Quantifying the migration rate of drainage divides from high-resolution topographic data

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Abstract

The lateral movement of drainage divides is co-influenced by tectonics, lithology, and climate, and therefore archives a wealth of geologic and climatic information. ~~Besides, i~~It also has wide-ranging ~~consequences~~ implications for topography, ~~the~~ sedimentary record, and biological evolution, thus has drawn much attention in recent years. Several methods have been proposed to determine the ~~direction of~~ drainage-divide's migration state (direction and rate), including geochronological ~~field-based~~approaches~~ investigations~~ (e.g., ^{10}Be~~cosmogenic nuclides sampling~~) and topography~~modeling~~-based approaches (e.g., χ-plots or Gilbert metrics). A key object in these ~~In the above~~ methods~~,~~ is the channel head, which separates the hillslope and channel~~, is an important analysis object~~. ~~Zhou et al.~~

~~(2022a) proposed a method to quantify a drainage divide's migration rate using both sides' high base-level χ values.~~ However, due to the limited ~~by the~~ resolution of topography data, the required channel-head parameters in the calculation often cannot be determined accurately, and empirical values are used in the calculation, which may induce uncertainties. ~~However, how to quantify the migration rate of drainage divides remains challenging.~~ Here, we propose ~~a new~~two ~~approach~~ methods to calculate the migration rate of drainage divides~~ from high-resolution topographic data~~. ~~The new method is based on the cross-divide comparison of channel-head parameters, including the critical upstream drainage area and the gradient of channel head, both of which are used to calculate the normalized channel steepness at the channel head.~~ , ~~one is~~ based on the ~~measured~~relatively accurate channel-head parameters derived from high-resolution topographic data~~, and the other is based on the improved method of Zhou et al (2022a)~~. We then apply the ~~new~~ methods to an active rift shoulder (Wutai Shan) in the Shanxi rift, and a tectonically stable area (Yingwang Shan~~a mountain range in the Loess Plateau~~) in the Loess Plateau~~in North China~~, to illustrate ~~the calculation of~~ how to calculate drainage-divide migration rates. Our results ~~find~~ show that the ~~divide in the~~ Wutai Shan drainage divide ~~range~~ is migrating northwestward at a rate ~~of~~ between 0.21 to 0.27 mm/yr, whereas the migration rates at the Yingwang Shan ~~in the Loess Plateau~~ are approximately zero.~~The northward migration rates at the Wutai Shan range from 0.10 to 0.13 mm/yr. The migration rates are approximately zero at the mountain range in the Loess Plateau.~~ This study indicates that the drainage-divide stability can be determined more accurately using high-resolution topographic data. Furthermore, ~~T~~this study takes ~~his study demonstrates that the migration rate of drainage divides can be determined more accurately once~~ the ~~influence of~~ cross-divide differences in the uplift rate of channel heads ~~are taken into account~~into account in the measurement of drainage-divide migration rate for the first time.

Keywords

Drainage divide; Migration rate; High-resolution topographic data; DEM; Channel head

1. Introduction

The evolution of the Earth's surface is jointly controlled by tectonics, lithology, and climatic conditions (e.g., Molnar and England, 1990; Whipple, 2009; ~~Bonnet, 2009;~~ Gallen, 2018; ~~Zondervan et al., 2020;~~ Bernard et al., 2021; Hoskins et al., 2023)~~. This~~, ~~provides~~ providing a basis for reconstructing the past tectonic (Pritchard et al., 2009; Kirby et al., 2012; ~~He et al., 2021;~~ Shi et al., 2021~~; Schildgen et al., 2022~~) or climatic processes (Tucker et al., 1997; Hancock et al., 2002; Schildgen et al., 2022) through topography. The evolution of unglaciated terrestrial terrains~~topography~~ is fundamentally coupled with changes in drainage systems~~,~~ ~~including~~ ~~which are~~through river's vertical (changes in river long profile) and lateral movements (drainage divide migration and river captures) (Whipple, 2001; Clark et al., 2004; Bonnet, 2009; Willett et al., 2014~~; Zeng and Tan, 2023~~). Previous studies have extensively investigated how river channel profiles respond to tectonic uplift (Whipple, 2001; Crosby and Whipple, 2006; Kirby et al., 2012~~; Pritchard et al., 2009; Kirby et al., 2012; Goren et al., 2014~~), lithological difference (Duvall et al., 2004; Safran et al., 2005; Forte et al., 2016), and precipitation perturbations (Schlunegger et al., 2011; Bookhagen and Strecker, 2012). ~~Knick points, channel steepness and r~~River's long profiles have been used to study the earthquake events (e.g., Burbank and Anderson, 2001; Wei et al., 2015)~~,~~ and the spatio-temporal ~~differences~~ variations of uplift ~~distribution~~ (e.g., Whipple et al., 1999; Kirby et al., 20~~12~~03; Pritchard et al., 2009; Goren et al., 2014)~~, and uplift history (e.g., Pritchard et al., 2009; Goren et al., 2014)~~. ~~However, r~~Recent studies show that the widespread lateral movement of river basins driven by geological and/or climatic disturbance (Yang et al., 2019; ~~Clark et al., 2004; Deng et al., 2020;~~ Zondervan et al., 2020~~Zhao et al., 2021~~; Zhou et al., 2022a; Bian et al., 2024) also interacts with the adjustment of channel profiles (Willett et al., 2014). Drainage-divide migration, one form of river lateral movement~~therefore~~, may not only carry information on geological and/or climatic disturbance (~~Yang et al., 2019;~~ Su et al., 2020; Zondervan et al., 2020; He et al., 2021; Shi et al., 2021; Zhou et al., 2022a; Zeng and Tan, 2023~~; Zeng and Tan, 2023~~) but also ~~impact~~ influence the extraction of tectonic information from channel profiles (Goren et al., 2014; Ma et al., 2020; Jiao et al., 2021). ~~Besides~~Moreover, it ~~also~~ has ~~wide-ranging~~ multi-facet consequences for ~~topography~~ landscape evolution (Scheingross et al., 2020; Stokes et al., 2022~~; Scheingross et al., 2020~~), ~~the~~ sedimentary ~~record~~ processes (Clift & Blusztajn, 2005; Willett et al., 2018; Deng et al., 2020; Zhao et al., 2021), and biological evolution (Waters et al., 2001; Zemlak et al., 2008; Hoorn et al., 2010; Musher et al., 2022). For this reason, the stability of drainage divides has drawn more and more attention in recent years (e.g., Authemayou et al., 2018; Vacherat et al., 2018; Chen et al., 2021; Shelef and Goren, 2021; Sakashita and Endo, 2023; Bian et al., 2024).

Drainage-divide migration is essentially controlled by the cross-divide difference in erosion and topographic slope (Beeson et al., 2017; Dahlquist et al., 2018; Chen et al., 2021; Zhou et al., 2022a~~; Stokes et al., 2022~~). The erosion rates are routinely derived from geochronological techniques, such as cosmogenic nuclides (e.g., ^{10}Be) concentration measurements (Mandal et al., 2015; Struth et al., 2017; Sassolas-Serrayet et al., 2019), which can be used to calculate the migration ~~velocities~~ rates of drainage divides (Beeson et al., 2017; Godard et al., 2019; Hu et al., 2021). However, these techniques are usually based on samples collected from ~~an~~ a catchment outlet that is several, or even tens of, kilometers away from the drainage divide and thus may not represent the erosion rates close to the drainage divide (Sassolas-Serrayet et al., 2019; Zhou et al., 2022a). Besides, the high cost of sample ~~testing~~ processing makes it ~~very~~ challenging to determine the drainage divide's motion by measuring the erosion rates throughout the ~~entire~~ large landscapes. Hence, it would be ideal to find an accessible and efficient method that can be applied to the entire landscape and ~~cross-checked to~~ make full use of the ^{10}Be-derived erosion rates.

The advancement of the digital elevation model (DEM)~~remote sensing technology~~ has promoted the development of geomorphic analysis ~~theory~~, making it possible to determine the drainage divide's transient motion through topography analysis. For example, Willett et al. (2014) ~~developed~~ applied the χ method to map the dynamic state of river basins. Forte and Whipple (2018) proposed the cross-divide comparison of "Gilbert metrics" (including channel heads' relief, slope, and elevation) to determine a drainage divide's ~~motion~~migration direction. Others adopted the comparison of slope angle or relief of the hillslopes across a drainage divide to deduce its stability (Scherler and Schwanghart, 2020; Ye et al., 2022; Zhou et al., 2022b). ~~Although t~~These geomorphic techniques ~~are quantitative~~, so far, ~~they~~ could only determine the migration direction of drainage divides. ~~No rates have been obtained.~~ Braun (2018) ~~raised~~ provided an ~~method~~ equation that considers both alluvial and fluvial areas to calculate the migration velocity of an escarpment (also a drainage divide). Zhou et al. (2022a) developed a technique to calculate the migration rate through the high base-level ~~cross-divide χ ratio of~~ χ values on both sides of a drainage divide~~high base-level channel segments~~. These new ~~above studie~~approaches require channel-head parameters to calculate the migration rate. However, the location of the channel heads sometimes cannot be accurately identified~~,~~ because of the limitation in ~~limited by~~ the resolution of DEMs in natural cases ~~(e.g., Zhou et al., 2022a)~~. For this reason, empirical values of channel-head parameters are used in these studies~~the above study (Zhou et al., 2022a)~~, which may induce uncertainties. ~~However, the channel-head parameter such as the critical upstream area is an empirical value from previous studies, which may not be applicable in specific natural areas and, therefore, could create great uncertainties in the result of migration rates.~~

This study aims to establish an approach to derive the migration rate of drainage divides, at a high precision and low cost, based on topographic analysis. ~~In this study,~~ ~~w~~We choose a tectonically active area~~,~~ (i.e., the Wutai Shan in the Shanxi ~~rift~~Rift) ~~system,~~ and a tectonically inactive area~~,~~ (i.e., ~~an unnamed mountain range~~the Yingwang Shan in the Loess ~~plateau~~Plateau)~~,~~ to demonstrate how to quantify drainage-divide migration rates (Fig. 1). We use the aerial photography acquired by unmanned aerial vehicles (UAVs) and the Structure from Motion (SfM) technology to obtain the ~~high-~~high-resolution ~~topography~~ DEM data of these two areas (0.67 m and 0.84 m spatial resolution in the Wutai Shan and the Yingwang Shan, respectively). Benefiting from the high-resolution data, the location of channel heads can be ~~accurately~~ identified more accurately. ~~Based on the high-resolution data, w~~We then develop~~ed~~ two methods to calculate the drainage-divide migration rates~~,~~. ~~o~~One is based on the measured channel-head parameters, and the other is based on ~~the~~ an improved method of Zhou et al (2022a).~~first identify the position of the channel heads and extract their geomorphic parameters. We then calculate the migration rates of the drainage divides using the channel-head parameters. Moreover, we improve the method in Zhou et al (2022a) to adapt it to areas where the elevations of outlets and channel heads are different across the drainage divide. We apply these two methods in each case to calculate the drainage-divide migration rates. This study aims to establish an approach to derive the migration rate of drainage divides, at a high precision and low cost, based on topographic analysis.~~ ~~Moreover, b~~Combining with~~enefiting from~~ the geological and low-temperature thermochronology studies of the Wutai Shan

(Middleton et al., 2017; Clinkscales et al., 2020)~~detailed tectonic research~~ ~~and the high-resolution topographic data on the~~of ~~Wutai Shan~~, we also ~~attempt to~~ quantify the ~~influence of the~~ cross-divide difference in uplift rates ~~on~~ to improve the precision of drainage-divide migration rate.

2. Methods

2.1 Channel-head-point method

According to the detachment-limited stream power model (Howard and Kerby, 1983; Howard, 1994), the channel's erosion rate (E) can be expressed as:

$$E = KA^{m}S^{n} \tag{1}$$

where K is the erosion coefficient, A is the upstream drainage area, S is the gradient of the river channel, and m and n are empirical constants.

Because of ~~the~~ threshold~~mechanisms~~s such as erosion threshold (the shear stress of overland flow must exceed the threshold of the cohesion of bed material to generate river incision) (Howard and Kerby, 1983; Perron et al., 2008) or landslide threshold (landslides occur when the threshold of soil or rock strength is exceeded in high relief region) (Burbank et al., 1996; Tucker et al., 1998), river channels (following Eq. 1) emerge at a certain distance from the drainage divide. The region between the channel head and the drainage divide is referred to as the hillslope area, where the erosion is controlled by landslide, collapse, and diffusion processes (Stoke and Dietrich, 2006; Stark, 2010; Braun et al., 2018; Dahlquist et al., 2018). The channel-head point is the highest and the closest point to the drainage divide on a river channel (Clubb et al., 2014). Therefore, the erosion rate at channel-head points (E_{ch}) can be described as:

$$E_{ch} = KA_{cr}^{m}S_{ch}^{n} \tag{2}$$

where E_{ch} is the erosion rate at channel-head points, A_{cr} is the critical upstream drainage area of a channel-head point (Duvall et al., 2004; Wobus et al., 2006), and S_{ch} is the channel-head gradient measured along the channel ~~at~~ near the channel-head point.

~~To investigate the influence of the key parameters on the channel-head erosion rate, we plot the curves of the channel-head erosion rate against the critical area based on Eq. 2 for varying channel-head gradient and erosion coefficient (Fig. 1). The plots~~ Eq. 2 ~~show that the channel-head erosion rate (E_{ch}) increases monotonically with the critical area (A_{cr}). When the critical area is invariant, the channel-head erosion rate also increases with the channel-head gradient. A large erosion coefficient also creates a high channel-head erosion rate. The results~~ indicates that the side of a drainage divide with a higher A_{cr} or S_{ch} can have a higher erosion rate than the other side, ~~of the drainage divide~~ and is more likely to pirate the opposite drainage basin. Besides, a high erosion coefficient can amplify the drainage ~~basins'~~ basin's erosion rate.

~~The d~~Drainage-divide migration is essentially controlled by the cross-divide difference in erosion rates and topographic slope (Beeson et al., 2017; Dahlquist et al., 2018; Chen et al., 2021; Zhou et al., 2022a; Stokes et al., 2022). Furthermore, the differential uplift should also be considered when using ~~when one uses~~ the cross-divide erosion rates at the channel heads to calculate the erosion difference across the divide, ~~one should also consider the influence of differential uplift rates in these channel heads (Zhou et al., 2022a),~~ especially in the case of tectonic tilting uplift (Zhou et al., 2022a). The drainage-divide migration rate (D_{mr}) can be obtained according to the cross-divide difference in erosion rate and uplift rate and the slopes across the divide (Zhou et al., 2022a):

$$D_{mr} = \frac{\Delta E_{ch} - \Delta U_{ch}}{tan\alpha + tan\beta} \qquad (3)$$

where ΔE_{ch} is the difference in erosion rate ~~difference~~ between the two sides (annotated as α and β) of the drainage divide ($\Delta E_{ch} = E_{ch\alpha} - E_{ch\beta}$~~),~~). The choice of α or β is arbitrary, and the positive direction of the migration ~~velocity~~~~velocity~~rate is assigned ~~as~~ from the α to the β side whereas the negative is the opposite. ΔU_{ch} is the cross-divide difference in ~~rock~~ uplift rate ($\Delta U_{ch} = U_{ch\alpha} - U_{ch\beta}$), and tanα and tanβ are the gradients on ~~both~~ each side~~s~~ of the drainage divide. ~~Combining Eqs. 2 and 3,~~ Assuming ~~the~~ erosion coefficient (K) is the same on both sides of a drainage divide, Eqs. 2 and 3~~one can~~ allow us to derive the equation of ~~migration velocity of~~ the drainage divide's migration ~~velocity~~rate~~s~~ according to the parameters at the channel-head points:

$$D_{mr} = \frac{K\left[(A_{cr}^{m} S_{ch}^{n})_{\alpha} - (A_{cr}^{m} S_{ch}^{n})_{\beta}\right] - \Delta U_{ch}}{tan\alpha + tan\beta} \qquad (4)$$

~~The choice of α or β is arbitrary, and the positive direction of the migration velocity is assigned as from the α to β side whereas the negative is the opposite. In this equation, we assume the erosion coefficient is unchanged in the vicinity of a drainage divide.~~ If the exact value of K ~~value~~ is unknown, the drainage divide's unilateral erosion rate can be used as a substitution:

$$D_{mr} = \frac{E_{\alpha}\left[1-\frac{(A_{cr}^{m}S_{ch}^{n})_{\beta}}{(A_{cr}^{m}S_{ch}^{n})_{\alpha}}\right]-\Delta U_{ch}}{tan\alpha+tan\beta} \qquad (5)$$

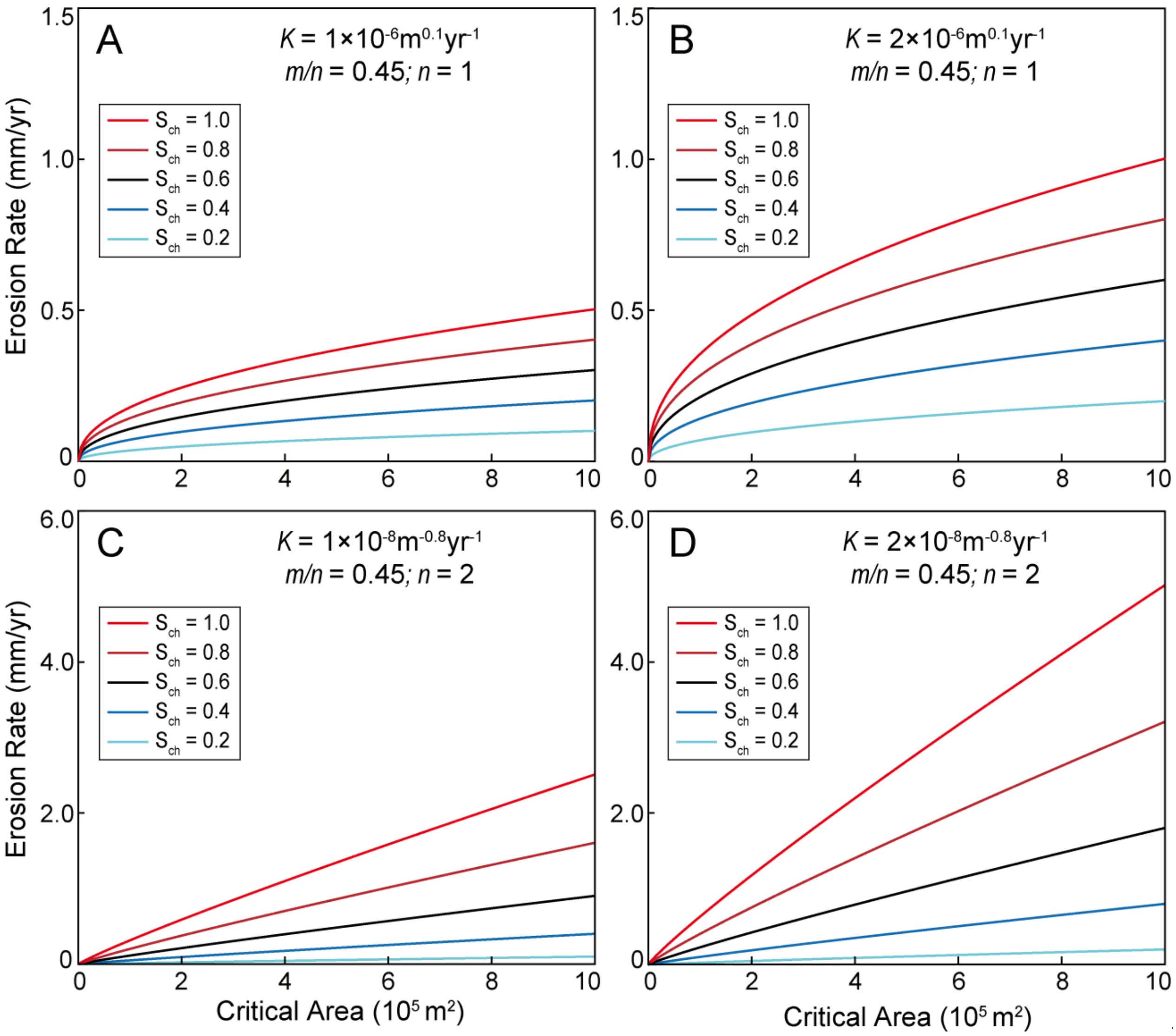
or:

$$D_{mr} = \frac{E_{\beta}\left[\frac{(A_{cr}^{m}S_{ch}^{n})_{\alpha}}{(A_{cr}^{m}S_{ch}^{n})_{\beta}}-1\right]-\Delta U_{ch}}{tan\alpha+tan\beta} \qquad (6)$$

E_α and E_β are the erosion rates of the α ~~to~~ and the β side of the drainage divide, respectively, which can be derived through ~~the~~ cosmogenic nuclides (^{10}Be) concentration measurements (Beeson et al., 2017; Godard et al., 2019; Hu et al., 2021). The regional average erosion rate (~~$\bar{E}$~~$\bar{E} = \frac{E_\alpha+E_\beta}{2}$) can also be used to calculate the migration rate:

$$D_{mr} = \frac{2\bar{E}\left[\frac{(A_{cr}^{m}S_{ch}^{n})_{\alpha}-(A_{cr}^{m}S_{ch}^{n})_{\beta}}{(A_{cr}^{m}S_{ch}^{n})_{\alpha}+(A_{cr}^{m}S_{ch}^{n})_{\beta}}\right]-\Delta U_{ch}}{tan\alpha+tan\beta} \qquad (7)$$

Based on Eqs. 4-7, the migration ~~velocity~~ rate of drainage divides can be estimated using channel-head parameters combined with one of the erosion-related parameters, ~~(~~erosion coefficient (K), erosion rate at one side of a drainage divide (E_α or E_β), or regional average erosion rate ($\bar{E}$).



~~**Figure 1**. Curves of the channel-head erosion rate (E_{ch}) against the critical area (A_{cr}) under different values of channel-head gradient (S_{ch}) and erosion coefficient (K). We assume m = 0.45 and n = 1 in (A) and (B), and m = 0.9 and n = 2 in (C) and (D).~~

2.2 Channel-head-segment method

A ~~Channel~~channel-head segment is the channel segment just below the channel-head (Zhou et al., 2022a). Zhou et al. (2022a) developed a method based on the cross-divide χ contrast of channel-head segments to calculate the migration ~~velocity~~ rate of drainage divides. The essence of the method is the cross-divide comparison of the channel-head segments' normalized channel steepness (k_{sn}) values. . k_{sn} is a widely used index ($k_{sn} = \left(\frac{E}{K}\right)^{\frac{1}{n}}$) (Whipple et al., 1999; Wobus et al., 2006; Hilley and Arrowsmith, 2008; Kirby and Whipple, 2012) that is quantitatively related to erosion rate (*E*) and erosion coefficient (*K* ($k_{sn} = \left(\frac{E}{K}\right)^{\frac{1}{n}}$)). χ is an integral function ($\chi = \int_{x_b}^{x} \left(\frac{A_0}{A(x)}\right)^{\frac{m}{n}} dx$) of a channelss's upstream area (*A*) to horizontal distance (*x*) (Royden et al., 2000; Perron and Royden, 20132), and A_0 is an arbitrary scaling area to make the integrand dimensionless.

In the researchmethod of Zhou et al. (2022a), limited by the resolution of DEM, the location of channel heads cannot be accurately identified, because it is limited by the resolution of DEM. Therefore, an empirical value of $A_{cr} = 10^5$ m^2 was used in the calculation. Benefiting from the high-resolution DEM in this study, we improve the method in Zhou et al. (2022a) and use the real location of channel heads to calculate the migration rate. Zhou et al. (2022a) proposed a cross-divide contrast of χ values, on behalf of the inverse of k_{sn}, which requires the same elevation of the channel heads and outlets across the drainage divide. Here, we release this restriction and make this method more applicable. When the regional erosion coefficient (*K*) is known and unchanged in the vicinity of the drainage divide, the drainage-divide migration rate can be estimated by the following equation:

$$D_{mr} = \frac{K\left[k_{sn(\alpha)}{}^{n} - k_{sn(\beta)}{}^{n}\right] - \Delta U_{ch}}{tan\alpha + tan\beta} = \frac{K\left\{\left[\frac{(z_{ch}-z_b)_\alpha}{\chi\alpha}\right]^n - \left[\frac{(z_{ch}-z_b)_\beta}{\chi\beta}\right]^n\right\} - \Delta U_{ch}}{tan\alpha + tan\beta} \qquad (8)$$

where z_{ch} and z_b are the elevations of the channel heads and catchment outlets, respectively, and χ is an integral function of channels' upstream area (*A*) to horizontal distance (x) (Perron and Royden, 2013; Willet et al., 2014). The detailed derivation of Eq. 8 is in the sSupplementary mMaterials. The drainage divide's unilateral erosion rate (E_α or E_β) can also be used as a substitution for the K value:

$$D_{mr}=\frac{E_\alpha\left\{1-\left(\frac{\chi_\alpha}{\chi_\beta}\right)^n\left[\frac{(z_{ch}-z_b)_\alpha}{(z_{ch}-z_b)_\beta}\right]^{-n}\right\}-\Delta U_{ch}}{tan\alpha+tan\beta} \qquad (9)$$

or:

$$D_{mr}=\frac{E_\beta\left\{\left(\frac{\chi_\alpha}{\chi_\beta}\right)^{-n}\left[\frac{(z_{ch}-z_b)_\alpha}{(z_{ch}-z_b)_\beta}\right]^{n}-1\right\}-\Delta U_{ch}}{tan\alpha+tan\beta} \qquad (10)$$

Alternatively, one can use the regional average erosion rate ($\bar{E}$) to calculate the migration rate:

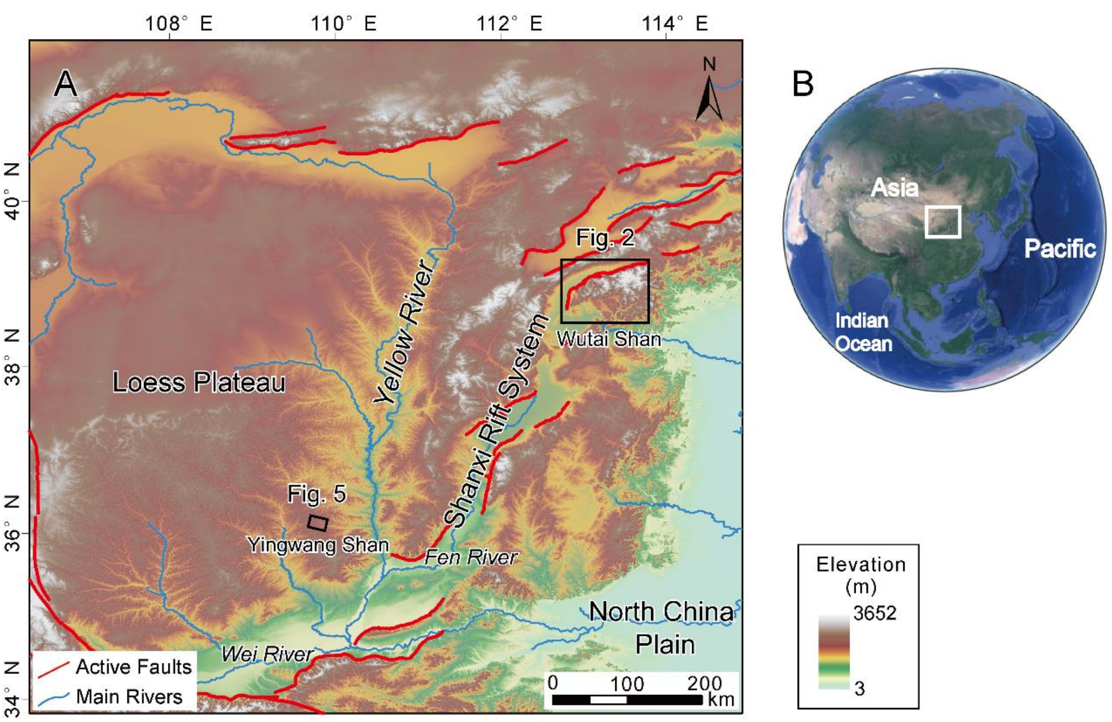
$$D_{mr}=\frac{2\bar{E}\left\{\frac{\left[\frac{(z_{ch}-z_b)_\alpha}{(z_{ch}-z_b)_\beta}\right]^{n}-\left(\frac{\chi_\alpha}{\chi_\beta}\right)^n}{\left[\frac{(z_{ch}-z_b)_\alpha}{(z_{ch}-z_b)_\beta}\right]^{n}+\left(\frac{\chi_\alpha}{\chi_\beta}\right)^n}\right\}-\Delta U_{ch}}{tan\alpha+tan\beta} \qquad (11)$$

Based on Eqs. 8-11, the drainage-divide migration rate can be estimated using the χ values of high-base-level channel segments combinedng with one of the erosion-related parameters (, erosion coefficient (K), erosion rate at one side of a drainage divide (E_α or E_β), or regional average erosion rate ($\bar{E}$)erosion coefficient, erosion rate at one side of a drainage divide, or regional average erosion rate).

We use UAV-acquired aerial photography and structure from motion (SfM) photogrammetry to derive the high-resolution DEM of the two study areas, the Wutai Shan in the Shanxi Rift, and the Yingwang Shan in the Loess Plateau, both located in North China (Fig. 1). (The spatial resolution is 0.67 m in the Wutai Shan, and 0.84 m spatial resolution in the Wutai Shan and in the Yingwang Shan respectively). Based on the high-resolution topography data, we extract the relevant parameters and calculate the drainage-divide migration rate using the two methods above for each case. Analysis of the data is based on the Matlab toolbox TAK (Forte and Whipple, 2019) and TopoToolbox (Schwanghart and Scherler, 2014).

3. Applications to natural cases

We apply the new methods to two natural examples in North China, the Wutai Shan, in the Shanxi Rift and the Yingwang Shan in the Loess PlateauLoess Plateau (Fig. 12), to demonstrate how to calculate the drainage-divide migration rates (Fig. 1). We use UAV-acquired aerial photography and structure from motion (SfM) photogrammetry to derive the sub-meter digital elevation model of the two study areas. Based on the high-resolution topography data (sub-meter), we extract the relevant parameters and calculate the drainage-divide migration rate using the two methods above for each case. Analysis of the data is based on the Matlab toolbox TAK (Forte and Whipple, 2019) and TopoToolbox (Schwanghart and Scherler, 2014).



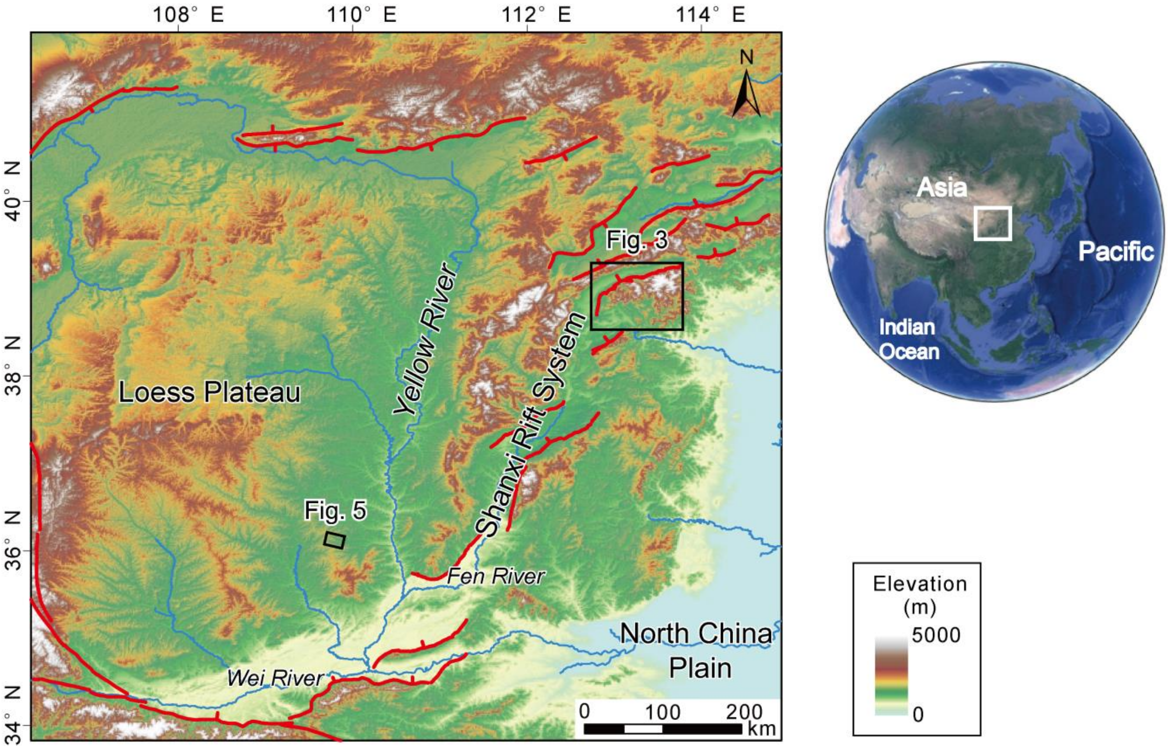


Figure 1~~2~~. Locations and tectonic background of the two nature cases in North China. The figure is modified ~~according to the~~ from Fig. 7 in Shi et al. (2021). (A) Red ~~curves~~ lines represent the main active faults. Black rectangles show the locations of the two nature cases. Red curve denotes active fault, ~~The fault data is downloaded~~

sourced from ~~the site (~~https://www.activefault-datacenter.cn/~~)~~. The topography data (ALOS DEM, 12.5 m resolution) is downloaded from the Alaska Satellite Facility (ASF) Data Search (https://search.asf.alaska.edu/). **(B)** The satellite image ~~is~~ downloaded from Google Earth. White rectangles show the location of ~~p~~Panel A. ~~The satellite image is downloaded from Google Earth.~~

3.1 Wutai Shan

The Wutai Shan is a tilted fault block on the shoulder of the Shanxi Rift System located in the central North China craton (Fig. 1~~A~~) (Xu et al., 1993; Su et al., 2021). The tilting uplift of the Wutai Shan is controlled by the Northern Wutai Shan fault ~~(Fig. 3A)~~, and there is no active fault along the south edge of the Wutai Shan horst (Fig. 2~~A~~). The bedrock of the Wutai Shan area consists mainly of ~~is mainly~~ metamorphic and igneous basement rocks (Clinkscales et al., 2020~~; Zhou et al 2022a~~) and there is no obvious variation in rock erodibility and precipitation in this area (Fig. S2 & S3). Zhou et al. (2022b) reveal~~s~~ that the Wutai Shan drainage divide is migrating northwestward due to the tilting uplift and predicts the drainage divide will move ~10 km to the northwest to achieve a steady state if all geological conditions remain. ~~Morphological~~ Geomorphic evidence also ~~shows~~ exhibits a ~~clear~~ northwestward migration of the drainage divide~~s~~ (Fig. 3). ~~Figure 3~~The plan and satellite views show~~s~~ several barbed tributaries and a captured area ~~in~~around the Wutai Shan drainage divide, which indicate that the tributaries formerly part of the northern drainage have become ~~became~~ part of the southern drainage (Fig. 3A&B)~~,~~ ~~where there are clear barbed tributaries and a capture point~~. The χ-plots analysis shows the southern side of the drainage divide has steeper channels, higher k_{sn}, and lower χ. The χ-plots of paired rivers ~~show~~ illustrate obvious characteristics of ~~aggressor~~shrinking-expanding~~victim~~ and captured-beheaded rivers (Fig. 3C).

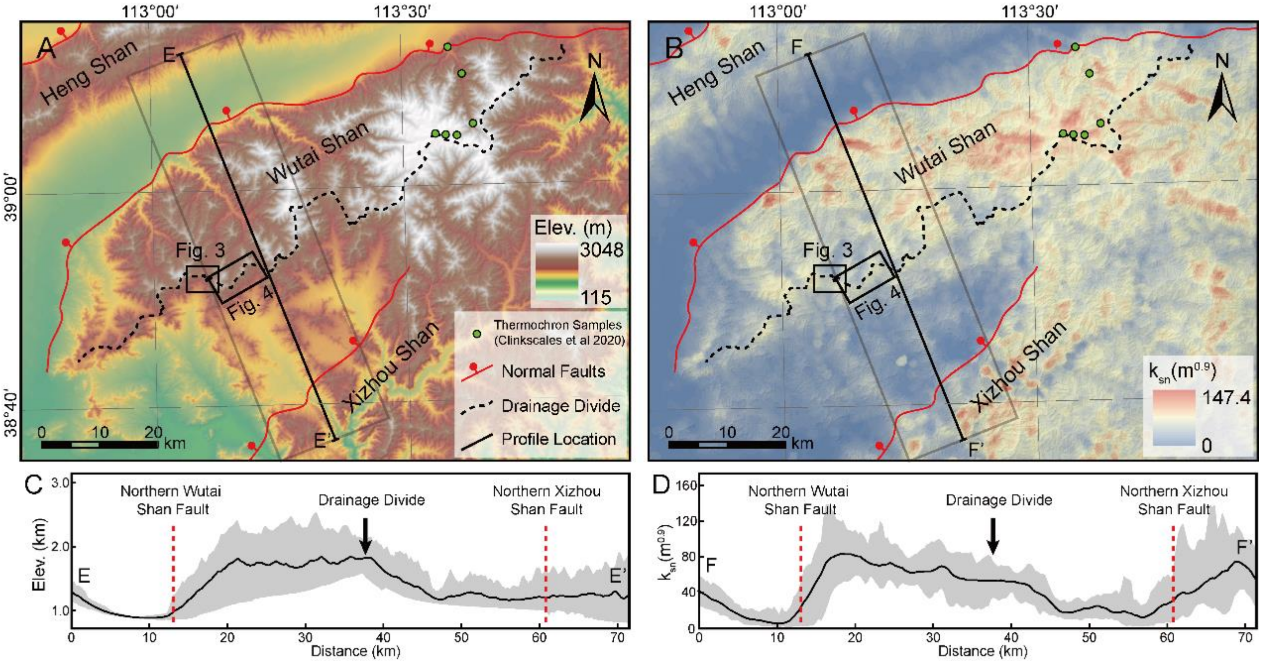
To derive the erosion coefficient of the Wutai Shan area, we calculate the channel steepness (k_{sn}) ~~values~~ of this region, ~~under the assumption of~~ assuming $n = 1$ and $m = 0.45$ (Wobus et al., 2006; DiBiase et al., 2010; Perron and Royden, 2012; Wang et al., 2021). We then ~~and~~ use the Kriging interpolation ~~technique~~ method to generate the k_{sn} distribution map (Fig. 2~~3~~B). In addition, ~~The~~ results ~~of~~ under the assumptions of m = 0.35 and 0.55, respectively, are shown in ~~the s~~Supplementary ~~m~~Materials (Fig. S4). The average k_{sn} value of the upthrown side -near the Northern Wutai Shan fault ~~of this area~~ is ~80 $m^{0.9}$ (Fig. 2~~3~~D). ~~The~~ Previous geological study shows that the Quaternary throw rates of the Northern Wutai Shan fault are 0.8-1.6 mm/a (Middleton et al., 2017). The~~According to a~~ low-temperature thermochronology study shows that the time-averaged long-term throw rates in the late Cenozoic ~~of the Wutai Shan (Clinkscales et al., 2020), the erosion rate of the sampling area (in the footwall block of the northern boundary fault of the Wutai Shan)~~ is about 0.25 mm/yr, and there is an accelerated activity in the Wutai Shan area ~~in the late Cenozoic~~(Clinkscales et al., 2020). According to ~~the above geological and low-temperature thermochronology~~ these studies, we assume a 0.50 ± 0.25 mm/yr uplift/erosion rate in the northern margin of the Wutai Shan (at in the footwall of the Northern Wutai Shan fault). The average k_{sn} value of this area is ~ 80 $m^{0.9}$ (Fig. 3). According toCombining with the equation, $K = \frac{E}{{k_{sn}}^{n}}$, and following the approach of previous studies (Kirby and Whipple, 2001; Kirkpatrick et al., 2020; Ma et al., 2020), the erosion coefficient (*K*) is calculated to be (6.25 ± 3.13) ~3 $\times 10^{-6}$ $m^{0.1} yr^{-1}$ in the Wutai Shanis area. Because there is no obvious variation in rock erodibility and precipitation in this area (Fig. S2 & S3), we use this value as the erosion coefficient (*K*) of the Wutai Shan area.

We then apply the two above new methods in this area to calculate the migration velocity rate of the drainage divide in the Wutai Shan. We first randomly choose three pairs of rivers (Fig. 4A) and make acquire their slope-area plots (Figs. 4B, E, H) and the χ-plots (Figs. 4C, F, I). According to the location of the river'scatchment outlets (Fig. 4A), we obtain the river's outlet elevations (z_b) from the river's long profiles. According to the breaking point of the slope-area regression lineplot (Duvall et al., 2004) (Figs. 4B, E, H), we obtain the values of the critical upstream drainage area (A_{cr}). According to these values, and its corresponding position on the χ plot, we can separate hillslope and channel areas and mark the position of the channel heads on the χ-plots and the topography map (Fig. 4A). For the slope-area plots, we derive the value of critical upstream drainage area (A_{cr}) according to the position of the channel heads. The tanα and tanβ are in line with the gradient of channel-head points (S_{ch}) on each side of the drainage divide (Figs. 4D, G, J).Because the slopes of the channel-

~~head points varies, we use the average slope of the hillslope area as the value of channel-head gradient (S_{ch}). Moreover, f~~For the χ-plots (Figs. 4C, F, I), we obtain the elevations of ~~outlets (z_b) and~~ channel heads (z_{ch}) ~~of the channel segment,~~ and ~~the~~ χ values ~~according to~~ based on the ~~position~~ coordinate of the channel-head points. According to the location of the channel heads on the river's long profiles, we calculate the slope of the channel heads' tangent lines, and derive the channel-head gradient (S_{ch}). ~~The~~ Topographic gradient (tanα or tanβ) is calculated through the average slope of the hillslope segment near the channel head (Stokes et al., 2022) (not including the hilltop part).

If we assume the rock uplift rate decreases linearly from 0.~~2~~5 to 0 mm/yr from northwest to southeast of the Wutai Shan horst (~40 km wide), the cross-divide uplift difference in the channel-head points (ΔU_{ch}) (the distance perpendicular to the ~~along the normal~~ direction of the boundary fault is ~600 m) is ~0.0084 mm/yr. ~~The tanα and tanβ are in line with the gradient of channel-head points (S_{ch}) on each side of the drainage divide (Figs. 4D, G, J). We assume n = 1 and m = 0.45 in the calculation following previous studies (Wobus et al., 2006; DiBiase et al., 2010; Perron and Royden, 2013; Wang et al., 2021).~~ After determining these parameters, we adopt the channel-head-point (Eq. 4) and channel-head-segment (Eq. 8) methods, respectively, to calculate the migration rates. The required data for calculation and the migration rates are shown in Table 1. The calculated results ~~of~~ for m = 0.35 and 0.55, respectively, are shown in ~~the s~~Supplementary ~~m~~Materials (Table S1).

The rivers have different characteristics on both sides of the drainage divide, according to as illustrated on theirBoth the slope-area plots (Figs. 4B, E, H) and the χ-plots (Figs. 4C, F, I). show that distinct character of the rivers across the drainage divide. For the first site (Fig. 4D), the migration rates calculated by both the channel-head-point and channel-head-segment methods are 0.12 21 mm/yr (northward) and 0.26 mm/yr (northwestward), respectively. For the second site (Fig. 4G), the migration rates derived from the two methods are 0.11 23 mm/yr (northward) and 0.13 27 mm/yr (northwestward), respectively. For the third site (Fig. 4J), the migration rates are 0.12 21 mm/yr (northward) and 0.10 22 mm/yr (northwestward), respectively. The drainage divides of all three points are predicted to migrate migrating northwestward, which is consistent with the previous result inferred by the cross-divide contrast of slopes in this area (Zhou et al., 2022b). -Furthermore, the migration velocities rates calculated by the two methods are comparable in all three sites. Morphological evidence also shows a clear northward migration of the drainage divides (Fig. 3). Figure 3 shows a captured area in the Wutai Shan, where there are clear barbed tributaries and a capture point. The south side of the drainage divide has steeper channels, higher k_{sn}, and lower χ. The χ-plots of rivers show obvious characteristics of aggressor-victim and captured-beheaded rivers (Fig. 3).



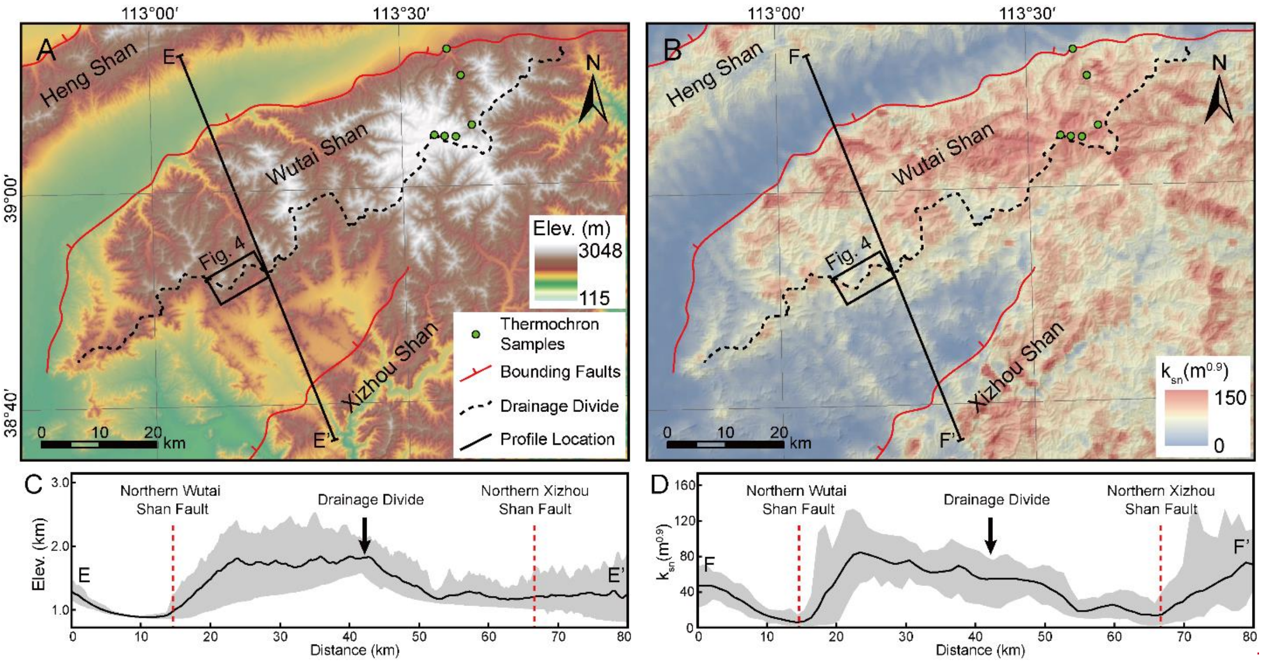


Figure 2~~3~~. ~~(A & B)~~ Topography (A) and normalized channel steepness (k_{sn}) (B) distribution of the Wutai Shan horst and surrounding area in the Shanxi Rift System. The black dashed ~~curve~~ line shows the location of the main drainage divide. Red ~~curves~~ lines show the main ~~bounding~~ active faults. The black ~~straight~~ lines show the location of ~~the~~ profiles E-E' and F-F'. Black rectangles show the area of ~~aerial photography (~~Fig. 3B & 4A~~)~~. Gray ~~rectangles~~ boxes show the area of the swath profiles in ~~p~~Panels C~~&~~ and D. Green dots denote the locations of the low-temperature thermochronology samples in Clinkscales et al. (2020). The topography data (ALOS DEM, 12.5 m resolution) is downloaded from the Alaska Satellite Facility (ASF) Data Search (https://search.asf.alaska.edu/). The k_{sn} is calculated using TopoToolbox (Schwanghart and Scherler, 2014) ~~based on Matlab~~, and the interpolation uses the Kriging method on ArcGIS. (**C**) ~~The t~~Topography swath profile along E-E'. See location in ~~Fig. 3p~~Panel A. (**D**) ~~The~~ k_{sn} swath profile along F-F'. See location in ~~Fig. 3p~~Panel B. The swath profiles are extracted using TopoToolbox (Schwanghart and Scherler, 2014). The red ~~dotted~~ dashed lines show~~s~~ the location of the main ~~bounding~~ active normal faults, and the black arrow shows the location of the main drainage divide. Both swath profiles are 20 km wide (10 km on each side). ~~The extent of the swath profiles is represented by the grey boxes in Panel A&B.~~

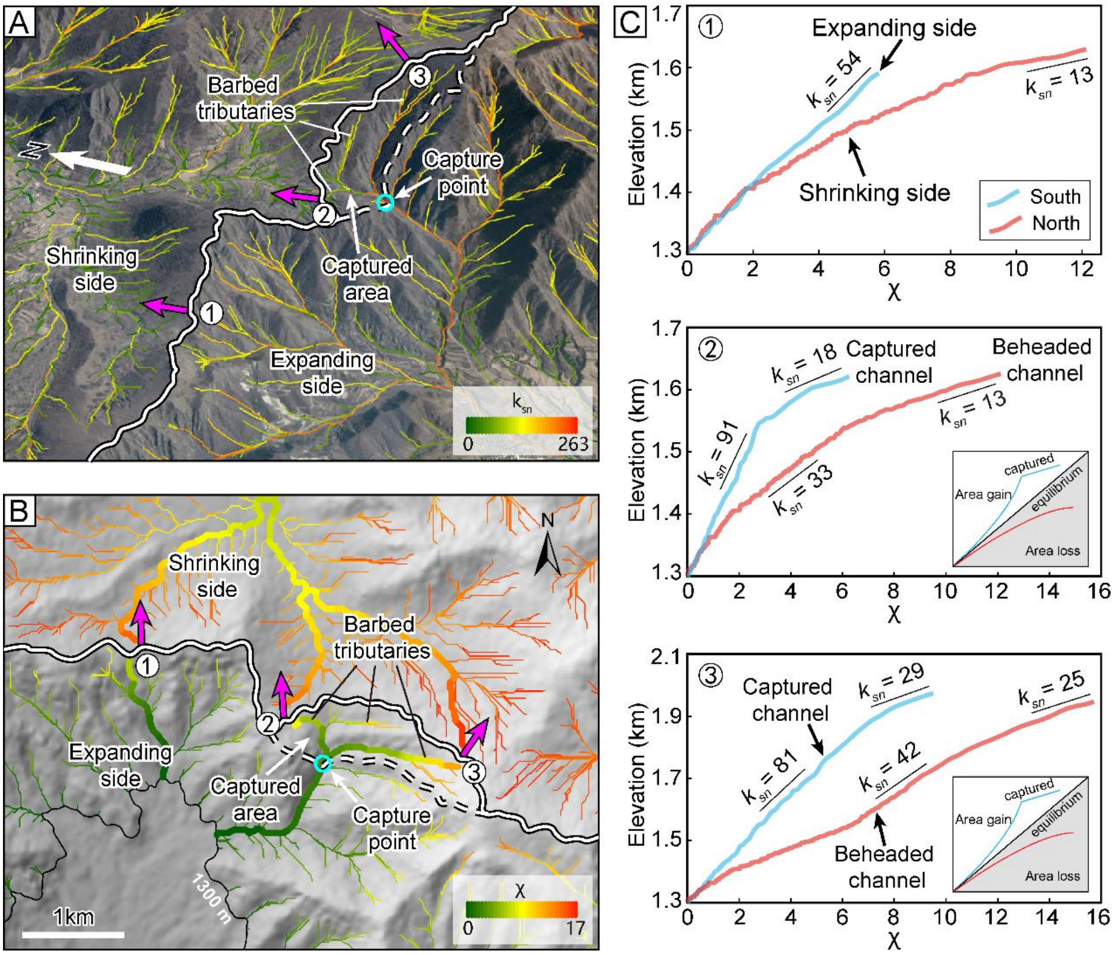
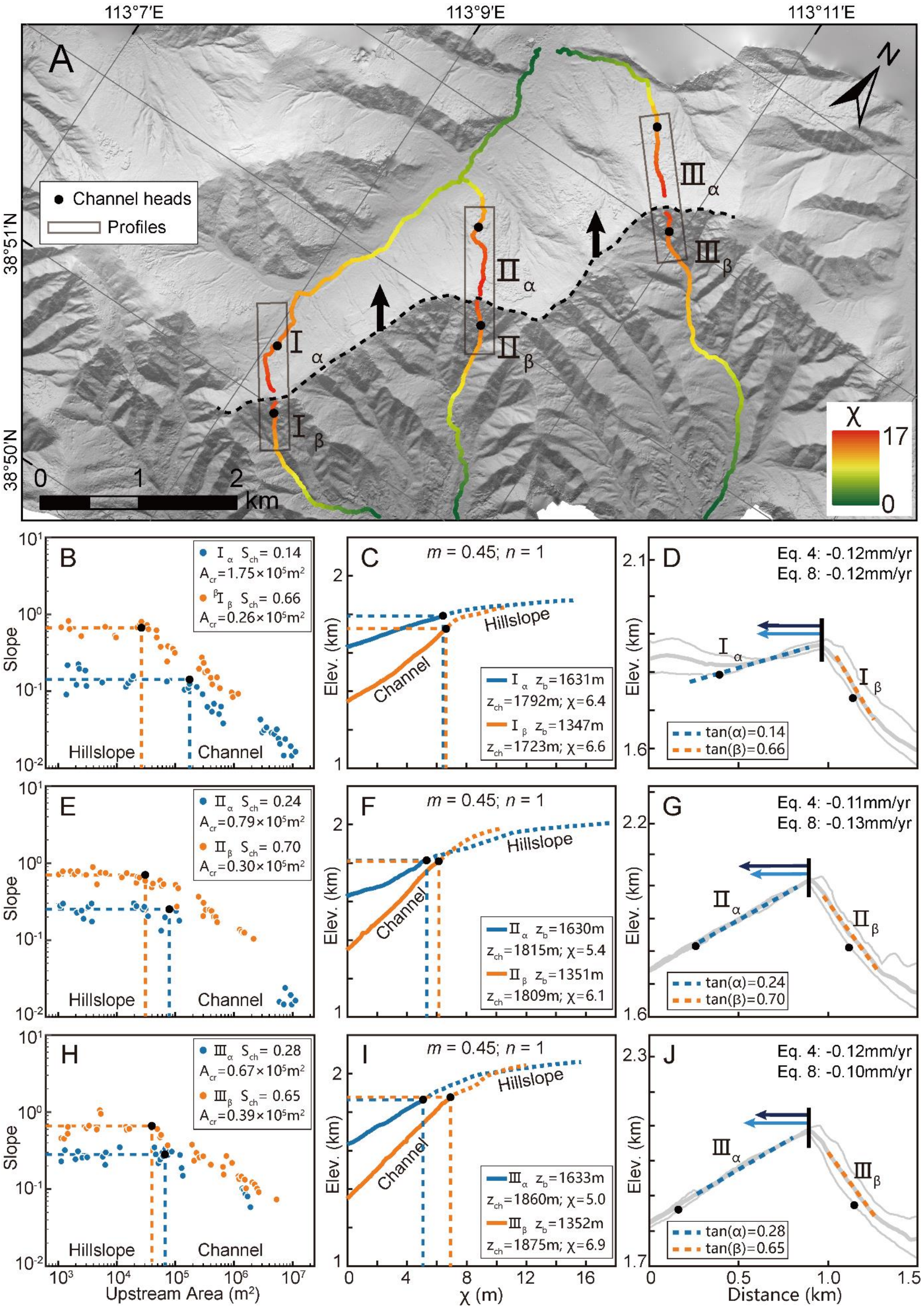
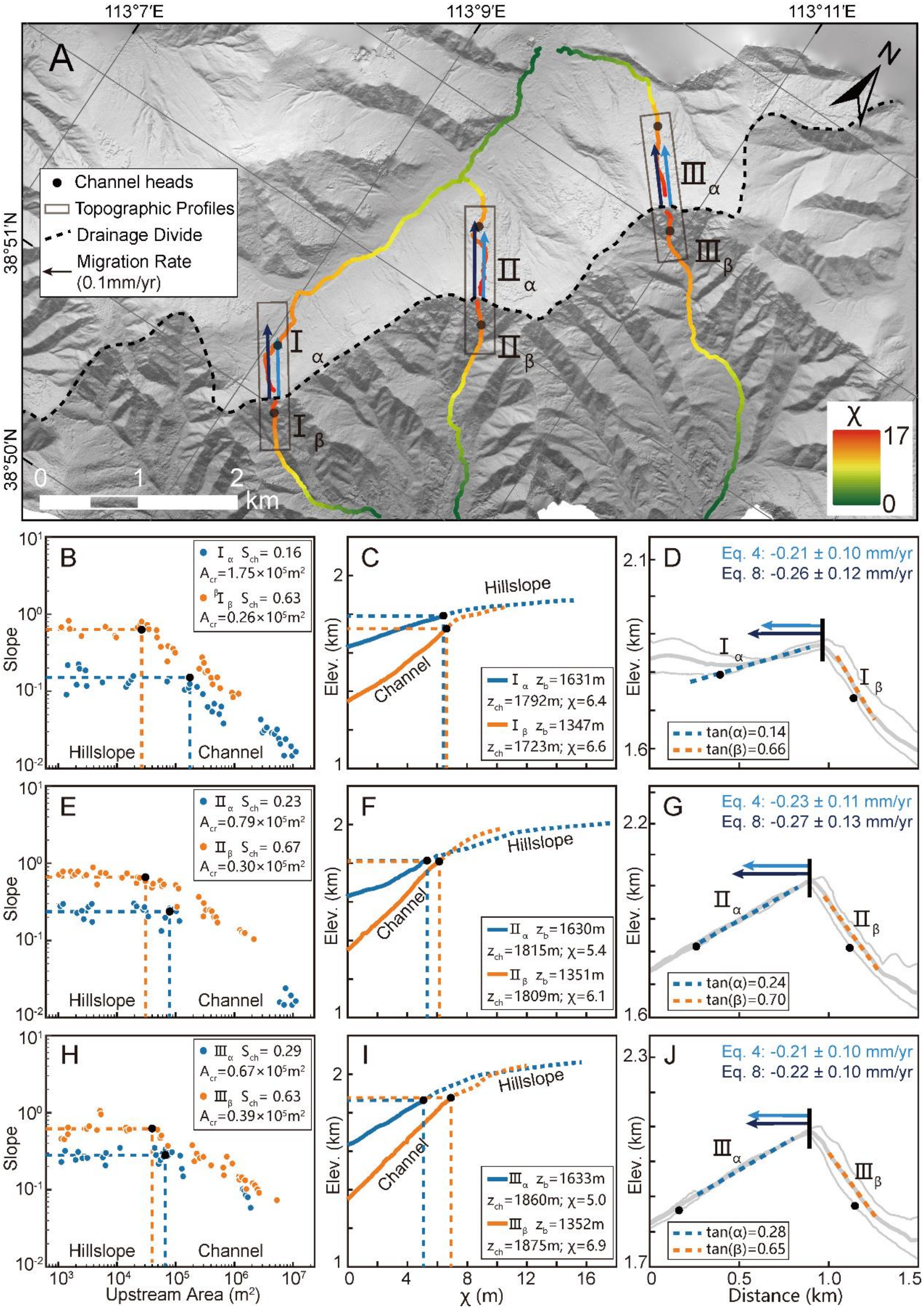


Figure 3. Perspective views and χ map of the drainage divide in the Wutai Shan (~~The location is shown in~~ see Fig. 2 for location). (A) Perspective views of ~~the~~ a captured area and the channels mapped with k_{sn}. The south side of the drainage divide has steeper channels and higher k_{sn} than the north side. ~~Red~~ Magenta arrows show drainage divide migration directions. The satellite image is ~~downloaded~~ from Google Earth. (B) ~~The~~ χ ~~M~~map ~~in~~ of this area with the outlet elevation of 1300 m. The south side of the drainage divide has lower χ values than the north side. It should be noted that the catchment outlet at the north side of the drainage basins (the 1300 m contour) is out of the map. The χ-plots of the rivers in bold lines are shown in ~~p~~Panel C. The topography data (ALOS DEM, 12.5 m resolution) is downloaded from the Alaska

Satellite Facility (ASF) Data Search (https://search.asf.alaska.edu/). (C) χ-plots of the three paired rivers in ~~p~~Panel B. The blue and red curves ~~are~~ correspond to the rivers on the south and north sides, respectively. The χ-plot of River 1 is steeper on the south side, indicating that the river on the south side is ~~the aggressor~~ expanding and ~~is the victim~~ the river on the north side is shrinking. The χ-plots of Rivers 2~~&~~ and 3 in the captured area show obvious characteristics of the captured and beheaded rivers. The χ-plot is extracted using TAK (Forte and Whipple, 2019) and TopoToolbox (Schwanghart and Scherler, 2014).



113°7′E
113°9′E
113°11′E
38°51′N
38°50′N
A
N
Channel heads
Profiles
Ⅰα
Ⅰβ
Ⅱα
Ⅱβ
Ⅲα
Ⅲβ
χ
17
0
0
1
2
km
B
Ⅰα Sch= 0.14
Acr=1.75×10⁵m²
Ⅰβ Sch= 0.66
Acr=0.26×10⁵m²
Slope
Hillslope
Channel
C
m = 0.45; n = 1
Elev. (km)
Hillslope
Channel
Ⅰα zb=1631m
zch=1792m; χ=6.4
Ⅰβ zb=1347m
zch=1723m; χ=6.6
D
Eq. 4: -0.12mm/yr
Eq. 8: -0.12mm/yr
Elev. (km)
tan(α)=0.14
tan(β)=0.66
E
Ⅱα Sch= 0.24
Acr=0.79×10⁵m²
Ⅱβ Sch= 0.70
Acr=0.30×10⁵m²
F
m = 0.45; n = 1
Ⅱα zb=1630m
zch=1815m; χ=5.4
Ⅱβ zb=1351m
zch=1809m; χ=6.1
G
Eq. 4: -0.11mm/yr
Eq. 8: -0.13mm/yr
tan(α)=0.24
tan(β)=0.70
H
Ⅲα Sch= 0.28
Acr=0.67×10⁵m²
Ⅲβ Sch= 0.65
Acr=0.39×10⁵m²
I
m = 0.45; n = 1
Ⅲα zb=1633m
zch=1860m; χ=5.0
Ⅲβ zb=1352m
zch=1875m; χ=6.9
J
Eq. 4: -0.12mm/yr
Eq. 8: -0.10mm/yr
tan(α)=0.28
tan(β)=0.65
Upstream Area (m²)
χ (m)
Distance (km)


113°7′E
113°9′E
113°11′E
A
N
Channel heads
Topographic Profiles
Drainage Divide
Migration Rate
(0.1mm/yr)
38°51′N
38°50′N
Ⅰα
Ⅰβ
Ⅱα
Ⅱβ
Ⅲα
Ⅲβ
0
1
2
km
χ
17
0
B
Ⅰα Sch= 0.16
Acr=1.75×10⁵m²
Ⅰβ Sch= 0.63
Acr=0.26×10⁵m²
Slope
Hillslope
Channel
C
Hillslope
Channel
Elev. (km)
Ⅰα zb=1631m
zch=1792m; χ=6.4
Ⅰβ zb=1347m
zch=1723m; χ=6.6
D
Eq. 4: -0.21 ± 0.10 mm/yr
Eq. 8: -0.26 ± 0.12 mm/yr
tan(α)=0.14
tan(β)=0.66
E
Ⅱα Sch= 0.23
Acr=0.79×10⁵m²
Ⅱβ Sch= 0.67
Acr=0.30×10⁵m²
F
Ⅱα zb=1630m
zch=1815m; χ=5.4
Ⅱβ zb=1351m
zch=1809m; χ=6.1
G
Eq. 4: -0.23 ± 0.11 mm/yr
Eq. 8: -0.27 ± 0.13 mm/yr
tan(α)=0.24
tan(β)=0.70
H
Ⅲα Sch= 0.29
Acr=0.67×10⁵m²
Ⅲβ Sch= 0.63
Acr=0.39×10⁵m²
Upstream Area (m²)
I
Ⅲα zb=1633m
zch=1860m; χ=5.0
Ⅲβ zb=1352m
zch=1875m; χ=6.9
χ (m)
J
Eq. 4: -0.21 ± 0.10 mm/yr
Eq. 8: -0.22 ± 0.10 mm/yr
tan(α)=0.28
tan(β)=0.65
Distance (km)

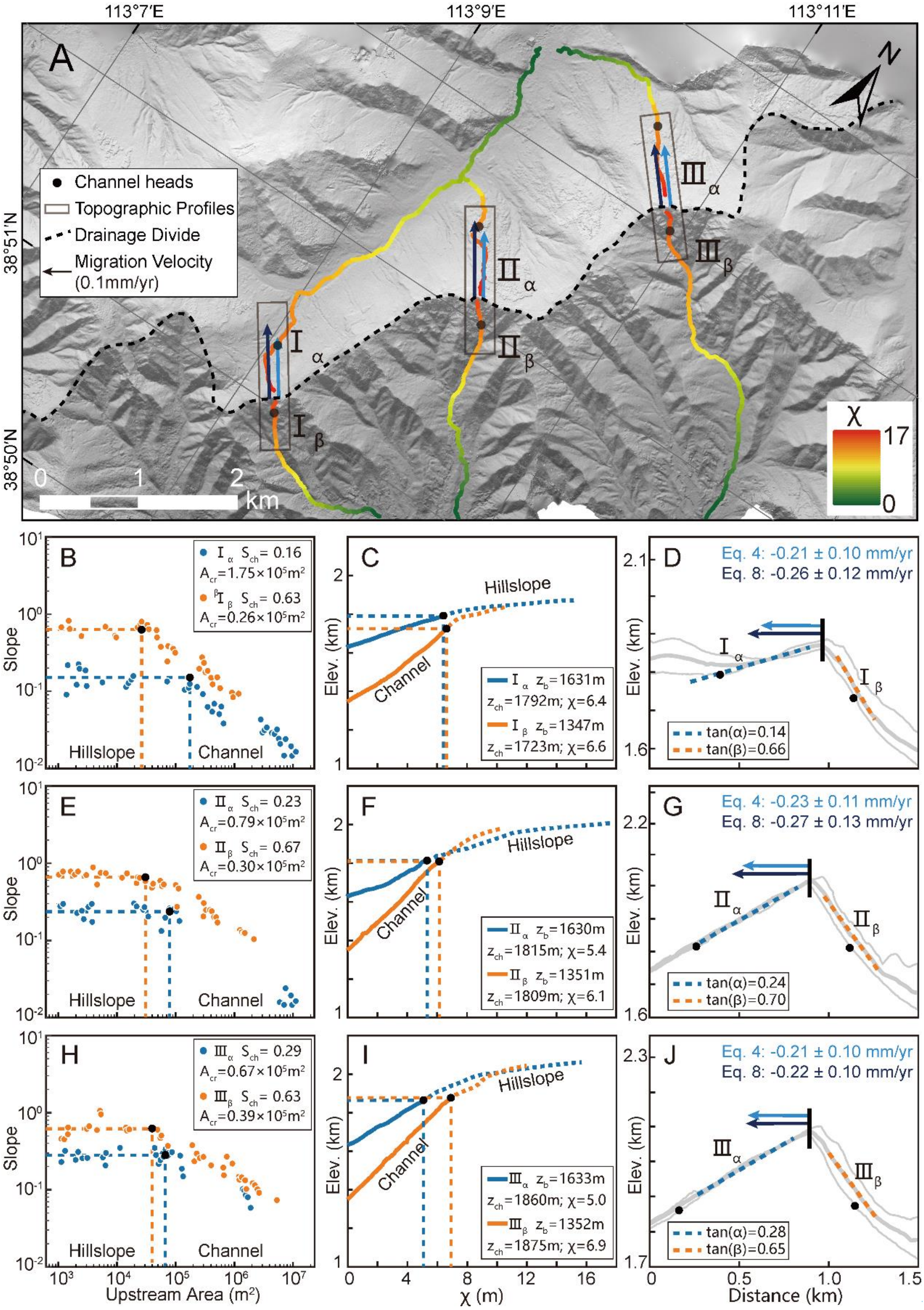


Figure 4. Analytical results of the Wutai Shan drainage divide. (**A**) High-resolution hill-shade~~topographic~~ map (0.67 ~~sub-~~m~~eter~~ spatial resolution) of the Wutai Shan. The black dashed ~~curve~~ line shows the location of the main drainage divide. Colored

~~curve~~lines show the three pairs of selected channels used for analysis. The black dots are the channel heads. Black rectangles show the location of the cross-divide topography swath profiles. The black arrows show the direction of drainage-divide migration (**B, E, H**) Slope-area plots of the three pairs of selected channels. The blue and orange dots are the slope-area plots of the north (α) and south (β) sides of the drainage divide respectively. The black dots represent the channel heads. (**C, F, I**) χ-plots of the selected channels. The blue and orange ~~curve~~lines are the χ-plots of the north (α) and south (β) sides of the drainage divide respectively. The black dots represent the channel heads. (**D, G, J**) Cross-divide topography swath profiles with the drainage-divide migration rates. The locations of the profiles are in ~~Fig. 4~~pPanel A. The light and dark blue arrows are the drainage-divide migration rates calculated by the channel-head-point (Eq. 4) and channel-head-segment (Eq. 8) methods respectively.

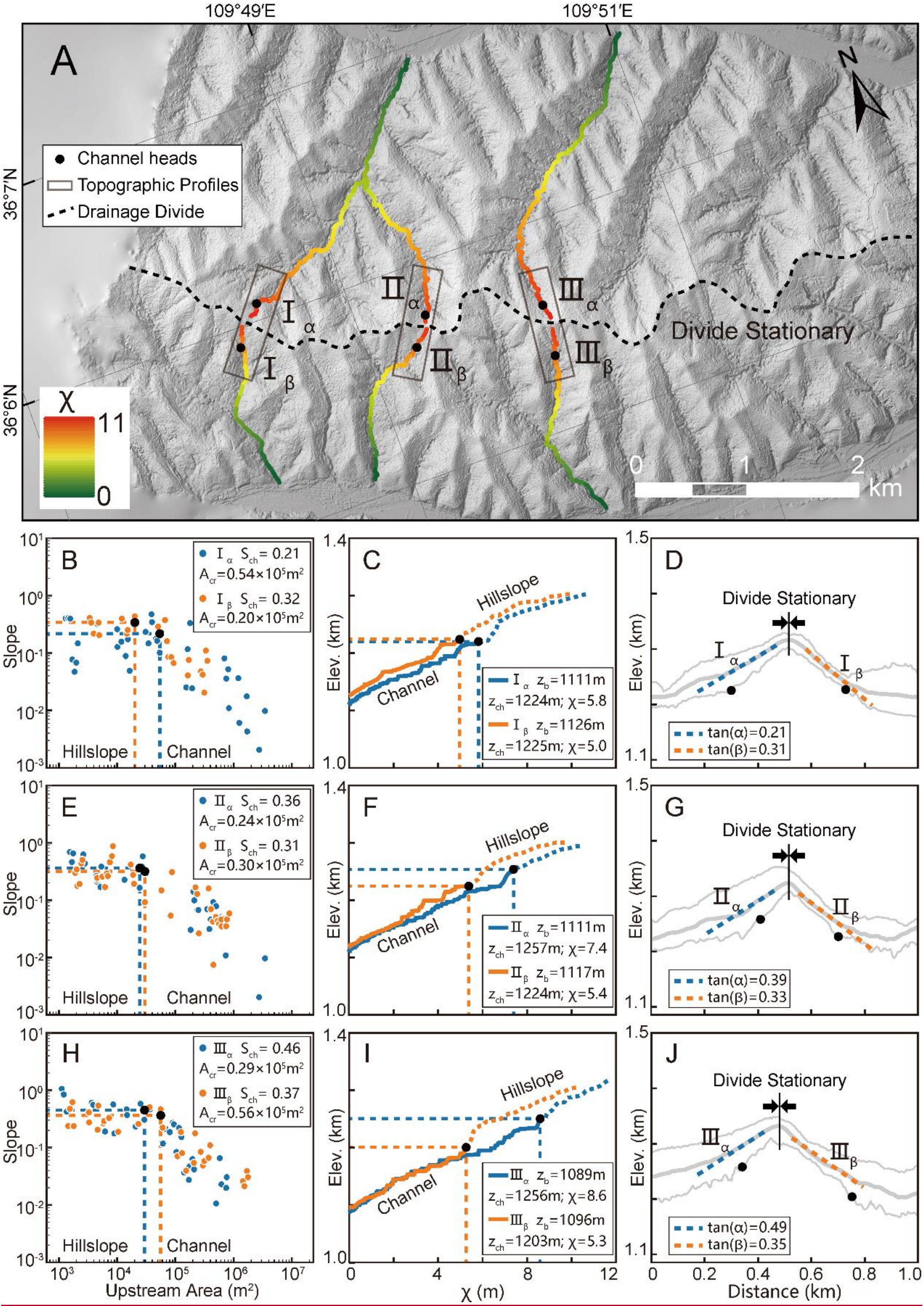
3.2 ~~An unnamed mountain range in the Loess Plateau~~Yingwang Shan

The Loess Plateau is hosted by the tectonically stable Ordos Block of the North China craton (Yin, 2010; Su et al., 2021). Over the past 2.6 million years, iIt has ~~accumulates~~ accumulated tens to hundreds of meters of eolian sediments ~~over the past 2.6 million years~~ (Yan et al., 2014), draping preexisting topography (Xiong et al., 2014). There is no active fault ~~within the study area. The lithology of the study site is mainly loess; there~~and ~~is~~ little to no variation in rock erodibility and precipitation within the area (Shi et al., 2020; Zhou et al., 2022b).

We apply the two methods ~~in this area~~ to Yingwang Shan of Loess Plateau to calculate the drainage-divide migration rate. Similar to the Wutai Shan ~~case~~site, we ~~first make~~ obtain the ~~randomly choose three pairs of rivers and make their~~ slope-area plots (Figs. 5 B, E, H) ~~and~~, the χ-plots (Figs. 5 C, F, I), and extract the~~. Then we mark the position of the channel-head points on the topography map (Fig. 5A), slope-area plots, and χ-plots. According to its position, we derive the A_{cr}~~ values of A_{cr}, S_{ch}, z_b, z_{ch}, χ, tanα and tanβ of the rivers. ~~from the slope-area plots (Figs. 5 B, E, H) and the χ values and the elevations of channel-head segments' outlets (z_b) and heads (z_{ch}) from the χ-plots (Figs. 5 C, F, I). We also acquire the average slope of the hillslope area and derive the S_{ch}, tanα, and tanβ values.~~

The rate of soil erosion in the study area is about 500 t·km^{-2}yr^{-1} according to the distribution of silt discharge (Fu, 1989). ~~If we~~Combining with the assumption~~e~~ of the density of ~~L~~loess,~~ is~~ 1.65 t·m^{-3}, the present-day ~~average~~ erosion rate ~~here~~ in the study area is ~~about~~ calculated to be 0.3 mm·yr^{-1}. Because there is no obvious unequal uplift in this region, we ~~assume~~ assign that ΔU_{ch} is zero. We also assume n = 1 and m = 0.45 in the calculation (Wobus et al., 2006; DiBiase et al., 2010; Perron and Royden, 2012; Wang et al., 2021). Then, we use the methods of channel-head parameters (Eq. 7) and channel segments (Eq. 11) to calculate the drainage-divide migration rates. The required data for calculation and the migration rates are shown in Table 1.

All results of the three points show that the drainage-divide migration rate here is close to zero, no matter which method is used in the calculation. The results show that the drainage divide of the study site is in topographical equilibrium, which is consistent with the inference in previous studies (Willett et al., 2014, Zhou et al., 2022b).


109°49′E
109°51′E
36°7′N
36°6′N
A
N
Channel heads
Topographic Profiles
Drainage Divide
Divide Stationary
χ
11
0
0
1
2
km
B
C
D
E
F
G
H
I
J
Slope
Upstream Area (m²)
Elev. (km)
χ (m)
Distance (km)
Hillslope
Channel
Divide Stationary
tan(α)=0.21
tan(β)=0.31
tan(α)=0.39
tan(β)=0.33
tan(α)=0.49
tan(β)=0.35

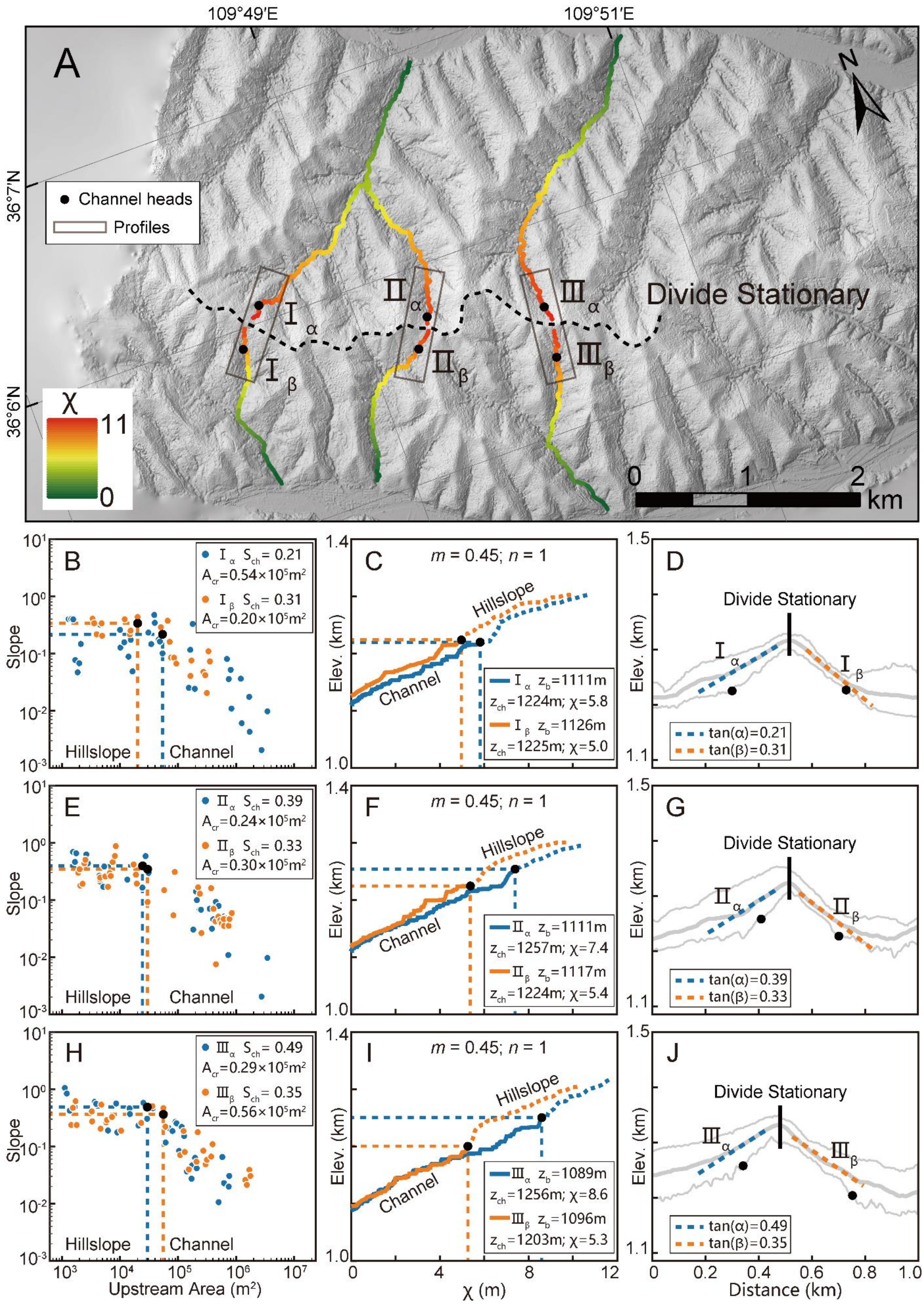


Figure 5. Analytical results of the Yingwang Shan a mountain range in the Loess

Plateau. (**A**) High-resolution hill-shade~~topographic~~ map (~~sub-meter~~0.84 m spatial resolution). The black dotted ~~curve~~line shows the location of the main drainage divide. Colored ~~curve~~lines show the three pairs of selected channels used for analysis. The black dots represent the channel heads. Black rectangles show the location of the cross-divide topography swath profiles. (**B, E, H**) Slope-area plots of the three pairs of selected channels. The blue and orange dots are the data of the north (α) and south (β) sides of the drainage divide respectively. The black dots represent the channel heads. (**C, F, I**) χ-plots of the selected channels. The blue and orange ~~curve~~lines are the χ-plots of the north (α) and south (β) sides of the drainage divide respectively. The black dots represent the channel heads. (**D, G, J**) The cross-divide topography swath profiles. The locations of the swath profiles are in Panel A.

Table 1. Channel's parameters and the migration rates of the drainage divides inof the two fieldnatural cases.

Natural Cases	No.	A_{cr} (×10^{5}m^2)	S_{ch}	z_b (m)	z_{ch} (m)	χ	tanα	tanβ	ΔU_{ch} (mm/yr)	D_{mr} (mm/yr) (Channel-head-point method)	D_{mr} (mm/yr) (Channel-head-segment method)
Wutai Shan	Fig. 4 I$_{\alpha}$	1.75	0.16	1631	1792	6.4	0.14	0.66	~ 0.008	-0.21 ±0.10	-0.26 ±0.12
	Fig. 4 I$_{\beta}$	0.26	0.63	1347	1723	6.6					
	Fig. 4 II$_{\alpha}$	0.79	0.23	1630	1815	5.4	0.24	0.70	~ 0.008	-0.23 ±0.11	-0.27 ±0.13
	Fig. 4 II$_{\beta}$	0.30	0.67	1351	1809	6.1					
	Fig. 4 III$_{\alpha}$	0.67	0.29	1633	1860	5.0	0.28	0.65	~ 0.008	-0.21 ±0.10	-0.22 ±0.10
	Fig. 4 III$_{\beta}$	0.39	0.63	1352	1875	6.9					
LoessYingwang PlateauShan	Fig. 5 I$_{\alpha}$	0.54	0.21	1111	1224	5.8	0.21	0.31	0	~ 0.03	~ -0.01
	Fig. 5 I$_{\beta}$	0.20	0.32	1126	1225	5.0					
	Fig. 5 II$_{\alpha}$	0.24	0.36	1111	1257	7.4	0.39	0.33	0	~ 0.02	~ -0.01
	Fig. 5 II$_{\beta}$	0.30	0.31	1117	1224	5.4					
	Fig. 5 III$_{\alpha}$	0.29	0.46	1089	1256	8.6	0.49	0.35	0	~ 0.02	~ -0.01
	Fig. 5 III$_{\beta}$	0.56	0.37	1096	1203	5.3					

4. Discussion

4.1 Location of channel heads

Willett et al. (2014) pioneered the use of cross-divide χ contrast to gauge the horizontal motion of drainage divides. According to their method, drainage divides are predicted to move toward the side with a higher χ value to achieve geomorphic equilibrium. However, in a region with spatially variable uplift rates, lithology, or precipitation, χ contrast may fail to reflect the drainage-divide migration (Willett et al., 2014; Whipple et al., 2017; Forte and Whipple, 2018; Wu et al., 2022; Zhou and Tan, 2023). In the a tectonically active area, the cross-divide χ contrast can only be used in a small area where rock type, precipitation, and uplift rate are nearly uniform (Willett et al., 2014). Forte and Whipple (2018) proposed the Gilbert metrics to measure the stability of drainage divides. Zhou et al. (2022a) combined cCombining the advantages of the χ and Gilbert metrics methods, Zhou et al. (2022a) proposed to use the χ contrast with a high base level to calculate the k_{sn} values at the channel heads on both sides of a drainage divide, and quantified the migration rate of drainage divides at the eastern margin of Tibet.

To reduce the cross-divide difference in uplift rate, precipitation, and rock strength, these the Gilbert metrics or χ-comparison method in Zhou et al. (2022a)methods should compare the parameters of points (slope, relief, elevation, and k_{sn}) on both sides of the divide as closely as possible. As the hillslope area (above the channel head) does not follow Eq. 1 (Stoke and Dietrich, 2006; Stark, 2010; Braun et al., 2018; Dahlquist et al., 2018)~~)~~, the channel heads are the closest point to the divide, following Eq. 1. Channel heads, therefore, are suitable for measuring the drainage-divide stability with ~~the~~ parameters of the upstream drainage area and channel gradient (Forte and Whipple, 2018; Zhou et al., 2022a~~; this study~~). However, limited by the resolution of DEM, the location of the channel heads ~~sometimes~~ cannot always be accurately identified. The channel head parameters for calculating the migration rates ~~is~~are usually ~~usually~~ based on empirical ~~parameters~~values in ~~the~~ previous ~~study~~ studies (e.g., $A_{cr} = 10^5$ m^2 in Zhou et al. (2022a)), which may induce uncertainties.~~which may introduce errors in the result of drainage-divide stability.~~

In this study, we advocate the use of high-resolution DEM to determine a more accurate position and related parameters of the channel head~~,~~. The use of UAVs to obtain the local DEM has become highly efficient. ~~given that~~~~Because the use of UAVs to obtain the local DEM has become highly efficient.~~ We advance the theory to calculate the drainage-divide migration rate based on the measured channel-head parameters. ~~Because the use of UAVs to obtain the local DEM has become highly efficient.~~ With the help of the aerial photography of UAVs and the SfM techniques, it is possible to~~one can~~ obtain the ~~sub-meter~~high-~~-~~resolution topography data of drainage divides (Figs. 4A & 5A) and get the required parameters (including the exact locations of the channel heads across the drainage divide) through topography analysis, which could improve the quantitative research on the drainage-divide migration. Furthermore, the method provides a new avenue to combine with catchment-wide ^{10}Be erosion rate or low-temperature thermochronology data to calculate the migration rate, which has great potential~~s~~ ~~of~~ for application in places where some variables are hard to be constrained.

4.2 Cross-divide difference in the uplift rate of the channel heads

Although the channel heads across the divide are very close on the spatial scale of an orogenic belt, differential uplift between the channel heads (ΔU_{ch}) could still exist, especially in a tilting horst, such as the Wutai Shan. The cross-divide difference in uplift rate could impact the calculation of the migration rate of drainage divides (Zhou et al., 2022a). ~~Although the differential uplift rate is usually small enough to be ignored in some natural cases, its influence on the migration rate of drainage divides should be taken into account theoretically (Zhou et al., 2022a).~~

In this study, we quantify the influence of the cross-divide difference in rock uplift rate (ΔU_{ch}) on the calculation of the migration rate of drainage divides at the Wutai Shan, benefiting from the available tectonic and chronological research (Clinkscales et al., 2020) and the newly obtained high-resolution topographic data. In the Wutai Shan horst, ΔU_{ch} across the drainage divide is ~0.~~004~~ 008 mm/yr. We estimate~~d~~ the influence of ΔU_{ch} on the drainage-divide migration rate in ~~the~~ this case study~~ of the Wutai Shan~~, which can reduce the error theoretically. If ΔU_{ch} is ignored, the drainage-divide migration rate would decrease by ~4% in the Wutai Shan case. Although ~4% seems to be negligible, such a ratio will increase if the mountain belt is narrower, the tilting uplift is stronger, or the divide is closer to the steady state (i.e., the migration rate is lower) (Whipple et al., 2017; Ye et al., 2022). In other words, the differential uplift may play a significant influence on the measurement of drainage-divide stability in some situations. If we ~~C~~consider an extreme example~~: when~~ where the main drainage divide of a tilting mountain range (relatively narrow in width) is at a steady state, the gradient, relief, and elevation of the channel heads (collectively called “Gilbert metrics”) (Forte and Whipple, 2018)~~)~~ will show a systematic cross-divide difference in theory. In this case, the drainage divide would be considered unstable if ΔU_{ch} were neglected. Therefore, ~~we suggested~~ this study highlights that ΔU_{ch} should be taken into account, either in a qualitative or a quantitative evaluation of the stability of drainage divides using the parameters on the channel heads.

4.3 ~~Error~~Limitations and uncertainties

This study develop~~ed~~s the method to calculate the drainage-divide migration rate based on the measured channel-head parameters. However, uncertainties still exist because of the limitations of this technique. First~~ly~~, we assume the erosion coefficient (K) is the same on both sides of a drainage divide in the derivation of the equations. If there are differences in rock erodibility or precipitation ~~differences~~ across the divide, uncertainties should exist in the results. Second~~ly~~, the calculation of ~~the~~ migration rate~~s~~ is based on the erosion rates at the channel area in this study. However, the occurrence of drainage~~-~~-divide migration is directly driven by the differential erosion of the hillslope area across the divide, mainly via the processes including landslide, collapse, and diffusion (Stoke and Dietrich, 2006; Stark, 2010;

Braun et al., 2018; Dahlquist et al., 2018). Such discontinuous processes in the hillslope area make it challenging to constrain erosion rates over such short timescales. Over a relatively longer ~~timescale~~ period (i.e., spanning multiple seismic and climatic cycles), the erosion rate at the channel head area in this study can be comparable with that at the hillslope area (Hurst et al., 2012; Godard et al., 2020).

The accuracy of the data and parameters can also impact the reliability of the results. First~~ly~~, we use the typical values of n = 1 and m/n = 0.45 in the two natural cases to calculate the migration rate. If the actual values largely deviate from the assumption, ~~the~~ errors would ~~exist~~ be introduced into the results. For this reason, we have added the cases of m/n = 0.35 and 0.55 in ~~the in the s~~Supplementary ~~m~~Materials. Further estimation of these values (Mudd et al., 2018) could improve the accuracy of the results. Second~~ly~~, in the case ~~study~~ of the Wutai Shan, we refer to the geological and low-temperature thermochronology studies~~,~~ and assume ~~assuming~~ a 0.50±0.25 mm/yr erosion rate ~~in~~at the northern margin of the Wutai Shan (i.e., the footwall of the North Wutai Shan fault). Combining with the present-day k_{sn}, we calculate the erosion coefficient (K) and derive the ~~range of~~ migration rates of the drainage divide. If the present-day erosion rate deviates from the assumption, ~~the~~ errors would ~~exist~~ be inevitable in the results. Moreover, the horizontal and vertical errors of the DEM data, as well as the calculation errors in slope, upstream area and channel steepness can also affect the reliability of the results. In the case study of the Yingwang Shan, the lush vegetation may bring errors to the DEM data based on the SfM technology. The application of airborne light detection and ranging (LiDAR) technology may help reduce this error. In summaryNonetheless, despite the challenges in the accuracy of the results at present is affected by many factors that present challenges, but we believe this study provides a useful and important method to calculate the drainage divide migration rate.Future studies should take these challenges into account and overcome them.

5. Conclusions

We have developed a new method- (called the "channel-head-point" method-here) to calculate the migration rate of drainage divides based upon channel-head parameters. We have also improved the previously proposed "channel-head-segment method" in the previous study (Zhou et al., 2022a) to adapt the theory to areas where the parameters of channel-heads can be accurately determined.

elevations of outlets and channel heads are different across the drainage divide.

Using the new methods and high-resolution topographic data, we determined the exact locations of the channel heads on both sides of the drainage divide and quantified the drainage-divide migration rates in two natural cases in North China (the : Wutai Shan in the Shanxi Rift System, and an unnamed mountain rangethe Yingwang Shan in the Loess Plateau) in North China. The migration rates of the study sites in the Wutai Shan are 0.1021-0.13 27 mm/yr (moving northwestward). The rates are close to zero in the Yingwang ShanLoess Plateau.

Based on the locations of the channel heads and the uplift gradient of the Wutai

Shan~~mountain~~, we calculated the cross-divide difference in the uplift rate at the channel heads (ΔU_{ch}), which is taken into account in the calculation of the drainage-divide migration rate for the first time. If ΔU_{ch} is overlooked, the drainage-divide migration rate of the study sites in the Wutai Shan ~~would~~ will be ~~~4%~~ underestimated by ~4% . ~~We suggest~~ Our study highlights that ΔU_{ch} should be considered ~~if one aims to~~in the assessment of ~~the~~ drainage divide stability ~~of drainage divides~~ based on the cross-divide difference in channel-head parameters.

Data availability. The analysis of data is based on the Matlab toolbox TAK (Forte and Whipple, 2019) and TopoToolbox (Schwanghart and Scherler, 2014). The topography data (ALOS DEM, 12.5 m resolution) is downloaded from the Alaska Satellite Facility (ASF) Data Search (https://search.asf.alaska.edu/).

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Competing interests. The authors declare that they have no conflict of interest.

Author contributions. XT and CZ contributed to the design of the research scheme. CZ performed the geomorphic analyses. CZ, XT, and FS carried out field data collection. CZ, XT, YL, and FS contributed to the text and reviewed the paper.

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