Geomorphological signatures of the evolution of active normal faults along the Langshan Mountains, North China

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ABSTRACT

Segmentation, propagation, and linkage of normal faults often occur in regions of active extension, and observations of the distribution and structural properties of segment boundaries can provide important insights for seismic hazard assessment. In this study, we carry out quantitative geomorphological analysis to evaluate the relative tectonic activity along the Langshan Piedmont Fault (LPF), which bounds the NW margin of the Hetao Graben, North China. On the basis of obtained morphometric indices (HI, BS, Smf, VF, SLK, and χ1), tectonic knickpoint heights, footwall topography, and small unmanned aerial vehicles (sUAV)-based field observations, we demonstrate that: (i) The Langshan landscape is in a state of disequilibrium in response to active rock uplift and channel incision; (ii) The LPF consists of two major fault segments with lengths of 65 and 95 km, respectively, which likely have been linked with each other; (iii) Rupturing of the whole of one segment can generate an earthquake of $M_s \sim 7.3–7.5$, and earthquake magnitude may reach $M_s \sim 7.8$ if the entire fault trace of ~160 km is ruptured, posing a significant seismic risk in the western Hetao Graben. These findings would further our understanding of normal fault evolution through space and time in actively extending regions.

1. Introduction

Fault segmentation commonly occurs in regions of active extension, and potential segment boundaries may act as barriers to inhibit rupture propagation, providing important insights into seismogenic behaviors of active normal faults (e.g., Crone & Haller, 1991; Ding, 1990; DuRoss et al., 2016; Ganas, Roberts, & Memou, 1998; Ganas et al., 2005a; Machette, Personius, Nelson, Schwartz, & Lund, 1991; Schwartz & Coppersmith, 1984; Swan, Schwartz, & Cluff, 1980; Zhang, Mao, & Slemmons, 1999; Zhang, Slemmons, & Mao, 1991). Nevertheless, due to stress feedback between adjacent fault arrays, fault segments tend to grow laterally and hence become linked with each other (Cowie, 1998; Cowie & Roberts, 2001). Therefore, studies with aim to demonstrate normal fault evolution scenarios (segmentation and linkage) have substantial implications for seismic hazard assessment. However, there exists a general lack of high-resolution paleo-seismic data to unravel detailed rupture history along the whole fault trace. As a consequence, topographic expressions associated with active normal faulting have often been utilized to evaluate tectonic activity, such as fault-generated scarps (e.g., Bubeck et al., 2015; Ganas, Palvides, & Karastathis, 2005b; Ganas et al., 2004; He, Wei, & Densmore, 2016; Rao, Lin, Yan, Jia, & Wu, 2014), and triangular facets (e.g., DePolio & Anderson, 2000; Petit et al., 2009; Rao, Cheng, Yu, Yan, & Lin, 2017; Topal, Keller, Bufe, & Koçyiğit, 2016; Tsimi & Ganas, 2015). Because active deformation also affects rock uplift and channel incision processes (Attal, Tucker, Whittaker, Cowie, & Roberts, 2008; Cowie et al., 2006; Keller & Pinter, 2002), the morphological features of channel longitudinal profiles (e.g., Amato et al., 2017; Kirby & Whipple, 2001; Pavan, Pazzaglia, & Catalano, 2016; Snyder, Whipple, Tucker, & Merritts, 2000; Wobus et al., 2006) and footwall landscape (e.g., Ferrarini et al., 2017; Kent, Boulton, Stewart, Whittaker, & Alçiçek, 2016; Roda-Boluda & Whittaker, 2018; Whittaker & Walker, 2015) have also been used to detect active structures. Moreover, benefiting from the progress in geographic information system (GIS) techniques and the globally covered Digital Elevation Models (DEMs), morphotectonic indices can be accurately acquired to quantitatively and efficiently evaluate the relative tectonic activity in a given region (e.g., Bagha et al., 2014; Cheng et al., 2018; Delcaillau et al., 1998, 2010; El Hamdouni, Iriaray, Fernández, Chacón, & Keller, 2008; Gao, Zeilinger, Xu, Wang, & Hao, 2013; Giaconia et al., 2012; Matoš, Pérez-Peña, & Tomljenović, 2016; Menier et al., 2017;
in China (Figure 1(a)), provide excellent chances to investigate tectonic characteristics and geomorphology in actively extending regions (e.g., Deng, 2007; Deng & Liao, 1996; Dong, Zhang, Zhang, Zheng, & Chen, 2018a; Dong et al., 2018b; He, Ma, Long, Wang, & Özkaymak, 2015; Pedrera, Pérez-Peña, Galindo-Zaldívar, Azañón, & Azor, 2009; Pérez-Peña, Azor, Azañón, & Keller, 2010; Wu, Xiao, & Yang, 2014; Yildirim, 2014).

The continental rifts characterized by active normal faults around the tectonically stable Ordos Block in China (Figure 1(a)), provide excellent chances to investigate tectonic characteristics and geomorphology in actively extending regions (e.g., Deng, 2007; Deng & Liao, 1996; Dong, Zhang, Zhang, Zheng, & Chen, 2018a; Dong et al., 2018b; He, Ma, Long, Wang, & Özkaymak, 2015; Pedrera, Pérez-Peña, Galindo-Zaldívar, Azañón, & Azor, 2009; Pérez-Peña, Azor, Azañón, & Keller, 2010; Wu, Xiao, & Yang, 2014; Yildirim, 2014).
Figure 2. Simplified geological map draped over hillshade map, showing the distribution of lithological units and major active faults in the western Hetao Graben (modified after Geological Team of Inner Mongolia (GTIM), 1981). Note: LPF, Langshan Piedmont Fault; SPF, Seertengshan Piedmont Fault.

Figure 3. 5-km-wide swath topographic profiles of four selected transects showing landscape topography across the Langshan Mountains. Notes: Steep slopes and high reliefs characterize the southeastern flank. The swath profiles are all constructed with sampling interval of 100 m using the SwathProfiler, an ArcGIS add-in shared by Pérez-Peña et al. (2017). The relief values are calculated using a sampling circular window of 30 m. Locations are shown in Figure 1(c).
C. HE ET AL.

as a whole, or consists of several segments with distinct rupture histories. To date, only few studies on individual geomorphic indices have been carried out (e.g. Dong et al., 2018a; Liu et al., 2016), systematic morphotectonic analysis indicative of the level of tectonic activity in the Langshan region is still lacking.

In this study, we integrate the morphometric characteristics of drainage basins, channel long-profiles and range-fronts with the features of tectonic landforms mapped from small unmanned aerial vehicles (sUAV)-acquired DEMs during field surveys, to evaluate the relative tectonic activity along the LPF. As a result, we demonstrate the segmentation and likely linkage of this major fault, and discuss seismic potentials in the study area. Meanwhile, the results of this study would be helpful in better understanding structural

Zhang, 2018; Jiang, Xiao, & Xie, 2000; Rao, Chen, Hu, Yu, & Qiu, 2016; Rao, Lin, & Yan, 2015; Zhang, Jia, Wang, & Zheng, 1985; Zhang, Yang, Zhong, & Mi, 1995; Rao et al., 2014, 2017, 2018; State Seismological Bureau (SSB), 1988; Xu, Ma, & Deng, 1993; Zhang, Mercier, & Vergély, 1998). In contrast to other rift-border faults with earthquakes of \( M \geq 7 \), there is an obvious lack of historical records about strong earthquakes along the Langshan Piedmont Fault (LPF) bounding the northwest margin of the Hetao Graben (Figures 1 and 2). However, existing paleoseismic data demonstrate that the ~160-km-long LPF has been active during the Holocene and is capable of generating ground-rupturing earthquakes (Dong et al., 2018b; Li, Ran, Chen, Wu, & Lei, 2015; Rao et al., 2016, 2018; SSB, 1988). But, it remains unclear whether this major basin-bounding fault moves simultaneously as a whole, or consists of several segments with distinct rupture histories. To date, only few studies on individual geomorphic indices have been carried out (e.g. Dong et al., 2018a; Liu et al., 2016), systematic morphotectonic analysis indicative of the level of tectonic activity in the Langshan region is still lacking.

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Figure 4. Schematic diagrams showing the morphometric indices applied in this study (modified from Keller and Pinter (2002), Özsayın (2016) and references therein): (a) hypsometric curve. (b) hypsometric integral (HI). (c) drainage basin shape (BS). (d) mountain front sinuosity (Smf). (e) ratio of valley floor width to valley height (VF). (f) normalized stream-length gradient (SLK).
### Table 1. Morphometric parameters of the drainage basins in the study area.

| No. | Basin Area (km²) | Trunk channel (km) | Elevation (m) Min. | Mean | Local relief (m) Max. | Mean | Slope (°) | Max. | Mean |
|-----|------------------|--------------------|-------------------|------|----------------------|------|-----------|------|------|
| 1   | 57.45            | 23.66              | 1629.37           | 1133.87 | 1428.57             | 495.50 | 17.68     | 3.38 |
| 2   | 81.07            | 23.45              | 1739.26           | 1130.87 | 1492.51             | 608.39 | 21.41     | 4.61 |
| 3   | 30.75            | 17.21              | 1657.34           | 1045.95 | 1438.56             | 611.39 | 48.53     | 9.79 |
| 4   | 43.48            | 19.14              | 1622.35           | 1025.97 | 1378.62             | 626.37 | 48.47     | 9.40 |
| 5   | 119.40           | 30.60              | 1755.24           | 1075.92 | 1383.62             | 679.32 | 44.67     | 9.89 |
| 6   | 69.51            | 28.09              | 1767.23           | 1046.95 | 1472.53             | 720.28 | 46.62     | 9.68 |
| 7   | 37.93            | 25.94              | 1743.26           | 1036.96 | 1400.60             | 706.29 | 38.29     | 12.36 |
| 8   | 79.91            | 29.34              | 1792.21           | 1044.96 | 1457.54             | 747.25 | 50.94     | 12.25 |
| 9   | 146.73           | 31.87              | 1914.09           | 1073.92 | 1533.47             | 838.16 | 56.95     | 14.88 |
| 10  | 38.01            | 19.60              | 1899.10           | 1048.95 | 1476.52             | 850.15 | 53.49     | 16.63 |
| 11  | 76.15            | 20.84              | 2027.97           | 1059.94 | 1489.51             | 968.03 | 54.87     | 19.86 |
| 12  | 36.49            | 14.71              | 2065.93           | 1054.95 | 1441.56             | 1010.99 | 54.09     | 22.12 |
| 13  | 65.31            | 18.89              | 2083.92           | 1058.94 | 1551.45             | 1024.98 | 48.83     | 20.10 |
| 14  | 116.01           | 29.14              | 2148.85           | 1067.93 | 1705.29             | 1080.92 | 57.20     | 19.57 |
| 15  | 36.74            | 17.77              | 2121.88           | 1036.96 | 1571.43             | 1084.92 | 57.65     | 20.69 |
| 16  | 28.37            | 15.33              | 2031.97           | 1038.96 | 1399.60             | 993.01 | 52.57     | 22.39 |
| 17  | 59.38            | 31.73              | 2095.90           | 1040.96 | 1609.39             | 1054.95 | 54.99     | 21.10 |
| 18  | 49.24            | 22.25              | 2148.85           | 1050.95 | 1473.53             | 1097.90 | 56.17     | 22.30 |
| 19  | 151.88           | 43.00              | 2248.75           | 1032.97 | 1832.17             | 1214.79 | 54.45     | 14.59 |
| 20  | 47.47            | 21.44              | 2310.69           | 1034.97 | 1684.32             | 1275.72 | 71.72     | 22.19 |
| 21  | 105.09           | 30.97              | 2254.75           | 1038.96 | 1521.48             | 1215.78 | 47.99     | 19.05 |
| 22  | 92.69            | 36.88              | 2180.82           | 1029.97 | 1646.35             | 1150.85 | 46.63     | 15.75 |
| 23  | 79.35            | 28.75              | 2073.93           | 1029.97 | 1476.52             | 1043.96 | 54.81     | 18.40 |
| 24  | 134.04           | 31.76              | 2167.83           | 1029.97 | 1579.42             | 1137.86 | 49.88     | 18.88 |
| 25  | 162.21           | 48.75              | 2054.95           | 1032.97 | 1539.46             | 1021.98 | 47.96     | 15.20 |
| 26  | 96.39            | 27.73              | 2042.96           | 1030.97 | 1485.51             | 1011.99 | 44.78     | 16.41 |
| 27  | 56.17            | 21.49              | 1622.38           | 1044.96 | 1305.69             | 577.42 | 44.17     | 12.62 |

**Figure 5.** Hypsometric curves of the 27 drainage basins (1–27 from southwest to northeast).

Notes: The obtained curves are convex- or S-shaped. The hypsometric curves and integral (Hi) values (Figure 6(a)) were acquired by using the CalHypso Tools, an ArcGIS add-in developed by Pérez-Peña et al. (2009a).
...bedrocks and Quaternary sediments, and within the sediments with an average dip of 60° (SSB, 1988; Li et al., 2015; Rao et al., 2018). The estimated vertical slip rates (throw rates) of ~0.5–2.2 mm/yr based on relative chronology of tectonic landforms are with significant uncertainties due to the general lack of precise age constraints (Deng, Cheng, Min, Yang, & Ren, 1999; Huang, Zhang, Li, Liu, & Feng, 2012; Rao et al., 2018). The fault strike changes near its center from ~N35°E to the southwest to ~N50°E to the northeast (Figures 1(c) and 2). Even if there is no recorded earthquake of $M \geq 7$ in the western Hetao Graben (Figure 1(a) and (c); China Earthquake Networks Center [CENC], 2017; Deng, 2007; SSB, 1988; Wen, 2014), recent paleoseismological investigations demonstrated that ground-rupturing earthquakes have occurred on this fault during the Holocene with average recurrence interval of ~2450–2500 years (Dong et al., 2018b; Li et al., 2015; Rao et al., 2016, 2018), and some of them likely had ruptured the whole fault trace (Dong et al., 2018b).

Topographically, the high relief and steepness on the southeastern flank of the Langshan Mountains are in contrast to the gentler slopes on its northwestern flank as revealed by the 5-km wide ridge-perpendicular swath profiles (Figure 3). The range height, relief, and...
Table 2. The values of geomorphic indices and parameters used for calculation

| Basin No. | Hl | B1 (m) | B2 (m) | BS | Ln (m) | Ls (m) | S | Vsp (m) | Ew (m) | Em (m) | Er (m) | VF |
|-----------|----|--------|--------|----|--------|--------|---|--------|--------|--------|--------|----|
| 1         | 0.65 | 17834.25 | 3939.76 | 4.53 | 9151.28 | 8797.39 | 1.04 | 71.67 | 1475.24 | 1473.25 | 1405.56 | 1.04 |
| 2         | 0.59 | 18055.32 | 6112.52 | 2.95 |        |        |    |        |        |        |        |    |
| 3         | 0.62 | 13148.25 | 3217.17 | 4.09 | 9713.91 | 9112.51 | 1.07 | 85.61 | 1555.87 | 1542.93 | 1425.47 | 0.69 |
| 4         | 0.57 | 11782.41 | 5909.32 | 1.99 | 13364.08 | 11224.88 | 1.39 | 77.64 | 1503.12 | 1505.11 | 1484.20 | 1.30 |
| 5         | 0.64 | 18822.31 | 6204.48 | 3.04 |        |        |    |        |        |        |        |    |
| 6         | 0.69 | 21168.45 | 4841.25 | 4.37 | 4922.53 | 3935.25 | 1.11 | 87.60 | 1538.95 | 1542.93 | 1361.76 | 0.54 |
| 7         | 0.61 | 19448.68 | 3209.18 | 3.85 | 3745.60 | 3510.00 | 1.07 | 112.48 | 1537.96 | 1523.02 | 1309.00 | 0.51 |
| 8         | 0.57 | 13722.61 | 6991.03 | 1.96 |        |        |    |        |        |        |        |    |
| 9         | 0.65 | 20645.98 | 10524.21 | 1.96 |        |        |    |        |        |        |        |    |
| 10        | 0.52 | 10394.78 | 2843.38 | 3.66 | 3875.82 | 3560.71 | 1.09 | 97.55 | 1486.28 | 1485.32 | 1279.14 | 0.44 |
| 11        | 0.59 | 22291.05 | 3249.41 | 6.86 | 4319.36 | 3619.36 | 1.04 | 100.54 | 1470.81 | 1438.41 | 1279.14 | 0.44 |
| 12        | 0.45 | 16796.72 | 3149.21 | 5.33 | 3011.99 | 2739.62 | 1.10 | 77.64 | 1468.28 | 1468.28 | 1280.14 | 0.31 |
| 13        | 0.67 | 29655.25 | 6160.05 | 4.91 | 4083.58 | 3710.81 | 1.10 | 99.54 | 1873.42 | 1573.79 | 1292.08 | 0.18 |
| 14        | 0.50 | 15680.12 | 6215.02 | 2.52 | 11940.60 | 10401.80 | 1.15 | 111.49 | 1562.84 | 1562.84 | 1279.14 | 0.42 |
| 15        | 0.48 | 22228.05 | 7709.99 | 1.51 | 20569.00 | 15253.95 | 1.35 | 123.43 | 1568.81 | 1568.81 | 1425.47 | 0.79 |
| 16        | 0.57 | 17322.61 | 6991.03 | 1.96 |        |        |    |        |        |        |        |    |
| 17        | 0.65 | 20645.98 | 10524.21 | 1.96 |        |        |    |        |        |        |        |    |
| 18        | 0.52 | 13722.61 | 6991.03 | 1.96 |        |        |    |        |        |        |        |    |
| 19        | 0.67 | 29655.25 | 6160.05 | 4.91 | 4083.58 | 3710.81 | 1.10 | 99.54 | 1873.42 | 1573.79 | 1292.08 | 0.18 |
| 20        | 0.50 | 15680.12 | 6215.02 | 2.52 | 11940.60 | 10401.80 | 1.15 | 111.49 | 1562.84 | 1562.84 | 1279.14 | 0.42 |
| 21        | 0.48 | 22228.05 | 7709.99 | 1.51 | 20569.00 | 15253.95 | 1.35 | 123.43 | 1568.81 | 1568.81 | 1425.47 | 0.79 |
| 22        | 0.57 | 17322.61 | 6991.03 | 1.96 |        |        |    |        |        |        |        |    |
| 23        | 0.65 | 20645.98 | 10524.21 | 1.96 |        |        |    |        |        |        |        |    |

mean slope increase from SW to NE, reach the maximum values on the profile C–C’, and slightly decrease adjacent to the Seertengshan Mountains (Figure 3). Based on the optically stimulated luminescence (OSL) dating of river terraces in the Langshan area, Jia et al. (2015) demonstrated that uplift was uneven between ~58 and 42 ka, being faster in the central and northeastern portions, whereas it became almost constant in space after ~32 ka.

3. Study methods

DEM-based morphotectonic analysis was carried out in order to identify tectonic signals from landscape topographic features of the Langshan Mountains. Firstly, channel networks were extracted from 90-m spatial resolution Shuttle Radar Topography Mission (SRTM) DEMs using ArcGIS ArcHydro Tools. As a result, 27 drainage basins of >28 km² and their main channels have been acquired. Then, morphometric indices and their distribution features were analyzed to explore first-order along-strike variations of resulting structures. In particular, we utilized the CalHyppo Tools developed by Pérez-Peña, Azañón, and Azor (2009a) to obtain hypsometric curves and hypsometric integral (HI) values. Geological information was also compiled to decipher the effect of lithological contrasts on shapes of channel longitudinal profiles. Consequently, major lithological and tectonic knickpoints were mapped and differentiated. In addition, we carried out field surveys to verify the results of our geomorphological analysis. Combining with the obtained SLK values interpolated using kriging method (Pérez-Peña, Azañón, Azor, Delgado, & González-Lodeiro, 2009b), the Langshan topographic (relief, slope, and width) and drainage Chi (x) values (Perron & Royden, 2013; Royden & Perron, 2013; Willett, McCoy, Perron, Goren, & Chen, 2014; Yang, Willett, & Goren, 2015), we demonstrated the tectonic activity and segmentation behaviors of the LPF. In this study, swath topographic profiles were built using the SwathProfiler, an ArcGIS add-in shared by Pérez-Peña et al. (2017).

3.1. Hypsometric curves and hypsometric integral (HI) values

The shapes of hypsometric curves usually reflect distinctive stages of topographic development of drainage basins in terms of equilibrium between relief building forces and erosion processes (Figure 4(a)): convex, sigmoidal, and concave shapes for youthful, mature, and older basins, respectively. The HI index describes the relative volume that has not been eroded (Schumm, 1956; Strahler, 1952), and is defined as the area below a hypsometric curve (Figure 4(b); Alipoor, Poorkermani, Zare, & El Hamdouni, 2011; Mayer, 1990; Pike & Wilson, 1971):

\[ HI = \frac{(H_{\text{average}} - H_{\text{min}})}{(H_{\text{max}} - H_{\text{min}})} \]

In general, higher HI values often correlate with a younger topography that might be affected by active tectonics, and lower HI values reflect an older landscape that have been eroded for a long time and hence seldom influenced by recent tectonism. Accordingly, it has been widely used to evaluate the level of tectonic activity in a specific region (e.g. Alipoor et al., 2011; Mahmood & Gloaguen, 2012; Ntokos, Lykoudi, & Rondoyanni, 2016; Wu et al., 2014).
lack of active structures or the decrease of deformation rate (Bull & McFadden, 1977). The BS index describes the elongation ratio of a drainage basin and is expressed as follows (Figure 4(c); Cannon, 1976):

\[
BS = \frac{B_l}{B_w}
\]

### 3.2. Drainage basin shape (BS)

The shape of a drainage basin may also record the influence of tectonic processes. In general, significant elongation in basin shape characterizes active tectonic regions, while sub-circular basins are indicative of the lack of active structures or the decrease of deformation rate (Bull & McFadden, 1977). The BS index describes the elongation ratio of a drainage basin and is expressed as follows (Figure 4(c); Cannon, 1976):

\[
BS = \frac{B_l}{B_w}
\]
where $B_l$ is the straight-line distance from headwater to mouth, and $B_w$ is the maximum width of a drainage basin. As a consequence, higher BS values reveal more elongated basins.

3.3. Mountain front sinuosity (Smf)

The Smf index reveals the sinuosity of mountain fronts, reflecting the balance between the stream erosion processes that tend to create sinuous mountain fronts, and the active vertical motions that tend to produce straight mountain fronts (Figure 4(d); Bull & Mcfadden, 1977; Keller, 1986). It was defined by Bull (1978) as:

$$\text{Smf} = \frac{L_{mf}}{L_s}$$

where $L_{mf}$ and $L_s$ are the real and straight-line lengths of a mountain front, respectively. Thus, lower Smf values often respond to higher tectonic activity. Previous investigations (e.g. Selçuk, 2016; Silva, Goy, Zazo, & Bardaji, 2003) divided the Smf values into three classes: Class 1 (1.0 ≤ Smf < 1.5; with an inferred slip rate of >0.5 mm/yr); Class 2 (1.5 ≤ Smf < 2.5); and Class 3 (2.5 ≤ Smf; with an inferred slip rate of <0.05 mm/yr).

3.4. Ratio of valley floor width to valley height (VF)

The VF index describes the shape of a valley cross section, and is defined as the ratio of the width of a valley floor to its average height (Figure 4(e); Bull & Mcfadden, 1977; Bull, 1978). It is expressed as:

$$VF = \frac{2V_{fw}}{E_{ld} + E_{rd} - 2E_{sc}}$$

where $V_{fw}$ is the average width of a valley floor; $E_{ld}$ and $E_{rd}$ are the elevations of the divides on the left and right sides of the valley, respectively; $E_{sc}$ is the average elevation of the valley floor. In general, steep and narrow (V-shape) valleys (VF ≤ 1) indicate relatively high uplift rates, and flat-floored (U-shaped) valleys (VF >1) reflect relatively low uplift rates (Bagha et al., 2014; Keller, 1986; Keller & Pinter, 2002; Özsayın, 2016). However, their shapes may significantly change if measured at different locations along the stream channels (Ramirez-Herrera, 1998). Therefore, the VF values have often been measured within a given distance upstream from catchment outlets, facilitating the comparisons among different stream channels (Mahmood & Gloaguen, 2012; Silva et al., 2003). Considering the drainage basin sizes of the study area (Table 1), the distances of ~0.5–1.0 km from catchment outlets were chosen.

Figure 8. Distribution of major non-lithological knickpoint heights of each catchments above the LPF, ranging from 39 to 392 m.

Note: The red dotted lines delimit the probable segment boundary.

Figure 9. Map view of SLK values of the study area interpolated using the Kriging method (Pérez-Peña et al., 2009b).

Notes: High values are mostly concentrated near the catchment outlets, demonstrating the landscape topography affected by the active deformation along the Langshan range front and piedmont.
3.5. Normalized stream-length gradient (SLK)

The gradient of a stream channel results from a long-period ($10^4$–$10^6$ years) adjustment between the erosion and the tectonism (Demoulin, 2011; Hack, 1973; Pizzuto, 1992). Hack (1973) defined the stream-length gradient (SL) as:

$$\text{SL} = \frac{\Delta H}{\Delta L} \cdot L$$

$\Delta H / \Delta L$ is the average gradient of an evaluated channel segment, and $L$ is the total length from the divide to its midpoint (Figure 4(f)). SL is sensitive to the variations of rock uplift rates, lithology, climate, and hydrology; high SL values often reflect high tectonic activity and/or high rock resistance (Azor, Keller, & Yeats, 2002; Brookfield, 1998; Font, Amorese, & Lagarde, 2010; Hack, 1973). In order to eliminate the influence of channel length, a normalized stream-length gradient (SLK) index is defined (Chen, Sung, & Cheng, 2003; Pérez-Peña et al., 2009b), and follows the equations:

$$K = \frac{H_{\text{total}}}{\text{Ln} \left( L_{\text{total}} \right)}$$

$$\text{SLK} = \frac{\text{SL}}{K}$$

where $K$ is a parameter representing the SL index calculated for the entire channel, $H_{\text{total}}$ and $L_{\text{total}}$ are the altitude difference and length of the entire channel, respectively (Figure 4(f)). Perturbations of SLK often reveal river channel response to lithological contrasts and/or ongoing tectonism (Pérez-Peña et al., 2009b). Accordingly, SLK has often been used to assess tectonic activity in regions where rock resistance differences are negligible (e.g., Monteiro, Missura, & Correa, 2010; Wu et al., 2014). Major knickpoints or knick zones can be identified from channel gradients of river long profiles. As well, tectonic-controlled knickpoint heights together with range topographic features are helpful for deciphering fault evolution history (e.g., Boulton & Whittaker, 2009; Kent, Boulton, Whittaker, Stewart, & Alçıçek, 2017; Whittaker & Boulton, 2012).

3.6. Chi ($\chi$) analysis

The parameter $\chi$ is sensitive to the loss of drainage area and disequilibrium across drainage divides (Perron & Royden, 2013; Royden & Perron, 2013; Willett et al., 2014; Yang et al., 2015). Since $\chi$ removes the effect of drainage area, it can be compared among catchments of different sizes. Theoretically, water divides tend to move away from channels with low $\chi$ values towards channels with high $\chi$ values (Willett et al., 2014). Construct of $\chi$ map follows a specific protocol, and high resolution

Figure 10. Distribution of color-coded streams with $\chi$ (chi) values. The differences indicate that drainage divides in the study area tend to migrate from the channels with lower values northwestwards to that with high values. (a) Map view. (b) Close-up view. (c) Perspective view of the $\chi$ values draped over Google Earth image.
DEM if available have often been used (Willett et al., 2014). We firstly extracted hydrological information (flow direction, flow length, and flow accumulation) in ArcGIS Spatial Analysis Tools from 30-m spatial resolution Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) data (the highest resolution now available for us), a joint product of the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). Then, in combination with a Matlab script shared by Sean Willett, $\chi$ values of each streams were calculated with a reference concavity of 0.45, and a critical area of 0.5 km² to define the threshold for the minimum contributing upstream drainage area.

4. Results

4.1. Morphotectonic indices

In the study area, 18 of the total 27 hypsometric curves of drainage basins are convex in shape, and the other 9 are sigmoidal (Figure 5). The obtained HI values range from 0.42 (basin No. 27) to 0.69 (basin No. 6), with an average value of 0.56 (Figure 6(a); Table 2). BS values of the selected drainage basins vary from 1.51 (basin No. 12) to 6.86 (basin No. 17) (Figure 6(b); Table 2). The Smf values range from 1.04 (basin Nos. 1, 2, and 17) to 1.35 (basin Nos. 12–14) (Figure 6(c); Table 2). Among them, some neighboring drainage basins share the same Smf values. Even if the values of the basins (Nos. 12–14) near the fault center are higher, they are still <1.5, and hence can be categorized into Class 1 as described previously (Table 2). The acquired VF values are between 0.18 (basin No. 19) and 1.30 (basin No. 4) (Figure 6(d); Table 2). Except for few relatively higher values measured near fault tips (Nos. 1, 2, and 4 in the southwest, and No. 27 in the northeast), most of them are <1. The large-scale convexity of channel longitudinal profiles combined with the abnormally high SLK values demonstrate the development of knickpoints or knickzones (Figure 7). Specifically, some of them are situated at lithological contacts, i.e. lithological knickpoints as shown in Figure 2, which are excluded in the subsequent analysis. Non-lithological knickpoints markedly change their heights along the trend of the Langshan Range, ranging from 39 m to 392 m (Figure 8).
The along-strike variations are also prominent in map view of SLK values: the highest in basin Nos. 5–8 and the lowest in basin Nos. 12 and 27 (Figure 9). The obtained χ map reveals obvious differences across the main water divides, i.e. the channels on the northwestern side are with higher values than that on the southeastern side (Figure 10), suggesting that the river networks draining the Langshan Mountains are in a disequilibrium state and need to adjust their drainage area through divide migration or river capture to bring the divide to a stable position (Willett et al., 2014).

### 4.2. Tectonic landforms

To validate the results of our morphotectonic analysis, field surveys were also carried out along the southeastern flank of the Langshan range, where pronounced tectonic landforms have been observed.

At Sites 1 and 2 along a southeast-flowing river (R3 in Figure 7), two knickpoints identified from stream long profile have been observed in the field with throw heights of ~2–4 m (Figure 11). Considering the same rock type (granite) crops out both up- and downsides of the knickpoints, their formation is attributed to tectonic uplift rather than differential rock resistances. Sites 3–9 situated along the Langshan piedmont provide evidence of active deformation along the LPF. Site 3 is located near the center of the LPF, where two identified fault traces are nicely displayed by a panoramic photo (view to the northwest) (Figure 13(a)). Near the Langshan range front, striations on bedrock fault plane demonstrate a dominant normal slip-sense (Figure 13(b) and (c)), which are consistent with previous field observations.
divides tend to migrate from the steep southeastern flank towards the gentler northwestern flank. Accordingly, the drainage networks in the Langshan Mountains are in disequilibrium state probably in response to active rock uplift and channel incision. This inference is supported by the dominant V-shaped valleys in elongated drainage basins suggestive of intensified incision (Figure 6(b) and (d)). Nevertheless, the obtained major channel gradients with high SLK values are mostly concentrated near catchment outlets (Figure 9), suggesting the landscape topography is mostly affected by recent deformation along the range fronts that have low Smf values (<1.4; Figure 6(c)). The tectonic activity of this basin-bounding fault inferred from geomorphological analysis is also verified by the widespread fault scarps mapped in the present (Figures 11–16) and previous active tectonic studies (Dong et al., 2018b; SSB, 1988; Li et al., 2015; Rao et al., 2016, 2018). However, along-strike variations of the tectonic activity are also pronounced as revealed by the fluctuations of obtained morphometric indices (Figure 6; Table 2). In combination with the Langshan landscape topography (Figure 17), two major fault segments (SW and NE, respectively) have been designated with a boundary approaching the drainage basin No. 12 based on the following observations: (1) changes of the range front and fault trends from ~N35°E in the southwest to ~N50°E in the northeast, serving as a geometric boundary (DuRoss et al., 2016; Machette et al., 1991; Zhang et al., 1991); (2) tectonic activity is higher in the centers of each segments (as delineated

5. Discussion

All the obtained hypsometric curves are convex- and S-shaped with high HI values (average value of 0.56; Figures 5 and 6(a)), indicating that drainage basins are with low to intermediate maturity (El Hamdouni et al., 2008; Keller & Pinter, 2002; Pérez-Peña et al., 2009a). It is consistent with the observed transient rivers containing both tectonic and lithological controlled knickpoints as revealed by the channel longitudinal profiles and associated SLK values (Figures 7 and 8). The Langshan topographic features (relief and slope steepness; Figure 3) combined with χ values (Figure 10) suggest that water divides tend to migrate from the steep southeastern flank towards the gentler northwestern flank. Accordingly, the drainage networks in the Langshan Mountains are in disequilibrium state probably in response to active rock uplift and channel incision. This inference is supported by the dominant V-shaped valleys in elongated drainage basins suggestive of intensified incision (Figure 6(b) and (d)). Nevertheless, the obtained major channel gradients with high SLK values are mostly concentrated near catchment outlets (Figure 9), suggesting the landscape topography is mostly affected by recent deformation along the range fronts that have low Smf values (<1.4; Figure 6(c)). The tectonic activity of this basin-bounding fault inferred from geomorphological analysis is also verified by the widespread fault scarps mapped in the present (Figures 11–16) and previous active tectonic studies (Dong et al., 2018b; SSB, 1988; Li et al., 2015; Rao et al., 2016, 2018). However, along-strike variations of the tectonic activity are also pronounced as revealed by the fluctuations of obtained morphometric indices (Figure 6; Table 2). In combination with the Langshan landscape topography (Figure 17), two major fault segments (SW and NE, respectively) have been designated with a boundary approaching the drainage basin No. 12 based on the following observations: (1) changes of the range front and fault trends from ~N35°E in the southwest to ~N50°E in the northeast, serving as a geometric boundary (DuRoss et al., 2016; Machette et al., 1991; Manighetti et al., 2015; Zhang et al., 1991); (2) tectonic activity is higher in the centers of each segments (as delineated

Figure 13. Tectonic landforms at Site 4 near the center of the LPF (see Figures 1(c) and 2 for the location). (a) Panoramic photograph showing the distribution of two sets of fault scarps. (b) Bedrock fault plane. (c) Observed striations demonstrating a dominant normal slip.
of the resulting faults if there is no significant change of base level on either side of the range (Densmore, Dawers, Gupta, & Guidon, 2005).

Segment boundaries may play significant roles in perturbing or arresting earthquake rupture, whereas large earthquake is still able to rupture smaller structural discontinuities (Zhang et al., 1999). Due to stress feedback between adjacent fault arrays, they might finally become linked with each other (Cowie, 1998; Cowie & Roberts, 2001). Combining with existing data, the recent paleoseismic study by Dong et al. (2018b) demonstrated that three Holocene earthquakes might have ruptured the entire fault trace, indicating the linkage of fault segments in terms of rupture behaviors. This scenario likely has been recorded by river incision processes, as the rates previously were uneven in the Langshan area but became spatially constant after ~32 ka (Jia et al., 2015). Nevertheless, due to the lack of historical records of earthquakes in the study area and the uncertainties

Figure 14. Topographic features across the fault scarp observed in Figure 13. (a) sUAV-acquired DEM highlighting the topographic features. (b) DEM-based topographic profiles across the fault trace demonstrate vertical separations range from 3.7 to 14.9 m.
Figure 15. Field photos at Sites 5–7 (see Figures 1(c) and 2 for the locations). (a) Fault scarps observed at Site 5 in the northwestern segment. The observed small scarplets were probably produced by recent earthquake event(s). Fault scarps have also been observed near the northwestern extremity: (b) Site 6. (c) Site 7. Note that higher level of river terraces have higher fault scarps, indicating slip accumulation at Site 6.

Figure 16. Fault scarps observed near the south tip of the LPF: (a) Site 8. (b) Site 9. Notes: Although the range decreases in elevation, fault scarps still can be traced in the field. Locations are shown in Figures 1(c) and 2.
As the LPF can be categorized into two major fault segments with lengths of ~65 km and ~95 km, respectively, seismic potentials of the Langshan and neighboring regions can be evaluated using the empirical relationship between the moment magnitudes ($M_w$) and the surface rupture lengths ($SRL$) of active normal faults worldwide (Wells & Coppersmith, 1994):

$$M_w = 4.86 + 1.32 \times \log (SRL)$$

of age constraints, we suggest that future work is still needed to determine whether the demonstrated earthquakes occurred as temporal clustering, or could be correlated as the same event (McCalpin & Nishenko, 1996; Rockwell et al., 2000). More precisely determined fault slip rates on multiple time scales together with complete rupture histories of each segments would further our understanding of structural evolution of this fault.

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$$M_w = 4.86 + 1.32 \times \log (SRL)$$

Figure 17. Along-strike topographic variations along the Langshan Mountains. (a) Slope map. (b) 5-km-wide ridge-parallel swath profiles (The central line is shown in Figure 17(a)). (c) Relief and mean slope of each drainage basins. (d) Range half-width. Note the abrupt changes near the drainage basin No. 12.
If rupturing the whole of one segment, earthquake magnitude would be $M_w \approx 7.3$–7.5. It may reach $M_w \approx 7.8$ if the entire ~160-km-long fault trace is ruptured by single event. In summary, the LPF is able to generate an earthquake of $M_w \approx 7.3$–7.8, posing a significant seismic risk in the western Hetao Graben. These findings would be helpful in better understanding seismic potentials associated with this major boundary fault.

### 6. Conclusions

On the basis of GIS morphotectonic analysis and sUAV-based field observations along the Langshan Mountains, North China, we have reached the following conclusions.

(i) The Langshan landscape is in a state of disequilibrium in response to the rock uplift and channel incision on its southeastern flank affected by the active LPF;

(ii) Morphometric indices together with range topography indicate that the LPF consists of two segments with fault lengths of 65 and 95 km, respectively, which likely have been linked with each other;

(iii) Rupturing of the whole one segment of the LPF will generate an earthquake of $M_w \approx 7.3$–7.5, and earthquake magnitude may reach $M_w \approx 7.8$ if the entire fault trace of ~160 km is ruptured, posing a significant seismic risk in the western Hetao Graben.

We suggest that future investigations integrating precise constraints on the slip rates and paleoseismic histories of each segments would be helpful in better understanding the evolution of this basin-bounding normal fault through space and time.

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