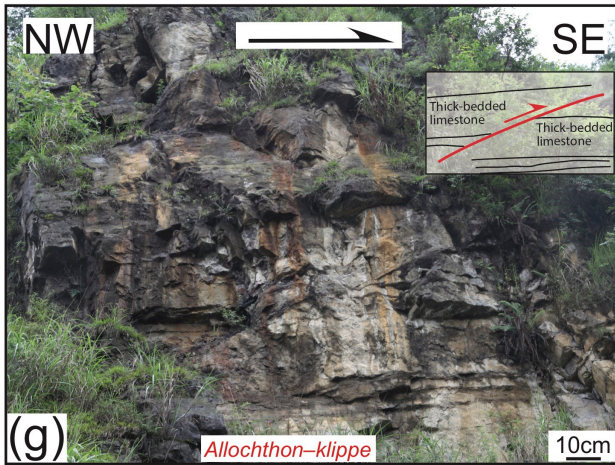
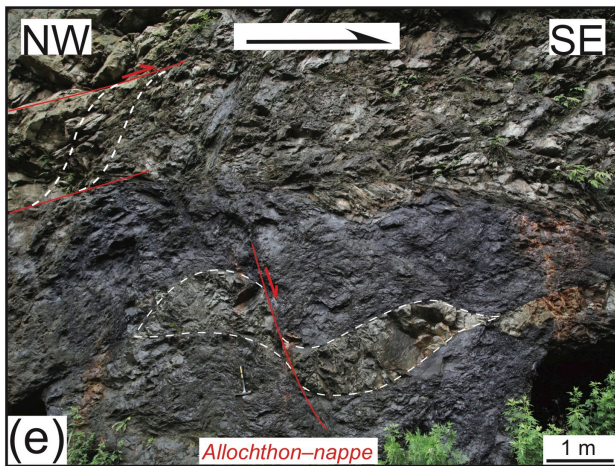
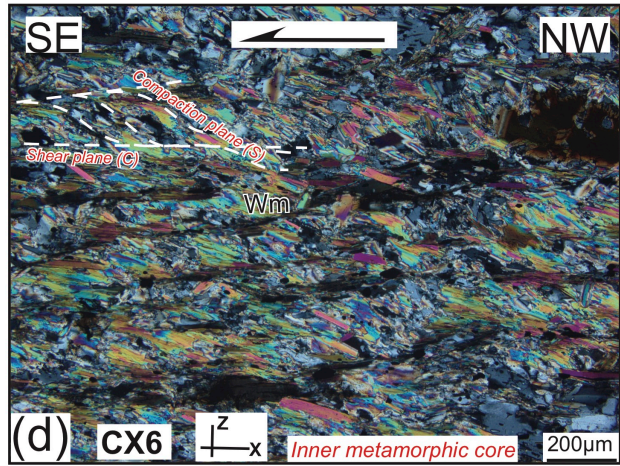
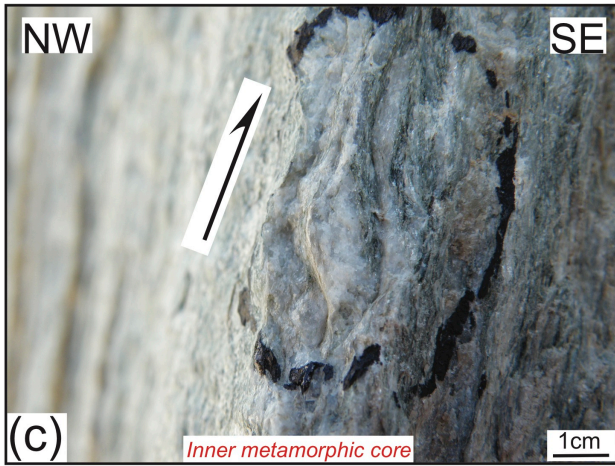
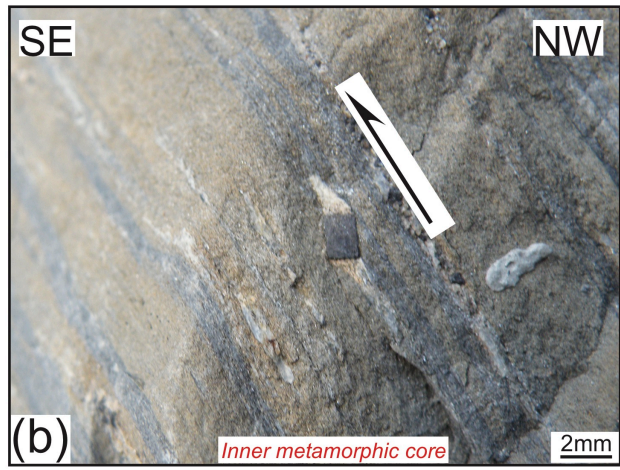


Figure 7

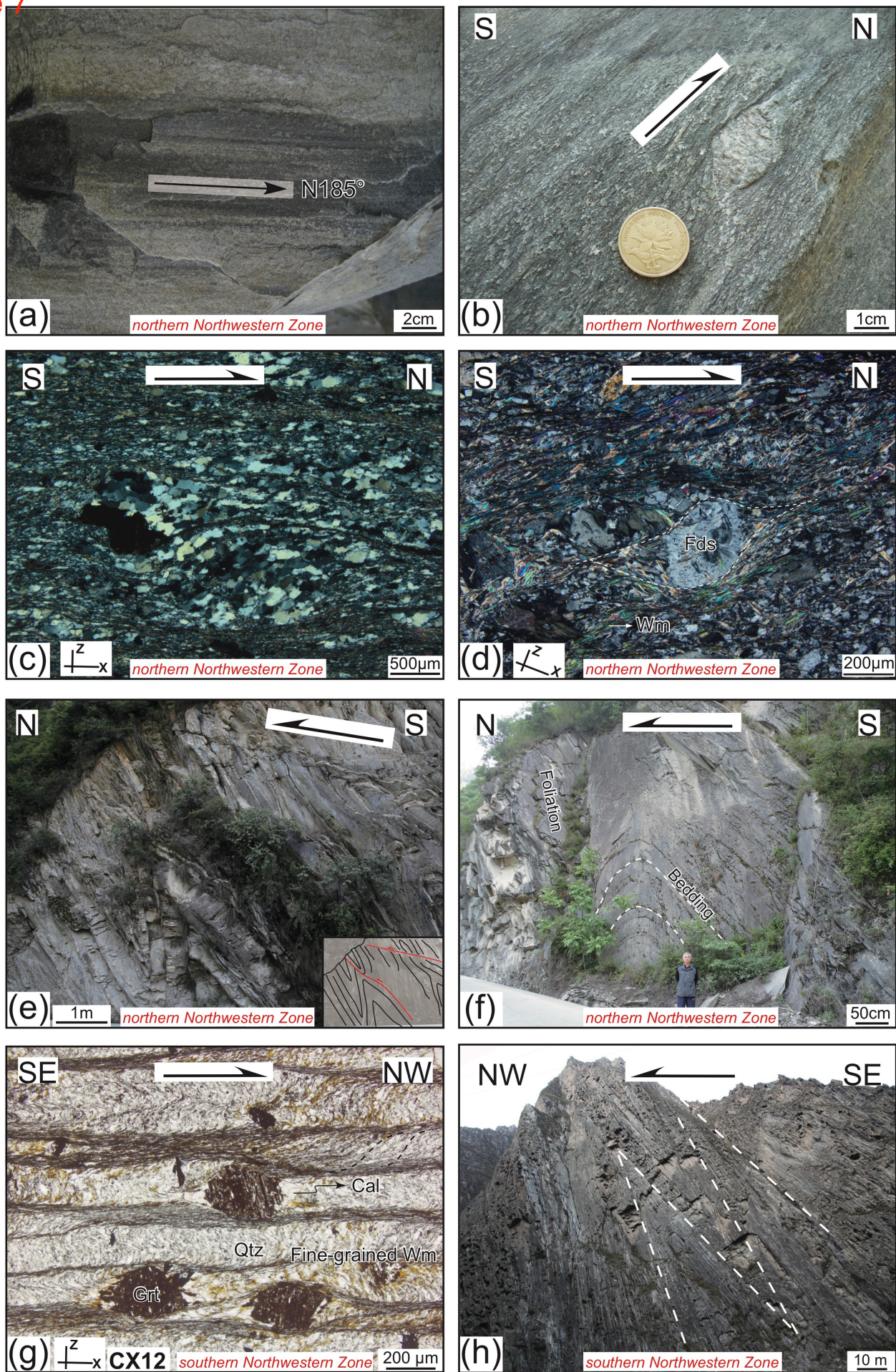
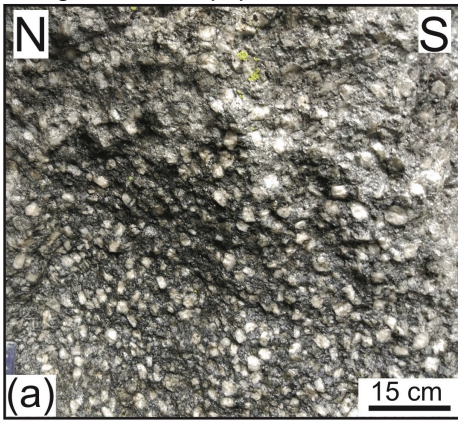
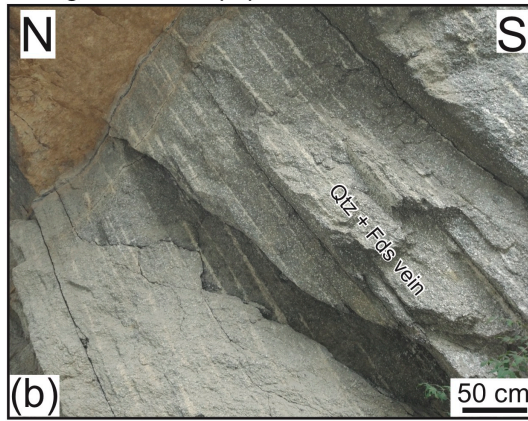


Figure 8

~30 meters north to the south margin of the Mupi pluton



~10–15 meters north to the south margin of the Mupi pluton



South margin of the Mupi pluton

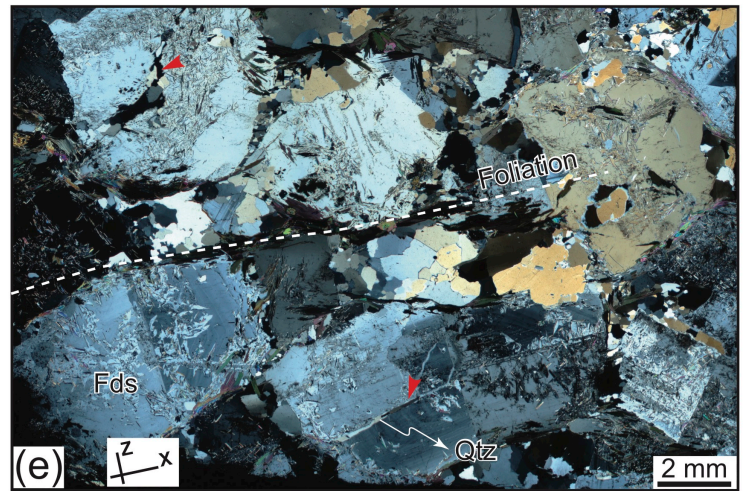
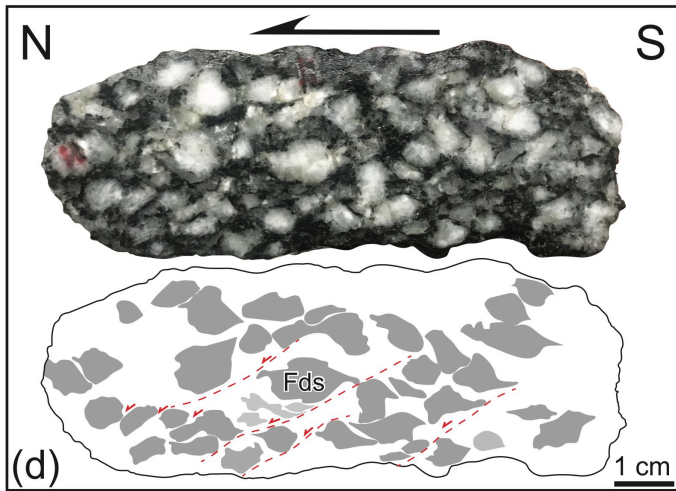
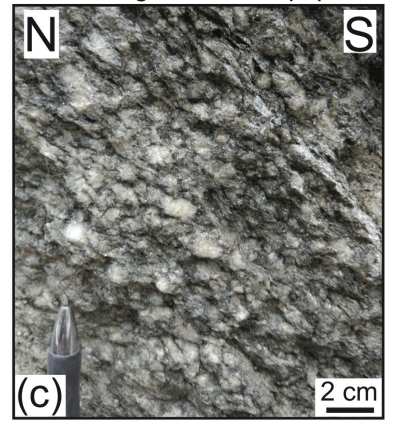
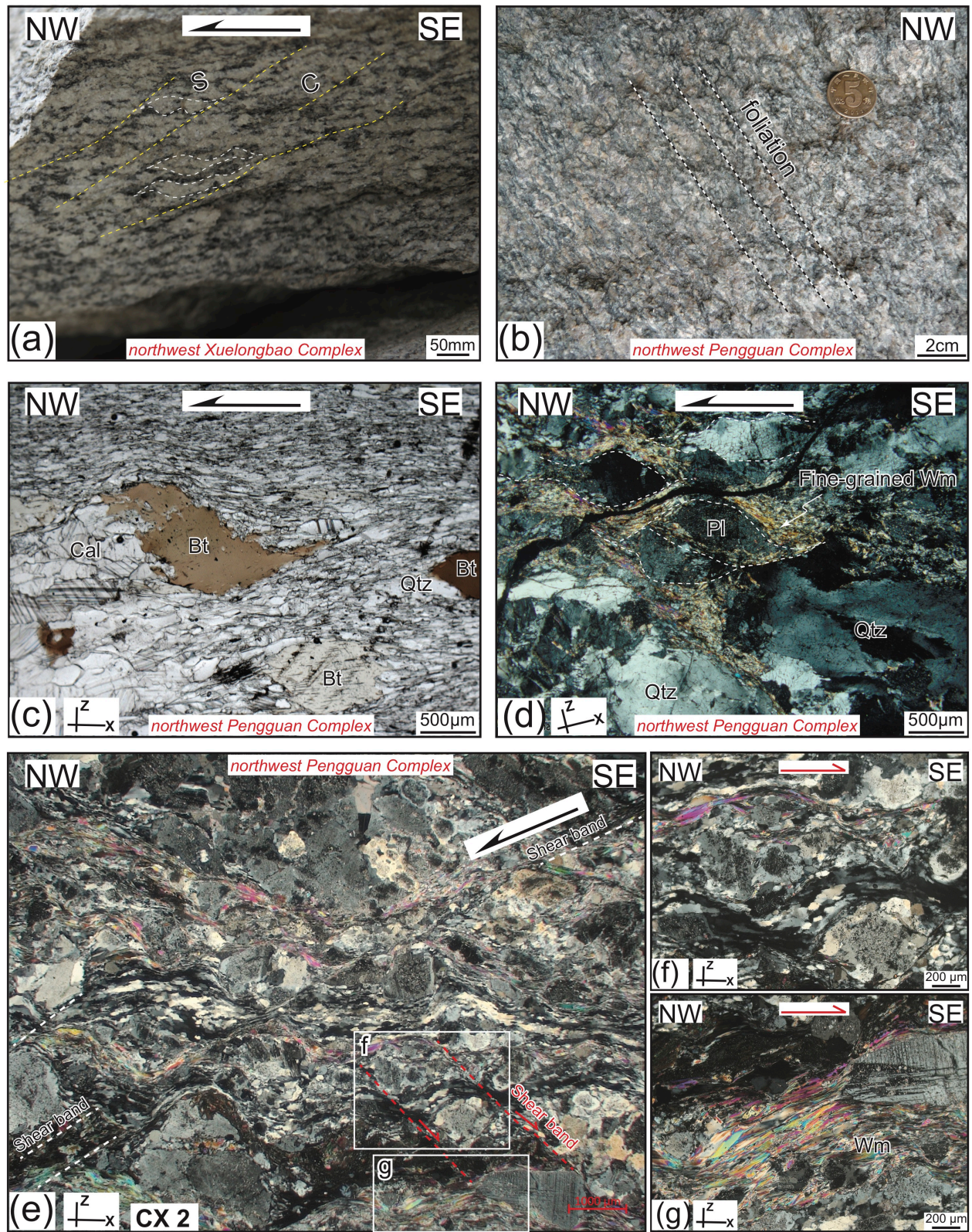


Figure 9





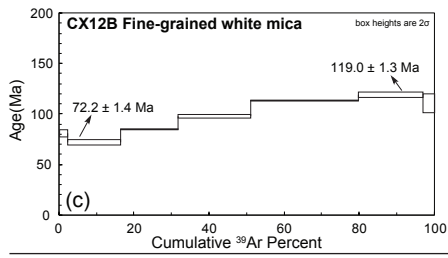
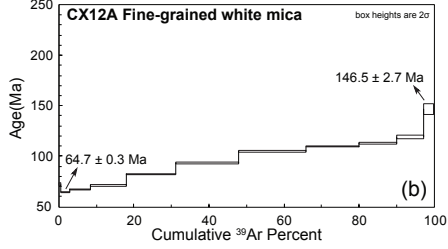
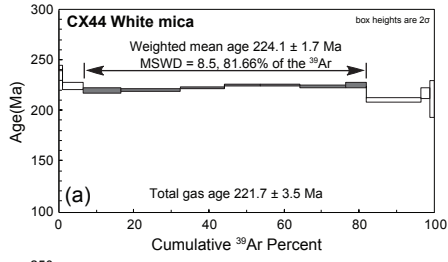
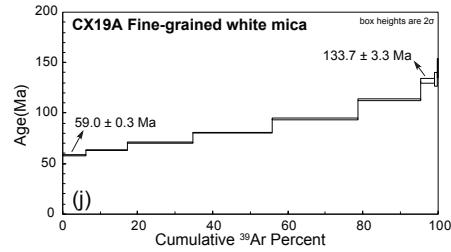
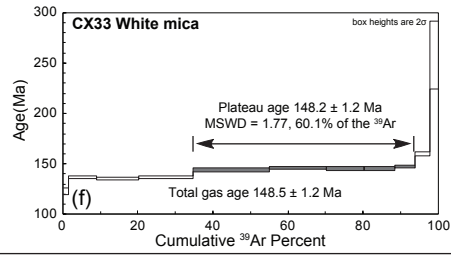
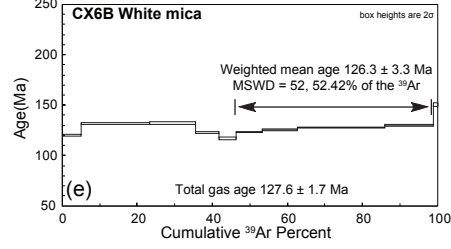
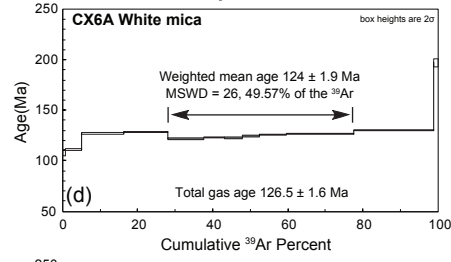
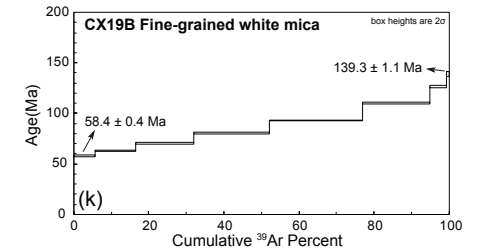
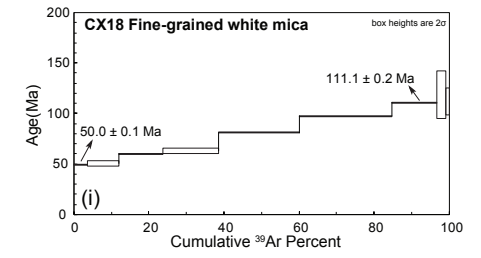
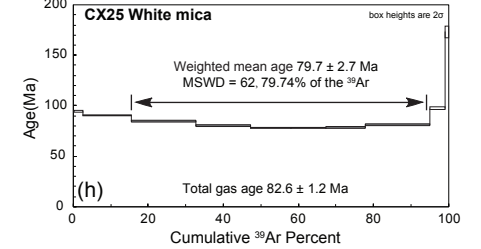
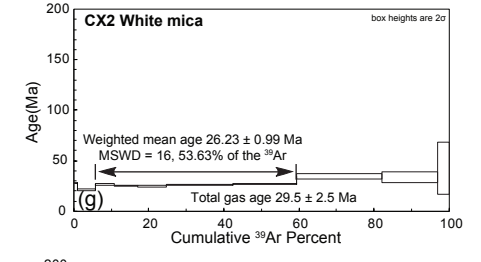
**Figure 10****Northwestern Zone****Southeastern Zone --  
Inner metamorphic core****Basement Complex**

Figure 11

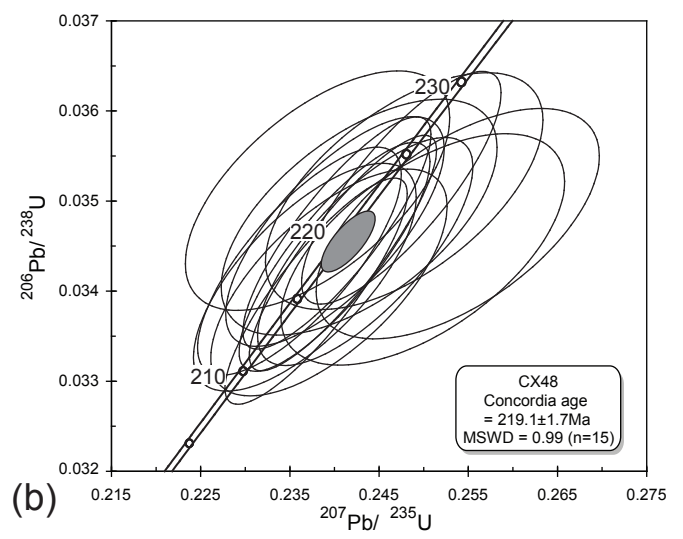
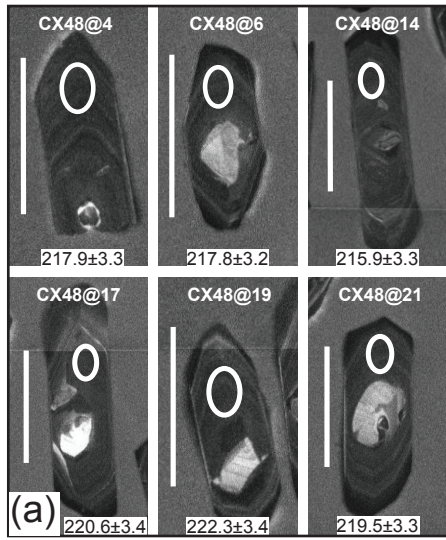


Figure 12

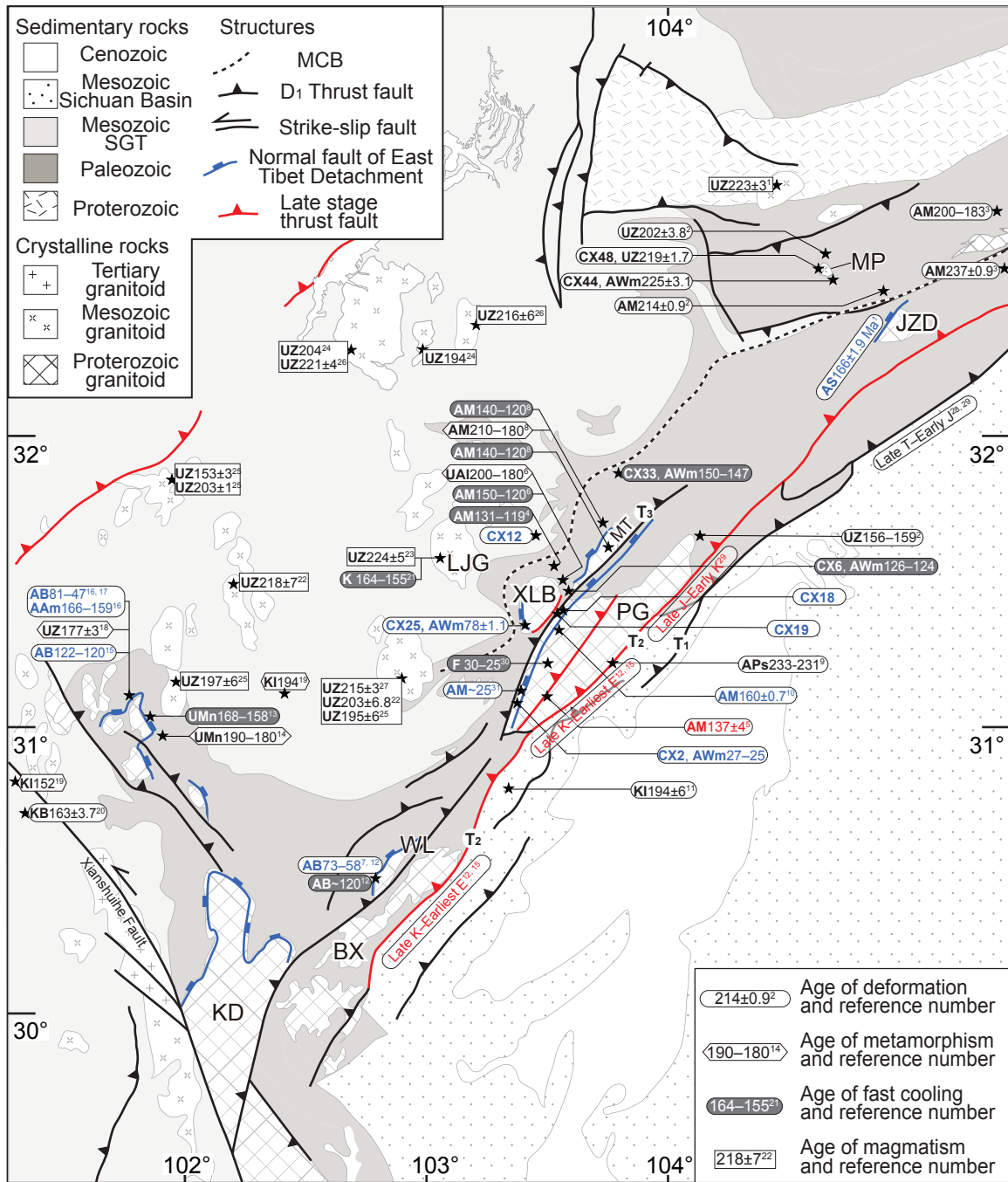


Figure 13

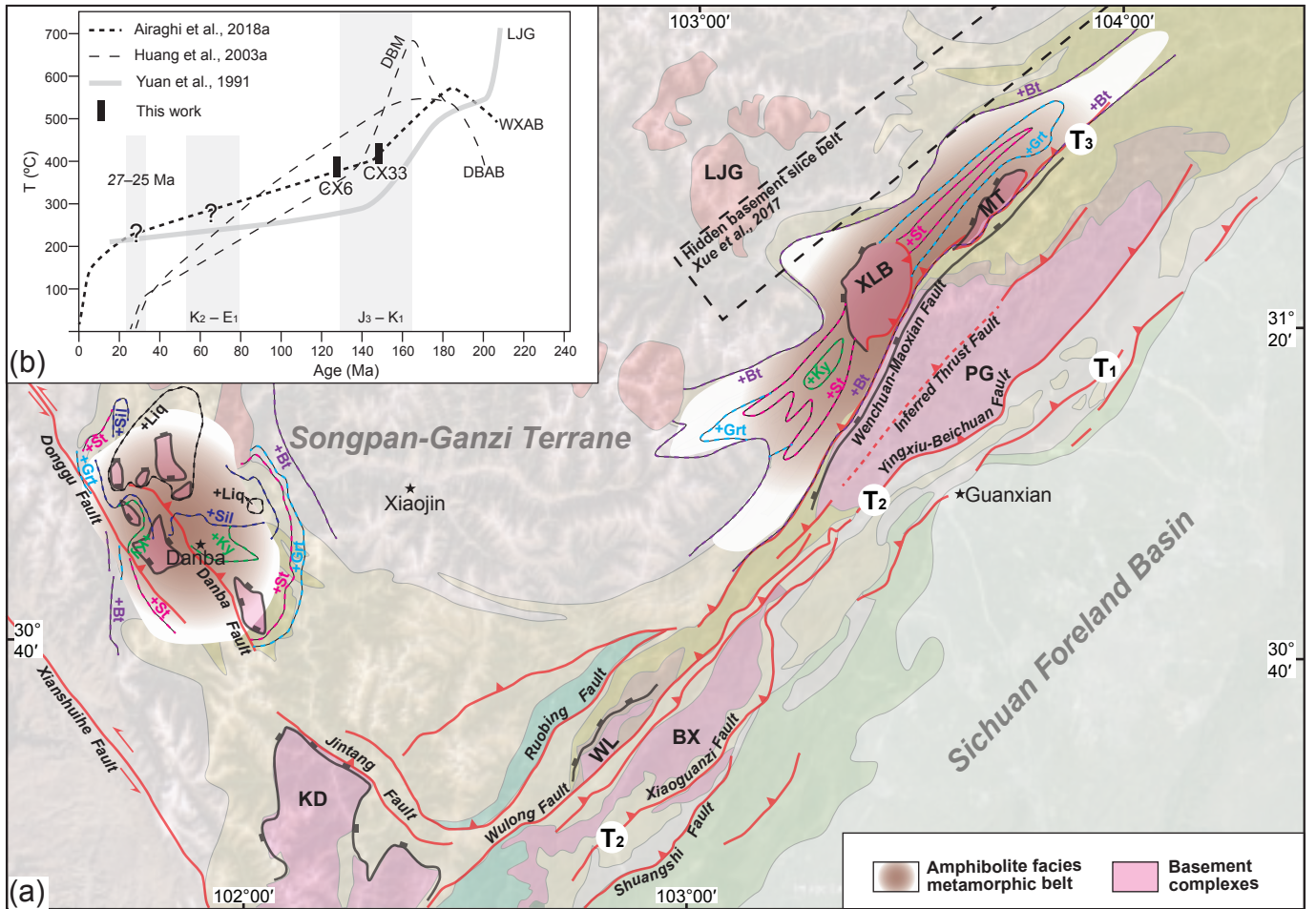
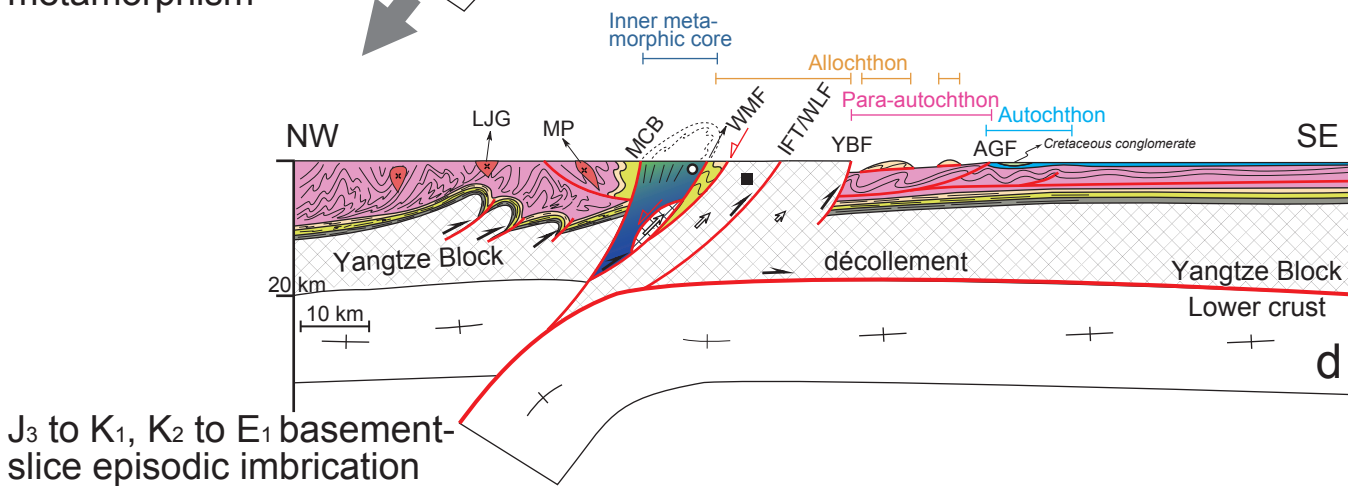
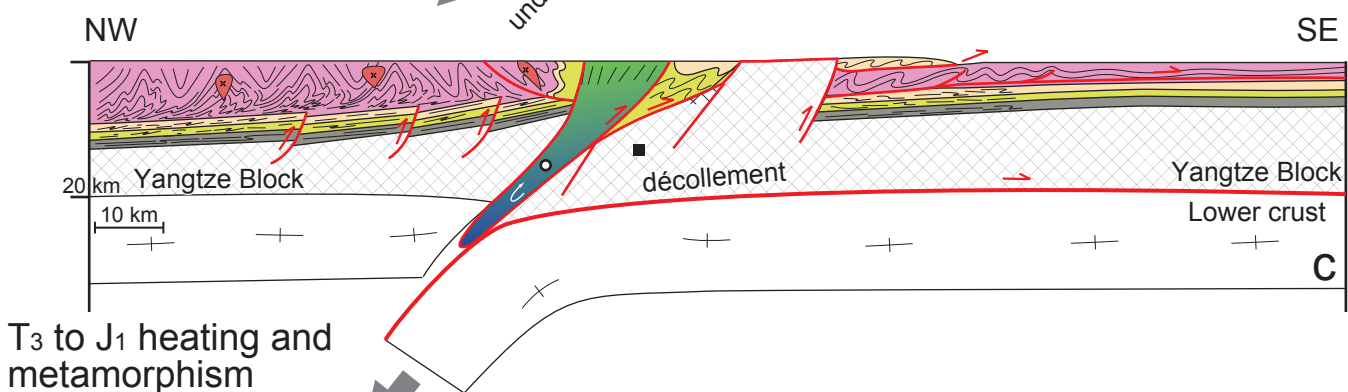
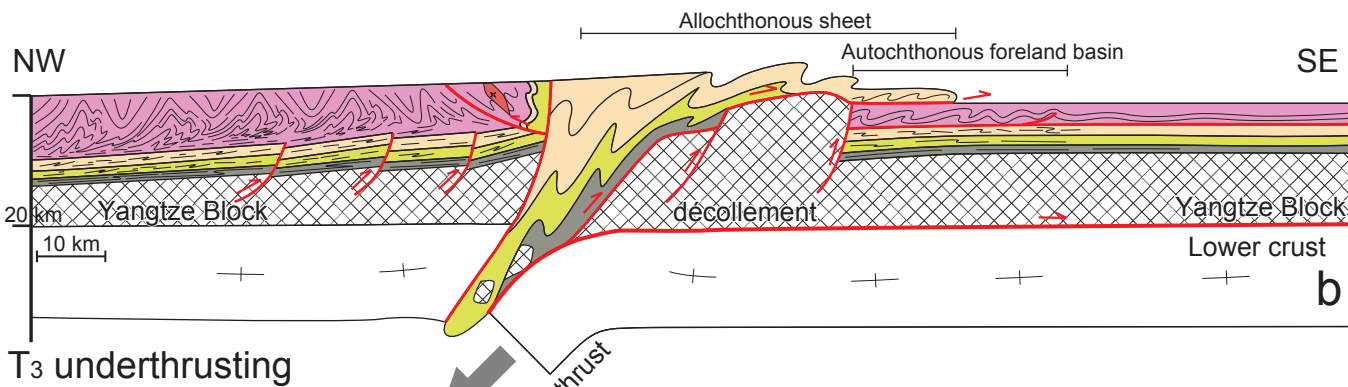
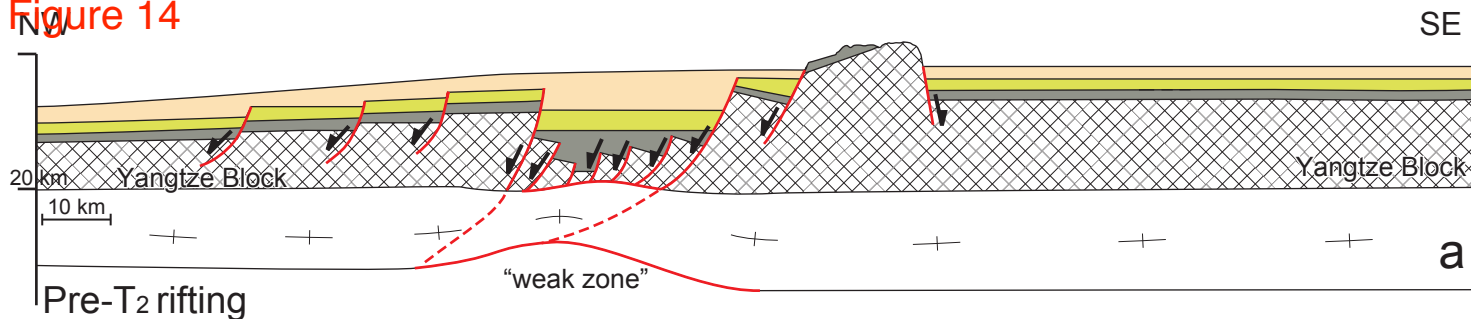
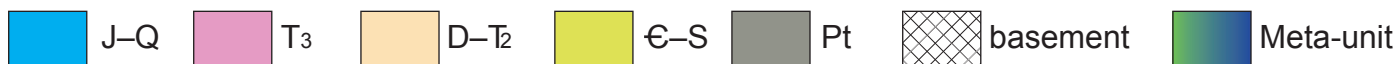


Figure 14



✓ Pre T<sub>2</sub> normal fault    / Reverse fault during T<sub>3</sub>-aJ<sub>1</sub>    ✓ / Episodic and synchronous NW-normal faulting and SE-thrusting during J<sub>3</sub>-K<sub>1</sub>, K<sub>2</sub>-E<sub>1</sub>



Zhenhua Xue, Wei Lin, Yang Chu, Michel Faure, Yan Chen, Wenbin Ji, and Huaning Qiu, 2021, An intracontinental orogen exhumed by basement-slice imbrication in the Longmenshan Thrust Belt of the Eastern Tibetan Plateau: *GSA Bulletin*, <https://doi.org/10.1130/B35826.1>.

## Supplemental Material

**Figure S1.** (a) Reflection image show location of the crack in feldspar, same crack in lower middle of Figure 8e from the Mupi pluton. (b) Same crack in Figure a, cross-polarized light. (c) Back scattered electron image show points selected for energy-dispersive X-ray spectrometer measurement. (d and h) Energy-dispersive X-ray spectra of point 1 and point 6 in the crack show typical feature of quartz. (e–g) Energy dispersive X-ray spectra of point 2, point 3, and point 5 indicate component of feldspar with different Ca content.

**Figures S2.** Features of the samples selected for  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  dating. Shear plane is defined by fine-grained white mica (c–d) or white mica (a–b, e–f, and g). (h) Field observation of sample CX6, where sigma-shaped quartz lens indicate a top-to-the-SE thrusting. Mineral abbreviations after Kretz (1983). CPL—cross-polarized light; PPL—plain-polarized light.

**Figure S3.** All samples show high radiogenic  $^{40}\text{Ar}$  (Table S2) and almost all steps are clustered at the  $^{39}\text{Ar}/^{40}\text{Ar}$  axis that do not define a real inverse isochron line. The initial  $^{40}\text{Ar}/^{36}\text{Ar}$  ratio originate from the inverse isochron line is meaningless as well. Most of the step-ages calculated both by using initial  $^{40}\text{Ar}/^{36}\text{Ar}$  of 298.56 (Lee et al., 2006) and from the “inverse isochron”, show nearly no differences (Table S2). Thus, the inverse isochron ages, though identical to their weighted mean ages or plateau ages, are meaningless and have not been discussed in the main text.

**Table S1.** Detailed SIMS U-Pb zircon results of sample CX48

**Table S2.**  $^{40}\text{Ar}/^{39}\text{Ar}$  VG3600 Furnace Step-Heating analytical results

Figure S1

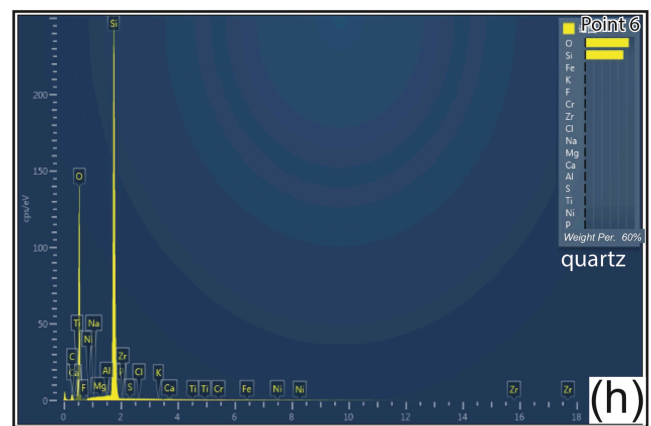
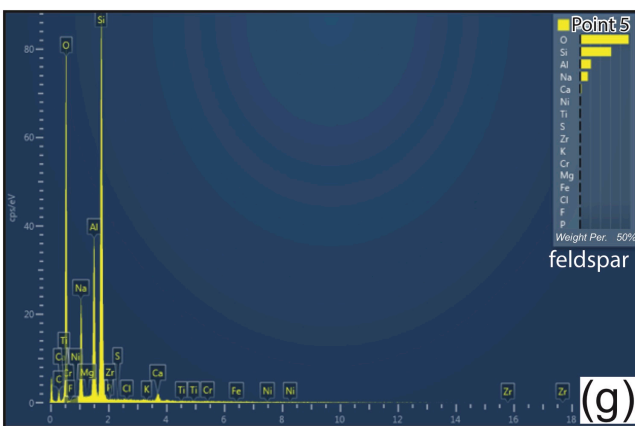
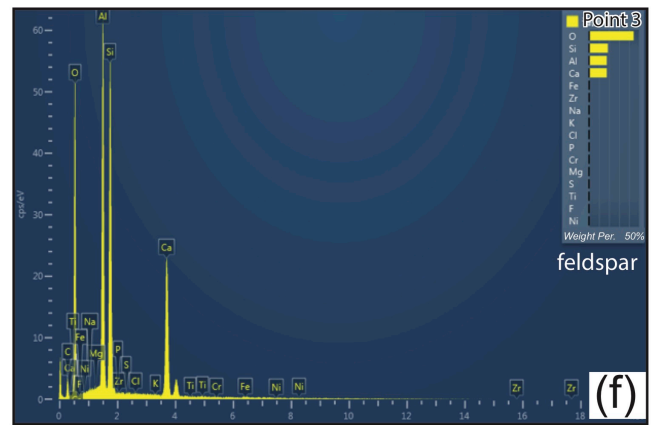
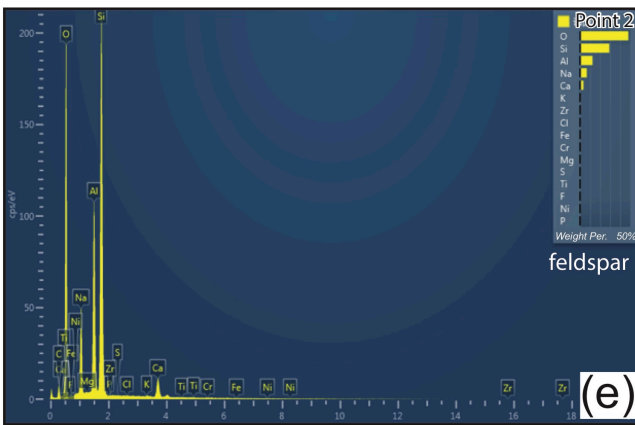
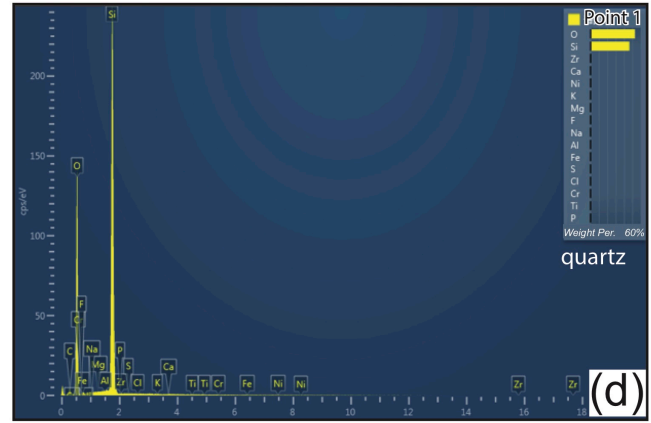
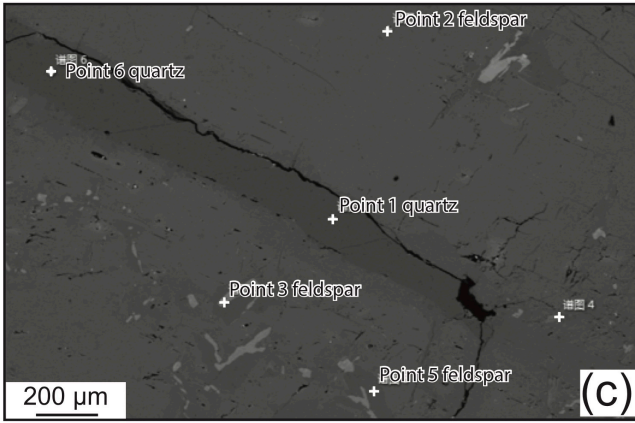
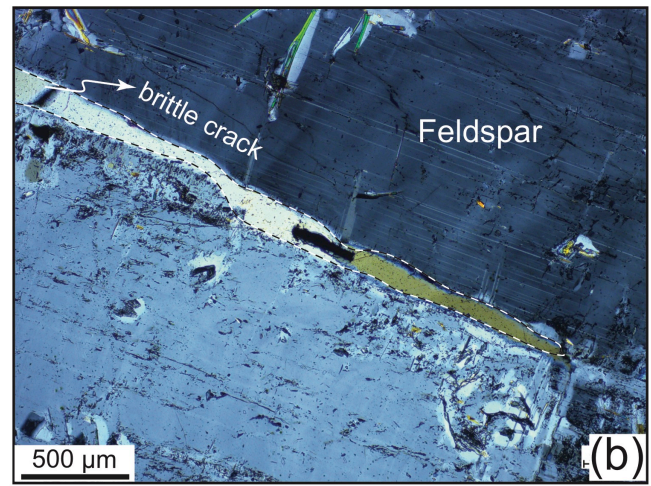
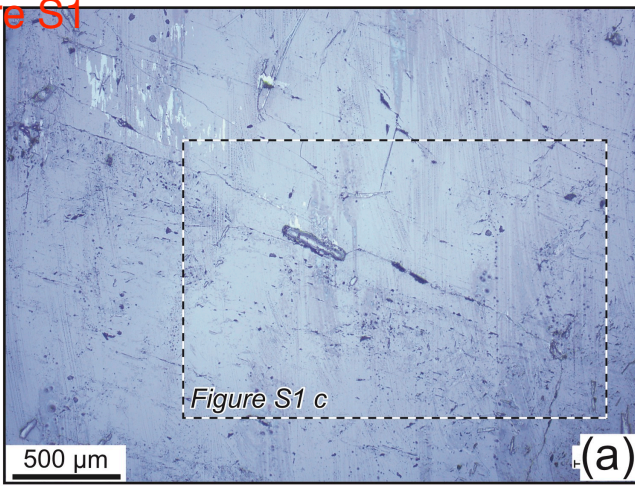
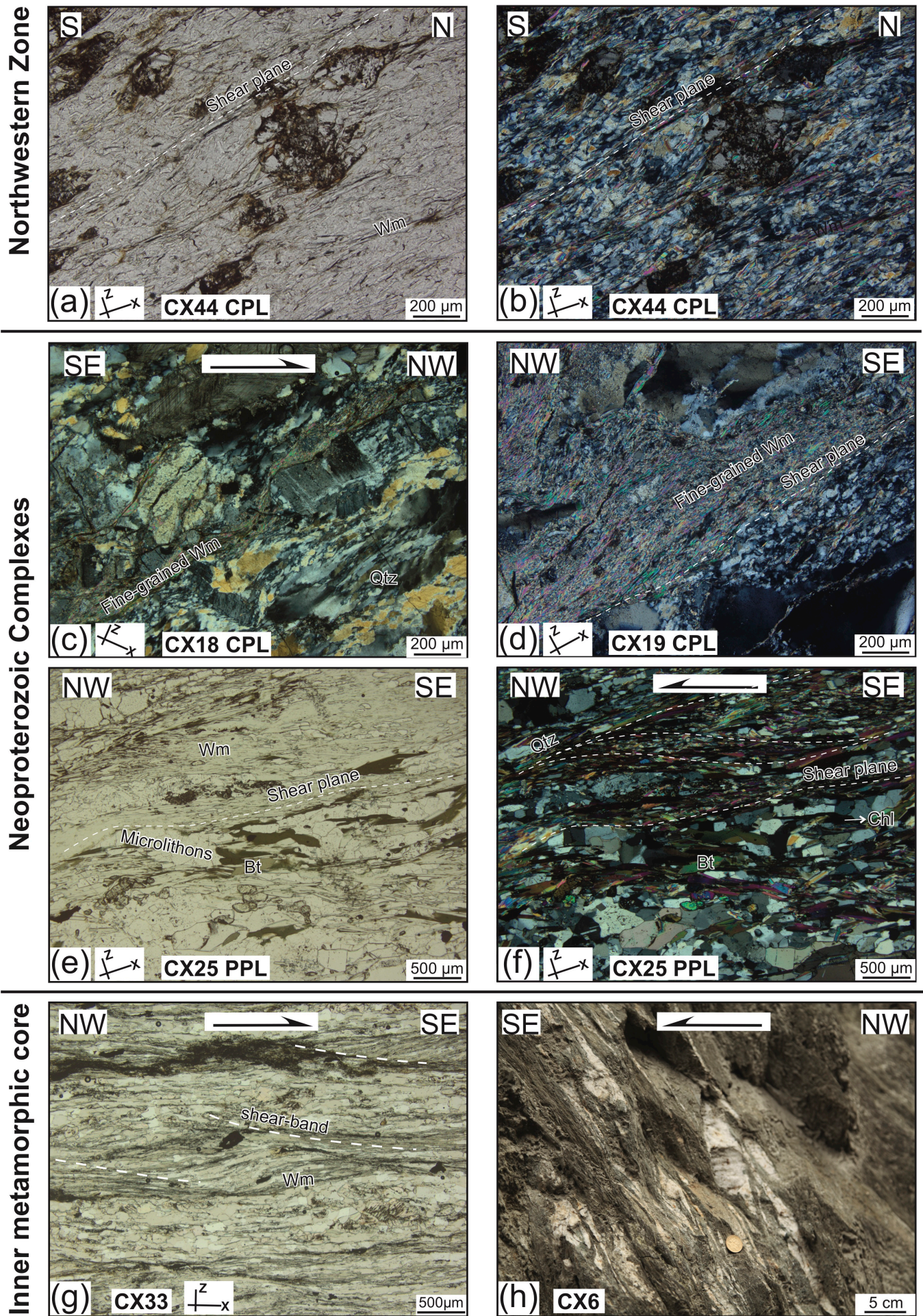


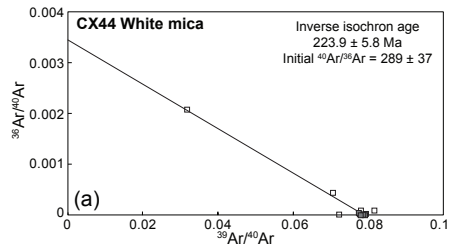
Figure S2



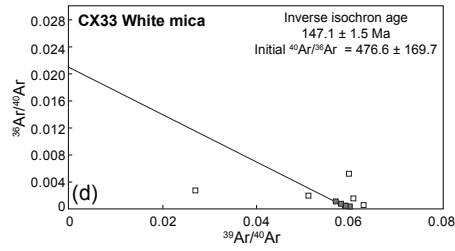
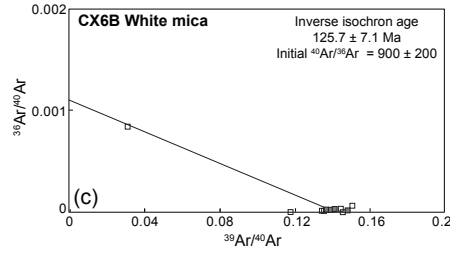
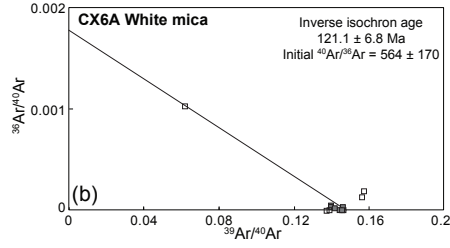


# Figure S3

## Northwestern Zone



## Southeastern Zone -- Inner metamorphic core



## Basement Complex

