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Credit authorship contribution statement

Zhiyuan He: Conceptualization, Field Investigation, Methodology, Writing - original draft. **Bo Wang:** Conceptualization, Field Investigation, Methodology, Writing - review & editing, Supervision. **Xinghua Ni:** Field Investigation, Methodology, Writing - review & editing. **Johan De Grave:** Writing - review & editing, Co-supervision. **Stephane Scaillet:** Methodology, Writing - review & editing. **Yan Chen:** Field Investigation, Writing - review & editing. **Jiashuo Liu:** Field Investigation, Writing - review & editing. **Xin Zhu:** Methodology, Writing - review & editing.

1 **Structural and kinematic evolution of strike-slip shear zones around**
2 **and in the Central Tianshan: insights for eastward tectonic wedging**
3 **in the southwest Central Asian Orogenic Belt**

4

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16

17 **Abstract**

18 In order to better understand the late Paleozoic tectonic evolution of the
19 southwestern Central Asian Orogenic Belt (CAOB), we carried out structural and

20 geochronological studies on the poorly investigated Xiaergou and Wulasitai shear
21 zones around and in the Chinese Central Tianshan. The Xiaergou shear zone is the
22 connecting segment between the North Tianshan Fault and Main Tianshan Shear Zone
23 along the northern margin of the Yili - Central Tianshan blocks, it strikes NW-SE with
24 a width of ~3-5 km and shows predominant dextral kinematics. Zircon U-Pb ages of
25 pre- and syn-kinematic granitic dykes within the Xiaergou shear zone indicate that the
26 dextral shearing was active at ~312-295 Ma. The Wulasitai shear zone is a high-strain
27 belt occurring in the interior of the Central Tianshan block, it extends NW-SE for
28 more than 40 km with variable widths of ~1-5 km, steep mylonitic foliations and
29 sub-horizontal stretching lineation are well developed and various kinematic
30 indicators suggest prevailing sinistral shearing. New biotite $^{40}\text{Ar}/^{39}\text{Ar}$ ages of two
31 meta-sedimentary rocks, together with the published metamorphic zircon ages
32 constrain the timing of the sinistral shearing at ~312-301 Ma. Our new results
33 combined with the previous studies reveal that the dextral strike-slip shear zones
34 framing the Central Tianshan formed almost simultaneously in the latest
35 Carboniferous (~310 Ma) and lasted until the middle to late Permian. They resulted
36 from the eastward tectonic wedging and relative rotations between continental blocks
37 in the SW CAOB. The sinistral shearing of the Wulasitai shear zone within the
38 Central Tianshan was likely generated due to differential eastward motions of the
39 northern and southern parts of the Central Tianshan.

40

41 **Keywords:** Late Paleozoic; Tianshan/Tien Shan; Intracontinental deformation;

42 Transcurrent tectonics; Oblique convergence and accretion; Block rotation

43

44 **1. Introduction**

45 Transcurrent tectonics generally refers to large strike-slip faulting system in
46 which the displacement vector is parallel to the strike of fault due to plate motions on
47 a sphere (Freund, 1974; Onstott and Hargraves, 1981; Beck, 1983; Sylvester, 1988).
48 Transcurrent tectonics usually forms at plate boundaries by oblique plate convergence
49 (Allen, 1965; Fossen et al., 1994; Dewey et al., 1998), and accretionary orogeny
50 (Mann, 2007). It can also develop as a transfer zone in a rift setting or a
51 fold-and-thrust belt (Wilson, 1965; Moore, 1979). As one important manifestation,
52 strike-slip shear zones stand for a deep version of intracontinental transcurrent
53 tectonics characterized by plastic deformation and a tabular to sheet-like, planar or
54 curvilinear domains (Berthé et al., 1979; Ramsay, 1980; Fossen, 2010; Davis et al.,
55 2011). Continental-scale strike-slip shear zones typically exhibit ductile deformation
56 fabrics with steeply-dipping foliations (Davis et al., 1986; Tapponnier et al., 1990;
57 Leloup et al., 1995; Cao and Neubauer, 2016; Zhang et al., 2017). As a prominent
58 dynamic process occurring in continental crust, they delimit mechanical and
59 rheological anomalies that tend to be reactivated or have distinct impact on structural
60 evolution during subsequent phases of tectonism (e.g., Daly et al., 1989; Holdsworth
61 et al., 1997; Metelkin et al., 2010; Bercovici and Ricard, 2012). Thus, understanding
62 the structural patterns and kinematics of strike-slip shear zones as well as their

63 tectonic mechanisms is an important issue in continental dynamics research.

64 The Tianshan (Tien Shan) Orogen lies in the southernmost part of the Central
65 Asian Orogenic Belt (CAOB), or the Altaïds, which is the largest Phanerozoic
66 orogenic system on the world formed by progressive amalgamation of various
67 microcontinents, island arcs, seamounts, oceanic plateaus, and accretionary
68 complexes (Şengör et al., 1993; Jahn et al., 2000; Xiao et al., 2003; Windley et al.,
69 2007; Wilhem et al., 2012). Following successive accretions to the northern margin of
70 the Tarim Craton in late Paleozoic, the Tianshan Orogen and adjacent areas underwent
71 large-scale transcurrent tectonics that greatly influenced the tectonic framework of the
72 SW CAOB (Allen et al., 1995; Şengör and Natal'in, 1996; Laurent-Charvet et al.,
73 2002, 2003; Wang et al., 2007a, 2009, 2014; Li et al., 2015, 2020). Therefore,
74 recognizing the styles of transcurrent deformation is crucial for deciphering the
75 orogenic history and tectonic transition from convergent to intracontinental evolution
76 of this giant belt.

77 One of the most remarkable features of the Tianshan Orogen is the occurrence of
78 two large-scale ductile shear zones that are parallel to major ophiolitic sutures (i.e. the
79 North Tianshan Fault-Main Tianshan Shear Zone and Nalati-Baluntai Fault,
80 respectively) (Figs. 1 and 2). Numerous studies have suggested that these two shear
81 zones resulted from Permian regional transpressional and/or transtensional tectonics,
82 with evidence of both general dextral strike-slip shearing and folding induced by
83 lateral displacements (Yin and Nie, 1996; Shu et al., 1999; Laurent-Charvet et al.,
84 2002, 2003; Y. Wang et al., 2008; Wang et al., 2009, 2014; de Jong et al., 2009;

85 Pirajno, 2010; Tang et al., 2011; Branquet et al., 2012; Cai et al., 2012). However,
86 other authors proposed that pure shear strain related to N-S coaxial compressional
87 tectonics was responsible for the formation of the Jueluotage shear zone (middle
88 segment of the Main Tianshan Shear Zone) and the Baluntai Fault, based on
89 symmetrical structures observed (Xu et al., 2003; Yang et al., 2007). Thus, there is no
90 consensus on the mechanism and geodynamic setting of their deformation so far. In
91 addition to these large shear zones along boundaries between major continental units,
92 several subordinate strike-slip faults were also reported within some continental
93 blocks, in which mylonitic rocks are widespread (e.g., Xingdi Fault, Cai et al., 2012;
94 Hulashan Fault, Lin et al., 2013; Wulasitai shear zone, Yang et al., 2004; He et al.,
95 2018a). However, structural data are scarce from these high-strain shear zones.
96 Meanwhile, it is also poorly understood how they were formed and responded to the
97 complex accretionary and collisional orogenesis, and what their structural relationship
98 is with large transcurrent tectonics marking the boundaries of tectonic units. Further
99 investigation is therefore needed to obtain more information on the activity of these
100 shear zones.

101 In this study, we investigated two contiguous strike-slip shear zones, namely, the
102 Xiaergou and Wulasitai shear zones, which hitherto have been poorly studied. The
103 former is a connecting part between the North Tianshan Fault and the Main Tianshan
104 Shear Zone along the northern boundary of the Yili - Central Tianshan blocks, and the
105 latter is a subordinate shear zone inside the Central Tianshan (Fig. 2; Yang et al., 2004;
106 He et al., 2018a). The detailed structural, kinematic and geochronological data allow

107 us to explore the possible formation mechanism of these strike-slip shear zones
108 developed at different scales and opposite kinematic features under an overall
109 consistent deformation regime. This study also places further constraints on the
110 post-orogenic intracontinental evolution of the Tianshan Orogen, and provides new
111 insights into the eastward wedging of tectonic units between the Tarim and Siberian
112 blocks.

113

114 **2. Regional Geology**

115 ***2.1. Tectonic units in the Chinese Tianshan***

116 The Tianshan Orogen stretches east-west for about 2500 km from eastern
117 Xinjiang in NW China to central Uzbekistan (Fig. 1). This orogenic belt was built by
118 multi-stage subduction of the Paleo-Asian oceanic plate and the subsequent welding
119 between the Kazakhstan-Yili block and Tarim Craton during the Paleozoic (e.g., Allen
120 et al., 1993; Gao et al., 1998, 2009; Charvet et al., 2007, 2011; Wang et al., 2008,
121 2011, 2018; Xiao et al., 2013), and was reactivated during the Meso-Cenozoic as a
122 far-field response of Qiangtang-Lhasa and India-Asia collisions (e.g., Molnar and
123 Tapponnier, 1975; Avouac et al., 1993; De Grave et al., 2007; Glorie and De Grave,
124 2016). The Chinese segment of the Tianshan Orogen is sandwiched between the
125 Junggar and Tarim basins (Fig. 1B). According to the differences in basement nature
126 and tectonic settings, the Chinese Tianshan is traditionally subdivided into four
127 tectonic units separated by regional crustal-scale faults, namely, the North Tianshan,

128 Yili Block, Central Tianshan and South Tianshan from north to south (Fig. 2; Xiao et
129 al., 1992, 2004; Gao et al., 1998; Charvet et al., 2007).

130 The North Tianshan is an accretionary complex formed by the subduction and
131 accretion of the Junggar - North Tianshan oceanic plate. It is composed of late
132 Paleozoic sedimentary-volcanic sequences and magmatic intrusions, which occur in
133 the Kazakhstan-Yili blocks to the west and around the Turpan-Hami (Tu-Ha) basin in
134 the east. (e.g., Wang et al., 2006; Han et al., 2010; Zhang et al., 2016; Wali et al.,
135 2018). The Yili Block represents the eastern part of the Kazakhstan microcontinent,
136 and is a wedge-shaped area between the North and Central Tianshan blocks (Figs. 1B
137 and 2), it consists of Meso- to Neoproterozoic basements, Paleozoic sedimentary
138 covers and magmatic arc rocks that were generated mostly by the southward
139 subduction of the Junggar oceanic plate (e.g., Gao et al., 1998, 2009; Hu et al., 2000;
140 Charvet et al., 2007, 2011; Wang et al., 2007b, 2014a; Liu et al., 2014; Cao et al.,
141 2017; Zhu et al., 2019a). Bordered by the Main Tianshan Shear Zone to the north and
142 the Baluntai Fault to the south, the Central Tianshan refers to a ribbon-like domain
143 extending from the Nalati Range in the west to Xingxingxia areas in the east (Fig. 2),
144 it consists of Precambrian metamorphic basement (e.g., Hu et al., 2000; He et al.,
145 2014, 2015, 2018b; Gao et al., 2015; X.S. Wang et al., 2017), early Paleozoic
146 magmatic arc sequences, late Paleozoic sedimentary strata and Paleozoic intrusions
147 (e.g., Shi et al., 2007; Dong et al., 2011; Lei et al., 2011; Ma et al., 2014; Zhong et al.,
148 2015). The South Tianshan is confined to the region between the Nalati - Baluntai
149 faults and the northern Tarim margin. This unit contains an early Paleozoic

150 continental arc and late Paleozoic sedimentary cover, which were formed during the
151 successive closure of the South Tianshan Ocean and several back-arc basins (e.g., Gao
152 et al., 1998, 2009; Wang et al., 2010, 2011, 2018; Jiang et al., 2014; Alexeiev et al.,
153 2015; Han et al., 2016; Zhong et al., 2017, 2019).

154

155 ***2.2. Large-scale shear zones in the Chinese Tianshan***

156 The main tectonic units described above contact with each other by large-scale
157 shear zones that extends roughly east-west and are sub-parallel to the ophiolitic
158 mélange zones developed along the Bayingou - Mishigou - Gangou and Atbashi -
159 Kekesu - Wuwamen areas (Figs. 1 and 2; Wang et al., 2008; Charvet et al., 2011).

160 The Main Tianshan Shear Zone (MTSZ) (Shu et al., 1999; Laurent-Charvet et al.,
161 2002; Liu et al., 2020) is the tectonic boundary between the North Tianshan and
162 Central Tianshan and it stretches for over 700 km from Xiaergou-Gangou eastward to
163 Weiya (Fig. 1B) (XIGMR, 2007). Along this shear zone, Precambrian schists and
164 gneisses, Paleozoic granitoids and volcanics, as well as ophiolitic rocks were
165 mylonitized and they generally exhibit sub-vertical mylonitic foliations with
166 sub-horizontal stretching lineation (Shu et al., 1999, 2002; Laurent-Charvet et al.,
167 2002, 2003; Li et al., 2020). Consistent asymmetric fabrics indicate a right-lateral
168 strike-slip movement, with thrusting and/or normal faulting components, probably
169 formed in transpressional and/or transtensional settings (Laurent-Charvet et al., 2003;
170 Wang et al., 2008; Yang et al., 2009; Li et al., 2020; Liu et al., 2020). The North

171 Tianshan Fault (NTF) is essentially the westward continuation of the MTSZ and it
172 runs into Kazakhstan, separating the Yili block to the south from the Chinese North
173 Tianshan to the north (Fig. 2). Kinematic features along the NTF also indicate a
174 dextral ductile shearing (Zhou et al., 2001; Wang et al., 2006, 2009; de Jong et al.,
175 2009; Yang et al., 2009; Zhu, 2011; Liu et al., 2020).

176 The Nalati Fault (NF) occurs along the Haerke-Nalati ranges in the South
177 Tianshan (Fig. 1B), and is a large ductile shear zone ~5-15 km wide (e.g., Wang et al.,
178 2010; Charvet et al., 2011; Han et al., 2011). It continues eastwards to merge with the
179 NTF near the Bingdaban area (Figs. 1B and 2). This ductile shear zone was active
180 mainly in the Permian and reworked the Carboniferous suture zone (Akeyazi-Kekesu
181 ophiolite mélanges and high-pressure metamorphic belt) (Fig. 1B) formed by the
182 subduction of the South Tianshan oceanic plate (e.g., Gao et al., 1998, 2009; Lin et al.,
183 2009; Qian et al., 2009; Wang et al., 2009, 2010; Long et al., 2011; Xu et al., 2013;
184 Zhong et al., 2017, 2019). Diverse mylonites, foliated meta-sedimentary rocks and
185 gneissic granitoids are well exposed in this shear zone, and structural studies from the
186 Kekesu high-pressure metamorphic belt and north of Bayinbulak (Fig. 1B) indicate
187 dextral kinematics (XBGMR, 1993; Li and Liu, 1997; Wang et al., 2007c, 2010; Lin
188 et al., 2009; Zhong et al., 2019).

189 The Baluntai Fault (BF) stands for the boundary between the Central Tianshan to
190 the northeast and the South Tianshan to the southwest (Alexeiev et al., 2015; Wang et
191 al., 2018; Zhong et al., 2019). It extends from the north of Bayinbulak, nearly parallel
192 to the NTF - MTSZ, to the Sangshuyuanzi area to the east (Figs. 1B and 2) (XIGMR,

193 2007). Foliated schists and gneisses, mylonitic rocks and ductilely deformed
194 granitoids are widely distributed along the BF, which also partially reworked the
195 Wuwamen - Guluogou ophiolite mélanges (Fig. 2) (XBGMR, 1993, Yang et al., 2004;
196 Deng et al., 2006; M. Wang et al., 2014; Wang et al., 2018). Localized coaxial pure
197 strain was described in the south of Baluntai regions and was considered as the result
198 of N-S compression (Yang et al., 2007); however, most structural investigations from
199 the Sangshuyuanzi, Baluntai areas and their eastward continuation demonstrated
200 dextral strike-slip shearing (Laurent-Charvet et al., 2003; Y. Wang et al., 2008; Wang
201 et al., 2009; Xu et al., 2011; Cai et al., 2012; Zhong et al., 2015; Li et al., 2020).

202

203 **3. Overall geometry, structures and kinematics of the Xiaergou and** 204 **Wulasitai shear zones**

205 Our structural investigations were conducted along several sections crossing the
206 Xiaergou and Wulasitai shear zones around and within the Central Tianshan (Figs.
207 2-10). In the following sections, we present the main lithological units in the two
208 shear zones and their structural and kinematic features.

209

210 ***3.1. Xiaergou Shear Zone***

211 As the eastern part of the NTF, the Xiaergou Shear Zone (XSZ) is a ~NW-SE
212 trending mylonitic belt with a width of ~3-5 km, and was locally reworked or

213 truncated by brittle reverse and/or left-lateral strike-slip faults (Figs. 2 and 3). Due to
214 difficult physical conditions our field observations were limited to a 5-km-long
215 section mainly along its strike near the Xiaergou village (Figs. 3B and 4).

216

217 *3.1.1. Lithological units*

218 Silurian to Devonian marine sequences were affected by the ductile deformation
219 along the XSZ. Silurian meta-sediments belong to the middle Ahebulake Group and
220 consist of marbles, greywackes, schists, phyllites and calcareous sandstones with
221 interlayered tuff. Devonian sequences are represented by the middle Tiangeer Group
222 that is dominated by basaltic tuffs, tuffaceous sandstones and marbles (XBGMR,
223 1993). Both groups are in contact with each other along a steep N-dipping reverse
224 fault (Figs. 3 and 4).

225 Early Paleozoic granodiorites and late Paleozoic granites are well exposed
226 within and across the shear zone (Figs. 3B and 4). The late Paleozoic granites were
227 dated at ~370-337 Ma (zircon U-Pb ages) and were interpreted to be related to the
228 subduction of the North Tianshan oceanic plate and the collision between the Central
229 and North Tianshan (including Tu-Ha basin) during the early Carboniferous (Ma et al.,
230 2014; Yin et al., 2017). In addition, numerous undeformed granitic and diabase dykes
231 of unknown ages intruded into Silurian-Devonian meta-sedimentary and volcanic
232 rocks as well as the Paleozoic plutons (Figs. 3 and 4).

233

234 *3.1.2. Structures and kinematics*

235 Except for the undeformed granitic and diabase dykes intruding the XSZ, all
236 other lithological units mentioned above underwent intensive ductile shearing,
237 showing well-defined ~E-W or ~ENE-WSW-striking steep (40° to 78°) mylonitic
238 foliations (S1) associated with pervasive stretching lineation (L1) gently plunging
239 ($<40^\circ$) to E/NE or W/SW (Figs. 4A-B and 5A-D). Both the strikes of S1 foliations
240 and the plunges of L1 lineation are sub-parallel to the overall strike of the shear zone.
241 The mylonitic foliations and stretching lineation are usually defined by elongated
242 quartz and feldspar ribbons and mica aggregates (Figs. 5 and 6). In the
243 Silurian-Devonian metasedimentary rocks, the S1 is predominantly dipping to the
244 ~N-NNE with variable dip angles ranging from 42° to 76° , and is parallel to the
245 locally preserved S0 bedding planes (Fig. 4A-B). The K-feldspar porphyroclasts are
246 elongated and oriented parallel to the shearing foliations. In addition, mylonitic felsic
247 dykes intruding the marbles and schists also exhibit steep foliations and
248 sub-horizontal mineral stretching lineation, which are defined by a preferred
249 orientation of elongated feldspar and quartz grains (Figs. 4C and 5D). Leuco-granitic
250 dykes and their host granitic pluton both display ~NE-SW-striking mylonitic
251 foliations with ~ENE/WSW plunging lineation (Figs. 4A-B and 5A), which are
252 oblique to the general strike of the shear zone, probably due to localized rotation
253 related to the NE-striking brittle reverse fault (Fig. 4A).

254 Disjunctive cleavage in granodiorites shows a general strike of 160° , sub-parallel
255 to the shear zone; and shear bands suggest a dextral sense of shearing (Fig. 5E). In

256 highly deformed marbles, sheath folds and A-type folds were well preserved, whose
257 hinges are parallel to the stretching lineation; on the X-Z plane (perpendicular to
258 foliation and parallel to lineation), the asymmetric fold shapes present a dextral
259 shearing (Fig. 5F). S-C fabrics can be recognized in marbles as well, the S-foliation is
260 represented by elongated calcite veins, and a dextral sense of movement is also
261 indicated (Fig. 5G). It is worth noting that sinistral shearing was also occasionally
262 preserved, as revealed by asymmetric quartz lens in a small-scale greenschist outcrop
263 (Fig. 5H). Under microscope, mylonitic granitoids and tuffaceous sandstones contain
264 plenty of kinematic indicators, such as S-C fabrics, feldspar bookshelf texture,
265 sigmoid asymmetric feldspar porphyroclasts and mica pressure shadows showing a
266 principal dextral sense of shearing (Fig. 6A-D), sinistral kinematics was only locally
267 developed and is associated with dextral kinematics (Fig. 6E-F).

268

269 **3.2. Wulasitai Shear Zone**

270 The Wulasitai shear zone (WSZ) is a remarkable subordinate high-strain
271 deformation zone occurring within the Central Tianshan, it extends NW-SE, nearly
272 parallel to the NTF and BF, for more than 40 km with variable widths of ~1-5 km
273 (Figs. 2 and 7). This high-strain mylonitic belt merged westwards into the NF, and it is
274 covered eastwards by strongly weathered granites, vegetation and glacier (Fig. 2), it is
275 possible that the WSZ connects the MTSZ in the Yuergou area (XIGMR, 2007).

276

277 *3.2.1. Lithological units*

278 A variety of rocks are well exposed along the WSZ and were significantly
279 deformed by ductile shearing, they mainly include Proterozoic paragneiss, early
280 Paleozoic sedimentary rocks and granodiorites, and late Paleozoic granites (Fig. 7B;
281 XBGMR, 1993).

282 Proterozoic paragneiss occur north of the Wulasitai village (Fig. 7B) and were
283 previously assigned to the Paleoproterozoic Xingxingxia Group (XBGMR, 1993;
284 XIGMR, 2007). However, recent zircon U-Pb dating indicated that some of these
285 meta-sedimentary rocks were likely deposited in the early Devonian to late
286 Carboniferous (Shu et al., 2013; Wang et al., 2018). Early Paleozoic
287 meta-sedimentary rocks dominantly comprise paragneiss, marbles, greenschists,
288 deformed quartz sandstones and greywackes, they were considered as Silurian in age,
289 but some of them were recently constrained as Devonian (He et al., 2018a).

290 Paleozoic plutonic rocks along the WSZ include early Paleozoic granodiorites
291 and late Paleozoic granites intruding the “Proterozoic” and “Silurian”
292 meta-sedimentary rocks (Fig. 7B). Migmatites are frequently associated with the
293 granodiorites and can also be observed in the meta-sandstones. Some late Paleozoic
294 granites exposed along the WSZ were dated at ~354-332 Ma (He et al., 2018a).

295 These ductilely deformed and metamorphosed sedimentary rocks are
296 unconformably covered by undeformed and gently tilted Jurassic sandstones (Fig.
297 7B).

298

299 *3.2.2. Structures and kinematics*

300 Along the WSZ, ~E-W or ~NW-SE-striking, diversely S/SW- or N/NE-dipping
301 mylonitic foliations (S1) and associated mineral stretching lineation (L1) are well
302 developed in most lithological units (Figs. 8 and 9A-E). The dip angles of foliations
303 vary from 30° to 80°, and the plunging angles of lineation are 3°-40° (Fig. 8). In
304 general, the steeper foliations bearing shallower lineation occur along the straight
305 segment, and gentle foliations with nearly down-dip lineation are mostly observed at
306 the turning segment of the WSZ (Figs. 7 and 8). Silurian meta-greywackes underwent
307 intensive ductile deformation displaying steep mylonitic foliations and gentle
308 stretching lineation (Fig. 9A). Some paragneiss and phyllites show gently
309 south-dipping foliations and sub-horizontal stretching lineation defined by elongated
310 ribbons of felsic melts, and coeval sub-S-N crenulation cleavages (L1') represented
311 by hinges of microfolds full of mica and sericite (Fig. 9B-C). In migmatites,
312 foliation-parallel leucocratic veins reflect a low-degree partial melting, elongated
313 K-feldspar and quartz ribbons in the leucosome indicate a syn-kinematic transport of
314 melts (Fig. 9B). The granitic rocks were also ductilely deformed showing mylonitic
315 foliations and ~E-W-trending stretching lineation characterized by elongated feldspar
316 and quartz ribbons and oriented micas (Fig. 9D-E).

317 Overall bending geometry suggests that localized transpressional deformation
318 affected the WSZ. For example, along a ~NE-SW profile across the bending segment

319 of the WSZ, folded and duplicated quartz veins occur in mylonitic granites with the
320 axial planes parallel to the S1 foliation, asymmetric folds and shear bands indicate a
321 top-to-the-southwest shearing (Fig. 9F). Moreover, strike-slip motions along the WSZ
322 were well recorded by a series of apparent kinematic indicators. At the field scale,
323 asymmetric intrafolial microfolds in the meta-rhyolites (Fig. 9G), shear bands in the
324 meta-sandstones (Fig. 9H), and fractured and offset felsic veins in the mylonitic
325 granites (Fig. 9I) suggest a sinistral shearing along the strike of the shear zone. In
326 addition, microscopic textures such as the sigmoid biotite mica fishes (Fig. 10A),
327 shear bands and pressure shadows composed of mica around K-feldspar
328 porphyroclasts (Fig. 10B-C), S-C fabrics and σ -type feldspar porphyroclasts (Fig.
329 10D-E) consistently demonstrate a sinistral sense of shear. However, dextral motion is
330 also indicated by sigmoid quartz and feldspar porphyroclasts (Fig. 10F) that are
331 occasionally visible in few samples showing predominantly sinistral shearing.

332

333 **4. Temperature conditions of the ductile deformation**

334 Quartz is one of the most sensitive minerals during plastic deformation. In a
335 shear zone, quartz can be deformed via different mechanisms under various
336 temperature conditions. Previous studies established relationships between
337 deformation mechanisms and physical conditions based on naturally and
338 experimentally deformed rocks, e.g., types of quartz dynamic recrystallization and
339 corresponding temperatures, are widely applied in studies of shear zones (e.g., Hirth

340 et al., 2001; Stipp et al., 2002a, 2002b; Passchier and Trouw, 2005; Law, 2014). Here
341 we estimated deformation temperatures of these two shear zones according to the
342 criteria for quartz dynamic recrystallization proposed by Stipp et al. (2002a). The
343 studied samples were collected from the axial parts of the shear zones (Figs. 4 and 8)
344 so that they may reflect the peak conditions of ductile shearing. In order to avoid
345 possible large uncertainty brought by the sampling effect, at least two samples were
346 taken from each sampling site for thin section observation. Detailed microstructural
347 descriptions and temperature estimations are given in supplementary Table S1.

348 Our observations suggest that the sub-grain rotation is the dominant mechanism
349 of quartz dynamic recrystallization in both the XSZ and WSZ (Fig. 11; Table S1). In a
350 number of samples, numerous new small grains produced by both bulging and
351 sub-grain rotation mechanisms occur around the original quartz grains, revealing a
352 typical core-mantle structure (Fig. 11A, B and D), and the elongated quartz ribbons
353 parallel to main foliations reflect intensive dislocation creep deformation (Fig. 11C, E
354 and F). Grain boundary migration recrystallization appears more frequently in the
355 XSZ (Fig. 11C), indicating a higher temperature condition compared to the WSZ.
356 Generally, deformation temperatures in the XSZ are estimated as ~460-510 °C,
357 slightly higher than the temperature conditions of the WSZ (~450-485 °C) (Fig. 12;
358 Table S1). In addition, feldspar only displays bulging recrystallization and no clear
359 evidence for sub-grain rotation was identified in both shear zones, suggesting a
360 maximum temperature threshold of ~550-600 °C for ductile shearing. It is noted that
361 the estimated temperatures here only refer to the pervasive dextral shearing of the

362 XSZ and sinistral shearing of the WSZ. Meanwhile, sinistral kinematics within the
363 XSZ and dextral kinematics along the WSZ are only locally preserved as described
364 before, their corresponding deformation temperatures are thus difficult to be
365 determined without efficient indicators.

366

367 **5. Geochronology**

368 In order to constrain the timing of ductile deformation, new isotopic data were
369 obtained by zircon LA-ICP-MS U-Pb and biotite $^{40}\text{Ar}/^{39}\text{Ar}$ dating. Sample locations
370 are marked on Figs. 4 and 8, analytical procedures are described in Appendix, and
371 analytical data are provided in supplementary Tables S2 and S3.

372

373 *5.1. Zircon U-Pb ages for pre- and syn-kinematic granitic dykes in the Xiaergou*

374 *Shear Zone*

375 Pre- and syn-kinematic plutons develop along the XSZ. The syn-kinematic ones
376 were emplaced during the ductile shearing, some occur as migmatitic veins due to in
377 situ partial melting of the host rocks and some injected from deep-seated magma via
378 foliations or faults (Hutton, 1988; Pitcher, 1997; Pirajno, 2010; Wang et al., 2014b).
379 One distinct character of syn-kinematic dykes is that their distributions are only
380 limited within the shear zone. This situation differs from that of the pre-kinematic
381 dykes, which are distributed not only within but also outside the shear zone and they

382 usually crosscut the shear zone or lithological boundaries (Searle, 2006; Rolland et al.,
383 2009; Cao et al., 2011; J. Liu et al., 2020). From the XSZ, one sample of
384 pre-kinematic granite dyke and another of syn-kinematic dyke intruding the Silurian
385 marbles and late Paleozoic granites (~370-337 Ma; Ma et al., 2014; Yin et al., 2017)
386 (Fig. 4), were dated using the zircon LA-ICP-MS U-Pb method.

387 Sample 44-B was taken from a granitic dyke of ~1m wide (Fig. 13A), which
388 displays sharp contact with the host rocks. Both the dyke and its host rocks show
389 similar deformation fabrics, i.e., steeply N-dipping mylonitic foliations and shallowly
390 plunging lineation, indicating a strike-slip shearing, and a pre-kinematic emplacement
391 of the granite dyke. The sample mainly contains K-feldspar and quartz with minor
392 biotite and muscovite (Fig. 13B). The zircon grains from this sample are commonly
393 euhedral and 100-150 μm in length, their CL (Cathodoluminescence) images
394 generally show well-developed concentric oscillatory zoning (Fig. 13C). A total of
395 fifteen analyses were carried out on twelve zircons, showing Th/U ratios of 0.4-0.8
396 (Table S2), indicating a magmatic origin according to the descriptions of Corfu et al.
397 (2003). Therein, 12 out of 15 analyses yielded a concordant age of 311.9 ± 2.4 Ma
398 (MSWD = 0.21; Fig. 13D), including two analyses on the modified rims (Nos. 1 and
399 14; Fig. 13C), while the unmodified parts of these two zircons yielded older
400 $^{206}\text{Pb}/^{238}\text{U}$ ages of ~342 Ma and ~331 Ma (Fig. 13D), comparable to the ages of the
401 host granites, from which these two zircons were likely derived. One additional zircon
402 yielded much older age of ~431 Ma, and it is probably inherited.

403 Sample 49-C was collected from another granitic dyke intruding the Silurian

404 marbles and tuffaceous sandstones (Fig. 4). The dyke is ~1-1.5 m wide and shows
405 boudinage structure and well-developed mylonitic foliations and stretching lineation
406 (Fig. 13E), consistent with those of the host rocks. Generally parallel contact between
407 the dyke and its host rocks to the main mylonitic foliations, and high-strain
408 superplastic creep of quartz (Fig. 13F), i.e., high-temperature syn-magmatic
409 deformation, indicate a syn-kinematic emplacement of the dyke. The sample is
410 fine-grained and consists of feldspar, quartz and fine-grained muscovite (Fig. 13F).
411 Subhedral zircon crystals from this sample have length/width ratios of 2.5:1-1:1 with
412 variable long axes of 50-200 μm (Fig. 13G). Sixteen zircons were dated, concordant
413 and consistent results were obtained from nine zircons with typical oscillatory zoning,
414 indicative of an igneous origin together with their relatively high Th/U ratios
415 (0.14-1.25) (Fig. 13G; Table S2); these nine analyses yielded a weighted mean
416 $^{206}\text{Pb}/^{238}\text{U}$ age of 294.6 ± 3.7 Ma (MSWD = 1.6; Fig. 13H), which is interpreted to
417 represent the crystallization age of this syn-kinematic dyke. Five zircon grains yielded
418 older ages ranging from ~332 Ma to ~1476 Ma, indicating derivation from older
419 crustal rocks. Two additional analyses show high degrees of discordance (>10%) (Nos.
420 12 and 15; Table S2) of which the meaning is still unclear.

421

422 ***5.2. Biotite $^{40}\text{Ar}/^{39}\text{Ar}$ ages for meta-sedimentary rocks in the Wulasitai Shear Zone***

423 Biotite $^{40}\text{Ar}/^{39}\text{Ar}$ dating was performed on two samples from meta-sedimentary
424 rocks of the Silurian Ahebulake Group in the WSZ, both samples were collected from

425 the axial part of the shear zone (Fig. 8B) and were subjected to intensive ductile
426 shearing. Sample 01-B is a paragneiss and mainly composed of quartz, feldspar and
427 biotite (Fig. 14A). Preferred orientation of biotite assemblages and quartz ribbons
428 define foliations and lineation, and quartz shows undulose extinction and sub-grain
429 rotation dynamic recrystallization (Fig. 14A). Sample 02-B is a meta-sandstone
430 mainly containing quartz, plagioclase, K-feldspar and biotite (Fig. 14B). Despite
431 sporadic distribution, elongation of fine-grained biotites assigned along the main
432 foliations and lineation and filled in between the granular quartz and feldspar grains,
433 which also show undulose extinction, bulging dynamic recrystallization, and
434 sometimes grain boundary migration recrystallization or even probable superplastic
435 creep as indicated by equidimensional quartz grains with relatively straight grain
436 boundaries (Fig. 14B). Overall oblique orientation and sigmoidal shape of biotite
437 aggregates indicate a sinistral sense of shearing (Fig. 14A-B).

438 The $^{40}\text{Ar}/^{39}\text{Ar}$ dating results of biotites from the meta-sedimentary rocks are
439 plotted in Fig. 14C-F, all ages are laser step-heating ages, and errors are quoted at the
440 1σ level. The age spectrum of biotite sample 01-B of a paragneiss are somewhat
441 scattered, without a clear trend through the degassing steps. Apart from the initial
442 steps, the other analyses yielded apparent ages ranging from 295 to 306 Ma (Table
443 S3), a Total-Gas Age (TGA) of 300.3 ± 2.5 Ma and a weighted mean age (WMA) of
444 300.5 ± 1.6 (MSWD = 3.7; 98% of $^{39}\text{Ar}_K$ released) are calculated (Fig. 14C). For the
445 biotite sample 02-B from a meta-sandstone, most analyses yielded generally
446 consistent apparent ages (298-310 Ma) except one step that shows a much younger

447 apparent age probably due to extremely low ^{39}Ar released (Table S3). The TGA and
448 WMA of this sample are calculated at 303.0 ± 2.5 Ma and 303.4 ± 1.3 Ma (MSWD =
449 1.7; $\sim 100\%$ of $^{39}\text{Ar}_K$), respectively (Fig. 14D).

450

451 **6. Discussion**

452 *6.1. Kinematic significance of the Xiaergou and Wulasitai shear zones*

453 According to the general geometry of the Xiaergou shear zone (XSZ), this
454 structure forms the connecting segment between the North Tianshan Fault (NTF) and
455 Main Tianshan Shear Zone (MTSZ) (Figs. 1 and 2). Based on our structural
456 observations and kinematic analysis of prevalent macro- and micro-kinematic
457 characteristics, the XSZ is dominated by a simple dextral shearing. This is in
458 agreement with previous investigations along both the NTF and MTSZ (Shu et al.,
459 1999; Laurent-Charvet et al., 2002, 2003; Wang et al., 2006, 2009; de Jong et al.,
460 2009; Li et al., 2020). At the same time, sinistral shearing is only locally recognized
461 along the XSZ. In the field, it only occurs in the greenschist from one observation site
462 (Fig. 5H); in a few thin sections (samples 45-A and 52-B; Table S1), it was locally
463 preserved along with the dominant dextral kinematics (Fig. 6E-F).

464 The Wulasitai shear zone (WSZ) was previously reported by Yang et al. (2004)
465 near the Wulasitai village, and He et al. (2018a) traced this shear zone far westward
466 and proposed that it can separate the Central Tianshan into northern and southern
467 parts (Fig. 2). Based on our field and microscopic investigations, the WSZ

468 geometrically is a bending strike-slip shear zone and is kinematically dominated by
469 sinistral shearing (Figs. 7B and 8), meanwhile, very limited dextral shearing can be
470 distinguished in thin section (sample 06-B; Table S1) to be associated with the
471 dominant sinistral kinematics (Fig. 10). In addition, at the bends and stepovers of the
472 WSZ, a component of top-to-the-southwest shearing is also associated with the
473 general sinistral shearing (Fig. 9F), and most likely resulted from strain partitioning
474 due to transpression at the stepovers along the bending WSZ (Fig. 7), as commonly
475 recognized in most bending strike-slip shear zones (e.g., Cunningham and Mann,
476 2007).

477 Therefore, both the XSZ and WSZ are characterized by a co-existence of
478 opposite kinematic features. Four possibilities might potentially explain
479 co-occurrence of these opposite kinematics within an identical shear zone: (1) strain
480 localization along shear zone, (2) strain partitioning between conjugate structures, (3)
481 low differential stress or coaxial shortening perpendicular to the shear zone, or (4)
482 multi-stage simple shear events with rotated shortening directions. Localized NE-SW,
483 NNW-SSE and N-S sinistral shearing was previously documented along the dextral
484 MTSZ, and was interpreted as a subordinate left-lateral shear zone conjugated with
485 the major WNW-ESE right-lateral shearing resulted from NNW-SSE bulk shortening
486 (Laurent-Charvet et al., 2002, 2003). In addition, sinistral ductile shearing was also
487 reported along the Baluntai Fault (or Southern Central Tianshan Fault) and considered
488 as the result of clockwise rotation of Tarim with respect to Central Tianshan (Deng et
489 al., 2006) or resulting from Devonian oblique convergence (Li et al., 2020). Some

490 authors also proposed that the ductile shearing along the Central and North Tianshan
491 formed under coaxial pure shear related to the NE-SW contraction induced by
492 convergence between the Tarim and Central Tianshan blocks (e.g., Xu et al., 2003;
493 Yang et al., 2007).

494 In the cases of the XSZ and WSZ, strain partitioning mostly occurred along the
495 bending segment of the WSZ as the top-to-the-SW shearing and changes of shear
496 directions can be observed there (Figs. 7, 9 and 10F). Shear directions also
497 dramatically change in the XSZ but only in the overlapping segments between the
498 overall NW-SE-striking ductile shear zone and the NE-SW-trending brittle strike-slip
499 reverse faults (Fig. 4A). The latter cut across lithological boundaries and the mylonitic
500 foliations of the shear zone, without any associated ductile deformation. They are not
501 conjugate (subordinate) shear zones coeval to the NW-SE main shear zone, but rather
502 posterior brittle faults. Local rotation related to these brittle reverse faults could be
503 partially responsible for the changes of shear directions along the XSZ shear zone.
504 Even though, strain partitioning and strain localization are unlikely the reasons for the
505 opposite kinematics in the XSZ and WSZ because kinematic senses remain consistent
506 when the shear directions (foliations) change.

507 In addition, the general sub-E-W stretching lineation and consistently low
508 plunging (Figs. 4 and 8) in both the XSZ and WSZ indicate simple shear instead of
509 pure shear or dominant coaxial contraction. Slight variations in lineation plunging
510 directions and angles are the effects of bending of the shear zone and localized strain
511 partitioning for the case of the WSZ, and the influence of localized fabrics rotation

512 related to later reworking by reverse faults for the XSZ. Moreover, development of
513 sheath folds and A-type folds in the XSZ (Fig. 5) and syn-kinematic granites in the
514 WSZ (Fig. 9) also indicate quite high strain rate in both shear zones, and the
515 possibility of low differential stress can be ruled out.

516 Considering that sinistral shearing is very locally preserved in the overwhelming
517 dextral kinematics of the XSZ, and that locally recognized dextral shearing is
518 observed only in a sample with predominant sinistral motions from the WSZ, it is
519 most likely that these opposite kinematics in both shear zones formed in different
520 stages of ductile deformation. In a multi-stage deformation belt like the Tianshan
521 Orogen, the most pervasive structures should be the result of the most intensive and
522 younger deformation events, and the fabrics formed in earlier deformation stage(s)
523 could be rarely preserved due to later strong overprinting and replacement. Thus, it is
524 reasonable to suggest that the occasionally observed sinistral kinematics in the XSZ
525 and dextral kinematics in the WSZ might represent locally preserved fabrics of earlier
526 deformation events. However, how and when these possible earlier structures were
527 formed is still not clear, and localized development of coeval but opposite kinematics
528 could not be completely excluded, thus, further investigations are needed in future.

529

530 ***6.2. Timing of strike-slip ductile shearing around and in the Central Tianshan***

531 Along the MTSZ, the northern boundary of the Central Tianshan, mica $^{40}\text{Ar}/^{39}\text{Ar}$
532 ages of 290-242 Ma were obtained from the Gangou, Mishigou and Hongyuntan areas

533 (Shu et al., 2002; Laurent-Charvet et al., 2003; Cai et al., 2012), together with a
534 muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of 309.7 ± 2.2 Ma for a mylonite from Mishigou (Xu
535 et al., 2011), it is suggested the dextral shearing along the MTSZ occurred during the
536 late Carboniferous to Early Triassic. Along the NTF, the westward continuation of the
537 MTSZ, the age of dextral ductile shearing was constrained between ~ 270 and ~ 245
538 Ma by mica $^{40}\text{Ar}/^{39}\text{Ar}$ dating on mylonitic slates and foliated granites in the Du-Ku
539 and Bingdaban areas (Laurent-Charvet et al., 2003; de Jong et al., 2009; Yang et al.,
540 2009).

541 In this study, pre- and syn-kinematic granitic dykes in the XSZ yielded zircon
542 U-Pb ages of 311.9 ± 2.4 Ma (Fig. 13D) and 294.6 ± 3.7 Ma (Fig. 13H),
543 approximately overlapping the oldest mica $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the MTSZ and NTF.
544 Taking into account that (1) igneous origins of the dated concordant zircons and both
545 pre- and syn-kinematic features of the granite dykes, and (2) the estimated
546 deformation temperatures ($450\text{-}550$ °C) are lower than crystallization temperature of
547 igneous zircons and closure temperature of zircon U-Pb system (>700 °C; Cherniak
548 and Watson, 2003), but higher than the closure temperatures of biotite and muscovite
549 argon system (365 ± 35 to 425 ± 70 °C; Harrison et al., 1985, 2009; McDougall and
550 Harrison, 1999; Scibiorski et al., 2015), we consider the new zircon U-Pb ages
551 ($312\text{-}295$ Ma) of the pre- and syn-kinematic granite dykes as the maximum age, i.e.
552 the initiation timing of the ductile dextral shearing along the XSZ, and previously
553 published mica $^{40}\text{Ar}/^{39}\text{Ar}$ ages ($290\text{-}242$ Ma) for the MTSZ and NTF as the cooling
554 ages of the ductile dextral shearing. It is worth noting that dextral shearing all along

555 the NTF-XSZ-MTSZ could have been active diachronously along different segments.
556 The timing of earlier sinistral deformation along the XSZ cannot at this point be
557 reliably constrained with the available data.

558 The WSZ represents a localized high strain belt inside the Central Tianshan (Fig.
559 2). Within the WSZ, our new biotite $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 301-304 Ma were obtained
560 from meta-sedimentary rocks showing sinistral kinematic fabrics (Fig. 10A-C). As the
561 estimated deformation temperatures ($>450\text{ }^{\circ}\text{C}$) of the WSZ are higher than the closure
562 temperature of biotite argon system ($335 \pm 50\text{ }^{\circ}\text{C}$), we therefore regard the newly
563 acquired $^{40}\text{Ar}/^{39}\text{Ar}$ ages as the cooling ages of the sinistral ductile deformation along
564 the WSZ. Moreover, metamorphic zircons from a mylonitic greywacke of the Silurian
565 Ahebulake Group within the WSZ yielded a mean age of $\sim 312\text{ Ma}$ (He et al., 2018a).
566 Thus, we infer that the sinistral shear of the WSZ likely took place during 312-301
567 Ma. As to the dextral deformation, its timing and regional context are however
568 difficult to be constrained.

569 Along the Baluntai Fault (BF), southern boundary of the Central Tianshan,
570 granitic mylonites from the Baluntai, Kumishi and eastward vicinities were dated at
571 311-248 Ma by $^{40}\text{Ar}/^{39}\text{Ar}$ dating on mica, feldspar and hornblende (Yin and Nie, 1996;
572 Laurent-Charvet et al., 2003; Yang et al., 2007; Y. Wang et al., 2008; Xu et al., 2011;
573 Cai et al., 2012; Li et al., 2020). In the northern Kumishi area, a mylonitic gneissic
574 granite was dated at $304 \pm 2\text{ Ma}$ (Li et al., 2020), and a syn-kinematic potassic granite
575 showing high-temperature superplastic creep deformation features yielded zircon
576 U-Pb age of $252 \pm 4\text{ Ma}$ (Wang et al., 2009). Dextral shear criteria are ubiquitous in

577 the mylonitic rocks along the Baluntai-Wuwamen-Kumishi section (Yin and Nie,
578 1996; Laurent-Charvet et al., 2003; Wang et al., 2009, 2018; Tang et al., 2011; Xu et
579 al., 2011; Cai et al., 2012; M. Wang et al., 2014; Zhong et al., 2015; Li et al., 2020).
580 Thus, the dextral ductile shearing along the BF occurred during the latest
581 Carboniferous to the end of Permian, and are hence comparable to the age span of the
582 dextral shearing along the MTSZ-NTF. In addition, within and outside of the BF and
583 in the MTSZ, sinistral shearing and N-S contractional deformation were previously
584 suggested to occur at ~399-393 Ma and ~358-356 Ma, respectively (Allen et al., 1993;
585 Deng et al., 2006; Yang et al., 2007; Li et al., 2020), prior to the dextral ductile
586 shearing. Thus, the locally preserved sinistral kinematics recognized in the XSZ could
587 be probably related also to this Devonian to early Carboniferous stage.

588 Farther westwards, the Nalati Fault (NF) also underwent dextral ductile
589 deformation, which was dated by (1) mica $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of ~285-252 Ma in
590 mylonites (Zhou et al., 2001; Wang et al., 2007c; de Jong et al., 2009), (2) 277 ± 3 Ma
591 zircon U-Pb age for a syn-kinematic intrusion in the Kekesu area (Wang et al., 2009),
592 and (3) ~307 Ma to ~255 Ma metamorphic zircon U-Pb ages for strongly foliated
593 early Paleozoic sandstones in the southern Nalati Range (Zhong et al., 2019).
594 Therefore, the dextral ductile shearing along the NF took place from the late
595 Carboniferous to end Permian, synchronous with the BF.

596

597 **6.3. Implications for late Paleozoic eastward tectonic wedging in SW CAOB**

598 Strike-slip faults developed in the entire CAOBS and played an important role in
599 building this large accretionary and collisional orogenic system (e.g., Sengör et al.,
600 1993; Allen et al., 1993, 1995; Choulet et al., 2011; Li et al., 2017, 2018). There are
601 different hypotheses concerning the formation mechanism and tectonic significance of
602 these orogen-scale strike-slip shear zones. Many strike-slip faults subparallel to the
603 orogens were considered to have formed during oblique subduction, duplicating and
604 juxtaposing different fragments of the same arc, and shifting the magmatic front and
605 overall geometry of orogens to form the oroclinal architecture of the Kazakhstan, SW
606 CAOBS (Şengör et al., 1993; Şengör and Natal'in, 1996, 2014). Alternatively, a
607 growing number of recent studies showed that the magmatic arcs in the SW CAOBS
608 were formed by multi-stage subduction of various oceanic basins within the
609 Paleo-Asian Ocean domain (e.g., Windley et al., 2007; Xiao et al., 2003, 2004;
610 Wilhem et al., 2012), and that the orogen-parallel strike-slip faults more likely
611 resulted from intra-continental tectonism after the Carboniferous oblique collision
612 between the Siberian and Tarim cratons (Allen et al., 1993, 1995; Yin and Nie, 1996;
613 Shu et al., 1999; Buslov et al., 2004; Wang et al., 2009; Pirajno, 2010).

614 In this context, Laurent-Charvet et al. (2002, 2003) and Cai et al. (2012)
615 emphasized the anticlockwise rotation of the Junggar block during the early Permian,
616 which resulted in dextral shearing along the NTF - MTSZ and sinistral transpression
617 of the Irtysh Shear Zone (ISZ) (e.g., Glorie et al., 2012). Li et al. (2015) suggested
618 that such coeval dextral and sinistral shearing was controlled by the lateral migration
619 of various units within the CAOBS. Y. Wang et al. (2008) proposed that series of

620 dextral strike-slip shearing were results of post-orogenic eastward extrusion of the
621 CAOB between the Siberian and Tarim Cratons. Similar eastward extrusion tectonics
622 was also documented by paleomagnetic studies (e.g., Wang et al., 2007a; Choulet et
623 al., 2011; Zhu et al., 2018, 2019b) suggesting that relative motions among the
624 Kazakhstan-Yili, Junggar, Tu-Ha, Tarim and Siberia blocks during the late
625 Carboniferous to Permian were characterized by significant anticlockwise rotations
626 and accommodated by lateral displacement along major strike-slip faults (Wang et al.,
627 2007a). The coeval horizontal displacements up to hundreds of kilometers along the
628 large-scale shear zones (sinistral Irtysh and dextral NF-BF) favor an eastward tectonic
629 wedging of Junggar-Yili-Central Tianshan in between the Siberia and Tarim blocks
630 (Wang et al., 2007a).

631 Reliable geological and paleomagnetic data indicate that the Tianshan Orogen
632 was formed by consumption of the Junggar-North Tianshan Ocean at ~310 Ma (e.g.,
633 Han et al., 2010) and by welding of the Kazakhstan-Yili terrane with Tarim at
634 ~320-310 Ma owing to the closure of the South Tianshan Ocean (e.g., Charvet et al.,
635 2011; X.S. Wang et al., 2018) and associated back-arc oceanic basins (Wang et al.,
636 2011, 2018). As mentioned above, although sinistral strike-slip kinematics recognized
637 along the BF and MTSZ possibly resulted from the Devonian to early Carboniferous
638 oblique subduction (Li et al., 2020), the more explicit and pervasive ductile strike-slip
639 shearing around and within the Central Tianshan initiated almost simultaneously at
640 312-310 Ma, and lasted until the end of Permian, except along the WSZ. Despite
641 uncertainties on the timing and genesis of the locally preserved (and possible earlier)

642 dextral kinematics in the WSZ, we suggest that the latest Carboniferous to Permian
643 (312-242 Ma) dextral strike-slip shearing along the MTSZ and BF, and the latest
644 Carboniferous (312-301 Ma) sinistral strike-slip shearing along the WSZ occurred in
645 post-orogenic intra-continental setting.

646 Combined with previous structural and paleomagnetic studies, our new results
647 further confirm that the previously welded Yili - Central Tianshan - Junggar blocks
648 simultaneously moved eastwards and wedged in between the Siberian and Tarim
649 cratons (Fig. 15A). This eastward wedging was accommodated by synchronous
650 dextral strike-slip shearing along the NF and BF, and then by the sinistral strike-slip
651 shearing along the ISZ since ~284 Ma (Li et al., 2015). The dextral ductile strike-slip
652 shearing along the NTF - MTSZ could be the result of differential eastward
653 displacement rates of Junggar relative to the Yili - Central Tianshan blocks. Similarly,
654 the sinistral WSZ probably resulted from relatively lower displacement velocity of the
655 northern part of the Central Tianshan (north of the WSZ) with respect to its southern
656 part (south of the WSZ), likely due to the backstop effect of the Tu-Ha terrane (Fig.
657 15B). Meanwhile, it is noteworthy that the movement along the ISZ during earliest
658 Permian was not well constrained due to lack of reliable geochronological data (e.g.,
659 Hu et al., 2020). This interpretation could be tested with further kinematic and
660 paleomagnetic studies to quantitatively assess the relative movement (rotation) rates
661 between different tectonic units. Finally, the eastward tectonic wedging of the
662 Kazakhstan-Yili, Central Tianshan and Junggar blocks was most likely triggered by
663 the sub-E-W convergent orogenesis of the late Paleozoic Uralides related to the

664 collision between the Baltica and Siberia blocks (e.g., Biske and Seltmann, 2010;
665 Ivanov et al., 2013).

666

667 **7. Conclusions**

668 (1) The Xiaergou shear zone along the northern boundary of the Central
669 Tianshan is the connecting segment between the North Tianshan Fault and Main
670 Tianshan Shear Zone. Large-scale and sample-scale structural and kinematic analyses
671 indicate principally ductile dextral strike-slip shearing with locally preserved sinistral
672 kinematics. The timing of dextral ductile shearing is dated at ~312-295 Ma by U-Pb
673 dating of zircons from pre- and syn-kinematic granitic dykes.

674 (2) The Wulasitai shear zone is generally a WNW-ESE-trending high-strain belt
675 developing in the interior of the Central Tianshan. Geometric, structural and
676 kinematic analyses suggest predominantly sinistral strike-slip shearing associated with
677 top-to-the-SW thrusting at the NW-SE bending segment of the shear zone, and dextral
678 kinematics is locally preserved. Biotite $^{40}\text{Ar}/^{39}\text{Ar}$ and metamorphic zircon U-Pb ages
679 of meta-sedimentary rocks constrain the timing of the sinistral motion at ~312-301
680 Ma.

681 (3) New structural and geochronological data from the Xiaergou and Wulasitai
682 shear zones together with the regional geological and paleomagnetic data suggest that
683 the latest Carboniferous to Permian ductile strike-slip shear zones in the Tianshan
684 Orogen, SW CAOB, formed in a post-orogenic intra-continental setting, and likely

685 resulted from the eastward tectonic wedging of the Kazakhstan-Yili, Central Tianshan,
686 Junggar blocks in between the Siberia and Tarim cratons.

687

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698

699 **Appendix: Analytical methods**

700 ***A.1. Zircon U-Pb dating***

701 Zircon grains from the samples 44-B and 49-C were concentrated via heavy
702 liquids and magnetic separation techniques, and then hand-picked under a binocular
703 microscope. Selected colorless zircons were mounted in epoxy resins and polished to
704 approximately half-section thickness to expose the grains' center. In order to examine

705 the internal texture of the zircon grains, cathodoluminescence (CL) imaging was
706 performed using the Mono CL 3+ Fluorescence Spectrometer (Gatan, USA) at
707 Nanjing Hongchuang Analytical Institute.

708 Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS)
709 U-Pb dating of zircon was conducted at the State Key Laboratory for Mineral
710 Deposits Research, Nanjing University, using an Agilent 7500s ICP-MS connected to
711 a New Wave 213nm laser ablation system with an in-house sample cell. Zircon
712 standard GEMOC GJ-1 ($^{207}\text{Pb}/^{206}\text{Pb}$ age of 608.5 ± 1.5 Ma; Jackson et al., 2004) was
713 measured to correct fractionation, and the accuracy was monitored using zircon
714 standard Mud Tank with an intercept age of 732 ± 5 Ma (Black and Gulson, 1978).
715 Samples were analyzed in runs of 15 analyses including 5 analyses on standard
716 zircons and 10 analyses on samples of unknown ages. All analyses were carried out
717 using a beam with a 32 μm diameter and a repetition rate of 5 Hz.

718 U-Th-Pb isotopic ratios and ages were calculated from the raw signal data using
719 the software package GLITTER. Correction for common Pb was performed via the
720 EXCEL program ComPbCorr#3_15G (Anderson, 2002). U-Pb Concordia diagrams
721 and probability density curves of ages were conducted using ISOPLOT 3.0 (Ludwig,
722 2003). Uncertainties are quoted at 1σ for individual analyses and at 2σ for mean ages.

723

724 **A.2. Biotite $^{40}\text{Ar}/^{39}\text{Ar}$ dating**

725 Single grains of biotite were carefully handpicked under a binocular microscope

726 from 0.3-2.0 mm size fractions of crushed rock samples 01-B and 02-B. The biotite
727 grains were then cleaned in distilled water and acetone before being weighed into Al
728 foil envelopes for irradiation.

729 After neutron irradiation for 10 h in the CLICIT Cd-lined slot of the Corvallis
730 Nuclear Reactor (Oregon State University, United States) along with the Fish Canyon
731 Tuff sanidine standard ($FCT\ 28.126 \pm 0.019\ Ma$ at 2σ) (Phillips et al., 2017),
732 $^{40}Ar/^{39}Ar$ analyses were performed using a high-resolution Helix SFT mass
733 spectrometer outfitted to a home-built CO_2 -laser based extraction system featuring
734 ultra-low argon blanks. Detailed operating conditions can be found in Corti et al.
735 (2019).

736 Ages and isotopes ratios are plotted and tabulated at $\pm 1\sigma$ and were calculated
737 according to Scaillet (2000). Weighted mean ages (WMA) are calculated by
738 inverse-variance weighting of the steps pooled in the weighted mean. Total-Gas ages
739 (TGA) are calculated by summing all fractions released and by quadratically
740 propagating the attached errors. Pooled age errors include procedural errors, and
741 decay constants and isotope abundance errors.

742

743 **Figure and Table captions:**

744 **Fig. 1.** (A) Simplified tectonic divisions of East Asia showing the location of the
745 Central Asian Orogenic Belt (CAOB). EEC, East European Craton; KZN, Kazakhstan;
746 QQ, Qaidam-Qinling (modified after Şengör et al., 1993; Jahn et al., 2000). (B)

747 Geological map of the SW CAO, including major tectonic units and boundaries
748 (after Windley et al., 2007; Choulet et al., 2011; Wang et al., 2012; Cao et al., 2017).
749 Abbreviations correspond to: IKMT, Ishim-Kyrgyzstan Middle Tianshan; SKNT,
750 Stepnyak-Kyrgyz North Tianshan; ACNT, Aktau-Chinese North Tianshan; NB, North
751 Balkhash; BY, Balkhash-Yili; CY, Chu-Yili; BA, Baidalet-Akbastau; BC,
752 Boshchekul-Chingiz; JB, Junggar-Balkhash; ZTS, Zharma-Tarbagatay-Saur; KM,
753 Karamay; WJ, West Junggar; CNT, Chinese North Tianshan; CCT, Chinese Central
754 Tianshan; BGD, Bogda; Bay, Bayinbulak; Gul, Guluogou; Kul, Kulehu; Wuw,
755 Wuwamen. Numbers denote major faults: 1 = North Tianshan Fault (NTF), 2 = Main
756 Tianshan Shear Zone (MTSZ), 3 = Nalati Fault (NF), 4 = Baluntai Fault (BF).

757

758 **Fig. 2.** Topographic and simplified geological map of the Central Tianshan and
759 adjacent areas (modified from XIGMR, 2007), showing the locations of the Xiaergou
760 shear zone (Fig. 3) and Wulasitai shear zone (Fig. 7). Abbreviations: NTF, North
761 Tianshan Fault; MTSZ, Main Tianshan Shear Zone; NF, Nalati Fault; BF, Baluntai
762 Fault; WSZ, Wulasitai Shear Zone.

763

764 **Fig. 3.** (A) Google Earth® Satellite image of the Xiaergou shear zone (XSZ). (B)
765 Geological map of the XSZ (after 1:200,000 geological map of Houxia by XBGMR,
766 1977a).

767

768 **Fig. 4.** (A) Structural map of the studied domain of the Xiaergou shear zone (XSZ)
769 (see Fig. 3 for location) (after 1:200,000 geological map of Houxia by XBGMR,
770 1977a), showing field structural data and sampling locations. (B) Stereonet plots
771 (equal area lower hemisphere) of beddings (S0 poles), mylonitic foliations (S1 poles)
772 and stretching lineation (L1) in the XSZ. (C) Cross-section across the XSZ showing
773 the sample numbers and locations.

774

775 **Fig. 5.** Field photographs of representative structures in the Xiaergou shear zone. (A)
776 Mylonitic foliation S1 and stretching lineation L1 in early Paleozoic granodiorite. (B)
777 Mylonitic foliation S1 in the tuffaceous sandstone. (C) Mylonitic foliation S1 and
778 stretching lineation L1 in Silurian marble. (D) Stretching lineation L1 in a leucocratic
779 granite dyke. (E) strain localization and shear bands in early Paleozoic granodiorite
780 indicating a dextral sense of shearing. (F) A sheath fold and A-type folds in a
781 mylonitic marble demonstrating dextral strike-slip movement. (G) S-C fabrics in
782 mylonitic marble suggesting a dextral sense of shear. (H) Sigmoid quartz clasts
783 locally recognized in a greenschist showing sinistral sense of motion.

784

785 **Fig. 6.** Photomicrographs showing kinematic features of representative mylonites
786 from the Xiaergou shear zone, thin sections were cut perpendicular to the foliation
787 and parallel to the stretching lineation. (A) Bookshelf textures of plagioclase (Pl)
788 porphyroclasts. (B-E) Asymmetric, sigmoid K-feldspar (Kfs) porphyroclasts and

789 pressure shadows indicating a dextral sense of shearing. (F) Locally recognized
790 K-feldspar porphyroclast and pressure shadows suggesting sinistral motion.

791

792 **Fig. 7.** (A) Google Earth[®] Satellite image of the Wulasitai shear zone (WSZ). (B)
793 Geological map of the WSZ (after 1:200,000 geological map of Baluntai by XBGMR,
794 1977b).

795

796 **Fig. 8.** (A-C) Structural maps of the studied domains (see Fig. 7 for locations) along
797 the Wulasitai shear zone (after 1:200,000 geological map of Baluntai by XBGMR,
798 1977b and 1:50,000 geological map of Wulasitai by XBGMR, 2015) showing sample
799 numbers and locations. (D) Stereonet plots (equal area lower hemisphere) of
800 mylonitic foliation (S1 poles), stretching lineation (L1) and associated crenulation
801 cleavages (L1').

802

803 **Fig. 9.** Field photographs of representative structures in the Wulasitai shear zone. (A)
804 Mylonitic foliation S1 in meta-greywacke. (B-C) Stretching lineation L1 and
805 crenulation cleavage L1' in paragneiss (B) and phyllite (C); Inset of Fig. 9B indicating
806 the in situ partial melting and syn-kinematic transport of melts. (D-E) Mylonitic
807 foliation S1 in meta-granite and syn-kinematic boudinage of felsic dyke (E). (F)
808 Microfolds and shear bands indicating top-to-the-South shearing. (G) Asymmetric

809 microfolds in meta-rhyolite indicating sinistral shearing. (H) S-shaped intrafolial folds
810 in meta-sandstone demonstrating a sinistral sense of shear, note the oblique relation
811 between tails of S-type folds and main foliations. (I) Offset of syn-kinematic quartz
812 veins in mylonitic granite suggesting a sinistral strike-slip movement.

813

814 **Fig. 10.** Photomicrographs of representative kinematic features of mylonites from the
815 Wulasitai shear zone, thin sections were cut perpendicular to foliation and parallel to
816 stretching lineation. (A) Biotite (Bt) mica fish indicating sinistral shearing. (B)
817 Asymmetric K-feldspar (Kfs) porphyroclasts and pressure shadows and shear bands
818 made of muscovite (Ms). (C-E) σ -type K-feldspar (Kfs) porphyroclasts and pressure
819 shadows of biotite (Bt) and S-C fabrics (D), all indicating a sinistral sense of shear. (F)
820 Sigmoid quartz (Qtz) and feldspar porphyroclasts and pressure shadows reflecting
821 localized dextral motion, note the relation between pressure shadow and main
822 foliations.

823

824 **Fig. 11.** Microstructural characteristics of dynamically recrystallized quartz grains in
825 representative mylonites from the Xiaergou (A-C) and Wulasitai (D-F) shear zones.

826

827 **Fig. 12.** Plots of estimated temperatures v.s. latitudes of sampling sites for the
828 ductilely deformed samples along the Xiaergou (A) and Wulasitai (B) shear zones.

829 Ranges of quartz recrystallization temperatures are based on Stipp et al. (2002a).

830 Abbreviations: BLG, bulging; SGR, sub-grain rotation; GBM, grain boundary

831 migration.

832

833 **Fig. 13.** (A and E) Field occurrences and (B and F) photomicrographs of the sampled

834 pre- and syn-tectonic granitic dykes in the Xiaergou shear zone. (C and G) CL images

835 of the analyzed zircons from the granitic samples. (D and H) Concordia diagrams of

836 U-Pb analytical results and mean age plots (insets).

837

838 **Fig. 14.** Photomicrographs (A-B), $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra (C-D) and chemical ratios

839 (E-F) for the dated biotites of the meta-sedimentary rocks from the Wulasitai shear

840 zone. Abbreviations: Bt = Biotite; Pl = Plagioclase; Qtz = Quartz.

841

842 **Fig. 15.** Interpretative sketch showing the intracontinental development of

843 regional-scale strike-slip shear zones induced by relative motions and tectonic

844 wedging of the Kazakhstan-Yili (K-Y), Central Tianshan (CT), Junggar (J) and Tu-Ha

845 (T-H) blocks eastwards in between the Siberia and Tarim cratons during the latest

846 Carboniferous. The shadowed areas around each block in (A) represent the loss of

847 continental margins during convergence.

848

849 **Supplementary Table S1.** Textural descriptions of quartz dynamic recrystallization
850 and temperature estimations for the mylonitic rocks from the Xiaergou and Wulasitai
851 shear zones.

852

853 **Supplementary Table S2.** LA-ICP-MS zircon U-Pb analytical data for the
854 syn-kinematic granitic rocks in the Xiaergou shear zone.

855

856 **Supplementary Table S3.** Laser total fusion $^{40}\text{Ar}/^{39}\text{Ar}$ analytical data of single biotite
857 grains from the meta-sedimentary rocks in the Wulasitai shear zone.

858

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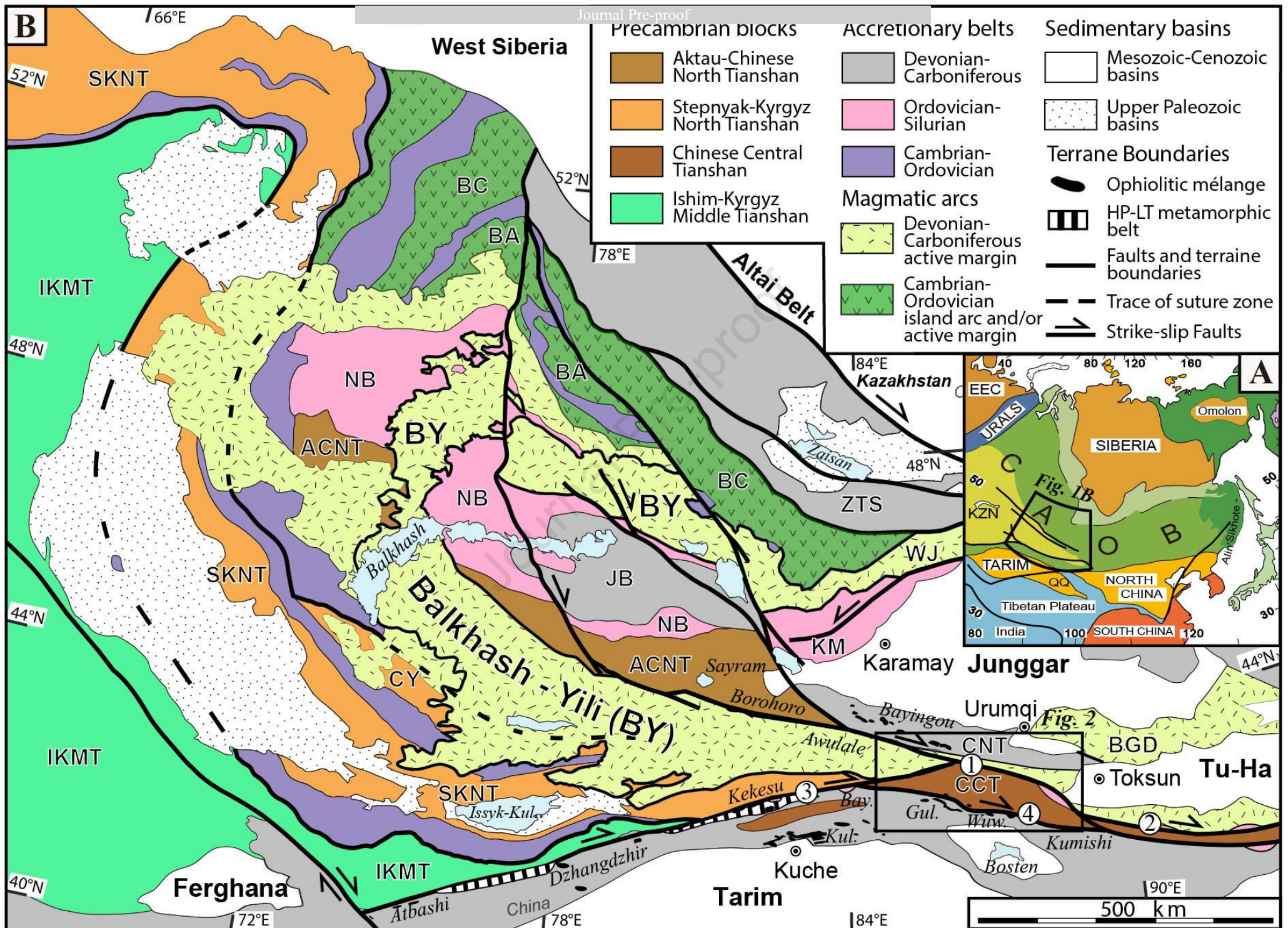
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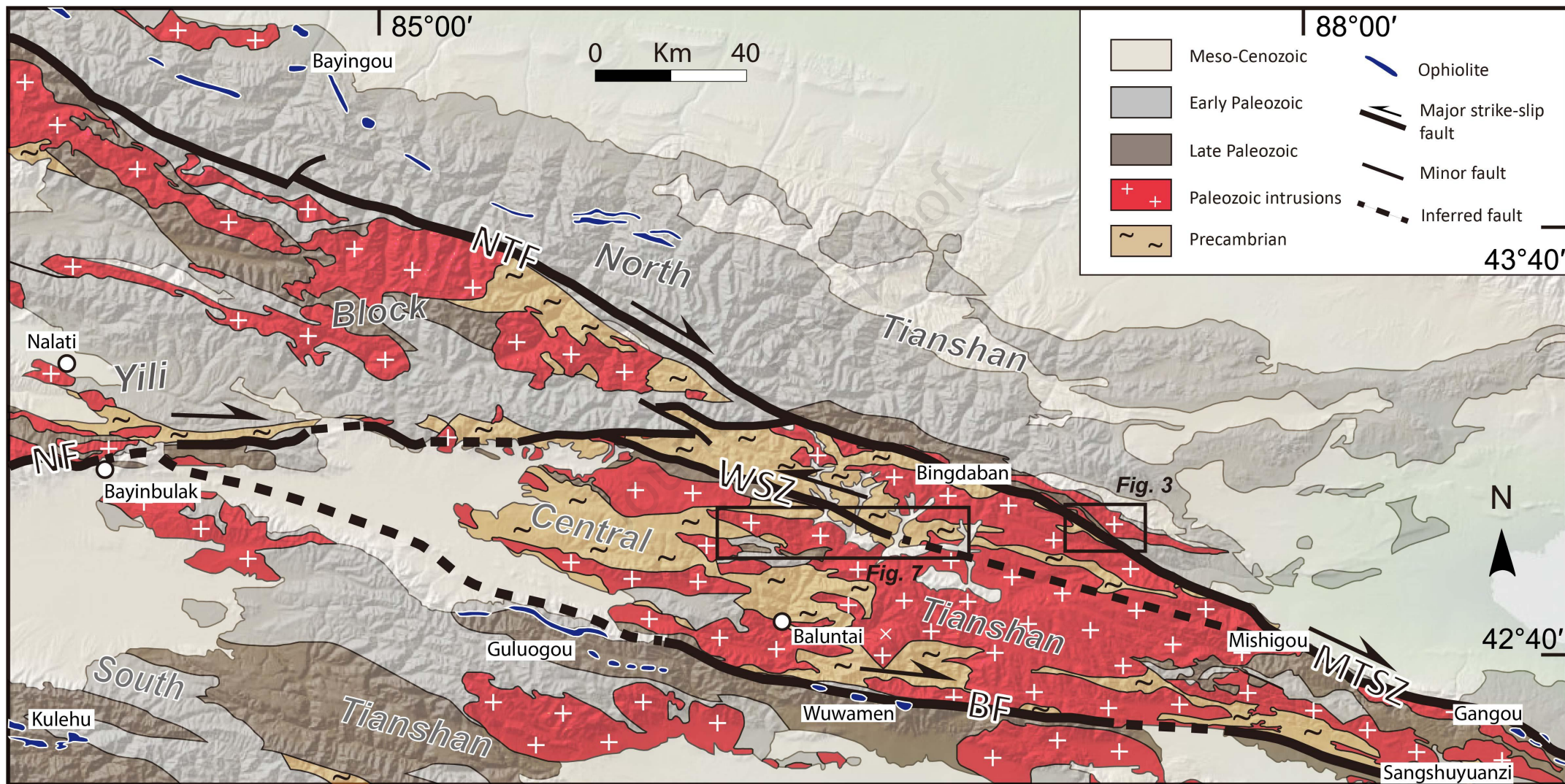
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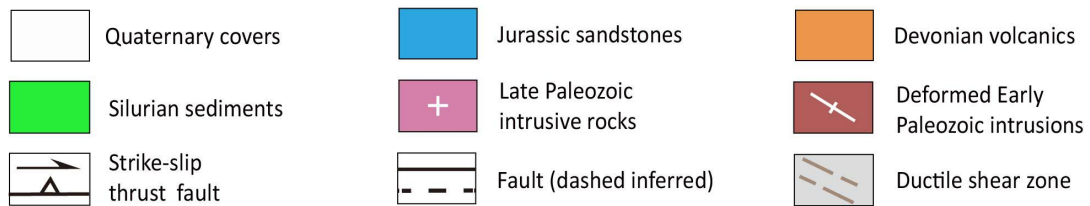
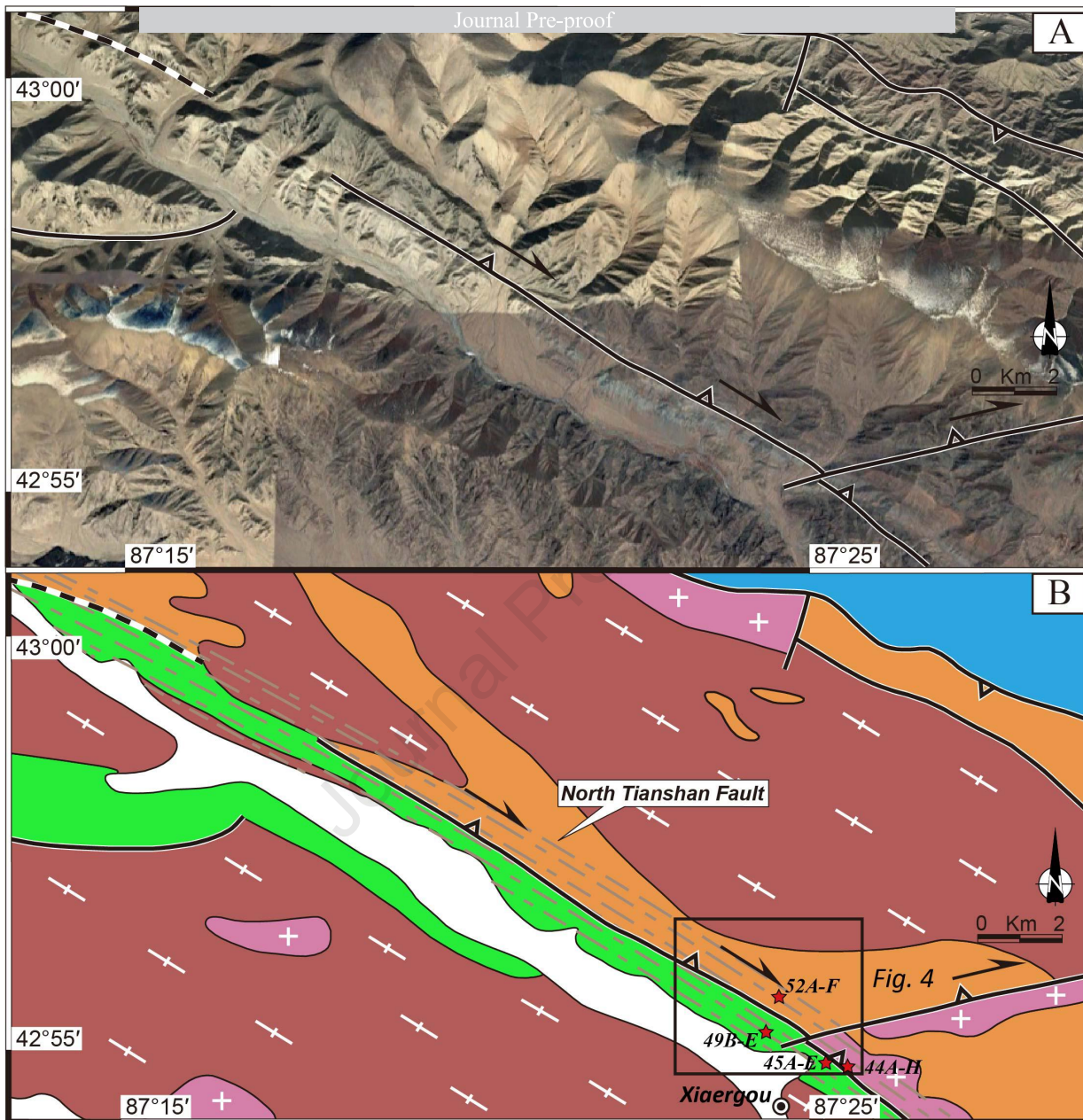
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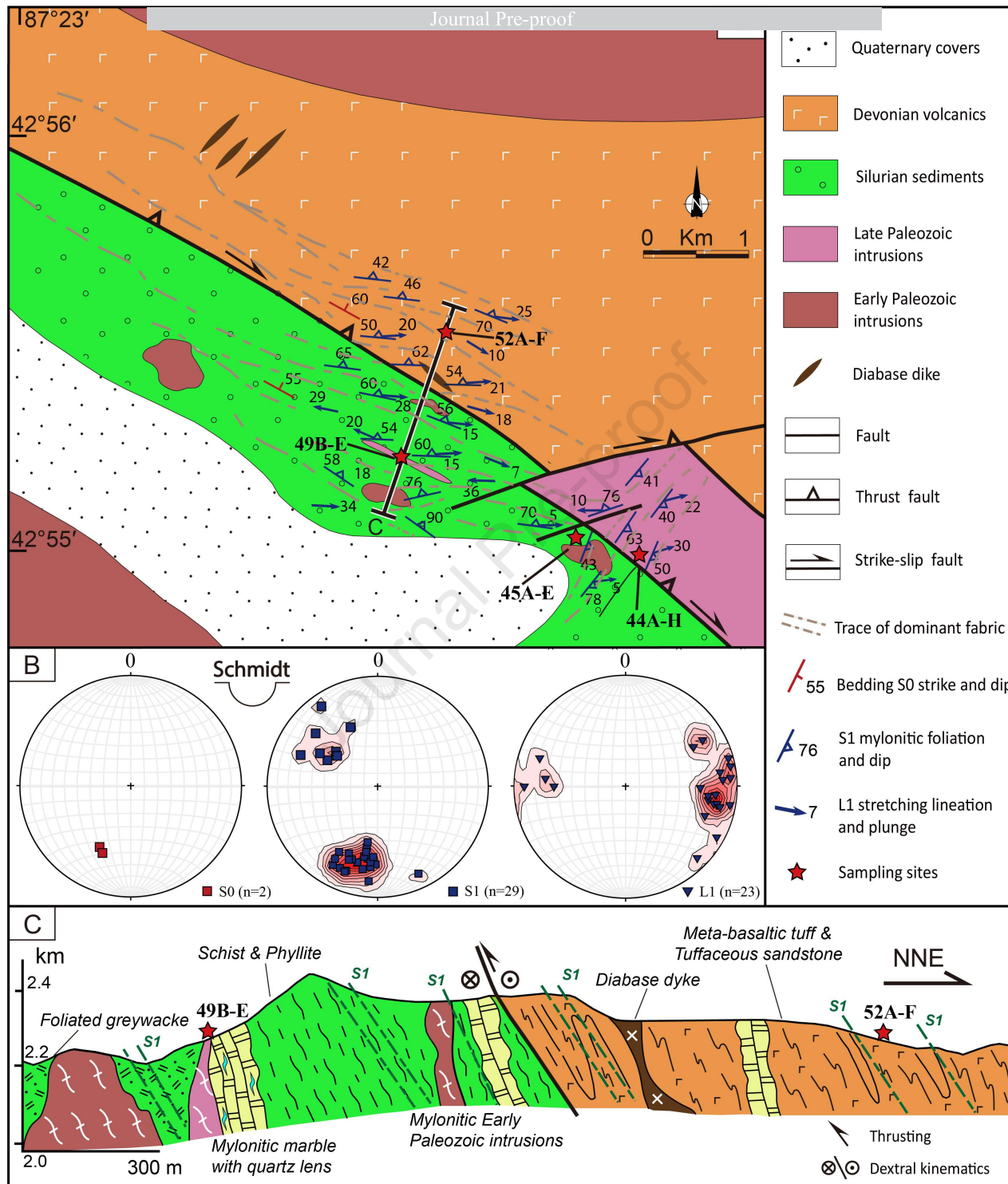
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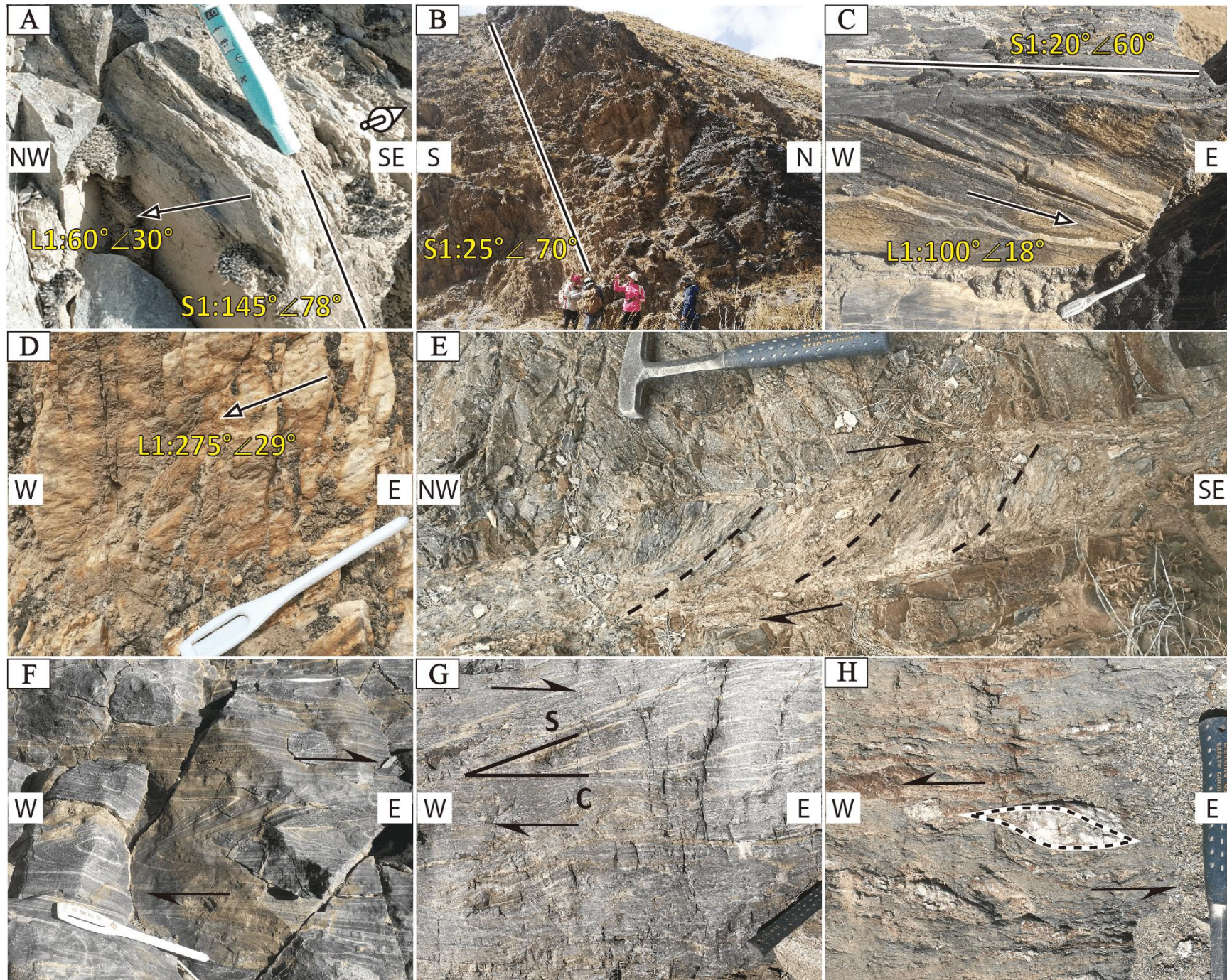
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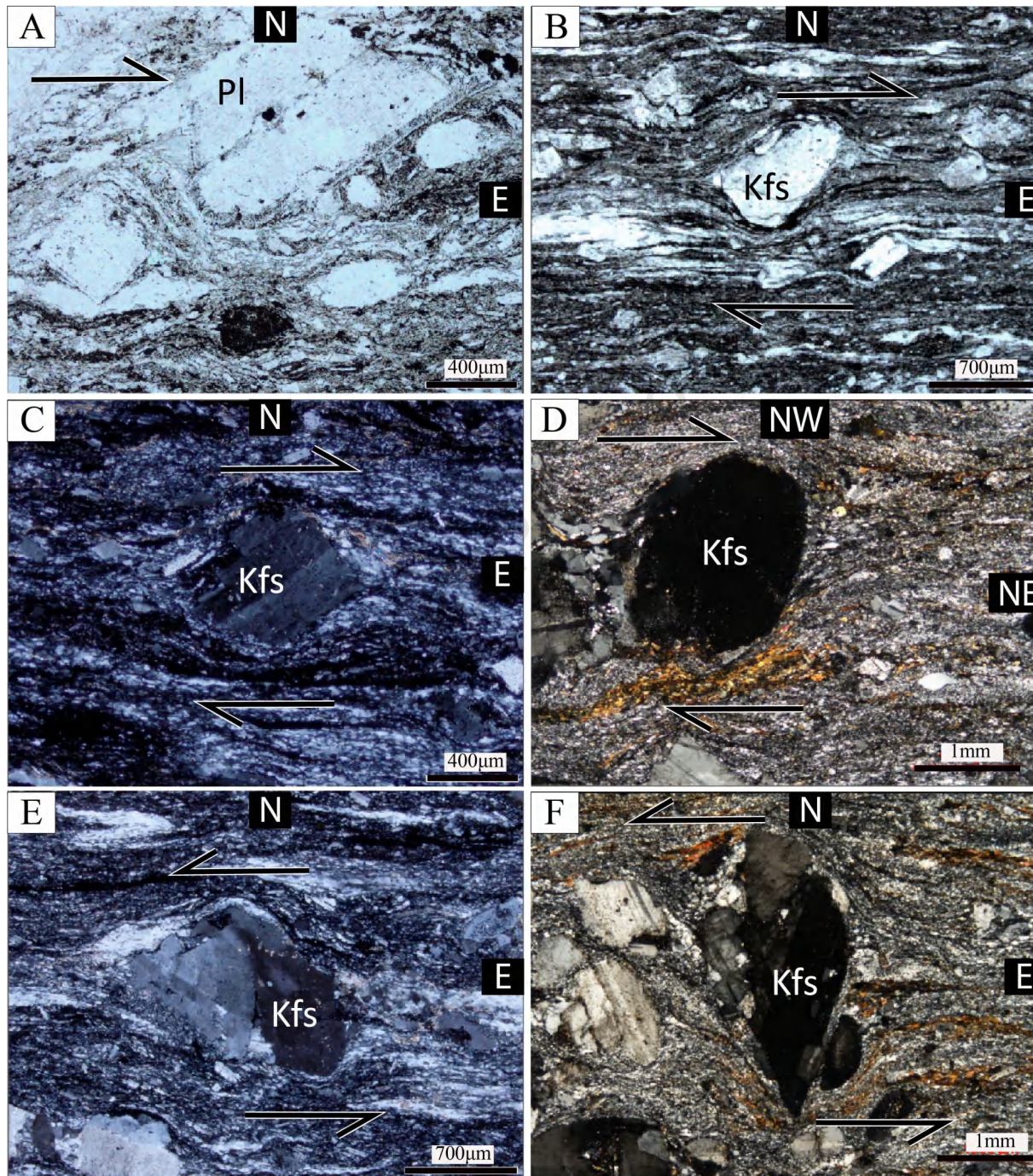


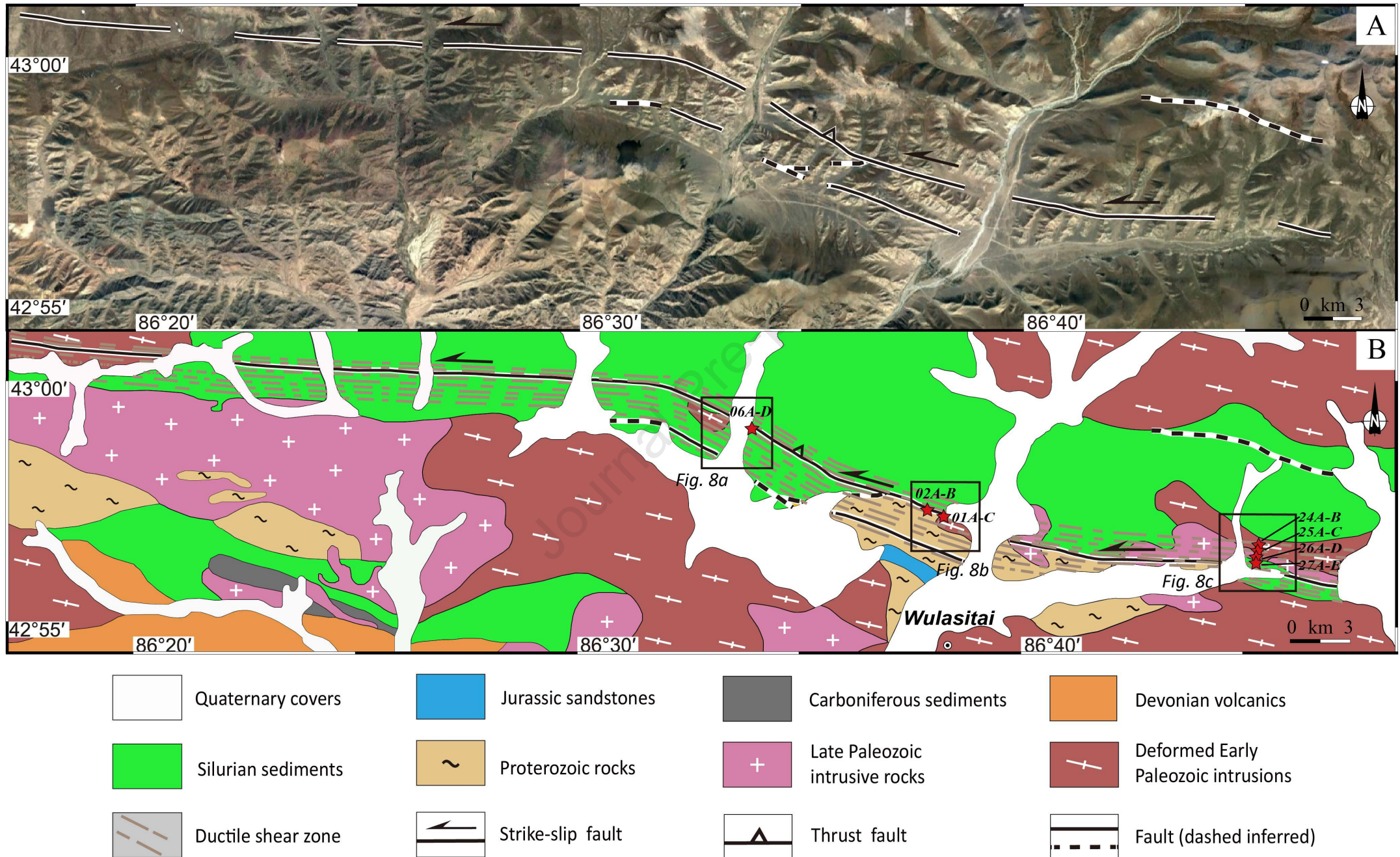


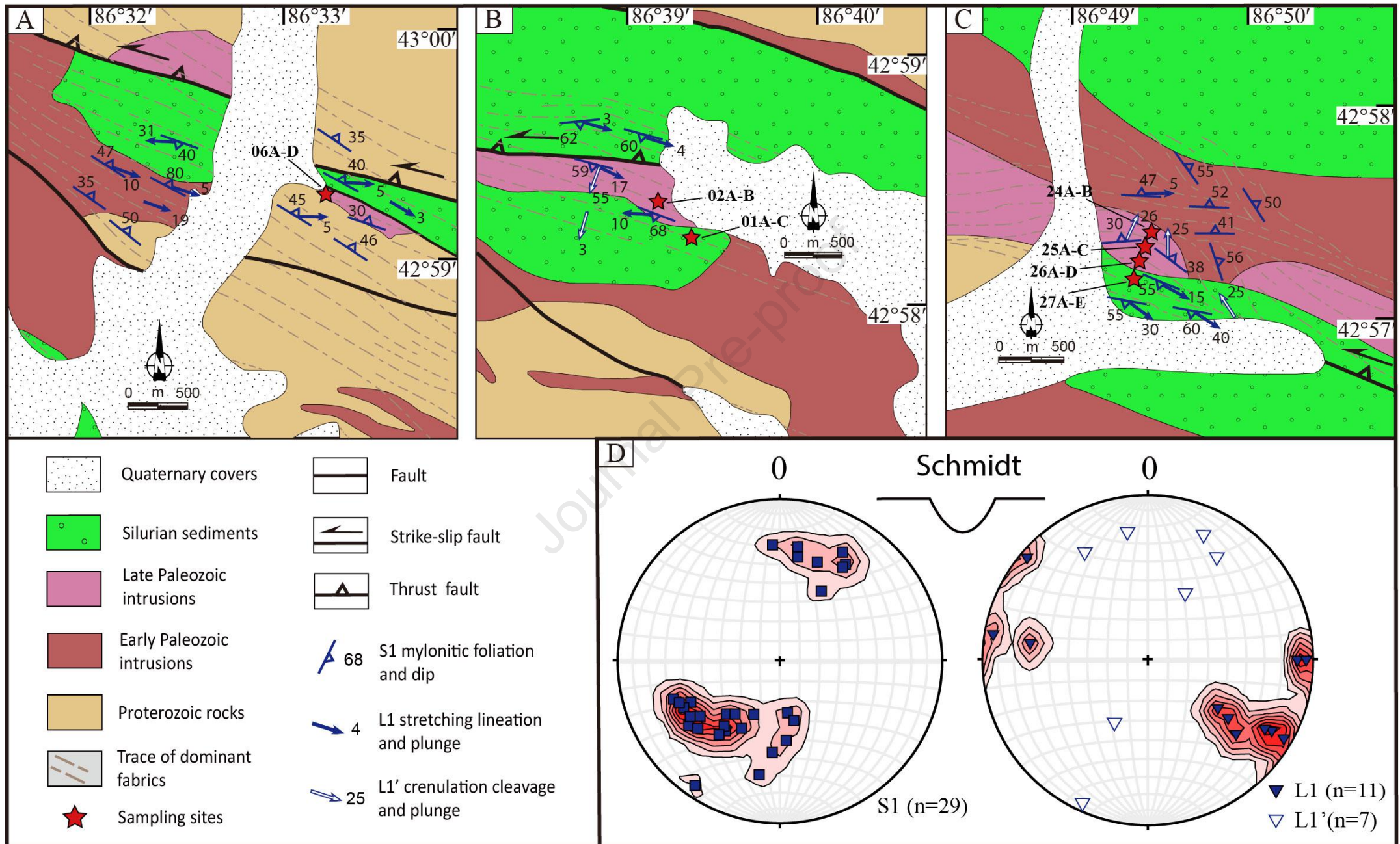


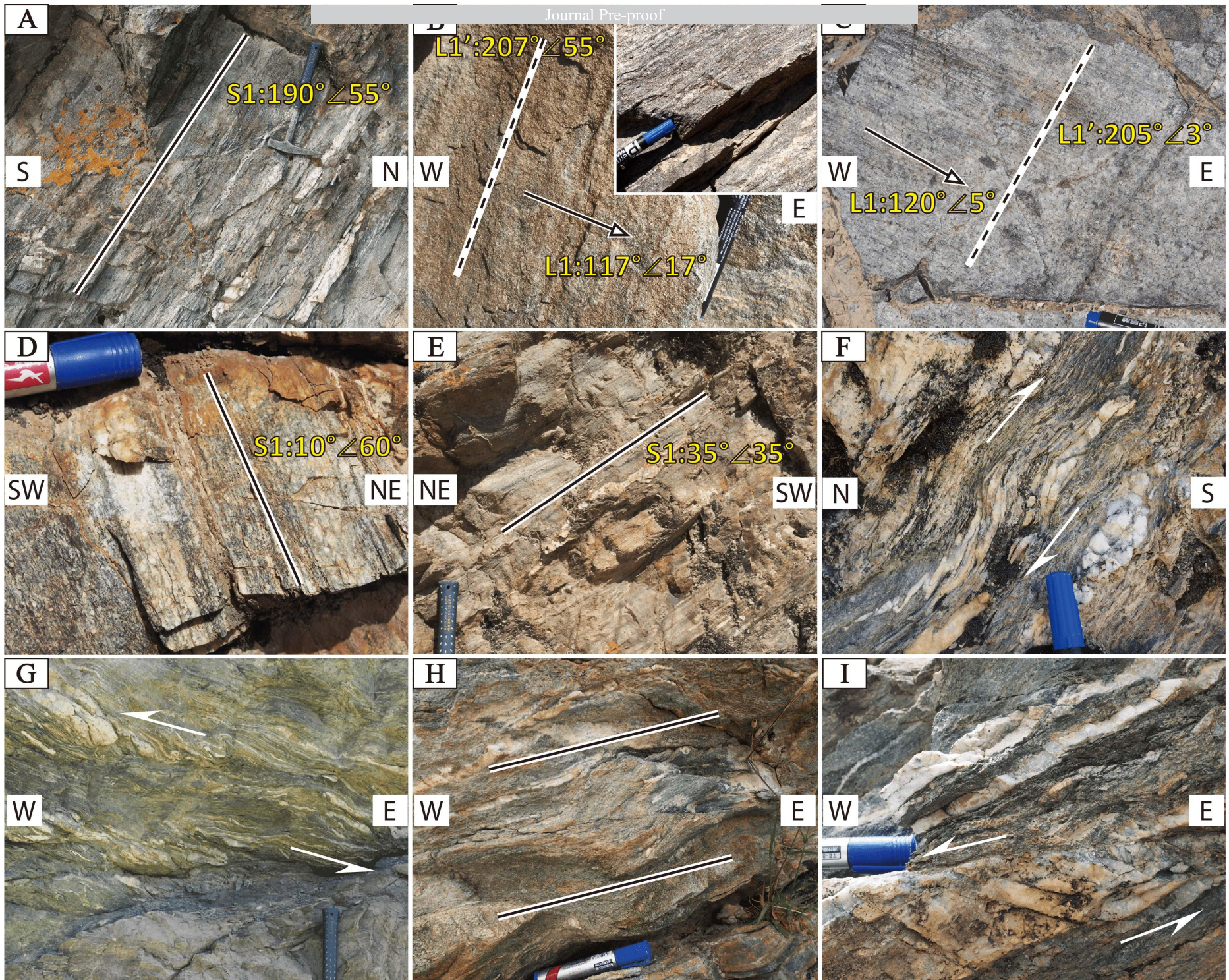


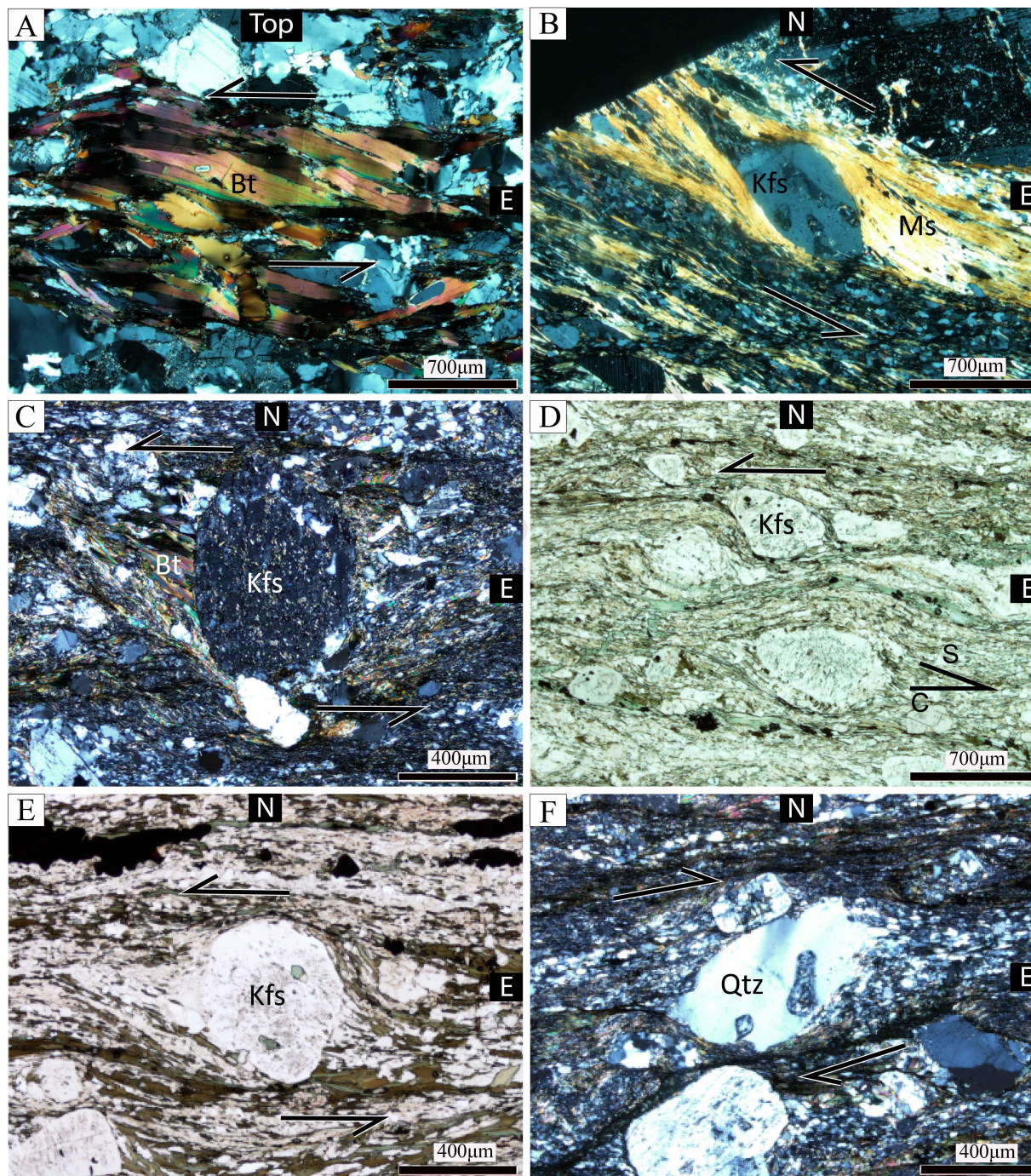


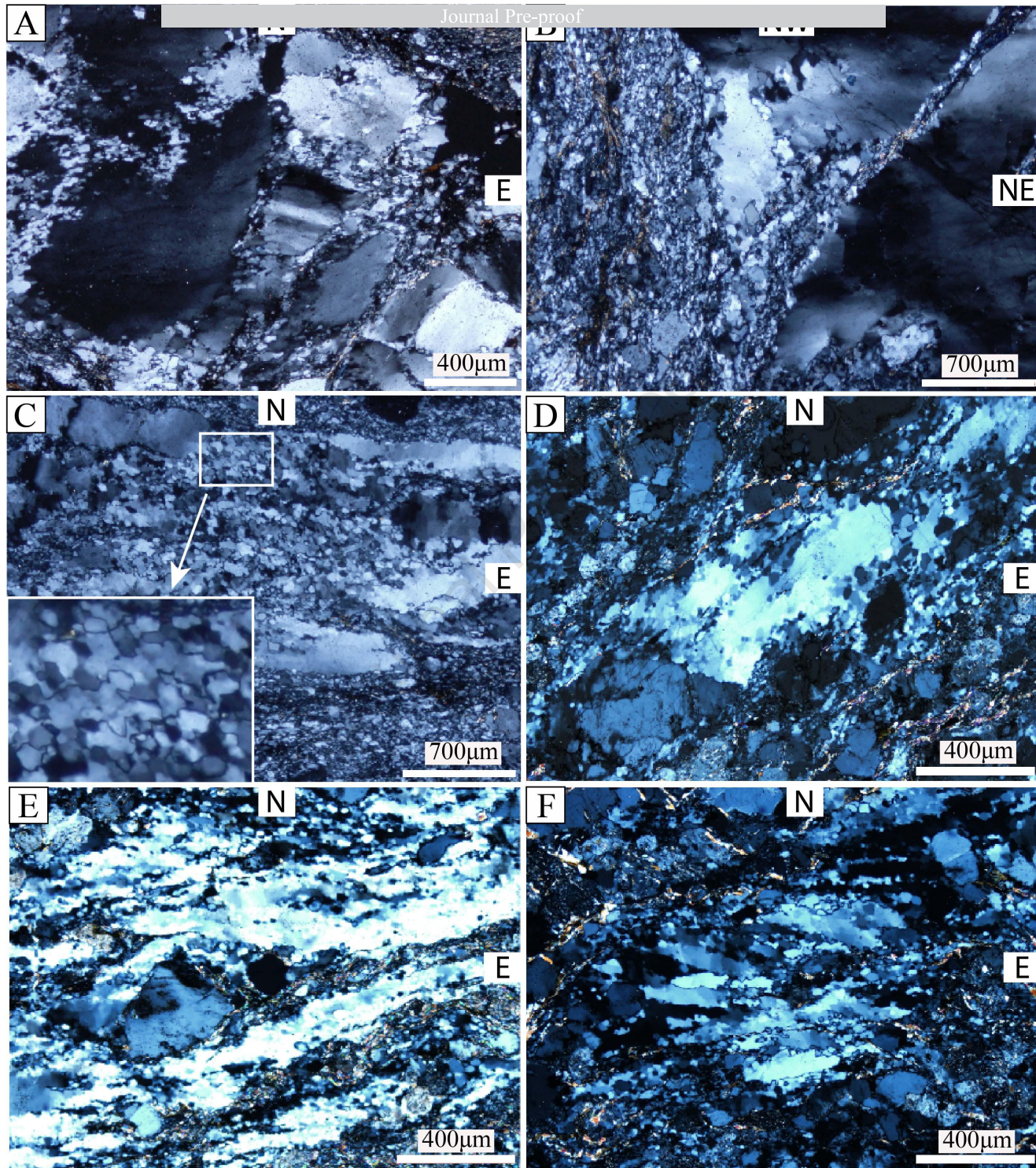


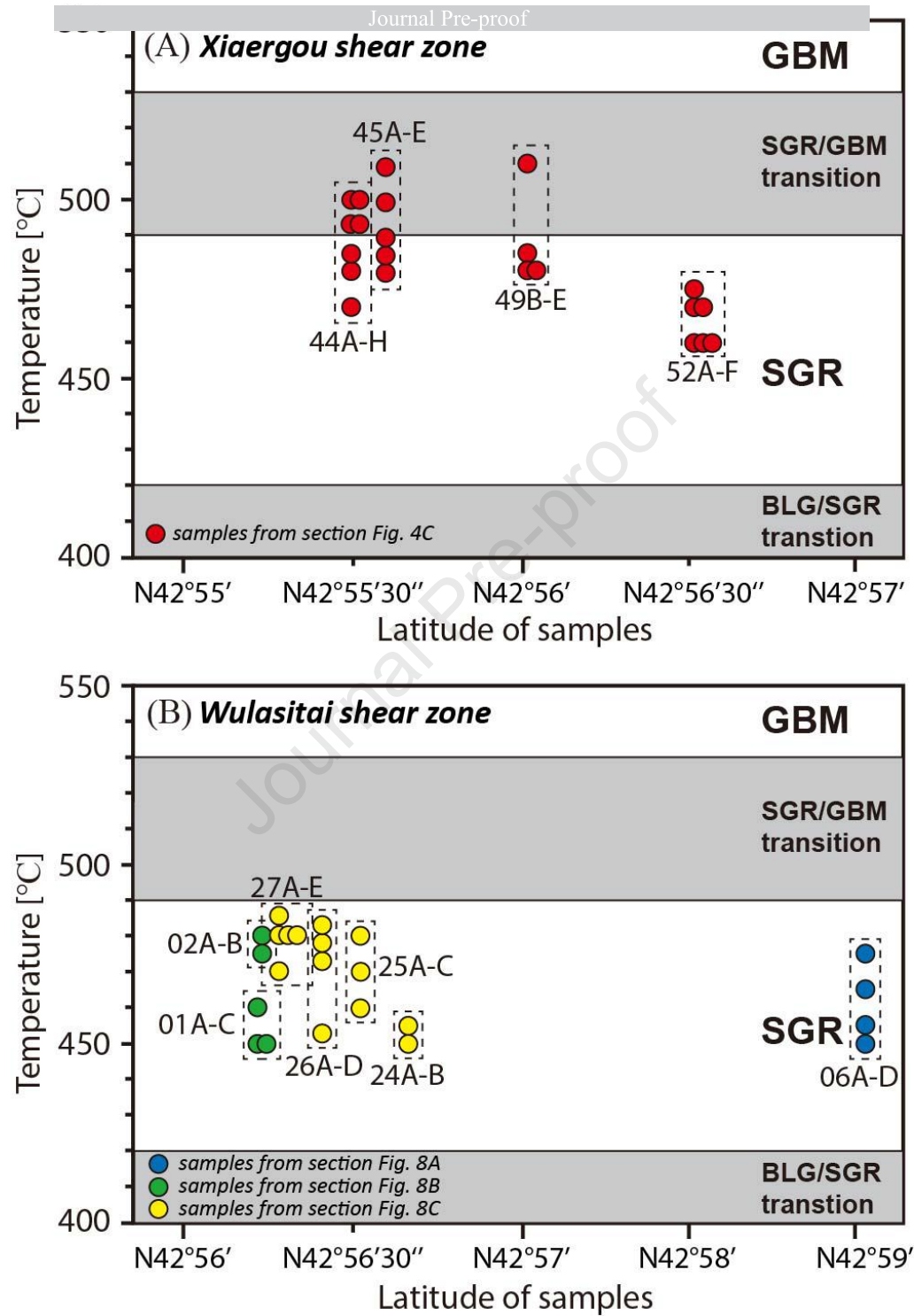


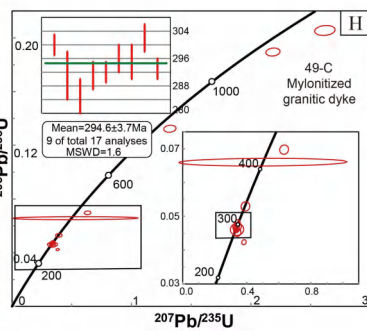
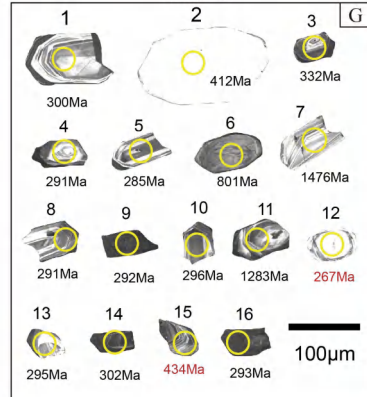
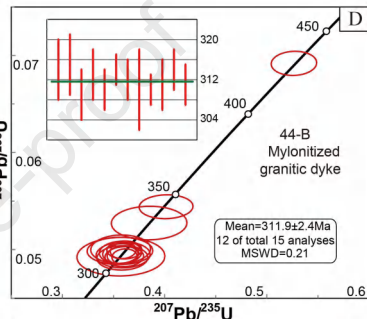
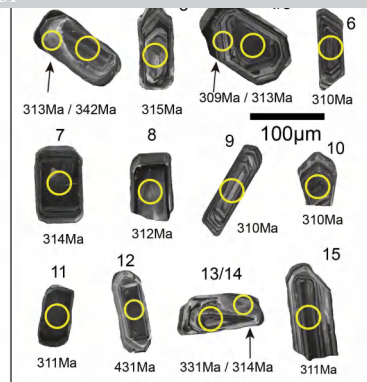
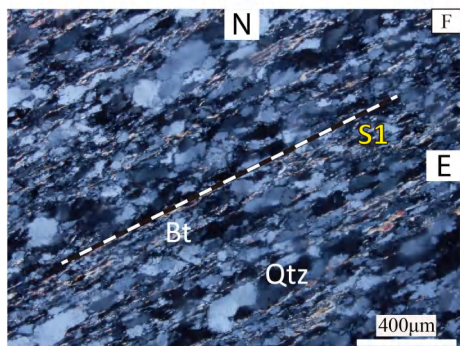
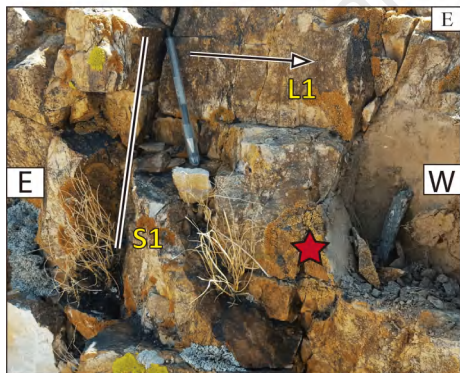
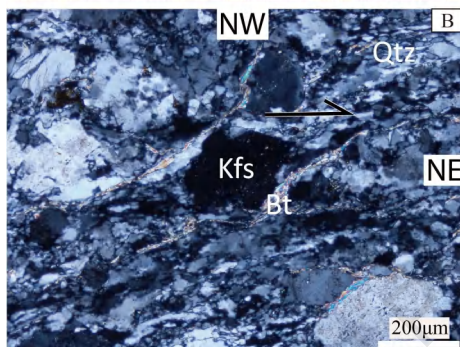


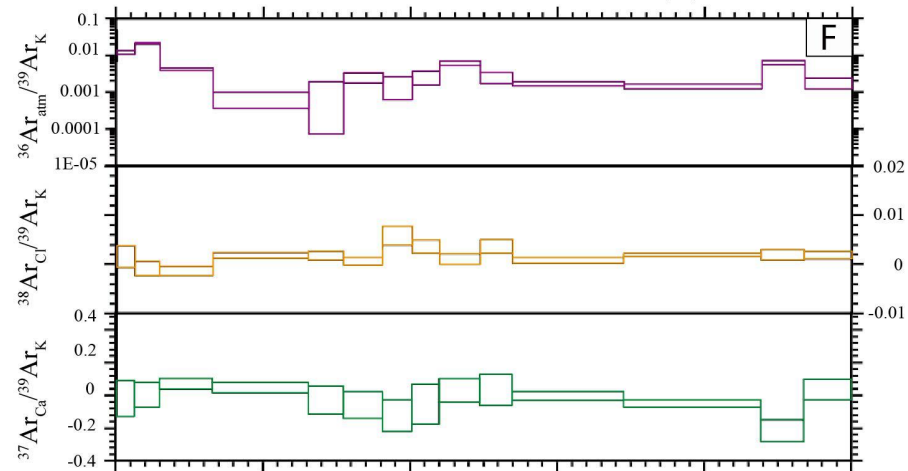
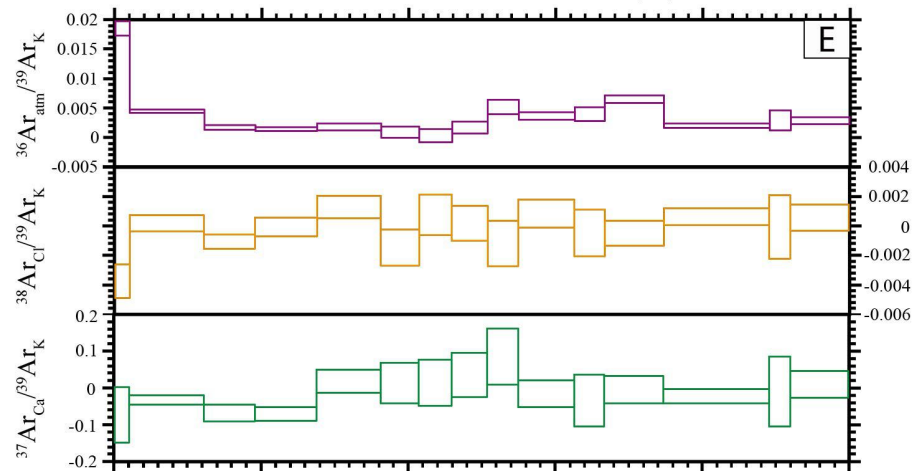
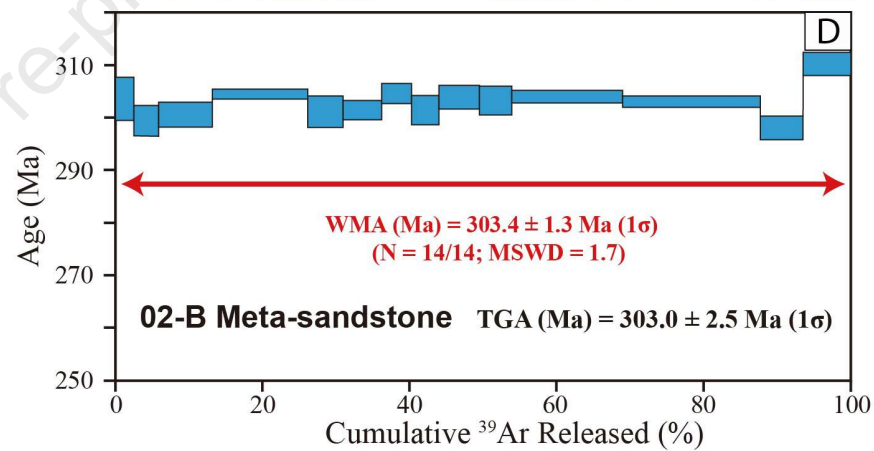
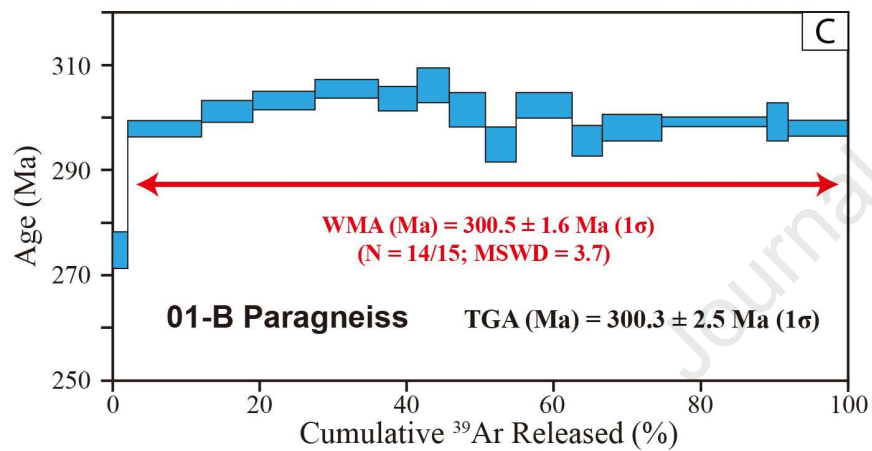
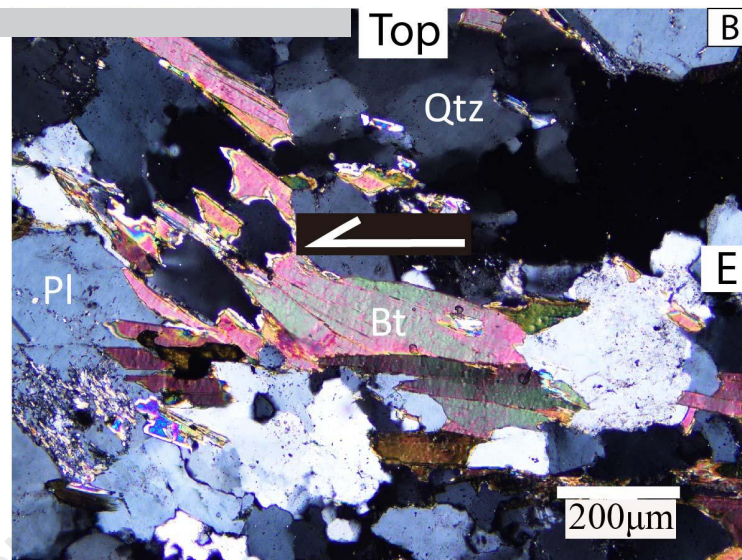
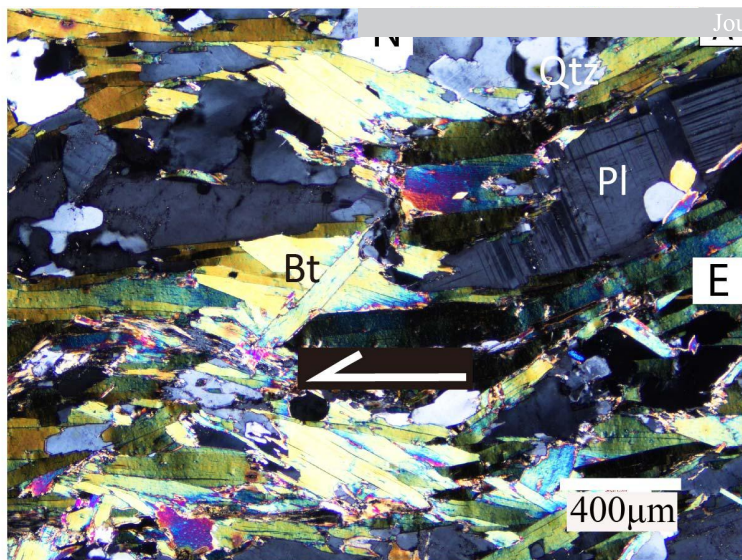




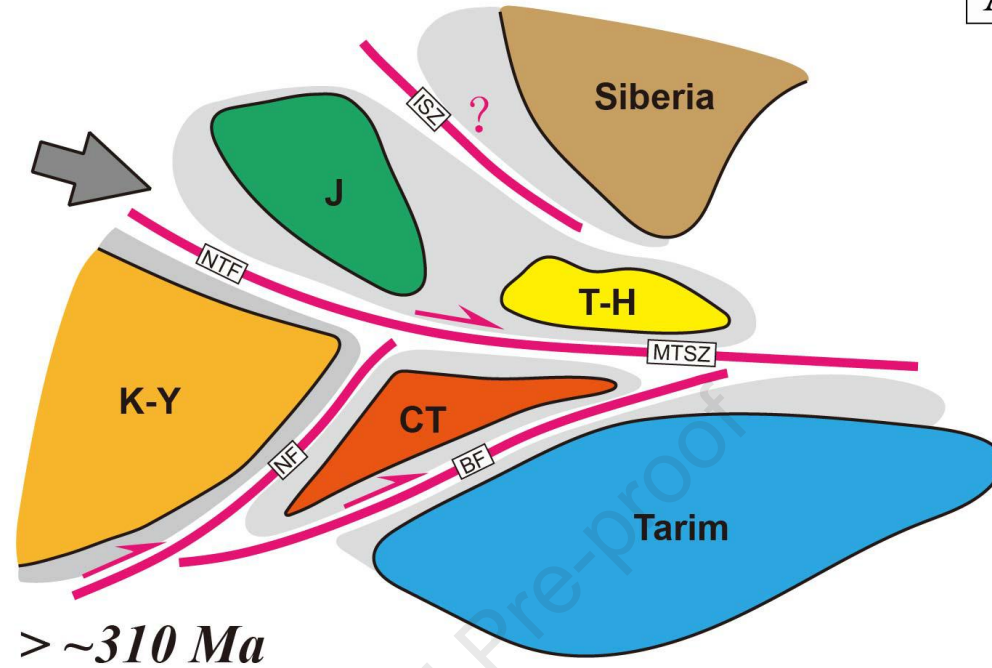




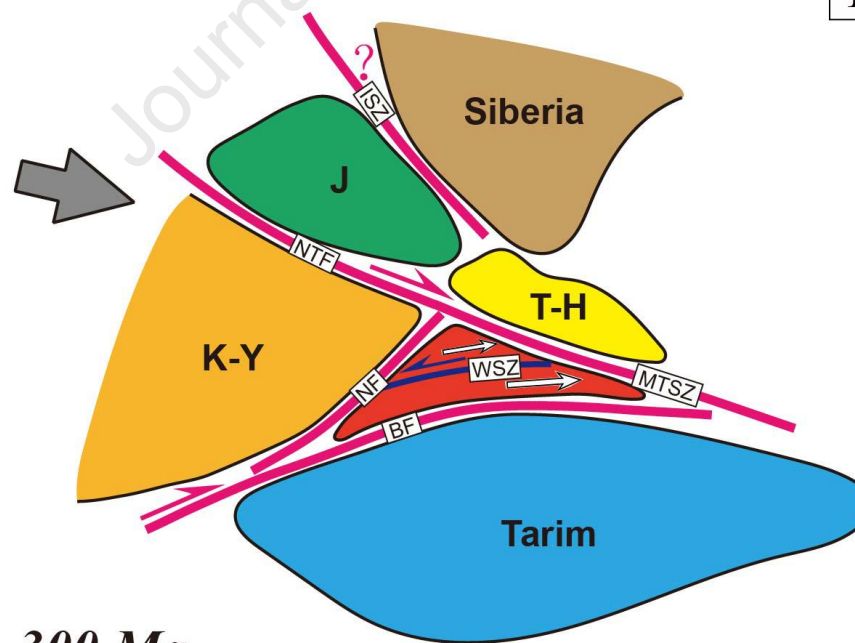




A

 $> \sim 310$ Ma

B

 $\sim 310-300$ Ma

Highlights:

- Xiaergou ductile strike-slip shear zone links the North Tianshan Fault and Main Tianshan Shear zone.
- Wulasitai ductile sinistral strike-slip shear zone occurs inside the Central Tianshan block.
- Ductile strike-slip shear zones around and in Central Tianshan initiated synchronously at ~310 Ma.
- Ductile strike-slip shear zones in SW CAOB denotes its eastward wedging in between Siberia and Tarim.

Declaration of competing interest

The authors declare that they are not aware of any competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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