How does a newly-formed drainage divide migrate after a river capture event? Insights from numerical simulations and two natural cases (Yarlung-Yigong, and Dadu-Anning) in the Tibetan Plateau region

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Abstract

Tectonic and/or climatic perturbations can drive drainage adjustment. The capture events, significantly changing the river network topology, are the major events in river network evolution. While they could be identified through field observations and provenance analysis, reconstructing this evolution process and pinpointing the capture time remain challenging. Following a capture event, the steady-state elevation of the captor river will be much lower than that of the beheaded river. Then, the newly-formed drainage divide will migrate towards the beheaded river, a process also known as river-channel reversal. The migration of the newly-formed drainage divide provides a new perspective for identifying the reorganization of the river network. Here, we employ numerical modeling to reproduce the characteristic phenomena of drainage-divide migration following capture events and analyze the effects of different parameters on the migration rate. We find that (1) the migration of newly-formed drainage divides can last for tens of millions of years, with the migration rate decreasing exponentially over time; (2) larger captured area, higher uplift rate, and lower erosional coefficient, all of which cause a higher cross-divide difference in steady-state elevation, will cause higher migration rate of the newly-formed drainage divide. This insight was further applied to the Dadu-Anning and Yarlung-Yigong capture events. We predict the present Dadu-Anning drainage divide would further migrate ~65–92 km southward to reach a steady state in tens of millions of years. The Yarlung-Yigong capture event occurred in the early-middle Cenozoic, which implies that the late-Cenozoic increased exhumation rate is not related to the capture event.

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Key Points:

- A newly-formed drainage divide following a capture event migrates for tens of millions of years, with a decreasing rate over time.
- The Dadu-Anning drainage divide would further migrate ~65–92 km southward to reach a steady state in tens of millions of years.
- The Yarlung-Yigong capture event occurred in the early-middle Cenozoic, which cannot drive the late-Cenozoic enhanced exhumation.

Abstract

Tectonic and/or climatic perturbations can drive drainage adjustment. The capture events, significantly changing the river network topology, are the major events in river network evolution. While they could be identified through field observations and provenance analysis, reconstructing this evolution process and pinpointing the capture time remain challenging. Following a capture event, the steady-state elevation of the captor river will be much lower than that of the beheaded river. Then, the newly-formed drainage divide will migrate towards the beheaded river, a process also known as river-channel reversal. The migration of the newly-formed drainage divide provides a new perspective for identifying the reorganization of the river network. Here, we employ numerical modeling to reproduce the characteristic phenomena of drainage-divide migration following capture events and analyze the effects of different parameters on the migration rate. We find that (1) the migration of newly-formed drainage divides can last for tens of millions of years, with the migration rate decreasing exponentially over time; (2) larger captured area, higher uplift rate, and lower erosional coefficient, all of which cause a higher cross-divide difference in steady-state elevation, will cause higher migration rate of the newly-formed drainage divide. This insight was further applied to the Dadu-Anning and Yarlung-Yigong capture events. We predict the present Dadu-Anning drainage divide would further migrate ~65–92 km southward to reach a steady state in tens of millions of years. The Yarlung-Yigong capture event occurred in the early-middle

Cenozoic, which implies that the late-Cenozoic increased exhumation rate is not related to the capture event.

Plain Language Summary

A capture event will lead to the formation of a new drainage divide between the capture point and the beheaded river. Then, the newly-formed drainage divide will migrate towards the beheaded river, a process called river-channel reversal. In this study, we used numerical modeling and natural examples to explore how a newly-formed drainage divide migrate after a river capture event. We find that the migration of newly-formed drainage divides can last for tens of millions of years, and the migration rate decreases exponentially over time. In addition, a larger captured area, higher uplift rate, or lower erosional coefficient can enhance the migration of the newly-formed drainage divide. We further applied our modeling to two natural examples. Our results show that the present Dadu-Anning divide is moving south and this process would last for tens of millions of years. The Parlung River has reversed its flow direction for over 200 km and reached a new steady state, which means an early formation of the modern Yarlung River, rather than the hypothetical Quaternary capture event of the Parlung River.

1 Introduction

The landscape equilibrium state can be upset by tectonic and/or climatic disturbances, as they alter the steady-state elevation of river channels (Whipple, 2001). When two river channels sharing a drainage divide have different steady-state elevations at their channel heads, the drainage divide will migrate toward the victim side with a higher steady-state elevation (Willett et al., 2014). The divide migration process will simultaneously decrease and increase the steady-state elevation of the victim and aggressor side, respectively, until the cross-divide difference is eliminated (Willett et al., 2014). The divide then reaches a new steady state and adapts to the new tectonic and climatic environment (He et al., 2021; Shi et al., 2021; Zhou et al., 2022a).

Contrary to continuous divide migration, discrete river capture events make a substantial adjustment in river network topology around the capture point (Morisawa, 1989; Bishop, 1995; Clark et al., 2004; Prince et al., 2011; Yanites et al., 2013; Lave, 2015; Stokes et al., 2018; Yang et al., 2020), and thus can rapidly change the steady-state elevation on both sides of the newly-formed drainage divide (Bishop, 1995; Goren et al., 2014; Willett et al., 2014; Shelef and Goren, 2021). As river capture events impact the evolution of the landscape, ecosystem, and even human civilizations (Winemiller et al., 2008; Willis et al., 2010; Hoorn et al., 2010; Xing et al., 2017), how and when they occurred is one of the major concerns for earth scientists (e.g., Clark et al., 2004; Fan et al., 2018; Yang et al., 2020). However, most capture events in case study remain controversial on their detailed processes and occurring time (Clark et al., 2004; Cina et al., 2009; Lang and Huntington, 2014; King et al., 2016; Gourbet et al., 2017; Govin et al., 2018; Zhang et al., 2019; Zhao et al., 2021a, b).

Past river capture events could be inferred from barbed tributaries, wind gaps, abandoned river channels, paleocurrent direction, and provenance analysis (Bishop, 1995; Clark et al., 2004; Brocard et al., 2011; Zhang et al., 2012; Bracciali et al., 2015; Chen et al., 2017; Fan et al., 2018, 2021; Harel et al., 2019; Xie et al., 2020; Yang et al., 2021; Zhao et al., 2021a, b). However, to obtain the exact time of dating the capture event is more challenging based upon these methods. This is partially because only the river relict sediments before the capture event can record the paleocurrent direction and provide a constraint on the capture event timing. A capture event usually occurred several or even tens of millions of years ago. It is not easy to find the paleochannel sediments on the main trunk of the beheaded, or the reversal and captor rivers (Clark et al., 2004; Fan et al., 2010, 2018; Wei et al., 2016), even though the sediments usually only provide an upper or lower limit to the capture time.

One way to study the river capture process, circumventing the caveats in the conventional, sediment-based techniques, is via the analysis of drainage divides. Immediately after a capture event, the steady-state elevation of the captor river is much lower than that of the beheaded river, which can cause a new and greater disequilibrium. Then, the newly-formed drainage divide will migrate from the capture point towards the beheaded-river side, which results in a small, but significant phenomenon called *river-channel reversal* (Clark et al., 2004; Clift et al., 2006; Harel et al., 2019; Yang et al., 2020; Shelef and Goren, 2021; Zeng and Tan, 2023). Therefore, the location and the stability of drainage divides, especially the newly-formed drainage divide between the reversal and the beheaded river channels, could provide new and independent constraints on the processes and time scales of the capture event.

In this study, we first use numerical modeling to explore the dynamics of river capture events and analyze the effects of captured area, uplift rate, and erosional coefficient on the migration rate of the newly-formed drainage divide. Then, we present two natural cases with significant river capture events, the Dadu-Anning in eastern Tibet and the Yarlung-Yigong in the eastern Himalayan syntaxis region to show how the modeling results are used to constrain the occurring time of capture events.

2 Background

To frame our analysis, we first make a conceptual overview of the river capture event. We then summarize analytical models of steady-state elevation at the channel heads. In addition, we briefly review the background on the Dadu-Anning and Yarlung-Yigong capture events, which are two typical natural cases of river capture on the Tibetan Plateau.

2.1 River capture event

River capture is a more common natural process with the interception of a river by an adjacent river as mountainous landscapes evolve (Bishop, 1995). So far, most identified river captures occurred between two tributaries with relatively small drainage areas (usually several to hundreds of square kilometers), accompanied by wind-gap migration (Shelef and Goren, 2021). This process is termed ***tributary shift*** here (Figs. 1B). As the divide migrates across these trunk-tributary confluences, the ongoing tributary shift towards the aggressor side causes slight fluctuations in the cross-divide difference in steady-state elevation (Fig. 1C).

On the other hand, a more severe scenario exists, in which a river captures a vast area (such as thousands of square kilometers or greater) all at once by cutting the trunk of the other river. Such a catastrophic process is called ***capture event***, and is usually regarded as the landmark of river network reorganization (Figs. 1D-E). A capture event reduces the steady-state elevation of the captor river by increasing the upstream area and raises the steady-state elevation of the beheaded river by decreasing the upstream area (Willett et al., 2014; Yang et al., 2015; Whipple et al., 2017). Therefore, a capture event makes a significant cross-divide steady-state elevation contrast (Fig. 1F). In this study, we focus primarily on the capture events.

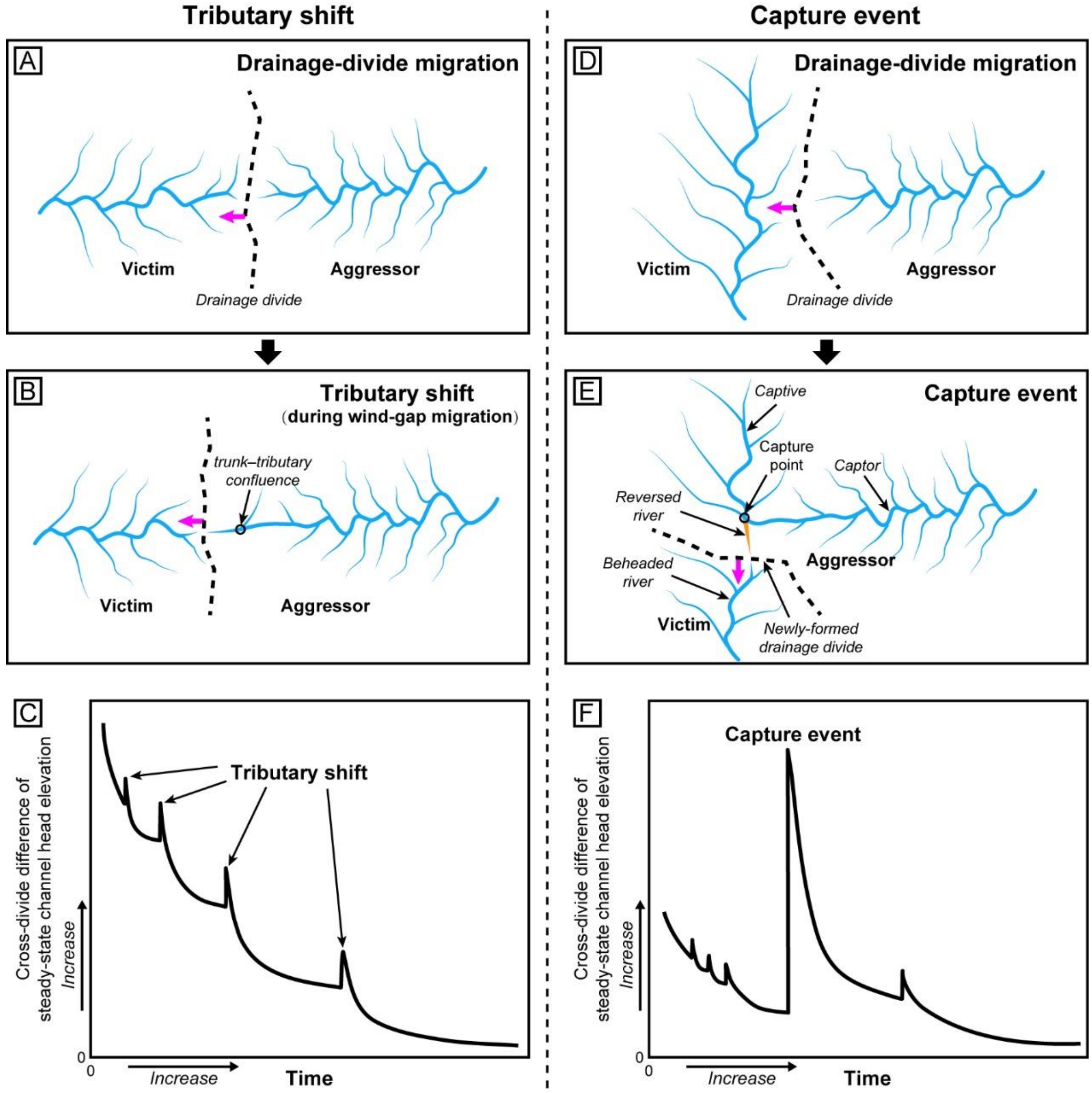

Fig. 1 Schematic illustration of tributary shift (A, B, C) and capture event (D, E, F). (A-B) A typical drainage-divide migration process with gradual shifts between tributaries. (C) The change of the cross-divide difference of steady-state channel-head elevation over time during the tributary shift process. The tributary shift can cause fluctuations in the cross-divide difference in steady-state elevation. (D-E) Illustrations of a significant drainage system reorganization after a capture event. Note the sudden, remarkable change in the river network. (F) The change of the cross-divide difference in steady-state channel-head elevation over time during the capture event. The capture event significantly increases the cross-divide difference of steady-state elevation.

2.2 Steady-state elevation and steady-state channel profile

Steady-state elevation is a theoretical value for which erosion would balance rock uplift (Whipple, 2001). It can be estimated from the model for river incision into bedrock (Whipple, 2001; Willett et al., 2014). According to the detachment-limited stream power model (Howard and Kerby, 1983), the erosion rate (*E*) is usually expressed as the following:

$$E = KA^{m}S^{n} \tag{2}$$

where *K* is the erosion coefficient, *S* is the channel gradient, *A* is the upstream area, and *m* and *n* are the area and slope exponents, respectively. At a steady state (*E* = *U*, *U* is uplift rate), Eq. (2) can be solved for the following expression (Kirby and Whipple, 2001):

$$S = \left(\frac{U}{K}\right)^{\frac{1}{n}} A^{\frac{-m}{n}} \tag{3}$$

The steady-state solution of a river channel profile (*z*) can be derived from integrating the channel distance (x):

$$z(x) = z_b + \int_{x_b}^{x} \left(\frac{U}{K}\right)^{\frac{1}{n}} A(x)^{\frac{-m}{n}} \, dx \tag{4}$$

where z_b is the elevation at the river base point. Parameter χ was introduced as an integral function of position in the river channel (Perron and Royden, 2013):

$$\chi = \int_{x_b}^{x} \left(\frac{A_0}{A(x)}\right)^{\frac{m}{n}} dx \tag{5}$$

where A_0 is an arbitrary scaling area to make the integrand dimensionless. Then, the steady-state solution of a river channel profile (*z*) can be expressed as:

$$z(x) = z_b + \left(\frac{U}{K}\right)^{\frac{1}{n}} (A_0)^{-\frac{m}{n}} \chi \tag{6}$$

2.3 Background on the Dadu-Anning capture event

The Dadu River, located in the eastern Tibetan Plateau, is a major tributary of the Yangtze River (Figs. 2A-B). It flows >600 km southwards from the Songpan-Ganze Terrane, and then makes an abrupt (~90°) loop at the town of Shimian, turning eastward into the Sichuan Basin. To the south of this river bend, a low and wide pass (wind gap) separates the Dadu River from the south-flowing Anning River. The Anning River drains a broad alluvial valley and finally converges with the Yangtze River (Fig. 2A). On the χ-plot (Fig. 2C), the Dadu River shows a high channel steepness in the middle reaches and less steep profiles in its upper and lower reaches, while the Anning River shows a gentle upper reach, and becomes steeper in its lower reach.

This river network pattern is suggested as a consequence of a capture event between the Dadu and Anning Rivers, based on the topography map, the existence of the wind gap, and fluvial sediments preserved within it (Clark et al., 2004; Yang et al., 2020; Zheng et al., 2023). The paleo-Dadu-Anning River originally flowed southward, and then was captured by an east-flowing paleo-Dadu River (Fig. 2B). The capture event formed the present Dadu River and beheaded the Anning River ("Anning" means quiet in Chinese). The newly-formed Dadu-Anning drainage divide was located close to the capture point (Shimian) and started to migrate southward (Fig. 2B). Yang et al. (2020) assigned this capture event at ~2.4 Ma based on provenance analysis, thermochronometry, topographic analysis, and numerical modeling.

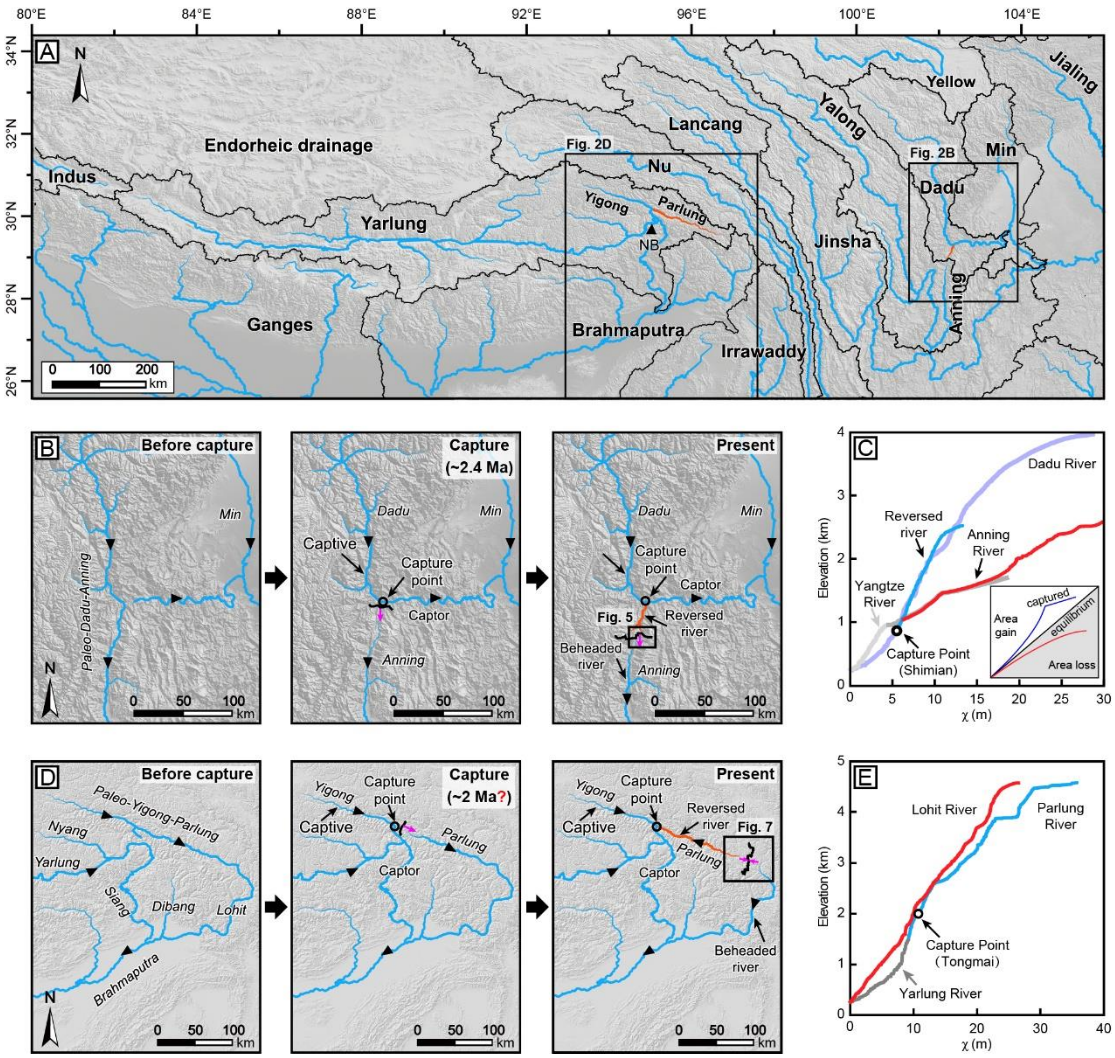

Fig. 2 (A) Overview of the major rivers and drainage basins in the Tibetan Plateau and surrounding region. (B) Illustration of the Dadu-Anning capture event. (C) χ-plots for the Dadu and Anning Rivers. (D) Illustration of the Yarlung-Parlung capture event. (E) χ-plots for the Parlung and Lohit Rivers.

2.4 Background on the Yarlung-Yigong capture event

In the eastern Himalayan orogenic belt, two major rivers, the southeast-flowing Yigong and northwest-flowing Parlung Rivers, incised the Namche Barwa massif and connected with the Siang River through the Tsangpo Gorge (Fig. 2A). After the confluence of the Siang, Dibang and Lohit Rivers, it becomes the Brahmaputra River. Along the Parlung River, all the barbed tributaries, wind gaps, and the low drainage divide indicated that it has experienced river capture and reversal (Burchfiel et al., 2000; Clark et al., 2004; Seward and Burg, 2008; King et al., 2016; Yang et al., 2021).

Two end-member models have been proposed to explain the complex drainage pattern. Some authors suggested that the Yarlung River once flowed east into the Irrawaddy River through the Parlung River, which was sequentially captured by headward erosion of the Siang-Brahmaputra (Burchfiel et al., 2000; Clark et al., 2004; Robinson et al., 2014). Others postulated a paleo-Yigong-Parlung-Lohit River, with the capture of an antecedent Yarlung-Siang-Brahmaputra River (Seward and Burg, 2008; Lang and Huntington, 2014; Govin et al., 2018). Regardless of the method of capture, the reversal of the Parlung River first occurs at the present Yigong-Parlung confluence (the town of Tongmai), and then the newly-formed drainage divide moves eastward to its current position (Fig. 2C). The headwaters of the Parlung River are separated from the Lohit River by the Parlung-Lohit drainage divide.

3 Numerical modeling on landscape evolution

To explore the dynamics of river capture event and its control factors, we performed 10 numerical experiments using the TopoToolbox Landscape Evolution Model (Campforts et al., 2017). In addition, we further analyzed the effects of captured area, uplift rate, and erosional coefficient on the location and migration rate of the newly-formed drainage divide.

3.1 Reference Model

We first conduct a landscape evolution modeling to reproduce the evolution of the newly-formed drainage divide migration after a river capture event. The reference model (Fig. 3) extends 200 km long in the E-W direction and 300 km wide in the N-S direction, which is resolved by a spatial resolution of 100 m. The initial elevation is set as a constant elevation of 1000 m on the northern edge, whereas the elevation at the southern edge is fixed to 0 m. The uplift rate is uniform across the model domain (3 mm/yr) except for a narrow zone in the east-central part of the model (X = 140–200 km; Y = 179–180 km), in which an eastward decreasing gradient zone of uplift rate is assigned to simulate an originally east-flowing river. Other model parameters in the reference model are set as follows: erosional coefficient (K) is 2×10^{-6}/year; area exponent (m), 0.5; slope exponent (n), 1; hillslope diffusivity, 0.03 m^2/year; and drainage area threshold, 0.1 km^2. The model was run for over 30 Myr, with a time step of 0.5 Myr (Movie S1).

Figure 3 shows selected representative snapshots of the reference model. At the initial stage, the drainage system contains a major, south-flowing river and a local, east-flowing river on the asymmetrically uplifted slope (Fig. 3A). Subsequently, the east-flowing river captures the south-flowing rivers, generating a new segment of the drainage divide between the reversal and the beheaded channels at the capture point (Fig. 3B). Due to this capture event, the area gain for the captor rivers increases the headwater channel steepness, and in turn leads to a fast erosion rate. In contrast, the beheaded river loses the upstream area, leading to a corresponding decrease in channel steepness and erosion rate. The cross-divide difference in erosion rate further drives the newly-formed drainage divide to migrate southward (Figs. 3C-D). As the divide migrates, the reversal river channel is elongated and the beheaded river channel shrinks. This results in an overall increase in the channel gradient of the beheaded river drainage compared to the reversal river drainage, and thus the drainage-divide migration rate slows down over time (Figs. 3D-F) (Braun, 2017; Whipple et al., 2017; Shelef and Goren, 2021).

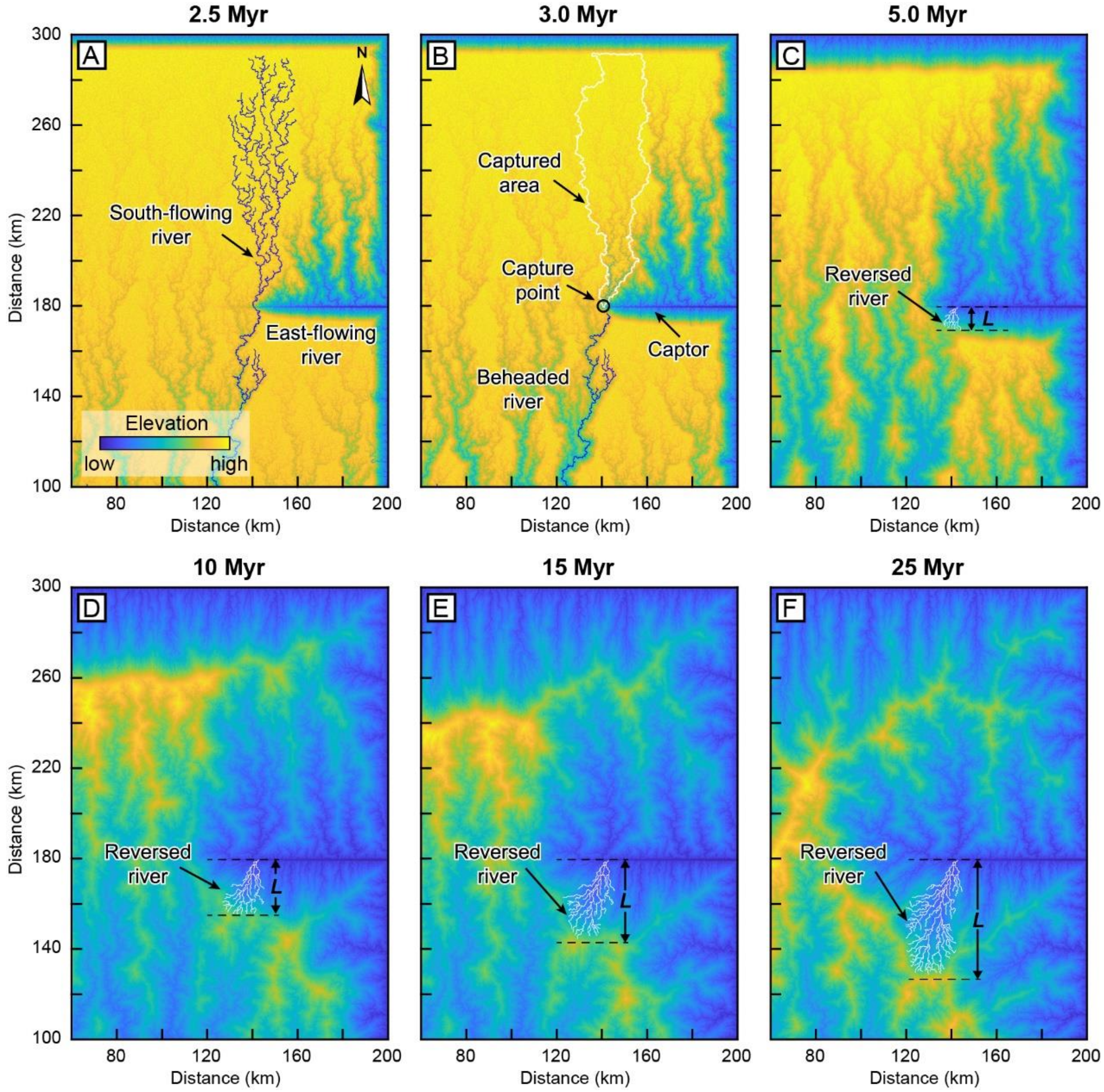

Fig. 3 Numerical landscape evolution model in response to a capture event. (A) The initial drainage system developed several south-flowing rivers and east-flowing rivers on the asymmetrically uplifted slope. (B) The originally south-flowing rivers are captured and turn to flow eastward. A new east-trending drainage divide was formed close to the capture point. (C-F) The newly-formed divide continues to migrate southward, resulting in an extension of the reversal channel. *L* represents the reversal distance, which refers to the vertical distance from the divide to the main trunk.

2.2 Effects of captured area

During the drainage-divide migration process, a river capture event instantaneously alters the drainage area, that is, the drainage area is removed from the beheaded and added to the captor rivers. This process leads to a change in the steady-state elevation of channel heads across the newly-formed drainage divide (Fig. 1F), which further promotes the drainage divide to migrate towards the beheaded-river side (Willett et al., 2014; Whipple et al., 2017; Shelef and Goren, 2021; Ye et al., 2022). To delineate the effect of the captured area on the migration of the newly-formed drainage divide, we systematically varied the size of the captured area by proportionally enlarging the model domain (Figs. 4A-B; Supplementary Fig. S1). Other parameters remained the same as the reference model.

We first obtained the location of the newly-formed drainage divide at each moment (at a time step of 0.5 Myr). The distance between the drainage divide and the main trunk of the east-flowing river is called *river-channel reversal distance* (Fig. 3). We measured the reversal distance at 2 Myr intervals (Fig. 4A), and calculated the mean reversal rate (Fig. 4B). The mean reversal rate, V, can be estimated by the equation of $V = (L_2-L_1)/(t_2-t_1)$, where L_2 and L_1 are the reversal distances at two instants of t_2 and t_1, respectively. Here, we obtained the mean reversal rate every 2 Myr (i.e., t_2-t_1), except for a rate at the very beginning with the interval of 1 Myr.

Under different scenarios, the reversal rates exhibit similar trends, in which the value is the greatest in the early stage, exponentially decreases to half after ~2–3 Myr, and further declines smoothly towards zero in the following tens of millions of years (Fig. 4B). In addition, the reversal rate and reversal distance increase with increasing captured area. When the captured area is set to ~2,200 km^2, the reversal rate is ~7.5 mm/yr at the very beginning of the experiment (1 Myr) and then gradually slows down (Fig. 4B). In this case, the drainage divide has migrated ~60 km within ~20 Myr (Fig. 4A). When the captured area is increased to ~25,000 km^2, the reversal distance is rapidly built up within the first ~8 Myr. The reversal rate in the early stage can reach the peak value of ~18 mm/yr, which is greater than those in other models.

2.3 Effects of uplift rate

Drainage adjustment is strongly controlled by vertical tectonic movement (Mitchell and Yanites, 2019; He et al., 2019; Shi et al., 2021; Ye et al., 2022), which can be represented by various uplift rates in this circumstance. To test the effects of tectonic on the migration rate of the newly-formed drainage divide, we assigned various uplift rates of 1, 2, 3, and 4 mm/yr (Figs. 4C-D) for model runs. The size of the captured area is constrained within a 10% error range with the reference model. The landscape evolution processes (Supplementary Fig. S2) are comparable to the reference model.

All the model results demonstrate that the newly-formed drainage divide after a capture event migrates southward for more than 30 Myr (and still yet to reach a steady state). The river-channel reversal rate decreases exponentially over time (Fig. 4D). Moreover, the uplift rate facilitates the river-channel reversal. A higher uplift rate results in a faster reversal rate and thus a longer reversal distance (Figs. 3C-D).

2.4 Effects of erosional coefficient

Lithology and climate can also affect the migration of drainage divides (e.g., Willett et al., 2001, 2014; Zondervan et al., 2020; Zhou et al., 2022a). Their effects are implemented in the rock erosion coefficient in our models. A smaller erosion coefficient means a stronger lithological unit or lower precipitation. Therefore, we designed one group of models to examine the influence of the erosional coefficient (Figs. 4E-F; Supplementary Fig. S3). The erosional coefficient is spatially uniform and varies between 10^{-6}/year and 10^{-5}/year for different models, which is comparable to the values in the natural landscapes (e.g., Stock and Montgomery, 1999).

In this series of models, our results show that a low initial rock erosion coefficient is beneficial for the migration of the newly-formed drainage divide (Figs. 4E-F). A minor rock coefficient induces a lower erosion rate, which results in a flat, plateau-like surface across the south-flowing rivers in the early stage (Supplementary Fig. S3). This allows the captor rivers to drive the drainage divide to migrate rapidly southward, which results in a faster reversal rate (Fig. 4F). In contrast, a higher erosion coefficient accelerates river erosion but hinders divide migration and river-channel reversal.

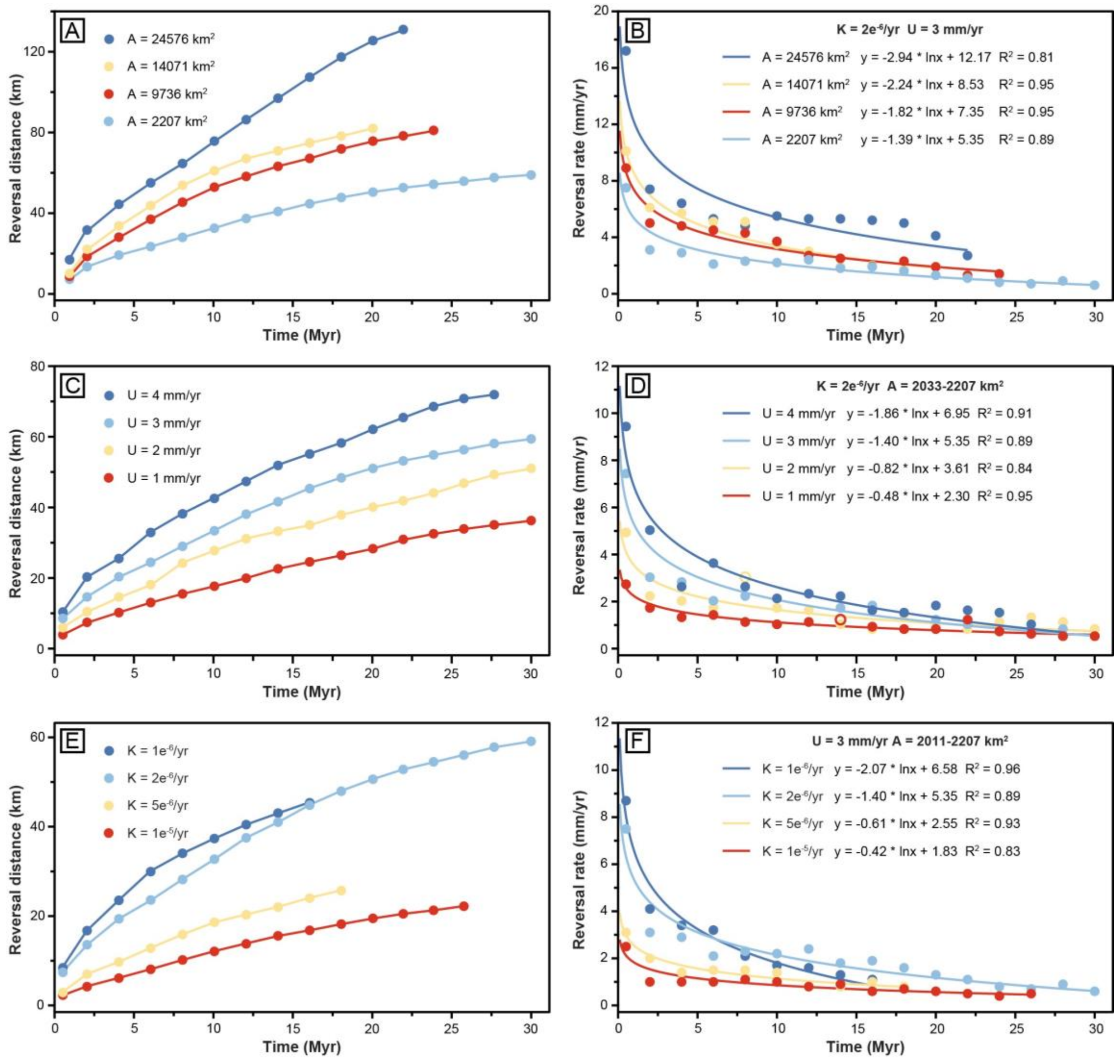

Fig. 4 The change of river-channel reversal distance and reversal rate over time in the models with different captured areas (A, B), uplift rates (C, D), and erosional efficiencies (E, F). The results show that the reversal rate exponentially decreases with time. The higher uplift rate, larger captured area, and lower erosional coefficient can lead to a faster reversal rate and thus longer reversal distance.

4 Application to natural landscapes

As above numerical modeling demonstrates, after a capture event, the newly-formed drainage divide between the reversal river and the beheaded river would migrate from the capture point towards the beheaded-river side until it reaches equilibrium or even undergoes an overturn. Therefore, in the case study, the stability and the location of the newly-formed drainage divides play a crucial role in revealing the river network reorganization process. Here, we evaluated the stability of the Dadu-Anning and Yarlung-Yigong drainage divides, respectively. With that, we predicate the future steady location of the Dadu-Anning drainage divide.

4.1 Dynamic Dadu-Anning drainage divide

Drainage-divide migration is essentially driven by the cross-divide difference in erosion rate (Willett et al., 2014; Forte and Whipple, 2018; He et al., 2021; Zhou et al., 2022a). Because the normalized channel steepness (k_{sn}) is positively and monotonically correlated with erosion rate (Kirby and Whipple, 2012), the comparisons on the k_{sn} value across the drainage divide have been used to evaluate the drainage-divide stability, assuming similar lithology and precipitation (Willett et al., 2014; Forte and Whipple, 2018; Chen et al., 2021). In particular, the k_{sn} value can be visualized by the slope of the χ-plots. Therefore, when comparing the top-most k_{sn} value (linear or quasi-linear χ-plots), a greater value (i.e., a steeper slope of χ-plot) would force the drainage divide to migrate towards the other side (Zhou et al., 2022b).

We compared the cross-divide differences in topographic features, k_{sn}, and χ by the satellite imagery and χ map (Fig. 5). The Dadu drainage has steeper channels, higher k_{sn}, and lower χ values than those in the Anning drainage (Figs. 5A, B, D). Here, we show three paired tributaries through similar lithologies to compute the χ-plots. Among them, a pair of rivers close to the broad valley is characterized by a signature of drainage area gain by tributaries shift in the χ-plot (Fig. 5C) (Willett et al., 2014; Beeson et al., 2017). For other rivers, the upper reaches of the Dadu River have higher k_{sn} values (greater slopes) than those of the Anning River (Fig. 5C), indicating that the drainage divide is migrating southward. In summary, the above different methods show consistent results, where the Dadu-Anning drainage divide is moving south.

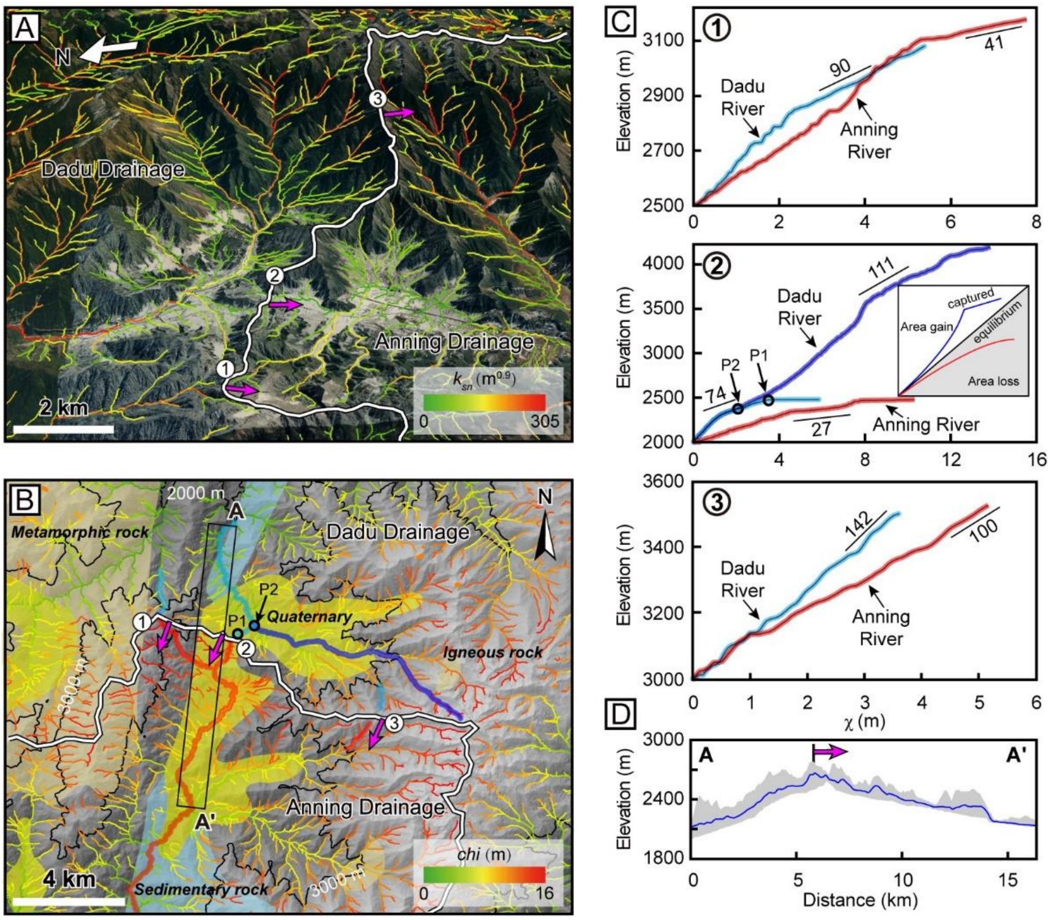

Fig. 5 Perspective views and χ map of channels for part of the Dadu-Anning drainage divides. The location is shown in Fig. 2B. (A) Perspective views of channels mapped with k_{sn}. The k_{sn} values in the Dadu drainage are generally larger than those in the Anning drainage. (B) Map of χ and geology. Arrows show the divide migration directions. P_1 and P_2 are the capture points. (C) χ-plots for three paired rivers across the divide. Numbers in the χ-plots are the average k_{sn} values. Rivers in red are the victims and those in blue are the aggressors. The results show that the Dadu-Anning divide is moving south. The reference drainage area is 10^5 m^2. (D) Swath profile A-A' of topography across the divide. Location of the swath is marked by the black rectangle in panel (B).

4.2 Future stable location of the Dadu-Anning drainage divide

To predicate the future steady location of the drainage divide, we calculated the cross-divide contrast index (*C*) (Zhou et al., 2022a). It amalgamates the across-divide differences in lithology, precipitation, channel height, and drainage-basin morphology by a quantitative theoretical relationship between the erosion coefficient (*K*), channel height (*H*), tortuosity coefficient (*T*), Hack's coefficient and exponent (*k* and *b*), area exponent (*m*), and slope exponent (*n*).

$$C = \left(\frac{K_\beta}{K_\alpha}\right)^{\frac{1}{n}}\left(\frac{H_\beta}{H_\alpha}\right)\left(\frac{T_\beta}{T_\alpha}\right)^{\frac{mb}{n}-1}\left(\frac{k_\beta}{k_\alpha}\right)^{\frac{m}{n}} \tag{1}$$

where subscripts α and β represent the two sides of the drainage divide. In this study, α is the northern side, and β is the southern side.

A pair of typical rivers close to the wind gap was selected (Fig. 6A). They flow into the main trunk of the Dadu and Yangtze Rivers, respectively. We measured the *H* and *T* at each side of the divide in ArcGIS software and determined the Hack's coefficient (k_α and k_β) and exponent (*b*) by fitting the drainage area and channel length (Fig. 6B) (Hack, 1957; Zhou et al., 2022a). Then, we calculated the *C* value combined with a uniform erosion coefficient ($K_\beta/K_\alpha = 1$). The detailed results are shown in Supplementary Table S1. Accordingly, we plotted the relationship diagram between the normalized drainage divide location ($D_\beta/(D_\alpha + D_\beta)$) and uplift rate ratio (U_β/U_α) (Fig. 6C). With a wide range of the U_β/U_α (0.5–1), the $D_\beta/(D_\alpha + D_\beta)$ value is determined as 63.2%–53.5%. Based on the present normalized location of the Dadu-Anning divide (~86.5%), we predict that the drainage divide would continue to migrate southward for ~65–92 km. It is worth noting that there may be errors in this value due to the inhomogeneous lithology (Supplementary Fig. S4) along the river channel.

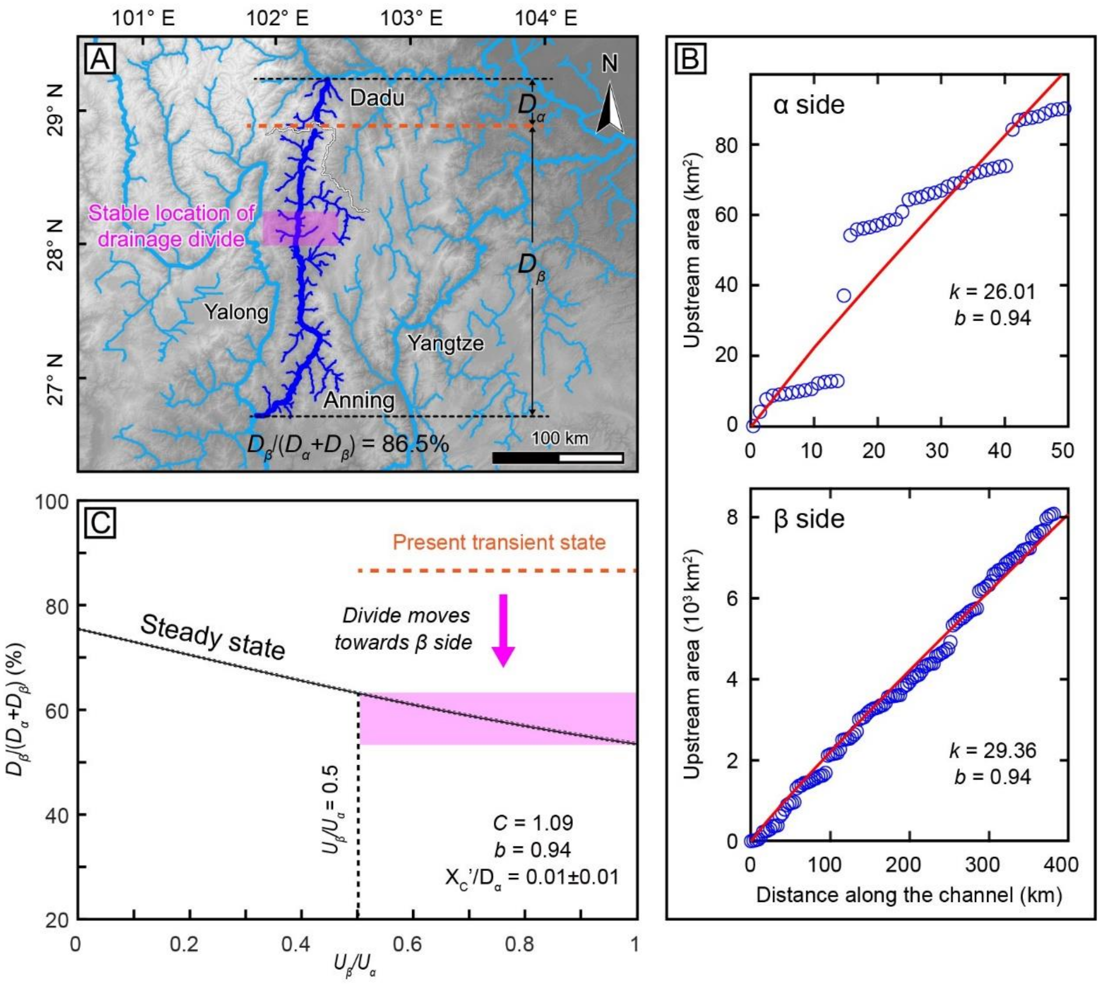

Fig. 6 Prediction for the steady location of the Dadu-Anning drainage divide. (A) Topography and drainage system. River segments highlighted in dark blue are measured and analyzed.

The burgundy area is the predicted steady location. (B) The Hack's coefficient and exponent (k and b). (C) The relationship diagram between the normalized drainage divide location (D_β / (D_α + D_β)) and uplift rate ratio (U_β/U_α).

4.3 Stable Yarlung-Yigong drainage divide

To analyze the stability of the Parlung-Lohit drainage divide, we first compared the difference in k_{sn} value across the divide (Willett et al., 2014; Scherler and Schwanghart, 2020). Fig. 7A is the k_{sn} distribution pattern yield by the ArcGIS software. Along a 500-meter-wide swath, the k_{sn} values are comparable between two sides of the drainage divide (Fig. 7B). We also measured the top-most k_{sn} value of four paired rivers across the drainage divide. These rivers are distributed in four sections of the Parlung-Lohit drainage divide (the ab, bc, cd, and de sections), respectively. The χ-plot pairs show near-parallel profiles and thus approximately equal k_{sn} values (Fig. 7C). Therefore, the results show that the Parlung-Lohit drainage divide is stable.

In addition, we adopted the Gilbert metrics method (Forte and Whipple, 2018) to analyze the four segments along the drainage divide. The Gilbert metrics incorporate the cross-divide differences in mean headwater local relief, mean headwater hillslope gradient, and channel elevation at a reference drainage area (Whipple et al., 2017; Forte and Whipple, 2018). The drainage divide will migrate towards the side with a lower slope, lower relief, or higher elevation in an asymmetrical mountain. In this study, we used a reference drainage area of 10^5 m^2 to calculate the Gilbert metrics. According to the standardized analysis of drainage migration direction (Fig. 7D), four segments show that the current divide is at a stable state, which is consistent with the results from the χ-plots.

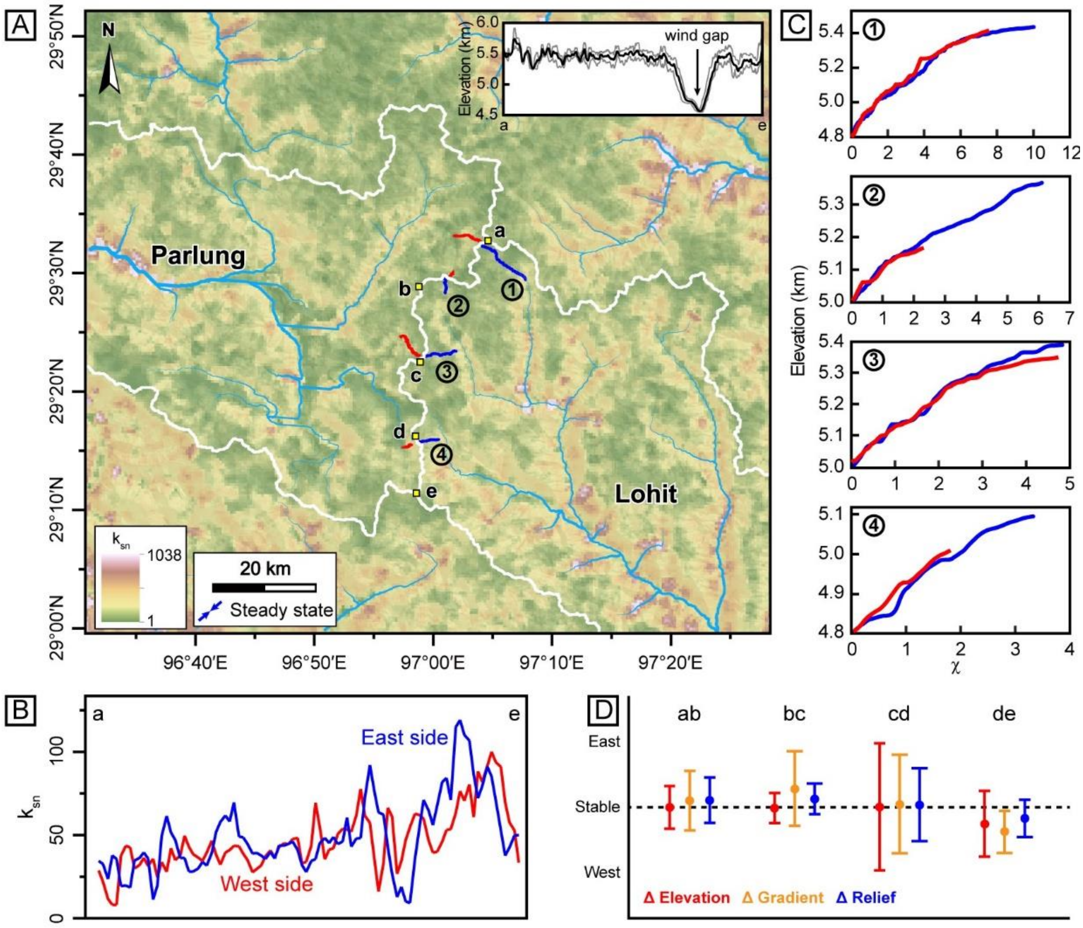

Fig. 7 (A) The k_{sn} map of the Yigong and Parlung drainages. See Fig. 2C for location. Insert figure is an elevation profile along the drainage divide (a-e), where the black arrows indicate the locations of the wind gaps. (B) Comparison of the k_{sn} values between the two sides of the Yigong-Parlung drainage divide along a 500-meter-wide swath. (C) χ-plots for four paired rivers across the divide. (D) Standardized delta plot for the four segments along the Yigong-Parlung drainage divide. The results are calculated by the DivideTools in TopoToolbox (Schwanghart and Scherler, 2014; Forte and Whipple, 2019). The different methods above show consistent results, where the Yigong-Parlung divide is steady.

5 Discussion

5.1 Effects of different parameters on divide migration following a capture event

A capture event can significantly adjust the river network topology, and thus cause an abrupt change of steady-state elevations along river channels. Willett et al. (2014) suggested that the drainage divide will migrate towards the river basin with higher steady-state elevation at the channel head. In this way, the drainage-divide migration following a river capture event is closely related to the cross-divide difference in steady-state elevation at the channel heads.

Based on the quantitative relationships (Eqs. 5 and 6) of the steady-state elevation, we analyzed the effects of capture area, uplift rate, and erosional coefficient on drainage-divide migration. A sudden adjustment in drainage area instantaneously changes χ but not riverbed elevation (Willett et al., 2014; Whipple et al., 2017). In general, the channel head of the captor river has a lower steady-state elevation than that at the future capture point, which drives the divide migration and eventually leads to the capture event. However, for brevity, we assume that the channel head of the captor river has a similar steady-state elevation to that at the future capture point before the capture event. That is to say, the pre-existing cross-divide difference of steady-state elevation before the capture event was not taken into account. After a capture event, the beheaded river loses lots of upstream areas, which causes the increase of χ and then yields a higher steady-state elevation (Fig. 8A) (Willett et al., 2014). Similarly, the decrease in χ with area gain for captor rivers leads to a lower steady-state elevation. Therefore, the capture event will substantially increase the contrast of the steady-state elevation across the newly-formed drainage divide. A larger captured area can theoretically expand this contrast (Fig. 8A). The numerical modeling results reveal that a larger captured area will drive faster drainage-divide migration when other conditions are the same (Figs. 4A-B).

In the case of increasing uplift rate or decreasing erosional coefficient (with other conditions being unchanged), the captor and beheaded rivers experience a uniform increase in riverbed elevation, and the steady state profile ($E = U$) becomes steeper accordingly (Fig. 8B). A capture event (with the same captured area) will increase the cross-divide difference in the steady-state elevation at the channel heads (Fig. 8B). Higher uplift rate or lower erosional coefficient will drive the higher cross-divide difference in the steady-state elevation at the channel heads, and further enhance the rate of drainage-divide migration, which is consistent with the result in the numerical modeling (Figs. 4C-F).

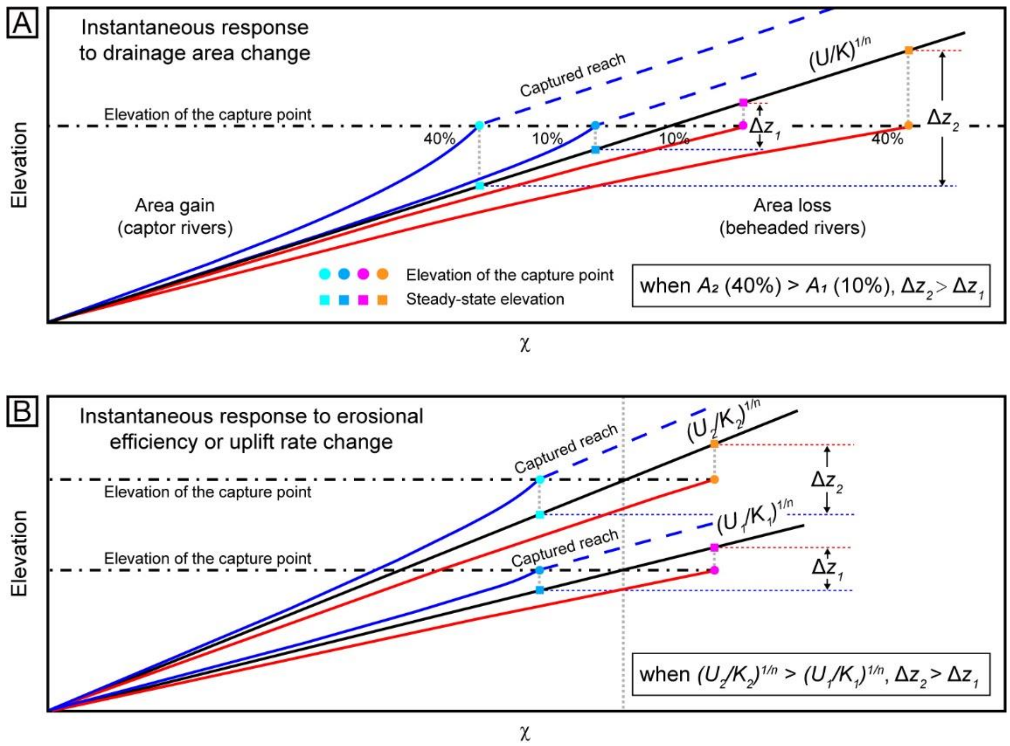

Fig. 8 (A) Schematic illustration of river profile response to drainage area change. A capture event will decrease the steady-state elevation for captor rivers gaining upstream area and increase the steady-state elevation for the beheaded rivers losing upstream area. A larger

captured area can expand this contrast, and accelerate the divide migration. (B) Schematic illustration of river profile response to uplift rate and erosion coefficient change. Increasing the uplift rate or decreasing the erosional coefficient can increase a cross-divide steady-state elevation contrast. Δz represents the cross-divide difference in steady-state channel-head elevation.

In summary, the larger captured area, higher uplift rate, or lower erosional coefficient can cause higher cross-divide differences in steady-state elevation of the channel heads, which facilitates the migration of the newly-formed drainage divide following a capture event.

5.2 The timescale of the Dadu-Anning drainage divide achieving a steady state

The modern Dadu and Anning Rivers have experienced an Early Pleistocene (~2.4 Ma) capture event (Yang et al., 2020), where the upper course of the original southward-flowing paleo-Dadu-Anning River was captured by an east-flowing paleo-Dadu River (Fig. 2B). The newly-formed Dadu-Anning drainage divide has migrated southward for ~40 km from the capture point (Fig. 2B). The result corresponds to a mean river-channel reversal rate of ∼16.7 mm/yr from the moment of the capture event to present.

Our results show that the Dadu-Anning drainage divide is moving south at present, and would further migrate ~65–92 km southward to reach a steady state (Fig. 6). It implies that the present Dadu-Anning drainage divide has only migrated less than half of the total migration (from the capture point to the final steady state of the drainage divide). Meanwhile, our numerical modeling indicates that the reversal rate rapidly decreases to half of the original value after ~2–3 Myr (Fig. 4). If, thereafter, the channel reversal rate decreases to ~8.4 mm/yr, the Dadu-Anning divide would take another ~11–8 Ma to reach a steady state. Taking into account that the reversal rate further decreases with time in the future (Fig. 4), this timescale of the drainage-divide migration to achieve an equilibrium will be significantly extended. Therefore, we conclude that the Dadu-Anning drainage divide would reach a steady state in tens of millions of years, which is consistent with that in the numerical modeling in this study (Figs. 3, 4) and those in previous studies (Shelef and Goren, 2021; Ye et al., 2022).

5.3 Constraints on the timing of the Yarlung-Yigong capture event

The current Parlung River has reversed its direction and flows northwest for more than 200 km. However, the timing of this capture event is a subject of controversy. One proposed explanation is that the paleo-Yarlung-Parlung-Irrawaddy River was captured by the Siang River, leading to the reversal of the Parlung River (Clark et al., 2004). This capture event was constrained at ~10 Ma (Brookfield, 1998; Robinson et al., 2014) or prior to ~4 Ma (Zeitler et al., 2001; Clark et al., 2004). Alternatively, recent studies have argued that the headward cutting Yarlung-Siang-Brahmaputra captured the Parlung River in the Quaternary, as indicated by thermochronological data (Seward and Burg, 2008; Zeitler et al., 2014; King et al., 2016; Yang et al., 2021) and provenance analysis (Lang and Huntington, 2014; Govin et al., 2018).

Our observations, based on the stability analysis and numerical modeling, provide a new perspective on this debate. We find that the Parlung-Lohit drainage divide is stable at present (Fig. 7), which implies that it has migrated ~200 km from the capture point towards the southeast and reached a steady state. According to the modeling results in this study (Fig. 4) and those in previous studies (Willett et al., 2014; Beeson et al., 2017; Whipple et al., 2017; Shelef and Goren, 2021), the river-channel reversal process could continue for tens of million years. Therefore, a Quaternary capture event would not be sufficient for a newly-formed drainage divide to achieve an equilibrium position. This idea can also be supported by the case of the Dadu-Anning capture, where the divide only migrated ~40 km to the south within ~2.4 Ma (Yang et al., 2020) and is currently moving south with a largely decreased migration rate but a longer remaining distance (~65–92 km) (Fig. 5). Furthermore, the area of the Yigong Drainage (~13000 km^2) captured by Yarlung-Brahmaputra or the Siang Rivers is much smaller than the captured area (~64000 km^2) by the paleo-Dadu River, making it even more unlikely that the time of the Yarlung-Yigong capture event is earlier than that of the Dadu-Anning capture event. Therefore, the results in this study support that the Yarlung-Yigong capture event occurred in the early-middle Cenozoic.

In the Namche Barwa syntaxis, bedrock and detrital thermochronology data revealed an acceleration of exhumation rates along the lower reaches of the Yigong and Parlung Rivers in the past 1–2 Ma (Seward and Burg, 2008; King et al., 2016; Bracciali et al., 2016; Yang et al., 2018, 2021; Govin et al., 2020). This rapid exhumation was suggested as a signal for the capture event of the Parlung River. However, our results tend to favor an early formation of the current Yarlung River pattern, rather than the hypothesis of Quaternary capture. It implies that the late Cenozoic increased exhumation rate is not driven by the capture event. In this case, the increased exhumation in the northern part may be attributed to a northward expansion of the syntaxis (Seward and Burg, 2008; Wang et al., 2014; King et al., 2016; Yang et al., 2018). In addition, spatiotemporal variations of precipitation may play a role in the rapid exhumation. The strengthened precipitation in the lower reaches of the Yarlung River can reduce the elevation of the riverbed, which can accelerate the exhumation in Namche Barwa syntaxis (Zeitler et al., 2001; Yu et al., 2011).

This study demonstrates the process of drainage-divide migration following a river capture event, which helps to understand the evolution of rivers and offers an opportunity to constrain the time of capture events from a new perspective. However, there are still some limitations in this study. Our modeling does not account for the presence of unconsolidated sediments, which are commonly associated with river capture events (Clark et al., 2004; Zeng and Tan, 2023). This may result in an underestimation of the simulated reversal rate. In addition, the tributaries and their avulsions on drainage-divide migration can play a critical role in the reversal rate and extent (Shelef and Goren, 2021), but are not considered in our models. How these two factors influence the migration of the newly-formed drainage divide following a river capture event, however, is beyond the scope of this study, and deserves rigorous analysis in future studies.

6 Conclusions

(1) Numerical modeling results show that the newly-formed drainage divide following a river capture event will migrate lasting for tens of millions of years, with the migration rate decreasing exponentially over time. A larger captured area, higher uplift rate, or lower erosional coefficient can increase cross-divide steady-state elevation contrast, and further enhance the rate of drainage-divide migration.

(2) The present Dadu-Anning divide is moving south, which would last for tens of millions of years and further migrate ~65–92 km southward to reach a steady state.

(3) The Parlung River has reversed its flow direction for over 200 km after the Yarlung-Yigong capture event, and the river network has reached a new steady state. Our findings support an early formation of the modern Yarlung River, rather than the hypothesis of the Quaternary capture event of the Parlung River. This implies that the late Cenozoic increased exhumation rate was not driven by the Yarlung-Yigong capture event.

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Data Availability Statement

The topography data is from https://search.asf.alaska.edu/. The precipitation data are downloaded from http://worldclim.org. Procedures to perform the calculations are implemented through the Topographic Analysis Kit (Forte and Whipple, 2019) and DivideTools (Forte and Whipple, 2018) based on TopoToolbox (Schwanghart and Scherler, 2014).

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