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1 Geomorphic analysis of active fold growth and landscape evolution in  
2 the central Qiulitage fold belt, southern Tian Shan, China

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19 **Abstract**

20 The Qiulitage fold-and-thrust system in the Kuqa foreland is a prominent NE-SW  
21 trending relief associated with active thrust-related folding in the southern Tian Shan. Based  
22 on open-access DEMs and field work, we carried out a detailed geomorphologic analysis of  
23 the Qiulitage topography based on drainage network characteristics and several  
24 morphometric indices. Our results suggest that the Qiulitage fold belt is composed of six  
25 morphological units, which are statistically confirmed by a principal component analysis.  
26 These morphologic structures have interacted during both vertical growth and lateral

27 propagation of the folds, associated with different patterns of fold connection and  
28 deformation partitioning. The structural evolution of the Qiulitage fold belt has significantly  
29 influenced major rivers crossing the fold belt and minor ones developing on the fold ridges.  
30 We finally propose a morphotectonic evolution of the fold belt integrating the influence of  
31 *décollement* distribution, deep inherited structures, and changes in shortening amount.

32       Keywords: Qiulitage fold belt, fault-related fold, geomorphological analysis,  
33 morphometric indices, Tian Shan.

## 34 1. Introduction

35       Geomorphic surfaces, such as alluvial fans, fluvial terraces or drainage basins, are useful  
36 markers of active tectonics (*e.g.*, Hardy and Poblet, 1994; Delcaillau et al., 1998; Dolan and  
37 Avouac, 2007, Amos et al., 2010, Burbank & Anderson, 2011) that allow documentation of the  
38 kinematic evolution of fault-related folds in mountain belts (*e.g.*, Suppe, 1983; Suppe and  
39 Medwedeff, 1984). Numerous studies have analyzed the along-strike changes in morphology  
40 of active fault-related folds to understand the mechanisms of anticline growth (*e.g.*, Jackson  
41 et al., 1996; Mueller and Talling, 1997; Delcaillau et al., 1998; Ramsey et al., 2007; Bull, 2009;  
42 Bretis et al., 2011; Keller and DeVecchio, 2013; Collignon et al., 2016; Giampaoli and Rojas  
43 Vera, 2018; Sissakian et al., 2019; Bahrami et al., 2020). For instance, relationships between  
44 the fold growth and the underlying active thrusts or *décollements* can be decrypted using the  
45 associated analyses of structural and geomorphic features, and by dating deformed  
46 geomorphic surfaces (*e.g.*, Keller et al., 1998; Jackson et al., 2002; Hetzel et al., 2004; Bennett  
47 et al., 2005). In addition, frontal anticlines above active thrust faults typically display drainage

48 and channel anomalies (*e.g.*, knickpoints) that evidence the landform evolution in response to  
49 tectonic and climatic forcings (*e.g.*, Poisson and Avouac, 2004, Boulton et al., 2014, Guerit et  
50 al., 2016). As pointed out by Jackson et al. (1998), the shape of landscapes and their drainage  
51 networks constitute a response of landforms to tectonic processes (*i.e.*, uplift and subsidence),  
52 more or less variably modulated by lithological parameters. The reconstitution of drainage  
53 pattern evolution, combined with the growth history of fold belts, contributes to  
54 understanding the evolution of mountain belts. In this paper, we address open questions such  
55 as 1) how landforms record fold growth (structural relief, topographic emergence, lateral  
56 propagation), and 2) how distribution of deformation within a fold belt is recorded at the  
57 catchment and topographic ridge scale. We examine the topography of a 200 km long  
58 structure, the Qiulitage fold belt, located at the southern margin of the Kuqa fold-and-thrust  
59 belt at the piedmont of southern Tian Shan, NW China (Fig. 1A). We investigate the landscape  
60 evolution of this active thrust-related fold system in its central part and document: i) the  
61 geomorphological response of landforms to differential uplift along the anticlinal ridges, and  
62 ii) how lateral propagation of folding is recorded by catchments and drainage networks. We  
63 used SRTM and ASTER DEMs (30 m resolution) to investigate the geomorphological properties  
64 of the study area, and explore how morphometric indices and topographic profiles record fold  
65 growth. We used morphometric indices such as drainage basin area, basin local relief,  
66 hypsometric integral, channel steepness index and incision (*e.g.*, Doornkamp and King, 1971;  
67 Schumm, 1977; Morisawa and Hack, 1985; Willemin and Knuepfer, 1994; Jackson et al., 1996),  
68 which allowed us to classify drainage basins along the folds according to their morphometric

69 signatures. Our results lead us to propose a geomorphic evolution of Qiulitage drainage basins  
70 in relation to the different styles of folding, and probable changes in rates of uplift.

71

## 72 2. Geological setting

### 73 2.1. The Tian Shan range

74 The Tian Shan is an intracontinental mountain range in Central Asia located to the north  
75 of the Tibetan Plateau. It is bounded by the Junggar and Tarim foreland basins, to the north  
76 and south, respectively (Fig. 1). During the Mesozoic, the Tian Shan is generally thought to be  
77 weakly active (Hendrix et al., 1994; Jolivet et al., 2010), whereas it has been strongly  
78 reactivated since the Cenozoic due to the collision between the Indian and the Eurasian plates  
79 (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1979). Fold and thrust belts along the  
80 northern and southern flanks of the Tian Shan have accommodated the propagation of  
81 deformation and the widening of the mountain belt (Avouac et al., 1993; Hendrix et al., 1994;  
82 Yin et al., 1998; Burchfiel et al., 1999; Charreau et al., 2005; Sun and Zhang, 2009; Sun et al.,  
83 2009; Jolivet et al., 2010; Qiu et al., 2019; Gao et al., 2020). GPS observations indicate that  
84 about 20 mm/yr of horizontal shortening is accommodated across the whole Tian Shan range  
85 (Abdrakhmatov, 1996; Zubovich et al., 2010). In the southern Tian Shan, GPS data suggest that  
86 about 5 mm/yr are presently accommodated across the Kuqa to Korla mountain fronts (Yang  
87 et al., 2008).

## 88                    2.2. Structures of the Qiulitage fold belt

89                    The Kuqa fold-and-thrust belt (KFTB) is located in the southern foothills of the Tian Shan  
90 mountains (Fig. 1A). It represents a major structural feature that develops in a Mesozoic and  
91 Cenozoic basin along the northern Tarim margin (Métivier and Gaudemer, 1997). Most of the  
92 stratigraphic sequence is composed of alternating layers of sandstones, shales and  
93 conglomerates, with very few carbonates (Fig. 2). Three peculiar formations are important  
94 due to their significant structural role in the deformation of the KFTB: these are the Jurassic  
95 coal strata, the Paleocene-Eocene evaporites and the early Miocene evaporitic strata (gypsum  
96 and halite). The latter two constitute a weak rheology in which major *décollement* levels  
97 controlling fault-related folds and thrusts are rooted (Wang et al., 2011) (Fig. 1C).

98                    The Qiulitage structures have been constrained by a dense dataset of bedding  
99 measurements, industrial seismic profiles and wells (Wang et al., 2011; Li et al., 2012; Tang et  
100 al., 2017; Izquierdo-Llavall et al., 2018). These data illustrate how the structural style evolves  
101 from a foreland-ward vergent dual fold system in the west (sections 1-3 in Fig. 1C) to a single  
102 monocline structure controlled by a back-thrust or anticline further east (sections 4 and 5 in  
103 Fig. 1C). Seismic profiles and well analyses have demonstrated that evaporites and salt-related  
104 tectonics have played an important control on the kinematics of the KFTB (Chen et al., 2004;  
105 Xu and Zhou, 2007; Li et al., 2012; Wang et al., 2011; Yu et al., 2014; Zhao and Wang, 2016;  
106 Tang et al., 2004; Tang et al., 2015). Early salt flow related to syntectonic deposition might  
107 have played an important role on the nucleation of folds (Li et al., 2012; Zhao and Wang, 2016).

108                    In detail, the Northern Qiulitage anticline (NQA) crops out with steeply to shallowly  
109 north-dipping beds in the northern limb, and mostly subvertical to overturned beddings in the

110 southern limb (sections 1-4 Fig. 1C). The southern limb is cut by a steeply-dipping south  
111 vergent thrust (*i.e.*, the Northern Qiulitage Thrust - NQT). The Southern Qiulitage anticline  
112 (SQA) is a tight fault-related fold characterized by steeply dipping to overturned northern and  
113 southern limbs, and a sub-vertical north-verging thrust in the core (*i.e.*, the Southern Qiulitage  
114 Thrust, SQT). Between the northern and southern Qiulitage folds, two small intermontane  
115 basins are filled with Quaternary deposits (Figs. 1B and 3B). The western intermontane basin  
116 (WIB) has a simple syncline shape (section 3 in Fig. 1C), whereas the eastern intermontane  
117 basin (EIB) is overthrust by the NQT. Restoration of seismic sections across the Qiulitage  
118 fold belt suggests a similar amount of shortening of ~ 12-14 km (Li et al., 2012; Izquierdo-  
119 Llavall et al., 2018; Pla, 2019), although some local higher values (16.5 km; section 4) have  
120 been estimated (Fig. 1B). The analysis of dip measurements allows recognition of growth  
121 strata and suggests that the NQA has initiated slightly subsequent to the SQA (Izquierdo-Llavall,  
122 et al., 2018). The initiation of the KFTB growth could date back to late Miocene (Hubert-Ferrari  
123 et al., 2007; Wang et al., 2011; Li et al., 2012, Tian et al., 2016; Tang et al., 2017; Charreau et  
124 al., 2020) and two pulses of accelerations in fold growth may have occurred during the  
125 Pliocene and the Pleistocene times (*e.g.*, Li et al., 2012; Charreau et al., 2020).

126

### 127 3. Methodology

128 In order to characterize the structural processes that control the growth and the  
129 evolution of the central Qiulitage fold belt, we analyzed landforms at meter to kilometre scales  
130 based on field studies and by analyzing Digital Elevation Models (DEM) and satellite images.

131 DEM data were collected from the NASA SRTM V.4.0 (90 m resolution) and ASTER programs  
132 (30 m resolution), whilst satellite images were extracted from Google Earth®. Based on these  
133 available datasets, we extracted 250 drainage basins for which we mapped and calculated the  
134 following morphometric parameters and geomorphic indices described in more detail  
135 hereafter: basin area ( $A$ ), hypsometry ( $HI$ ), basin asymmetry factor ( $A_f$ ), elongation ratio ( $R_e$ ),  
136 local relief ( $\Delta z$ ), fluvial incision factor ( $I_f$ ), normalized mean elevation, and normalized  
137 steepness index ( $k_{sn}$ ). Finally, we conducted an ascending hierarchical classification to  
138 separate the investigated drainage basins into several classes with similar geomorphological  
139 characteristics. Our goal was to observe whether drainage basins that share similar  
140 geomorphic characteristics are regionally separated or clustered within a specific zone of the  
141 Qiulitage landscape (Table 1). Then, from these classes and their location, our goal was to  
142 constraint the morphotectonic evolution of the Qiulitage fold belt and ultimately its growth  
143 history.

### 144 3.1. Topography

145 The Qiulitage fold belt between  $81.5^\circ$  and  $83^\circ E$  in longitude is split into two SW-NE  
146 parallel topographic ridges (Figs. 1B and 3). The Qiulitage anticline belt is a 225 km long fault-  
147 bend fold, 5-7 km in width and presenting up to  $\sim 1000$  m of relief (Hubert-Ferrari et al., 2007).  
148 New morphometric data and the well-preserved geomorphology provide a natural laboratory  
149 for exploring the detailed spatio-temporal evolutionary processes of a “mature fold” belt. The  
150 present structural relief of the Qiulitage fold-belt shows strong differences in elevation from  
151 west to east (Fig. 3): from 1500 to 2083 m for the Northern Qiulitage anticline of and from  
152 1150 to 2174 m for the Southern Qiulitage anticline. The southern ridge is about 165 km long,

153 and it is composed of the Southern Qiulitage, Kuqatawu and Misikantage anticlines. The  
154 northern ridge is much shorter (about 90 km long), consisting of the Northern Qiulitage and  
155 Yakelike anticlines. We extracted topographic profiles along the crestline for both ridges (light  
156 blue lines, Fig. 3B) so as to analyze how topography evolves along the fold belt. We also  
157 measured valley incision ( $I_f$ ) along a mid-flank profile (yellow lines) for both the northern and  
158 southern ridges to document the amplitude of incision along the fold limbs. Results indicate  
159 that both ridges are segmented with several domains of constant or increasing crestline  
160 elevation or incision values. This leads us to divide the fold belt into six morphostructures  
161 (MS1 to MS6), which are often separated either by water gaps or wind gaps (Fig. 3). Water  
162 gaps correspond to valleys that were carved during fold growth and that still host a flowing  
163 stream, whereas wind gaps constitute similar valleys that are presently dry and uplifted.  
164 Unfortunately, we cannot confirm whether the wind gaps preserve alluvial deposits, nor can  
165 we document whether transitions between adjacent morphostructures are controlled by  
166 structural features (fold tip, faults, etc.).

### 167 3.2. Drainage basin area

168 The drainage basin area corresponds to the planar area for each item. Sharp changes in  
169 area across a fold crestline are often linked to fold growth mechanisms and illustrate  
170 particularly mature fault-related folds (*e.g.*, Delcaillau et al., 1998). Additionally, sharp  
171 changes in basin area between adjacent catchments can reflect upstream/downstream  
172 drainage captures or basin shrinking through interfluvial and crestline migration, that are  
173 driven by growth mechanisms or erosion asymmetry (Bonnet et al., 2009). Progressive

174 changes along the fold strike can reflect fold lateral propagation dynamics (Mueller and  
175 Talling, 1997; Delcaillau et al., 1998).

### 176 3.3. Drainage basin hypsometry

177 The drainage basin hypsometry accounts for the distribution of elevation in a given area  
178 of a landscape (Strahler, 1952; Ohmiri, 1993). It can be plotted as the hypsometric curve and  
179 calculated through the Hypsometric Integral (HI). HI is defined as the area below the  
180 hypsometric curve and can be calculated with the formula (Pike and Wilson, 1971):

$$HI = \frac{h_{\text{mean}} - h_{\text{min}}}{h_{\text{max}} - h_{\text{min}}} \quad \text{Equation 1}$$

181 where  $h_{\text{mean}}$ ,  $h_{\text{min}}$  and  $h_{\text{max}}$  are the mean, minimum and maximum elevation,  
182 respectively. HI is a measurement of the erosional state or geomorphic age of a drainage basin  
183 as it represents the volume of drainage basin remaining above a basal plane of reference. The  
184 shape of the hypsometric curve reflects the evolution stage of the drainage basin (Strahler,  
185 1952), and therefore its erosion history. Particularly, it is either young when the hypsometric  
186 curve is convex-upward, mature when the curve is concave-upwards, or intermediate when  
187 the curve is S-shaped. HI is independent of basin area, so it provides a valuable tool to compare  
188 drainage basins to one another. The hypsometric integral could indicate not only the rate of  
189 geomorphological change that take place in watersheds (*e.g.*, Ciccacci et al., 1992), but it can  
190 also evidence the morphogenetic response of lateral propagation of an active anticline (*e.g.*,  
191 Delcaillau et al., 1998).

## 192 3.4. Basin Asymmetry Factor

193 The asymmetry factor ( $A_f$ ) is used to measure the areal drainage basin asymmetry of the  
194 two sides of the main trunk (Hare and Gardner, 1985; Keller and Pinter, 2002):

$$A_f = 100 \cdot \left( \frac{A_r}{A_t} \right) \quad \text{Equation 2}$$

195 where  $A_r$  and  $A_t$  are the drainage areas, in map view, of the right river-side ( $A_r$ ) and of  
196 the whole drainage basin ( $A_t$ ), respectively. If a stream flows in the middle of its drainage basin,  
197 then  $A_f = 50$  and the drainage basin is symmetrical. Therefore,  $A_f < 50$  and  $A_f > 50$  correspond  
198 to asymmetrical drainage basins, with a dominating left or right drainage area, respectively.  
199  $A_f$  can be considered as a proxy of tectonic tilting perpendicular to the main-trunk channel  
200 direction (Hare and Gardner, 1985), although some lithologic control is also possible (El-  
201 Hamdouni et al., 2008).

## 202 3.5. Elongation ratio

203 Drainage basin shape, or elongation ratio ( $R_e$ ), is defined as the ratio of the maximum  
204 width of a drainage basin ( $B_w$ ) to its maximum length ( $B_l$ ) (*e.g.*, Hurtrez, 1998):

$$R_e = \frac{B_w}{B_l} \quad \text{Equation 3}$$

205 To calculate the length of the watersheds, we measured the length of the centreline of  
206 the watershed. It is typically low for very elongated (elliptic) watersheds, which may be  
207 structurally controlled. On the contrary, circular basins ( $R_e \sim 1$ ) are weakly influenced by  
208 structural or lithological parameters.

## 209 3.6. Normalized mean elevation

210 Elevation corresponds to the height of a landform relative to a datum. For each  
 211 watershed, we calculate the basin average elevation that is normalized by subtracting the  
 212 outlet elevation value. This allowed us to correct the watershed average elevation from the  
 213 height of local base level height (*e.g.*, Ramsey et al., 2007; Hurtrez et al., 2011).

## 214 3.7. Local relief

215 Relief can be quantified in various ways (Hurtrez et al., 1999). In our study, we used in  
 216 the definition of local relief (Ahnert, 1970) as a function of the length (Vergne and Souriau,  
 217 1993; Weissel et al., 1994), calculated at the scale of a drainage basin (Lucazeau and Hurtrez,  
 218 1997; Hurtrez et al., 1999). The local relief ( $\Delta z$ ) is the average difference in elevation for a  
 219 given length (Weissel et al., 1994; Hurtrez et al., 1999):

$$\Delta z(l) = \langle |z(x+l) - z(x)| \rangle \quad \text{Equation 4}$$

220 where  $z$  is the elevation,  $l$  is the length scale, and  $x$  is the horizontal distance. The angle  
 221 brackets indicate spatial averaging. Local relief provides some measures of the topographic  
 222 roughness that is often controlled by climate changes and tectonic uplift rate at larger spatial  
 223 scales, while rock type and geologic structures at smaller spatial scales (Chase, 1992; Rinaldo  
 224 et al., 1995).

225 The behaviour of relief “ $R$ ” with length scale “ $l$ ” follows well the following power law  
 226 relationship (Weissel et al., 1994):

$$R(l) = R_0 \cdot l^H \quad \text{Equation 5}$$

227 where  $R_0$  is the amplitude factor, defined as relief at a length scale of 1 km, and the  
 228 scaling exponent  $H$  is the Hurst exponent. Equation 5 represents the roughness of the  
 229 watershed topography and thus its sensitivity to erosion. In our study, we extracted the relief  
 230 amplitudes at 0.2 km length scale, following Hurtrez et al. (1999).

### 231 3.8. Fluvial incision factor

232 Incision is the downcutting made by a vertical erosion. This is a geological process by  
 233 hydraulic action that deepens the channel of a stream (*e.g.*, Lavé and Avouac, 2001; Brocard  
 234 and van der Beek, 2006). The fluvial incision factor ( $I_f$ ) quantifies incision in a valley by  
 235 comparing the valley depth and width at a specific location:

$$I_f = 100. \left( \frac{L_R + L_l}{H} \right) \quad \text{EQUATION 6}$$

236 where  $L_r$  and  $L_l$  are the right and left riverbank widths, respectively.  $H$  is the height  
 237 between crestline and valley floor. In our work, we quantified the incision factor in each valley  
 238 along the Qiulitage fold ridges following topographic profiles parallel to the fold strike and  
 239 located at mid distance between the anticline crestline and the drainage basin outlet line.

### 240 3.9. Normalized steepness index

241 The channel slope ( $S$ ) is linked to the drainage area ( $A$ ) by an inverse power law as:

$$S = k_s \cdot A^{-\theta} \quad \text{EQUATION 7}$$

242 where  $k_s$  and  $\theta$  correspond to the steepness index and concavity index, respectively  
 243 (*e.g.*, Hack, 1957; Snyder et al., 2000). Channel longitudinal profiles and drainage areas were  
 244 generated from 30 m resolution DEMs using ASTER program software. Then, power law  
 245 regressions of channel slope as a function of drainage area were used to derive estimates of

246 channel concavity ( $\theta$ ) and steepness ( $k_s$ ). To compare between drainage basins of different  
247 size,  $K_{sn}$  is often normalized steepness index ( $K_{sn}$ ). The convex shape in a slope–area plot and  
248 a sudden rise of  $k_{sn}$  values along the streams are often interpreted as a transient river profile  
249 that is often caused by an increase in uplift rate (*e.g.*, Wobus et al., 2006; Whipple et al., 2013).  
250 The concavity index ( $\theta$ ) varies in channels between 0.4 and 0.6 under the influence of uplift  
251 rate, lithology and/or climate at steady states (*e.g.*, Wobus et al., 2006, Kirby and Whipple,  
252 2012).

### 253 3.10. Hierarchical analysis

254 We analyzed the variability in morphometric indexes with a statistical approach that  
255 includes six parameters: basin area, normalized elevation, local relief, hypsometric integral,  
256 elongation ratio and asymmetry factor. It was carried out using the Ward method within the  
257 R software using the "h.clust" (*e.g.*, Ward, 1963). The aim of this hierarchical analysis is to  
258 divide a population (here, of drainage basins) into different classes. Items (*i.e.*, catchments) in  
259 each class should be as similar as possible, whereas classes should be as dissimilar as possible.  
260 We then represented the hierarchical analysis results in the form of a dendrogram, from which  
261 we choose a level of hierarchy that allows us to split watersheds into seven classes (numbered  
262 from 1 to 7, Fig. 10). The further apart the numbers, the greater the dissimilarity. For instance,  
263 drainage basins in class 1 are statistically very different from drainage basins in class 7. On  
264 contrary, class 1 and class 2 drainage basins are statistically closer. In addition, "boxplots" are  
265 used to represent the statistical distribution of morphometric data in each class (Fig. 10B). The  
266 upper bound of the box corresponds to the third quartile (75% of the values are below),  
267 whereas the lower bound corresponds to the first quartile (25% of the values are below). The

268 central bar gives the value of the median and the uppermost and lowermost dashed lines  
269 represent the extreme values.

270

## 271 4. Results

### 272 4.1. Topography and incision

273 Both the northern and southern ridges of the Southern Qiulitage, Kuqatawu and  
274 Misikantage anticlines are segmented with several domains of constant or increasing crestline  
275 elevation or incision values. This leads us to divide the fold belt into six morphostructures  
276 (MS1 to MS6), which are often separated either by water gaps or wind gaps (Fig. 3). Water  
277 gaps correspond to valleys that were carved during fold growth and that still host a flowing  
278 stream, whereas wind gaps constitute similar valleys that are presently dry and uplifted.  
279 Unfortunately, we cannot confirm whether the wind gaps preserve alluvial deposits, nor we  
280 cannot document whether transitions between adjacent morphostructures are controlled by  
281 structural features (fold tip, faults, etc.).

#### 282 4.1.1. Southern ridge

283 From E to W, the crestline profile of the Southern Qiulitage ridge can be divided into  
284 three morphostructures: MS1, ~1600 m mean elevation (1978 m max. elevation), MS2 a  
285 western lower ridge (with 1400 m mean elevation), and MS3 a 1430 m mean elevated  
286 triangular landform (Fig. 3C, Table 2). MS1 and MS2 correspond to the Southern Qiulitage and  
287 Kuqatawu anticlines, respectively, whilst MS3 corresponds to the Misikantage anticline.

288 The crestline profile of MS1 displays a first order convex (or semi-elliptical) shape  
289 (dashed purple line on Fig. 3C), which starts from Yanshui water gap to the east (at ~1500 m  
290 in elevation), reaches a maximum elevation at the center of MS1 (~2000 m), and lowers to  
291 1400 m at a major wind gap. Along MS2, elevation gradually increases westward from ~1500  
292 to 1800 m. A major active water gap, associated with two narrow catchments draining the two  
293 intermontane basins (WIB and EIB), cuts MS2 through a deep gorge. MS3 is a short (15-20 km  
294 long) landform with a triangular plan-view profile (Figs. 1-C2 and 3).

295 The valley incision factor, calculated from the mid-flank profiles (yellow profiles, Fig. 3B),  
296 displays large variations in amplitude. The limits between domains of constant incision and  
297 domains of increasing/decreasing incision match quite well with the limits of the  
298 morphostructures. For instance, the average incision for MS3 is extremely low ( $I_f \sim 0.05$ ),  
299 whereas it increases to ~0.15 along MS2. In addition, the transition between MS2 and MS3  
300 occurs at a change in trend of the incision curve. It displays a plateau in  $I_f$  values of ~0.15 along  
301 MS2 and then increases gradually until 0.25 within MS1. For MS1, the incision pattern is more  
302 complex since our analysis proposes that it is divided into a western domain displaying a clear  
303 eastward increase in incision values ( $I_f$  from 0.05 to ~0.25), and a central-eastern domain  
304 showing a gentle decrease in incision values ( $I_f \sim 0.15$ ). The highest incision value occurs close  
305 to the transition between the domains of 1800 m and 2000 m constant crestline topography.

#### 306 4.1.2. Northern ridge

307 The crestline profile of the Northern Qiulitage ridge can be divided in three  
308 morphostructures (Fig. 3A): MS4, with profile showing a steady eastward decrease in  
309 elevation, MS5 with an average crestline elevation of 1558 m, and MS6 with a long and

310 elevated crestline (1889 m) decreasing to 1400 m at the eastern wind gap. As MS1, the  
311 crestline profile of MS6 also displays a first order “semi-elliptical” shape (dashed purple line  
312 on Fig. 3A). The correspondence between morphostructures and anticlines is such that reflects  
313 MS4 relates well to Yakelike anticline, whilst MS5 and MS6 correspond to the Northern  
314 Qiulitage anticline.

315         The incision values along the northern Qiulitage ridge indicate a simple pattern that  
316 matches the morphostructures. MS4 presents low incision values decreasing slightly eastward  
317 (from 0.1 to 0.05). The lowest values of incision (at 0.05) fit the MS4/MS5 transition. Then,  
318 from MS5 to MS6, incision increases gradually eastward and reaches high values around 0.2-  
319 0.25. Toward the east, incision reduces sharply to 0.1. Remarkably, the valley incision record  
320 does not display a sharp change at the MS5/MS6 transition, neither within MS5. The crestline  
321 profile of MS5, with two topographic highs separated by a wind gap, is not associated with a  
322 particular pattern in the incision data. These observations drove us to consider that MS5 and  
323 MS6 may have a common morphostructural history related to the Northern Qiulitage  
324 anticline. Preserved wind gaps across MS4, MS5 and MS6 would reflect the location of former  
325 transverse channels that maintained their course through the anticlines during early fold  
326 growth, but which were finally defeated and forced to deviate.

#### 327                 4.2. Drainage network

328         The drainage network of the study area can be divided in two categories: 1) major rivers  
329 crossing the Qiulitage fold belt, which generate deep water gaps and are associated with large  
330 drainage basins and large alluvial fans, and 2) minor rivers developing from the fold belt  
331 topography (Fig. 5A). The first ones are perennial flows that drain rain and snow melt from

332 the upper part of the Tian Shan landforms, whereas the latter are intermittent channels that  
333 occasionally flow during local rainfall events and develop as debris flows.

#### 334 4.2.1. Major cross-fold rivers

335 There are three major rivers that cross the Qiulitage fold belt and formed major water  
336 gaps or transverse gorges (Figs. 1, 3 and 4): from west to east, the Muzart-Weigan river  
337 system, and the Yanshui and Kuqa Rivers. Interestingly, they all cross the fold belt where  
338 topography consists of a single ridge, morphostructure MS1 of the Southern Qiulitage  
339 anticline. Water gaps (gorges) associated with these three rivers (Fig. 4B) display pronounced  
340 V-shaped valleys but also variations in bulk incision. Particularly, the topographic slopes of E-  
341 and W-facing hillslopes of the gorges are higher for the Weigan and Kuqa Rivers (about 20-  
342 28°) compared to the Yanshui River (average slope around 19-20°).

343 The drainage basins for these three rivers are remarkably different in terms of planar  
344 area (Fig. 4A). From the smallest to the largest, it varies from 300 km<sup>2</sup> for the Yanshui drainage  
345 basin, 2 960 km<sup>2</sup> for the Kuqa drainage basin and to 22 400 km<sup>2</sup> for the Weigan drainage basin.  
346 A two orders of magnitude difference in drainage basin area is observed between Weigan and  
347 Yanshui, although their water gap shapes are remarkably similar. This suggests that important  
348 changes in drainage basin areas have occurred in the past, likely due to drainage capture  
349 processes (see Discussion).

350 Several levels of fluvial terraces are preserved along the riverbanks of all these three  
351 rivers (Fig. 4C). Field observations of several of these terraces, notably in the Weigan and  
352 Yanshui watergap, indicate that they are mostly strath terraces capped by one to several

353 meters of alluvial deposits. They constitute important morphologic markers for further  
354 measures and dating with the aim of unravelling the growth history of the Qiulitage anticlines.

#### 355 4.2.2. Qiulitage drainage network

356 Most of the drainage network that developed across the Qiulitage fold belt consists of a  
357 trellis-type pattern (Fig. 5A). The main longitudinal rivers are oriented ENE-WSW and develop  
358 between the southern and northern anticlinal ridges, within the intermontane basins (WIB  
359 and EIB). Both rivers flowing from the WIB and EIB coalesce and flow out of the fold through  
360 a deep gorge. The area of this intermontane drainage basin is ~ 98 km<sup>2</sup>.

361 A parallel drainage network is developed onto the northern flank of the NQA (MS6) and  
362 onto the southern flank of the SQA (MS1). On the northern flank of the NQA, major transverse  
363 rivers trend NW–SE, perpendicular to the fold axis, and cut deep V shaped valleys, as  
364 documented from the mid-slope profile (Fig. 3). Locally, there are anomalous drainage  
365 configurations (drainage deflection), notably for the northern flank of MS6. Dendritic drainage  
366 networks are developed onto the southern flank of the SQA (MS2) with high headward erosion  
367 (vertical river incision values of ~2 km) (Fig. 8C). Small catchments developed onto the  
368 northern steep flanks of the SQA (MS1) and the southern steep flanks of the NQA (MS6),  
369 exhibit a high-density dendritic drainage pattern.

#### 370 4.3. Morphometry of the Qiulitage watersheds

371 After presenting the drainage network developed on the fold ridges, we quantified the  
372 morphometry of drainage basins, through several morphometric parameters, such as the  
373 longitudinal stream profiles, basin area, basin slope, basin relief, hypsometry, basin  
374 asymmetry, basin shape and  $K_{sn}$  (Figs. 5B and 6).

## 375 4.3.1. Drainage area

376 Most of the catchment areas are about 1.7 to 5 km<sup>2</sup> in size (average catchment area of  
377 2.78 km<sup>2</sup>, Table 2). The larger-sized catchments (13 to 26 km<sup>2</sup>) are located on the northern  
378 side of MS6 and southern side of MS2. In 75% of the investigated study area, watersheds are  
379 small (1.5 to 5 km<sup>2</sup>) and have a variable morphology (mostly elongated or sub-rounded).

## 380 4.3.2. Longitudinal stream profiles

381 The analysis of longitudinal stream profiles allows identification of localized breaks in  
382 slope (knickpoint or knickzones) along the main trunk channel, suggesting disequilibrium. The  
383 presence of knickpoints, combined with documented evidence for gorges and ridge anticlines  
384 (Stokes et al., 2008), can be explained as a result of transient fluvial incision across the region  
385 (*i.e.*, Wobus et al., 2003; Whittaker et al., 2007 and 2008; Kirby and Whipple, 2012; Miller et  
386 al., 2012). We explore the potential formation mechanisms of the knickpoints identified along  
387 the KFTB and their tectonic implications.

388 One longitudinal stream developed onto the northern flank of the Northern Qiulitage  
389 anticline has been investigated in detail (Figs. 5A and 7) based on remote sensing and field  
390 observations. The stream presents two major convex segments (Fig. 7C) that correspond to  
391 two sets of knickzones. In the upstream domain of the channel profile, very gentle channel  
392 gradients of < 1% are associated with semi-closed, perched sub-horizontal depressions that  
393 are partially filled with aeolian sands (labelled “2” in Fig. 7C). Downstream, we observed thick  
394 (~ 5-10 m) laminated fill terrace deposits preserved along the main trunk (“1” and “3” in Fig.  
395 7C.). The width of the channel also changes along the stream, being narrow upstream (5 m  
396 wide), widening in the central part (40-50 m wide) and finally narrowing again (5-10 m wide)

397 (Fig. 7A). A major ~300 m-long knickzone is observed in the downstream part of the channel  
398 together with two local knickpoints anchored on resistant and thick sandstone layers. The  
399 upper knickpoint ( $K_u$ ) (labelled “3” in Fig. 7C) is located at the downstream end of the wide  
400 channel segment (Fig. 7A). The lower knickpoint ( $K_l$ ) marks the upstream end of the 300 m  
401 long knickzone and the downstream end of the thick-slope laminated deposits. These deposits  
402 are horizontal and non-deformed. They unconformably overlie the northward dipping Upper  
403 Miocene rocks of the Kangcun Formation. The unconformity surface represents a paleo-  
404 thalweg that could be interpreted as a terraced paleo-topographic surface.

405         Along MS2, the two rivers draining the WIB and EIB have been investigated in terms of  
406 the shape of their longitudinal profile and fluvial style (labelled “2” in Fig. 7D). Valley incision  
407 has been also calculated along the water gap and within the EIB, downstream of the  
408 confluence (labelled “3” in Fig. 7D). Both the WIB and EIB channels present flat gradients  
409 within upstream reaches where the river flows across the Quaternary alluvial plain to their  
410 confluence, the longitudinal profiles of the two rivers show a sharp increase in slope value  
411 (knickzone labelled “ $K_1$ ”), which is accompanied by a change in fluvial style from braided to  
412 meandering channels (see section 4.3.2). Downstream of the confluence, another flat stream  
413 segment is observed before a major 5 km long knickzone (labelled “ $K_2$ ”).  $K_2$  is localized within  
414 the hanging wall of the E-W Southern Qiulitage back-thrust that breaks the hinge of the  
415 Southern Qiulitage anticline (labelled “3” in Fig. 7D).

#### 416         4.3.3. Normalized steepness index ( $k_{sn}$ )

417         For the Qiulitage drainage network, the lowest values ( $k_{sn} < 50$ ) are observed for rivers  
418 flowing through the Tarim plain, Baicheng Basin and in the two longitudinal intermontane

419 basins (WIB and EIB). Contrastingly, rivers intersecting the anticlines and cutting through their  
420 Cenozoic bedrock present the highest  $k_{sn}$  values. Indeed, the highest values ( $k_{sn} > 100-300$ ) are  
421 observed for rivers draining from the ridges. Steep rivers characterize the Kuqa and Kangcun  
422 formations and the titled alluvial fan deposits at the toe of the Southern Qiulitage anticline  
423 (Fig. 5B), where knickpoints exist. The concave-upward rivers also vary in  $k_{sn}$  values, ranging  
424 from 25 to 300 (Fig. 5B). The majority of them flow across thrust faults and the steeply-dipping  
425 northern and southern limbs of anticlinal ridges, as do the rivers with knickpoints.

#### 426 4.3.4. Basin asymmetry

427 In plan-view, MS5 and MS6 show a pronounced asymmetry of drainage area on the  
428 opposite limbs of the northern Qiulitage fold (Figs. 5A and 6A). Moderate-size catchments (2  
429 to 4 km<sup>2</sup>) are observed on the southern limb, whereas larger drainage basins (2 to 10 km<sup>2</sup>) are  
430 common on the northern limb. Similarly, MS1 shows an asymmetric anticline with a steep  
431 northern limb and a gently dipping southern limb. Small-size catchments (2 to 4 km<sup>2</sup>) are  
432 observed for the northern limb whereas larger catchments (3 to 15 km<sup>2</sup>) are observed for the  
433 southern limb (Fig. 5A and B). On the northern limb, drainage basins are narrow, highly incised  
434 and valley floors are steep (Figs. 3C and 6A; 25-30°).

435 Catchments are generally wider on the west-facing side than on the east-facing one (Fig.  
436 9A). This asymmetric configuration is clear along the entire length of MS6 northern flank, and  
437 it is particularly striking for the western drainage basins (Fig. 6E and labelled “a” and “b” in  
438 Fig. 9A). Accordingly, drainage-average slopes are steeper for east-facing hillslopes (30°) than  
439 for west-facing hillslopes (12 to 20°). In general, the slope values tend to decrease from west  
440 to east (labelled “a” to “d” in Fig. 9A and D).

441 In MS6, the axis of the anticline is approximately N60°E. From west to east, the main  
442 northward-flowing streams are oriented from N047 to N330, indicating an eastward decrease  
443 in deflection. We noticed a systematic eastward deflection of the main trunks (Fig. 9B, C and  
444 E). The two parameters (deflection and asymmetry) appear to be correlated (Fig. 9D). The  
445 deflection decreases with the decreasing basin asymmetry. Meanwhile, we observed an  
446 eastward decrease (4 to 2) in stream order as defined by Strahler (1952), and a decrease in  
447 drainage density (ratio of the total length of streams in a watershed over its contributing area)  
448 on MS6 (Fig. 9C). We interpret these variations as evidence for eastward fold propagation.  
449 Similar correlations between fold lateral growth, drainage deflection and drainage network  
450 asymmetry have been previously deciphered on other active folds, such as the Wheeler  
451 anticline in California, the Pakuashan anticline in the Western Foothills of Taiwan or the  
452 Marand anticline in the North-Tabriz Fault-Zone (NW Iran) (Mueller and Talling, 1997; Keller  
453 et al., 1998; Delcaillau et al., 2006).

#### 454 4.3.5. Local relief and normalized mean elevation

455 The highest values of local relief are observed in the western part of MS6 and the central  
456 part of MS1 (red and orange), *i.e.*,  $\Delta z_{(200m)}=50-80$  m and  $\alpha=25-30^\circ$ . Lowest values of local relief  
457 are observed for MS3 (dark blue), *i.e.*,  $\Delta z_{(200m)} < 20$  m and  $\alpha < 10^\circ$ . MS5 displays also small  
458 values of local relief ( $10 \text{ m} < \Delta z_{(200m)} < 30 \text{ m}$ ) and mean slope ( $5^\circ < \alpha < 15^\circ$ ).

459 The computation of normalized mean elevation, gives rise to a similar trend to that of  
460 local relief. The highest normalized elevations are measured for the central region of MS1  
461 ( $z=400-550$  m) and to a lower extent MS6 ( $z=300-400$  m). MS3, MS4 and MS2 present

462 intermediate ( $z=100-400$  m) values that are sometimes dissymmetric apart from the ridge  
463 crestline (*e.g.*, for MS2).

#### 464 4.3.6. Hypsometry

465 The analysis of hypsometric integrals in the northern and the southern flanks of  
466 Qiulitage ridges shows significant differences along the structures (Fig. 6D, Table 2). Along  
467 MS1, the hypsometric integral values are high on the southern flanks of the ridge ( $HI \approx 0.5$ ).  
468 Some of the highest hypsometric integral values ( $HI > 0.55$ ) are observed along this ridge. Such  
469 high values of HI, together with high incision values for those basins (Fig. 3), verify the intense  
470 river incision stage of these parts of the folds. It suggests a sustained recent uplift of the  
471 drainage basins and an active growth of the Southern Qiulitage fold, which is consistent with  
472 the ~600- to 700-m-high triangular facets interpreted as indicator of an active uplift across the  
473 hinge zone at the southern toe of the fold (Hubert-Ferrari et al., 2007). Hypsometric integrals  
474 are also high for MS6 and MS3 ( $< 0.4$  and  $< 0.6$  respectively), but are lowest for MS2 and MS5  
475 ( $< 0.3$  and  $< 0.5$  respectively). This suggests that both morphological structures MS2 and MS5  
476 are less active than the others, which also agrees with the lower values of crestline topography  
477 and valley incision (Fig. 3).

#### 478 4.3.7. Elongation ratio

479 The pattern of the elongation ratio is not as clear as for other morphometric indexes  
480 (Figs. 6F and 10). However, highly elongated drainage basins (in blue with low values of  $< 0.3$ )  
481 are mostly observed along the southern flank of the MS1 and the northern flanks of MS6 -  
482 MS5. MS2 shows weakly elongated and smaller basins on its northern flanks (values = 0.6).  
483 While MS3 presents a high proportion of weakly elongated basins (values  $< 0.4$ ) on both flanks,

484 MS2 and MS4 present somewhat circular shapes. The correlations between basin area and  
485 elongation ratio are complex but they are good for MS4 (low drained area and low elongation),  
486 average for MS5, very good on the southern flank of MS6 (very low drained area and very low  
487 elongation), low for MS3, good for the western part of MS2 (low drainage area and low  
488 elongation), very good on the northern flank (very low drainage area and very low elongation),  
489 and good for the eastern part of the southern flank (low drainage area and low elongation) of  
490 MS1.

#### 491 4.3.8. Morphometric synthesis

492 The map of statistical classes of basins (Fig. 10) highlights clearly the six morphological  
493 structures inferred from the topographic analyses (Fig. 3). Specifically, their limits match well.  
494 For instance, MS1 is the most clearly constrained and statistically homogeneous  
495 morphological structure, because it exposes mostly two classes all along its strike. In addition,  
496 it displays a clear separation between northern and southern limb catchments, where  
497 northern catchments belong to class 1, whilst southern catchments belong to class 2. Further  
498 east of the Weigan River water gap, drainage basins become more heterogeneous, and  
499 catchments belong to sets 4, 5, 6 and 7. MS2 displays catchments that are highly  
500 heterogeneous because of the seven classes of cluster observed. However, a trend can be  
501 distinguished because drainage basins belong mostly to classes 5 and 7. MS3 drainage basins  
502 are statistically very homogeneous since they essentially belong to class 3. MS4 is not  
503 sufficiently well constrained to be described, due to a lack of reliable drainage basin  
504 information. In contrast, MS5 and MS6 show quite homogeneous drainage basin statistics.  
505 The northern limb catchments belong dominantly to class 4, which suggests a genetic and

506 morphodynamic link between these two morphostructures. The eastern part of the MS6 is  
507 quite heterogeneous. This might be expected since this portion of the fold would express the  
508 connection between MS6 and MS5.

## 509 5. Discussion

### 510 5.1. Morphometry of the Qiulitage morphostructures

511 Based on our morphometric analysis of the Qiulitage topography, incision and  
512 watershed morphometry, we consider that both the southern and northern Qiulitage ridges  
513 can be divided into three morphostructural units. These are the eastern MS1, the central MS2  
514 and the western MS3 units for the southern ridge, and the western MS4, the central MS5 and  
515 the eastern MS6 units for the northern ridge. These ridges collectively display contrasting  
516 morphometric values that we can consider to account for differentiated fold growth history.

517 For MS1, high and fairly constant elevation ( $z \sim 1800$  m), high local relief ( $R > 50$  m), high  
518 hypsometric integrals ( $HI > 0.55$ ) and remarkably elongated basins (Figs. 3 and 6), would  
519 reflect a mature and actively uplifting morphological structure. This could mean that this  
520 landform may have reached locally a topographic steady state (Hubert-Ferrari et al., 2007). In  
521 addition, the high asymmetry of drainage basin area between the southern and northern  
522 flanks corroborates the northern vergence of the structure observed from field mapping and  
523 seismic interpretation.

524 For MS2, the slightly varying crestline elevation (1600 – 1700 m), low local relief ( $R <$   
525 40 m), low hypsometric integrals ( $HI < 0.5$ ) and weakly elongated basins (Figs. 3 and 6), would  
526 reflect a slightly uplifting structure. Similar values of slopes and areas along the two flanks of

527 the MS2 ridge do not decipher any specified vergence of the structure, as confirmed by the  
528 seismic profiles that image a symmetrical and tight anticline (Fig. 1). The transition between  
529 MS1 and MS2 coincides with a significantly low wind gap (elevation 1350 m) that we interpret  
530 to reflect a change in deformation accommodation along the Qiulitage fold belt.

531 For MS3, highly varying elevations (1500 – 1900 m), very low incision values (0.05)  
532 extremely low local relief ( $R < 20$  m), but high hypsometric integrals ( $HI > 0.5$ ) and very  
533 elongated basins (Figs. 3 and 6), suggest a very young and actively uplifting morphostructure.  
534 Considering the remarkable radial pattern of the drainage network, MS3 is likely controlled by  
535 a subsurface structure, such as an active salt diapir. The rapid uplift of MS3 could have  
536 integrated uplift of the western side of MS2, whose general topography is tilted eastward (Fig.  
537 3). In the MS3 area, the lateral growth of folds is recorded by stream network morphology (He  
538 and Li, 2009). It is also suggested that the relative position and activity of basement faults, as  
539 well as the thickness of deep salt have a significant influence on the structural styles of the  
540 western Qiulitage fold belt (Chen et al., 2004; Tang et al., 2004; Yu et al., 2006). These folds  
541 are underlain by the accumulation of thick salt which locally exceeds 3000 m (Wang et al.,  
542 2011).

543 Along the northern Qiulitage ridge, which is characterized by the western MS4 unit, the  
544 central MS5 unit and the eastern MS6 unit, we did not observe any geomorphic anomalies for  
545 MS4 associated with Yakelike anticline. Indeed, we failed to extract reliable information on  
546 the drainage basins, and the few catchments we analyzed did not allow us to draw any  
547 significant interpretations. As for MS5 and MS6, they are both geologically linked to the  
548 Northern Qiulitage anticline. Our geomorphological analysis shows how different the northern

549 and southern flanks are. While the northern flanks display high altitudes (1700 - 1900 m),  
550 medium local average relief ( $R = 30$  m), medium-to-large hypsometric integrals ( $HI = 0.5$ ) and  
551 very elongated basin, the southern flanks display smaller drainage surfaces, higher local relief  
552 and slightly elongated basins (Figs. 3 and 6, Table 2). Similarly, for MS1, the asymmetry of the  
553 drainage basin area and average slopes clearly reflects a south-vergent subsurface structure.

## 554 5.2. Partitioning and propagation of deformation

555 Correlation between the topography and incision values of both the northern and  
556 southern Qiulitage ridges provides insight into the growth mechanisms of Qiulitage fold belt.  
557 In the absence of reliable chronological control on the timing, we rely on geomorphic criteria  
558 to predict the deformation sequence (Burbank et al., 1997). As along-strike changes are  
559 pronounced for all the anticlines, thereby each of them could be the dominant structure  
560 accommodating shortening, reflecting partitioning of tectonic deformation. This deformation  
561 partitioning occurs between the western part where the Qiulitage fold-belt is composed in  
562 two fault-propagation folds, and the eastern part with a single overlapping structure with a  
563 northern vergence.

564 For instance, where MS6 and MS2 face one another, MS6 presents high elevation  
565 (~1900 m) and high incision values (~0.2), whereas MS2 presents low elevation (~1600 m) and  
566 low incision values (0.1-0.15) (Fig. 3). This suggests that at 82°E longitude, MS6 has  
567 accommodated most of the shortening, whereas less shortening has been incorporated on  
568 the southernmost MS2. In contrast, further east, MS6 presents low elevation (~1600 m) and  
569 decreasing incision values (0.15-0.1), whereas MS1 presents high elevation (~1800 m) and  
570 incision values (0.2-0.25). This suggests that deformation is partitioned between MS6 to the

571 north and MS1 to the south. Further east, shortening is solely consumed along MS1 (Southern  
572 Qiulitage), resulting in high crestline elevation and high incision values (0.25). Finally, toward  
573 the eastern end of our investigated area, deformation is partitioned between several  
574 structures that accommodate shortening. It is mainly MS1, since its relief is the highest, but  
575 also frontal Kuqa and Yakeng open anticlines (Fig. 1). This would explain why both elevation  
576 and incision decrease toward the Yanshui River.

577 In this study, we investigated the asymmetry factor of the Qiulitage drainage basins and  
578 noticed that these values were particularly high (> 60%) along the northern flank of MS6 (Figs.  
579 5A and 9A). This large asymmetry is illustrated by the pattern of the stream networks, with  
580 major tributaries coming from the right bank (Figs. 5A and 9B and C). This arrangement occurs  
581 because the small tributaries perpendicular to the main streams concentrate their erosion  
582 more on the northwestern side of the valley than on the southeastern side (Fig. 9B). The  
583 asymmetry factors generally show a uniform trend and river channels are affected by lateral  
584 tilting of the anticline ridge to the east. This asymmetry of the valleys seems to be controlled  
585 by a recent uplift of the fold in its western part.

### 586 5.3. River reorganization due to active folding

587 In this work, we document a two order of magnitude difference in drainage basin area  
588 between Weigan and Yanshui (Fig. 4A) which contrasts with a less significant difference in  
589 water gap shape (Fig. 4B). Therefore, we hypothesize that important changes in drainage basin  
590 areas have occurred in response to fold growth, involving likely drainage capture processes.  
591 Particularly, a much larger drainage basin than the present one would be expected to explain  
592 the large water gap of the Yanshui River. The Yanshui drainage basin may have been reduced

593 in size due to the capture of a portion of its drainage area by the Weigan fluvial system. For  
594 now, field arguments are still missing, but we consider that terrace analysis (notably source  
595 provenance analysis) might contribute to test this hypothesis.

596 In our work, we have interpreted several saddles along the crestline profiles of the  
597 northern and southern Qiulitage ridges as wind gaps. We did not have the opportunity to  
598 collect field evidence confirming this hypothesis, such as alluvial deposits at the saddles, but  
599 we consider this hypothesis reasonable (*e.g.*, Hubert-Ferrari et al., 2007; Zhang et al., 2021).  
600 For some examples, wind gaps are clearly preserved features that attest to the lateral  
601 propagation and linkage of anticlines (Jackson et al., 1996; Mueller and Talling, 1997; Keller et  
602 al., 1998; Hetzel et al., 2004; Ramsey, et al., 2007; Malik et al., 2010; Seong et al., 2011). For  
603 Qiulitage, we presume that several of the main saddles could be former water gaps. Those  
604 paleo water gaps would therefore evidence the paleo flow of ancient rivers across much  
605 younger and weakly elevated topographic ridges along the emerging Qiulitage fold belt. The  
606 Yakeng anticline (Hubert-Ferrari et al., 2007; Saint-Carlier et al., 2016; Zhang et al., 2021),  
607 south of the eastern Qiulitage anticline, could represent an analogue of what the early  
608 Qiulitage fold belt would have resembled. That is, a shallow anticline rising slightly above the  
609 regional datum which is traversed and gradually incised by several channels flowing from the  
610 upstream relief. Some channels may have enough stream power and discharge to maintain  
611 their course across the rising fold, but the others would be defeated and obliged to deviate.  
612 In addition, the appearance of a sinuous fluvial pattern for rivers flowing through the growing  
613 fold reflects a fluvial readjustment of the riverbed to an increase in the average slope linked

614 to the uplift of the central part of the Northern and Southern Qiulitage anticlines (MS2 and  
615 MS6) (Fig. 7D) (Schumm, 1993).

#### 616 5.4. Fluvial terrace and alluvial fan deposits

617 On the northern flank of the Northern Qiulitage anticline, we interpret fluvial fill terrace  
618 deposits as an indicator of strong incision of the valley due to a recent uplift and locally a  
619 lithological control (Fig. 7A, B and C). Indeed, the presence of a major ~300 m long knickzone  
620 immediately southward of the preserved fill-cut deposits might indicate that the channel  
621 underwent a transient response to a perturbation where the knickpoint propagated upstream.  
622 However, the two knickpoints anchored on indurated sandstone layers would have blocked  
623 the upstream progression of the uplift instability and forced the channel to maintain a gentle  
624 slope upstream. The base of the thick slope-laminated deposits would correspond to a paleo-  
625 thalweg that has been incised. The terminal valley is characterized by aggradational fill  
626 terraces whose filling was controlled by base-level fluctuations. The filling of the terrace was  
627 dependent on the paleo-thalweg profile (Fig. 7B and C), and on the widening of the valley  
628 segments between the monoclines composed of indurated sandstone layers (Fig. 7A and C).

629 On the northern edge of the Northern Qiulitage anticline, several fill-cut terraces and  
630 strath terraces were identified in the field and from satellite images. For instance, three major  
631 surfaces (T1, T2 and T3) were observed on the upstream eastern part of the Yanshui gorge  
632 (Figs. 1 and 11A; Zhang, 2016) and one single terrace was observed on its upstream right bank  
633 (Figs. 1 and 11B). These terrace deposits are folded and faulted (Fig. 12A) or tilted northward  
634 (Fig. 11B).

635 On the southern edge of the SQA, large fossil alluvial fans, with truncated apices, have  
636 also been identified at the outlet of drainage basins along MS1 southern flank. These alluvial  
637 fans are mainly composed of two surfaces, Qf2 and Qf1, from youngest to oldest (Fig. 12). We  
638 observed that the recent (likely Holocene) incision was as large as ~100 m (Fig. 12A and E) at  
639 the outlet of the drainage basins. As the rivers were deeply incised into the piedmont, a large  
640 amount of material would have been removed to feed the modern fans (Qh) (Fig. 12A).  
641 Interestingly, the apices of Qf1 are still connected to the ridge front that coincides with the  
642 active axial surface of the fold (Fig. 12C and D) (Hubert-Ferrari et al., 2007). Since the oldest  
643 fans (Qf1) do not seem to be tilted basinward at the foot of the triangular facets, and that the  
644 segmented fan deposits gradually and systematically thin from the front to the piedmont  
645 plain, this could indicate that large incision is likely controlled by a local moderate uplift of the  
646 southern flank of the SQA.

#### 647 5.5. Morphotectonic evolution of the Qiulitage fold belt

648 Here, we propose a planar morphostructural evolution of Qiulitage fold belt (Fig. 13)  
649 and provide some key 3D morphotectonic diagrams (Fig. 14) that account for a likely landscape  
650 evolution in the Kuqa Basin. These sketches integrate the results of previous studies (Hubert-  
651 Ferrari et al., 2007; Izquierdo-LLavall et al., 2018; Pla, 2019) and our morphometrics analyses.  
652 We propose a simultaneous evolution of the relief and drainage network. Ages for the  
653 different steps of this morphostructural story are based on published magnetostratigraphic  
654 dating of strata (*e.g.*, Charreau et al., 2020), and their kinematic relationships (pre-, syn- and  
655 post-tectonics) constrained from seismic investigations (*e.g.*, Izquierdo-LLavall et al., 2018).

656 Several factors exert a first order control on the geometry and kinematic evolution of  
657 the Kuqa fold-and-thrust belt: (1) the distribution of the two *décollements* in the Meso-  
658 Cenozoic sequence (*i.e.*, the Eocene-Oligocene and Miocene salt layers) and notably the  
659 position of salt pinch-out, (2) the reactivation of deep inherited structures, and 3) the changes  
660 in shortening amount accommodated within the fold belt. The change in syntectonic  
661 sedimentation rate across Kuqa Basin is also another factor that may have played a role in  
662 controlling this evolution, but we discarded it due to a lack of data for now.

#### 663 5.5.1. Late Miocene (6-5 Ma)

664 The initiation of the Qiulitage fold belt started during late Miocene times (Kangcun-Kuqa  
665 Fm transition, *i.e.*, 6-5 Ma) (Figs. 13A and 14A) according to several studies based on structural  
666 geology, magnetostratigraphy, shortening analysis and growth-strata analysis (*i.e.*, Wang et  
667 al., 2011, Li et al., 2012, Tang et al., 2017; Tian et al., 2016; Charreau et al., 2020). As the  
668 initiation of deformation along the Kuqa Basin is generally considered to start around 20-25  
669 Ma (Wang et al., 2011; Li et al., 2012), deformation was primarily accommodated along more  
670 hinterland structures like the Tuzimaza, Kumugeliemu and Suweiyi anticlines. Those structures  
671 are therefore thought to have accommodated shortening along the reactivated hinterland of  
672 the Tian Shan about 15-20 Ma before deformation propagated significantly basin-ward by 50-  
673 75 km. Surprisingly, the Qiulitage and Yakeng folds present approximately simultaneous ages  
674 of initiation around 6-5 Ma (Hubert-Ferrari et al., 2007), although their finite structures and  
675 morphologies are remarkably different. Both probably nucleated as blind structures, meaning  
676 that sedimentation rates were higher than uplift rates.

677 The position and strike (N70°E) of the Qiulitage ridge appears to be related to the  
678 external limit (pinch-out) of the Kumugeliemu evaporite layer, which is presumably itself  
679 controlled by an Oligocene extensional basin (Izquierdo-Llavall et al., 2018) (Fig. 14A). This  
680 extensional basin, that developed whilst the Tian Shan was experiencing thrusting and folding,  
681 would represent a local extensional stress regime along the foreland-basin forebulge. Cross-  
682 section restoration and balancing suggest that the Qiulitage structures started folding by limb  
683 rotation (Izquierdo-Llavall et al., 2018). The Paleogene Kumugeliemu evaporitic *décollement*  
684 was activated and allowed deformation to propagate toward the distal pinch-out of the  
685 viscous layer and to be concentrated along the Qiulitage fold belt. The subsalt geometry, and  
686 particularly the high-angle normal faults bounding the small graben centred beneath the  
687 Qiulitage fold belt (Izquierdo-Llavall et al., 2018), controlled the growth of Qiulitage (Fig. 14A).

688 North of Qiulitage, the Baicheng Basin became progressively a transported piggy-back  
689 basin (*e.g.*, Beer et al., 1990; Talling et al., 1995), and it can be considered as active wedge-  
690 top accumulations because completely contiguous with the foreland basin (De Celles et Giles,  
691 1996).

#### 692 5.5.2. Early to late Pliocene (5 – 2.6 Ma)

693 From the early to late Pliocene (*i.e.*, 5-2.5 Ma), while the syntectonic Kuqa Formation  
694 was deposited in the foreland, the Qiulitage anticline (western, central and eastern segments)  
695 probably emerged as a topographic ridge (Fig. 13B). Simultaneously, the Northern Qiulitage  
696 anticline (Izquierd-Llavall et al., 2018) and the Misikantage anticline (Tang et al., 2017) are  
697 thought to have nucleated, presumably as a buried feature first. The topographic emergence  
698 of Qiulitage was made possible only when the uplift rate surpassed the sedimentation rate.

699 Based on magnetostratigraphy, sedimentation rates in the foreland were quite low during  
700 early Miocene, and shortening and uplift of the Kuqa fold-and-thrust belt rates have probably  
701 increased during the late Miocene to Pleistocene (Pla, 2019). Early thrusting conjugated to  
702 detachment folding (Izquierdo-Llavall et al., 2018) could have contributed to accelerate uplift  
703 and favor topographic emergence of Qiulitage. (Fig. 13B). We presume that the Yakelike and  
704 Northern Qiulitage anticlines also nucleated during that period. As the early Southern  
705 Qiulitage topographic ridge emerge, it started to affect the alluvial plain drainage and its  
706 associated sedimentation patterns. The drainage response is expected to create antecedent  
707 rivers across the emerging anticline. Most rivers were probably not diverted by anticlinal  
708 ridges during fold uplift, meaning that the fluvial incision rate was higher than the uplift rate.

#### 709 5.5.3. Early Pleistocene (2.5 Ma)

710 During Early Pleistocene times (*i.e.*, 2.5 Ma) (Fig. 13C), a twofold increase in shortening  
711 rate is documented (Li et al., 2012; Charreau et al., 2020), which has likely accelerated the  
712 topographic growth of the Southern Qiulitage anticline, as well as the topographic emergence  
713 of the Northern Qiulitage and Yakelike anticlines. Thrusting, either blind or emergent, is  
714 expected to occur simultaneously with folding. The backward propagation of deformation  
715 from the Southern to the Northern Qiulitage is expected because deformation initially  
716 nucleated at the external pinch-out of the basal Kumugeliemu *décollement*. Consequently,  
717 deformation could not further propagate outward, but was forced instead to propagate  
718 backward, in the so-called “out-of-sequence” mode. Several analogue models have  
719 demonstrated this typical pattern of deformation propagation mode when deformation  
720 reached the distal pinch-out of a viscous silicone polymer (Costa and Vendeville, 2002;

721 Graveleau et al., 2012). The topographic emergence of the Yakelike and Northern Qiulitage  
722 folds, their growth and lateral propagation are expected to have deflected river streams  
723 crossing Southern Qiulitage ridge. Paleo channels dating from the time when the Yakelike and  
724 Northern Qiulitage anticlines were not emergent may have evolved toward water gaps and  
725 later toward wind gaps under the influence of fold uplift. Wind gaps between MS6 and MS1  
726 on one hand, and between MS4 and MS5 on the other hand, would represent topographic  
727 evidence of this early segmentation of Qiulitage fold and their latter linkage.

#### 728 5.5.4. Early to Middle Pleistocene (2-1 Ma)

729 From the Early to Middle Pleistocene (*i.e.*, 2-1 Ma) (Fig. 13D), the Qiulitage Northern  
730 anticline propagated predominantly eastward, which led to the formation of the Quaternary  
731 Intermontane Basin (EIB and WIB). This lateral propagation of the Northern Qiulitage anticline  
732 (MS6) is recorded by the deflection pattern of the MS6 northern flank drainage (Fig. 9C and E)  
733 and it would account for the partitioning of deformation between MS6 and MS1/MS2  
734 recorded in the ridge topography and highlighted by the MS1/MS2 wind gap. Simultaneously,  
735 we would expect that the Muzard River could have been captured by the Weigan River due to  
736 the closure of the water gap between the Yakelike and Northern Qiulitage folds. Paleo-water  
737 gaps of the Muzard river across the Southern Qiulitage fold would have evolved toward a  
738 minor river draining solely the two intermontane basins.

#### 739 5.5.5. Late Pleistocene to Present (0.5 to 0 Ma)

740 From the Late Pleistocene to the Present (0.5 to 0 Ma) (Figs. 13E and 14B), the Qiulitage  
741 frontal structure continued to grow accommodating laterally the shortening that was  
742 transferred from pre-salt structures. Another significant increase in shortening rate is

743 documented (Hubert-Ferrari et al., 2007; Wang et al., 2011; Tian et al., 2016), which is  
744 expected to have affected the structural evolution of the Qiulitage fold belt, and therefore its  
745 morphological evolution. This should have entailed accelerated uplift along Qiulitage and  
746 likely incision of cross-fold rivers. This favors the abandonment of alluvial terraces across the  
747 water gaps, as evidenced in the field (Fig. 4). Towards the Tarim Basin, the topographic  
748 emergence of the Yakeng anticline would be dated to 0.2-0.3 Ma (Wang et al., 2011; Hubert  
749 Ferrari et al., 2007).

## 750 6. Conclusion

751 The present morphological investigation of Qiulitage fold-belt in southern Tian Shan is  
752 based on the analysis of 30 m DEMs and field observations. The topography, the incision  
753 amount, and drainage networks have been analyzed for both the northern and southern  
754 Qiulitage ridges. Six morphometric indices were computed at the scale of the 250 extracted  
755 drainage basins and they were statistically confronted to analyze the geomorphological  
756 response of Qiulitage landforms to fold uplift and lateral propagation of deformation. Results  
757 propose the subdivision of the Qiulitage fold belt into six morphostructures (MS1 to MS6),  
758 whose morphometric parameters provide good indicators of lateral propagation of folding  
759 and partitioning of deformation within the fold belt. The observed drainage anomalies  
760 (drainage network, knickpoints, wind gaps) are interpreted as a record of differential uplift  
761 along the fold ridges. A geomorphic evolution model of the Qiulitage fold-belt is proposed and  
762 integrates the influence of *décollement* geometry, deep inherited structures and changes in  
763 shortening consumed in the fold-and-thrust belt. This model explains the suggested changes  
764 in drainage basin areas, particularly between Yanshui and Weigan rivers, and interprets

765 observed wind gaps and water gaps as indicators of drainage capture processes and defeated  
766 rivers diverted by fold growth.

767

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774

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## 1060 Figure captions

1061 **Figure 1:** (A) Topographic map of central Asia (topographic data from Nasa STRM V.4.0).  
 1062 (B) Geological map of the Qilutige fold belt (modified after Wang et al., 2011). (C) Geological  
 1063 cross-sections (modified from Li et al., 2012; Pla, 2019). Location shown in (B). QSN: Quele Salt  
 1064 Nappe, NQT: Northern Qilutige Thrust, SQT: Southern Qilutige Thrust, NQA: Northern  
 1065 Qilutige anticline, SQA: Southern Qilutige anticline, EQA: Eastern Qilutige anticline, WIB:  
 1066 Western Intermontane Basin, EIB: Eastern Intermontane Basin.

1067 **Figure 2:** Stratigraphic column of sedimentary formations in Kuqa Basin (modified after  
 1068 Jin et al., 2008 and Li et al., 2012). Significant *décollements* are indicated: LD (Lower  
 1069 *Décollement*), MUD (Main Upper *Décollement*) and mUD (minor Upper *Décollement*) following  
 1070 Izquierdo-Llavall et al., 2018. Note change in vertical scale for the Mesozoic and Cenozoic  
 1071 strata.

1072 **Figure 3:** Topography along the Northern and Southern Qilutige anticlines with  
 1073 topographic profiles along the crestline as insets (A and C). B: topographic data from NASA-  
 1074 SRTM. Light blue traces correspond to crestline profiles and yellow traces correspond to mid-  
 1075 flank profiles from which fluvial incision factors ( $I_f$ ) are computed. Topographic analysis allows  
 1076 subdivision of the fold belt into six first-order morphologic structures (MS1 to MS6). “WG”  
 1077 stands for “wind gap” and “wg” stands for “water gap”.

1078 **Figure 4:** A) Present drainage basins of major rivers flowing across the Qilutige fold belt.  
 1079 From west to east, these are intermontane rivers: the Weigan, Yanshui and Kuqa Rivers.  
 1080 Drainage basin areas are indicated. B) Google Earth image (CNES/Airbus/Maxar  
 1081 technologies/Landsat Copernicus) of the Weigan, Yanshui and Kuqa water gaps illustrating the

1082 overall valley incision and riverbank average slope. C) Field photographs of terraces preserved  
1083 across Weigan and Yanshui channels.

1084 **Figure 5:** A) Drainage network of Qiulitage fold belt. Letters refer to stream profiles of  
1085 Figures 7 and 9. B) Distribution of  $K_{sn}$  values along the Qiulitage fold belt.

1086 **Figure 6:** Morphometric indices along the Qiulitage fold belt. A) Area, B) Normalized  
1087 mean elevation, C) Local relief at 200m length scale, D) Hypsometric integral, E) Asymmetry  
1088 factor and F) Elongation ratio.

1089 **Figure 7:** A) Google Earth image (CNES/Airbus/Maxar technologies/Landsat Copernicus)  
1090 along a channel (see location on Fig. 5 – blue label a) that develops on the northern flank of  
1091 the Northern Qiulitage anticline. Channel width is bounded by white lines; yellow solid lines  
1092 indicate the Late Pleistocene slope deposits; thick dark blue curves indicate the river profile  
1093 knickzone. Inset #2 in the upper river valley represents the upstream depression. B) Field view  
1094 of slope deposits preserved along the channel and C) associated channel longitudinal  
1095 topographic profile and knickpoints. D) Google Earth image (CNES/Airbus/Maxar  
1096 technologies/Landsat Copernicus) and stream profile and fluvial style in the Western and  
1097 Eastern Intermontane Basins (WIB and EIB, respectively).

1098 **Figure 8:** Google Earth images (CNES/Airbus/Maxar technologies/Landsat Copernicus)  
1099 of channel network styles in A and C. A-B) Western Intermontane Basin (WIB) and C) Eastern  
1100 Intermontane Basin (EIB). Relationships between alluvial fans deposits and bordering  
1101 landforms are highlighted by black dotted lines. Blue dotted lines indicate headward erosion.  
1102 NQA: Northern Qiulitage anticline; SQA: Southern Qiulitage anticline.

1103           **Figure 9:** A) Transverse topographic profiles along the northern flank of the Northern  
 1104 Qiulitage anticline (location in Figure 5A) where the gradients of the east-facing and west-  
 1105 facing hillslopes are indicated. Grey inset represents the average trend of hillslope gradients  
 1106 for each profile. It indicates that drainage basin asymmetry tends to decrease eastward. B)  
 1107 Asymmetry map of drainage basins indicating the stream deflection lines. C) Spatial and  
 1108 temporal drainage network evolution from west to east of the northern limb of northern  
 1109 Qiulitage anticline. D) Correlation of asymmetry factors and drainage deflection with distance.

1110           **Figure 10:** Statistical analysis of morphometric parameters of catchment basins using an  
 1111 ascending hierarchical analysis. (A) Map of the hierarchical groups, labelled 1 to 7. (B) Results  
 1112 of statistical analysis for six different metrics: area, normalized mean elevation, local relief at  
 1113 200 m length scale, hypsometric integral, elongation ratio and valley asymmetry factor.

1114           **Figure 11:** Evidence of active tectonic deformation along the northern flank of Southern  
 1115 Qiulitage anticline (see location on Figure 1B). A) Uplifted terraces and faulted fan deposits  
 1116 (Zhang, 2016). B and C) Tilted Pleistocene debris-flow-dominated alluvial fan deposits along  
 1117 the north verging Southern Qiulitage Thrust (SQT).

1118           **Figure 12:** Google Earth image (CNES/Airbus/Maxar technologies/Landsat Copernicus)  
 1119 of alluvial fan entrenchment along the southern mountain front of Southern Qiulitage  
 1120 anticline. A-C) Quaternary (Qf1, Qf2) and Holocene (Qh) alluvial deposits are segmented and  
 1121 entrenched between triangular facets that dominate the topographic front. D-E) Incision  
 1122 larger than ~100 m has led to the entrenchment of fan deposits that do not appear folded  
 1123 across the active syncline axial surface.

1124           **Figure 13:** Morphotectonic evolution of central Qiluitage fold belt from A) Late Miocene  
1125 to E) Present. See text for details.

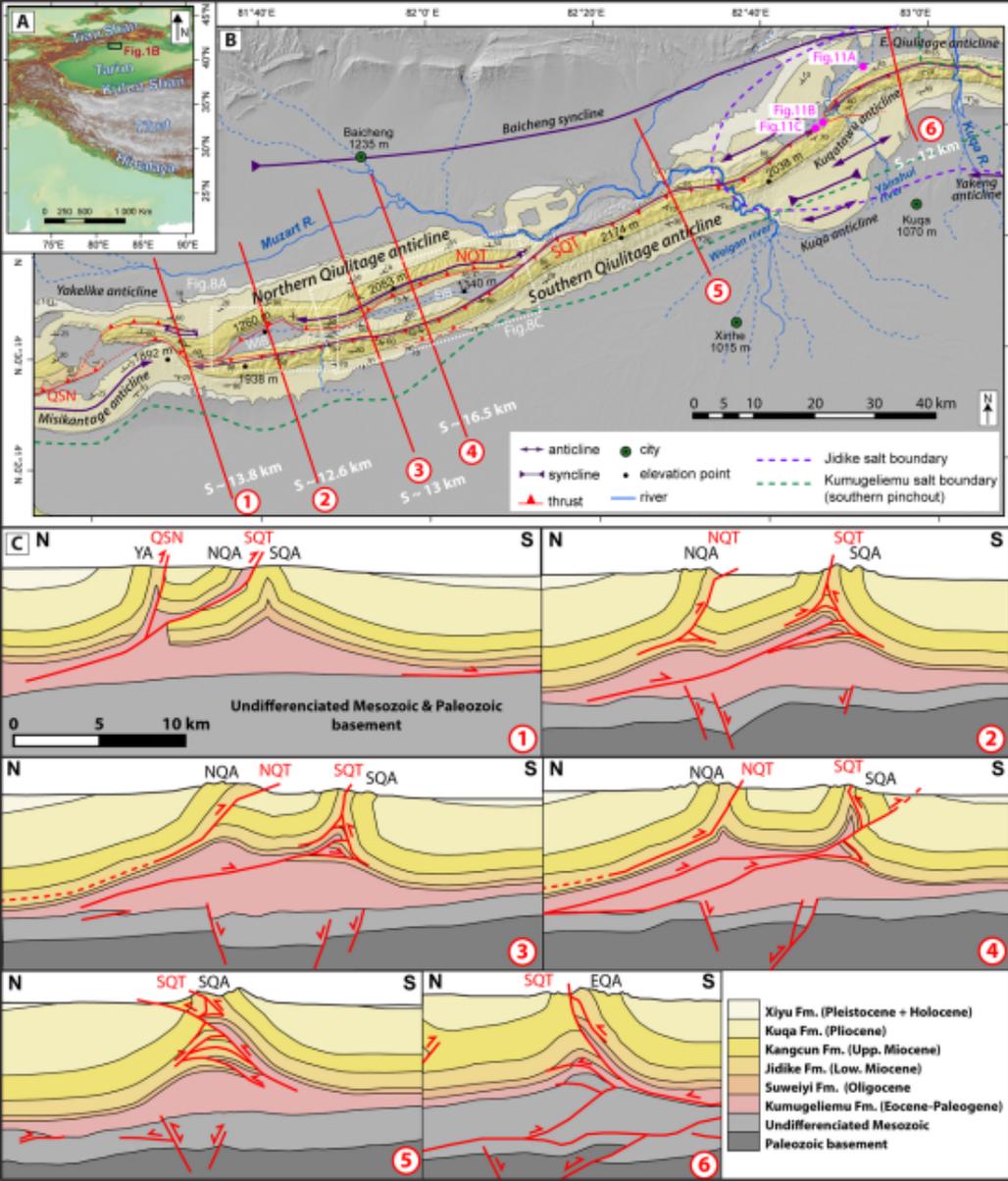
1126           **Figure 14:** 3-D block diagram of A) the initial stage (during Late Miocene) and B) the  
1127 present morphotectonics of central Qiluitage fold belt. Central Qiluitage fold belt formation  
1128 appears primarily controlled by the distal pinch-out position of the Eocene evaporite basin,  
1129 which was itself controlled by the presence of a deep Oligocene graben. This graben was  
1130 tectonically inverted which triggered the evaporite inflation in Qiluitage fold core and its  
1131 topographic growth. Sections 4, 5 and 6 in Fig.14A correspond to the names of sections in  
1132 Figure 1. See text for details.

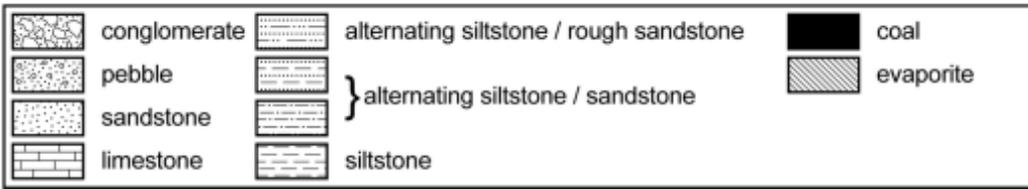
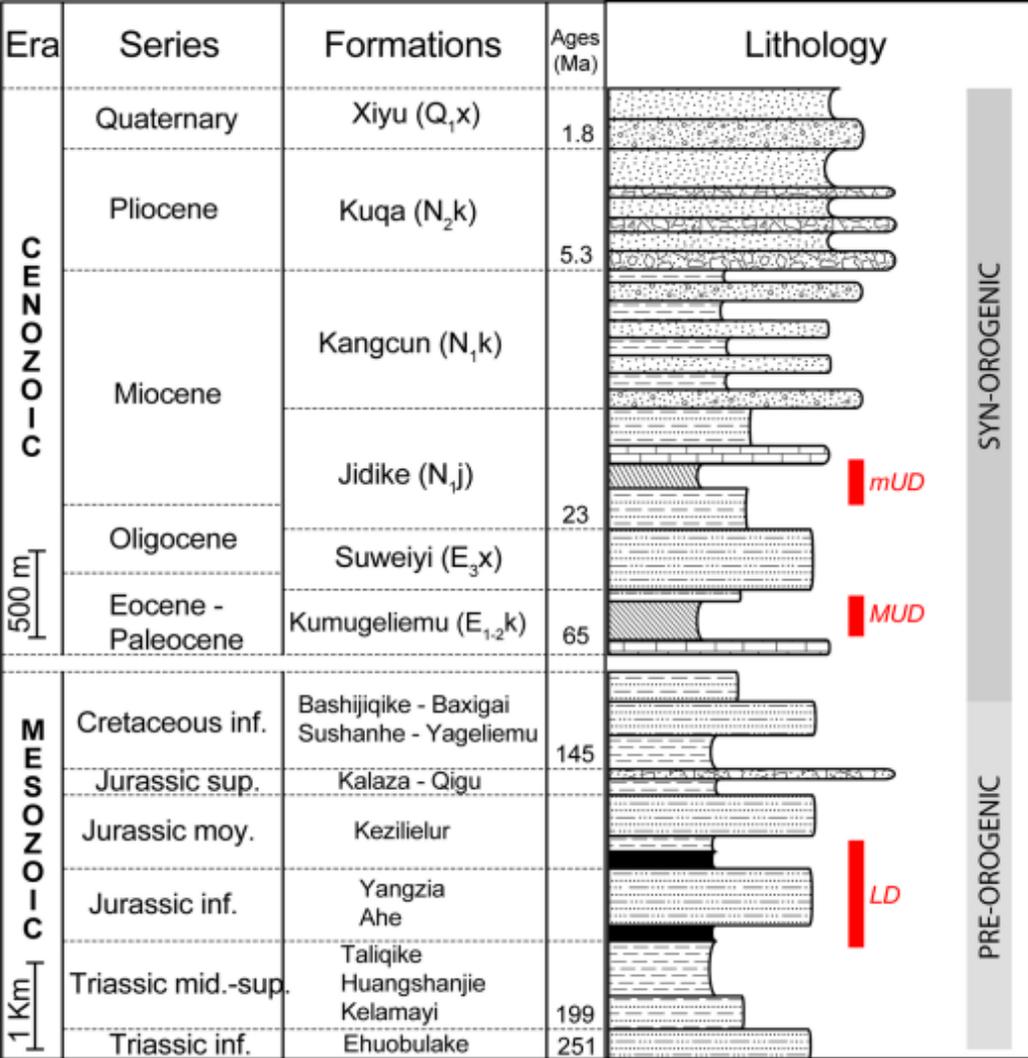
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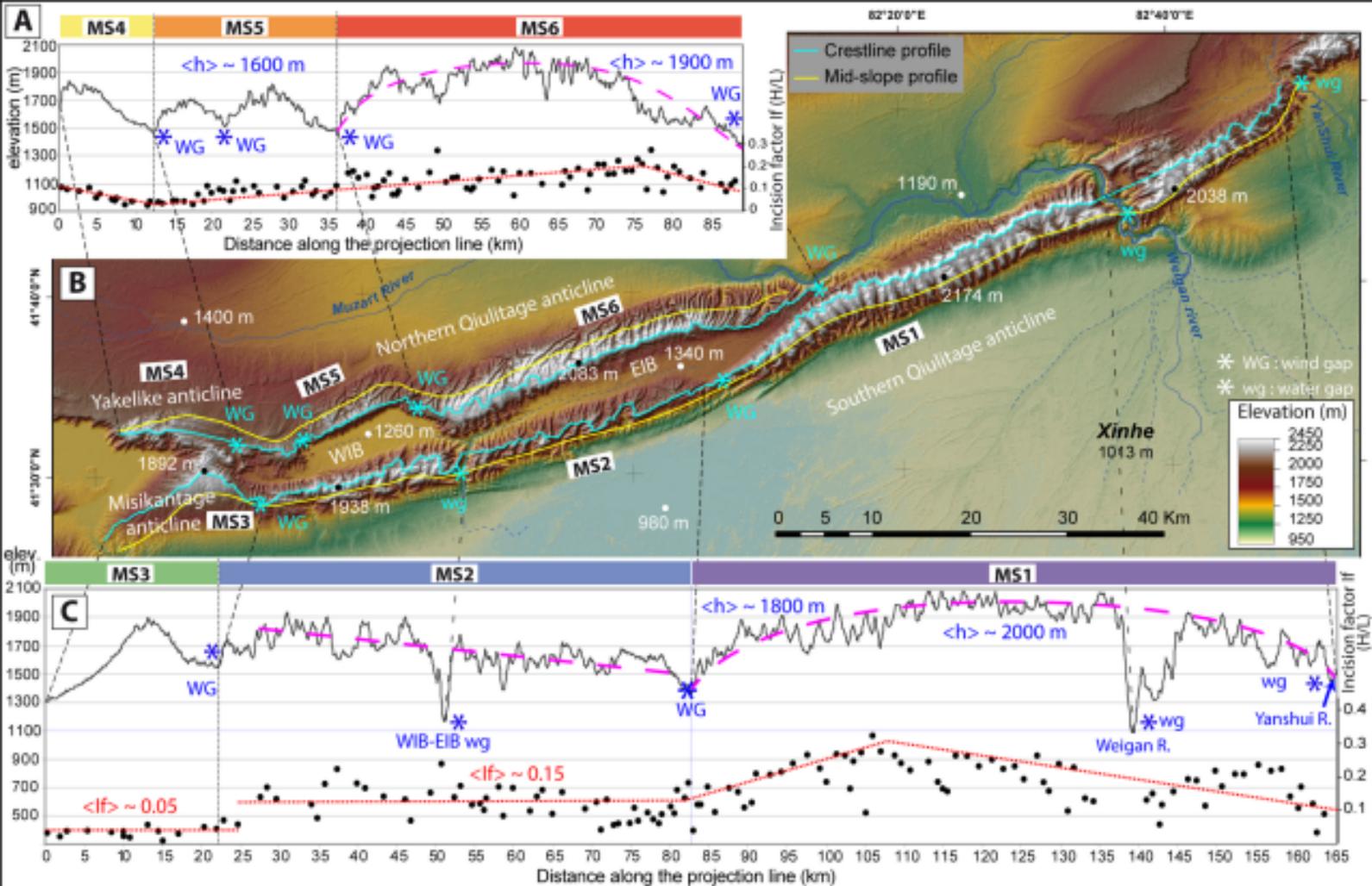
1134           **Table 1.** Definition of morphometric parameters used in this study.

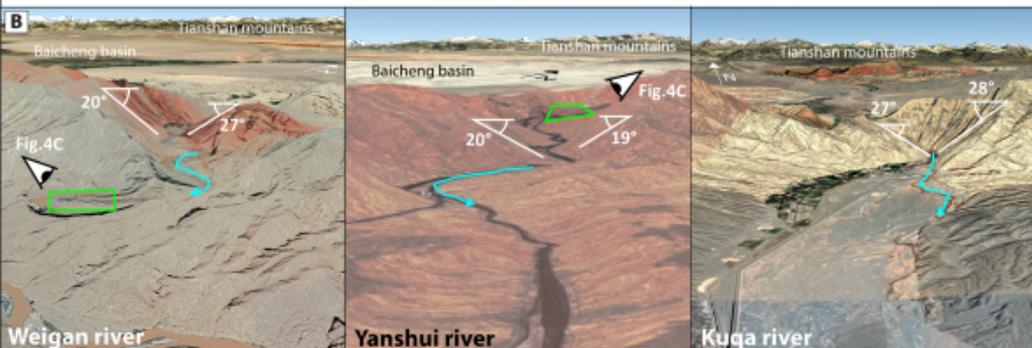
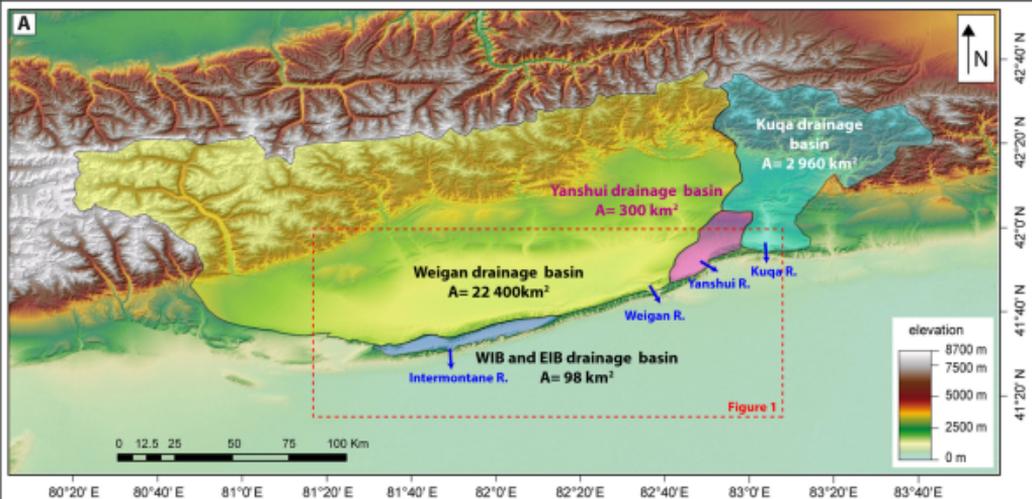
1135           **Table 2.** Average values of each morphometric parameter computed for the southern  
1136 and northern flanks of the six morphostructures. Average of mean elevation and mean slope  
1137 correspond to the spatial averaging (for each of mean values of each drainage basins).

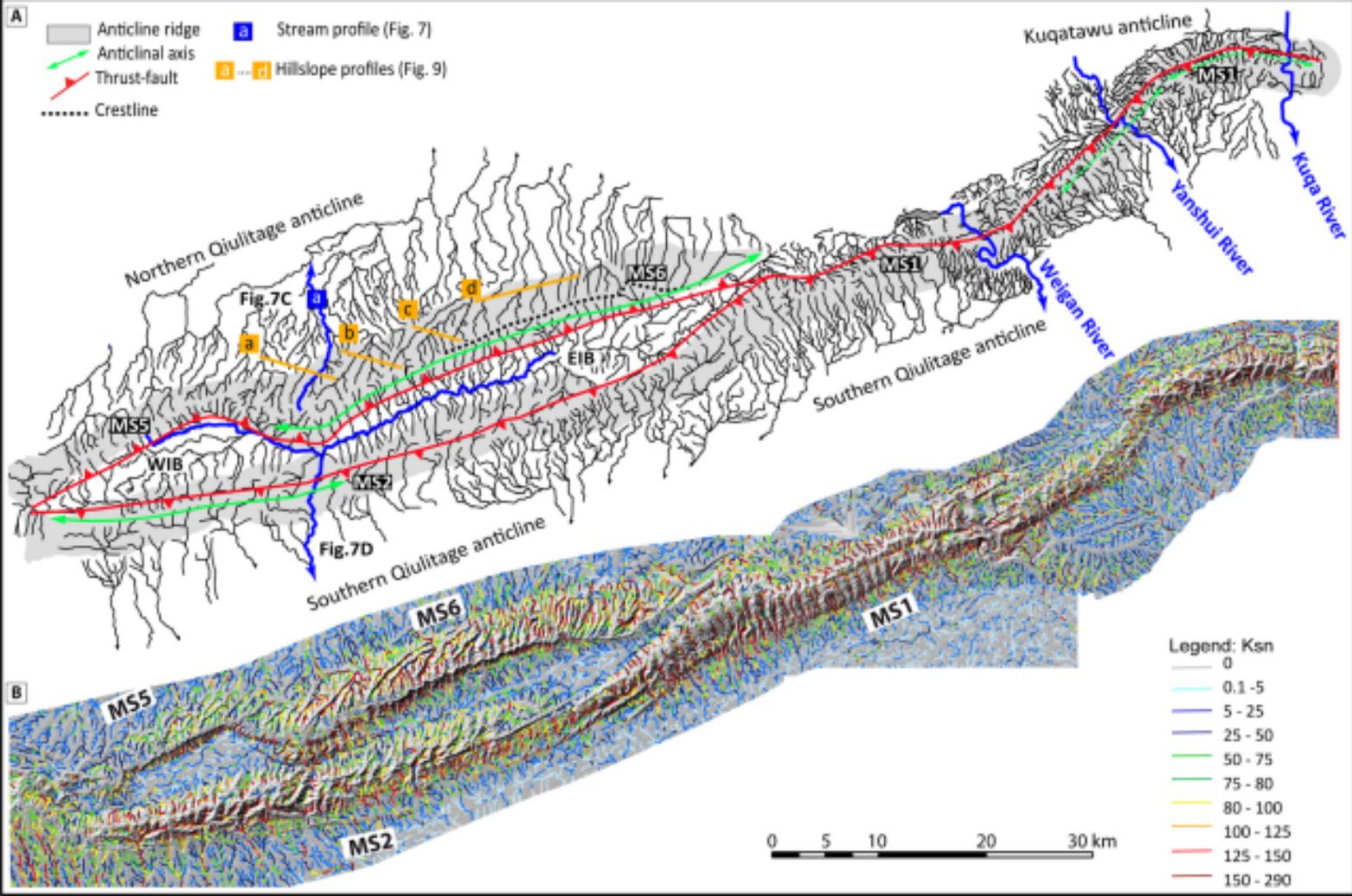
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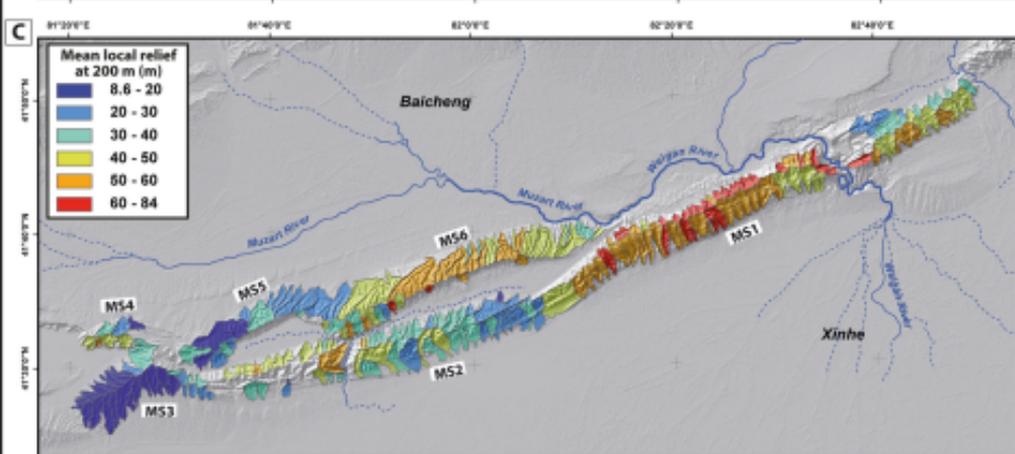
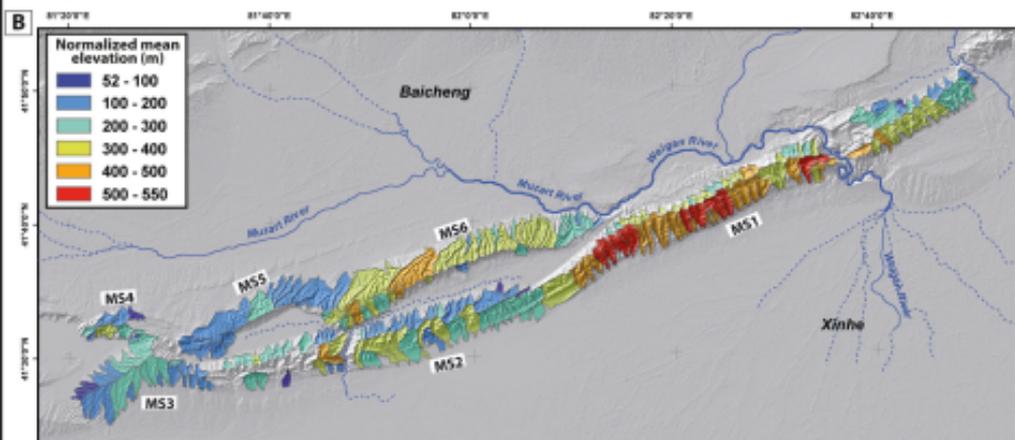
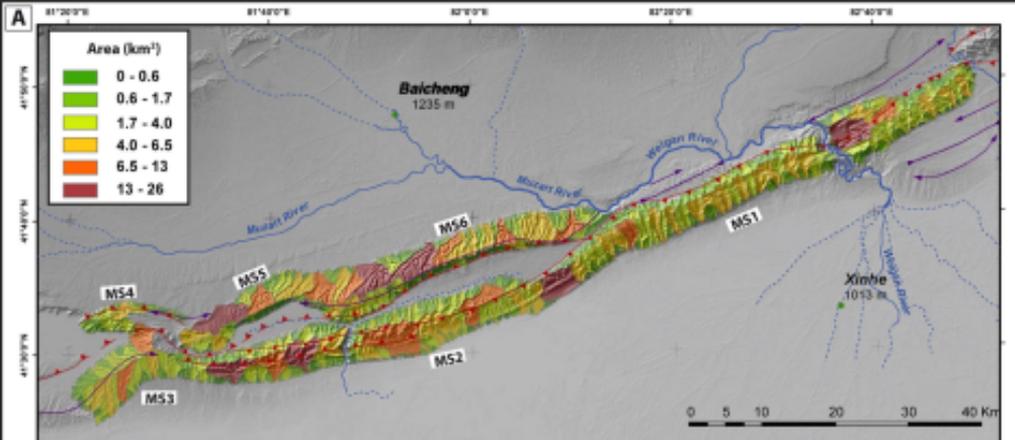


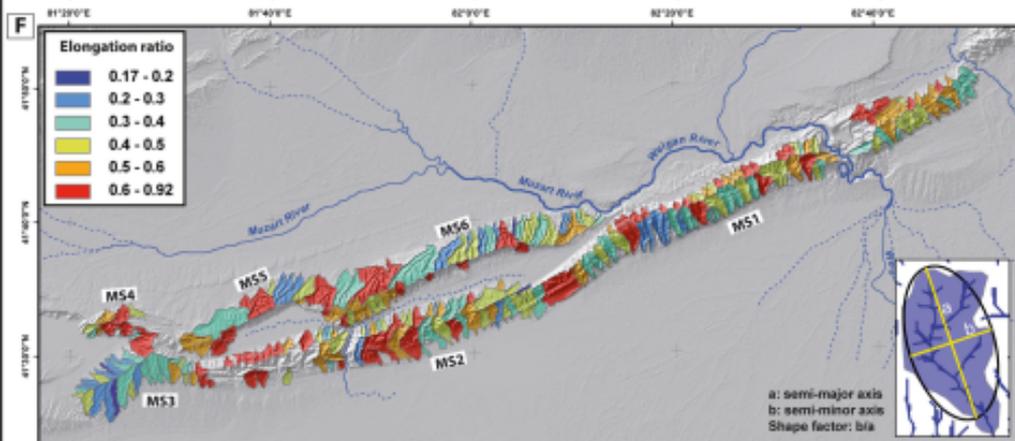
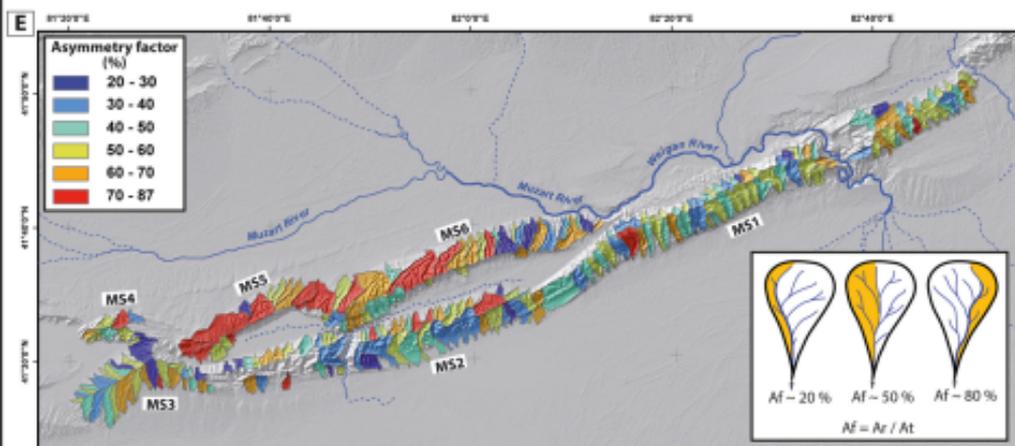
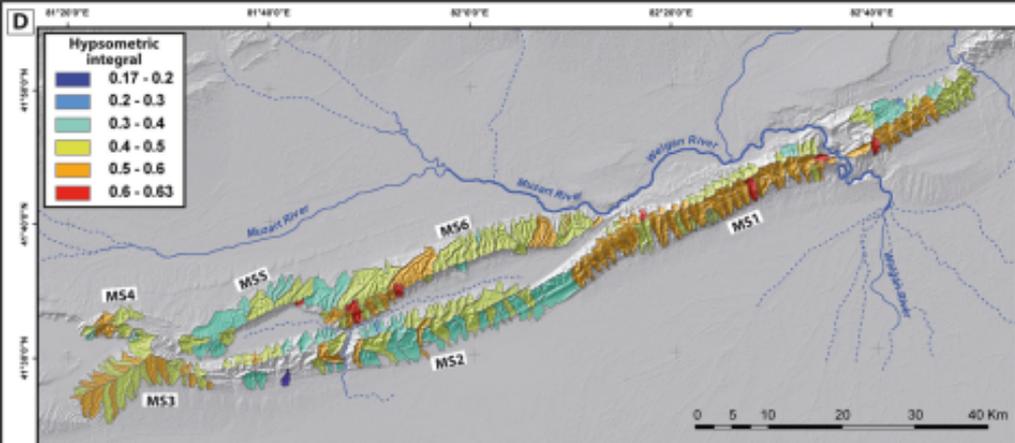




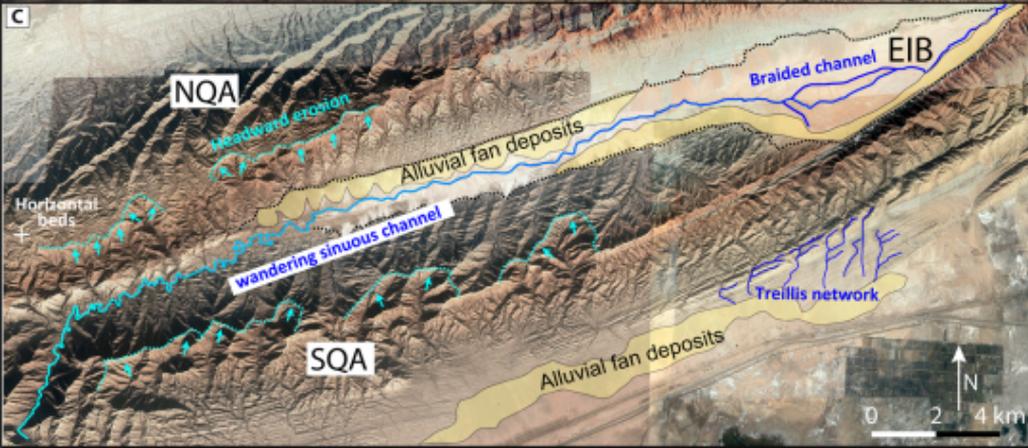
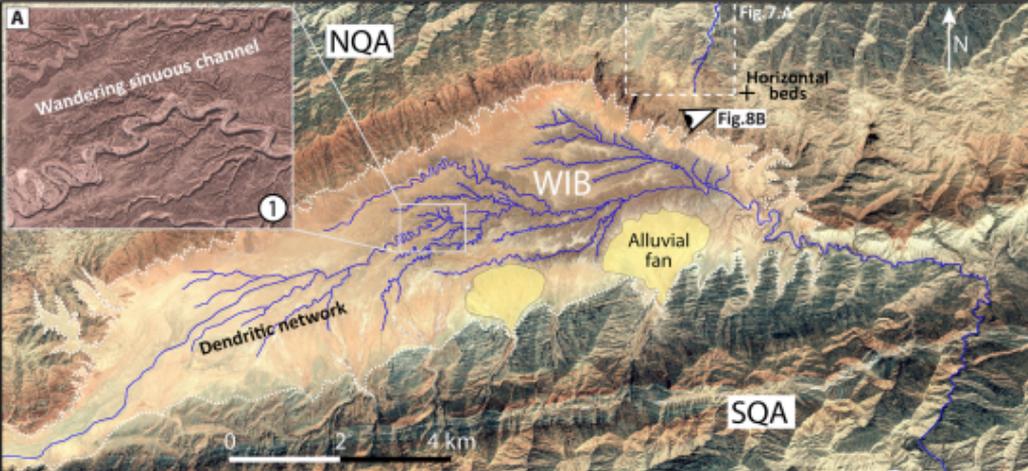


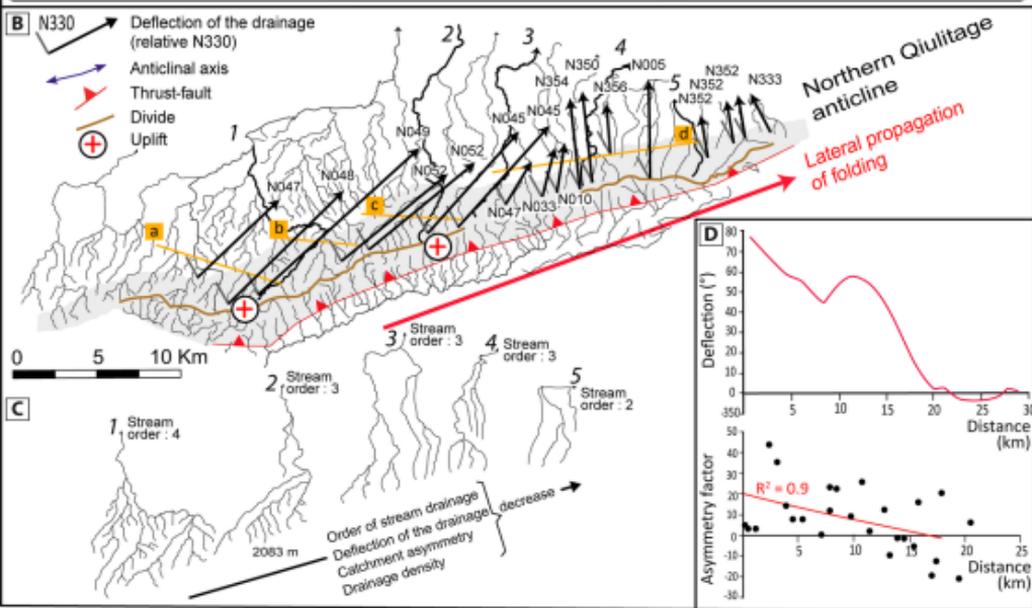
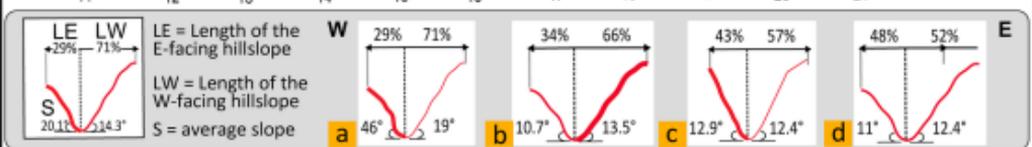
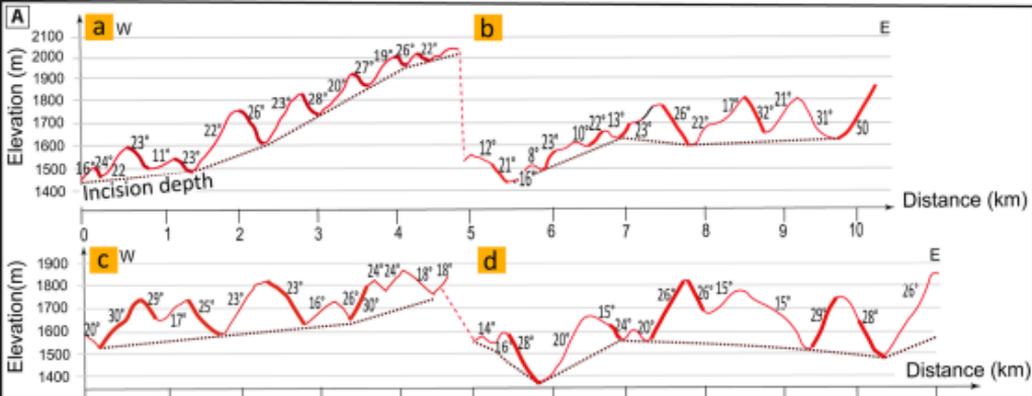


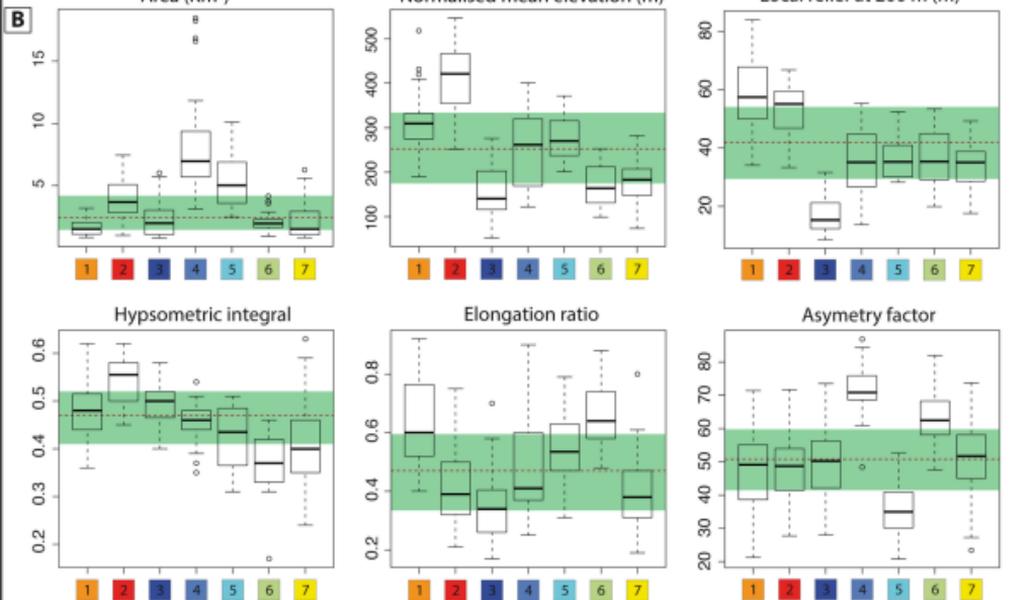
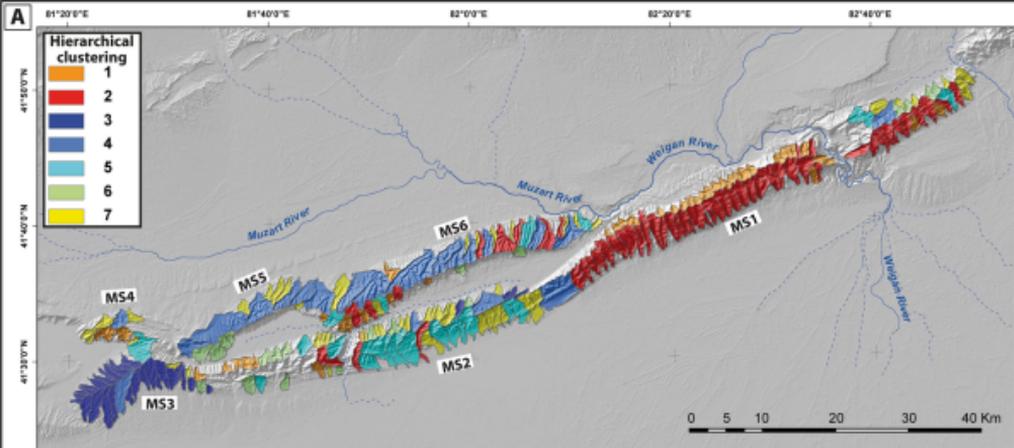


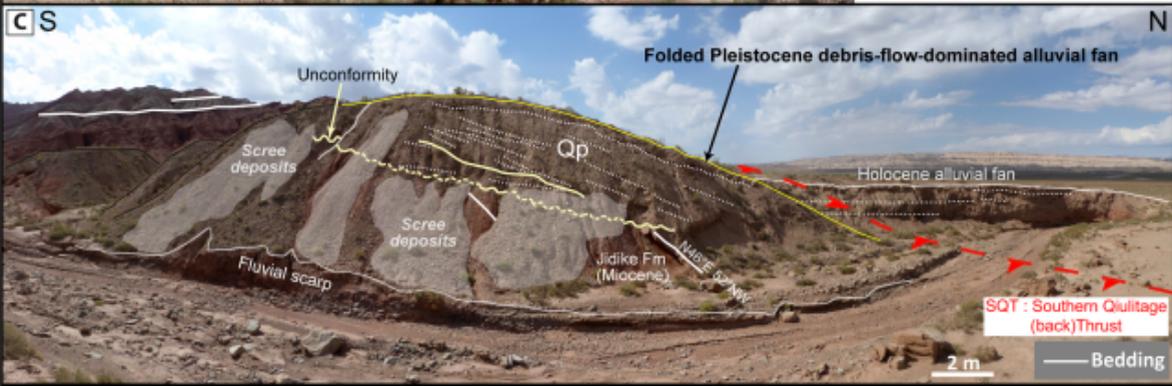
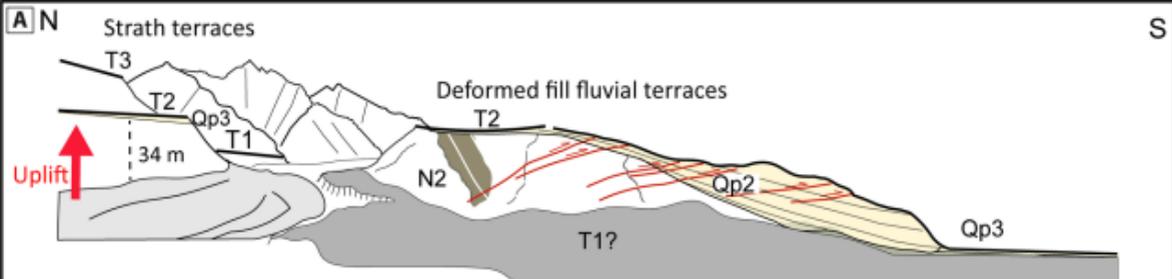


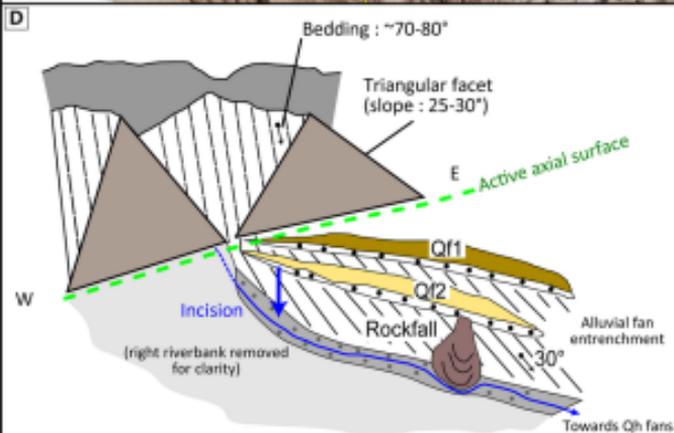
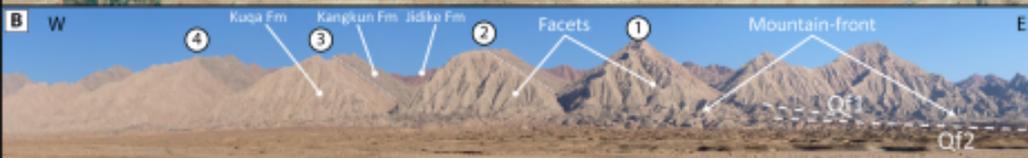
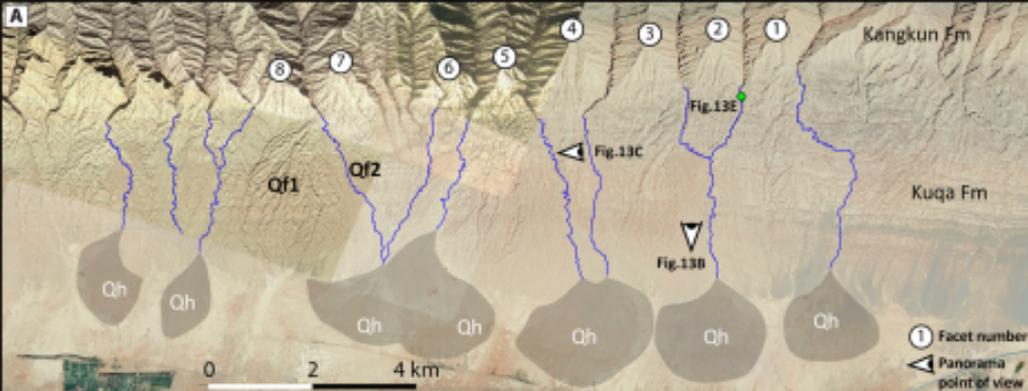


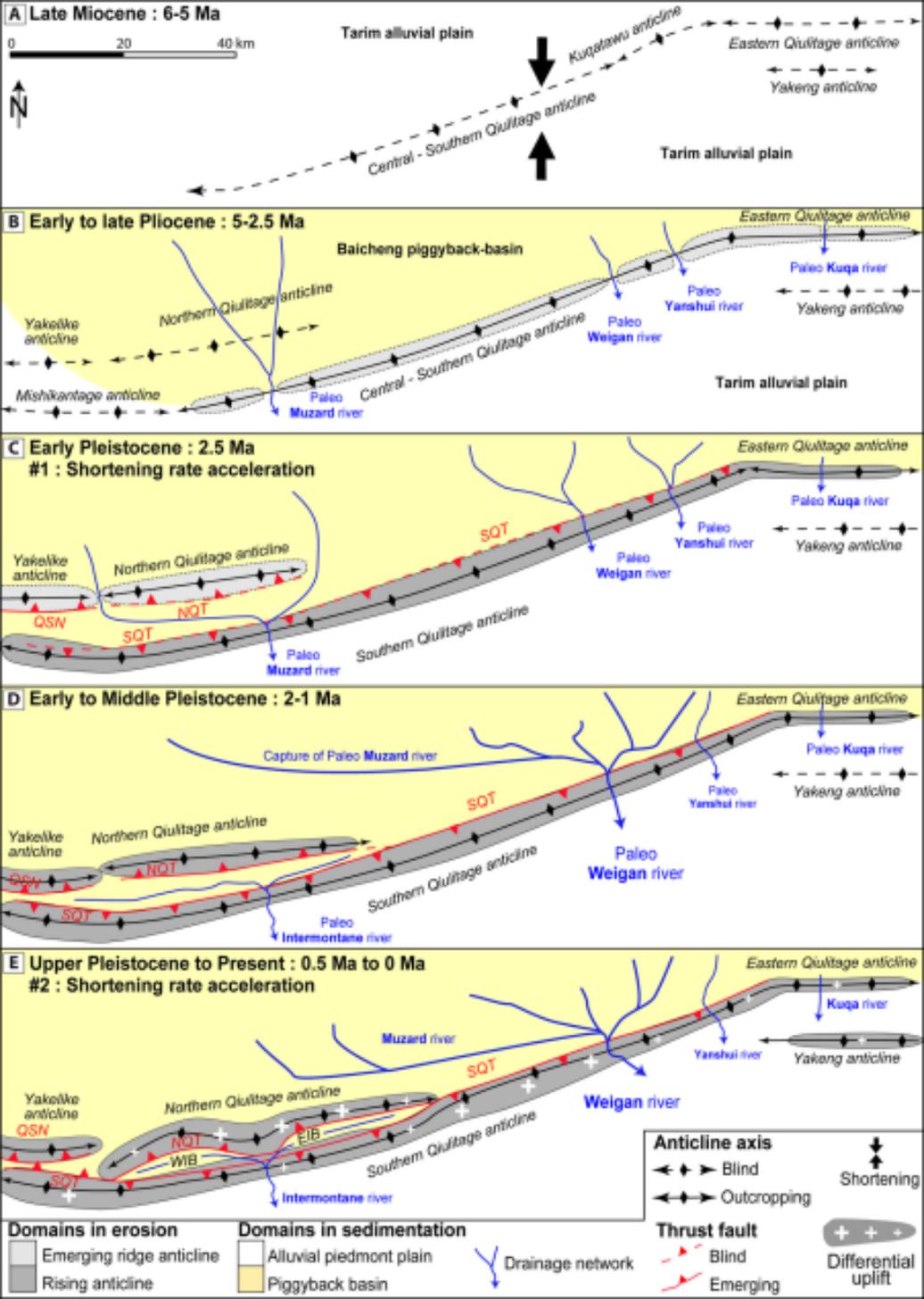




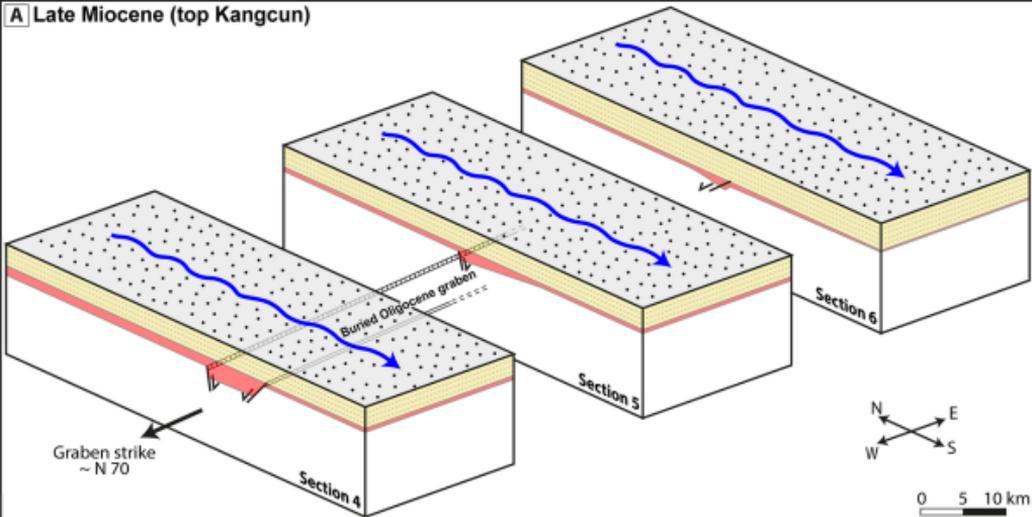




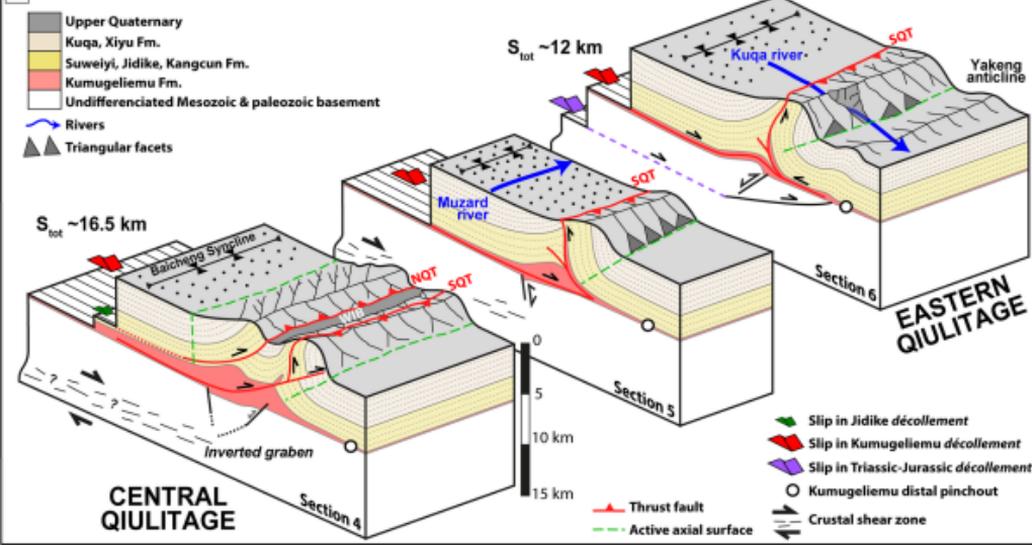




### A Late Miocene (top Kangcun)



### B Present



<i>Variables</i>	<i>Symbols</i>	<i>Interpretations</i>
<b>Drainage basin</b>		
Basin area	A	Geological structure, mean slope, age
Local relief	$\Delta r$ (1)	Provides measure of the roughness of the topography and is controlled by climate and uplift rate at long scales
Hypsometric curve and integral	HI (2)	Form and evolution of drainage basin; Young, mature, old-age drainage pattern ; Growth of structures
Main slope	$\alpha$ (3)	
Basin asymmetry factor	Af (4)	It is calculated from the ratio between the right river bank width (Lr) and the total valley width (LI)
Basin elongation ratio	Re (5)	Basin shape become more circular with time after cessation of ridge uplift
<b>Drainage pattern morphometry</b>		
Fluvial incision factor	If (6)	Differential erosion
Steepness index	S (7)	where ( $k_s$ ) and ( $\theta$ ) correspond to the steepness index and concavity index, respectively (e.g. Hack, 1957) Snyder et al., 2000), interpreted as as a transient profiles caused by an increase of uplift rate

(1)  $\Delta r : \Delta z(l) = z(x+l) - z(x)$  where  $\Delta z$  is the local relief,  $z$  is the elevation, and  $l$  is the length scale

(2) HI: The hypsometric curve is defined to divide the heights and areas by the total heights and total area, respectively. Hypsometric analysis has been performed to summarize the form and evolution of drainage basins (Strahler, 1952).

(3) Main slope ( $\alpha$ ): we measure the average of slope values for each basin.

(4)  $VA = 100 \cdot [Lr / (Lr + LI)]$

(5)  $Re = Bw / BI$ ; The basin elongation ratio is defined as the ratio of the maximum width of the drainage (Bw) to its maximum length (BI) (Schumm, 1956; Bull & McFadden, 1977)

(6) If Fluvial Incision factor  $If = 100 \cdot [W/H]$  where  $W$  is the right and left riverbanks width, respectively, and  $H$  is the height between crestline

(7)  $S = k_s \cdot A^{-\theta}$   $K_s$  Stream gradient index

Average of each parameter								
	A Area (km <sup>2</sup> )	Minimum elevation (m)	Mean elevation (m)	Maximum elevation (m)	HI (Hypsometric integral)	$\alpha$ Mean slope (°)	Maximum slope (°)	$A_f$ (Asymmetry factor)
Northern morphostructures								
<b>MS5</b>	2.15	1365	1558	1796	0.44	19	43	56
<b>MS6</b>								
Northern flank	4.96	1280	1521	1805	0.45	20	47	57
Southern flank	2.24	1298	1595	1889	0.49	21	51	50
Southern morphostructures								
<b>MS3</b>								
Northern flank	1.49	1293	1442	1593	0.49	10	23	45
Southern flank	1.92	1296	1418	1541	0.50	8.3	20	55
<b>MS2</b>								
Northern flank	1.61	1289	1423	1630	0.40	16	35	55
Southern flank	4.94	995	1267	1679	0.39	17	50	44
<b>MS1</b>								
Northern flank	1.81	1316	1565	1885	0.42	24	47	48
Southern flank	3.85	1213	1619	1978	0.53	25	49	51