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# Quantifying the transient landscape response to active faulting using fluvial geomorphic analysis in the Qianhe Graben on the southwest margin of Ordos, China

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7	Quantifying the transient landscape response to active faulting using fluvial
8	geomorphic analysis in the Qianhe Graben on the southwest margin of Ordos,
9	China
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#### 22 ABSTRACT:

River morphology has been widely used to record and track the transient landscape 23 24 response to active faulting. Here we evaluate the landscape response to active faulting 25 in the Qianhe Graben of southwest Ordos, China. In this region, it has been difficult to 26 determine the activity of mapped faults because of the presence of thick Quaternary 27 Loess; however, by analysing the presence and distribution of slope-break knickpoints 28 in river longitudinal profiles, the ongoing tectonic uplift of the Qianhe Graben can be 29 investigated. The alignment of vertical-step knickpoints gives a new insight into the 30 location of an active fault on the southern margin of Qianhe Graben. Additionally, 31 slope-break knickpoints, typical of fault controlled landscape change, were identified 32 from 24 river longitudinal profiles that drain across normal faults along both graben 33 margins. Along strike from north to south, the knickpoints varied systematically with relief, and the height of the knickpoints also decrease to the southeast. Indicating that 34 35 the rate of motion on the faults, likely is greater in the northwest and decays southeastwards. The horizontal knickpoint retreat rates range from 0.3 - 27.3 mm/yr, 36 37 constraining the landscape response time with fault initiation at  $1.2 \sim 1.4$  Myr. In comparison with other studies, the knickpoint recession triggered by base-level fall as 38 a result of faulting is relatively lower than when the base-level fall is the result of sea-39 40 level fall potentially the result of different mechanism of retreat. Finally, the potential 41 for earthquakes along the Taoyuan-Guichuansi Fault (TGF) before and after fault 42 linkage was assessed, indicating the potential for earthquakes of M<sub>w</sub> of 6.3 - 6.7 and

43	6.8 - 7.0, respectively. These observations not only suggest the knickpoints are
44	recording fault evolution in Qianhe Graben, but also provide information on seismic
45	hazard in this populous region.

**KEYWORDS:** Qianhe Graben; knickpoint; active faulting; transient landform response

#### 49 **1 Introduction**

Tectonic geomorphology is the investigation of the interaction between active tectonics 50 51 and surface processes, reflecting the coupling relationship between deep geophysical 52 structures and climate processes. Tectonic geomorphic landforms record the landscape response to the spatial distribution of active faults (Kirby et al., 2003; 53 54 Boulton and Whittaker, 2009; Kirby and Ouimet, 2011; Ozkaymak and Sözbilir, 2012; Hergarten et al., 2016; Topal et al., 2016; Dong et al., 2017; Owen et al., 2017). In 55 bedrock fluvial systems, rivers are sensitive to changes in boundary conditions, such 56 as structure, climate and lithology (Kirby et al., 2003; Whittaker, 2012; Whittaker and 57 58 Boulton, 2012; Allen et al., 2013; Cyr et al., 2014), and transmit the signal of tectonic and climatic change to the surrounding landscape by setting the landscape response 59 60 time (Whipple and Tucker, 1999; Kirby et al., 2003). Furthermore, rivers are an effective way to track neo-tectonic movement and topographic evolution (Whipple and 61 62 Tucker, 1999; Jiang et al., 2016). Previous studies have demonstrated that fluvial 63 geomorphologic parameters can record uplift rates, give insights into active faults, and 64 quantitatively study the external morphological characteristics formed by the internal dynamic geological process (e.g., Whipple and Meade, 2006; Whipple, 2009; 65 66 Castelltort et al., 2012; Kirby and Whipple, 2012; Boulton et al., 2014; Schanz and Montgomery, 2016; Kent et al., 2017). As a result, fluvial morphologic indices of river 67 longitudinal profiles have become a widespread and easily implemented method to 68 study faulting in active tectonic regions, characterised by transient landscapes 69 70 responding to boundary condition perturbation (Whipple, 2002; Whittaker et al., 2008;

Ozkaymak and Sözbilir, 2012; Whittaker and Boulton, 2012; Faghih et al., 2015; Yan
et al., 2015; Matoš et al., 2016; Topal et al., 2016; Tepe and Sözbilir, 2017).

73

74 In some locations, owing to the existence of various limitations, such as thick Quaternary sequences or physical (in)accessibility, it can be difficult to directly 75 76 measure the slip rate of faults. For example, the Qianhe Graben is a Cenozoic faulted 77 basin covered by thick extensional/transtensional deposits of Quaternary loess (~ 100 78 - 120 m thick) (Fan et al, 2016), located at the intersection of the Liupanshan Fault 79 (LPSF) and Qinling Fault (KLF) in China (Fan et al., 2018; Zhang et al., 2019) (Fig. 80 1b). The thick loess and high relief make the area difficult to explore in the field, and most recent research has focused on applying traditional methods (e.g., hypsometric 81 82 integral, stream length-gradient index, valley floor width-to-height ratio) (Chen et al., 2003; Cheng et al., 2018; Zhang et al., 2019) to reveal the geomorphic effect of the 83 84 faults. However, such methods cannot constrain rates of faulting or the rate of 85 landscape response to changing base level. To address this challenge, stream profile 86 analysis offers an alternative method to investigate neotectonic deformation, and the growth and linkage of faults of the study area (Kirby et al., 2003; Wobus et al., 2006; 87 88 Boulton and Whittaker, 2009; Kirby and Whipple, 2012; Boulton et al., 2014; Kent et al., 2017). In transient landscapes, knickpoint (the point in the long profile where the 89 90 rate of change of channel gradient reaches local maximum) (Haviv et al., 2010; 91 Whittaker and Boulton, 2012; Kent et al., 2016) characteristics and normalized channel 92 steepness ( $k_{sn}$ ) can be used to investigate fault slip rate and rock uplift rate by analysing digital elevation models (DEMs) (Snyder et al., 2000; Bishop et al., 2005;
Crosby and Whipple, 2006; Castillo et al., 2014; Castillo, 2017; Gailleton et al., 2019;
Robustelli, 2019). Therefore, in the absence of direct geodetic constraints in active
settings much information can be gained through the investigation of knickpoint
characteristics, giving new insights into active faulting.

98

In this study, the fluvial morphologic indices of longitudinal profiles in Qianhe Graben are extracted to investigate the landscape response to active faults based on digital elevation model (DEM) and GIS spatial analyses. Specifically, the main purposes of this study are: (1) to investigate the topographic response to active faulting by identifying the styles of knickpoints from river longitudinal profiles; (2) to quantify the transient fluvial landscape response to active faulting in this area; (3) to evaluate present and future earthquake hazard in the study area.

106

# 107 2 Geological background

The Qianhe Graben is the westernmost extent of the Weihe Graben, located at the intersection between the southwest margin of the Ordos block, the southeastern Liupan-Longxi Plateau, and the northern Qinling fold system (Fig. 1). The palaeosurface of the study area is buried by Quaternary loess, 100 - 120 m thick (Fan et al., 2016), but bedrock sedimentary strata are exposed dating from the Precambrian to Neogene. The graben is defined by a number of active faults (Wang et al., 2011; Li et al., 2013; Guo et al., 2016; Dong et al., 2017; Chen et al., 2018b; Cheng et al., 2018; Zhang et al., 2019), with four main NW-SE trending active faults; the TaoyuanGuchuansi Fault (TGF), the Guguan-Guozhen Fault, (GGF), the Qianyang-Biaojiao
Fault (QBF), and the Qishan-Mazhao Fault (QMF), and the minor fault Qinling Fault
(QLF) (Fig. 1c).

119

120 Previous studies have shown that earthquakes occur frequently in the study area (Fan 121 et al., 2018), and the possibility of large earthquakes (>  $M_w$  6.0) is high (Cheng et al., 122 2014). However, according to the existing seismicity data (Fig. 1c), the earthquakes 123 that have affected the region during the instrumental period (from 1990 to present) are 124 smaller,  $< M_w 5.5$ , while most are  $\le M_w 2.0$ . Even the 1556 Huaxian earthquake (M<sub>w</sub>) 125 8.5) and 1704 Longxian earthquake (M<sub>w</sub> 6.0) (Fig. 1a, b), which occurred relatively close to the study area, were over 300 years ago (Cheng et al., 2014; Hou et al., 1998). 126 127 Little information exists on the rates of fault slip. However, since 1.2 ~ 1.4 Ma, the 128 Quaternary activity with average slip rate on the QMF has been estimated, through a 129 combination of palaeoseismology, geomorphology, and deformation survey, as  $\sim 0.03$ 130 - 1.50 mm/yr, while GGF slip rate is ~ 0.03 mm/yr (Shi, 2011; Lin et al., 2015). Along 131 the southern margin of the Ordos block, fault activity has increased since 5 Ma owing 132 to the rapid uplift (2.94 ± 0.15 mm/yr) of the Qinling Mountains (Li et al., 2012) and 133 rifting of the Weihe Basin (Ren et al., 2015).

134

135 The active faults bound regions of distinct bedrock lithology. More than 50% of the 136 study area is Quaternary loess (Fig. 1c). To the north of the QMF, the bedrock is 137 composed of red sandstone and conglomerate forming the southwest margin of Ordos 138 block. These sedimentary rocks were deposited during the Jurassic to Cretaceous (Li 139 et al., 2013) and are exposed in river valleys that have incised through the overlying 140 loess. To the east of the GGF are Neogene, Ordovician and Cambrian marbles and 141 limestones, which were exposed by the extrusion of the Longxi block (Fan et al., 2003; 142 Lin et al., 2011; Liang et al., 2014), and to the west of GGF, there are outcrops of 143 Cretaceous conglomerates and sandstone. By contrast, to the west of TGF is a large 144 area of late Paleozoic and post-Triassic red granite (Fig. 1c).

145

146 In addition, there are distinct geomorphic regions within the study area controlled by 147 fault location and behaviour. Across the study area, the topography gradually 148 decreases in elevation from northwest to southeast (Fig. 2a). The highest points in the 149 northwest are composed of lower Paleozoic metamorphic rocks and Paleozoic 150 intermediate-acid intrusive rocks at altitudes of 1800 - 2200 m. The neotectonic uplift 151 driving topographic evolution has resulted in deep valleys and the steep ridges, which 152 form the watershed of the Weihe tributaries. By contrast, the low relief landscape of 153 the southeast gradually merges into the Weihe basin at an altitude of 600 - 700 m (Fig. 154 2a).

Since the late Cenozoic, in the Qianhe fault zone between the QMF and the QBF, five
asymmetric river terrace levels have developed along the Qianhe River (Sun, 2005;
Chen et al., 2018b) (Fig. 2a). Each terrace is composed of alluvial deposits and

covered by loess deposits, but the isochrones of paleosol sequences can be
accurately recognized (Zhang et al., 2019). The age of the terraces was determined
by magnetostratigraphic dating and field work (Chen et al., 2018b; Zhang et al. 2019),
providing ages for each terrace (T1 to T5): 0.01, 0.01 - 0.13, 0.12 - 0.60, 0.62 - 0.82,
and 1.2 - 1.4 Myrs, respectively (Li, 1991; Fan et al., 2018; Zhang et al., 2019).
Therefore, the oldest terrace provides a minimum age for the development of the
graben.

165

166 As shown in Figs. 2b, c, and d, three 100 km long strip profiles (AA', BB', CC') 167 perpendicular to the Qianhe fault zone were selected from northwest to southeast for 168 topographic and geomorphologic analysis of the Qianhe basin. It is clear that the TGF 169 and QMF faults are controlling the topography and form the major basin bounding 170 faults of Qianhe basin, which exhibits a basin and range-type topography. Under the 171 interaction of the four faults, the uplifted horsts and adjacent grabens, form the tectonic 172 structure of the region (Fig. 2e). Therefore, it is expected that the morphology of the 173 rivers crossing the Qianhe Graben will record evidence of river evolution and tectonic 174 uplift, providing a dataset for the study of the active faults.

175

#### 176 **3 Method and data collection**

177 That stream profiles can provide insights to tectonic uplift has been confirmed for many 178 years (Hack, 1973; Howard and Kerby, 1983). Rivers in areas of active faulting not 179 only modify their topography to the regional base-level but also set boundary conditions for the erosion and evolution of adjacent hillslopes (Castillo et al., 2017).
Therefore, a simple and efficient method of using river geomorphology to describe
bedrock channel forms and processes can reveal much information on the underlying
physical processes.

184

# 185 **3.1 River erosion model**

In order to analyze the fluvial geomorphic response of rivers to tectonic uplift in the
study area, a power law function of drainage area *A* and river channel slope *S* is used
as follows (Howard and Kerby, 1983; Whipple and Tucker, 1999; Kirby and Whipple,
2001; Bishop et al., 2005; Berlin and Anderson, 2007; Castillo et al., 2017; Scherler et
al., 2017):

$$E = K \times A^m \times S^n \tag{1}$$

191 Where *E* us the detachment-limited rate of bedrock channel erosion; *K* is erosion 192 coefficient related to lithologies, active faults, base level and climate; *m* and *n* are 193 constants.

194

195 In steady-state landscape, where the erosion equals uplift, the channel gradient can196 be solved by Equation 1 for slope giving Equation 2:

$$S = \left(\frac{U}{K}\right)^{\frac{1}{n}} A^{-\frac{m}{n}}$$
(2)

197 Where m/n represents the concavity, U is uplift rate, and the coefficient (U/K)<sup>1/n</sup>
198 represents the steepness.

To facilitate this calculation, the river hydraulic erosion model deduced from Equation 2 has been formed and widely used, along with the analysis of stream gradient and drainage area, in the study of tectonic geomorphology (Hack, 1973; Howard et al., 1994; Whipple, 2004; Boulton and Whittaker, 2009; Allen et al., 2013; Regalla et al., 2013; Kale et al., 2014; Nexer et al., 2015; Kent et al., 2017; Sembroni and Molin, 2018), thus:

$$S = k_s A^{-\theta} \tag{3}$$

$$k_s = \left(\frac{U}{K}\right)^{\frac{1}{n}} \tag{4}$$

$$\theta = \frac{m}{n} \tag{5}$$

206 Where  $\theta$  is the concavity index, and  $k_s$  is the steepness index.

207

The  $\theta$  describes the rate of change of local channel slope and is generally between 0.3 and 0.6 in steady-state rivers (Hack, 1973). Changes in  $k_s$  can be used to investigate the uplift rate if there is no significant lithologic variation and sediment erosion (Snyder et al., 2000; Kirby and Whipple, 2012; Xue et al., 2018). Both  $k_s$  and  $\theta$  can be obtained by a linear regression from log-log slope-drainage area plots for study rivers.

214

In such analyses, it has become an accepted approach to calculate a normalized steepness index ( $k_{sn}$ ) by using a reference  $\theta$ , to avoid the strong correlation of  $k_s$  and 217 θ (Kirby and Whipple, 2012; Azañón et al., 2015). Generally, 0.45 is chosen as the 218 reference concavity index  $\theta_{ref}$ . Therefore, the Equation 3 can be reformed as follows:

$$S = k_{sn} A^{-\theta_{ref}}$$
(6)

219

220 Not all rivers are in 'steady-state', and river longitudinal profiles can exhibit slope 221 discontinuities (knickpoints). A knickpoint is evidence of the transient state of the river, 222 and divides the channel into two parts with different steepness. Depending on the 223 shape of the knickpoints on a SA plot (Fig. 3), they can be divided into vertical-step 224 type knickpoints and slope-break type knickpoints (Wobus et al., 2006; Haviv et al., 225 2010; Kirby and Whipple, 2012). A slope-break knickpoint separates downstream 226 incision from the upstream channel yet to respond to changes in boundary conditions. 227 It has been found that when such knickpoints are produced by a singular base-level 228 fall, knickpoints move at the same retrogression rate proportional to the upstream area, 229 causing the knickpoints of different rivers to be at the same altitude (Crosby and 230 Whipple, 2006; Berlin and Anderson, 2007). By contrast, the elevation of knickpoints 231 can scale with fault slip rate on a bounding faults, where multiple river cross a single 232 structure (Boulton and Whittaker, 2009; Whittaker and Boulton, 2012).

233

Generally, a vertical-step knickpoint is related to a change bedrock strength, which appears at a lithologic boundary, fault zone or densely jointed zone, and the possibility of migration to upstream is limited (Whipple et al., 2013; Wang et al., 2015). Although the knickpoints formed by lithologic differences are generally considered fixed, the channel is also divided into upper and lower parts, but there is little to no variation in  $k_{sn}$  across the knickpoints.

240

Therefore, vertical-step knickpoints may have limited tectonic significance, while slope-break knickpoints can represent local uplift caused by enhanced tectonic movement (Fig. 3c and d), such as the initiation of faulting or an increase in slip on a fault. Therefore, knickpoint analysis is a useful way to locate structures and analyse geomorphologic evolution (Harkins et al., 2007; Boulton and Whittaker, 2009; Wang et al., 2015; Chen et al., 2018a).

247

# 248 **3.2 River longitudinal profile**

249 In the absence of knickpoints, it has been proposed that further information on 250 boundary processes can be gained from the shape of the longitudinal profile (Chen et 251 al., 2006; Dong et al., 2017). Steady-state conditions require that uplift = erosion and 252 as a result the elevation of the bedrock channel is invariant. However, if the uplift rate 253 is not equal to the river erosion rate, the steady-state will be broken by the increase in one of the two rates. If the uplift rate is higher, and the river elevation increases along 254 255 longitudinal profile with respect to time (dz/dt >0) then the linear relationship will transform into concave downward curve (Fig. 4a). By contrast, there will be an upward 256 257 concave curve when uplift rate < erosion (Chen et al., 2006). Based on Equation 3 258 above, we obtain logarithms on both sides as follows:

$$\log(S) = -\theta \times \log(A) + \log(k_s)$$
<sup>(7)</sup>

259

For steady-state profiles, the log(S) curve is in a straight line. Then, the log(S) curve is convex when the uplift rate is greater. By contrast, the curve tends to be concave (Fig. 4a), where uplift rates are lower.

263

According to the results of previous studies (e.g., Ohmori, 1991; Chen et al., 2003; Rädoane et al., 2003), the shape of the river profiles can also be categorized. The elevation Y of river longitudinal profile changes with the length X, and the profile can be categorised as linear, exponential, logarithmic or power function type related to different stages of landscape evolution (Chen et al., 2006; Dong et al., 2017) (Fig. 4b): (1) Following surface uplift in tectonically active areas, the concavity of river longitudinal profile can expressed as linear distribution (Y=a-bX);

271 (2) Where river incision is high, material is eroded from the upper and middle 272 reaches and transported to the lower reaches where sediment accumulates. As 273 a result, the curvature of the upper and middle reaches becomes larger, 274 gradually developing an exponential form ( $Y=ae^{bX}$ );

(3) Continuing erosion and deposition can further accentuate the profile curvature
 resulting in a transition to the logarithmic profile-type (*Y=alogX+b*);

277 (4) Under the influence of regional climate, bedrock fracture and other factors, 278 loose sediment is difficult to retain, the river erosion reaches a maximum, and 279 the concavity of longitudinal profile evolves into a power function ( $Y=aX^b$ ).

In summary, the use of the geometric changes in the steady-state river longitudinal profile can provide additional insights into the geomorphological evolution of a region and provide a deeper understanding of the regional tectonic uplift in the absence of knickpoints.

285

# 286 **3.3 Data collection**

287 The digital elevation model (DEM) data used here is the Shuttle Radar Topography 288 Mission (SRTM) DEM, which spans the 60°N to 56°S regions of the Earth's surface 289 from a radar topographic survey carried out jointly by National Aeronautics and Space 290 Administration (NASA) and National Imagery and Mapping Agency (NIMA), USA 291 (Hancock et al., 2006). This dataset covers 80% of the land surface, and the DEM is provided as SRTM1 (1"× 1") and SRTM3 (3"× 3") data types, corresponding to the grid 292 293 resolution of 30 and 90 m, respectively. Fortunately, free access to the 1 arc sec data 294 is now available for the research area through the USGS Earth Explorer interface 295 (https://earthexplorer.usgs.gov). Previous research results have shown that SRTM 296 can be used in river hydrological analysis and is superior to ASTER-GDEM (Farr et al., 297 2007; Arrowsmith and Zielke, 2009; Kirby and Whipple, 2012; Boulton and Stokes, 2018; Wang et al., 2018b). ArcGIS 10.2 software was used to reproject the DEM into 298 299 WGS 1984 UTM Zone 48N, convert DEM data, splicing, filling holes, etc., to 300 produce the final DEM of Qianhe Graben (Fig. 2a).

302 The horizontal and vertical accuracy of the STRM DEM is > 99 % (Dong et al., 2017; 303 Farr et al., 2007), which has not limited the interpretation of tectonic landforms in the region. Using the ArcHydrology toolbox and a MATLAB script program (StreamProfiler; 304 305 Whipple et al., 2007) to extract the river longitudinal profile and watershed catchment 306 area from SRTM data, the river slope can be calculated (Kirby and Whipple, 2012; 307 Zahra et al., 2017). The river channel morphology can be assessed by SA regression 308 to obtain concavity and steepness. The presence or absence of knickpoints can be 309 determined, shaping the subsequent analysis of knickpoint distribution or the shape of 310 the longitudinal profile (Figs. 3 and 4).

311

# 312 **4 Results**

313 Using ArcGIS 10.2, twenty-four river long-profiles from the Qianghe Graben were 314 extracted from the SRTM DEM. All tributaries are symmetrically distributed on both 315 sides of the main channel of the Qianhe and Jinlinghe Rivers. Twenty-three of them 316 cross TGF and QMF (Fig. 5). The longitudinal profile form and SA plots reveal 317 information regarding the underlying controls on river formation and elevation (Berlin 318 and Anderson, 2007; Harkins et al., 2007; Whittaker et al., 2007; Stokes et al., 2008; 319 Kirby and Whipple, 2012; Boulton et al., 2014; Giletycz et al., 2015), and record the 320 geomorphic constraints on uplift history (Olivetti et al., 2012; Rossi et al., 2017; 321 Robustelli, 2019). Therefore, the presence or absence of knickpoints was firstly 322 identified, allowing the subsequent analysis to be undertaken appropriately on the river 323 long profiles (Fig. 5). Sixteen rivers had knickpoints, of which eight rivers have two knickpoints and eight rivers have one knickpoint. Eight rivers are found to be without
knickpoints. For comparative analysis, rivers to the northeast and southwest of River
11 are divided into two separate groups representing the two margins of the Qianhe
Graben.

328

The length of the rivers with knickpoints ranges from 54.6 - 160.1 km (Table 1), with the longest river (R11) occurring in the center of Qianhe Graben and the shortest river (R24) on the southern margin of the Qianhe Graben. The total drainage area of these catchments varies between 3.3 and 194.9 km<sup>2</sup>. As for the rivers without knickpoints, these have an average length of 91.1 km (Table 2).

334

335 Fifteen rivers exhibit slope-break knickpoints (Figs. 5 and 6), while only River 2 has a 336 vertical-step knickpoint. These rivers have a moderate or high  $k_{sn}$  value, ranging from 11.0 to 115.0 m<sup>0.9</sup> (Table 1 and Fig. 6). The average of  $k_{sn}$  values downstream of the 337 south and north rivers are 71.1 and 50.5 m<sup>0.9</sup>, respectively, while the average  $k_{sn}$ 338 339 upstream are 41.0 and 27.1 m<sup>0.9</sup>, respectively. Therefore, southern rivers have higher  $k_{sn}$  values than northern rivers. River 10 has the highest  $k_{sn}$  values, where  $k_{sn}$  above 340 and below the knickpoint is 11.0 and 115.0 m<sup>0.9</sup>, respectively (Table 1). The  $k_{sn}$  is 341 342 significantly higher below the knickpoint than above for rivers exhibiting slope-break 343 knickpoints, while the  $k_{sn}$  of the river with vertical-step knickpoint is similar above and 344 below the knickpoint (Fig. 6). For example, the  $k_{sn}$  above and below the vertical-step

345	knickpoint in River 2 is 16.8 and 34.8 m <sup>0.9</sup> , respectively. While the rivers without
346	knickpoints only have one $k_{sn}$ value, ranging from 30.1 to 80.4 m <sup>0.9</sup> (Table 2).

347

To investigate the change of  $k_{sn}$  from above to below the knickpoints, the  $k_{sn}$  ratios of knickpoints can be investigated (Fig. 7). There is no significant difference between  $k_{sn}$ ratios of most knickpoints, ranging from 0.8 - 10.5. The average  $k_{sn}$  ratios of south and north knickpoints are 2.7 and 2.0, respectively. The  $k_{sn}$  values for River 9 and River 10 exceed 7, may confirm that the high change of slope in the north section of this study area.

354

To analyse the vertical distribution of knickpoints, two swath profiles (NN' and SS') with 355 356 a width of 20 km along the strike and paralleling the QMF and TGF are drawn to 357 compare relief against the knickpoint elevation (Fig. 8a and b). Northern knickpoints 358 range between 1000 - 1400 m in elevation, while southern knickpoints decrease in 359 height from 2300 m to 1100 m southwards. There is an obvious feature that the 360 knickpoints elevation is consistent with the relief (Fig. 8). The knickpoints at the 361 northwestern section of the Qianhe Graben have much higher elevation, while the 362 southeastern section are lower. For example, River 10 has the highest knickpoint at 363 2245 m and the highest relief of 1141 m. The knickpoint elevation against relief in south 364 and north profiles (NN' and SS') are plotted (Fig. 8c and d) and show a stronger linear 365 relationship for the knickpoints on the southern rivers ( $R^2 = 0.58$ ), than for the northern 366 rivers ( $R^2 = 0.33$ ).

367

368 When the horizontal distribution of knickpoints is considered, slope-break knickpoints 369 are present consistently upstream of faults. Whereas the vertical-step knickpoint in 370 River 2 is located on the trace of the GGF (Fig. 5). Additionally, we observe that the 371 upstream distance of knickpoints from faults is greater when the drainage area is larger (Fig. 9), where  $L \sim A^{0.64}$  with an  $R^2$  of 0.6. For example, River 10 has a drainage 372 373 area of 57.3 km<sup>2</sup> and the upstream distance of the knickpoint from the fault is 13.8 km, 374 while River 24 has a drainage area of 19.0 km<sup>2</sup>, but the knickpoint has only migrated 375 7.8 km. This relationship demonstrates that the distance from faults to knickpoints 376 scale with drainage area in these river systems and the knickpoints propagate upstream as a surrogate of stream discharge, in agreement with previous studies 377 378 (Boulton et al., 2014; Whittaker and Walker, 2015; Castillo, 2017; Kent et al., 2017). 379

It is interesting to note that the vertical-step knickpoint of River 2 is located on the GGF, and at the boundary between Cretaceous and Ordovician sandstone (Figs. 1c and 5).
As previously discussed, vertical-step knickpoints are not directly related to uplift (Haviv et al., 2010; Kirby and Whipple, 2012) and the potential for knickpoint migration upstream is limited (Harkins et al., 2007; Wang et al., 2015). To investigate the significance of the vertical-step knickpoint, further tributaries around River 2 were obtained (Fig. 10a).

388 Eight vertical-step knickpoints were located on the GGF (Fig. 10a), and the difference 389 of the  $k_{sn}$  above and below vertical-step knickpoints is minor (Fig. 10b), ranging from 26.7 to 49.9 m<sup>0.9</sup> (Table 3). Interestingly other rivers in Qianhe Graben, such as Rivers 390 391 3 to 7, also cross the GGF but do not have the vertical-step knickpoints (Fig. 5). River 392 2 traverses the change from Cretaceous to Ordovician sandstones and limestones whereas further north Cretaceous sediments are juxtaposed against Neogene 393 sediments of similar rheology (Fig. 1c). Therefore, the lithological strength contrast 394 395 across the fault is likely the cause of the vertical-step knickpoints, giving a new insight 396 into the location of this fault.

397

398 Finally, information on the eight longitudinal profiles without knickpoints was obtained 399 using log(S) curve on SA plot to reveal the uplift rate of these rivers, and applying 400 linear, exponential, logarithmic and power functions to regress the best shape for the 401 long profile (Table 2). As shown in Table 2, log(S) curves on SA plot are convex in 402 River 4, 13 and 15, and the other are linear. The logarithmic function is the best fit to 403 this subset of rivers, where the coefficients of determination ( $R^2$ ) are > 0.9 (Table 2). The exponent and power function are close to the logarithmic function, and  $R^2 > 0.79$ . 404 405 By contrast, the linear function shows a slightly weaker fit to the data. As discussed in 406 the methodology (Fig. 4b), the shape of logarithmic function shows that in all eight 407 channels incision is high, and the upstream material is transported the downstream 408 accumulation zones.

In summary, the southern margin of the Qianhe Graben has higher relief, elevation, slope, and  $k_{sn}$ , while the northern region exhibits lower values for all variables. In addition, the slope-break knickpoints are consistent with being the upstream extent of a transient wave of incision. The reasons for this are explored in the following sections.

414

# 415 5 Discussion

416 **5.1 Why are there knickpoints?** 

417 Previous studies have shown that knickpoints can be explained as the result of 418 transient fluvial incision across a region (Wobus et al., 2006; Berlin and Anderson, 419 2007; Stokes et al., 2008; Kirby and Whipple, 2012; Boulton et al., 2014), where the 420 topographic evolution is related to the interplay between climate, basement lithology 421 and tectonic uplift (Duvall, 2004; Burbank and Anderson, 2011; Kirby and Whipple, 422 2012; Whittaker and Boulton, 2012; Allen et al., 2013; D'Arcy and Whittaker, 2014; 423 Pérez-Fodich et al., 2014; Martins et al., 2017). In the study area, the knickpoint characteristics are consistent with being the upstream extent of a transient wave of 424 425 incision, but what caused the landscape perturbation? Here we explore mechanisms for knickpoint development. 426

427

Firstly, taking the annual mean precipitation distribution map in 2017 as a sample (Fig.
5b), the annual precipitation varies between 959 and 474 mm but with no clear N-S,
or W-E trends. There are also no clear trends shown in the annual precipitation maps
of the past 20 years. Additionally, the climatic changes over a longer period were also

432 considered. Sediment dating data records and the spatial-temporal distribution of 433 vegetation in the Chinese Loess Plateau (Sun et al., 2015, 2017; Xin et al., 2008) suggest that the Holocene climate was dry and cold between 6 and 3 Ka (Wang et al., 434 435 2012; Bian et al., 2014). Furthermore, the spatial distribution maps of geomorphic parameters (e.g., hypsometric integral (HI), Stream length-gradient index (SL)) 436 437 previously used to analyse the relationship between active tectonics and rainfall show no obvious features (Shi et al., 2018; Zhang et al., 2019). Therefore, the knickpoints 438 439 are unlikely the result precipitation trends, as there is no real variation in rainfall along 440 the Qianhe Graben.

441

442 Secondly, knickpoints can be traced along rivers and it is clear that the slope-break 443 knickpoints do not fall on mapped lithological boundaries (Fig. 1c). Interestingly northern knickpoints occur in Cretaceous sandstones, while the southern knickpoints 444 445 are found across a range of lithologies from Cretaceous sandstones to Early Paleozoic diorite (Fig. 1c and 5). Previous studies have discussed that lithological resistance will 446 447 not increase the  $k_{sn}$  below knickpoints (Snyder et al., 2000; Wobus et al., 2006), 448 suggesting that the presence of most slope-break knickpoints in this area is not caused 449 by the lithological variation.

450

451 Finally, is knickpoint formation the result of an increase in footwall uplift related to 452 active faulting? The evidence of slope-break knickpoints, high topographic relief and 453 gorge formation downstream of knickpoints and that topographic relief scales with
454 knickpoint elevation (Fig. 8) is all consistent with a fault control on knickpoint formation.
455

In summary, the presence of slope-break knickpoints and other field evidence suggest that knickpoint formation in the study area is the result of transient fluvial response to fault uplift during the late Cenozoic. Furthermore, the vertical-step knickpoints here cannot be ignored in that the lithological strength contrast at fault is likely the cause of these vertical-step knickpoints, giving a new insight into fault location.

461

#### 462 **5.2 Landscape response to active faults**

Previous studies have demonstrated that fault initiation or fault linkage results in an 463 464 acceleration of uplift, increasing channel steepness as a result of river incision (Tucker and Whipple, 2002; Harkins et al., 2007; Whittaker and Boulton, 2012; Whittaker and 465 466 Walker, 2015). The horizontal rate of subsequent knickpoint migration is proportion to stream discharge and drainage area (Crosby and Whipple, 2006; Boulton et al., 2014; 467 468 Whittaker and Walker, 2015; Castillo, 2017), while the vertical rate of knickpoint migration depends on the relative magnitude of fault perturbation or base-level fall 469 470 (Wobus et al., 2006; Whittaker and Boulton, 2012). Previous studies have also shown 471 that the  $k_{sn}$  has a significant positive correlation with rock uplift rate (Snyder et al., 472 2000; Wobus et al., 2006). However,  $k_{sn}$  is not directly transformable into uplift rates 473 (Snyder et al., 2000; Kirby et al., 2003). Using these principals, we can extract more 474 detail on the active faulting of the Qianhe Graben.

475

476 Firstly, the vertical component of knickpoint migration was measured as the elevation 477 difference between knickpoints (excluding vertical-step knickpoints) and the likely 478 causative fault (Fig. 11a). The mean and maximum channel elevation difference of this area are ~ 482 and 1136 m, respectively. There is a small decrease from north to south 479 480 in the elevation difference of the northern knickpoints (Fig. 11b), ranging from 600 -481 100 m in height and showing more or less in a linear trend. Southern knickpoints also 482 show a similar trend decreasing from 1150 m in the north to 180 m in the south. The 483 lowest knickpoint height occurs on River 5 at 159 m, which is slightly lower than 484 knickpoints in rivers on either side. Interestingly, this knickpoint is located at the stepover between two segments of TGF (Fig. 5a). 485

486

Previous studies have discussed that a fault linkage increases fault uplift rates and 487 488 forms knickpoints in channels upstream of the linked area as a result of slip acceleration owing to under-displacement of the fault in the linkage zone (Boulton and 489 490 Whittaker, 2009; Whittaker and Walker, 2015; Kent et al., 2017). In previous examples (i.e., Boulton and Whittaker, 2009; Kent et al., 2017) the knickpoint height along the 491 492 strike of the fault clearly follows the overall displacement profile on the fault with a 493 number of rivers/knickpoints defining each linked segment. This is not the case for 494 rivers crossing the northern boundary fault of the Qianhe Graben with knickpoint height 495 generally decreasing to the southeast. Nor is there a clear pattern for the rivers 496 crossing the southwestern margin of the graben, although there is a height minima

497 corresponding to the relay ramp along the TGF but knickpoint elevations are high at
498 either end of the fault array. This pattern of knickpoints indicates that the trend along
499 the southwestern fault is either decreasing to the southeast, or more typical of fault
500 segments but the full length of the faults is longer than previously mapped.

501

502 Here we also note that two knickpoints are present on eight of the rivers, where one 503 knickpoint is high in the channel with an upstream catchment area between  $1 \times 10^7$ 504  $m^2$  and 1 × 10<sup>8</sup>  $m^2$  (Fig. 5). Crosby and Whipple (2006) demonstrated that knickpoints 505 migrate upstream until channel incision at low drainage areas prevents efficient 506 incision and results in the knickpoint location at a threshold drainage area, which in 507 the case of the Waipaoa River (New Zealand) is between  $1 \times 10^5 \text{ m}^2$  and  $1 \times 10^6 \text{ m}^2$ . 508 Therefore, our observations suggest that is unlikely that the upper knickpoints are 509 pinned at the threshold drainage area as the drainage areas are at least an order of 510 magnitude greater than recorded by Crosby and Whipple (2006), suggesting that the 511 upper knickpoints are still migrating through the landscape.

512

As both fault initiation and fault linkage will increase channel steepness and incision causing knickpoint formation and propagation through the river system, it is likely that both signals are being preserved in the landscape of the Qianhe Graben (Tucker and Whipple, 2002; Whittaker and Boulton, 2012; Whittaker and Walker, 2015). Fault initiation occurs prior to fault linkage and therefore, the first incisional wave is marked by the higher knickpoint, while the lower knickpoints may be the result of later fault 519 linkage. Previous studies have shown that the fault segments may evolve without 520 obvious surface connection (soft linkage) or link by breaching the relay zone (hard 521 linkage) (Kim and Sanderson, 2005). There are no relay ramps on north-eastern side 522 of the graben in this study area, although two knickpoints in north-eastern rivers are observed, while the south-western side has a relay ramps along TGF (Fig. 5). 523 524 Therefore, it is possible that the faults defined the north-eastern side of the graben 525 maybe hard-linked outside of the study area, while the south-western side could be 526 soft-linked across the known relay ramp.

527

528 Interestingly the south-western rivers also have overall higher  $k_{sn}$  than the north, which 529 along with higher elevation knickpoints, indicates that the south-western margin is 530 experiencing higher uplift rates. This interpretation is supported by other lines of 531 evidence. Firstly, Song et al. (2001) used paleomagnetic measurements and 532 morphostratigraphy of red bed/clay sequences from pediments to determine that the 533 Liupan Mountain has been uplifting since about 3.8 Ma. Secondly, Chen et al. (2018b) 534 measured the height of highest river terrace (T1 - T5) in the northern of Qianhe Graben, 535 ranging from 8 - 10 m, 20 - 30 m, 60 - 80 m, 130 - 160 m, and 220 - 260 m, suggesting 536 that there is regional uplift with rate of 0.5 - 1.5 mm/yr (Zhang et al., 2019). These 537 results support our observations and suggest that the north-eastern margin of the 538 Qianhe Graben is experiencing lower rates of uplift than the south-western margin.

540 Additionally, in terms of the eight longitudinal profiles without knickpoints, although 541 these rivers are not analyzed in a same way, they are still responding to the regional 542 uplift rate. For example, River 4 does not exhibit knickpoints on the longitudinal profiles 543 but shows a convex log(S) form on SA plot (Fig. 6), suggesting that the uplift rate > 544 erosion rate in this location. On the opposite margin, the River 17 shows a linear log(S)545 form on SA plot, indicating that the uplift rate  $\approx$  erosion rate. Therefore, the south-546 western rivers without knickpoints have likely higher uplift rates than north-eastern 547 rivers as the erosion rate is assumed to be similar in the absence of erosion data. 548 Similar to the rivers exhibiting knickpoints, the  $k_{sn}$  is higher for the south-western rivers 549 without knickpoints than north-eastern rivers (Table 2), suggesting that the uplift rate is higher in south-western margin of Qianhe Graben. Although, these results do not 550 551 give absolute values of uplift rates, these data provide additional evidence into patterns of rock uplift where the rivers without knickpoints are located. 552

553

#### 554 Landscape response time

Previous studies have demonstrated that knickpoint retreat rates act as a pivotal part of the landscape response time, and that the propagation rate depends on the uplift rate of faults and strength of basement rocks in tectonically active settings (Boulton and Whittaker, 2009; Jansen et al., 2011; Whittaker and Boulton, 2012; Allen et al., 2013; Castillo et al., 2013, 2017; Castillo, 2017; Kent et al., 2017). Therefore, investigating the migration of the knickpoints triggered by fault uplift is another way to reveal the landscape response to active faulting. 562

As shown in Fig. 9, the function ( $L \sim A^{0.64}$ ) demonstrates that the knickpoints follow a 563 common scaling across the study area suggesting that the knickpoints formed at 564 565 similar times across the graben. Furthermore, the basal loess beds ages can be used to determine the age of river incision as the isochrones of loess sequences can be 566 567 accurately recognized (Zhang et a., 2019). Based on magnetostratigraphy, previous 568 studies have shown that fault initiation occurred before 1.2 - 1.4 Myr (Chen et al., 569 2018b; Zhang et al., 2019). Therefore, using the upstream distance from faults to 570 knickpoints and 1.2 - 1.4 Myr as the time of knickpoint formation, the retreat rates of 571 knickpoints was estimated (Fig. 12; Tables 1 and 4). We recognise that there are a number of uncertainties herein regarding the knickpoint formation mechanism, the 572 573 timing of a) fault initiation and b) fault linkage, and how the terraces ages relate to 574 these events; however, in the absence of other constraints, the 1.2 - 1.4 Myr age range 575 allows us to estimate knickpoint retreat rates for the highest knickpoint in each river 576 (Fig. 12). Furthermore, this timescale is similar to knickpoint ages quoted elsewhere 577 for extensional systems (i.e., Boulton and Whittaker, 2009; Kent et al., 2017).

578

The retreat rates of knickpoints in Qianhe Graben range from 0.3 to 27.3 mm/yr (Table 4), similar to the Gediz Graben (4.5 - 28.0 mm/yr) (Kent et al., 2017), and the Central Apennines of Italy (1.4 - 10.7 mm/yr) (Whittaker et al., 2007). As some previous studies show (Whittaker and Boulton, 2012; Castillo et al., 2017), the retreat rates of knickpoints increase quickly with the total drainage area above faults. As shown in Fig. 584 12, southern rivers with knickpoints have higher retreat rates and larger drainage area 585 above knickpoints than in the northern. For example, River 9 has higher knickpoint retreat rate (27.3 mm/yr at 1.2 Myr) and total drainage area (139.1 km<sup>2</sup>), while the 586 587 River 5 has the lowest retreat rate (4.0 mm/yr at 1.2 Myr) and total drainage area (66.3 km<sup>2</sup>). Furthermore, knickpoints retreat rates of TGF and QMF decrease from north to 588 589 south along the strike of fault array, consistent with knickpoint elevation and  $k_{sn}$ , further 590 supporting the interpretation that the fault uplift will increase to the northwest and 591 decrease with the loss of stream discharge to southeast. These results above indicate 592 that the higher uplift rates induced the knickpoints to migrate further in the north.

593

594 Finally, to compare with other knickpoints in different sites (e.g., Hayakawa and 595 Matsukura, 2003; Bishop et al., 2005; Whittaker et al., 2007; Loget and Van Den 596 Driessche, 2009; Whittaker and Boulton, 2012; Ye et al., 2013; Castillo, 2017; Kent et 597 al., 2017), selecting 1.4 Myr as the minimum age of the fault initiation in Qianhe Graben 598 and all the knickpoints (except for the lower knickpoints) retreat rates against drainage 599 area are shown in Fig. 13. Of these different sites, the knickpoint retreat rates related to Messinian Salinity Crisis (MSC) in the Mediterranean Sea (Loget and Van Den 600 601 Driessche, 2009) are the fastest (0.25 - 20.00 m/yr), occurred over 0.1 - 1.0 Myr, which 602 induced by base-level fall as a result of sea-level fall. While the retreat rates of Puerto Vallarta in west-central Mexico (Castillo, 2017) are the slowest (0.07 - 0.72 mm/yr), 603 604 and the age of the rock uplift is 12.5 Kyr, which was caused by base-level fall as a 605 result of faulting.

Interestingly, published data can be divided into two groups based upon the mechanism of knickpoint formation, where the first group induced by base-level fall as a result of faulting has the higher linear fit ( $R^2 = 0.80$ ), while linear fit of the second group caused by eustatic sea-level fall is 0.62 (Fig. 13). These robust fits indicate that the fault controlled knickpoints generally have slower retreat rates, than when triggered by sea-level fall, and that fault slip rate likely strongly controls the speed of knickpoint migration (c.f., Boulton and Whittaker, 2009).

614

615 When base-level fall as a result of sea-level fall is considered, the knickpoint retreat 616 rate does not seem to be related to the age of sea-level fall events. By contrast, the 617 retreat rates caused base-level fall as a result of faulting seem to be negatively related 618 to the time of faulting events, indicating that the older faulting events have lower 619 knickpoint retreat rates. Older faulting events having lower retreat rates can be 620 explained as a result of the drainage area decreasing as knickpoints migrate upstream 621 resulting in a loss of erosional efficiency and slowing down knickpoint migration 622 (Crosby and Whipple, 2006; Castillo, 2017).

623

However, it is not clear why this is also not true of sea-level fall knickpoints or why the scaling relationship is different depending on the knickpoint trigger mechanism. Ye et al., (2013) suggests that the knickpoint retreat rate on Tahiti may be independent of drainage area as a result of the generally small size of the catchments studied. Yet, 628 this is not the case for knickpoints studied by Loget and Van Den Driessche (2009) 629 who show the drainage area dependency on knickpoints formed during the MSC. 630 Therefore, the difference in scaling is unlikely the result of drainage area differences. 631 However, it is notable that most sea-level fall knickpoints are described as steep waterfalls that migrate because of plunge-pool erosion (i.e., Ye et al., 2013) as 632 633 opposed to stream-power dependent erosion along a steep bedrock river. Therefore, 634 we hypothesise that different mechanisms of erosion account for the difference in 635 scaling observed.

636

# 637 **5.3 Fault linkage causing knickpoints**

As shown previously, we hypothesize that the two segments of TGF faults are currently 638 639 linked (Fig. 5a and 14a). However, relay breaching faults are not observed leading to 640 some uncertainty in the current fault geometry. Fault linkage and growth are important 641 processes in basin-bounding normal fault systems (Peacock, 2002; Kairanov et al., 642 2019) where normal fault segments are composed of overlapping segments (Childs et 643 al., 2009; Wang et al., 2018a). Previous studies have addressed that fault growth 644 occurs via increasing fault length and displacement (Walsh and Watterson, 1988; 645 Walsh et al., 2003), where the final fault length will be estimated by the fault's slip 646 history and will grow mainly by displacement accrual (Nicol et al., 2010; Jackson and Rotevatn, 2013; Rotevatn et al., 2018). Additionally, the fault displacement-length 647 648 model (Wells and Coppersmith, 1994; Soliva and Benedicto, 2004; Kim and 649 Sanderson, 2005; Rotevatn et al., 2018; Wang et al., 2018a), allows individual faults

to have finite lengths and thus along-strike strain or displacement variations can be
predicted (Nicol et al., 2002; Fossen and Rotevatn, 2016). Therefore, these models of
fault scaling can be used to study the character of normal TGF growth and linkage.

Many researchers have proposed that faults have a constant  $d_{max}/L$  ratio for individual fault arrays (Soliva and Benedicto, 2004; Kim and Sanderson, 2005; Schultz et al., 2008; Soliva et al., 2008; Li et al., 2018; Torabi et al., 2019), where the  $d_{max}$  and L are the maximum cumulative displacement on a fault and the maximum length of the fault, respectively. The  $d_{max}/L$  ratio depends on the tectonic regime and the rate of fault propagation (Peacock and Sanderson, 1996; Kim and Sanderson, 2005).

660

661 As shown in Fig. 14a, two stages are used to describe the patterns of TGF (southern fault) before and after fault linkages. During stage 1, two initially isolated fault 662 663 segments of TGF are 40.1 and 48.3 km in length, respectively, and propagate towards 664 each other. The displacements of north and southern sections are calculated by the 665 ratio  $d_{max}/L = 0.04$  (Kim et al., 2001), resulting in a displacement of 1.6 and 1.9 km, respectively (Fig. 14b). At stage 2, the faults segments interact with each other and 666 667 may be linked by breaching the relay zone (Fig. 14a). After linkage, fault length will be 84.9 km (Fig. 14c). The displacement is estimated by the ratio  $d_{max}/L = 0.025$  (Kim and 668 669 Sanderson, 2005), resulting in a predicted displacement of 2.1 km after fault linkage 670 (Fig. 14b). This event will cause slip rates to increase in the center of the fault as a

671 result of under displacement resulting in a second phase of knickpoint propagation to672 take place.

673

674 This thought experiment is important because it can reveal how normal faults grow 675 and link in the basin, the frequency and magnitude of seismic hazard along the length 676 of a fault array (Cowie and Roberts, 2001; Soliva et al., 2008; Boulton and Whittaker, 677 2009; Nicol et al., 2010; Kent et al., 2017) and the long-term tectono-stratigraphic 678 development of graben (Gawthorpe and Leeder, 2000; Ge et al., 2018). The seismic 679 hazard of this loess-covered area is not well known. Therefore, it is possible to use the 680 fault displacement-length model and fault surface rupture length to predict the 681 magnitude of potential earthquakes before and after fault linkage. In an earthquake, 682 between one-half and one-third of the total fault length will rupture (Mark, 1977; Kayabali and Akin, 2003). Following Wells and Coppersmith (1994), the magnitude 683 684  $(M_w)$  can be expressed as follows:

685

$$Mw = 4.86 + 1.32 \log L \tag{8}$$

686 Where  $M_w$  is moment magnitude *L* is fault rupture length (in km).

687

For the northern TGF segment, rupture of one half to one third of the fault would be 13.4 and 20.1 km, while the ruptures of southern segments are 16.1 and 24.2 km, respectively. Before linkage, this could result in earthquakes on the northern and southern faults with predicted  $M_w$  of 6.3 - 6.6 and 6.5 - 6.7, respectively. After linkage, 692 the ruptures of one-third to one-half of the TGF are 28.3 and 42.5 km, potentially 693 resulting in an earthquake with predicted M<sub>w</sub> of 6.8 - 7.0. As for the QMF in the northern margin, the ruptures of one-third to one-half of the QMF are 21.0 and 31.5 km, and 694 695 there will be potential earthquake with predicted  $M_w$  of 6.6 - 6.8. These results are 696 similar to Cheng et al. (2014) discussed before ( $M_w > 6.0$ ), and consistent with risk 697 map of this area (Fan et al., 2016). Therefore, even one-third of the fault segment will 698 produce a high magnitude earthquake and increase the risk of the seismic hazard after 699 fault linkage. This new finding not only shows the potential risk of seismic hazards 700 revealed by fault linkage event which previous studies never documented, but also 701 stresses that more attention should be paid to the relationship between earthquake 702 and fault length in this area.

703

# 704 6 Conclusions

705 To investigate the fault activity in the Qianhe Graben of Southwest margin of Ordos, 706 China, we used patterns of knickpoints in longitudinal profiles to analyse the transient 707 fluvial response to active faulting. Vertical-step knickpoints were identified along the 708 trace of the southern part of the GGF revealing new information on the location of this 709 little known structure. Whilst, slope-break knickpoints were identified across the region 710 and were interpreted as the response to the initiation of the main northern (QMF) and 711 southern graben (TGF) boundary faults at 1.2 - 1.4 Myr. These knickpoints migrate 712 upstream, and the effects of the new tectonic boundary conditions propagate 713 throughout the catchment. Calculated retreat rates of knickpoints in this area are in

the range 0.3 - 27.3 mm/yr, and consistent with other studies of fault-driven knickpoint
formation. Comparison with other previous studies suggests that knickpoints
recession induced by base-level fall as a result of faulting are relatively slower than
base-level fall as result of sea-level fall.

718

719 Finally, although further research is required to confirm that the southern TGF fault 720 segments are linked, a displacement-length model is used to study the evolution of 721 two TGF isolated segments, and predict the potential earthquake magnitude before 722 and after fault linkage, resulting in M<sub>w</sub> of 6.3 - 6.7 and 6.8 - 7.0, respectively. 723 Demonstrating that the growth and linkage of TGF will increase the magnitude and 724 frequency of the earthquakes and other hazards along this structure. All of these 725 observations derived from geomorphic analysis are powerful tools for the geoscientist 726 as they not only quantify the transient landscape response to active faulting but also 727 provide a new insights into seismic hazards and tectono-stratigraphic development, 728 especially in areas difficult to access. Such insights can be critical for future 729 sustainable environmental development and management in areas vulnerable to 730 seismic and related hazards.

731

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**Fig. 1.** Simplified regional geological map of Qianhe Basin. (a) map of China, data from http://www.dsac.cn/; (b) map of the regional geological background, adapted from (Rao et al., 2017; Cheng et al., 2018; Han et al., 2018), with earthquake data from (Cheng et al., 2014; Fan et al., 2016, 2018). The red lines are faults in central China: QLF: Qinling Fault; HYF: Haiyuan Fault; KLF: Kunlun Fault; LPSF: Liupanshan Fault; LSTB: Longmen Shan Thrust Belt; (c) The geological map modified from (Chen et al., 2004), showing the main lithologies and the significant regional faults. The four red NW faults are the target fault of this research, Qianhe Basin fault zone. QMF: Qishan-Mazhao Fault; QBF: Qianyang-Biaojiao Fault; GGF: Guguan-Guozhen Fault; TGF: Taoyuan-Guichuansi Fault. Key

cities: Lx, Longxian; Cb, Caobi; Qy, Qianyang; Xg, Xiangong. I: Uplift region of southwestern Ordos's margin; II: Differential descent area of Weihe Basin; III: Differential uplift region of Liupan-Longshan; IV: Qinling uplift area.



**Fig. 2.** Geomorphology of the study area. (a) SRTM (1 arc-second, NASA/USGS) was used as the digital elevation model of the Qianhe fault zone, the black terrace lines on the north side of Qianhe modified from (Chen et al., 2018b). Key cities: Lt, Liangting; Cb, Caobi; Qy, Qianyang; Qs, Qishan; Bj, Baoji; Fx, Fengxiang. LF, Linyou Fault; CF, Chishazhen Fault; DF, Duijiashan Fault; QLF, Qinling Fault; WF, Weihe Fault. (b) ~ (d) The topographical profiles of AA', BB', CC', respectively. (e) Tectonic framework modified from Shi (2011).



**Fig. 3.** Knickpoints patterns in terms of river longitudinal profile and log-log slope-area plot. Both morphologies may represent the fluvial response to active faults, modified from Kirby and Whipple (2012).



**Fig. 4.** (a) Standard logarithmic S-A plot of stream-power incision model, modified from (Chen et al., 2006); (b) Fit to the river profile by mathematic models. Where *Y* is elevation; *X* is the length of the river, *a*, *b* are coefficients independently determined for each profile, modified from Dong et al. (2017).



**Fig. 5.** (a) The distribution of main rivers and knickpoints in study area. The black points are the slopebreak knickpoints and the red point is the vertical-step knickpoint. River 1 to River 11 are south rivers, River 12 to River 24 are north rivers. The red box indicates the location of potential fault linkage in the future. NN' and SS' are two profiles along the strike and paralleling the QMF and TGF. (b) Annual mean



precipitation distribution map in 2017, resampled from PERSIANN-Cloud Classification System (PERSIANN-CCS). See Fig. 1 for fault names.

**Fig. 6.** The left columns show representative examples of river longitudinal profiles (black solid lines), the relationship between downstream distance and drainage area (red solid lines), and black points mark the knickpoints location. While the right columns show the SA plots extracted from SRTM1, and the concavities,  $\theta$ , and normalised steepness index,  $k_{sn}$ , where  $\theta$  =0.45 are also shown on the SA plots. The black line on SA plot of River 4 is log(S) curve. All these rivers show different river longitudinal profiles with vertical-step knickpoints, without knickpoints, and slope-break knickpoints, respectively.



Fig. 7. The *k*<sub>sn</sub> ratios of knickpoints along strike.





**Fig. 8.** The relationship between the elevation of the knickpoints and profile relief plotted along strike, which shows that there is a similar trend between the elevation of the knickpoints and relief. (a) and

(b) are the north and south profile relief along strike, respectively. (c) and (d) are the north and south profile (NN' and SS') relief against knickpoint elevation, respectively.



Fig. 9. The map of upstream distance from faults to knickpoints against total drainage area.



**Fig. 10.** (a) The topography map of Jinlinghe Graben. (b) Representative Slope-Area plots for two tributaries on northside of River 2.



**Fig. 11.** (a) River longitudinal profile shows the difference between fault and knickpoints. The dashed line shows the projected profile for upper reach. (b) The elevation difference in fault and knickpoints of Qianhe Graben.

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**Fig. 12.** Retreat rates of knickpoints (except for the lower knickpoints) along strike in this study area, showing a range of fault initiation at 1.4 Myr.



**Fig. 13.** The map of knickpoint retreat rates of knickpoints against drainage area in different areas. 1.4 Myr was selected as the age of the fault initiation in this study area (see text for details).





**Fig. 14.** (a) Plot of different states before and after fault linkage. (b) The relationship between faults length and displacement of TGF. (c) Fault linkage model (Wells and Coppersmith, 1994; Kim and Sanderson, 2005; Fossen and Rotevatn, 2016; Wang et al., 2018a).

Table 1.	Table 1. The statistics of extracted long rivers with knickpoints. * donates rivers with second (higher) knickpoints.											
River Number	Distance along strike	river length	Relief	Active fault elevation	Total Drainage area	Knickpoint elevation	Upstream distance of knickpoints	<i>k</i> sn above knickpoint	<i>k</i> sn below knickpoint	<i>k</i> <sub>sn</sub> ratio	Knickpoint retreat rate (at 1.2 Myr)	Knickpoint retreat rate (at 1.4 Myr)
	km	km	m	m	km²	m	km	m <sup>0.9</sup>	m <sup>0.9</sup>		mm/yr	mm/yr
1*	76.3	54.9	952	843	123.2	1687	17.7	26.8	59.2	2.2	14.8	12.6
						1324	12.2	59.2	67.2	1.1	10.2	8.7
2	62.7	56.3	1033	1076	3.3	1119	0.4	16.8	34.8	2.1	0.3	0.3
3*	71.3	108.8	878	1109	36.2	1713	14.5	42.1	49.1	1.2	12.1	10.4
						1572	11.0	49.1	62.5	1.2	9.2	7.9
5	53.0	109.3	875	1091	66.3	1250	4.8	101.0	84.3	0.8	4.0	3.4
8*	43.2	137.2	925	1092	115.8	1909	26.8	29.6	71.8	2.4	22.3	19.1
						1562	15.4	71.8	97.4	1.4	12.8	11.0
9*	33.1	143.9	1174	1125	139.1	2125	32.7	12.9	14.7	1.1	27.3	23.4
						2061	30.1	14.7	106.0	7.2	25.1	21.5
10	27.7	134.5	1285	1209	57.3	2245	13.8	11.0	115.0	10.5	11.5	9.9
11	2.9	160.1	892	1324	194.9	1907	22.9	56.6	91.0	1.6	19.1	16.4
12*	2.4	111.0	760	1151	108.6	1720	15.1	18.6	28.0	1.5	12.6	10.8
						1546	25.7	28.0	88.1	3.1	21.4	18.4
14*	16.1	123.3	452	945	100.5	1330	23.3	20.0	43.1	2.3	19.4	16.6
						1100	16.3	43.1	45.8	1.1	13.6	11.6
16*	26.9	106.7	524	888	93.4	1288	19.9	23.7	24.6	1.0	16.6	14.2
						1155	16.5	24.6	46.8	1.9	13.8	11.8
18	34.5	93.2	534	832	67.7	1184	21.2	24.3	43.1	1.8	17.7	15.1
20	45.8	80.2	462	897	43.4	966	3.4	22.7	43.8	1.9	2.8	2.4
21	51.6	79.0		874	87.9	1002	8.7	28.6	70.8	2.5	7.3	6.2
23	61.7	61.0	517	989	26.6	1371	10.1	17.2	59.3	3.5	8.4	7.2
24*	65.9	54.6	586	1023	19.0	1395	7.8	27.5	46.7	1.7	6.5	5.6
						1250	5.3	46.7	65.7	1.4	4.4	3.8

Table 1. The statistics of extracted long	g rivers with knickpoints.	* donates rivers with second	(higher) knickpoints

No	Length	Log(S)	k	θ	± -	$R^2$			
	( <i>km</i> )	Curve	Ksn			Linear	Exponential	Logarithmic	Power
4	111.4	Convex	80.4	0.53	0.03	0.76	0.84	0.97	0.89
6	99.5	Linear	46.6	0.43	0.03	0.74	0.80	0.95	0.93
7	102.0	Linear	50.3	0.32	0.07	0.78	0.83	0.95	0.92
13	78.6	Convex	60.7	0.55	0.05	0.74	0.81	0.95	0.92
15	106.7	Convex	43.2	0.37	0.03	0.86	0.90	0.93	0.88
17	83.6	Linear	30.1	0.37	0.04	0.87	0.90	0.90	0.88
19	63.1	Linear	36.3	0.38	0.03	0.83	0.88	0.90	0.87
22	83.7	linear	45.9	0.26	0.04	0.85	0.92	0.93	0.83

Table 2. The information about long river profiles without knickpoints.

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Table 3. The statistics of the vertical-step knickpoints in the River 2 tributaries.

River number	River length (km)	<i>k</i> sn above knickpoints	<i>k</i> sn below knickpoints	<i>k</i> sn ratio
R2-5	55.2	40.2	39.4	1.0
R2-6	49.4	49.9	40.8	0.8
R2-7	44.7	24.4	38.6	1.6
R2-8	42.9	29.2	40.4	1.4
R2-9	40.5	34.9	39.7	1.1
R2-10	38.6	33.0	39.1	1.2
R2-11	36.4	27.6	39.7	1.4
R2-12	34.4	26.7	42.0	1.6

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Table 4. Statistics of knickpoints retreat rates (mm/yr) between the two sides of Qianhe Graben.

Foult	Maxi	mum	Minii	mum	Mean		
Fault	at 1.4 Myr	at 1.2 Myr	at 1.4 Myr	at 1.2 Myr	at 1.4 Myr	at 1.2 Myr	
TGF	23.4	27.3	0.3	0.3	12.1	14.1	
QMF	16.6	19.4	2.4	2.8	10.3	12.0	