Divide migration and escarpment retreat: numerical models and application to the rift margin of Madagascar

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Abstract

A great escarpment at a rift margin can correspond directly to a major water divide but at many margins, including in Madagascar, the escarpment often appears as a steep knickzone on rivers that have their main water divides in the interior of the high plateau. We hypothesize that this variability in morphology is a reflection of the frequency and size of drainage area captured from the high plateau over the escarpment. To test this hypothesis, we document morphological features and weathering conditions from river sediment of Madagascar. We propose that the existence of a weathered weak surface layer of crystalline bedrock encourages large river captures from the upper plateau, leading to a dominance of knickpoint type rivers. We demonstrate that this is feasible, using 2-D landscape evolution models and show that an easily-eroded surface layer is prone to fast divide migration through frequent river capture and reversal. A positive scaling relationship between captured area and escarpment retreat rate is found from models. We demonstrate that this scaling is also observed in the great escarpments of Madagascar and India.

1 Introduction

A great escarpment at a passive margin is generally characterized by asymmetrical topography with a steep escarpment on the edge of a flat plateau, often with the top edge of the escarpment acting as the water divide. Alternatively, the water divide can be found internal to the plateau, at some distance from the steep escarpment. In the latter case, a significant area of the high plateau drains over the escarpment and the escarpment appears in the form of a knickzone on an escarpment river profile. The two morphologically distinct escarpment types have been referred to as "shoulder-type" and "arch-type", respectively (Bishop, 2007; Matmon et al., 2002), to indicate a different geodynamic formation mechanism.

The retreat of an escarpment with a water divide at its crest is driven by the differential erosion rates across the water divide where the steep escarpment erodes faster than the relatively slow eroding highland (Braun, 2018; Kooi and Beaumont, 1994; Tucker and Slingerland, 1994; Willett et al., 2018). In this case, it is the fluvial incision processes that set the rate of both divide and escarpment retreat, as demonstrated by a number of models (Braun, 2018; Willett et al., 2018). In the case where the water divide is located inland from the escarpment, these models will not apply and it is not clear whether the drainage basin morphology is set by other processes, such as flexural uplift (Tucker and Slingerland, 1994), or if the divide location is a transient feature set by capture of plateau area (Giachetta and Willett, 2018). The capture of highland rivers creates a spatial offset between the major divide and the escarpment, making a local segment of the escarpment appear to have a knickzone as it crosses the escarpment. In the case of isolated river capture with a subsequently stable water divide, the knickzone will migrate upstream returning the form of the river profile to a non-stepped, concave-up profile with the escarpment corresponding to the water divide. In this paper, we will discuss the morphology and genesis of escarpment rivers and will use the terms "divide-type" and "knickzone-type", to refer to the two morphologically distinct river profiles.

River capture is a common occurrence at many escarpments. For example, on the Serra Geral escarpment in southern Brazil, the current escarpment rivers have captured the inland plateau drainages during the retreat, leaving morphological traces of elbows, underfit valleys, and other evidence of river network rearrangement (de Sordi et al., 2018). Fluvial terraces filled with round pebbles are found on the crest of the Blue Ridge escarpment in the Appalachians, implying a capture of big, formerly plateau-confined rivers by the escarpment rivers (Prince et al., 2010). Morphological features of highland rivers and hillslopes might control patterns of captures (frequency and scale). Harel et al. (2019) demonstrated that progressive reversal and capture of highland rivers by escarpment rivers could be facilitated by lithological differences where a softer substrate fills a highland river valley. Harel et al. (2019) proposed a mechanism where windgap/water divide migration is independent of the escarpment retreat, or at least, where they are spatially separated and migrating together.

The conventional interpretation of knickpoints on rivers is that they represent temporal or spatial changes in uplift rate or rock erodibility (Gallen, 2018; Kirby and Whipple, 2012). If they are the result of a temporal change in uplift rate, they should propagate upstream, independent of any motion of the water divide. Alternatively, if knickpoints represent widespread river capture due to escarpment retreat (Giachetta and Willett, 2018), their formation and retreat should be linked to the jumps of the water divide. In this case, arch-type escarpments dominated by knickzone-type rivers are not genetically different from shoulder-type escarpments, but are simply a reflection of more common river capture. Such a model is supported by the presence of both types of river profiles on the same escarpment which has been documented, for example, in Madagascar (Wang and Willett, 2021).

In this paper, we use data from Madagascar to examine the processes of escarpment retreat by divide migration and river capture. In particular, we investigate the occurrence and frequency of rivers of both knickzone- and divide-type, that is those that exhibit large knickzones and those that terminate at an escarpment-top divide. To explain the large numbers of each type of river profile, we hypothesize that river capture is encouraged by the existence of a thick, easily-eroded, surface layer on the high plateau of Madagascar that is a result of widespread and extensive weathering. We demonstrate that this affects both the rate of escarpment retreat and the frequency of river captures. We explore these implications with 2-D models of landscape evolution.

2 Geomorphic characteristics of the escarpment and water divide of Madagascar

2.1 Spatial offset between divide and escarpment

A great escarpment is characterized by a high relief zone rimming an inland low-relief, high-elevation plateau. Eastern Madagascar is characterized by a great escarpment that extends inland of the coastal plain for ~1000 km (Gunnell and Harbor, 2008; Wang et al., 2021). The major continental water divide that separates eastern and western flowing rivers approximately follows the top of the escarpment (Fig. 1a and inset). There is a spatial offset between the island divide and the escarpment (Fig. 1a). Although there are times when the divide follows the escarpment, it is, however, not rare for it to be located kilometers to 10s-100s kilometers distant from the escarpment (Fig. 1a). The area between the divide and the escarpment edge is characterized by low-gradient river reaches, similar to the plateau rivers on the other side of the water divide (Fig. 1b). Regardless of where the divide is located, the steep escarpment reaches stand in contrast to both the low-gradient coastal reaches and the plateau reaches of escarpment rivers (Fig. 1b). We summarize the river profile shapes in Fig. 2. Approximately 33% of Madagascar escarpment rivers are knickzone-type, and 57% of rivers are divide-type with the remaining rivers indeterminate at the scale of our analysis (Fig. 2 b-e). The two forms of the river profiles appear almost randomly along the strike of the escarpment with no spatial patterns or long, consistent segments.

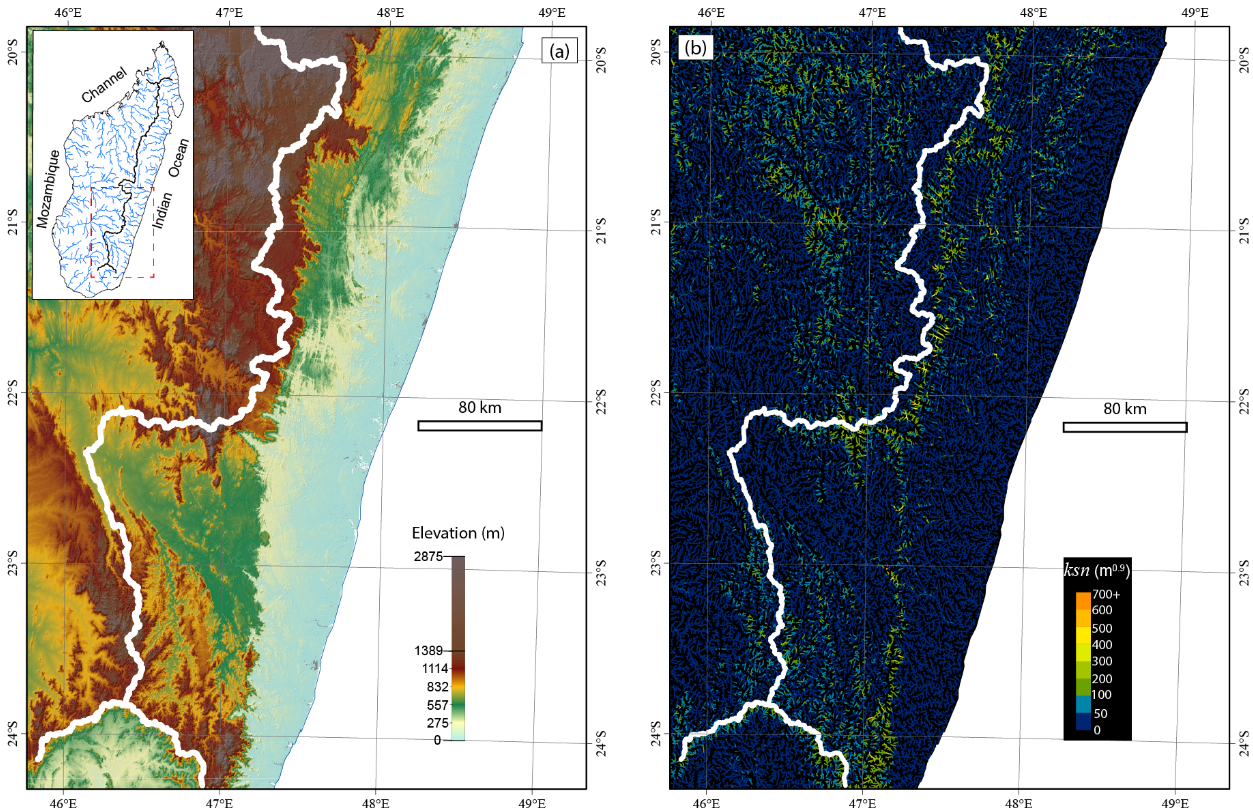

Fig. 1 (a) Topography of Madagascar, with the main water divide in white and major rivers shown in the inset. (b) Normalized river steepness index (Wobus et al., 2006). The topography is from the Shuttle Radar Topography Mission (SRTM) 90 m digital elevation model (DEM) (Jarvis et al., 2008). Rivers are extracted from 90 m HydroSHEDS DEM (Lehner et al., 2008) and clipped to a minimum drainage area of 5 km^2.

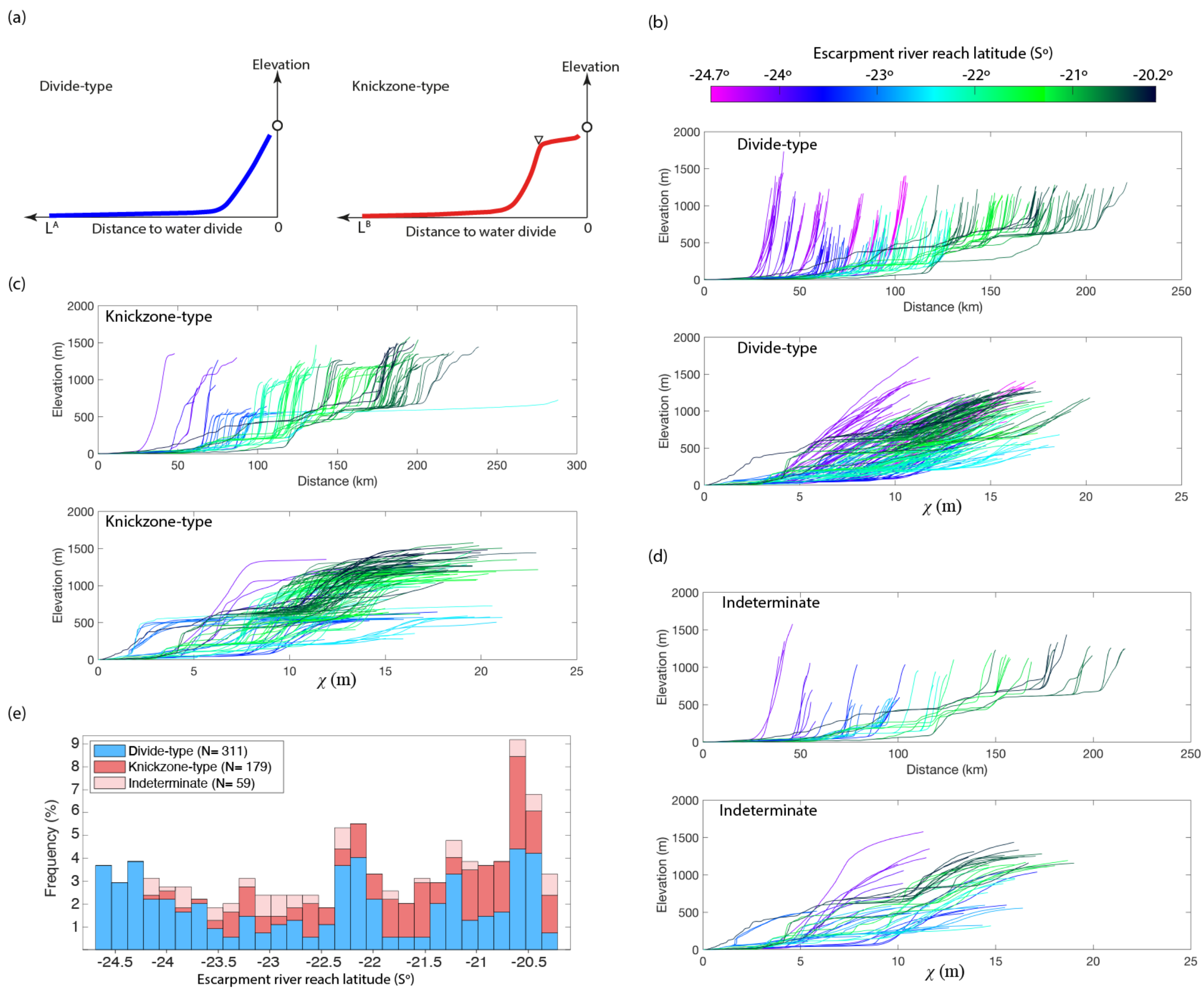

Fig. 2 Escarpment river types of eastern Madagascar. The location of the studied escarpment is shown in Fig. 1a. (a) Schematic summary of divide-type and knickzone-type river profiles. (b) Escarpment river profiles exhibiting divide-type, plotted against distance and normalized distance (Perron and Royden, 2013) and colored by the latitude of channel head. (c) Escarpment river profiles exhibiting knickzone-type , plotted in the same manner as (b). (d) Escarpment river profiles of indeterminate form, plotted in the same manner as (b). (e) Spatial distribution of escarpment river types along the strike of the great escarpment.

2.2 River capture

Paleo-captures of highland rivers by escarpment-draining rivers are common in Madagascar. We expect that these occur at multiple scales, and with a variety of patterns of reversal or flow redirection. For example, in southern Madagascar, the capture of the Mananara River has driven the divide ~200 km away from the escarpment (Fig. 3a). Delaunay (2018) and Schreurs et al. (2010) pointed out the water divide of the Mananara River basin is established through captures of three big, and many small, plateau tributaries and reversal of the trunk channel on the flat plain (Fig. 3a). The neighboring Manampatrana River, is also advancing its headwater divide into the plateau with a similar pattern of drainage reversal and progressive capture of tributaries (Fig. 3a). This capture of plateau area could be at the expense of the Mananara, or previously west-flowing rivers, depending on the order of the capture events, which is unknown. The abandoned watercourse at the head of the Manampatrana is identified from Google Earth images and indicated in Fig. 3c. Rivers on top of the plateau in the aggressive escarpment basin are low gradient (Fig. 3b) and the junction angles between the tributaries and the trunk channel are usually larger than 90 degrees (Fig. 3a, 3c). Similar situations of capture-driven decoupling of water divides and escarpments are found at other sites along the escarpment.

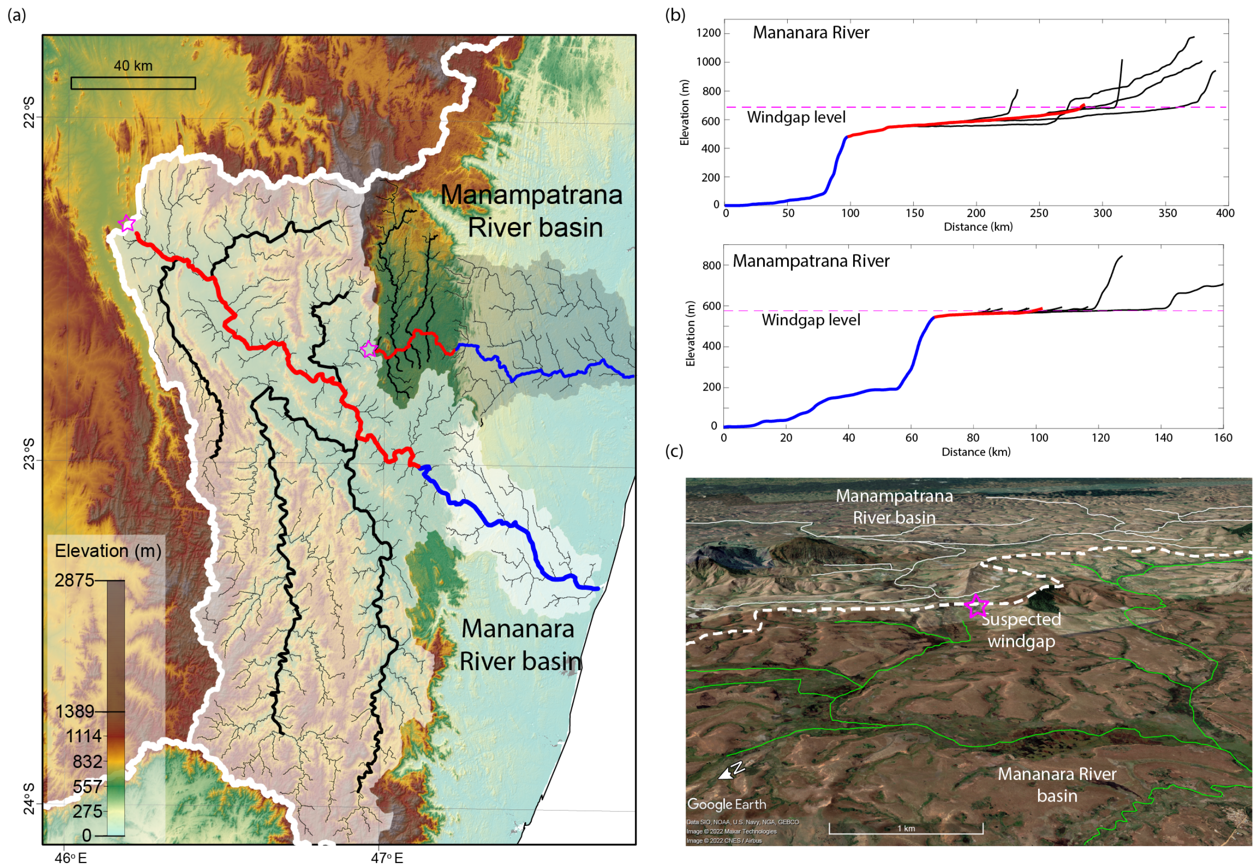

Fig. 3 (a) Escarpment-draining basins in southern Madagascar showing major river capture events. Black lines mark the major captured tributaries where the trunk channels on the plateau (red) are reversed and captured by the escarpment reach (blue). The thick white line is the island water divide. The Mananara River basin (shaded in white) is interpreted to be a major capture from west to east-flowing. The Manampatrana River (shaded in grey) is also interpreted to have captured area that used to be west-flowing. The stars indicate the identified windgap at the head of the reversed reach. (b) River profiles of the Mananara and the Manampatrana rivers. (c) Google Earth image showing the abandoned river course between the Mananara (the green) and the Manampatrana (the white) rivers where the white dashed line marks the divide between them.

2.3 Weathered high plateau of Madagascar

The relative weathering intensity of silicate rock can be assessed with the relative abundance of major elements. The relative weathering intensity indices calculated on riverine sediment, especially on suspended sediment, represent the average weathering conditions of a catchment (Guo et al., 2018; Lecomte, 2014). A survey conducted by the China Geological Survey, Shenyang Section, sampled a total of 1136 samples of bedload river sediment in the study area and measured major elements. 90% of the sampled catchments are in the range of 10s-100s km^2, with 55.5% smaller than 100 km^2. Samples were sieved to a size fraction below 850 μm, and major elements were measured at the Mineral Resource Supervise Examine Center in Zhengzhou, China. Major elements were measured using XRF (SiO_2 and Al_2O_3) and ICP-MS (CaO, K_2O, MgO, and Na_2O). To estimate the general degree of bedrock weathering, we calculated the commonly used chemical index of weathering (CIW) (Harnois, 1988). High CIW indicates a high degree of weathering.

South of the Alaotra-Ankay graben area, the study area comprises three geological domains of the Precambrian shield that are differentiated based on geological age, lithology, climate, and metamorphic fabrics. These are referred to as the Antananarivo, Ikalamavony, and Anosyan domains (Tucker et al., 2014). Our calculated weathering indices indicate differences in the degree of weathering between these geologic domains as well as between the modern morphological domains (Fig. 4). The Antananarivo Domain is intensively weathered on the highland above the escarpment and the coastal plain. The escarpment zone is less weathered. The Ikalamavony Domain shows a low degree of weathering throughout Madagascar. The southernmost Anosyan Domain shows a high degree of weathering, including the escarpment. Other weathering indexes, i.e. the chemical index of alteration, the Plagioclase index of alteration, and the weathering index of Parker show the same weathering pattern as the CIW (Supplement Figures S1-S3).

We expect that the CIW reflects the degree of weathering intensity and the thickness of the weathered zone across Madagascar. A thick regolith layer has been described on the highly weathered plateau of Madagascar (Wells et al., 1997; Wells and Andriamihaja, 1993, 1990). This regolith layer is fractured and altered from the crystalline Precambrian bedrock. It acts as an important surface water aquifer for the central plateau of Madagascar (Davies, 2009; Rahobisoa et al., 2014). The relatively weak regolith layer is also manifested from high-density of hillslope failures which excavate up to 10s meters of regolith on the central Madagascar Plateau (Brosens et al., 2022; Cox et al., 2010). We posit that this layer also affects the pattern of river profiles and the frequency of river capture, as we explore in the subsequent section.

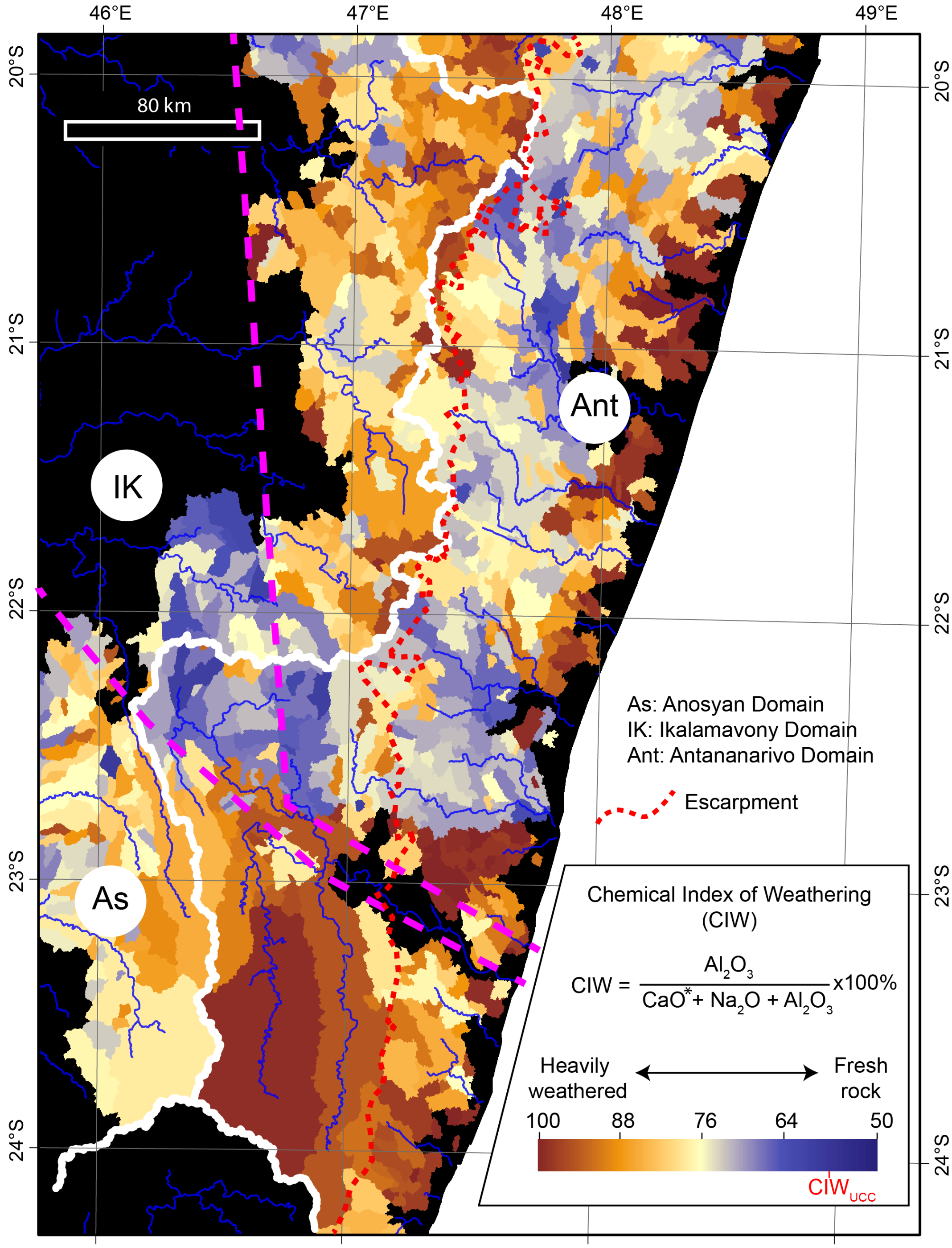

Fig. 4 Chemical index of weathering (CIW) from river sediment of Madagascar. The mean CIW of average elemental compositions of upper continental crust (CIW_{UCC}) is from Rudnick and Gao (2005). The three geological domains (As, IK, and Ant) are indicated and are different in age and major lithological composition (Tucker et al., 2014). Compositional and morphological effects are evident with low CIW in

the IK and on the escarpment. Higher values of CIW are observed on both the plateau and the coastal lowlands.

3 Modeling of escarpment retreat with an erodible surface layer

We hypothesize that the regolith-mantled high plateau of Madagascar has facilitated the many observed captures and the frequency of the knickzone-type Madagascar escarpment rivers. The regolith layer can be generalized as an erosionally weak surface layer. Given the systematic weathering contrast between the high plateau and the escarpment, homogeneous erosion-resistant substrate can be assumed to characterize the substrate of the escarpment and the underlying unweathered bedrock. To test this hypothesis, we construct a series of numerical models of the landscape evolution, including fluvial incision processes with differentially erodible bedrock. We use the Divide and Capture (DAC) landscape evolution model (Goren et al., 2014) which includes an explicit, and therefore a precise representation of water divides and river capture (Goren et al., 2014).

3.1 Model set-up

To simulate a weak surface layer, we apply a layer covering the entire plateau (Fig. 5). The weak surface layer is characterized by the thickness, T_{hw}, and the erodibility, K_w, both of which are constant in time (Fig. 5). The underlying bedrock has a lower erodibility value, K_b. On the plateau side, plateau rivers always incise into the weak layer and given sufficient time or proximity to the escarpment, will incise through the weak layer reaching the more erosion-resistant bedrock. On and below the escarpment, the weak surface layer is not present or fully removed by erosion.

The model consists of a two-dimensional domain, representing a planform surface over which water is routed into rivers, which subsequently incise into the substrate following a stream-power law (Whipple and Tucker, 1999):

$$E = KA^m S^n \quad (1)$$

The river erosion rate, E, is physically characterized by the shear-stresses on the substrate and the rock erodibility, K. Shear stress is approximated with the drainage area, A, and channel slope, S. m and n are empirical parameters. We use the landscape evolution code, DAC, to solve the stream-power equation at each numerical grid point. DAC calculates water routing and incision and applies geometric rules for river capture and precise divide positioning (Goren et al., 2014). Regions upstream of a threshold drainage area are regarded as hillslope dominated and are assigned a steady, threshold slope.

We construct a reference escarpment retreat model for comparison with the weak surface layer model. In the reference model, a uniform erodibility, K_b, is used for all grid nodes throughout time and space.

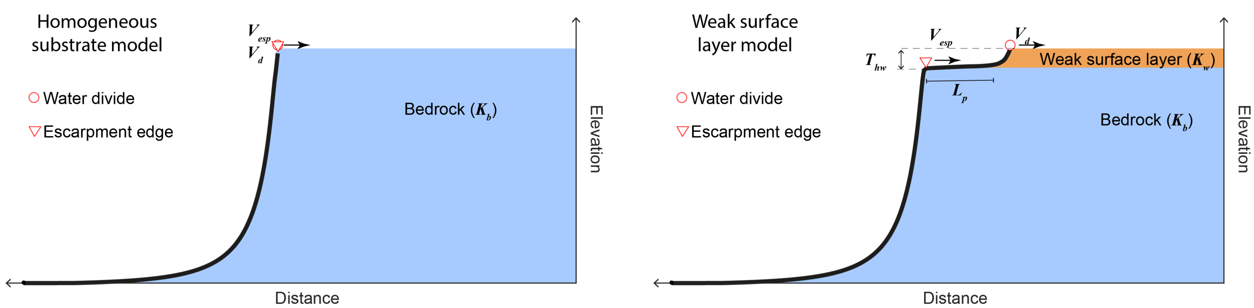

Fig. 5 Cross-section view of the reference homogeneous substrate model and the weak surface layer model. In the weak surface layer model, a surface layer (thickness T_{hw}, erodibility K_w) mantles the highland, overlying the bedrock (erodibility K_b). The thick black line is a schematic of an escarpment river. The divide and escarpment retreat at rates of V_d and V_{esp}, respectively.

3.2 Results of escarpment retreat model for a homogenous substrate

We run a simulation, S0, to study the homogeneous substrate case. The simulation starts from an initial escarpment landscape and river network (Fig. 6 a1). The initial escarpment rivers are of the divide-type:

the top edge of the escarpment acts as the major water divide that separates the plateau rivers and escarpment rivers. The steep reaches of the initial escarpment rivers dictate a regular escarpment front with little sinuosity.

In the homogenous substrate model, the escarpment retreats and continues to define the major water divide for most of space and time (Fig. 6 a1-a5, Supplement Movie S1). The position of the major water divide approximately corresponds to the escarpment edge in space (Fig. 6 b), with transient exceptions when a river capture forces a region of the plateau to drain over the escarpment edge, creating a spatial offset between the major divide and the escarpment. On average, the divide and the escarpment retreat steadily both temporally and spatially as predicted by theory (Braun, 2018; Willett et al., 2018) (Fig. 6 b). The escarpment front is regular, although more sinuous than the initial condition. Sinuosity is transient, reflecting the occurrence and size of river captures (Fig. 6 c).

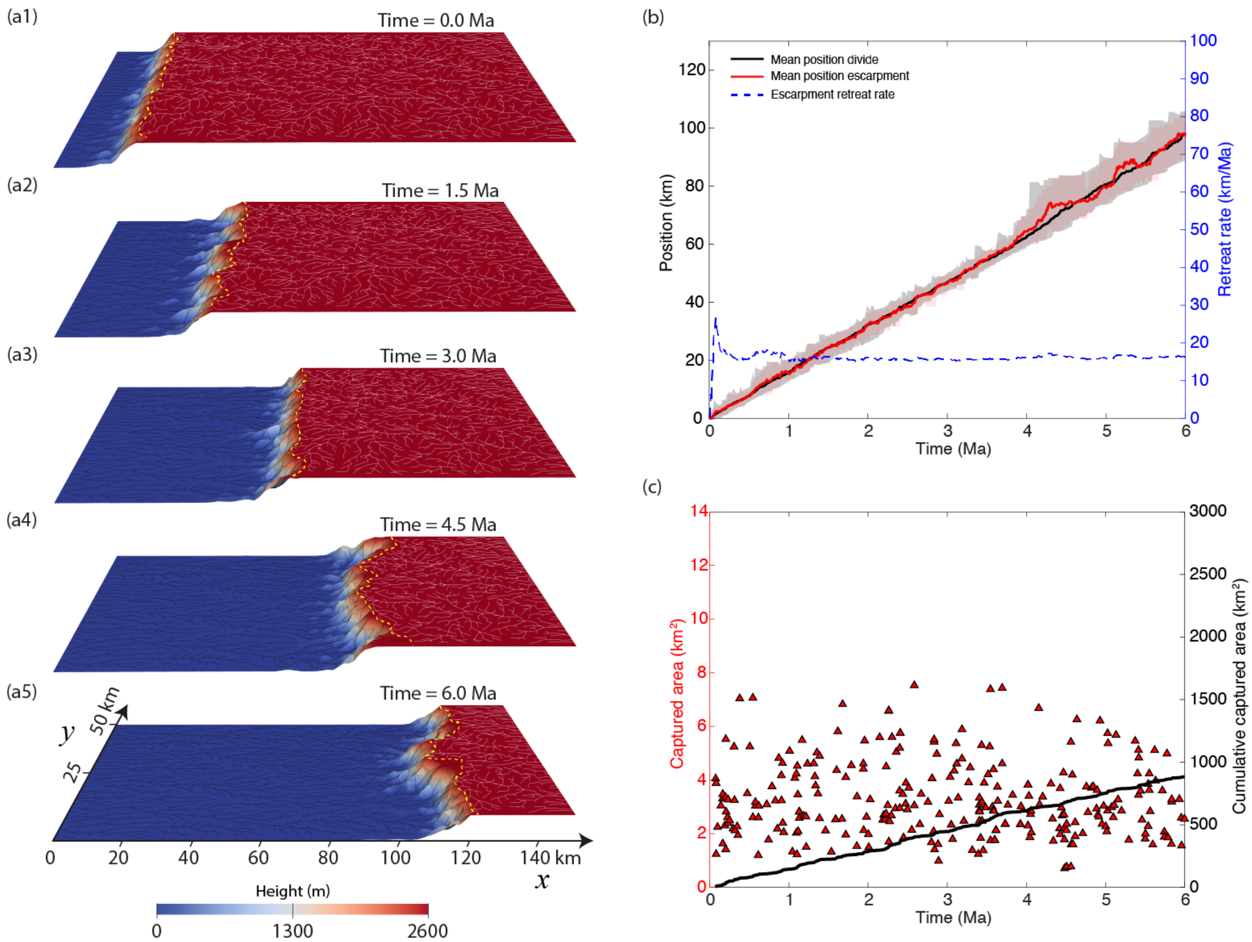

Fig. 6 Results of the homogeneous substrate model of simulation S0. Model dimensions are 100 km in y-direction and 150 km in the x-direction. The landscape and river network is shown every 1.5 Ma (a1-a5), although we note that time scales directly with K_b for this model. Escarpment rivers (in black) flow to the left boundary, which are separated by the major water divide (dashed in yellow) with plateau rivers (in white) that flow to the right boundary. (b) Mean position of the major divide and the escarpment shows the near coincidence between the two features in space. The grey and red shading indicate the min and max positions of the divide and escarpment, respectively. The dashed blue line indicates the retreat rate of the escarpment. (c) Individual capture events are indicated with their drainage area. The solid black line marks the cumulative captured area. See Supplement Tables S1, S2 for the parameters of this simulation.

3.3 Results of escarpment retreat with a weak surface layer

To make direct comparisons of the topographic morphology and retreat rates, we construct simulation S1. The initial condition of S0 and S1 are identical (Fig. 6 a1 and Fig. 7 a1). All model parameters are identical, except for the erodibilty of the surface layer; below this weaker, more erodible, surface layer the substrate is the same as simulation S0. Other input parameters are summarized in Supplement Tables S1 and S2.

The contrast between the models with and without a weak layer is clear. The weak layer results in an escarpment that retreats faster and is more sinuous (Supplement Movie S3). River capture events are more common and larger, systematically creating a spatial offset between the steep escarpment front and the water divide (Fig. 7 a1-a5, Supplement Movie S2). Many of the river captures are not single events, but are represented by a sequence of captures, where an initial capture or reversal leads to other captures due to rapid incision into the weak surface layer. The mean spatial offset between the divide and the escarpment fluctuates but is maintained at an approximately constant mean distance once the system stabilizes, and therefore the escarpment retreats at a constant rate and maintains the stepped, knickzone-type river profile that would be regarded as typical for an arch-type margin (Fig. 7 b). Along the strike of the escarpment, retreat rates vary spatially in that the escarpment is sinuous and embayments and salients are observed (Fig. 7 a2). Erosional remnants are also formed when the main escarpment has swept past but not fully eroded all bedrock (Fig. 7 a3-a5). The divide-escarpment system retreats at a near-steady rate but there are fluctuations in the rate due to larger river captures.

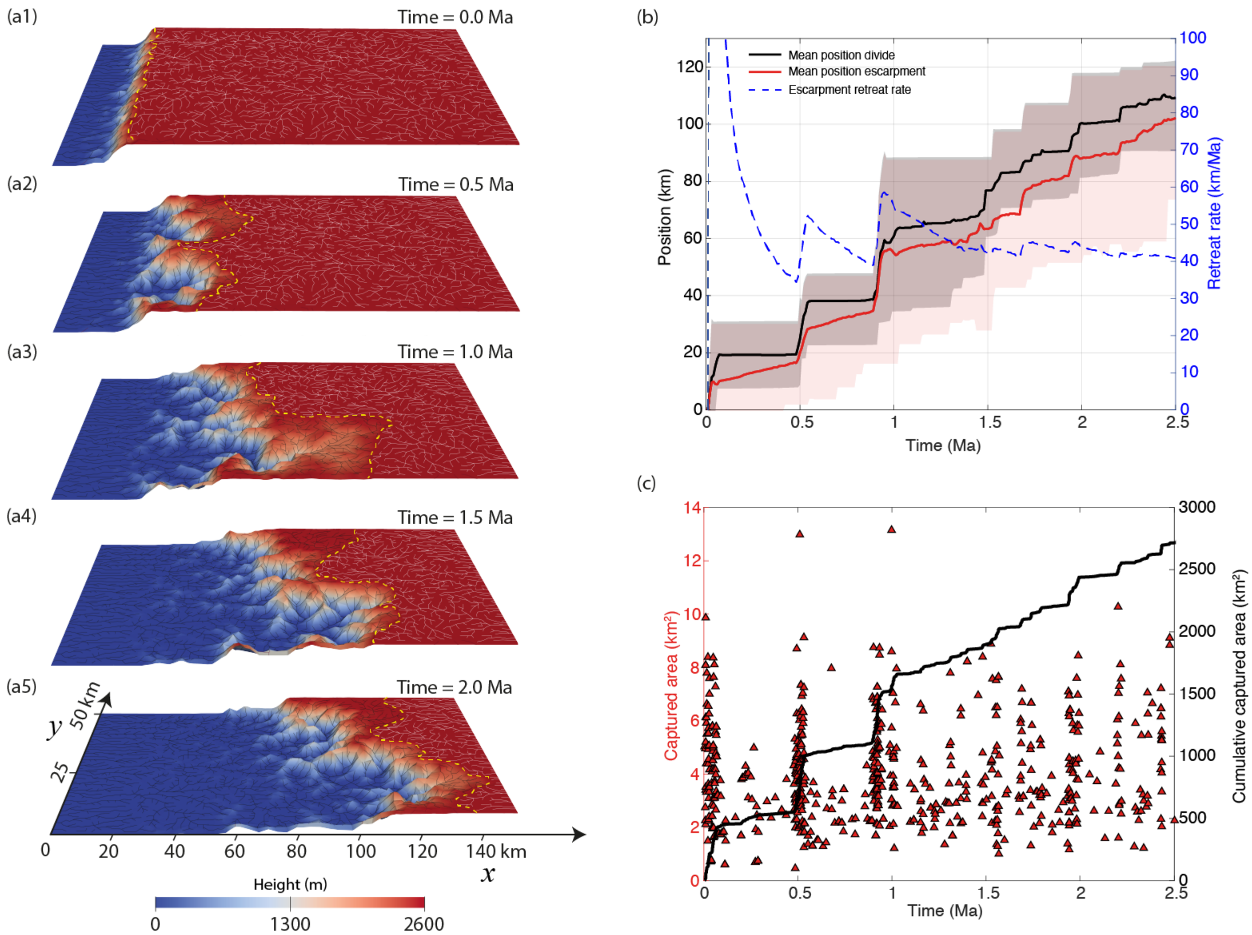

Fig. 7 Results of simulation S1 for an escarpment with a weak surface layer. The landscape and river network is shown every 0.5 Ma (a1-a5). A spatial offset between divide and escarpment is common due to the higher frequency and size of capture events, relative to model S0. (b) The mean positions of the main divide and the escarpment show the systematic offset between the two features in space. The grey and red shading indicate the min and max positions of the divide and escarpment, respectively. The dashed blue line indicates the retreat rate of the escarpment. (c) Individual capture events are indicated according to their drainage area. The solid black line marks the cumulative captured area. See Supplement Tables S1, S2 for the parameters of this simulation.

3.4 Parametric controls on retreat rate

The existence of the weak surface layer affects the retreat rate as well as the morphology of the escarpment. To investigate how these characteristics depend on the model parameters, we ran a series of models varying the important parameters, including the plateau height, the erodibility of the surface layer, K_w, and its thickness, T_{hw}. For each model we tracked the important characteristics, including the retreat rate and frequency, and area involved in river captures.

Plateau or escarpment height provides the potential energy for erosional processes, so it has been argued that retreat rate should scale with height (Willett et al., 2018). We have confirmed this result by conducting 7 simulations using the same initial river pattern and homogeneous erodibility as in model S0, but varying the plateau height (simulations S2-S8) (Figure 8a). These models were run until a dynamic steady retreat rate was achieved. (Supplement Movie S4). These models provide a comparative baseline for the weak layer models.

The basement erodibility, K_b, also provides a direct scaling of the retreat rate for the homogeneous models (Willett et al., 2018). With the linear ($n=1$) stream power model, and homogeneous material, model time scales directly with K_b, so there is a direct and linear dependence on erodibility, assuming time-independent hillslope processes. For the weak-layer models, we express the erodibility of the weak layer as a ratio to the basement erodibility, noting that results will all scale with K_b.

The existence of the weak surface layer increases the retreat velocity by increasing the frequency and size of river captures. By capturing upstream drainage area, the discharge over the steep escarpment increases along with the incision rate and thus the retreat rate. A weak surface layer increases the plateau drainage area and the area at any given time will be larger with a more erodible layer (Fig. 8b) or a thicker layer (Fig. 8c). The parametric relationship between the weak layer and the retreat rate can be generalized by plotting retreat rate against the area above the escarpment (Fig. 8d). This collapses all model results onto a single scaling relationship.

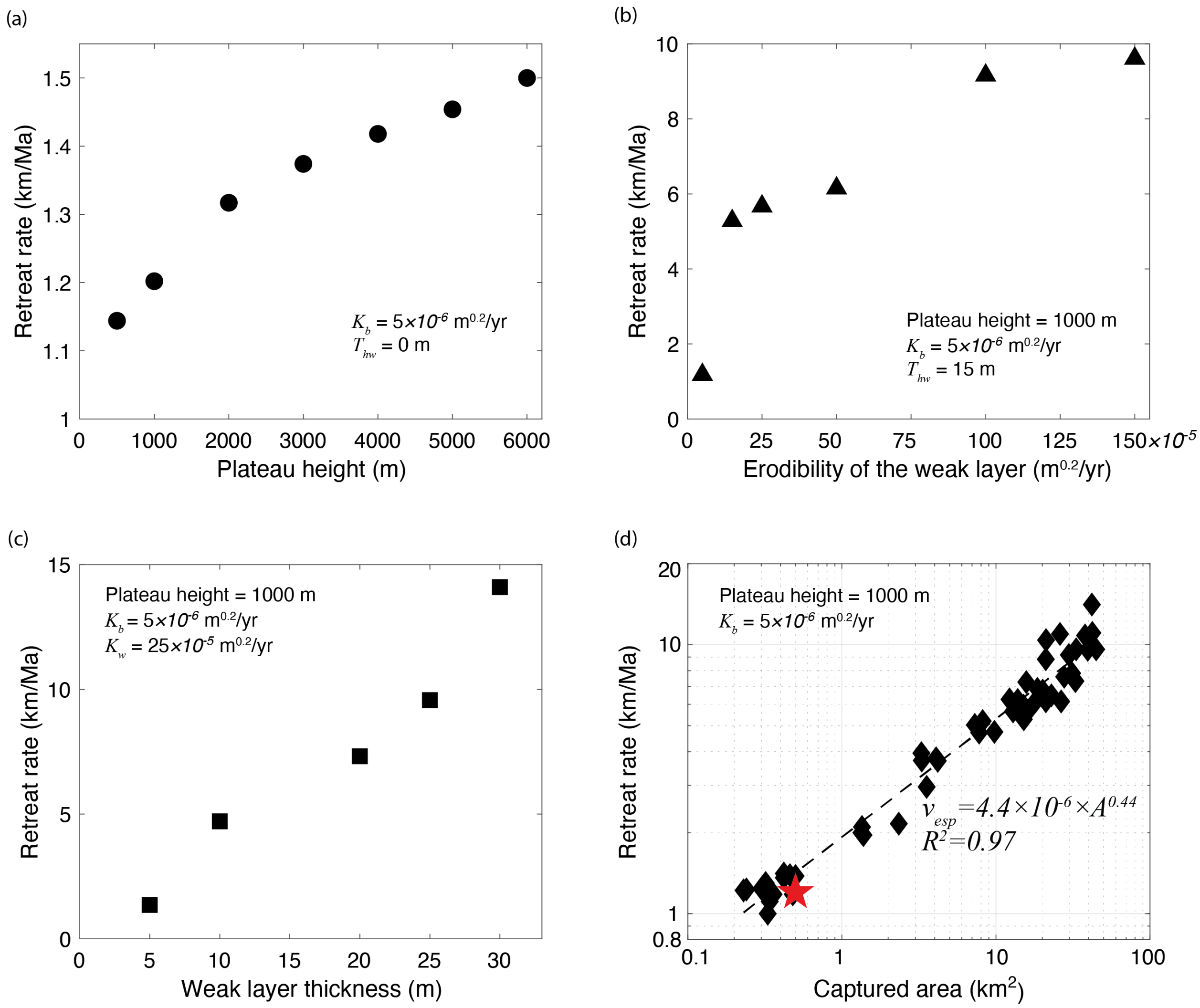

Fig. 8 Parametric dependence of escarpment retreat rates in numerical models. (a) Retreat rate against plateau height for a homogeneous erodibility (simulations S2-S8). (b) Effect of erodibility of surface layer of constant thickness (simulations S9-S14). (c) Effect of surface layer thickness with a fixed erodibility contrast of K_w/K_b (simulations S15-S19). (d) Combined effects of surface layer thickness and erodibility expressed through the instantaneous drainage area above the escarpment of constant plateau height. Black diamonds are from simulations S9-S19 of the weak surface layer model. The red star is from simulation S3 of the homogeneous substrate model. The regression (dashed line) of the retreat rate, V_{esp} (m/yr) and

captured area, A (m^2) is shown. See Supplement Tables S3 and S4 for the parameters of simulations S2-S19.

4 Discussion

4.1 Retreat rate and morphology of escarpment river profiles during retreat

Our models demonstrated that a knickzone-type escarpment whereby river profiles show a distinct morphological step at the escarpment face, but an inland water divide can emerge through processes of escarpment and divide migration with a heterogeneous substrate. A more erodible surface layer, such as occurs through weathering of crustal rocks can predispose an escarpment to large or frequent river captures and thus higher occurrence of stepped river profiles. With a surface layer that has sufficient thickness and weak rock strength, the divide migrates through discrete captures and reversals of plateau rivers at rates that are sufficiently fast to maintain a significant distance with the escarpment, and therefore, maintaining the stepped shape of the escarpment-divide system during retreat.

A key model observation is that although the escarpment and water divide evolve into a statistically stationary form with a constant separation distance, this is only a statistical relationship and individual rivers will deviate from the mean. In particular, any given margin, or even a specific drainage basin may exhibit both stepped- and unstepped river profiles (e.g. eastern Madagascar in Figure 2 and the conjugate margin of western India in Supplement Figure S4), depending on the history of river capture in the upstream reaches. This is a consequence of the discrete nature of divide migration through river capture. The dendritic nature of the plateau river network also affects the geometry of the drainage basins and the frequency and size of captures. Water divides with head-to-head river valleys exhibit more gradual divide migration whilst rivers head-to-trunk lead to more discrete captures (Bishop, 1995). Discrete captures bring additional erosional power to the escarpment, and therefore drive the escarpment retreat rate at a higher rate. However, depending on the relative rate of the escarpment retreat and the water divide, the plateau area may either increase or decrease, leading to transience in the escarpment retreat rate. In extreme cases, the divide-escarpment system can oscillate between the knickzone-type and the divide-type due to discrete capture-driven divide migration, followed by escarpment retreat bringing the escarpment to the water divide. Collectively, the escarpment-divide retreat system is a 2D problem that can exhibit considerable variability in both space and time.

The common occurrence of two types of escarpment-draining rivers across the escarpment of Madagascar (Fig. 2) supports this model for the formation of stepped, knickzone-type profiles. The fact that both types of rivers coexist along the escarpments of Madagascar suggests that the escarpment morphology is not a characteristic of the uplift pattern, but represents a perpetual state of a divide-escarpment migration with a large average distance between the escarpment and the water divide. Given the weathered plateau surface of Madagascar (Cox et al., 2010; Wells et al., 1997; Wells and Andriamihaja, 1993, 1990) and established river capture events near the major divide, we suggest that the current morphology reflects the retreat of the escarpment-divide system through progressive, discrete capture of the high plateau, and that this process has been active since continental rifting (Braun, 2018; Wang et al., 2021; Wang and Willett, 2021).

Although river captures occur on divide-type escarpments, the occurrence of a weak surface layer on the upper plateau greatly increases the frequency and size of captures. The increase is largely the result of complex, sequential captures. For example, the pattern of headward piracy, whereby a major river is reversed and all its tributaries captured is encouraged by an erodible surface layer (Harel et al., 2019). This sequence occurs frequently in the numerical models as well as in Madagascar as demonstrated by the Mananara and Manampatrana examples (Fig. 3). From the model observations, a thicker and weaker surface layer is prone to drive faster divide migration and therefore faster escarpment migration. The overall impact of the weak surface layer on retreat rate can be directly expressed by the captured area which we show scales positively with retreat rate (Fig. 8d). The capture history of individual escarpment rivers or catchments is complex and retreat rates unsteady; the captured area, however, provides a snapshot of the current retreat rate which can be tested with natural data.

Within this framework, the distinction between divide-type escarpment rivers and knickzone-type escarpment rivers can be seen as artificial. All escarpments migrate by divide migration, river reversal and capture, but with differing degrees of transience. A divide-type escarpment river profile can be seen as the end-member mode where, at least locally, no river capture has occurred in the recent past. If an escarpment shows a predominance of divide-type rivers, it is an indication that conditions are not optimal for reversals and captures, e.g. no weathered weak layer, or the river pattern on the upper surface is not favorable for river capture. The counter case, where a margin escarpment shows dominantly stepped profiles, may reflect conditions favourable to river reversal and capture, rather than a fundamental difference in uplift pattern, i.e. arching of the passive margin. Given that river capture accelerates retreat rates, the divide-type rivers represent a "background" retreat rate. This background rate will scale with plateau height and rock erodibility (e.g. Willett et al., 2018), but will be locally enhanced wherever river capture occurs (Supplement Movie S5). This enhancement should follow a scaling with captured area (Fig. 8d).

4.2 Comparison with the escarpments of Madagascar and the Western Ghats of India

Madagascar and the Western Ghats of India represent conjugate margins (Thompson et al., 2019), each of which is characterized by a large escarpment. The climate of the two escarpments is similar with both dominated by monsoonal and orographic precipitation (Gunnell, 1997; Scroxton et al., 2017; Varikoden et al., 2019). The lithology of the two escarpments is primarily Precambrian metamorphic rock. Studies show that the Deccan plateau inland of the great escarpment of the Western Ghats in India is highly weathered as we inferred for Madagascar (Beauvais et al., 2016; Bonnet et al., 2016, 2014). Both knickzone-type and divide-type escarpment river profiles are found in the Western Ghats. About 33% of the escarpment rivers of the Western Ghats show knickzone-type or indeterminate morphology (Supplement Figure S4). We test the scaling relationship of retreat rate and drainage area with the DCN ^{10}Be concentration-derived retreat rates of both the Madagascar escarpment and the Western Ghats using the results of Wang et al. (2021). We select escarpment-draining basins with a significant portion of plateau area. This is complicated by the fact that an escarpment-draining basin can have multiple tributary rivers that originate from the plateau but have a variable area above the escarpment edge.

DCN ^{10}Be concentration-derived retreat rates of the Madagascar escarpment and the Western Ghats escarpment positively scale with the drainage area above the escarpment edge (Fig. 9). One basin (marked with a red open box) deviates from the trend, and has an unusual morphology with deep and narrow gorges and significant captured plateau area but minimal lowland area, leading to large uncertainty in the derived retreat rate (Wang and Willett, 2021). Taking out this outlier basin, the remaining data show a statistically strong correlation ($p<0.001$ for the regression in log-log space).

The remaining variability in retreat rate can be partially explained by variability in plateau height and rock erodibility of the escarpment. The plateau height of Madagascar and India escarpment covers a wide range of 500 m-2500 m (Fig. 9). Although there is not a clear correlation between height and retreat rate, some large residuals seem to be related to height variations (Fig. 9). Given the heterogeneity of the escarpment substrate, rock erodibility could also explain some of the variance in Figure 9. Although the primary lithology of both margins is Precambrian metamorphic rock, a variety of lithology is present in different individual basins and there is some variance reduction by considering specific rock types in the catchments (Supplement Figure S5).

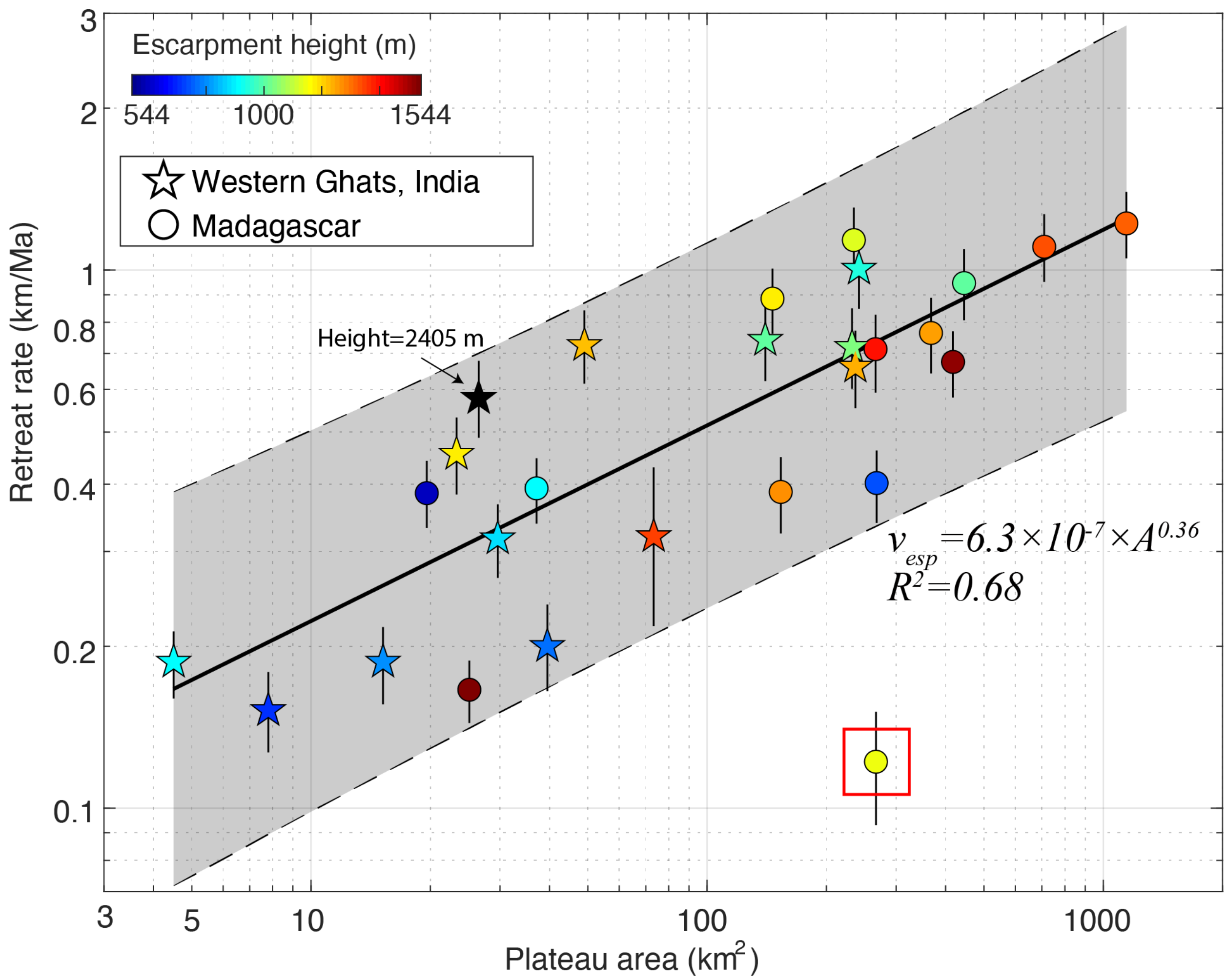

Fig. 9 Measured retreat rates of the Madagascar escarpment and the Western Ghats escarpment from detrital cosmogenic nuclide ^{10}Be concentrations. Regression omitting one outlier for retreat rate, V_{esp} (m/yr), and captured area, A (m^2) is shown. Measured escarpment retreat rates from Wang et al. (2021). Grey shading is the 95% confidence envelope.

5 Conclusions

In this paper, we have used theory, numerical models, geomorphological and geochemical data to support the idea that the morphological difference in escarpment river profiles, in particular, the spatial offset between the main water divide and escarpment is a consequence of river captures that occur as the escarpment migrates. Escarpments are characterized by rivers that head against the escarpment and others that drain part of the upper plateau. We argue that the relative proportion of each type depends on the ease with which river capture occurs and thus the size and frequency of captures. Large and frequent captures are particularly encouraged by a more easily eroded upper surface of the plateau, a condition that we argue is present in Madagascar and the Western Ghats of India due to surface weathering. High surface weathering is encouraged by the warm, wet climate and low physical erosion rates of the highlands. Our 2D landscape evolution models confirmed the hypothesis and revealed a power-law scaling between the retreat rate and the captured area. The retreat rates of the great escarpments of Madagascar and India are consistent with this hypothesized scaling.

Code availability

Codes of the landscape evolution models are available at https://github.com/yanyanwangesd/DAC-weaksurfacelayer or upon request to the corresponding author.

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